Development of Asymmetric Catalysts Based on Planar-Chiral π-Complexes of Nitrogen Heterocycles with Iron

by

James Craig Ruble

B. S. Chemistry
Indiana University, 1994

Submitted to the Department of
Chemistry in Partial Fulfillment of the
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ABSTRACT

A new approach to introducing asymmetry into nucleophilic catalysts while minimizing steric bulk in the vicinity of the nucleophilic atom was explored. Because many of the most effective nucleophilic catalysts have planar structures (e.g., 4-(dimethylamino)pyridine, pyridine, and imidazole), we were interested in the synthesis of chiral analogs of these catalysts. Since the nucleophilic atom in each of these molecules is sp^2-hybridized, this goal presented a challenge. Steric bulk in the vicinity of the nitrogen atom would decrease its nucleophilicity, but some steric bulk was needed to establish asymmetry. Rather than focusing on molecules containing a necessarily bulky tertiary stereogenic center in the 2-position of the heterocycle, we investigated planar-chiral pi-complexes of 2-substituted heterocycles with cyclopentadienyliron fragments. We viewed the chirality of these complexes as being derived from effective differentiation of left from right (substituent vs. H) and of top from bottom (void vs. metal fragment).

Although several iron complexes with pyrroles were known (azaferrocenes), we found that these complexes lacked the stability desired in a catalyst. We discovered that the use of the pentamethylcyclopentadienyliron (Cp*-Fe) fragment resulted in pyrrolyl complexes with enhanced stability over their Cp analogs. A route to an enantiopure pyrrolyl-Fe-Cp* complex was discovered. Although initial reactivity studies indicated that the azaferrocene-derived complexes could serve as nucleophilic catalysts, their reactivity was not as high as we had hoped, so complexes containing pyrindine-derived ligands were also synthesized.

Because the parent pyrindinyl-Fe-Cp* complex was found to be only a weak catalyst, we developed a synthesis of 4-(dimethylamino)pyrindine and prepared its pentamethylcyclopentadienyliron complex. We viewed this complex as a chiral analog

of DMAP and demonstrated that it was active as a catalyst for acylation of alcohols with acetic anhydride, acylation of alcohols with diketene, cyanosilylation of aldehydes with triethylsilylcyanide, and addition of alcohols to ketenes. The DMAP analog was resolved by chiral HPLC, but resulted in a disappointing selectivity when used as a catalyst for the kinetic resolution of 1-phenylethanol by acylation with acetic anhydride.

By using the pentaphenylcyclopentadienyliron fragment, a new chiral DMAP derivative was prepared with increased top-bottom differentiation. The pentaphenyl derivative was found to be very effective as a catalyst for asymmetric acylation of alcohols with acetic anhydride, particularly when the reactions were conducted with a tertiary alcohol as the solvent. Experiments were performed to explore the substrate scope and mechanism of this reaction. Arylalkylcarbinols and certain allylic alcohols were found to be acylated with high selectivity. An X-ray crystal structure was determined for an *N*-acylpyridinium salt of the catalyst.

The rearrangement of certain *O*-acylated enolates to beta-dicarbonyls was also shown to be catalyzed by our planar-chiral pi-complexes. A chiral analog of PPY was synthesized and found to be the catalyst of choice for this oxygen-to-carbon acyl transfer reaction. Enol carbonates derived from the *O*-acylation of azlactones were the best substrates for this reaction, rearranging in high yield and with excellent enantiomeric excess at the newly-formed quaternary stereocenter. The products of this carbon-carbon bond-forming reaction were ring opened with alcohols and amines to form the corresponding esters and amides and with sodium borohydride to form a protected alpha-methylserine. Preliminary mechanistic and kinetic studies indicated that the catalyst is acylated in the resting state of this reaction.

Thesis Supervisor: Gregory C. Fu

Title: Professor of Chemistry

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Ruble, J. C.; Fu, G. C. "Chrial π-Complexes of Heterocycles with Transition Metals: A Versatile New Family of Nucleophilic Catalysts," *J. Org. Chem.* **1996**, *61*, 7230-7231.

Ruble, J. C.; Latham, H. A.; Fu, G. C. "Effective Kinetic Resolution of Secondary Alcohols with a Planar-Chiral Analogue of 4-(Dimethylamino)pyridine. Use of the Fe(C_5Ph_5) Group in Asymmetric Catalysis," *J. Am. Chem. Soc.* **1997**, *119*, 1492-1493.

Dosa, P. I.; Ruble, J. C.; Fu, G. C. "Planar-Chiral Heterocycles as Ligands in Metal-Catalyzed Processes: Enantioselective Addition of Organozinc Reagents to Aldehydes," *J. Org. Chem.* **1997**, *62*, 444-445.

Ruble, J. C.; Tweddell, J.; Fu, G. C. "Kinetic Resolution of Arylalkylcarbinols Catalyzed by a Planar-Chiral Derivative of DMAP: A New Benchmark for Nonenzymatic Acylation," *J. Org. Chem.* **1998**, *63*, 2794-2795.

Liang, J.; Ruble, J. C.; Fu, G. C. "Dynamic Kinetic Resolutions Catalyzed by a Planar-Chiral Derivative of DMAP: Enantioselective Synthesis of protected α-Amino Acids from Racemic Azlactones," *J. Org. Chem.* **1998**, *63*, 3154-3155.

Ruble, J. C.; Fu, G. C. "Enantioselective Construction of Quaternary Stereocenters: Rearrangements of *O*-Acylated Azlactones Catalyzed by a Planar-Chiral Derivative of 4-(Pyrrolidino)pyridine," *J. Am. Chem. Soc.* **1998**, *120*, 11532-11533.

Hodous, B. L.; Ruble, J. C.; Fu, G. C. "Enantioselective Addition of Alcohols to Ketenes Catalyzed by a Planar-Chiral Azaferrocene: Catalytic Asymmetric Synthesis of Arylpropionic Acids," *J. Am. Chem. Soc.* **1999**, *121*, 2637-2638.

Tao, B.; Ruble, J. C.; Hoic, D. A.; Fu, G. C. "Non-Enzymatic Kinetic Resolution of Propargylic Alcohols by a Planar-Chiral DMAP Derivative; Crystallographic Characterization of the Acylated Catalyst," *submitted for publication.*

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That brings me to graduate school, the last 55 (but who's counting) months of my life. I owe a great deal thanks to my advisor, Professor Greg Fu. Greg took me in with very little lab experience and trusted me with a fabulously interesting and fruitful project. I feel especially fortunate, having been one of his first students, that Greg took the time to work one on one with me on so many occasions. He deserves special thanks for not uttering a single unkind word when I destroyed a $5,000 HPLC column on the first day that we had it.

What Greg didn't teach me, I learned from the four graduate students who came before me in the group: David, Mike, Diego, and Chris. I thank them all for tolerating my countless questions. Also deserving of special mention are the four people who endured sharing a bay with me: Ken, Hallie, Peter, and Brian. I am happy to say that they are all still my friends. I owe a special debt to Ken; if he hadn't suggested that I use a Cp* ligand in my catalysts, I may have spent the last 4 years in the dark! Brain also

gets special mention, as he was the only one not smart enough to run away when I was searching for proofreaders for my thesis. I have particularly enjoyed having the opportunity to work with three undergraduates: Wendy, Ivory, and Adriane. I think they taught me more than I taught them, and I thank them. There is one person from the group with whom I have had a special bond over the last 4 years. Jack Liang's incredible tolerance for junk food made him the perfect lunch partner for me. If we ever meet again, I'm sure it will be at a McDonalds. It's been a pleasure serving with you, Jack. I'd also like to thank all of the rest of the Fu group members, present and past. I won't try to list them all, because I wouldn't want to forget anyone.

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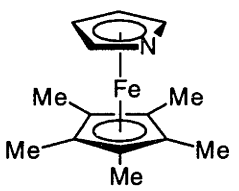
ABBREVIATIONS

Cp*	1,2,3,4,5-pentamethylcyclopentadienyl
d	doublet
DABCO	1,4-diaza-bicyclo[2.2.2]octane
DCC	1,3-dicyclohexylcarbodiimide
DMAP	4-(dimethylamino)pyridine
eq	equation
equiv	equivalent(s)
GC	gas chromatography
h	hour(s)
HPLC	high pressure liquid chromatography
HRMS	high resolution mass spectroscopy
IR	infrared
LDA	lithium diisopropylamide
min	minute(s)
MTO	methyltrioxorhenium
NMR	nuclear magnetic resonance
ppm	parts per million
PPY	4-(pyrrolidino)pyridine
q	quartet
quint	quintet
r.t.	room temperature
s	singlet
t	triplet
TES	triethylsilyl
THF	tetrahydrofuran
TLC	thin-layer chromatography

STRUCTURES FREQUENTLY ENCOUNTERED IN THIS THESIS



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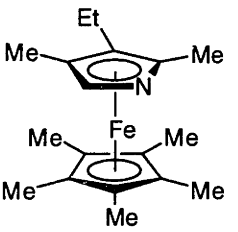

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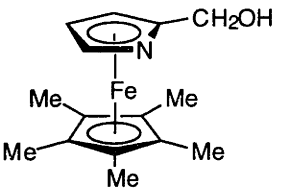

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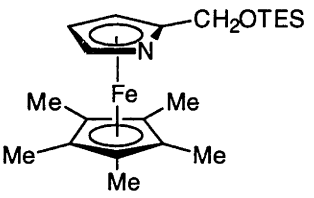

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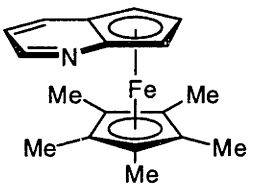

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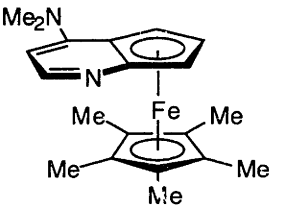

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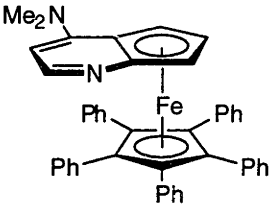

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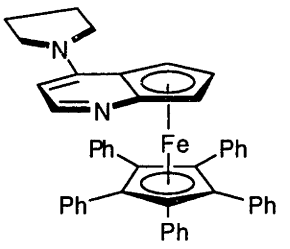

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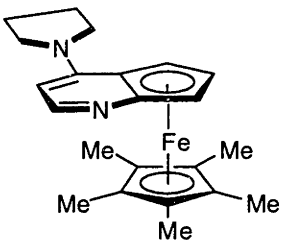


(-)-**3.13**

Introduction

While the past decades have seen a flurry of activity in the development of chiral Lewis acid catalysts for a variety of synthetically useful reactions,[1] the field of chiral Lewis base catalysis remains in relative infancy. This despite the fact that a wide range of potentially asymmetric reactions are known to be catalyzed by Lewis bases. Among these reactions are the acylation of alcohols,[2] the addition of alcohols to ketenes,[3] the cyanosilylation of aldehydes,[4] the silylation of alcohols,[5] and the cycloaddition of 2-butynoates with electron-deficient olefins,[6] to name a few. In principle, there are at least three broad types of mechanistic schemes in which a Lewis base can function in a catalytic reaction; it can function as a nucleophilic catalyst, as a ligand for a metal, or as a Brønsted base.

In the case of nucleophilic catalysis, the catalyst becomes transiently bonded to one or more of the reactants. This bonding of the catalyst imparts some change in reactivity to the substrates, resulting in the desired reaction with subsequent ejection of the catalyst. An excellent example of this sort of mechanism is seen in the Baylis-Hillman reaction, a carbon-carbon bond-forming reaction between an electron-deficient olefin and an aldehyde.[7] In the mechanism proposed for this reaction (Scheme i.1), the nucleophilic catalyst (e.g., 1,4-diaza-bicyclo[2.2.2]octane (DABCO)) adds in a conjugate fashion to the activated olefin, thus increasing the nucleophilicity of the carbon α to the activating group. The α-carbon then adds to

---

1 Maruoka, K.; Yamamoto, H. In *Catalytic Asymmetric Synthesis*; Ojima, I., Ed.; VCH: New York, 1993; Chapter 9.

2 (a) Pyridine: Verley, A.; Bölsing, F. *Ber. Dtsch. Chem. Ges.* **1901**, *34*, 3354-3358. (b) DMAP: Steglich, W.; Höfle, G. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 981. (c) Tributylphosphine: Vedejs, E.; Diver, S. T. *J. Am. Chem. Soc.* **1993**, *115*, 3358-3359.

3 Tidwell, T. T. *Ketenes*; Wiley: New York, 1995.

4 Kobayashi, S.; Tsuchiya, Y.; Mukaiyama, T. *Chem. Lett.* **1991**, 537-540.

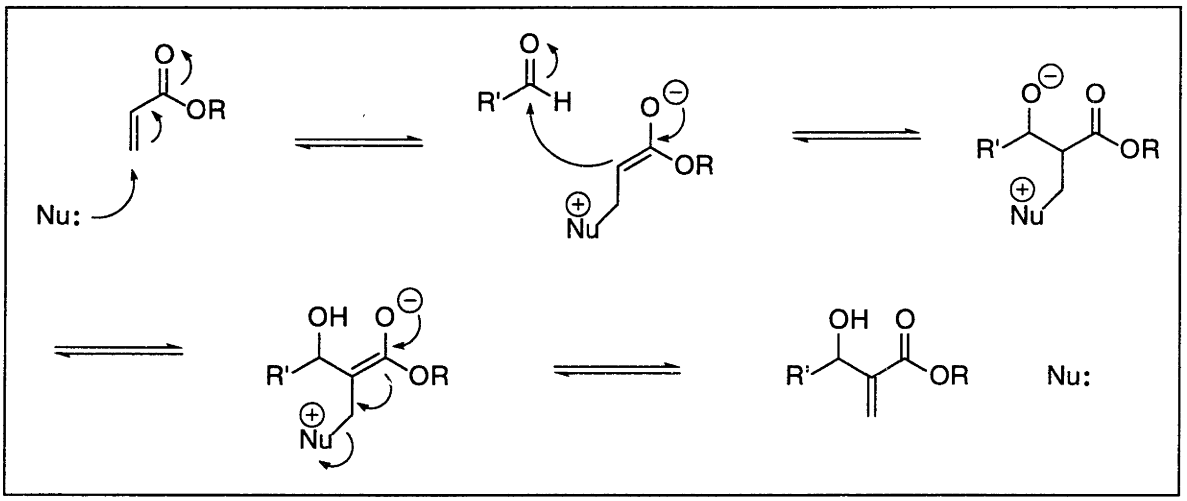
5 (a) Imidazole: Corey, E. J.; Venkateswarlu, A. *J. Am. Chem. Soc.* **1972**, *94*, 6190-6191. (b) Pyridine: Ogilvie, K. K. *Can. J. Chem.* **1973**, *51*, 3799-3807. (c) DMAP: Chaudhary, S. K.; Hernandez, O. *Tetrahedron Lett.* **1979**, 2, 99-102.

6 Zhang, C.; Lu, X. *J. Org. Chem.* **1995**, *60*, 2906-2908.

7 For a review of the Baylis-Hillman reaction, see: Drewes, S. E.; Roos, G. H. P. *Tetrahedron* **1988**, *44*, 4653-4670.

an aldehyde with subsequent proton transfer and elimination of the catalyst to regenerate the olefin.

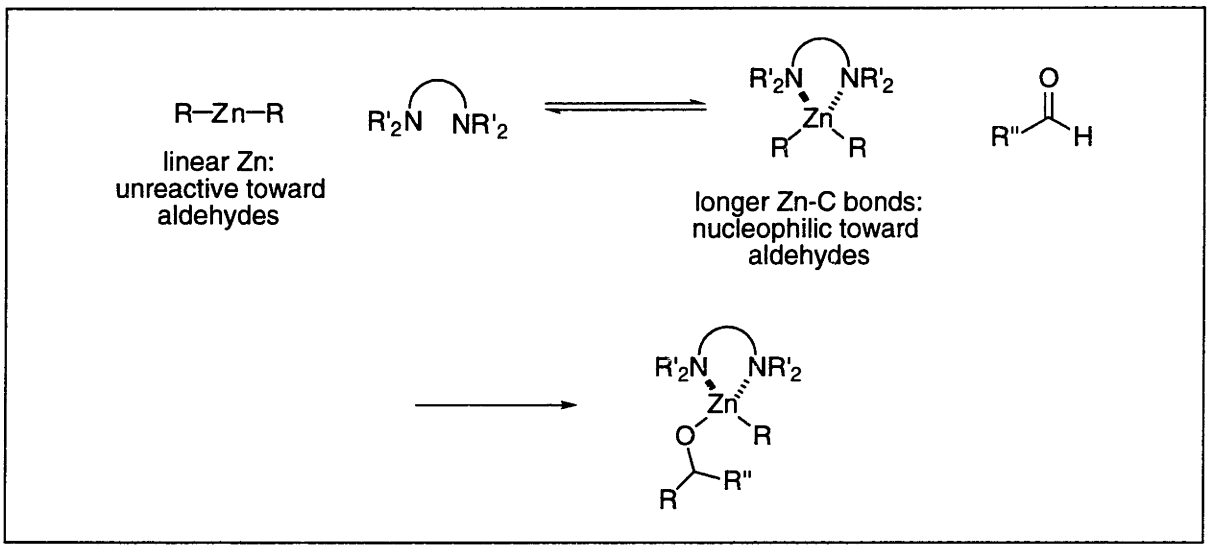
Scheme i.1. An Example of the Baylis-Hillman Reaction.



A Lewis base may also function catalytically in a reaction by acting as ligand for a metal. While conceptually very similar to the case of nucleophilic catalysis, a distinction can be drawn between those mechanisms in which the Lewis base is interacting with organic components of the reaction mixture and those in which the chief interactions of the Lewis base are with a metal. One well known example of catalysis by a Lewis base acting as a ligand for a metal is seen in the addition of dialkylzinc reagents to aldehydes, Scheme i.2.[8] In this reaction, the Lewis base coordinates to the initially linear and unreactive Zn species, causing it to adopt a more tetrahedral geometry. This change in geometry results in a lengthening of the zinc-carbon bonds and a corresponding increase in their nucleophilicity.

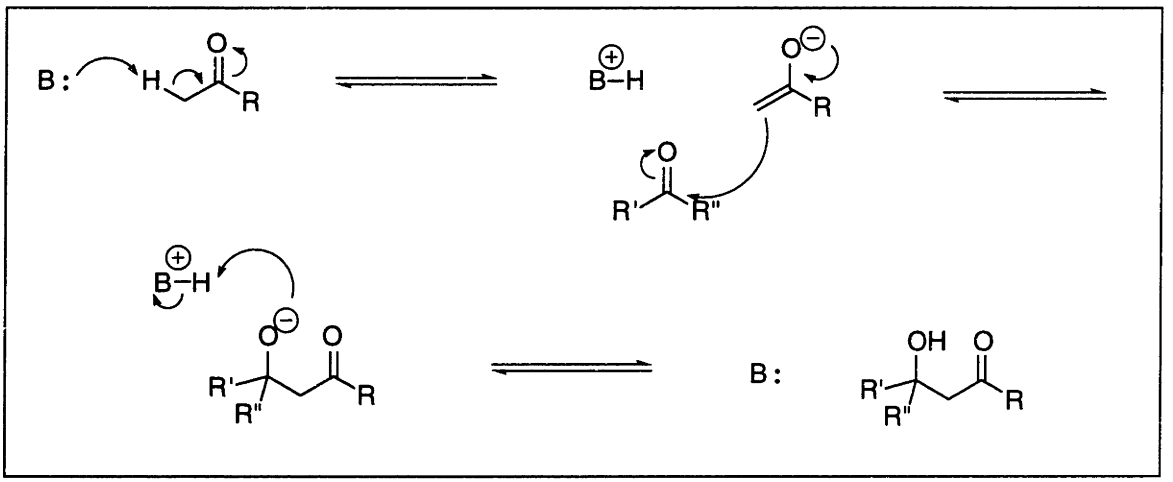
8 Soai, K.; Niwa, S. *Chem. Rev.* **1992**, *92*, 833-856.

Scheme i.2. Addition of a Dialkylzinc to an Aldehyde.



The third mechanistic role of a Lewis base to be considered is that of a Brønsted base. Perhaps the best known mechanism of this type is that of the aldol reaction, Scheme i.3.[9] In this mechanism, the role of the catalyst is simply the removal and delivery of protons at specific points along the reaction pathway.

Scheme i.3. The Base-Catalyzed Aldol Reaction.



While it is the ultimate goal of this group to develop new chiral catalysts for each of the above types of reactions, they each present unique challenges, and the present

9 March, J. *Advanced Organic Chemistry*, 4th ed.; Wiley-Interscience: New York, 1992; p 937.

work is dedicated primarily to the development of chiral *nucleophilic* catalysts. When setting out to develop a new chiral nucleophilic catalyst, one almost immediately finds oneself stuck between the proverbial rock and a hard place; while a certain amount of steric bulk is certainly necessary to establish a chiral environment, the nucleophilicity of the catalyst is diminished by steric bulk in the vicinity of the nucleophilic atom. This effect of sterics on nucleophilicity has been systematically studied in the case of pyridine derivatives, which are among the most commonly used nucleophilic catalysts. In an excellent review of the chemistry of 4-(dimethylamino)pyridine (DMAP), Scriven has assembled relative rate data for a variety of pyridine derivatives as catalysts in the benzoylation of *m*-chloroaniline and benzyl alcohol.[10] These results are shown in Table i.1.

Table i.1. Relative Rates of Benzoylation of *m*-Chloroaniline and of Benzyl Alcohol in the Presence of a Variety of Amine Bases.

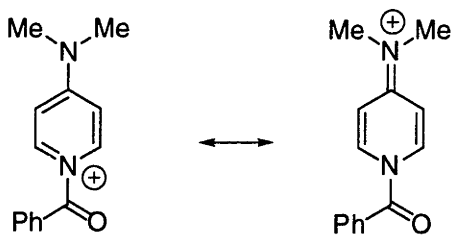
Entry	Catalyst	pK_a (R_3NH^+)	Relative Rate	
			m-chloroaniline	benzyl alcohol
1	3-Pyridinecarbonitrile	1.39	14	12
2	Quinoline	4.87	138	545
3	Pyridine	5.23	568	9.29×10^3
4	Isoquiniline	5.40	2.62×10^3	3.39×10^3
5	2-Methylpyridine	5.96	29	435
6	3-Methylpyridine	5.63	1.12×10^3	2.29×10^4
7	4-Methylpyridine	6.02	2.96×10^3	3.98×10^4
8	4-Phenoxypyridine	6.25	4.80×10^3	7.98×10^4
9	2,6-Dimethylpyridine	6.72	8	115
10	DMAP	9.70	3.14×10^6	3.45×10^8
11	triethylamine	10.65	21	-

A comparison of the results for the three mono-methyl substituted pyridines (entries 5-7) clearly shows the impact of steric bulk on reactivity. Even though the pK_a of the conjugate acid remains virtually unchanged as the methyl group is

10 Scriven, E. F. V. *Chem. Soc. Rev.* **1983**, *12*, 129-161.

moved to different positions on the ring, the catalytic activity is changed by as much as two orders of magnitude!

While steric bulk in the 2-position is known to lower the activity of pyridines as nucleophilic catalysts, an electron-donating group in the 4-position can greatly enhance the catalytic activity. Comparison of pyridine and DMAP in the benzoylation of benzyl alcohol (entries 3 and 10) reveals that DMAP is approximately 3 X 10^4 times more active as a catalyst in this nucleophile-catalyzed process than is pyridine, presumably due to resonance stabilization of the proposed intermediate **i.1**. Given that the electronic activation of an amino group may help to overcome the steric deactivation from the presence of a stereocenter in the 2-position, it would seem reasonable that one might combine the two in an attempt to make a pyridine-derived nucleophilic catalyst that is both highly active and enantioselective.

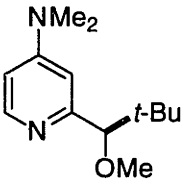


i.1

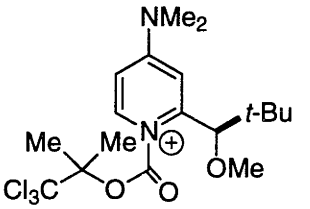
At about the time that our work in this area was beginning, we became aware of work by Vedejs aimed at just such a catalyst. In early 1996, he reported the synthesis of chiral DMAP derivative **i.2** as a single enantiomer.[11] Unfortunately, the bulk of the stereogenic carbon atom in the 2-position of the pyridine overwhelms the activating effect of the 4-dimethylamino group, and **i.2** was not reported to be a catalyst for acylation reactions. Instead, a pre-formed acylpyridinium salt, **i.3**, was prepared and used in asymmetric acylation reactions. Although the selectivity was

11 Vedejs, E.; Chen, X. *J. Am. Chem. Soc.* **1996**, *118*, 1809-1810.

promising, the Vedejs compound clearly has too much bulk near the nucleophilic nitrogen atom of the pyridine.



i.2



i.3

This thesis presents our work on a fundamentally different approach to creating an effective chiral nucleophilic catalyst. Instead of relying upon a necessarily bulky stereogenic carbon atom, we propose to introduce asymmetry in the vicinity of the nucleophilic atom through π-complexation of an unsymmetrically substituted heterocycle to a metal fragment. Details on the design and synthesis of two classes of these planar-chiral catalysts are presented in Chapter 1, followed by initial reactivity studies. Chapter 2 describes our work with these catalysts in the kinetic resolution of secondary alcohols by asymmetric acylation, using either diketene or an anhydride as the acylating agent. Described in Chapter 3 is our work on an asymmetric variant of the Steglich rearrangement of *O*-acylated enolates to β-dicarbonyls.

Chapter One:

Design, Synthesis, and Initial Reactivity Studies of Nucleophilic Catalysts Based on Planar-Chiral π-Complexes of Nitrogen Heterocycles with Iron

Chapter One, Part A: Introduction to Heterocyclic π-Complexes

A wide range of reactions are known to be subject to catalysis by nucleophiles. Among these are such interesting and potentially useful reactions as the cyanoacylation of aldehydes,[1] cycloadditions of ketenes,[2] the addition of nucleophiles to the γ-position of ynones,[3] the Baylis-Hillman reaction,[4,5] and the ring opening of epoxides with TMS-Cl.[6] Despite this fact, the goal of making an effective chiral nucleophilic catalyst with general applicability to the asymmetric versions of these reactions had met with little success when we entered the field in 1995. A brief look at some of the most widely employed nucleophilic catalysts may hold a clue as to why this was the case (Figure 1.1). While it is true that over 1,000 chiral phosphines have been reported[7] and that chiral tertiary amines are found in many alkaloids,[8] chiral versions of the other catalysts shown in Figure 1.1, namely derivatives of pyridine, 4-(dimethylamino)pyridine (DMAP), and imidazole, are much more scarce.

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1 Hoffmann, H. M. R.; Ismail, Z. M.; Hollweg, R.; Zein, A. R. *Bull. Soc. Chem. Jpn.* **1990**, *63*, 1807-1810.

2 (a) Wynberg, H.; Staring, E. G. J. *J. Chem. Soc., Chem. Commun.* **1984**, 1181-1182. (b) For a recent application of this reaction to the asymmetric synthesis of dipropionate synthons, see: Calter, M. A.; Guo, X. *J. Org. Chem.* **1998**, *63*, 5308-5309.

3 Trost, B. M.; Li, C.-J. *J. Am. Chem. Soc.* **1994**, *116*, 3167-3168.

4 Baylis, A. B.; Hillman, M. E. D. *German Patent 2155113*, **1972**.

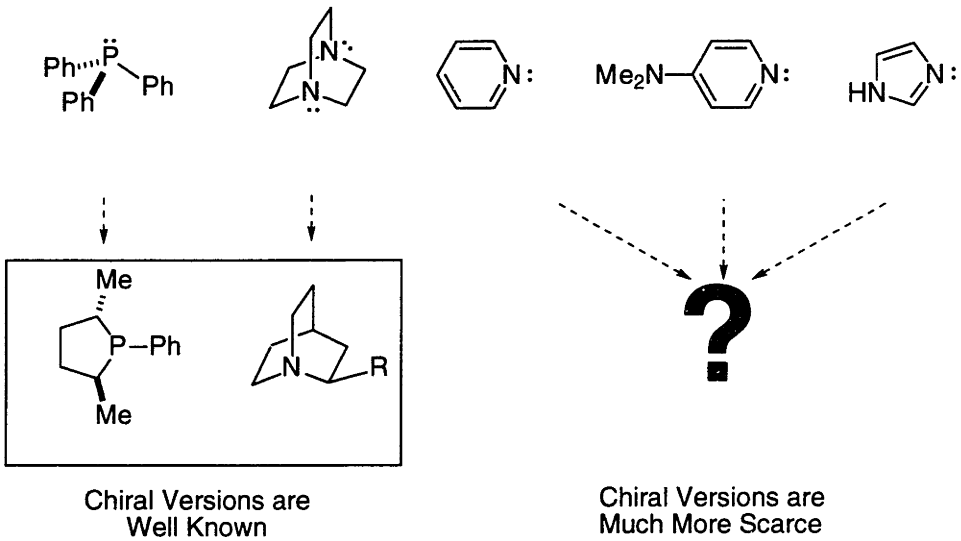
5 For a review, see: Drewes, S. E.; Roos, G. H. P. *Tetrahedron* **1988**, *44*, 4653-4670.

6 Andrews, G. C.; Crawford, T. C.; Contillo, L. G., Jr. *Tetrahedron Lett.* **1981**, *22*, 3803-3806.

7 (a) Brunner, H. *Top. Stereochem.* **1988**, *18*, 129-247. (b) Brunner, H., Zettlmeier, W., Eds. *Handbook of Enantioselective Catalysis*; VCH: New York, 1993; Vol. 2.

8 For a review of asymmetric catalysis by alkaloids, see: Wynberg, H. *Top. Stereochem.* **1986**, *16*, 87-129.

Figure 1.1. Commonly Used Nucleophilic Catalysts.



This scarcity is perhaps due to the fact that the nucleophilic atom in these cases is sp^2-hybridized. The conceptually most straightforward approach to the generation of a chiral derivative of these planar nucleophilic catalysts would be to install a stereogenic carbon atom in the 2-position of the heterocycle, as in Figure 1.2. This approach unfortunately suffers from two serious drawbacks. First, the stereogenic atom is two bonds removed from the nucleophilic atom, thus reducing, to a first approximation, the likelihood of asymmetric induction. Second, the activity of pyridine derivatives as nucleophilic catalysts is known to be quite sensitive to steric bulk in the 2-position; the presence of even a methyl group being enough to lower catalytic activity by two orders of magnitude relative to electronically similar derivatives.[9] Since a carbon atom should be at least tertiary to be a stereocenter, it is reasonable to expect that a compound such as that in Figure 1.2 will not be highly active as a catalyst. This lack of catalytic activity was observed by Vedejs in 1996 for just such a compound (R^1=*t*-Bu, R^2=OMe).[10] Clearly, a completely different approach to the development of a chiral nucleophilic catalyst was warranted.

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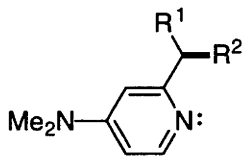
9 Scriven, E. F. V. *Chem. Soc. Rev.* **1983**, *12*, 129-161.

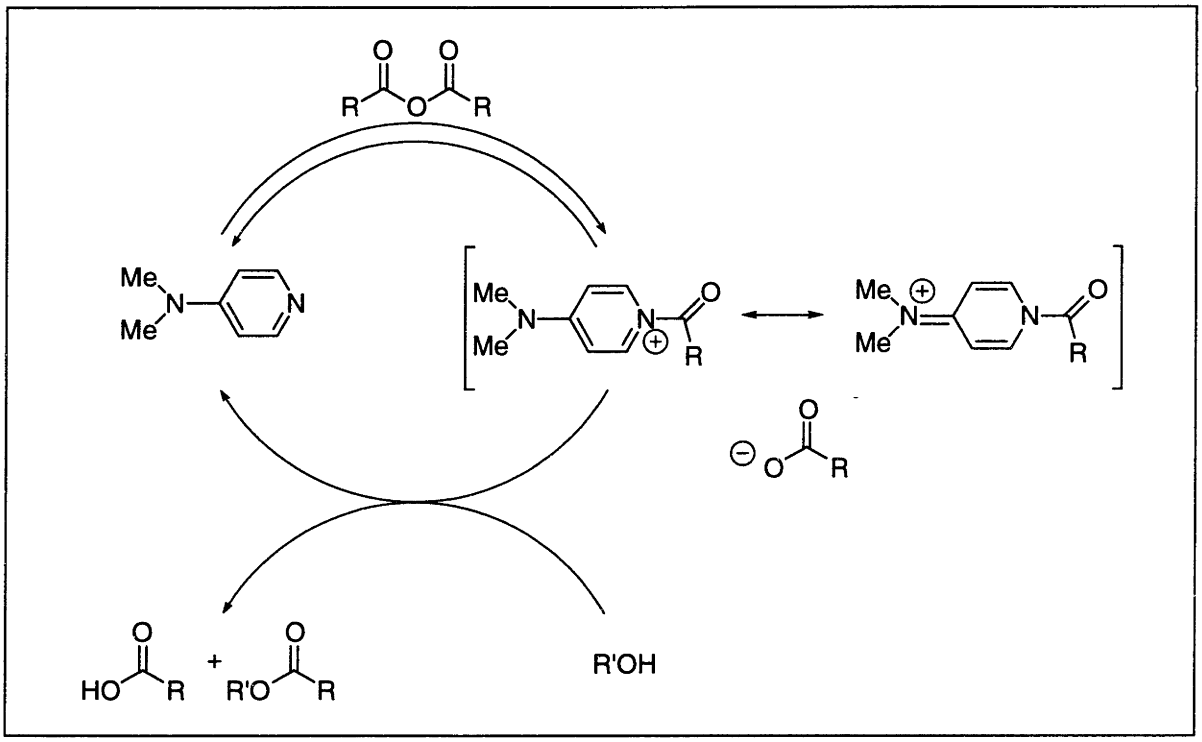
10 Vedejs, E.; Chen, X. *J. Am. Chem. Soc.* **1996**, *118*, 1809-1810.

Figure 1.2. Likely Candidate for Chiral sp^2-Hybridized Nucleophilic Catalyst.



From the outset of our work in this field, we have had the goal of developing a highly enantioselective version of the DMAP-catalyzed acylation of alcohols with anhydrides. Therefore, the mechanism of this reaction, shown in Scheme 1.1, was always kept in mind when we considered possible solutions to the above challenge. That this is the operative mechanism suggests a couple of important facts. First of all, DMAP must be more nucleophilic toward the anhydride than is the alcohol. Secondly, the resonance-stabilized *N*-acylpyridinium salt intermediate must be a better acylating agent for alcohols than acetic anhydride. A careful look at this mechanism makes clear our challenge if we are to construct the desired enantioselective catalyst: We must build a system in which the active acylating agent (*N*-acylpyridinium salt) effectively presents asymmetry to approaching alcohols, but we must not bulk up the molecule in the vicinity of nitrogen to the point of suppressing *either* its acylation by anhydride or its deacylation by alcohol.

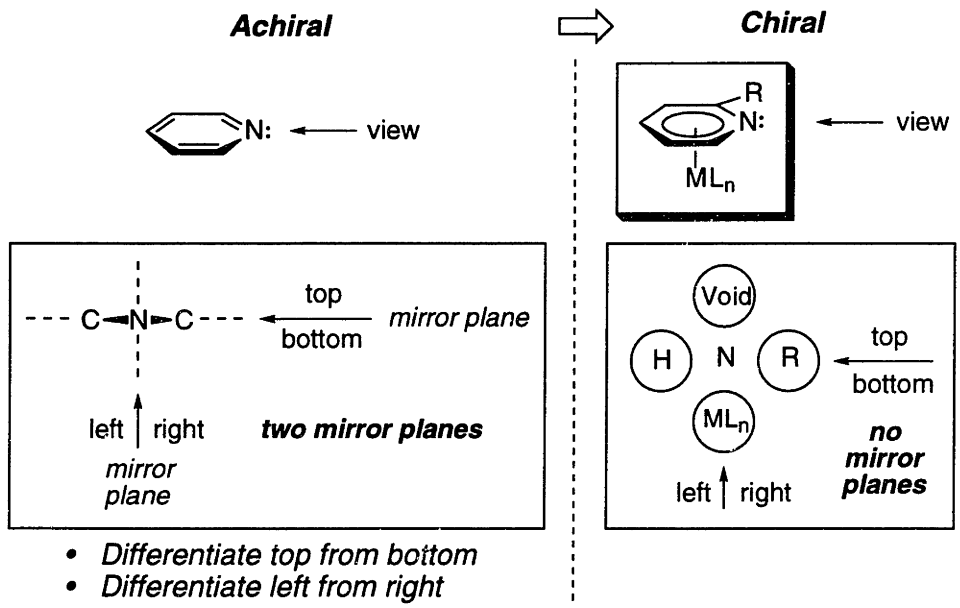
Scheme 1.1. Mechanism of the DMAP Catalyzed Acylation of Alcohols.



So, how does one make a chiral version of a planar catalyst without employing a stereogenic center? Our approach was to turn this question around and ask ourselves what makes molecules of this sort *achiral*. Most chemists are taught in sophomore organic chemistry that a molecule is achiral if it contains a mirror plane. Pyridine, then, is obviously achiral by virtue of its two mirror planes, one defined by the plane of the heterocycle and the other perpendicular to the first and passing through the nitrogen and para carbon atom. If, however, we systematically destroy the two mirror planes of pyridine by first π-complexing a metal fragment to one face of the heterocycle and then introducing a 2-substituent, the resulting complex is chiral.[11] This is the basis of our proposed catalysts, as shown in Figure 1.3.

11 For a review of planar-chirality, see: Schlögl, K. *Top. Curr. Chem.* **1984**, *125*, 29-62.

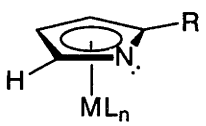
Figure 1.3. A Planar-Chiral Heterocycle.



We felt that planar-chiral heterocycles might offer several important advantages over other catalyst systems. Perhaps most importantly, the 2-substituent in our catalysts would not have to contain a bulky stereogenic center and could be as small as a methyl group. This fact led us to hope that these compounds might be quite active as nucleophilic catalysts. Another important factor is that the asymmetry in the vicinity of the nucleophilic atom should be very well-defined. If one imagines the view down the (lone pair) - (nitrogen atom) axis of such a molecule, the effect of our stepwise desymmetrization should be clear: there is a complete void on top of the heterocycle and a large metal fragment below, a proton on the left-hand side and a larger substituent on the right-hand side. Furthermore, the degree of this asymmetry should be easily tunable. Using a larger metal fragment or a larger 2-substituent should loosely correspond to making the molecule "more chiral." Finally, the electronics of the system might also be tunable, either by introduction of a remote substituent on the heterocycle (as in DMAP) or by the choice of a different metal fragment.

Having a design in mind for a new kind of chiral nucleophilic catalyst, we were quickly made aware of the harsh realities of chemistry. Pyridine π-complexes are difficult to synthesize unless there are bulky substituents in the 2- and/or 6-positions to prevent bonding of the nitrogen to the metal in a σ-fashion.[12] Although this problem can be overcome by the use of easily removed silyl groups in these positions to favor π-complexation,[13] we initially chose to avoid the complication altogether by focusing on pyrrolyl anions as the heterocyclic components of our catalysts. Thus, our initial synthetic efforts focused on the synthesis of azametallocenes of the sort shown in Figure 1.4, in which a pyrrolyl anion is π-bound to a metal fragment.[14]

Figure 1.4. Proposed Planar-Chiral (π-Pyrrolyl) Metal Complexes (Azametallocenes).



Having settled upon the heterocyclic component of our proposed catalysts, we were then faced with the decision of which metal fragment to use. Although a variety of metal fragments have been shown to form π-complexes with pyrrolyl anions,[14] we felt that the choice of an electron-rich, relatively inert metal fragment was warranted. Because the cyclopentadienyliron fragment meets these requirements, we turned our attention to derivatives of azaferrocene, **1.1**, as our first-generation catalysts.[15]

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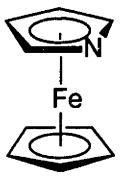
12 Davies, S. G.; Shipton, M. R. *J. Chem. Soc. Perkin Trans. 1* **1991**, 501-507.

13 Elschenbroich, C.; Koch, J.; Kroker, J.; Wünsch, M.; Massa, W.; Baum, G.; Stork, G. *Chem. Ber.* **1988**, *121*, 1983-1988.

14 For a review of σ,π-complexes of five-membered monoheterocycles, see: Sadimenko, A. P.; Garnovskii, A. D.; Retta, N. *Coord. Chem. Rev.* **1993**, *126*, 237-318.

15 For a overview of the use of chiral ferrocene derivatives in asymmetric synthesis, see: Richards, C. J.; Locke, A. J. *Tetrahedron: Asymmetry* **1998**, *9*, 2377-2407 and references therein.

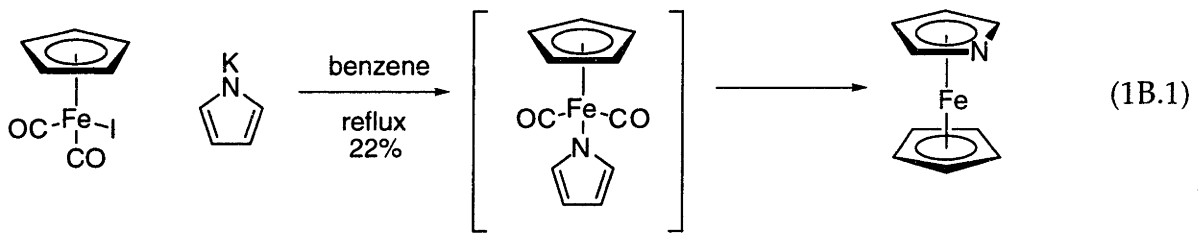


1.1

Chapter One, Part B: Synthesis of Azaferrocene-Derived Complexes

Background

Since it was first reported almost simultaneously by the groups of King[16] and Pauson[17] in 1964, azaferrocene, **1.1**, and its derivatives have been the subject of extensive study. Pauson's synthesis of azaferrocene, the better of the two initially reported, starts from dicarbonylcyclopentadienyliron iodide and the potassium salt of pyrrole. Heating the two components to reflux for 3 hours in benzene affords the desired π-complex in 22% yield after chromatography on alumina, followed by sublimation (eq 1B.1). The postulated intermediate σ-complex, **1.2**, was reported by Pauson in a subsequent publication to be chemically competent in this reaction.[18,19] More recently, Zakrzewski has reported a photochemical synthesis of **1.2** and milder conditions for the decarbonylation which allow **1.1** to be isolated in an overall yield of 61%.[20] With respect to the stability of azaferrocene, Pauson noted that it is "considerably less stable" than ferrocene. King added that it "turns brown slowly over a period of days in air and darkens on heating above its melting point."



1.2 **1.1** (1B.1)

Pauson also reported a synthesis of the tricarbonylmanganese π-complex of the pyrrolyl anion, azacymantrene, **1.3** (eq 1B.2).[17] Interestingly, he reported that the

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16 King, R. B.; Bisnette, M. B. *Inorg. Chem.* **1964**, *3*, 796-800.

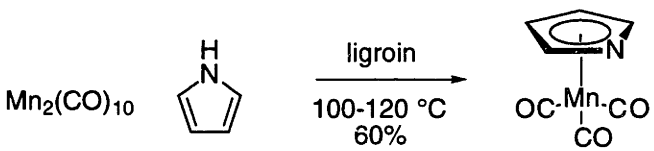
17 Joshi, K. K.; Pauson, P. L.; Qazi, A. R.; Stubbs, W. H. *J. Organomet. Chem.* **1964**, *1*, 471-475.

18 Pauson, P. L.; Qazi, A. R. *J. Organomet. Chem.* **1967**, *7*, 321-324.

19 Interestingly, the conversion of **1.2** into **1.1** was later shown to be reversible. Furthermore, this π to σ rearrangement could be effected by several π-acidic ligands, including CO, PF_3, $(CH_3)_2NPF_2$, $(CH_3CH_2)_2NPF_2$, C_6H_5NC, *t*-BuNC, *n*-PrNC, and $(CH_3)_2N(CH_2)_3NC$. Efraty, A.; Jubran, N. *Inorg. Chim. Acta.* **1980**, *44*, L191-L192.

20 Zakrzewski, J.; Giannotti, C. *J. Organomet. Chem.* **1990**, *388*, 175-179.

pK_a of the protonated form of **1.1** is 4.5 in aqueous ethanol, while **1.3** is not sufficiently basic under those conditions to make more than a crude estimate of pK_a = 1.6. These data are in accord with our initial proposal that the more electron-donating cyclopentadienyliron metal fragment would be an appropriate starting point when trying to make a nucleophilic catalyst.[21]



(1B.2)

1.3

Several other aspects of the reactivity of azaferrocene and its derivatives that have been described in the literature also bode favorably for the possibility of developing a chiral nucleophilic catalyst from this family of molecules. Perhaps most importantly, the ability of the nitrogen atom of azaferrocenes to act as a nucleophile has been demonstrated. Pauson reported that **1.1** reacts with methyl iodide to give "a rather unstable salt" which he proposed to be **1.4** (eq 1B.3). No characterization was provided.[17] This reaction was reinvestigated by Zakrzewski in 1990, and he reported that **1.4** could be isolated and characterized as the hydrate.[22] He reported the salt to be unstable in solution, but that it can be stored for months as a solid at -20 °C in the dark. The importance of the metal fragment was again demonstrated, as **1.3** is reported to be unaffected my methyl iodide.[17]

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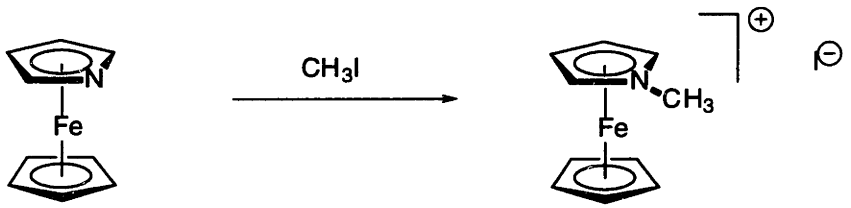
21 Although nucleophilicity refers to a kinetic phenomenon while basicity refers to a thermodynamic phenomenon, a correlation does exist between the two. For a detailed discussion of this relationship as it relates to nucleophilic catalysis, see: Diver, S. T. Ph.D. Thesis, University of Wisconsin at Madison, 1995.

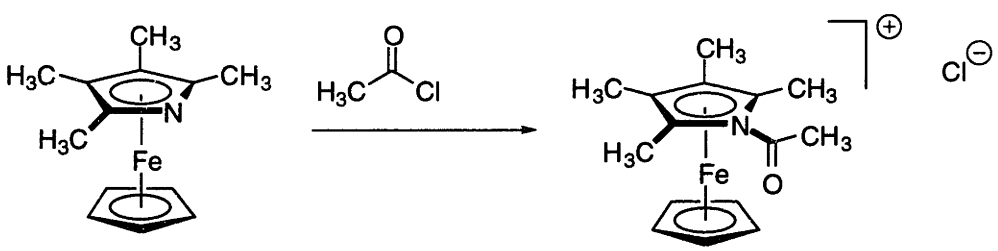
22 Zakrzewski, J. *Bull. Soc. Chim. Belg.* **1990**, *99*, 357-358.



(1B.3)

1.1 **1.4**

Of more immediate interest to us with respect to the creation of a catalyst for acylation is the reported reaction of 2,3,4,5-tetramethylazaferrocene, **1.5**, with acetyl chloride to form salt **1.6** (eq 1B.4).[23] This salt, structurally related to a potential intermediate in catalytic acylation of alcohols, is said to be stable and can be purified by recrystallization. Furthermore, it is even somewhat resistant to hydrolysis. The nucleophilicity of **1.5** toward methyl iodide, diborane, and $Fe_2(CO)_9$ was also demonstrated. This reaction with iron was not the first example of an azaferrocene acting as a ligand. Setkina reported η^1-*N*-coordination of **1.1** to Pt and Pd in 1984.[24] Also, Zakrzewski has studied the coordination of **1.1** to various transition metal macrocyclic complexes and has recently reviewed the progress in that area.[25] Taken together, the above reactions provided significant evidence that azaferrocene-derived compounds might possess the necessary reactivity at nitrogen to be useful both as nucleophilic catalysts and as ligands.



(1B.4)

1.5 **1.6**

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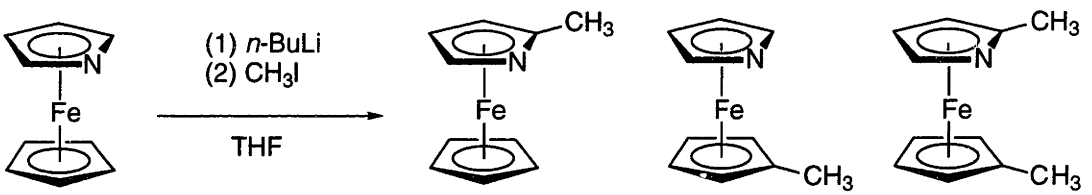
23 Kuhn, N.; Schulten, M.; Zauder, E.; Augart, N.; Boese, R. *Chem. Ber.* **1989**, *122*, 1891-1896.

24 Pyshnograeva, N. I.; Setkina, V. N.; Kursanov, D. N. *Izv. Akad. Nauk. SSSR, Ser. Khim.* **1984**, *12*, 2778-2780. (English translation pages 2544-2546).

25 Zakrzewski, J.; Giannotti, C. *Coord. Chem. Rev.* **1995**, *140*, 169-187.

Literature precedent also existed for functionalizing azaferrocene at its 2-position, a transformation that was expected to prove useful in the synthesis of *chiral* derivatives. Setkina has reported that treatment of **1.1** with 2 equivalents of *n*-BuLi in THF at -50 °C for 2 hours, followed by methyl iodide, results in the formation of mono- and dimethyl derivatives **1.7, 1.8,** and **1.9** with nearly quantitative recovery of the iron in one of the three forms (eq 1B.5).[26] Although the isomers could not be separated, NMR analysis suggested a ratio of 49:36:15. The authors note that when the metallation was allowed to proceed for only 15 minutes before the addition of methyl iodide, only the monomethyl derivatives were formed, again in nearly quantitative yield and in the same ratio as before. They suggest that this behavior indicates rapid monolithiation of **1.1** with a slight bias for reaction at the pyrrolyl ligand. The second lithiation is much slower and proceeds at nearly the same rate for both isomers. Similar results were reported when either D_2O or TMSCl was used as the electrophile.



1.1 **1.7** **1.8** **1.9** (1B.5)

A later report from the same group indicates that high selectivity in a metallation-trapping sequence may be obtained with proper choice of electrophile. Thus, when **1.1** was treated with *n*-BuLi and TMEDA in ether at -50 °C, followed by the addition of benzophenone, the desired 2-substituted compound **1.10** was isolated as the *sole* product in 40% yield (eq 1B.6).[27] Unfortunately, no mention is made as to the mass balance except to say that the yield is 70% with respect to reacted **1.1**.

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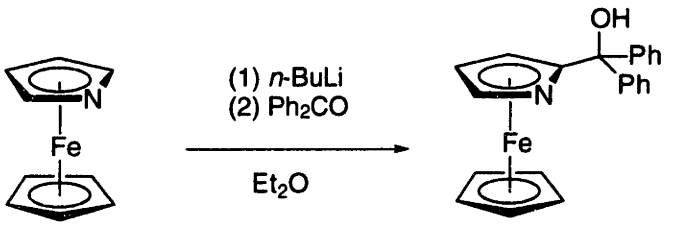
26 Pyshnograeva, N. I.; Setkina, V. N.; Kursanov, D. N. *J. Organomet. Chem.* **1983**, *251*, C41-C43.
27 Pyshnograeva, N. I.; Setkina, V. N.; Batsanov, A. S.; Struchkov, Yu. T. *J. Organomet. Chem.* **1985**, *288*, 189-195.

Presumably, **1.1** that is lithiated on the cyclopentadienyl ring is unreactive toward the benzophenone and simply reverts back to **1.1** when the reaction mixture is quenched. To prove that the electrophile was the selectivity-determining factor, the authors note that using methyl iodide as the electrophile under otherwise identical conditions resulted in a nearly quantitative yield of 2- and 1'-methylazaferrocenes, **1.7** and **1.8**.



1.1 **1.10** (exclusive product) (1B.6)

Schlögl has reported the partial resolution of 2-methylazferrocene, **1.7**, with no mention of racemization,[28] a fact that boded well for our hopes of creating chiral nucleophilic catalysts based on this scaffold. Treatment of racemic **1.7** (prepared from the potassium salt of 2-methylpyrrole and cyclopentadienylirondicarbonyl iodide in dioxane) with 1 equivalent of (-)-6,6'-dinitrodiphenic acid in ethanol resulted in an amorphous solid. A crystalline salt was obtained by treating the mother liquor with petroleum ether. Two further recrystallizations from acetone yielded (-)-**1.7** which was estimated to be of 30-40% ee.

Given the literature precedents showing that azaferrocenes are relatively stable, possess nucleophilic character at nitrogen, can be easily derivatized at the 2-position, and can be resolved into enantiomers, we felt confident that they were a good starting point for the synthesis of a new family of chiral nucleophilic catalysts with a well-defined chiral environment in the vicinity of the nucleophilic atom. The section that follows will describe our efforts at the synthesis and resolution of several members of this family.

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28 Bauer, K.; Falk, H.; Schlögl, K. *Angew. Chem. Internat. Edit.* **1969**, *8*, 135.

Results and Discussion

In an effort to become familiar with the handling and reactivity of azaferrocenes, our initial experiments focused on the parent heterocycle, **1.1**. Although this molecule lacks a 2-substituent and is achiral, we believed that its ready availability from commercially available pyrrole and cyclopentadienylirondicarbonyl iodide made it an attractive starting point for studies of catalytic activity. Since a 2-substituent might be expected to lower the catalytic activity of azaferrocenes (as is the case for pyridines), we felt that a reaction must show considerable rate acceleration in the presence of **1.1** if there were to be any chance of effective catalysis by a 2-substituted (chiral) derivative.

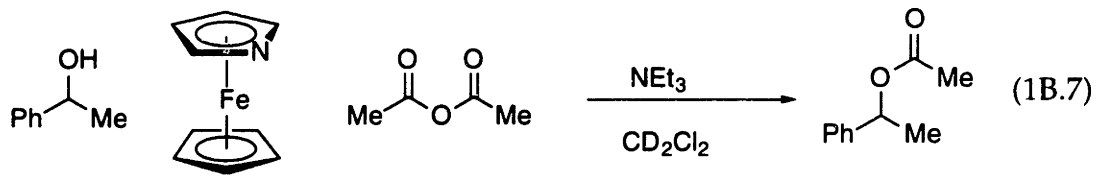
We synthesized **1.1** by the method of Pauson[29] and were pleased to find that it is sufficiently stable to be purified by flash chromatography on silica gel without any special precautions. NMR spectra of the product matched those reported in the literature, but the spectra had to be recorded immediately after the sample was prepared, or the peaks broadened significantly, even for samples prepared in a glove box. An observation that precipitate formed in NMR samples of **1.1** only on the side of the tube closest to the overhead lighting led us to suspect that solutions of **1.1** might be light-sensitive. Careful experiments confirmed this suspicion: When a solution of **1.1** in CD_2Cl_2 was split into two NMR tubes, one protected from light and the other exposed to light, markedly different stabilities were observed. Although the light sensitivity of **1.1** in solution has not been explicitly stated in the literature, Zakrzewski alludes to it when he says that *solid* samples of **1.1** are stable if stored under argon at 0 °C and in the *dark*.[14]

Once we confirmed the light sensitivity of **1.1** and began taking the necessary precautions, we were able to demonstrate in crude experiments that the complex does accelerate the acylation and silylation of 1-phenylethanol with acetic anhydride

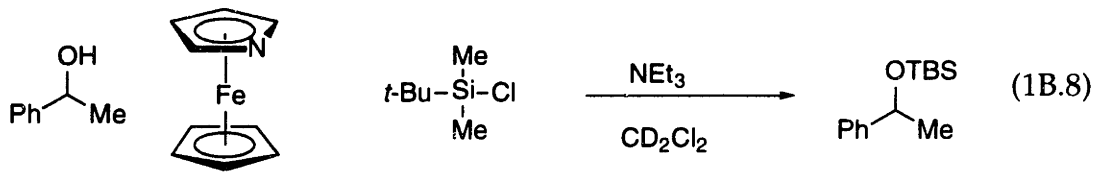
---

29 THF was used as the solvent, rather than benzene (reference 17).

and *t*-butyldimethylsilyl chloride, respectively (eqs 1B.7 and 1B.8). Unfortunately, concerns over the stability of **1.1** forced us to abandon its study as a catalyst and to search for more stable derivatives.



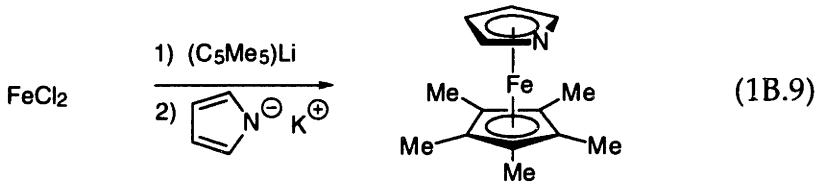
(1B.7)



(1B.8)

This search did not require a significant change of focus. Following the advice of Dr. Ken Stockman, we simply prepared 1',2',3',4',5'-pentamethylazaferrocene, **1.11**. Treatment of iron(II) chloride with the lithium salt of 1,2,3,4,5-pentamethyl-1,3-cyclopentadiene (Cp*-H), followed by potassium pyrrolide, results in a 53% yield of the desired complex as an orange solid (eq 1B.9). The pentamethyl complex, **1.11**, is much more stable than **1.1**.[30] While solutions of **1.11** are somewhat air-sensitive, NMR samples prepared in a glove box show no signs of light sensitivity. In addition to the added stability, it was hoped that the larger Cp* fragment might help increase the top-versus-bottom steric differentiation that is key in our proposed chiral catalyst design and possibly result in a favorable electronic effect (Cp* is more electron-rich than Cp).

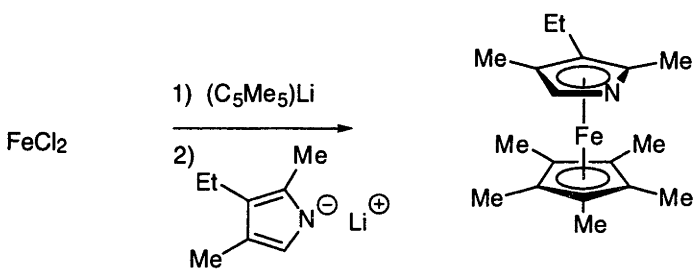
30 Increased stability of pentamethylcyclopentadienyl metal fragments versus the parent cyclopentadienyl metal fragments has often been observed. For leading references, see: Kerber, R. C. In *Comprehensive Organometallic Chemistry II*; Abel, E. W.; Stone, F. G. A.; Wilkinson, G., Eds.; Elsevier: Tarrytown, New York, 1995; Vol. 7, Chapter 2.



(1B.9)

1.11

After initial experiments again showed rate acceleration in the acylation and silylation of 1-phenylethanol, we began to explore the possibility of making chiral derivatives of **1.11**. In principle, the simplest approach to this problem would be to start with a 2-substituted pyrrole. Thus, treatment of iron(II) chloride with Cp*-Li, followed by the lithium salt of 2,4-dimethyl-3-ethylpyrrole results in a 54% yield of racemic 3-ethyl-1',2,2',3',4,4',5'-heptamethylazaferrocene, **1.12** (eq 1B.10). Like **1.11**, **1.12** shows no sensitivity to light, even when in solution.



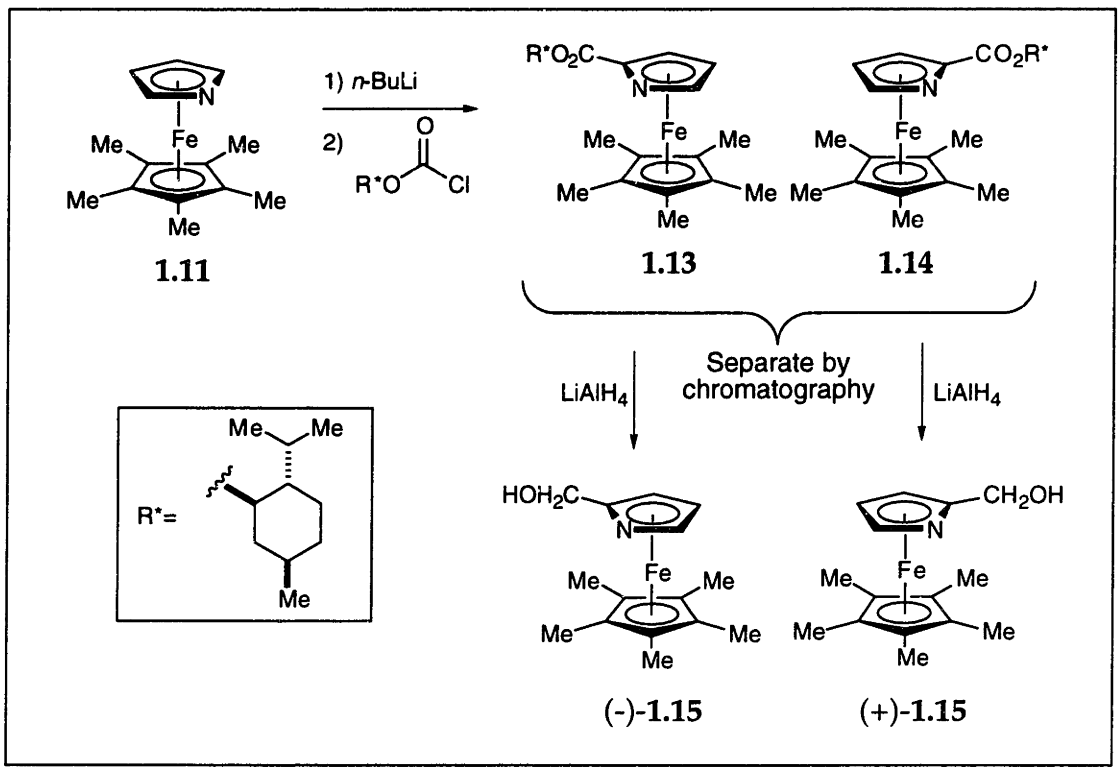
(1B.10)

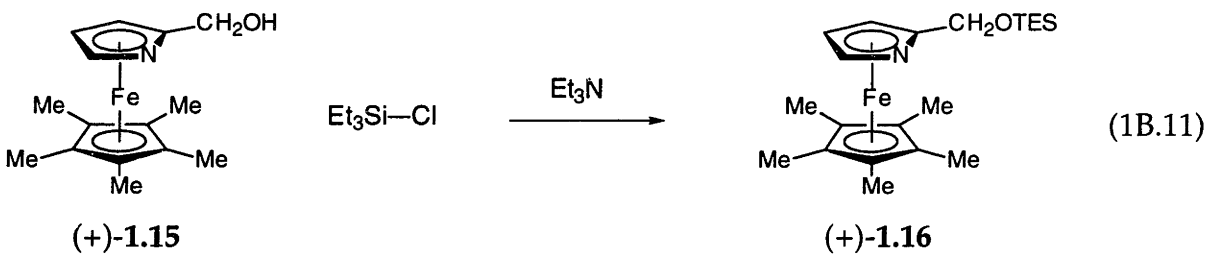
1.12

Because we ultimately wanted complexes as single enantiomers, we began to think about ways in which to resolve chiral azaferrocenes. The first method that proved fruitful involved the separation of diastereomeric derivatives by flash chromatography (Scheme 1.2). Lithiation of **1.11** with *n*-BuLi, followed by quenching with (-)-menthylchloroformate, results in the formation of diastereomeric esters **1.13** and **1.14**. Purification of the reaction mixture by flash chromatography results in separation of the diastereomers, **1.13** being slightly more polar. Although **1.13** and **1.14** are rather unstable, they can be reduced with $LiAlH_4$ to give the enantiomers of **1.15** in high optical purity. Because we were interested in

catalyzing reactions involving alcohols, the hydroxyl of **1.15** was protected as a triethylsilyl ether (**1.16**, eq 1B.11).

Scheme 1.2. Resolution of a Chiral Azaferrocene via Diastereomers.



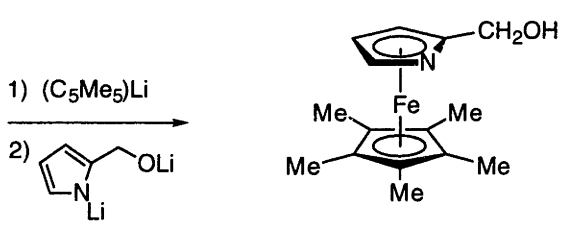


(1B.11)

Although the sequence in Scheme 1.2 provided us with our first access to **1.15** and **1.16** as single enantiomers, the procedure had several problems. The yield was low (21%), and the purification of the diastereomers was tedious. Most troubling, though, was that inconsistent results were obtained in asymmetric reactions catalyzed by **1.16** made by this route. We speculated that this may be due to small amounts of an impurity derived from lithiation of the Cp* methyl groups. Such an

impurity would not have a substituent in the 2-position of the heterocycle and might be significantly more active as a nucleophilic catalyst than **1.16**. This means that very small amounts of these impurities could be enough to result in difficulties with reproducibility. We therefore sought an alternate synthetic route to enantiopure **1.16**.

We found that racemic **1.15** could be easily prepared by the reaction of iron(II) chloride with Cp*-Li, followed by the dilithium salt of pyrrole-2-methanol (eq 1B.12). The enantiomers of **1.15** were separated by semi-preparative chiral HPLC on a Daicel CHIRALCEL OD column. We have come to view chiral HPLC as the method of choice for resolving our catalysts on a small scale. Because analogs often separate under nearly identical conditions (column, solvent composition), we can obtain the enantiomers of several catalysts within a family without the need to develop a new resolution via diastereomers for each individual compound. Although the throughput is often quite limited, separation of enantiomers by HPLC allows us to rapidly screen new catalysts for asymmetric induction in reactions of interest.



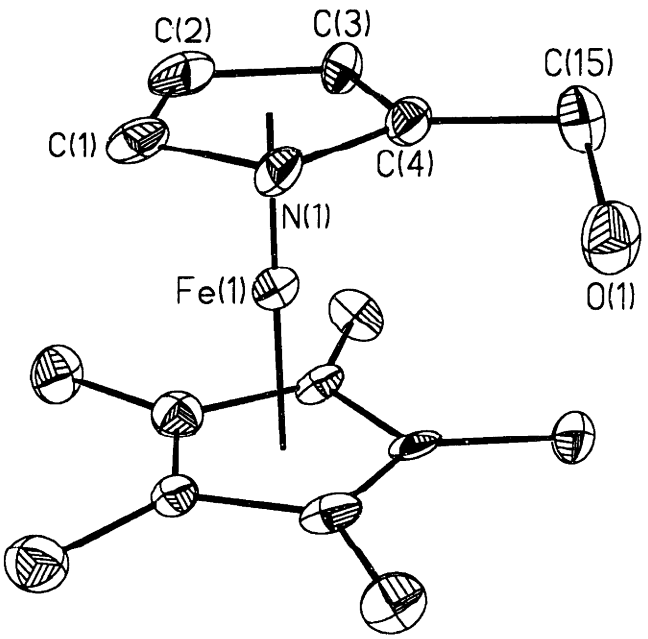
1.15
(racemic)

(1B.12)

Once resolved into enantiomers, protection of the hydroxyl group of **1.15** to give **1.16** was carried out as before. In addition to yielding material of much higher purity than that from the route in Scheme 1.2, the improved route avoided unstable intermediates and provided much higher throughput.

The absolute configurations of **1.15** and **1.16** were established by X-ray crystallographic analysis of a single crystal derived from the 1:1 complex of (+)-**1.15** and (*S*)-(+)-camphor-10-sulphonic acid. The ORTEP drawing of the azaferrocene component of this salt is shown in Figure 1.5.[31]

Figure 1.5. ORTEP Representation of the (*S*)-(+)-Camphor-10-sulphonic Acid Salt of (+)-1.15 (the sulphonic acid has been omitted for clarity).



Although we now had access to several potential catalysts based on the 1',2',3',4',5'-pentamethylazaferrocene skeleton, initial reactivity studies (detailed in Part D of this chapter) indicated that these complexes were not sufficiently active catalysts for the acylation of alcohols with anhydrides. A modification of the catalyst that provides a boost to the reactivity of these complexes was needed. Inspired by the great difference in reactivity seen between pyridine and DMAP due to the electron-donating ability of the 4-dimethylamino group, we decided to explore various ways in which the electron density of the pyrrole ring in our system could be enhanced.

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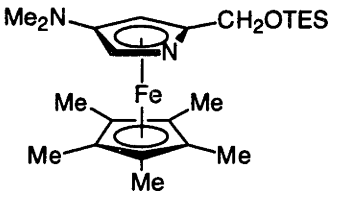
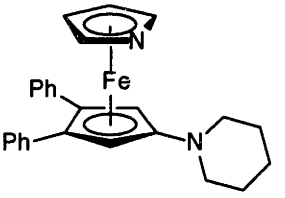
31 The details of the X-ray structure are presented in Appendix II.

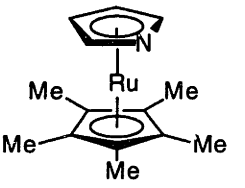
Unfortunately, electron-rich pyrroles are quite unstable, so our efforts directed at the synthesis of analogs of **1.16** bearing dialkylamino groups, such as **1.17**, have not yet been fruitful. In principle, another way in which electron density might be added to the pyrrolyl ring is through the use of a more electron-rich metal fragment. This approach has been studied in our group with modest success by Christine Garrett. She prepared analogs bearing an aminocyclopentadienyl ligand (**1.18**) as well as analogs in which the iron was replaced by a less electronegative (and larger) ruthenium (**1.19**).[32]



1.17



1.18



1.19

Yet another approach to more electron-rich catalysts involves the use of indoles. Since electron-rich indoles are known and even commercially available,[33] this approach seemed quite easy. Pauson reported in 1967 that indolyl π-complexes with cyclopentadienyliron can be formed, but noted that they are less stable than the corresponding pyrrole complexes and that they were not characterized.[18] Hoping that our use of the Cp* ligand would confer more stability to the indolyl complexes, as it had to the pyrrolyl complexes, we attempted the synthesis of complexes **1.20**, and **1.21** from indole and 5,6-dimethoxyindole, respectively. In both cases, we believe that the desired π-complex formed (based on TLC and the upfield shift of pyrrole peaks in ^{1}H NMR) but was too unstable to isolate in pure form. Work on the use of other indolyl ligands is still underway in our laboratories.[34]

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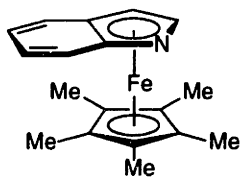
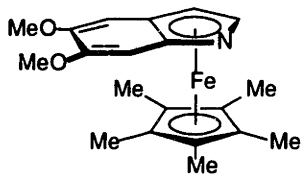
32 Garrett, C. E. Ph.D. Thesis, Massachusetts Institute of Technology, 1998.
33 5,6-Dimethoxyindole can be purchased from Aldrich.
34 Suginome, M. unpublished results.

Although the indole complexes did not provide stable catalysts, they did lead us into our next area of research in catalyst synthesis, complexes derived from pyrindines, as discussed in Part C of this chapter.



1.20



1.21

Conclusions

We have prepared a variety of iron complexes containing π-pyrrolyl ligands that might be useful as nucleophilic catalysts. Although the parent azaferrocene, **1.1**, first prepared by Pauson and King, is light-sensitive in solution, initial reactivity studies showed promise and led us to prepare more stable derivatives. We have found that replacing the Cp ring of azaferrocene with a Cp* ring provides a new complex, **1.11**, with greatly increased stability. Chiral complexes based on this 1',2',3',4',5'-pentamethylazaferrocene scaffold were prepared both by metallation of the 2-position of an unsubstituted pyrrolyl complex and by direct complexation of 2-substituted pyrroles. The enantiomers of the 2-hydroxymethyl derivative, **1.15**, were prepared by the separation and subsequent reduction of diastereomeric menthyl esters, as well as by the separation of the racemate by semi-preparative chiral HPLC. The absolute configuration of (+)-**1.15** was determined by X-ray crystallographic analysis of a salt formed with an entiopure sulphonic acid. Possible routes to more electron rich pyrrolyl complexes were explored. Two π-indolyl complexes were prepared, but these complexes were too unstable for our purposes.

Experimental

General. Pyrrole (Aldrich) and triethylamine (Fisher) were distilled from calcium hydride prior to use. 1,2,3,4,5-Pentamethyl-1,3-cyclopentadiene (Cp*-H; Strem), iron(II) chloride (Aldrich), *n*-BuLi (Aldrich, Strem), 2,4-dimethyl-3-ethylpyrrole (Aldrich), pyrrole-2-carboxaldehyde (Aldrich), indole (Aldrich), and 5,6-dimethoxyindole (Aldrich) were used without further purification. Potassium hydride (35 wt. % dispersion in mineral oil; Aldrich) was washed with hexanes and dried under vacuum. Triethylsilyl chloride (Aldrich), and (-)-menthylchloroformate (Aldrich) were distilled prior to use. Pyrrole-2-methanol was prepared according to the method of Silverstein.[35]

Solvents were distilled from the indicated drying agents: benzene (sodium/benzophenone); tetrahydrofuran (sodium/benzophenone); dichloromethane (calcium hydride).

Analytical thin layer chromatography was performed using EM Reagents 0.25 mm silica gel 60 plates, and visualization was accomplished with potassium permanganate or with ethanolic phosphomolybdic acid. Flash chromatography was performed on EM Reagents silica gel 60 (230-400 mesh).

^{1}H and ^{13}C nuclear magnetic resonance spectra were recorded on a Varian XL-300, Varian Mercury 300, Varian Unity 300 or a Varian VXR 500 spectrometer at ambient temperature. ^{1}H data are reported as follows: chemical shift in parts per million downfield from tetramethylsilane (δ scale), multiplicity (br = broad, s = singlet, d = doublet, t = triplet, q = quartet, and m = multiplet), integration, and coupling constant (Hz). ^{13}C chemical shifts are reported in ppm downfield from tetramethylsilane (δ scale). All ^{13}C spectra were determined with complete proton decoupling.

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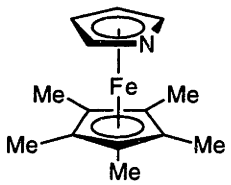
35 Silverstein, R. M.; Ryskiewicz, E. E.; Chaikin, S. W. *J. Am. Chem. Soc.* **1954**, *76*, 4485-4486.

Infrared spectra were obtained on a Perkin-Elmer Series 1600 FT-IR spectrophotometer. High resolution mass spectra were recorded on a Finnegan MAT System 8200 spectrometer. Melting points were obtained on a Thomas Hoover Unimelt capillary melting point apparatus.

All reactions were carried out under an atmosphere of nitrogen or argon in oven-dried glassware with magnetic stirring, unless otherwise indicated.

Preparation of Catalysts

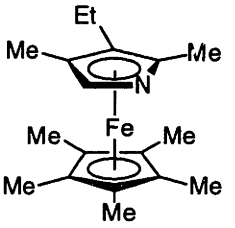
Potassium pyrrolide. Pyrrole (10 mL, 144 mmol) was added dropwise by syringe to a slurry of KH (5.11 g, 127 mmol) in 100 mL of THF at 0 °C, resulting in the evolution of hydrogen. The resulting slurry was heated at reflux for 8.5 h. After cooling to room temperature, the solvent was removed, affording potassium pyrrolide as a tan solid.



1′,2′,3′,4′,5′-Pentamethylazaferrocene (1.11). *n*-BuLi (1.68 M in hexane; 8.7 mL, 14.6 mmol) was added to a 0 °C solution of Cp*-H (1.99 g, 14.6 mmol) in 25 mL of THF, resulting in a milky-white precipitate. This slurry was allowed to warm to room temperature for five minutes, and then it was cooled to 0 °C and added by cannula to a rapidly stirring 0 °C slurry of $FeCl_2$ (1.86 g, 14.7 mmol) in 50 mL of THF. Upon completion of the addition, the resulting forest green solution was allowed to warm to room temperature, and then a slurry of potassium pyrrolide (1.54 g, 14.6 mmol) in 25 mL of THF was added by cannula. The resulting brown-orange solution was stirred for 4 hours at room temperature, then filtered through a plug of silica gel. The silica gel was washed with EtOAc until all of the orange color was

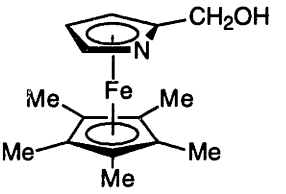
gone, and the combined organics were concentrated, leaving an orange solid, which was purified by flash chromatography (50% → 75% EtOAc/hexanes) to afford 2.00 g (53%) of a bright orange solid.

^{1}H NMR (300 MHz, C_6D_6) δ 4.91 (s, 2H), 3.82 (s, 2H), 1.80 (s, 15H). ^{13}C NMR (75MHz, C_6D_6) δ 92.9, 80.9, 74.3, 11.5. FTIR (KBr) 3080, 2904, 1475, 1374, 1006 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{14}H_{19}FeN$ (M^+) 257.0867, found 257.0867. mp 116-117 °C.



3-Ethyl-1', 2, 2', 3', 4, 4', 5'-heptamethylazaferrocene (1.12). The complex was prepared in a manner analogous to **1.11** above except that the lithium salt of the pyrrole (prepared just before use from 2,4-dimethyl-3-ethylpyrrole and *n*-BuLi) was used. Purification by flash chromatography (25% → 75% EtOAc/hexanes) afforded 2.07 g (54%) of an orange oil that solidified upon standing.

^{1}H NMR (300 MHz, C_6D_6) δ 4.62 (s, 1H), 2.1 (m, 1H), 2.05 (s, 3H), 1.9 (m, 1H), 1.73 (s, 15H), 1.58 (s, 3H), 0.83 (t, 3H, J=7.2). ^{13}C NMR (75MHz, C_6D_6) δ 101.3, 91.2, 88.5, 85.9, 80.0, 17.8, 15.3, 13.2, 10.6, 9.5. FTIR (KBr) 2964, 2905, 1477, 1449, 1376, 1306, 1138, 1030, 930, 830 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{18}H_{27}FeN$ (M^+) 313.1499, found 313.1499. mp 52 °C.



2-Hydroxymethyl-1',2',3',4',5'-pentamethylazaferrocene (1.15). Method A: *n*-BuLi (0.63 mL, 1.6 M in hexanes, 1.0 mmol) was added dropwise by syringe at -78 °C to an

orange solution of 1',2',3',4',5'-pentamethylazaferrocene, **1.11**, (260 mg, 1.0 mmol) in THF (10 mL). After 15 minutes at -78 °C, the mixture was allowed to warm to r.t., resulting in a deep red solution after 1 h. The solution was cooled to -40 °C, and a solution of (-)-menthylchloroformate (222 mg, 1.0 mmol) in THF (10 mL) was added by cannula, resulting in an orange/brown solution. This solution was warmed to r.t. for 1 h, after which the solvent was removed, and the residue was purified by flash chromatography using 10% → 75% EtOAc/hexanes. The 2 diastereomers of product (R_f = 0.73 and 0.56 in 50% EtOAc/hexanes) were collected separately as unstable orange oils. Yields were 53 mg (12%) of the faster running diastereomer and 40 mg (8.9%) of the slower running diastereomer. Although ^1H NMR of the products was inconclusive due to extreme broadening of the peaks, HRMS analysis of the slower diastereomer did show the desired molecular ion (EI, *m/e*) calcd for $C_{25}H_{37}FeNO_2$ (M^+) 439.2174, found 439.2174.

Reduction of the faster running diastereomer with $LiAlH_4$ in ether resulted in the formation of (+)-**1.15**, while reduction of the slower running diastereomer resulted in the formation of (-)-**1.15**. For characterization and absolute configuration, see method B.

Method B: *n*-BuLi (1.6 M in hexane; 17.3 mL, 27.7 mmol) was added at 0 °C to a solution of Cp*-H (3.78 g, 27.7 mmol) in 75 mL of THF, resulting in a milky-white precipitate. This slurry was allowed to warm to room temperature for 15 minutes, and then it was cooled to 0 °C and added slowly by cannula to a rapidly stirring 0 °C slurry of $FeCl_2$ (3.50 g, 27.6 mmol) in 50 mL of THF. Upon completion of the addition, the resulting green solution was allowed to warm to room temperature for 30 minutes, after which a solution of the dilithium salt of pyrrole-2-methanol [made just prior to use by the reaction of *n*-BuLi (1.6 M in hexane; 34.6 mL, 55.4 mmol) with pyrrole-2-methanol (2.69 g, 27.6 mmol) in 50 mL of THF] was added by cannula. The resulting orange slurry was stirred at room temperature for 1.5 hours. Water

(10 mL) was added,[36] and the mixture was quickly filtered through a short plug of silica using aspirator vacuum. The silica was washed with EtOAc until no further orange color was coming through. The orange solution was then concentrated and purified by flash chromatography (50% EtOAc/hexanes → acetone), yielding 3.31 g (42%) of orange solid.

The enantiomers of the product were separated using semi-preparative HPLC (Daicel CHIRALCEL OD, 1 cm X 25 cm, hexane/isopropanol 90:10, 2.5 mL/min, retention times of enantiomers: 9.5 min and 13.0 min). Separation of 511 mg of racemic material yielded 159 mg of the faster-running enantiomer ($[\alpha]^{20}_D$ = +92° (c = 1.0, benzene)) and 146 mg of the slower-running enantiomer ($[\alpha]^{20}_D$ = -88° (c = 1.0, benzene)), after passage through a plug of silica. The failure to recover **1.15** quantitatively is most likely due to air oxidation in solution. Analytical chiral HPLC (Daicel CHIRALCEL OD, 4.6 mm X 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: (+)-**1.15**, 6.5 min and (-)-**1.15**, 10.6 min) showed that each enantiomer was > 98% ee.

The absolute configuration of (+)-**1.15** was determined by X-ray crystallography using a crystal grown from a 1:1 mixture of (+)-**1.15** and (*S*)-(+)-camphor-10-sulphonic acid in toluene.

^{1}H NMR (C_6D_6) δ 5.70 (s, 1H), 4.88 (d, 1H, J = 12.6), 4.71 (d, 1H, J = 12.3), 4.65 (s, 1H), 3.87 (s, 1H), 3.69 (s, 1H), 1.77 (s, 15H). ^{13}C NMR (C_6D_6) δ 106.3, 91.9, 81.4, 76.0, 73.1, 60.1, 11.2. FTIR (KBr) 3205, 2945, 2905, 2858, 1479, 1384, 1234, 1139, 1022, 750 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{15}H_{21}FeNO$ (M^+) 287.0973, found 287.0972. mp 105-107 °C (rac) and 144-145 °C (enantiomerically pure).

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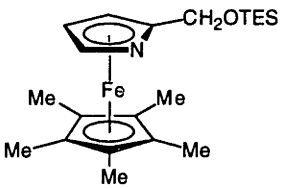
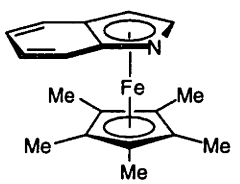
36 The benefits of adding water at the end of this reaction were discovered by Mr. Peter Dosa.



1′,2′,3′,4′,5′-Pentamethyl-2-trimethylsilyloxymethylazaferrocene (1.16). Triethylamine (85 μL, 0.61 mmol) was added to a solution of (+)-2-hydroxymethyl-1′,2′,3′,4′,5′-pentamethylazaferrocene (134.4 mg, 0.468 mmol) in 5 mL of CH_2Cl_2. Triethylsilyl chloride (79.2 mg, 0.525 mmol) in 5 mL of CH_2Cl_2 was then added slowly by pipet. After 8.5 hours, the mixture was concentrated and purified by flash chromatography (10% → 50% Et_2O/pentane), affording a 98% yield of the desired silyl ether as an orange oil ($[\alpha]^{20}_D$ = +63° (c = 1.0, benzene)). Repeating the procedure with (-)-2-hydroxymethyl-1′,2′,3′,4′,5′-pentamethylazaferrocene gave a 93% yield of product ($[\alpha]^{20}_D$ = -64° (c = 1.0, benzene)).

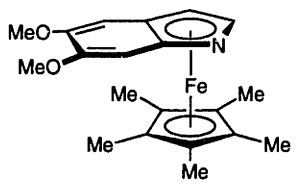
^{1}H NMR (C_6D_6) δ 4.92 (d, 1H, J = 12.0), 4.85 (s, 1H), 4.74 (d, 1H, J = 11.9), 4.07 (s, 1H), 3.84 (s, 1H), 1.79 (s, 15H), 1.05 (t, 9H, J = 7.9), 0.69 (q, 6H, J = 8.0). ^{13}C NMR (C_6D_6) δ 106.1, 93.0, 81.0, 76.0, 72.8, 62.1, 11.3, 7.5, 5.6. FTIR (KBr) 2952, 2908, 2875, 1458, 1381, 1072, 1015, 815, 742 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{21}H_{35}FeNOSi$ (M^+) 401.1837, found 401.1838.



π-Indolyl-π-1,2,3,4,5-pentamethylcyclopentadienyliron (1.20). The complex was prepared in a manner analogous to **1.11** above except that the lithium salt of indole (prepared 3.5 hours prior to use from indole and *n*-BuLi) was used. TLC of the crude reaction mixture after 3 hours showed a red spot (R_f=0.46 in 75% EtOAc/hexanes) that was assumed to be product. After 12 hours, the THF was removed by rotary

evaporation, and the mixture was purified by flash chromatography using 10% → 75% EtOAC/hexanes. All fractions containing the product were contaminated with free indole, even though the indole is much less polar, thus indicating decomposition on the silica gel. Recrystallization from pentane at -35 °C in the dark resulted in a sample the NMR spectrum of which allowed for unambiguous assignment of the product peaks, but even this sample was contaminated with free indole.

^{1}H NMR (CD_2Cl_2) δ 7.51 (d, 1H, J=9.3), 7.35 (d, 1H, J=8.1), 7.05-7.25 (m, 2H), 4.97 (s, 1H), 4.81 (s, 1H), 1.63 (s, 15H).



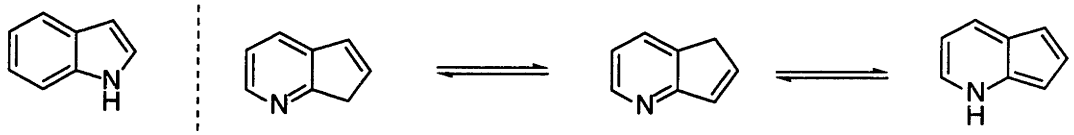
π-5,6-Dimethoxyindolyl-π-1,2,3,4,5-pentamethylcyclopentadienyliron (1.21). The complex was prepared in a manner analogous to **1.11** above except that the lithium salt of the indole (prepared 1 hour prior to use from 5,6-dimethoxyindole and *n*-BuLi) was used. TLC of the crude reaction mixture after 4 hours showed a purple spot (R_f=0.16 in 75% EtOAc/hexanes) that was assumed to be product. A solid was present in the reaction mixture, so it was filtered through a frit in a glove box. Evaporation of the filtrate resulted in a purple crystalline solid. A small amount of the product was purified using a "pipet column" on alumina inside a glove box. The column was eluted with pentane, ether, CH_2Cl_2, and CH_3CN. The product eluted with CH_3CN as a pink solution. The CH_3CN was evaporated, and an NMR of the residue showed the desired product contaminated with free 5,6-dimethoxyindole, but unambiguous assignment of the product peaks was possible.

^{1}H NMR (CD_2Cl_2) δ 6.68 (s, 1H), 6.47 (s, 1H), 4.77 (s, 1H), 4.59 (s, 1H), 3.90 (s, 3H), 3.85 (s, 3H), 1.66 (s, 15H).

Chapter One, Part C: Synthesis of Pyrindine-Derived Complexes

Background

Our brief incursion into the synthesis of π-indolyl complexes described in Part B of this chapter, while not directly providing any complexes of suitable stability to be considered as potential catalysts, did provide the intellectual bridge from azaferrocene derivatives to our second main class of catalysts, the π-pyrindinyl complexes. Reasoning that more stable complexes might result if the metal were bound to a carbocyclic ring rather than directly to the heterocycle (ferrocene is much more stable than azaferrocene), we considered what would happen if the nitrogen of indole, **1.21**, were simply moved from the 5-membered ring to the corresponding position in the 6-membered ring. The result would be 7*H*-1-pyrindine, **1.22**, which exists along with its tautomer 5*H*-1-pyrindine, **1.23**, and a trace of 1*H*-1-pyrindine, **1.24**.[37] For the sake of simplicity, the tautomeric mixture of **1.22**, **1.23**, and **1.24** will simply be referred to as pyrindine. We reasoned that metals would bind the pyrindinyl anion through the 5-membered ring, resulting in more stable complexes, while maintaining the planar-chirality.



1.21 **1.22** **1.23** **1.24**

A survey of the literature revealed that only one π-complex of pyrindine had been reported, despite the fact that the ligand can be easily made in three steps from commercially available[38] 2,3-cyclopentenopyridine, **1.25** (eq 1C.1).[39] The synthesis of

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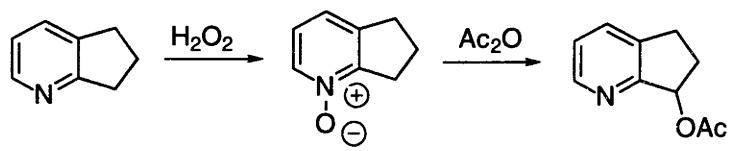
37 Review of the chemistry of 1-pyrindines: Freeman, F. *Adv. Heterocyclic Chem.* **1973**, *15*, 187-231.

38 2,3-Cyclopentenopyridine is no longer commercially available.

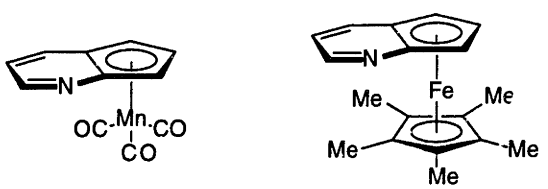
39 Ji, L.-N.; Kershner, D. L.; Rerek, M. E.; Basolo, F. *J. Organomet. Chem.* **1985**, *296*, 83-94.

pyrindine, reported by Robison in 1958,[40] starts with oxidation of **1.25** with hydrogen peroxide in acetic acid to give the *N*-oxide, **1.26**. Heating **1.26** in acetic anhydride results in formation of acetate **1.27**, which eliminates to pyrindine upon heating with sulfuric acid. The sequence can be easily carried out on a multigram scale, and the pyrindine can be stored for months at -35 °C.



1.25 **1.26** **1.27** **1.22, 1.23, 1.24** (1C.1)

The only pyrindinyl π-complex of which we were aware before we began our work was the manganese tricarbonyl complex, **1.28**, published by Basolo.[39] The complex was prepared by treatment of the potassium salt of pyrindine with $Mn(CO)_5Br$ and was used in a study of how the kinetics of CO substitution reactions at the metal are affected by the ligands.



1.28 **1.29**

Because we felt that an electron-rich metal fragment was important, we decided to pursue studies of complex **1.29**. In addition to the extra stability that we felt **1.29** and its derivatives might have over azaferrocenes, we were also hopeful that they might provide more active catalysts. This hope was rooted in the unusual stability of α-ferrocenyl cations. Ferrocenes are well-known to be effective at stabilizing a positive charge on an adjacent carbon atom.[41] Given this stabilization, we reasoned

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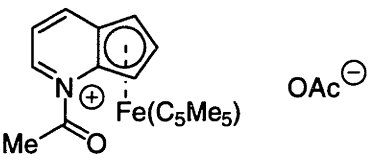
40 Robison, M. *J. Am. Chem. Soc.* **1958**, *80*, 6254-6257.

41 For a discussion of the unusual stability of ferrocenylcarbenium ions, see: Vogel, P. *Carbocation Chemistry*, Elsevier: New York, 1985.

that the positive charge on nitrogen in the proposed intermediate in alcohol acylation with anhydrides, **1.30**, might also be stabilized. Depending on the degree and exact nature of this stabilization, significant rate accelerations could be observed in acylation reactions employing **1.29** as a catalyst.[42]



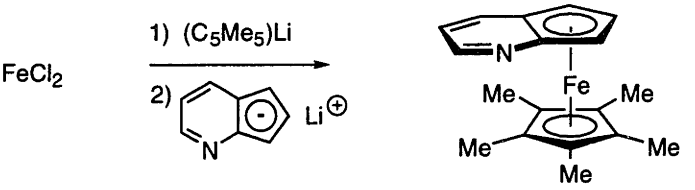
1.30

The following section details our synthesis of the first π-pyrindinyl iron complex, **1.29**, and our subsequent synthesis of the more electron-rich 4-dimethylamino analog.

42 Because ruthenocenylcarbenium ions are even more stable than their iron counterparts, one might expect that ruthenium derived catalysts would be more active. This hypothesis has been explored in our group, see: Garrett, C. E.; Lo, M. M.-C.; Fu, G. C. *J. Am. Chem. Soc.* **1998**, *120*, 7479-7483.

Results and Discussion

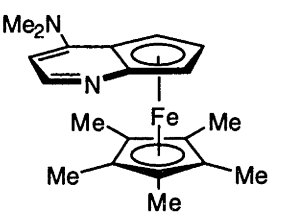
Complex **1.29** was easily prepared by the treatment of iron(II) chloride with Cp*-Li followed by the lithium salt of pyrindine (eq 1C.2). The complex was isolated in 50% yield as a highly crystalline purple solid. While not completely air stable in solution, **1.29** did show improved stability over the azaferrocene complexes. X-ray crystallography confirmed that the metal is bonded to the anionic 5-membered ring, resulting in a ferrocene-like structure.[43]



(1C.2)

1.29

Initial experiments using **1.29** as a catalyst for acylation with anhydrides were disappointing (see Part D of this chapter), so we again began to search for more electron rich complexes. Hoping that the introduction of a 4-dimethylamino substituent might result in the same sort of activation that is seen in going from pyridine to DMAP, we became interested in the synthesis of chiral DMAP analog **1.31**.



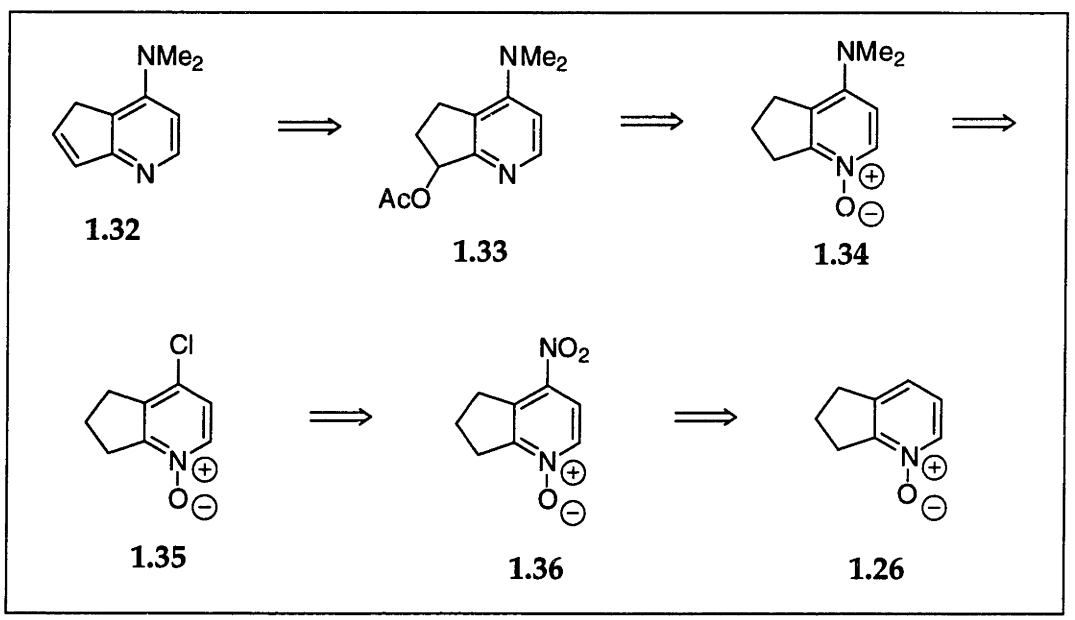
1.31

Retrosynthetically, we felt that **1.31** would best be made from complexation of 4-dimethylaminopyrindine, **1.32**, so that the number of steps involving the metal fragment were minimized. By analogy with Robison's synthesis of pyrindine, we

43 For details of the crystal structure, see Appendix II.

felt that **1.32** might be obtained from elimination of the acetate, **1.33**, which might be made by the reaction of dimethylamino-*N*-oxide **1.34** with acetic anhydride. We felt that the amino group should be easily installed by nucleophilic substitution on chloro-*N*-oxide **1.35**. Although **1.35** was a known compound,[44] we hoped that it could be more quickly prepared by nitration of the unsubstituted *N*-oxide, **1.26**, followed by nucleophilic displacement of the nitro group with chloride. This bias toward using **1.26** as the starting material stemmed from the fact that we already had a supply of it from our earlier synthesis of complex **1.29**. Our full retrosynthetic analysis is shown in Scheme 1.3.

Scheme 1.3. Retrosynthetic Analysis of 4-Dimethylaminopyrindine.



In the forward direction, our synthesis met with problems in the first step. Although nitration reactions of pyridine-*N*-oxide derivatives using HNO_3/H_2SO_4 often proceed in high yield and with excellent selectivity to the 4-position,[45] we have not been able to obtain yields better than approximately 20% in the nitration of

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44 Katano, K.; Ogino, H.; Iwamatsu, K.; Nakabayashi, S.; Yoshida, T.; Komiya, I.; Tsuruoka, T.; Inouye, S.; Kondo, S. *J. Antibiot.* **1990**, *43*, 1150-1159.

45 Ochiai, E. *J. Org. Chem.* **1953**, *18*, 534-551.

1.26 under these conditions. In addition to being low yielding, this nitration reaction has serious safety concerns, as compound **1.36** is a relatively high energy molecule that can decompose violently at temperatures just above the reaction temperature.[46] This information, taken together with the fact that the nitration reaction often results in a large exotherm ultimately led us to abandon **1.36** as an intermediate. Its inclusion in this thesis is for the sake of completeness and as a cautionary note.

Despite its problems, the nitration reaction of **1.26** is quite clean, providing only **1.36** and a small amount of unreacted **1.26** after an aqueous workup. The balance of the mass is presumably oxidized into water-soluble by-products. The desired nitro compound can be easily separated from the much more polar starting material by flash chromatography. Once purified, **1.36** can be converted into **1.35** in good yield by heating with ethanolic HCl.

At about the same time that concerns were raised with respect to the safety of **1.36** as an intermediate, the only commercial supplier of **1.25**, from which we had been synthesizing **1.26**, stopped selling it. We therefore began an effort to improve upon the synthesis of **1.35** from adipoyl chloride that had been reported by Jäger (Scheme 1.4, steps 1-3)[47,48] and Kondo (Scheme 1.4, steps 4-6).[49]

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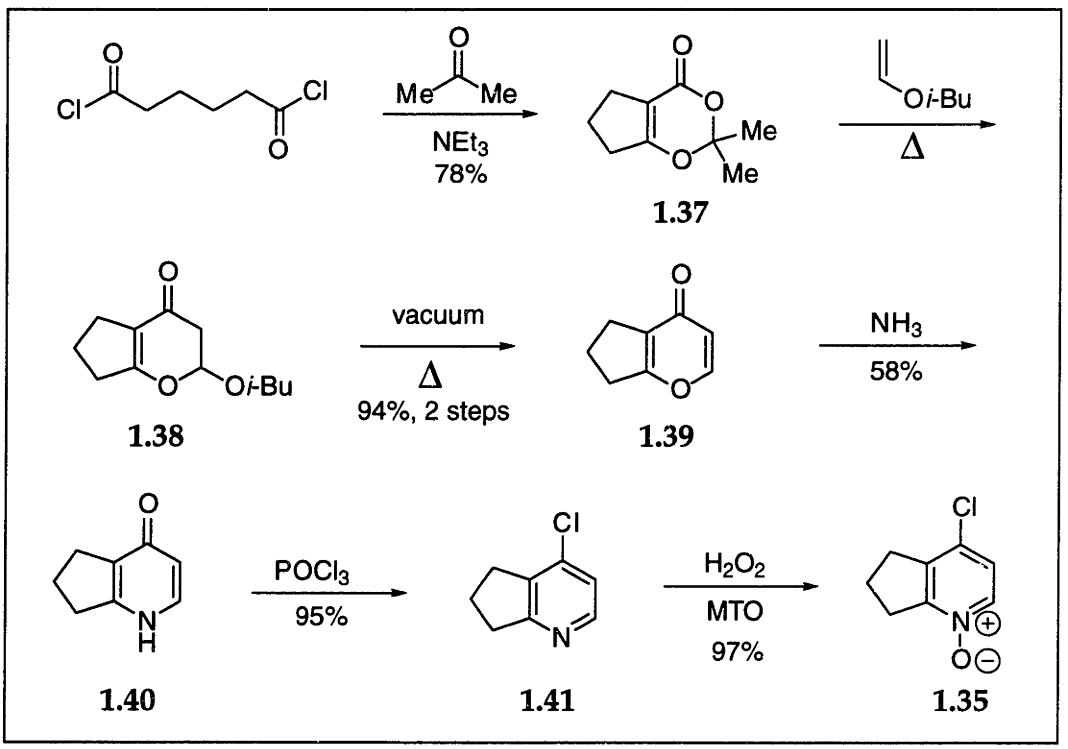
46 We would like to thank Dr. Tom Roper of Glaxo Wellcome for bringing this possible danger to our attention and Mr. Roy Flanagan, also of Glaxo Wellcome, for conducting calorimetry experiments.

47 Jäger, G. *Chem. Ber.* **1972**, *105*, 137-149.

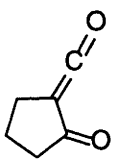
48 Jäger, G.; Wenzelburger, J. *Liebigs Ann. Chem.* **1976**, 1689-1712.

49 Katano, K.; Ogino, H.; Iwamatsu, K.; Nakabayashi, S.; Yoshida, T.; Komiya, I.; Tsuruoka, T.; Inouye, S.; Kondo, S. *J. Antibiot.* **1990**, *43*, 1150-1159.

Scheme 1.4. Optimized Synthesis of 4-Chloro-6,7-dihydro-1,5-pyrindine-*N*-oxide.



Jäger reported that cycloaddition product **1.37** could be obtained in 72% yield upon treatment of a solution of adipoyl chloride and acetone with triethylamine, the proposed intermediate being acylketene **1.42**. Although Jäger's procedure includes treatment with charcoal followed by recrystallization to purify the product, we have found that the crude material, obtained by filtration to remove the triethylamine hydrochloride and evaporation of the solvent, is suitable for use without further purification. Our crude yield of **1.37** is 78%.



1.42

In a subsequent paper, Jäger reported that heating **1.37** and an excess of isobutyl vinyl ether in xylenes results in the formation of new cycloaddition product **1.38**.

Again the intermediacy of **1.42** is suspected. The reported yield after treatment with charcoal, filtration, and removal of solvent is 76%. Heating **1.38** under partial vacuum then results in elimination to give pyrone **1.39** in 77% yield. In our hands, this sequence is much higher-yielding and again requires no purification. Thus, we have found that removal of the xylenes and residual isobutyl vinyl ether from the crude **1.38** by rotary evaporation, followed by vacuum distillation of isobutyl alcohol from the residue, gives **1.39** in 94% yield (for two steps) after simply washing the residue with pentane. The crude material is once again of suitable purity to carry forward.

The conversion of the pyrone into pyridone **1.40** was reported by Kondo to proceed upon heating in aqueous ammonia.[49] The product crystallized as the reaction cooled and was isolated in 96% yield after washing with water and drying. Kondo also reported the conversion of **1.40** to 4-chloropyrindine derivative **1.41** in 87% yield by heating with $POCl_3$. In our hands, these reactions have been found to proceed in 58% and 95% yield, respectively. Important to note is that no further purification is necessary after either step.

Kondo went on to convert **1.41** into the desired *N*-oxide by heating with hydrogen peroxide in acetic acid. The reported yield is only 69%, possibly owing to the solubility of the product in the large amount of water that is present after the acetic acid is neutralized with saturated $NaHCO_3$ at the end of the reaction.[49] Instead of following Kondo's procedure, we chose to attempt the oxidation with hydrogen peroxide and a catalytic amount of methyltrioxorhenium (MTO). Our interest in this method stemmed from a recent report by Sharpless that **1.25**, as well as a variety of other pyridine derivatives, can be oxidized under these conditions.[50] We were quite pleased to find that **1.35** was formed in nearly quantitative yield by

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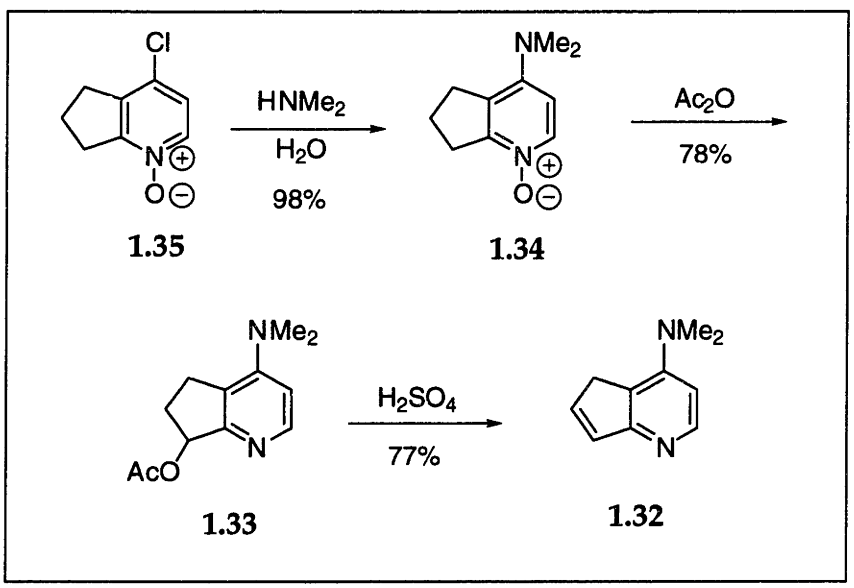
50 Copéret, C.; Adolfsson, H.; Khuong, T.-A. V.; Yudin, A. K.; Sharpless, K. B. *J. Org. Chem.* **1998**, *63*, 1740-1741.

MTO-catalyzed oxidation of **1.41**. Although the crude product is quite clean by ^1H NMR, the peaks are significantly broadened. Whatever trace impurity causes this problem can be removed by filtration of the product through a short plug of silica. The yield of **1.35** after filtration is 97%.

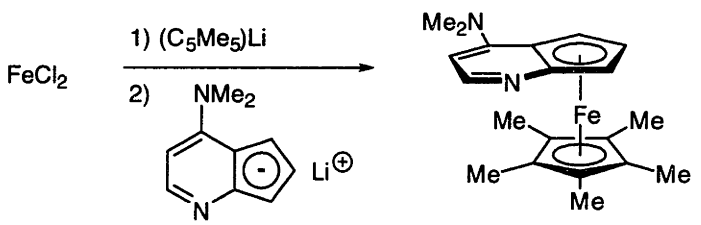
Fortunately, the conversion of **1.35** into the desired pyrindine, **1.32**, proceeded exactly as planned in our retrosynthesis (Scheme 1.5). Heating **1.35** with aqueous dimethylamine resulted in a 98% yield of the 4-dimethylamino derivative, **1.34**, which could be carried forward without purification. Heating **1.34** with acetic anhydride resulted in a 78% yield of the 4-dimethylamino-7-acetoxy compound, **1.33**, after purification by flash chromatography. The 4-dimethylaminopyrindine, **1.32**, was then obtained by warming **1.33** with concentrated sulfuric acid. The yield of **1.32** was 77% after purification by flash chromatography.

Scheme 1.5. Conversion of 1.35 into 1.32.



By analogy with **1.29**, chiral DMAP **1.31** was prepared by the treatment of iron(II) chloride with the Cp*-Li, followed by the lithium salt of **1.32** (eq 1C.3). After purification by flash chromatography, the complex was isolated in 88% yield as a beautiful burgundy solid, which is only slightly air-sensitive in solution. The

overall yield of **1.31** was 21% over 10 steps from adipoyl chloride. Important to note is that each of the steps can easily be done on multigram scale, the final step having been done to yield more than 6 g of product from a single reaction. Also worthy of note is the ease with which **1.31** can be purified. Due to its basicity, the complex does not move on silica gel with 100% ethyl acetate as the eluant. The addition of a few percent of triethylamine to the solvent system causes it to elute as a tight, pink band. At the end of a typical reaction, it is therefore straightforward to separate **1.31** from the other components of the reaction mixture, so long as they are not also basic.



(1C.3)

1.31

The enantiomers of **1.31** were separated by semi-preparative chiral HPLC on a Daicel CHIRALCEL OD column. Figure 1.5 shows the analytical HPLC trace of this separation. Because the dead volume of the column corresponds to approximately 4 minutes, this is quite an efficient separation ($\alpha > 2$). In practical terms, this means that several hundred milligrams of racemate can be separated in one day using a 1 cm column.

The absolute configuration of **1.31** was assigned by X-ray crystallography (anomalous dispersion). The ORTEP representation of the structure is shown in Figure 1.6. Again, the metal fragment is bound to the anionic 5-membered ring as expected. A concern that was brought to bear by this structure is the ability of the Cp* ring to effectively differentiate the bottom of the heterocycle from the top, a key element in our design. Because the metal is not directly beneath the heterocyclic ring, we began to fear that this differentiation may suffer in the pyrindine complexes, relative to the azaferrocene complexes.

Figure 1.5. HPLC Trace of Complex 1.31 on Chiralcel OD Column.

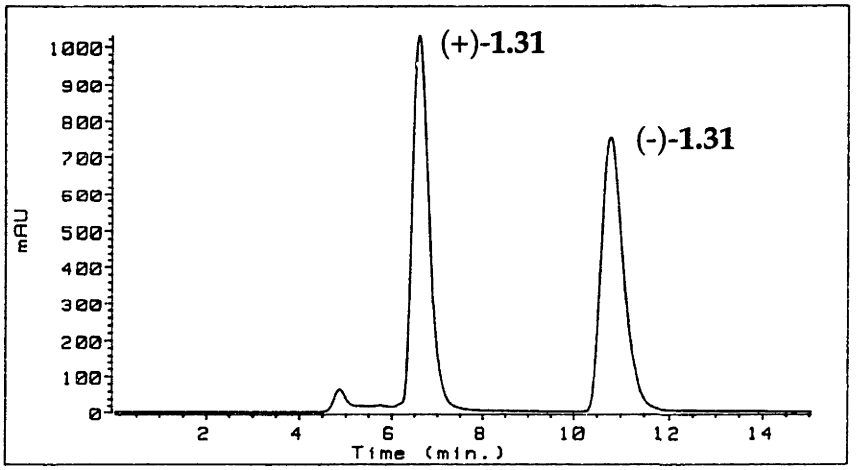
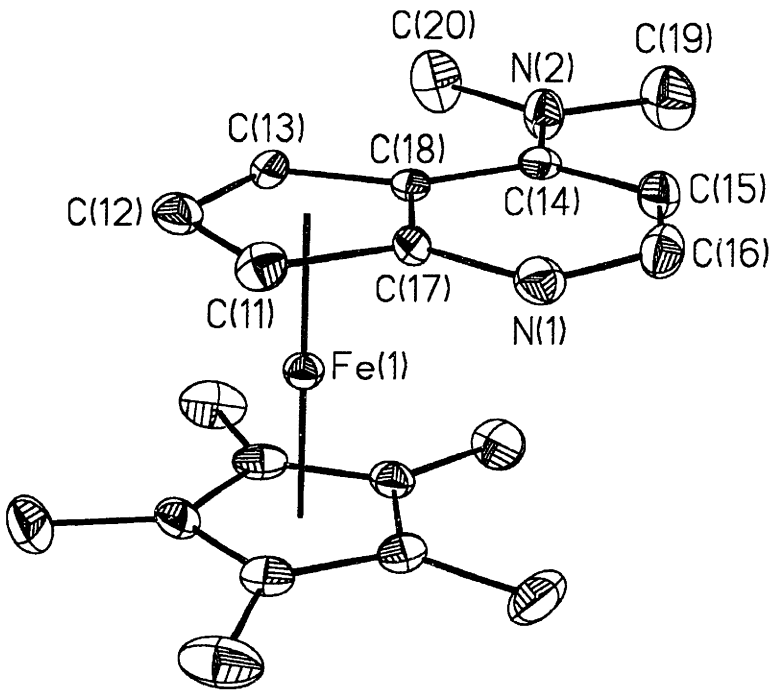


Figure 1.6. ORTEP Diagram of Chiral DMAP Complex 1.31.



Conclusions

In an effort to obtain complexes that might be more active as nucleophilic catalysts than the azaferrocene derivatives described in Part B of this chapter, we began to explore the synthesis of iron Cp* complexes of pyrindine and its derivatives. The unsubstituted parent compound, **1.29**, was easily prepared from readily available pyrindine. This compound was only the second π-complex to be reported with a pyrindinyl ligand, the first being the $Mn(CO)_3$ complex described by Basolo.[39] Although we were pleased with its relative stability, initial reactivity studies were disappointing, and we turned our sights to the 4-dimethylamino derivative, **1.31**, in the hope that the electronic effect of the amino group might result in a more active nucleophilic catalyst.

We were able to synthesize the desired 4-(dimethylaminopyrindinyl) complex in 10 steps and in 21% overall yield from adipoyl chloride. This synthetic approach allows access to **1.31** in multigram quantities. The enantiomers of **1.31** were separated by chiral HPLC, and the absolute configuration of (+)-**1.31** was assigned by X-ray crystallography.

Experimental

General. 1,2,3,4,5-Pentamethyl-1,3-cyclopentadiene (Cp*-H; Strem), iron(II) chloride (Aldrich), *n*-BuLi (Aldrich, Strem, Alfa Aesar), 2,3-cyclopentenopyridine (Lancaster, Pfizer, Acros), acetic anhydride (Mallinckrodt), adipoyl chloride (Alfa Aesar), methyltrioxorhenium (Strem), H_2O_2 (30%, EM), fuming nitric acid (90%, Baker), dimethylamine (40% in H_2O; Fluka), acetyl chloride (Fluka), and phosphorous oxychloride (Alfa Aesar) were used without further purification. 6,7-Dihydro-1,5-pyrindine-*N*-oxide and pyrindine were prepared according to the method of Robison.[40]

Tetrahydrofuran was distilled from sodium/benzophenone.

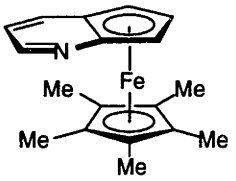
Analytical thin layer chromatography was performed using EM Reagents 0.25 mm silica gel 60 plates, and visualization was accomplished with potassium permanganate or with ethanolic phosphomolybdic acid. Flash chromatography was performed on EM Reagents silica gel 60 (230-400 mesh).

^1H and ^{13}C nuclear magnetic resonance spectra were recorded on a Varian XL-300, Varian Mercury 300, Varian Unity 300 or a Varian VXR 500 spectrometer at ambient temperature. ^1H data are reported as follows: chemical shift in parts per million downfield from tetramethylsilane (δ scale), multiplicity (br = broad, s = singlet, d = doublet, t = triplet, q = quartet, and m = multiplet), integration, and coupling constant (Hz). ^{13}C chemical shifts are reported in ppm downfield from tetramethylsilane (δ scale). All ^{13}C spectra were determined with complete proton decoupling.

Infrared spectra were obtained on a Perkin-Elmer Series 1600 FT-IR spectrophotometer. High resolution mass spectra were recorded on a Finnegan MAT System 8200 spectrometer. Melting points were obtained on a Thomas Hoover Unimelt capillary melting point apparatus.

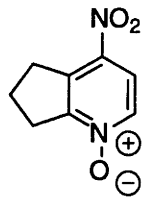
All reactions were carried out under an atmosphere of nitrogen or argon in oven-dried glassware with magnetic stirring, unless otherwise indicated.

Preparation of Catalysts



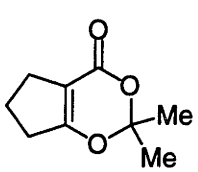
Pentamethylcyclopentadienylpyrindinyliron (1.29). *n*-BuLi (1.68 M in hexane; 17.9 mL, 30.0 mmol) was added dropwise to a 0 °C solution of Cp*-H (4.08 g; 30.0 mmol) in 60 mL of THF, resulting in a milky-white precipitate. This slurry was allowed to warm to room temperature for 1 hour, and then it was cooled to 0 °C and added by cannula to a rapidly stirring 0 °C slurry of $FeCl_2$ (3.81 g, 30.1 mmol) in 80 mL of THF. Upon completion of the addition, the resulting green solution was allowed to warm to room temperature for 3 hours, and then a slurry of the lithium salt of pyrindine [made immediately prior to use by the reaction of *n*-BuLi (1.68 M in hexane; 17.9 mL, 30.0 mmol) and pyrindine (3.50 g, 29.9 mmol) in 60 mL of THF] was added by cannula. The resulting purple solution was stirred for 3 hours at room temperature, then filtered through a plug of silica gel. The silica gel was washed with EtOAc, the combined organics were concentrated, and the resulting purple solid was purified by flash chromatography (10% → 75% EtOAc/hexanes), affording 4.60 g (50%) of product as a purple, highly crystalline solid.

^{1}H NMR (CD_2Cl_2) δ 8.56 (dd, 1H, J = 3.9, 1.0), 7.82 (dd, 1H, J = 8.7, 1.2), 6.86 (dd, 1H, J = 8.7, 4.5), 4.67 (dd, 1H, J = 1.8, 0.6), 4.28 (dd, 1H, J = 2.2, 1.3), 3.90 (t, 1H, J = 2.2), 1.63 (s, 15H). ^{13}C NMR (C_6D_6) δ 151.6, 138.9, 117.8, 110.1, 82.0, 78.5, 77.1, 67.9, 63.9, 10.5. FTIR (KBr) 2968, 2898, 1588, 1509, 1308, 1028 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{18}H_{21}FeN$ (M^+) 307.1023, found 307.1024. mp 106 °C.



4-Nitro-6,7-dihydro-1,5-pyrindine-*N*-oxide (1.36).[51] (Caution! The use of a blast shield is recommended). 6,7-Dihydro-1,5-pyrindine-*N*-oxide (5.4 g, 40 mmol) was added slowly to 17 mL of concentrated H_2SO_4 in a 3-neck flask equipped with a thermometer and a septum. A condenser topped with an argon inlet was added. The flask was placed into a room temperature water bath, and 9.5 mL of fuming nitric acid were added by syringe over 10 minutes. The water bath was heated to 95 °C over 50 min. After 100 min at 95 °C, the contents of the flask were poured over ice and neutralized with K_2CO_3. The resulting solution was extracted with EtOAc (6 x 100 mL). The EtOAc solution was dried over K_2CO_3, concentrated, and passed through a short plug of silica. Removal of solvent yielded 1.50 g (21%) of product as a yellow solid.

^{1}H NMR ($CDCl_3$) δ 8.11 (d, 1H, J = 7.2), 7.95 (d, 1H, J = 7.8), 3.56 (t, 2H, J = 7.5), 3.21 (t, 2H, J = 7.8), 2.29 (quintet, 2H, J = 7.7). ^{13}C NMR ($(CD_3)_2CO$) δ 156.6, 141.7, 139.7, 139.2, 120.5, 34.1, 30.7, 22.3. FTIR (KBr) 3417, 3048, 3009, 2958, 1594, 1439, 1347, 1261, 1010, 802 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_8H_8N_2O_3$ (M^+) 180.0535, found 180.0537.



2,2-Dimethyl-6,7-dihydro-5*H*-cyclopenta<1,3>dioxin-4-one (1.37). This compound was made by a procedure essentially identical to that of Jäger.[47] Adipoyl chloride (137 g, 0.746 mol) was added to an argon purged 3-L 3-neck flask along with

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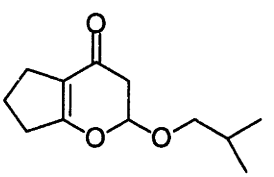
51 For a related reaction, see: Stolle, W. T.; Sih, J. C.; Hsi, R. S. P. *J. Labeled Compd. Radiopharm.* **1988**, *25*, 891-900.

acetone (110 mL, 1.50 mol) and ether (1.8 L, unpurified). The flask was then equipped with a condenser, a mechanical stirrer, and an addition funnel. The addition funnel was charged with triethylamine (215 mL, 1.55 mol) which was added over 30 minutes, resulting in the formation of a precipitate and refluxing of the ether. After the addition was complete, a heating mantle was added, and the mixture was kept at reflux for an additional 30 minutes. After the mixture had cooled, the precipitate was filtered off and washed with ether. Evaporation of the combined ether yielded the product as 98.2 g (78%) of orange solid. This material was used without further purification. For the purposes of characterization, a small amount was purified by flash chromatography using 25% Et_2O/pentane (R_f=0.33), resulting in a white solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ 2.52-2.63 (m, 4H), 1.93-2.04 (m, 2H), 1.70 (s, 6H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 171.8, 160.2, 108.3, 103.2, 31.8, 26.0, 25.4, 19.3. FTIR (KBr) 2945, 1736, 1646, 1419, 1256, 1202, 1147, 1088, 987, 888 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_9H_{12}O_3$ (M^+) 168.0786, found 168.0786. mp 42-43 °C (Lit. 38 °C).[47]

The ^{1}H NMR and IR spectra are consistent with those previously reported.[52]

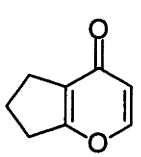


2-Isobutoxy-2,3,6,7-tetrahydro-5*H*-cyclopenta<*b*>pyran-4-one (1.38). This compound was made by a procedure essentially identical to that of Jäger and Wenzelburger.[48] Isobutyl vinyl ether (220 mL, 1.69 mol) was added to a 2-L 2-neck flask with a stir bar and xylenes (550 mL). The flask was equipped with a condenser and an addition funnel. The addition funnel was charged with 2,2-dimethyl-6,7-dihydro-5*H*-cyclopenta<1,3>dioxin-4-one (**1.37**, 94.6 g, 0.562 mol) in 175 mL of

52 Leung-Toung, R.; Wentrup, C. *J. Org. Chem.* **1992**, *57*, 4850-4858.

xylenes. The flask was then heated in an oil bath. When the bath temperature reached 120 °C, the addition was started. The addition was complete in 25 minutes, after which time the temperature had risen to 135 °C. The temperature was maintained at 130-140 °C for 65 minutes, after which the heat was removed. The solution was then transferred in portions to a smaller 1-neck flask, and the xylenes were removed by rotary evaporation. Heating at 70 °C overnight under vacuum removed the last traces of solvent and left the product as 112 g (94%) of an orange oil. This material was used without further purification. A crude ^{1}H NMR showed the desired product contaminated with **1.39** and other very small impurities. For the purposes of characterization, a small amount of the product was purified by flash chromatography using 25% Et_2O/pentane (R_f=0.11 in 10% Et_2O/pentane), resulting in a pale yellow oil.

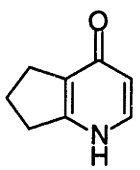
^{1}H NMR (300 MHz, $CDCl_3$) δ 5.42 (dd, 1H, J=5.4, 3.9), 3.62 (dd, 1H, J=9.3, 6.6), 3.34 (dd, 1H, J=9.3, 6.6), 2.50-2.68 (m, 6H), 1.80-1.98 (m, 3H), 0.90 (d, 3H, J=6.9), 0.90 (d, 3H, J=6.9). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 187.9, 174.4, 114.3, 103.5, 76.2, 41.6, 32.7, 28.3, 25.4, 19.1. FTIR (KBr) 2958, 2872, 1669, 1623, 1425, 1298, 1106, 1014, 852 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{12}H_{18}O_3$ (M^+) 210.1256, found 210.1254.



6,7-Dihydro-5*H*-cyclopenta<*b*>pyran-4-one (1.39). This compound was made by a procedure essentially identical to that of Jäger and Wenzelburger.[48] A flask containing the crude 2-isobutoxy-2,3,6,7-tetrahydro-5*H*-cyclopenta<*b*>pyran-4-one (**1.38**, 111g, 0.527 mol) was fitted with a distillation head, and the pressure was reduced to 20 mm Hg. The flask was then heated in a 150 °C oil bath for 65 minutes, during which time isobutyl alcohol distilled over and the crystalline solid product began to sublime onto the sides of the flask (Care should be taken that the product

doesn't block the distillation head and create a closed system; it may be necessary to knock the crystals of product down into the flask from time to time to prevent this). Upon cooling, a brown solid was left in the reaction flask. This solid was moved to a filter paper and washed with 500 mL of pentane. The product was left on the filter paper as 73.1 g (102%) of an oily, brown solid (since the starting material already contained some product, >100% yield is reasonable). This material was used without further purification. For the purposes of characterization, a small amount of the product was purified by recrystallization from EtOAc/hexanes.

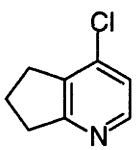
^{1}H NMR (300 MHz, $CDCl_3$) δ 7.68 (d, 1H, J=6.0), 6.27 (d, 1H, J=6.0), 2.88 (t, 2H, J=7.8), 2.77 (t, 2H, J=7.5), 2.08 (pent, 2H, J=7.8). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 177.3, 168.8, 154.4, 126.3, 116.4, 31.4, 25.9, 19.3. FTIR (KBr) 2926, 1650, 1614, 1448, 1299, 1150, 1034, 996, 861, 828 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_8H_8O_2$ (M^+) 136.0524, found 136.0522. mp 109-110 °C (Lit. 107-108 °C).[48]



1,5,6,7-Tetrahydro-[1]pyrindin-4-one (1.40). This compound was made by the procedure of Kondo.[49] 6,7-Dihydro-5*H*-cyclopenta<*b*>pyran-4-one (**1.39**, 70.9 g, 0.52 mol) was divided into six batches, and each batch was added to a Schlenk tube with 100 mL of 30% aqueous ammonia (ammonium hydroxide). The Schlenk tubes were sealed and heated for 3 hours at 100 °C behind blast shields. At the end of the 3 hours, the Schlenk tubes were carefully vented, and the hot solutions were poured into an Erlenmeyer flask. The Schlenk tubes were rinsed with 400 mL of water to wash the last of the product into the Erlenmeyer. The product began almost immediately to crystallize. After cooling to 4 °C overnight, the crystals were collected and washed with cold water, followed by pentane. After several hours of

air drying, the product was heated under vacuum at 95 °C overnight. This left the product as 40.9 g (58%) of a cream colored solid that was pure by ^{1}H and ^{13}C NMR.

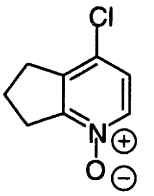
^{1}H NMR (300 MHz, $CDCl_3$) δ 7.64 (d, 1H, J=7.2), 6.32 (d, 1H, J=6.9), 4.95 (br s, 1H), 2.96 (t, 2H, J=7.5), 2.79 (t, 2H, J=7.5), 2.12 (pent, 2H, J=7.5). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 178.8, 155.1, 138.3, 129.9, 116.0, 32.5, 28.8, 22.9. HRMS (EI, *m/e*) calcd. for C_8H_9NO (M^+) 135.0684, found 135.0681. FTIR (KBr) 3053, 2918, 2456 (br), 1622, 1537, 1446, 1372, 1316, 1291 cm^{-1}. mp 210-211 °C.



4-Chloro-6,7-dihydro-1,5-pyrindine (1.41). This compound was made by the procedure of Kondo.[49] 1,5,6,7-Tetrahydro-[1]pyrindin-4-one (**1.40**, 20.7 g, 0.153 mol) was evenly divided between two Schlenk tubes and placed under argon. Phosphorus oxychloride (40 mL, 0.43 mol) was divided in two portions and added to the Schlenk tubes, resulting in a small amount of bubbling. The Schlenk tubes were then sealed and placed into an oil bath at 140 °C for 2 hours. After cooling, the excess $POCl_3$ was removed from each Schlenk tube by vacuum. The residues were combined and added to a separatory funnel with 200 mL of 1 M HCl. The resulting solution was washed with 200 mL of ether. The ether layer was then extracted with 100 mL of 1 M HCl, and the combined HCl layers were neutralized with 6 M NaOH. The product was extracted into 4 X 250 mL of ether. The ether was dried over $MgSO_4$ and evaporated, leaving the product as 22.3 g (95%) of orange oil that was pure by ^{1}H and ^{13}C NMR.

^{1}H NMR (300 MHz, $CDCl_3$) δ 8.22 (d, 1H, J=5.4), 7.04 (d, 1H, J=5.4), 3.09 (t, 2H, J=7.5), 3.00 (t, 2H, J=7.5), 2.15 (pent, 2H, J=7.5). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 167.0, 148.3, 140.5, 135.6, 121.2, 35.0, 30.0, 22.0. FTIR (KBr) 2960, 1583, 1557, 1457, 1390, 1315,

1141, 902, 816 cm^{-1}. HRMS (EI, *m/e*) calcd. for C_8H_8ClN (M^+) 153.0345, found 153.0343.



4-Chloro-6,7-dihydro-1,5-pyrindine-*N*-oxide (1.35). Method A (from the nitro compound):[53] Absolute ethanol (25 mL) was added to a 100 mL Schlenk tube which was then fitted with a septum and cooled to 0 °C. Acetyl chloride (13 mL, 180 mmol) was added slowly by syringe. A solution of 4-nitro-6,7-dihydro-1,5-pyrindine-*N*-oxide (**1.36**, 1.53 g, 8.49 mmol) in 20 mL of absolute ethanol was added by syringe to the Schlenk tube, resulting in a yellow solution. The Schlenk tube was then sealed with a stopcock and placed into an 80 °C oil bath for 11.5 hours. The resulting orange solution was neutralized with saturated aqueous $NaHCO_3$ and extracted with EtOAc (6 x 100 mL). The EtOAc solution was dried over $MgSO_4$ and then concentrated, leaving a brown solid. Purification of this material by flash chromatography (EtOAc → acetone) yielded 1.13 g (79%) of the desired product as a yellow-brown solid.

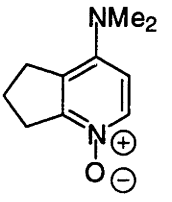
Method B (by oxidation of the chloropyrindane using Sharpless' conditions):[50] Although this oxidation has been previously reported using acetic acid/H_2O_2,[49] we have found the following procedure to be quite convenient.

To a round bottom flask containing a stir bar were added 4-chloro-6,7-dihydro-1,5-pyrindine (**1.41**, 30.6 g, 0.199 mol), methyltrioxorhenium (300 mg, 0.0012 mol), and CH_2Cl_2 (80 mL) under air. To this orange solution was added 30 % aqueous H_2O_2 (40 mL, 0.40 mol) in one portion, resulting in a yellow, 2-phase mixture. After 39.5 hours of stirring, approximately 30 mg of manganese dioxide was added to

53 For a related reaction , see reference 51.

decompose the excess peroxide. After the bubbling had stopped, the mixture was added to a separatory funnel with 75 mL of saturated aqueous NaCl and 75 mL of CH_2Cl_2. The phases were separated, and the aqueous phase was extracted with an additional 4 X 150 mL of CH_2Cl_2. The combined CH_2Cl_2 was dried over $MgSO_4$ and evaporated, leaving the product as 33.2 g (98%) of light gray solid. Although the ^1H NMR spectrum of the product was quite clean, the peaks were significantly broadened. Filtration of 6.33 g of the product through a 2" plug of silica gel using 10% isopropanol/90% acetone resulted in the recovery of 6.27 g of material, the ^1H NMR of which was quite sharp (97% overall yield after filtration). A green color was observed to remain at the top of the silica. For safety reasons, we recommend that this material be filtered through the plug of silica before use, especially if it is to be reacted with dimethylamine in the next step. On two separate occasions, sealed Schlenk tubes have exploded when conducting the dimethylamination of unpurified material. Under otherwise identical conditions, we have never had any problems when we used the purified material or material made by Method A.

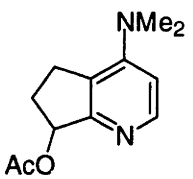
^1H NMR (300 MHz, $CDCl_3$) δ 7.99 (d, 1H, J = 6.9), 7.08 (d, 1H, J = 6.9), 3.23 (t, 2H, J = 7.8), 3.06 (t, 2H, J = 7.8), 2.23 (pent., 2H, J = 7.8). ^{13}C NMR (75.4 MHz, $(CD_3)_2CO$) δ 154.4, 140.7, 139.4, 127.0, 125.1, 31.8, 31.2, 21.8. FTIR (KBr) 3398, 3115, 2969, 1641, 1425, 1259, 1015, 821 cm^{-1}. HRMS (EI, *m/e*) calcd for C_8H_8ClNO (M^+) 169.0294, found 169.0294. mp 120-121 °C.



4-Dimethylamino-6,7-dihydro-1,5-pyrindine-*N*-oxide (1.34). 4-Chloro-6,7-dihydro-1,5-pyrindine-*N*-oxide (**1.35**, 6.08 g, 35.8 mmol) was added to a Schlenk tube along with a stir bar and 55 mL of 40% aqueous $HNMe_2$ under air. The Schlenk tube

was sealed and heated in a 75 °C oil bath for 24 hours. After the mixture was allowed to cool, it was added to a flask containing K_2CO_3 (6 g), and the water was removed by rotary evaporation. The product was then extracted from the residue with 5 X 120 mL of warm acetone (solid-liquid extraction). The acetone was dried over Na_2SO_4 and evaporated leaving the product as 6.28 g (98.3%) of tan solid.

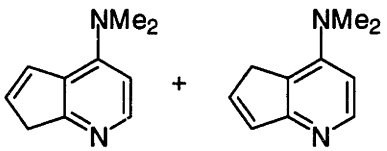
^{1}H NMR (300 MHz, $CDCl_3$) δ 7.82 (d, 1H, J = 7.1), 6.32 (d, 1H, J = 7.2), 3.07 (t, 2H, J = 7.7), 3.03 (t, 2H, J = 7.4), 2.88 (s, 6H), 2.05 (quintet, 2H, J = 7.6). ^{13}C NMR (75.4 MHz, CD_3OD) δ 155.3, 151.9, 138.3, 126.6, 110.4, 41.9, 34.5, 30.7, 23.6. FTIR (KBr) 3372, 2956, 1620, 1507, 1433, 1374, 1236, 977, 816, 735 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{10}H_{14}N_2O$ (M^+) 178.1106, found 178.1107. mp 161-162 °C.



4-Dimethylamino-7-acetoxy-6,7-dihydro-1,5-pyrindine (1.33). Acetic anhydride (18 mL, 190 mmol) was added to a flask containing the 4-dimethylamino-6,7-dihydro-1,5-pyrindine-*N*-oxide (**1.34**, 3.74 g, 21.0 mmol) and a stir bar under air. The resulting mixture was then stirred in a 100 °C oil bath for 15 hours, after which the remaining acetic anhydride was removed by rotary evaporation. The black residue was dissolved in CH_2Cl_2 and loaded onto a column of silica gel. It was first eluted with 50% EtOAc/50% hexanes and then with 10% NEt_3/45% EtOAc/45% hexanes. Product R_f=0.32 in 10% NEt_3/45% EtOAc/45% hexanes. The product was isolated as 3.62 g (78%) of a tan solid.

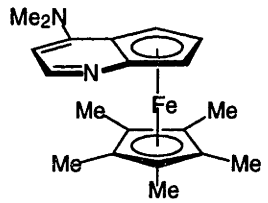
^{1}H NMR (300 MHz, $CDCl_3$) δ 8.21 (d, 1H, J = 6.0), 6.42 (d, 1H, J = 5.7), 6.01 (dd, 1H, J = 7.2, 4.8), 3.20 (m, 1H), 3.03 (s, 6H), 3.01 (m, 1H), 2.55 (m, 1H), 2.13 (s, 3H), 2.00 (m, 1H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 171.2, 161.2, 154.9, 149.8, 122.9, 108.4, 78.0, 41.3,

30.9, 29.7, 21.5. FTIR (KBr) 2945, 1732, 1587, 1244 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{12}H_{16}N_2O_2$ (M^+) 220.1212, found 220.1211. mp 74-75 °C.



4-Dimethylaminopyrindine (1.32). Concentrated H_2SO_4 (5.3 mL) was added under air to a 25 mL flask containing 4-dimethylamino-7-acetoxy-6,7-dihydro-1,5-pyrindine (**1.33**, 3.08 g, 14.0 mmol) that had been ground to a fine powder. The resulting mixture was stirred in a 60 °C oil bath for 90 minutes and then poured over ice. The mixture was adjusted to pH=12 with 6 M NaOH, and the product was extracted into 10 X 50 mL of EtOAc. Approximately 10 mL of NEt_3 were added to the extracts, and they were dried over Na_2SO_4. The volume of solvent was reduced to approximately 15 mL by rotary evaporation, and the mixture was applied to a silica gel column that had been loaded in 10% NEt_3/45% EtOAc/45% hexanes (we have some evidence that the product decomposes on silica gel in the absence of NEt_3). The product was eluted with that solvent system (R_f=0.34) and was isolated as 1.73 g (77%) of a yellow-brown, crystalline solid.

This product is an inseparable mixture of two isomers. ^1H NMR (300 MHz, $CDCl_3$) Major isomer: δ 8.17 (d, 1H, J = 5.9), 6.94 (dt, 1H, J = 5.7, 1.8), 6.76 (dt, 1H, J = 5.6, 2.0), 6.34 (d, 1H, J = 5.9), 3.62 (t, 2H, J = 1.8), 3.13 (s, 6H). Minor isomer: δ 8.10 (d, 1H, J = 5.9), 7.12 (dt, 1H, J = 6.1, 1.9), 6.44 (d, 1H, J = 6.0), 6.40 (dt, 1H, J = 6.2, 2.0), 3.43 (t, 2H, J = 1.8), 3.10 (s, 6H). ^{13}C NMR (75.4 MHz, $CDCl_3$) Major isomer: δ 164.8, 152.2, 148.4, 136.7, 133.8, 119.8, 105.2, 41.1, 39.4. Minor isomer: δ 166.7, 150.4, 146.0, 130.2, 129.0, 123.5, 106.5, 41.9, 40.7. FTIR (KBr) 3360, 2888, 1690, 1591, 1568, 1504, 1439, 1386, 1373, 1029 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{10}H_{12}N_2$ (M^+) 160.1000, found 160.1001. mp 60-61 °C.



4-Dimethylaminopyrindinyl-pentamethylcyclopentadienyliron (1.31). *n*-BuLi (2.62 M in hexane; 8.72 mL, 22.8 mmol) was added to a solution of Cp*-H (3.11 g, 22.8 mmol) in THF (150 mL), resulting in a milky-white precipitate. This slurry was added by cannula to a slurry of $FeCl_2$ (2.82 g, 22.2 mmol) in THF (50 mL) at 0 °C over 25 minutes (an additional 50 mL of THF was used to rinse leftover Cp*-Li from the flask). A forest green solution resulted. After 2 hours, the ice bath was removed, and a solution of the lithium salt of 4-dimethylaminopyrindine [made 1.5 hours prior to use by the reaction of *n*-BuLi (2.62 M in hexane; 7.57 mL, 19.8 mmol) and 4-dimethylaminopyrindine (3.18 g, 19.8 mmol) in 40 mL of THF at r.t.] was added rapidly by cannula, resulting in a burgundy solution (an additional 10 mL of THF was used to rinse the leftover lithium salt from the flask). The reaction mixture was stirred at room temperature for 15 hours. It was then filtered through a short plug of silica using aspirator vacuum (this operation should be done as quickly as possible, as the crude reaction mixture seems to be rather air sensitive until it is filtered). The silica was washed with 10% NEt_3/90% EtOAc until no more pink color was coming through. The solvent was removed by rotary evaporation, and the residue was purified by flash chromatography (50% EtOAc/hexanes → 10% NEt_3/70% EtOAc/hexanes), which provided 6.12 g (88%, 21% from adipoyl chloride) of a burgundy crystalline solid. R_f=0.27 in 10% NEt3/45% EtOAc/45% hexanes.

^{1}H NMR (300 MHz, $CDCl_3$) δ 8.24 (d, 1H, J = 5.7), 5.70 (d, 1H, J = 4.5), 4.57 (dd, 1H, J = 2.7, 1.2), 4.33 (dd, 1H, J = 3.0, 0.9), 3.76 (t, 1H, J = 2.7), 3.24 (s, 6H), 1.65 (s, 15H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 159.2, 152.0, 111.4, 94.7, 78.5, 74.7, 73.6, 67.2, 64.3, 41.6, 9.9. FTIR (KBr) 2965, 2903, 1539, 1352). HRMS (EI, *m/e*) calcd for $C_{20}H_{26}N_2Fe$ (M^+)

350.1445, found 350.1441. Anal. Calcd for $C_{20}H_{26}FeN_2$ (350.3): C, 68.58; H, 7.48; N, 8.00. Found: C, 68.39; H, 7.72; N, 7.88. mp=162-163 °C.

The enantiomers were separated using semi-preparative HPLC (Daicel CHIRALCEL OD, 1 cm x 25 cm, isopropanol/hexanes/diethylamine 50:50:0.2, 2.5 mL/min). Enantiomer (+)-**1.31** ($[\alpha]^{20}_D$ = +1560° (c = 0.10, $CHCl_3$)) was collected from 7.67 minutes to 9.25 minutes, and enantiomer (-)-**1.31** ($[\alpha]^{20}_D$ = -1600° (c = 0.10, $CHCl_3$)) was collected from 12.0 minutes to 15.5 minutes.

The absolute configuration of (+)-**1.31** has been tentatively assigned on the basis of an X-ray crystallographic study (anomalous dispersion). The crystal was grown by cooling a toluene solution of (+)-**1.31** to -35 °C.

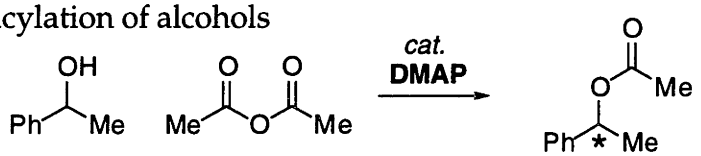
Chapter One, Part D: Activity of Heterocyclic π-Complexes as Catalysts

Background

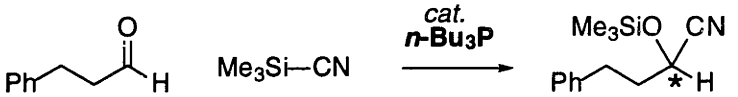
Having succeeded in synthesizing members of two new families of potential nucleophilic catalysts, our efforts turned toward determining if these complexes served as catalysts for reactions of interest. The set of reactions in which we were initially interested is shown in Figure 1.7, along with an example of a nucleophile known to catalyze each reaction.

Figure 1.7. Some Nucleophile-Catalyzed Reactions of Interest.

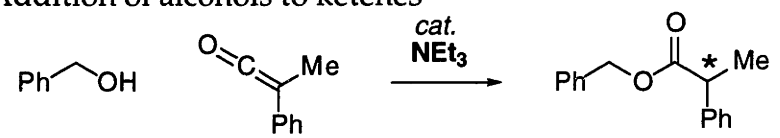
- Acylation of alcohols



- Cyanosilylation of aldehydes



- Addition of alcohols to ketenes



Perhaps the most well-known example of a nucleophile-catalyzed reaction is the acylation of alcohols with acetic anhydride catalyzed by DMAP.[54,55] The proposed mechanism of this reaction is shown in Scheme 1.1. Although there is no new stereocenter created in this reaction, a chiral catalyst would be of interest to effect kinetic resolutions of racemic substrates.[56] Other common nucleophiles known to catalyze this reaction include pyridine[57] and tributylphosphine.[58]

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54 Steglich, W.; Höfle, G. *Angew. Chem., Int. Ed. Engl.* **1969**, *8*, 981.
55 For an excellent review of the chemistry of DMAP, see reference 9.
56 For an extensive discussion of kinetic resolutions, see Chapter 2.
57 Verley, A.; Bölsing, F. *Ber. Dtsch. Chem. Ges.* **1901**, *34*, 3354-3358.
58 Vedejs, E.; Diver, S. T. *J. Am. Chem. Soc.* **1993**, *115*, 3358-3359.

A second nucleophile-catalyzed reaction in which we had an interest was the cyanosilylation of aldehydes with silylcyanide reagents. This carbon-carbon bond-forming reaction, which *does* lead to the creation of a new stereogenic center, was reported by Mukaiyama to be catalyzed by a variety of tertiary and hindered secondary amines as well as by tributylphosphine, triphenylphosphine, triphenylarsine, and triphenylantimony.[59,60] The proposed intermediate is the pentavalent silicate in which the nucleophilicity of the cyanide is increased by coordination of the catalyst to the silicon.[61]

The third reaction in which we had immediate interest as a testing ground for our catalysts was the addition of alcohols to ketenes. If the ketene bears two different substituents, a new stereocenter is formed, so these reactions are fundamentally quite different from the standpoint of asymmetric catalysis than other alcohol acylation reactions. This reaction has been shown to be catalyzed by pyridines as well as tertiary amines.[62] In ketene solvolysis reactions where the catalyst may function either as a nucleophile or as a Brønsted base the mechanism of this reaction is still a matter of debate.

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59 Kobayashi, S.; Tsuchiya, Y.; Mukaiyama, T. *Chem. Lett.* **1991**, 537-540.

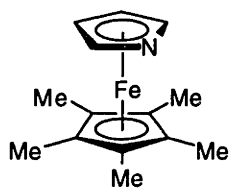
60 The triphenylphosphine-catalyzed cyanosilylation of *p*-quinones had earlier been reported. Evans, D. A.; Wong, R. Y. *J. Org. Chem.* **1977**, *42*, 350-352.

61 For a review of nucleophile-catalyzed reactions of organosilicon compounds, see: Furin, G. G.; Vyazankina, O. A.; Gostevsky, B. A.; Vyazankin, N. S. *Tetrahedron* **1988**, *44*, 2675-2749.

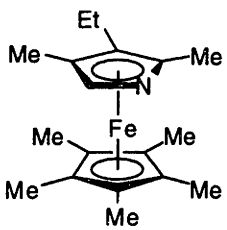
62 Tidwell, T. T. *Ketenes*; Wiley: New York, 1995.

Results and Discussion

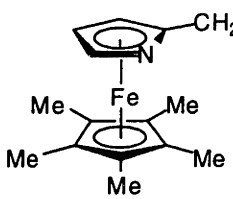
Having devised suitable synthetic routes to azaferrocene derived complexes **1.11**, **1.12**, and **1.16** as well as pyrindinyl complexes **1.29** and **1.31**, we began systematic studies of their reactivity in a series of nucleophile-catalyzed reactions of interest. The first reaction studied was the acylation of 1-phenylethanol with acetic anhydride (eq 1D.1).



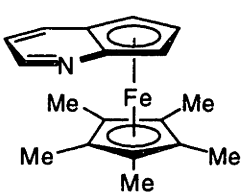
1.11



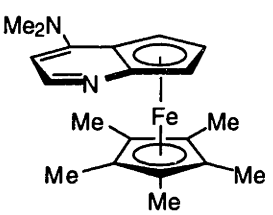
1.12



1.16



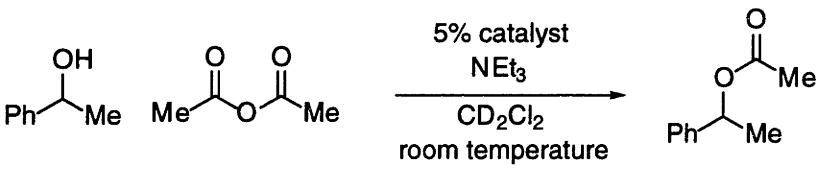
1.29



1.31

To compare the relative efficiencies of complexes **1.11**, **1.12**, **1.29**, and **1.31** as catalysts, the half-life of the reaction was determined by ^{1}H NMR in the presence of 5 mol% catalyst. A stoichiometric amount of triethylamine was added to prevent deactivation of the catalysts by the acetic acid that was produced as the reaction progressed. Under these conditions, there was a background (triethylamine-catalyzed) reaction with a half-life of 2,600 minutes. Both the unsubstituted (achiral) azaferrocene derivative, **1.11**, and the trisubstituted azaferrocene, **1.12**, showed modest rate acceleration, reducing the half-life to 580 minutes and 1,700 minutes, respectively. In the presence of the parent pyrindinyl complex, **1.29**, the rate of the reaction was not significantly different from that of the background reaction. The 4-

(dimethylamino)pyrindinyl complex, **1.31**, on the other hand, was quite an efficient catalyst for acylation, providing a rate acceleration of more than two orders of magnitude, reducing the half-life to only 20 minutes. Important to note from these data is that the presence of a 2-substituent on an azaferrocene attenuates catalytic activity (**1.11** versus **1.12**), while the presence of a 4-dimethylamino group on a pyrindine greatly enhances the activity (**1.29** versus **1.31**). These effects were expected by analogy with pyridine derivatives.



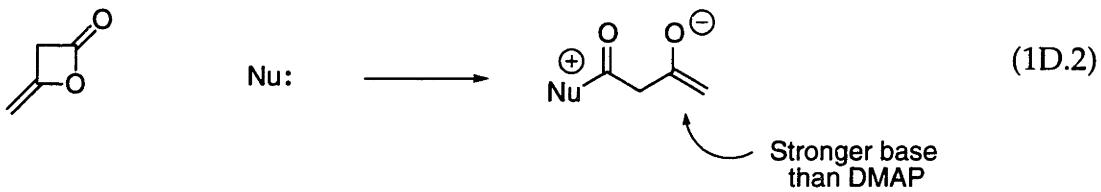
(1D.1)

complex	half-life (min)
1.11	580
1.12	1,700
1.29	no catalysis
1.31	20
none	2,600

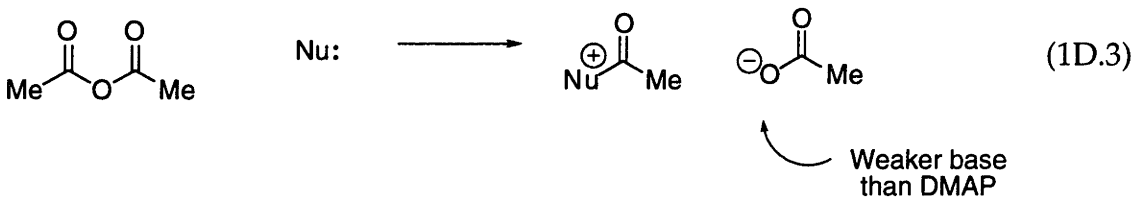
Although we had shown that chiral DMAP derivative **1.31** was effective at catalyzing alcohol acylation with acetic anhydride, the result was, at the time, bittersweet. Because we had not yet discovered that chiral HPLC is an effective method for the resolution of the enantiomers of **1.31**, the only complex of the five shown above to which we had access as a single enantiomer was azaferrocene derivative **1.16**. Unfortunately, even the most active azaferrocene derivative, unsubstituted **1.11**, is not sufficiently active relative to the background (triethylamine catalyzed) reaction to be practical for use as a chiral catalyst in this reaction. When triethylamine was omitted from the above reactions, the background reaction was almost completely shut down (<5% reaction after 5,000 minutes), but the catalysts were each deactivated by protonation with the acetic acid

that was produced as the reaction progressed. This observation led us to look for an acylating agent that did not require the addition of a stoichiometric amount of base.

A survey of the literature revealed that acylations using diketene as the acylating agent might be ideal. Acylations with diketene catalyzed by DMAP are known,[63] and there is essentially no background reaction. When diketene is ring-opened by a nucleophile, it releases an enolate rather than the carboxylate that is liberated when an anhydride is attacked (eq 1D.2 versus eq 1D.3). Because the enolate is a stronger base than DMAP, the catalyst does not get protonated, and the reaction can proceed to completion without difficulty.



(1D.2)

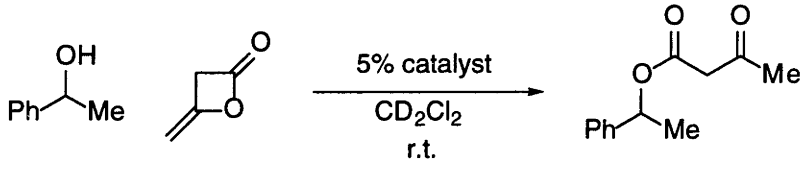


(1D.3)

To investigate the abilities of our complexes to serve as catalysts for acylations with diketene, we once again determined reaction half-lives by ^{1}H NMR for the acylation of 1-phenylethanol (eq 1D.4). We were pleased to find that 5 mol% of catalyst was sufficient to observe significant rate acceleration for both azaferrocene- and pyrindinyl-derived complexes. While the background reaction showed no acylation after 3,500 minutes, achiral azaferrocene derivative **1.11** catalyzed the reaction with a half-life of only 16 minutes. Addition of a 2-substituent resulted in a much slower reaction, as was shown by the 810 minute half-life of the reaction

63 (a) Wilson, S. R.; Price, M. F. *J. Org. Chem.* **1984**, *49*, 722-725. (b) Nudelman, A.; Kelner, R.; Broida, N.; Gottlieb, H. E. *Synthesis* **1989**, 387-388.

catalyzed by the 2-triethylsilyloxymethyl derivative, **1.16**. Even the parent pyrindinyl complex **1.29**, which showed no acceleration versus background in acylation with acetic anhydride, was active as a catalyst for acylation with diketene, albeit with a half-life of approximately 50,000 minutes. Again, the 4-(dimethylamino)pyrindinyl complex, **1.31**, was by far the most active catalyst, resulting in a reaction half-life of less than 3 minutes. Thus, by eliminating the need for the addition of stoichiometric base, the use of diketene as an acylating agent allows us to observe useful rate enhancements with chiral azaferrocene derivative **1.16** as well as with chiral DMAP derivative **1.31**. The same trends in reactivity are observed as with acylation with acetic anhydride: A 2-substituent lessens the activity of azaferrocene derivatives, and a 4-dimethylamino group increases the activity of pyrindinyl derivatives.

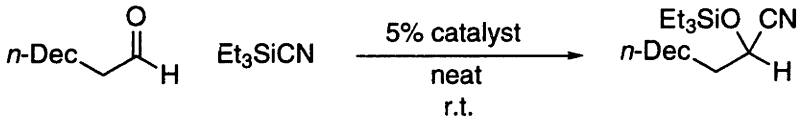


(1D.4)

complex	half-life (min)
1.11	16
1.16	810
1.29	~50,000
1.31	<3
none	no reaction (3,500 min)

We also investigated the catalytic activity of our complexes in the cyanosilylation of dodecanal with triethylsilylcyanide (eq 1D.5). These reactions were quite conveniently conducted neat, and the percent conversion was determined by ^1H NMR analysis of aliquots. Again, we were pleased to observe catalysis by both classes of complexes. Unsubstituted azaferrocene **1.11** provided nearly two orders of magnitude of rate acceleration versus the background reaction, the half-lives being 31 minutes and 2,300 minutes, respectively. Again, 2-substituted azaferrocene **1.16**

was slower than **1.11**, with a half-life of 280 minutes. Interestingly, even the parent pyrindinyl complex, **1.29**, was a reasonable catalyst for cyanosilylation, giving a half-life of 180 minutes. The fastest of our catalysts was once again chiral DMAP derivative **1.31** with a half-life of less than 2 minutes.



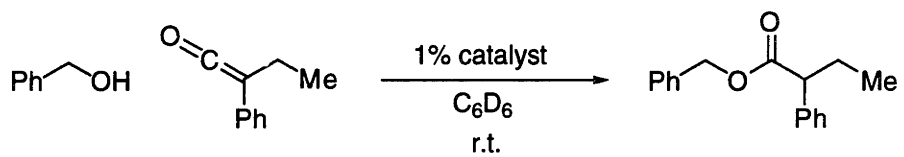
(1D.5)

complex	half-life (min)
1.11	31
1.16	280
1.29	180
1.31	<2
none	2,300

The last reaction for which we examined the relative activity of our complexes was the addition of benzyl alcohol to phenylethylketene. Because nucleophilic attack at a ketene produces an enolate, as was the case with diketene, this reaction represents another example of an acylation reaction in which the addition of stoichiometric base is not required. Once again, each of the four complexes examined showed significant catalytic activity (eq 1D.6). There was some degree of background reaction under these conditions, and the exact rate of that background reaction varied slightly with each batch of ketene.[64] Because of this, caution must be exercised when comparing half-lives, unless all of the reactions were done side-by-side with the same batch of ketene. The relative efficiencies of the complexes as catalysts of this reaction were measured by ^{1}H NMR determination of the reaction half-lives. The reactions were conducted in C_6D_6 with 1 mol% catalyst. While the uncatalyzed reaction proceeded with a half-life of 600 minutes, unsubstituted azaferrocene **1.11** and 2-triethylsilyloxymethyl derivative **1.16** catalyzed the reaction

64 One possible explanation of this problem is the presence of residual tertiary amine from the dehydrohalogenation reaction that was used to form the ketene.

with half-lives of 7 and 16 minutes, respectively. Even parent pyrindinyl complex **1.29** was an effective catalyst for the ketene addition reaction, giving a half-life of 20 minutes. Not surprisingly, chiral DMAP **1.31** was again the best catalyst among our complexes, resulting in a half-life of 2 minutes.



(1D.6)

complex	half-life (min)
1.11	7
1.16	16
1.29	20
1.31	2
none	600

Because chiral DMAP analog **1.31** was superior among our complexes in the catalysis of each of the above reactions, we chose to investigate its ability to serve as a catalyst for preparative scale ($\geq$ 1mmol) reactions. Thus, when 1-phenylethanol was acylated with acetic anhydride in the presence of 3 mol% of **1.31** and stoichiometric triethylamine, the desired acetate was isolated in an average yield of 85% after 7 hours. When diketene was the acylating agent, the product was isolated in an average yield of 89% after four hours with only 1 mol% of **1.31**. The cyanosilylation of dodecanal with triethylsilylcyanide proceeded to give an average yield of 94% after 75 minutes with 1 mol% of **1.31**. The addition of benzyl alcohol to phenylethylketene was particularly efficient, giving an average yield of 98% after only 60 minutes with 0.5 mol% of **1.31** as the catalyst.

Conclusions

The ability of heterocyclic π-complexes with iron to serve as catalysts in four reactions of interest was shown. In the case of acylation of 1-phenylethanol with acetic anhydride, only 4-(dimethylamino)pyrindinyl complex **1.31** provided substantial rate acceleration as compared to the background (triethylamine-catalyzed) reaction. Although azaferrocene derivatives **1.11** and **1.12** showed a slight rate enhancement, the use of azaferrocenes as catalysts in the asymmetric variant of this reaction is not practical. When the reaction was conducted without triethylamine, the background reaction was suppressed, but the catalysts became deactivated by the acetic acid that was produced as the reaction progressed.

To avoid competitive catalysis by the stoichiometric base, we also explored acylations of 1-phenylethanol using diketene. No acid is generated in this reaction, so the addition of a base was not necessary. As was hoped, there was no significant background reaction between diketene and 1-phenylethanol. The reaction did, however, proceed in the presence of each of the four heterocyclic π-complexes that we investigated, with 4-(dimethylamino)pyrindinyl complex **1.31** again being the most active of our catalysts.

The cyanosilylation of dodecanal with triethylsilylcyanide was also shown to be catalyzed by our heterocyclic π-complexes. Although there was a background reaction, an acceleration of the reaction rate was observed with azaferrocene derivatives **1.11** and **1.16** as well as with pyrindinyl complexes **1.29** and **1.31**. As expected, **1.31** was the most active of the complexes.

The addition of benzyl alcohol to phenylethylketene was investigated and gave results very similar to those seen for cyanosilylation. Although there was a background reaction, each of the four heterocyclic π-complexes employed resulted in acceleration of the reaction, with complex **1.31** being the best catalyst of those investigated.

From the four reactions studied, two important reactivity trends were seen. The 2-unsubstituted (achiral) azaferrocene, **1.11**, was a better catalyst in each case than its 2-substituted derivatives, **1.12** or **1.16**. Also, the 4-(dimethylamino)pyrindinyl complex, **1.31**, was a better catalyst in each case than the parent pyrindinyl complex, **1.29**. These trends are the same as those observed for pyridine derivatives in nucleophile-catalyzed reactions.

The ability of complex **1.31** to catalyze preparative ($\geq$ 1 mmol) scale reactions was also shown. Isolated yields of >85% were obtained for each of the four reactions studied when **1.31** was used as the catalyst. Catalyst loadings were low, ranging from 3 mol% for acylation 1-phenylethanol with acetic anhydride to 0.5 mol% for addition of benzyl alcohol to phenylethylketene. The reaction times were convienient, with 7 hours being the longest required.

In conclusion, we have shown that π-complexes of nitrogen heterocycles with iron can be effective catalysts for a range of interesting reactions. Our work has focused on two classes of complexes, those based on an azaferrocene scaffold and those based on a pyrindinyliron scaffold. Of the complexes included in this study, 4-(dimethylamino)pyrindinyl complex **1.31** was the most active in each reaction.[65]

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65 In subsequent work in our group, Christine Garrett has shown that the ruthenium analogs of these complexes are sometimes more active. See Reference 42.

Experimental

General. 1-Phenylethanol (Aldrich), benzyl alcohol (Mallinckrodt), diketene (Aldrich), triethylsilyl chloride (Aldrich), and dodecanal (Aldrich) were distilled prior to use. Triethylsilylcyanide was prepared according to the method of Becu and Anteunis.[66] Phenylethylketene was prepared according to the method of Tidwell.[67]

Solvents were distilled from the indicated drying agents: benzene (sodium/benzophenone); tetrahydrofuran (sodium/benzophenone); dichloromethane (calcium hydride).

Analytical thin layer chromatography was performed using EM Reagents 0.25 mm silica gel 60 plates, and visualization was accomplished with potassium permanganate or with ethanolic phosphomolybdic acid. Flash chromatography was performed on EM Reagents silica gel 60 (230-400 mesh).

^{1}H and ^{13}C nuclear magnetic resonance spectra were recorded on a Varian XL-300, Varian Mercury 300, Varian Unity 300 or a Varian VXR 500 spectrometer at ambient temperature.

All reactions were carried out under an atmosphere of nitrogen or argon in oven-dried glassware with magnetic stirring, unless otherwise indicated.

Determination of Reaction Half-Lives

The reported data (eq 1D.1 and 1D.4-1D.6) are the average of two runs with two independently prepared sets of catalysts. The two runs produced essentially identical results (within 2 minutes for half-lives shorter than 20 minutes; within 5% for half-lives longer than 20 minutes).

The experiments were set up in a glove box under an atmosphere of nitrogen.

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66 Becu, C.; Anteunis, M. J. O. *Bull. Soc. Chim. Belg.* **1987**, 96, 115-117.

67 Baigrie, L. M.; Seiklay, H. R.; Tidwell, T. T. *J. Am. Chem. Soc.* **1985**, *107*, 5391-5396.

Acylation of 1-phenylethanol with acetic anhydride (eq 1D.1). Stock solutions (0.087 M) of each catalyst were prepared in CD_2Cl_2 (a total of nine stock solutions were made since two independently prepared and purified batches of each catalyst were tested and since a single stock solution of 4-dimethylaminopyrindine was made to test its activity). 210 µl (1.74 mmol) of 1-phenylethanol, 200 µl (2.12 mmol) of acetic anhydride, and 290 µl (2.08 mmol) of triethylamine were added by syringe to a vial containing 5.0 ml of CD_2Cl_2. 0.5 ml of this solution was then added to each of ten screw-cap NMR tubes. 100 µl of catalyst stock solution was added to nine of the tubes, and 100 µl of CD_2Cl_2 was added to a control tube. The reactions were followed by ^1H NMR, and the percent completion was determined by comparing the signal of the methyl protons of 1-phenylethanol with that of the corresponding protons of the acetate. The tube containing 4-dimethylaminopyrindine turned bright orange upon mixing and showed no catalytic activity. Separate experiments confirm that pyrrole, 2,4-dimethyl-3-ethyl-pyrrole, and pyrindine also have no catalytic activity under these conditions.

Acylation of 1-phenylethanol with diketene (eq 1D.4). Stock solutions (0.087 M) of each catalyst were prepared in CD_2Cl_2 (a total of nine stock solutions, since two independently prepared and purified batches of each catalyst were used, along with a single stock solution of 4-dimethylaminopyrindine). 1-Phenylethanol (40 µL, 0.33 mmol) and diketene (31 µL, 0.40 mmol) were added to a vial containing 5.0 mL of CD_2Cl_2. This solution (0.5 mL) was then added to each of ten screw-cap (Teflon-liner) NMR tubes. Catalyst stock solution (20 µL) was added to nine of the tubes, and 20 µL of CD_2Cl_2 was added to the control tube. The reactions were followed by ^1H NMR, and the percent conversion was determined by comparing the signal of the methyl protons of 1-phenylethanol with the signal of the corresponding protons of the acylated product. The 4-dimethylaminopyrindine did catalyze the reaction with a half-life of approximately 13 minutes.

Separate control experiments established that pyrrole, 2-triethylsilyloxymethyl-pyrrole,[68] and pyrindine do not serve as effective catalysts under these conditions (<20% reaction after 3500 minutes).

Cyanosilylation of dodecanal with Et_3SiCN (eq 1D.5). Dodecanal (50 μL, 0.23 mmol) and Et_3SiCN (59 μL, 0.34 mmol) were added to a vial containing catalyst (0.012 mmol). Aliquots of the reaction mixture were removed periodically and diluted with C_6D_6. The percent conversion was then determined by ^1H NMR by comparing the signal of the aldehydic proton of the aldehyde with the signal of the corresponding proton of the silylated cyanohydrin (a five-second delay was employed). Two independently prepared and purified batches of each of the four catalysts were tested separately.

4-Dimethylaminopyrindine and pyrindine catalyze the cyanosilylation reaction with half-lives of 3 minutes and 147 minutes, respectively. Pyrrole and 2-triethylsilyloxymethylpyrrole do not catalyze the reaction.

Addition of benzyl alcohol to phenylethylketene (eq 1D.6). Stock solutions of each catalyst (0.0068 M) were prepared in C_6D_6 (a total of eight stock solutions were made, since two independently prepared and purified batches of each catalyst were examined). Phenylethylketene (20.0 μL, 0.136 mmol) and benzyl alcohol (15.5 μL, 0.150 mmol) were added to a vial containing 1.4 mL of C_6D_6. This solution was divided between two NMR tubes, and 100 μL of a catalyst stock solution was added to each tube. The progress of the reaction was monitored by ^1H NMR by comparing the signal of the benzylic protons of the alcohol with the signal of the corresponding protons of the ester. This procedure was repeated for the remaining catalyst stock solutions and for a control reaction using 100 μL of C_6D_6 rather than a catalyst solution.

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68 Prepared by silylation of pyrrole-2-methanol with TES-Cl.

4-Dimethylaminopyrindine and pyrindine catalyze the reaction with half-lives of 12 minutes and 311 minutes, respectively. Pyrrole and 2-triethylsilyloxymethyl-pyrrole do not catalyze the reaction.

Preparative-Scale Reactions With Catalyst 1.31

Acylation of 1-phenylethanol with acetic anhydride. To a flask containing 11 mg (0.03 mmol) of catalyst **1.31** was added 5 ml of CH_2Cl_2. 129 mg (1.05 mmol) of 1-phenylethanol, 125 mg (1.24 mmol) of triethylamine, and 130 mg (1.28 mmol) of acetic anhydride were added by syringe, and the resulting purple solution was stirred for 7 hours. The solvent was removed by vacuum, and the residual oil was purified by flash chromatography (5% → 10% EtOAc/hexanes) yielding the product as 137 mg (83%) of a colorless oil.

When this procedure was repeated using an independently prepared and purified batch of catalyst **1.31**, an isolated yield of 88% was obtained.

Acylation of 1-phenylethanol with diketene. 1-Phenylethanol (134 mg, 1.10 mmol) and then diketene (137 mg, 1.63 mmol) were added by syringe to a flask containing catalyst **1.31** (3.8 mg, 0.011 mmol) in 5 mL of CH_2Cl_2. The resulting yellow solution was stirred at room temperature for 4 hours. The reaction mixture was then concentrated, and the residual oil was purified by flash chromatography (10% → 25% EtOAc/hexanes) yielding 183.1 mg (81%) of the desired product as a colorless oil.

When this procedure was repeated using an independently prepared and purified batch of catalyst **1.31**, an isolated yield of 96% was obtained.

Cyanosilylation of dodecanal with Et_3SiCN. Dodecanal (204 mg, 1.10 mmol) was added to a flask containing catalyst **1.31** (3.8 mg, 0.011 mmol). To the resulting pink solution was added Et_3SiCN (242 mg, 1.71 mmol), and the resulting pink solution was stirred at room temperature for 75 minutes. The reaction mixture was then

purified by flash chromatography (2% → 5% EtOAc/hexanes), yielding 345 mg (96%) of the desired product as a colorless oil. The catalyst was recovered by flushing the column with triethylamine.

When this procedure was repeated using an independently prepared and purified batch of catalyst **1.31**, an isolated yield of 92% was obtained.

Addition of benzyl alcohol to phenylethylketene. Benzyl alcohol (129 mg, 1.19 mmol) and then phenylethylketene (166 mg, 1.13 mmol) were added by syringe to a flask containing catalyst **1.31** (1.9 mg, 0.0054 mmol) in 5 mL of C_6H_6. The resulting purple solution was stirred for 1 hour at room temperature. The reaction mixture was then concentrated, and the residual oil was purified by flash chromatography (5% → 10% EtOAc/hexanes), yielding 280 mg (97%) of the desired product as a colorless oil. The catalyst was recovered by flushing the column with triethylamine.

When this procedure was repeated using an independently prepared and purified batch of catalyst **1.31**, an isolated yield of 98% was obtained.

Chapter Two:

Kinetic Resolution of Alcohols by Acylation Catalyzed by Planar-Chiral π-Complexes

Chapter Two, Part A: Introduction to Kinetic Resolution

In the simplest terms, a kinetic resolution is a reaction in which the two enantiomers of a compound react at different rates. The first example of such a reaction to be recognized was reported by Pasteur in 1858, just 10 years after he first separated the enantiomers of ammonium sodium tartrate under his microscope.[1] What Pasteur noticed was that when racemic ammonium tartrate was *partially* fermented by a mold, the starting material was recovered with optical activity. Kinetic resolution, starting with Pasteur's example and covering the next 130 years, has been the subject of an excellent review by Kagan, so only those aspects most relevant to our chemistry will be presented in this thesis.[2,3] A kinetic resolution is different from most asymmetric reactions because the observed enantiomeric excess depends not only on the inherent selectivity of the reaction, but also on the conversion. Another difference is that the unreacted starting material, rather than the product, of a kinetic resolution is often the compound of interest. In fact, the product of a kinetic resolution does not necessarily have to be chiral (e.g., the enantioselective oxidation a secondary alcohol into an achiral ketone).[4]

Because the ee is dependent on conversion, it is useful in discussions of kinetic resolutions to quantify the selectivity without having to specify both ee and conversion. This may be accomplished by use of the selectivity factor (s), the ratio of the first-order or pseudo-first-order rate constants for the conversion of the enantiomers into their respective products (eq 2A.1).

$$s = \frac{k_R}{k_S} \qquad (2A.1)$$

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1 Pasteur, L. *C. R. Hebd. Seance Acad. Sci. Paris* **1858**, *46*, 615-618.

2 Kagan, H. B.; Fiaud, J. C. *Top. Stereochem* **1988**, *18*, 249-331.

3 For a discussion of kinetic resolution containing more recent examples, see: Diver, S. T. Ph.D. Thesis, University of Wisconson, 1995.

4 For a recent example, see: Rychnovsky, S. D.; McLernon, T. L.; Rajapakse, H. *J. Org. Chem.* **1996**, *61*, 1194-1195.

The value of s is related to the percent conversion (C) and the ee of the unreacted starting material (ee):

$$s = \frac{\ln[(1-C)(1-ee)]}{\ln[(1-C)(1+ee)]} \qquad (2A.2)$$

In the special case where the enantiomeric starting materials are converted into enantiomeric products (as is the case with acylation of alcohols), s can also be expressed in terms of the ee of the product (ee'):

$$s = \frac{\ln[1-C(1+ee')]}{\ln[1-C(1-ee')]} \qquad (2A.3)$$

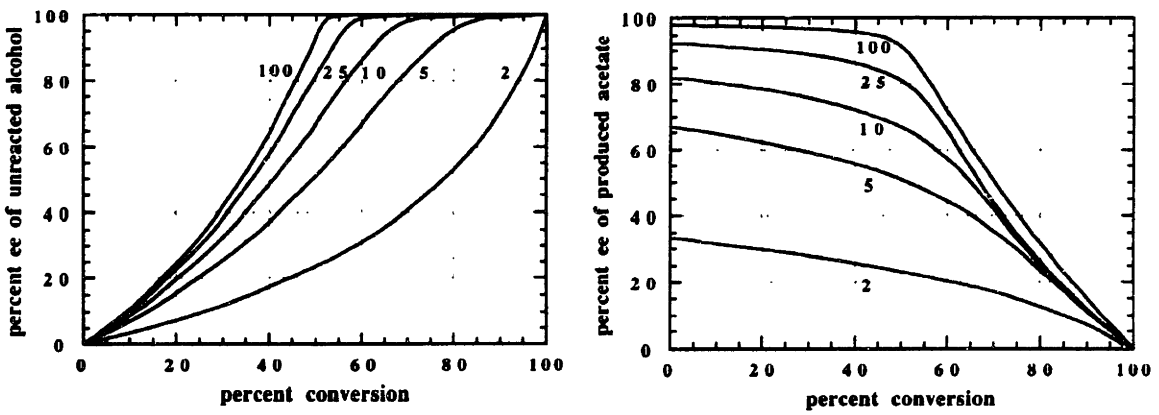
Since ee and ee' are related to C by equation 2A.4, it is possible to calculate the value of s given any two of the three pieces of data: ee, ee', or C. In practical terms, it is often easiest to determine s by measuring the ee's of starting material and product so that an accurate determination of the conversion is not required.

$$\frac{ee}{ee'} = \frac{C}{1-C} \qquad (2A.4)$$

Because the ee of the starting material increases with conversion, it is possible to obtain material of high enantiomeric purity, even with reactions having low selectivity, by simply carrying the reaction to an appropriately high conversion. Unfortunately, the ee of the product becomes quite low at high conversion, so this approach is not without a price. The relationships between the percent conversion and the ee's are shown in Figure 2.1. The left graph shows the ee of unreacted starting material versus percent conversion for several values of s, and the right graph shows the ee of the product versus percent conversion for the same values of s. Important to notice is that once the selectivity reaches double digits, high ee's of starting material can be obtained starting at about 60% conversion. For s greater than 49.0, unreacted starting material with greater than 99% ee can be obtained at

less than 55% conversion. If one is interested in both the starting material and the product, s values above 58.4 allow for the isolation of starting material and product *each* having greater than 90% ee.

Figure 2.1. Graphs of ee Versus Pervent Conversion.



While kinetic resolution is a powerful technique for the separation of enantiomers, it should not be viewed strictly as an alternative to asymmetric synthesis. In some cases, the two may represent complementary techniques. Because the maximum yield of a given enantiomer in a simple kinetic resolution of a racemate is only 50%, the best approach to obtaining large amounts of a single enantiomer of a product in high ee might be asymmetric synthesis, followed by kinetic resolution to raise the ee to the desired level. This is particularly true if very high optical purity is required, because the starting material of a kinetic resolution can theoretically be recovered with arbitrarily high ee.

The remainder of this chapter will be dedicated to the kinetic resolution of secondary alcohols by catalytic asymmetric acylation. After a brief description of the work of others in this area, our results will be presented in detail.

Chapter Two, Part B: Asymmetric Acylation of Alcohols Catalyzed by Planar-Chiral π-Complexes

Background

Due to the synthetic utility of chiral secondary alcohols, much effort has been put forth to obtain them as single enantiomers. Although great advances in the catalytic asymmetric synthesis of secondary alcohols have been made, kinetic resolution by asymmetric acylation[5] remains an attractive method and is an area of active study. While highly enantioselective acylations catalyzed by enzymes have been reported for many substrates,[6] the search for a highly selective non-enzymatic catalyst has been less fruitful.

The first example of non-enzymatic kinetic resolution of secondary alcohols by acylation was published by Wegler more than 60 years ago.[7,8] He demonstrated that optically active secondary alcohols could be isolated after treating the racemates with acyl halides or anhydrides in the presence of stoichiometric amounts of brucine. Unfortunately, the exact value of his selectivity cannot be determined from the data reported. A more easily quantified report of this approach was published by Horner in 1989.[9] He reported that when racemic 1-phenylethanol, acetyl chloride, and optically pure *N*, *N*-dimethyl-1-phenylethylamine are mixed in a ratio of 2:1:1, ester having up to 68% ee is isolated (eq 2B.1). If the reaction is assumed to proceeded to completion, this corresponds to a selectivity of 11.

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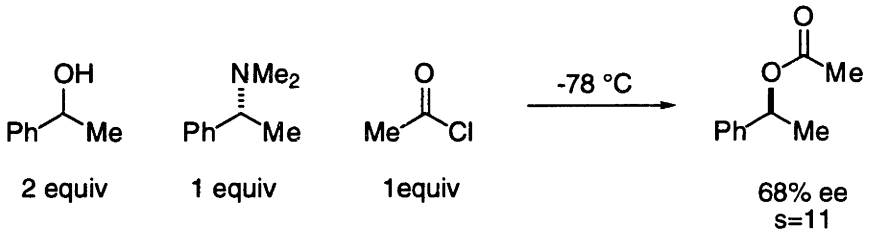
5 For the purposes of this thesis, discussion will be limited to those cases in which the actual acyl fragment is achiral. In other words, diastereoselective acylations will not be considered.

6 (a) Wong, C.-H.; Whitesides, G. M. *Enzymes in Synthetic Organic Chemistry*; Pergamon: New York, 1994; Chapter 2. (b) Klibanov, A. M. *Acc. Chem. Res.* **1990**, *23*, 114-120. (c) Sih, C. J.; Wu, S.-H. *Top. Stereochem.* **1989**, *19*, 63-125.

7 Wegler, R. *Liebigs Ann. Chem.* **1932**, *498*, 62-76.

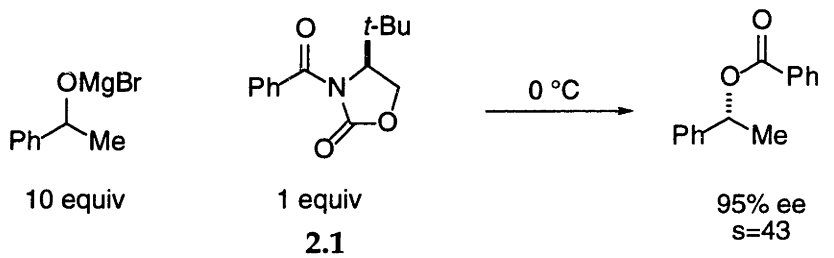
8 For a recent overview of nonenzymatic kinetic resolution of secondary alcohols, see: Somfai, P. *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 2731-2733.

9 Weidert, P. J.; Geyer, E.; Horner, L. *Liebigs Ann. Chem.* **1989**, 533-538.



(2B.1)

Until recently, the best results for non-enzymatic asymmetric acylation had been obtained using a stoichiometric chiral acylating agent. The two best systems of this type have come from the laboratories of Evans and Vedejs. The Evans system, reported in 1993, relies on a chiral *N*-benzoyloxazolidinone as the acylating agent (eq 2B.2).[10] Treatment of *N*-benzoyloxazolidinone **2.1** with 10 equivalents of the magnesium bromide salt of 1-phenylethanol results in the formation of ester with 95% ee. The calculated selectivity in this case is 43. The selectivities for phenyl-*n*-alkylcarbinols (Et, *n*-Pr, *n*-Bu) are in the range of 20-30, but the selectivity drops to only 5 with 2-methyl-1-phenylpropanol.



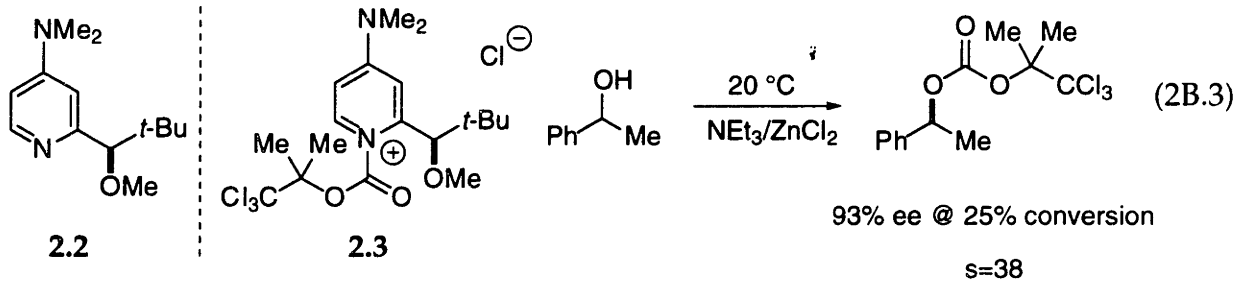
(2B.2)

In 1996 Vedejs reported a system based on chiral DMAP derivative **2.2**. Although **2.2** itself was not reported to be a catalyst for asymmetric acylation, salt **2.3**, made by the reaction of **2.2** with a commercially available chloroformate, effects the kinetic resolution of a range of arylalkylcarbinols when used in the presence of a tertiary amine and a Lewis acid (eq 2B.3).[11] The mixed carbonate of 1-phenylethanol was formed in 93% ee at 25% conversion for a selectivity of 38. With this system, increasing the size of the alkyl group to ethyl (1-phenylpropanol) results in a

10 Evans, D. A.; Anderson, J. C.; Taylor, M. K. *Tetrahedron Lett.* **1993**, *34*, 5563-5566.

11 Vedejs, E.; Chen, X. *J. Am. Chem. Soc.* **1996**, *118*, 1809-1810.

selectivity of 22, while increasing the size of the aryl group to naphthyl (1-(2-naphthyl)ethanol) results in a selectivity of 45. Interestingly, both the tertiary amine and the Lewis acid are necessary for acyl transfer to proceed at a reasonable rate at room temperature.



(2B.3)

The first report of a non-enzymatic kinetic resolution of a secondary alcohol by acylation that was both highly selective (s>10) and for which turnover was demonstrated also came from Vedejs.[12] Following up on earlier work in which it was reported that tributylphosphine is an excellent catalyst for acylation of alcohols with anhydrides,[13] Vedejs reported in 1996 that chiral phospholane **2.4** catalyzes the acylation of 2,2-dimethyl-1-phenylpropanol with *m*-chlorobenzoic anhydride to give an 82% ee of acylated product and a 29% ee of recovered alcohol (eq 2B.4). These values correspond to a selectivity of 13. This was, however, the only combination of reagents reported to give high selectivity. The use of other alcohols as substrates or of acetic anhydride as the acylating agent results in selectivities of less than 6. Other drawbacks of this system are the relatively high catalyst loading (16 mol%) and the use of a non-commercially available anhydride.

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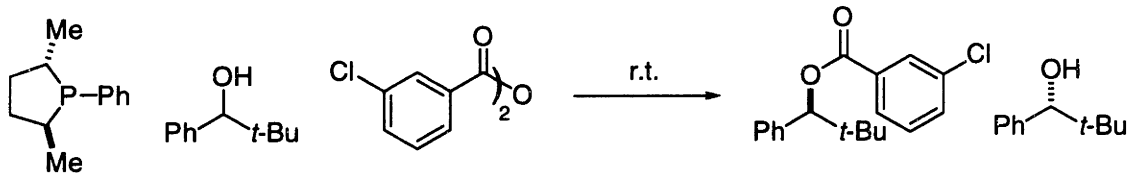
12 Vedejs, E.; Daugulis, O.; Diver, S. T. *J. Org. Chem.* **1996**, *61*, 430-431.

13 Vedejs, E.; Diver, S. T. *J. Am. Chem. Soc.* **1993**, *115*, 3358-3359.



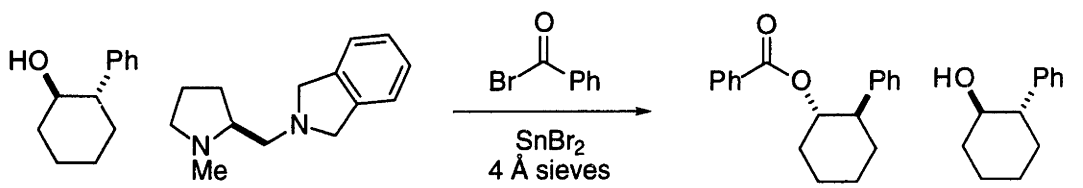
2.4

82% ee 29% ee

s=13

(2B.4)

Another example of a highly selective, catalytic, non-enzymatic kinetic resolution of secondary alcohols by acylation came from Oriyama in 1996.[14] With the chiral proline-derived diamine **2.5** as the catalyst, certain classes of secondary alcohols are kinetically resolved with very high selectivity. Specifically, *trans*-2-substituted cycloalkanols give excellent results. The best substrate reported, *trans*-2-phenyl-1-cyclohexanol, is resolved with an s over 100 (eq 2B.5). The use of other classes of substrates results in significantly lower s values; the selectivity for 1-phenylethanol being only 6.0 while that for 1-(2-methylphenyl)ethanol is 12. The catalyst loading in this system is quite high (30 mol%), and the use of $SnBr_2$ as a co-catalyst is recommended, but the ready availability of **2.5** in two steps from proline renders the former point somewhat less relevant. It should be noted that more recent work by the same author reported highly enantioselective acylations of *meso*-diols catalyzed by as little as 0.5 mol% of diamine in the presence of a stoichiometric amount of triethylamine.[15]



racemic **2.5**

97% ee 84% ee

s>100

(2B.5)

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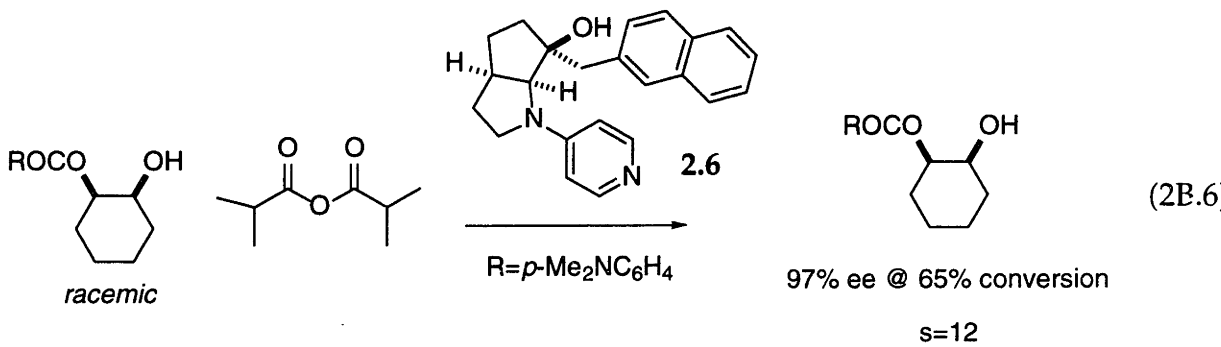
14 Oriyama, T.; Hori, Y.; Imai, K.; Sasaki, R. *Tetrahedron Lett.* **1996**, *37*, 8543-8546.

15 Oriyama, T.; Imai, K.; Sano, T.; Hosoya, T. *Tetrahedron Lett.* **1998**, *38*, 3529-3532.

The use of novel chiral PPY derivative **2.6** as a catalyst for asymmetric acylation was reported by Fuji in 1997.[16] Citing Vedejs' results with **2.2**, the authors reasoned that a stereocenter in the 2-position should be avoided in the design of a chiral catalyst. Instead, their design includes a remote stereocenter with a naphthalene substituent that is proposed to have a π-π interaction with the acylpyridinium portion of the molecule after acylation on nitrogen. The best reported selectivity in an acylation catalyzed by **2.6** involves the use of isobutyric anhydride as the acylating agent and *cis*-1,2-cyclohexanediol monoacylated with a *p*-dimethylaminobenzoyl group as the substrate (eq 2B.6). In this case, a 97% ee of recovered starting material is observed at 65% conversion, corresponding to an s of 12. Again, this system is not general, and even minor changes in the acyl portion of the substrate result in much lower selectivities.



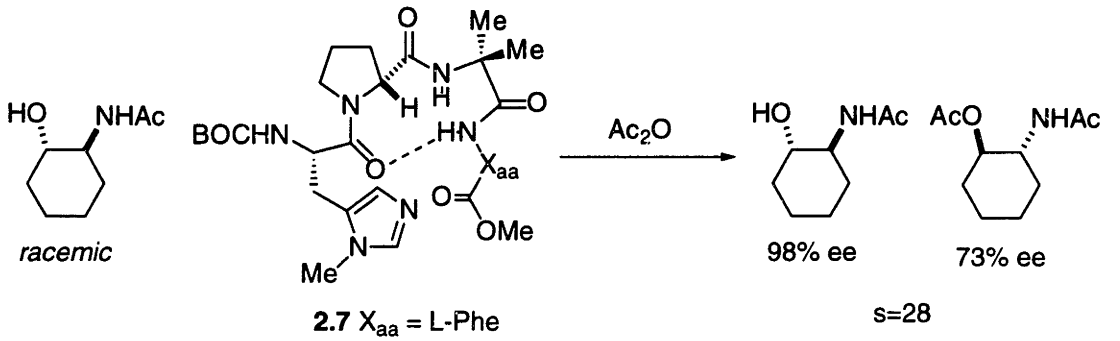
(2B.6)

As part of efforts directed at making small-molecule catalysts that mimic peptides, Miller published two communications in 1998 describing the use of peptides containing *N*-alkylimidazole residues as catalysts for asymmetric acylation reactions.[17] Although five different catalysts were reported to give s values over 10, the best results reported were with **2.7**, in which X_{aa} is a natural phenylalanine residue. When *trans*-2-(*N*-acetylamino)cyclohexan-1-ol is acylated with acetic

16 Kawabata, T.; Nagato, M.; Takasu, K.; Fuji, K. *J. Am. Chem. Soc.* **1997**, *119*, 3169-3170.

17 (a) Miller, S. J.; Copeland, G. T.; Papaioannou, N.; Horstmann, T. E.; Ruel, E. M. *J. Am. Chem. Soc.* **1998**, *120*, 1629-1630. (b) Copeland, G. T.; Jarvo, E. R.; Miller, S. J. *J. Org. Chem.* **1998**, *63*, 6784-6785.

anhydride in the presence of **2.7**, starting alcohol is recovered with 98% ee while the acetate has 73% ee for a calculated s of 28 (eq 2B.7). The only substrates for which selectivity has been reported have been *trans*-2-substituted cycloalkanols with an acetamido group in the 2-position, presumably because the selectivity of this system stems from hydrogen bonding of the substrate to the catalyst. Interestingly, the sense of selectivity of the catalysts can be reversed by changing the configuration of the proline residue.

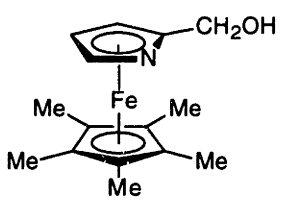


(2B.7)

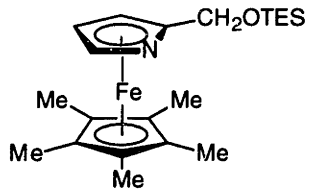
Even today, the state-of-the-art in non-enzymatic, catalytic, asymmetric acylation of secondary alcohols leaves much to be desired. Issues of selectivity as well as catalyst availability and generality all represent unsolved problems. The following section presents our results in this area using planar-chiral π-complexes as catalysts.

Results and Discussion

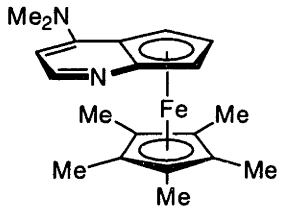
Because azaferrocene derivative **1.15** was the first of our planar-chiral π-complexes to which we had access as a single enantiomer, our initial studies of asymmetric acylation focused on its triethylsilyl ether, **1.16**, as a catalyst. As was discussed in Chapter 1, azaferrocene derivatives are not sufficiently active catalysts to be effective in acylations with acetic anhydride. With diketene as the acylating agent, however, the lack of a background reaction makes asymmetric reactions catalyzed by **1.16** quite feasible.



(+)-**1.15**



(+)-**1.16**



(-)-**1.31**

Initial experiments using **1.16** as a catalyst for the kinetic resolution of 1-phenylethanol in the presence of diketene resulted in modest selectivity, so a careful solvent study of the reaction was performed.[18] Because the enantiomer ratio observed in the *product* of a kinetic resolution at very low conversions (when the ratio of the enantiomers of starting material is still approximately 1) is approximately equal to the selectivity factor, a convenient method for rapidly screening a range of solvents is to carry out the reaction in the presence of a large excess of substrate. Direct comparison of the product ee's then reveals the best set of conditions without the need for careful determination of % conversion (notice that the slope of the graphs of product ee versus percent conversion in Figure 2.1 are all relatively flat at low conversion). Table 2.1 shows the results of the kinetic resolution of 1-phenylethanol (10 equiv) in the presence of diketene (1 equiv), and

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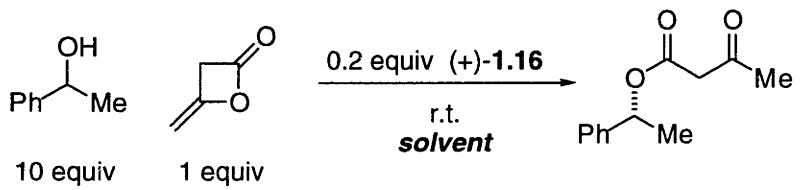
18 For an example of enzyme-catalyzed kinetic resolution of secondary alcohols with diketene, see: Jeromin, G. E; Welsch, V. *Tetrahedron Lett.* **1995**, *36*, 6663-6664.

(+)-**1.16** (0.2 equiv). Although carbon tetrachloride gave the highest selectivity among those solvents screened, it resulted in catalyst decomposition, so benzene was used for subsequent reactions.

Table 2.1. Solvent Study for Asymmetric Acylation with Diketene.

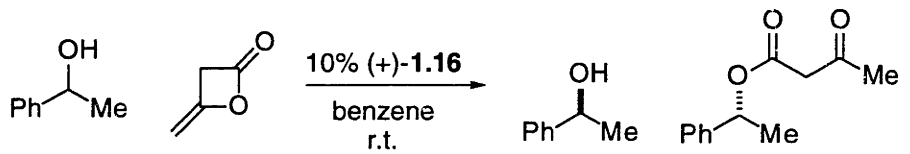


10 equiv 1 equiv

solvent	% ee of product	s[a]	solvent	% ee of product	s[a]
toluene	30	1.9	MTBE	33	2.1
THF	10	1.2	benzene	39	2.4
ether	21	1.6	$PhCF_3$	38	2.3
CH_2Cl_2	22	1.6	hexanes	22	1.6
CCl_4	47	2.9	dioxane	2.0	1.0
CH_3CN	7.6	1.2	CH_3NO_2	2.1	1.0

[a] Assuming complete reaction

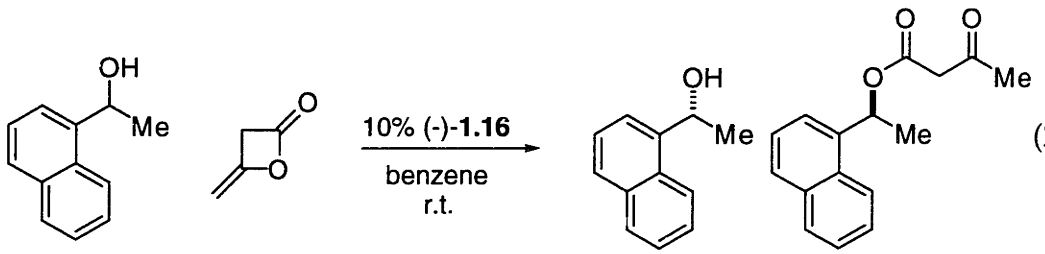
Using benzene as solvent, kinetic resolution reactions catalyzed by **1.16** were carried out to higher conversion for 1-phenylethanol (eq 2B.8) and for α-methyl-1-naphthalenemethanol (eq 2B.9). In the former case, unreacted alcohol was recovered with 54% ee while the acetoacetate was isolated with 38% ee. These ee values correspond to an s of 3.7 at 58% conversion. Use of the latter substrate resulted in an 87% ee of alcohol and a 43% ee of acetoacetate, corresponding to a selectivity of 6.5 at 67% conversion. While these selectivities are less than impressive by today's standards, they were better than any that had been reported for those substrates with a non-enzymatic catalyst when our study was published in 1996.



54% ee 38% ee

s=3.7 @ 58% conversion

(2B.8)

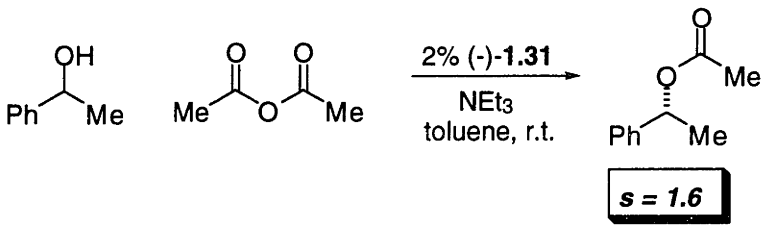


87% ee 43% ee

s=6.5 @ 67% conversion

(2B.9)

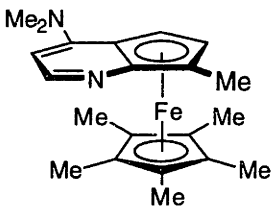
The discovery by Dr. Hallie Latham that the enantiomers of chiral DMAP derivative **1.31**, a much more active catalyst than **1.16**, could be easily separated by chiral HPLC moved our studies of asymmetric acylation into the next phase. She first attempted the kinetic resolution of 1-phenylethanol with diketene using **1.31** but found that the product formed was essentially racemic (s≈1.0). Since **1.31** had been shown to be active as a catalyst for acylation with acetic anhydride as well (see Chapter 1), Latham next conducted a kinetic resolution of 1-phenylethanol catalyzed by **1.31** using acetic anhydride as the acylating agent (eq 2B.10). The observed selectivity was a disappointing 1.6.



(2B.10)

Unwilling to give up on our basic catalyst design, we concluded that **1.31** must either be lacking efficient left-right differentiation or top-bottom differentiation. To

explore a system with increased left-right differentiation relative to **1.31**, Latham prepared the 7-methyl derivative, **2.8**, by metallation of **1.31** with *n*-BuLi, followed by trapping with methyl iodide. Unfortunately, **2.8** is not an effective catalyst for alcohol acylation with acetic anhydride, probably because of steric hindrance in the vicinity of nitrogen.



2.8

Latham next turned to the idea of increased top-bottom differentiation. Because the top of the nucleophilic nitrogen was already void, this required the use of a larger metal fragment. Exchange of the Cp* ring for the much larger 1,2,3,4,5-pentaphenylcyclopentadienyl ring was an attractive approach, because the requisite 1,2,3,4,5-pentaphenyl-1,3-cyclopentadiene (Ph_5C_5H) is commercially available from Aldrich[19] and because it might be substituted directly into the last step of our catalyst synthesis.[20,21] Latham found this to be the case and obtained complex **2.9** as a beautiful purple solid that is quite air-stable (eq 2B.11). In its present state, the synthesis of **2.9** provides a 21% overall yield in 10 steps from adipoyl chloride. The enantiomers of **2.9** are separated by chiral HPLC on a Chiralcel OD column, but the

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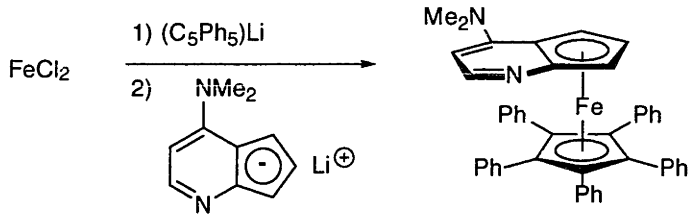
19 Although rather expensive at > $60 per gram, the Ph_5C_5H can be easily prepared from the much less expensive tetraphenylcyclopentadienone: Field, L. D.; Ho, K. M.; Lindall, C.; M.; Masters, A. F.; Webb, A. G. *Aust. J. Chem.* **1990**, *43*, 281-291.

20 Other η^5-C_5Ph_5 complexes with iron have been reported. For the first example, see: McVey, S.; Pauson, P. L. *J. Chem. Soc.* **1965**, 4312-4318.

21 For an overview of the use of bulky cyclopentadienyl ligands, see: Janiak, C.; Schumann, H. *Adv. Organomet. Chem.* **1991**, *33*, 291-393.

separation is quite tedious, and the faster-running enantiomer is generally the only one isolated with high ee.[22,23]

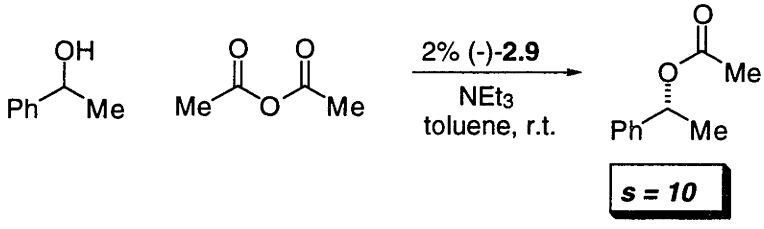


(2B.11)

2.9

(enantiomer shown is (-)-**2.9**)

When Latham conducted the kinetic resolution of 1-phenylethanol with (-)-**2.9** under conditions where complex (-)-**1.31** had given a selectivity of 1.6, we were delighted to observe a selectivity of 10 (eq 2B.12). This represents, to the best of our knowledge, the first case in which increased steric bulk of a remote cyclopentadienyl ligand of an organometallic catalyst results in higher enantioselectivities.[24] As hoped, the replacement of the Cp* with the Ph_5C_5 affected the magnitude, but not the sense of the selectivity.



(2B.12)

After a brief screening of common solvents and anhydrides, the conditions shown in Table 2.2, which resulted in an s of 14 for 1-phenylethanol, were settled

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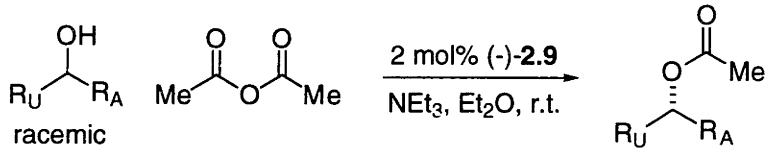
22 We have recently found that the enantiomers of **2.9** can also be separated on a Regis Whelk O-2 column. Although the separation is only marginally better, the Regis column has the advantage of being available in either enantiomer.

23 The absolute configuration of (+)-**2.9** has been tentatively assigned on the basis of an X-ray crystallographic study (anomalous dispersion).

24 It has been demonstrated in the rhodium-catalyzed hydroboration of styrene that substitution of a ferrocene-based ligand bearing an η^5-C_5Me_5 group for an otherwise identical ligand bearing a *smaller* η^5-C_5H_5 group results in higher enantioselectivity: Abbenhuis, H. C. L.; Burckhardt, U.; Gramlich, V.; Martelletti, A.; Spencer, J.; Steiner, I.; Togni, A. *Organometallics* **1996**, *15*, 1614-1621.

upon. Thus, reactions were carried out at room temperature[25] with 2 mol% of (-)-**2.9** as the catalyst, acetic anhydride as the acylating agent, Et_2O as the solvent, and triethylamine present to neutralize the acetic acid generated. Under these conditions, effective kinetic resolutions were observed for a range of secondary alcohols in which one of the two groups on the carbinol carbon was unsaturated.

Table 2.2. Selectivities for a Range of Substrates in the Asymmetric Acylation Catalyzed by (-)-2.9 in Ether.



entry	unreacted alcohol, major enantiomer	% ee of unreacted alcohol (% conversion)	s[a] (selectivity)
1	R = Me	95.2 (62)	14
2	Et	98.8 (62)	20
3	*i*-Pr	97.7 (55)	36
4	*t*-Bu	92.2 (51)	52
5	CH_2Cl	98.9 (69)	12
6	X = F	99.2 (64)	18
7	OMe	94.5 (60)	15
8		99.7 (63)	22
9		99.1 (67)	14
10		99.0 (61)	22
11		98.7 (60)	22

25 Acylations carried out at lower temperatures resulted in higher selectivities but were significantly slower.

The results in Table 2.2 show several important trends. First of all, the selectivity for simple phenylalkylcarbinols is highly dependent upon the steric bulk of the alkyl group and increases as this bulk increases (entries 1-4). For the *t*-butyl derivative, a very good selectivity of 52 was observed, although the reaction was quite slow. In contrast, the selectivity of this system is rather insensitive to the electronic nature of the aryl group (entries 1, 6, and 7). No significant change in selectivity was observed when the 4-substituent was changed from methoxy to hydrogen to fluro, although the fluoro derivative reacted marginally faster than 1-phenylethanol.

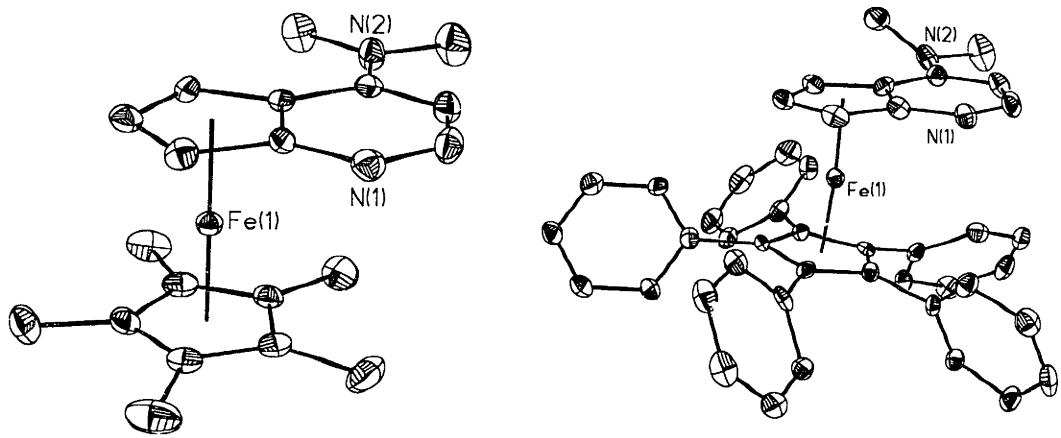
Although somewhat insensitive to electronic effects of the arene, the data suggest that the selectivity is dependent upon the sterics of that group. Specifically, an ortho substituent on the aryl group results in slightly higher selectivity (entries 1, 8, and 11). Changing the phenyl to either a 1-naphthyl group or to a 2-methylphenyl group boosted the selectivity from 14 to 22. Perhaps more difficult to understand is that the rate of the reaction also increased significantly in going from entry 1 to entry 8, an observation that was counterintuitive and will be discussed in more detail later in this chapter.

While an unsaturated group must be attached to the carbinol carbon to observe high selectivities, this group is not restricted to aryl rings. Some secondary cinnamyl alcohols were also kinetically resolved with high selectivities (entries 9 and 10). At the time, the selectivities reported in Table 2.2 were the best ever reported for each of the substrates listed. Unfortunately, attempts to kinetically resolve non-cinnamyl allylic alcohols and dialkylcarbinols under these conditions did not result in useful selectivities.

The increased selectivity observed with **2.9** versus **1.31** might be understood by comparing the X-ray crystal structures of the two catalysts (Figure 2.2). Because the metal fragment is not η^6-bound to the heterocyclic ring, the steric bulk below the nitrogen atom of **1.31** (and, therefore, the top-bottom differentiation) is not as much

as was called for in our original proposal. As can be seen in Figure 2.2, replacing the Cp* with the Ph_5C_5 ligand results in much more differentiation because the phenyl groups extend past the pyridine nitrogen. Furthermore, the slight tilt of the phenyl groups projects some of their bulk upward, even closer to the nitrogen atom. This interaction of the phenyl rings with the pyridine ring manifests itself in a 9.75° tilt between the planes of the cyclopentadienyl rings in **2.9**. In the case of complex **1.31**, this angle is only 1.9°. Although the crystal structure of **2.9** shows the phenyl rings in a propeller-like conformation, the ^{13}C NMR of the complex shows only 4 lines for the phenyl carbons at room temperature, suggesting that they can rotate rapidly.

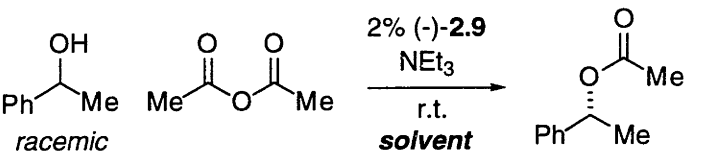
Figure 2.2. ORTEP Diagrams of Chiral DMAP Complexes 1.31 and 2.9.



After a brief hiatus in our asymmetric acylation chemistry, we became intrigued by a report in a Ph.D. thesis from the Vedejs group in which asymmetric acylation reactions were reported to be carried out in *t*-butanol as the solvent.[3] The tertiary alcohol is sufficiently inert toward acylation that good yields of the desired acetates of secondary alcohols were obtained. Thinking that our acylations might behave very differently in *t*-butanol than in more traditional solvents, we ran the experiment and found that the reaction was not only more selective, but also much faster! Because we hoped to take advantage of this increased rate by lowering the temperature, we changed from *t*-butanol (mp = 25 °C) to *t*-amyl alcohol (mp = -12

°C). With the help of Jen Tweddell, a thorough solvent study was conducted. By measuring the percent conversion after 1.0 hours, the approximate rate as well as the selectivity was measured in each solvent. As can be seen from Table 2.3, the reaction in *t*-amyl alcohol was more than twice as selective and approximately three times faster than in any other solvent.[26]

Table 2.3. Solvent Study for Kinetic Resolution with 2.9.



solvent	% conversion after 1.0 h	s
DMF	6	3.4
CH_3CN	10	3.6
CH_2Cl_2	14	7.0
acetone	8	8.7
THF	4	9.6
EtOAc	6	11
toluene	13	11
Et_2O	8	13
t-amyl alcohol	36	27

Because of the significant rate enhancement, Tweddell was able to further optimize the system by lowering the temperature to 0 °C and reducing the catalyst loading to only 1 mol%. A range of substrates were examined under these new conditions, and the observed selectivity for each was compared to that observed in Et_2O (Table 2.4). We were pleased to observe a significant increase in selectivity for each of the arylalkylcarbinols examined in going from the old conditions to the new. In the case of our bellwether substrate, 1-phenylethanol, the selectivity improved

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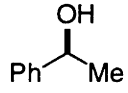
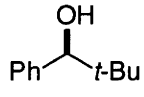
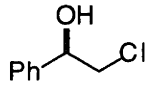
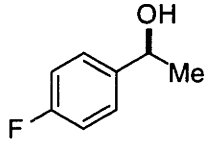
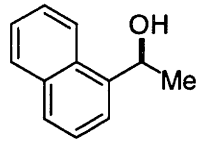
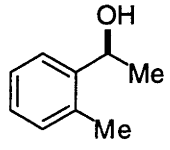
26 It has been suggested that the DMAP-catalyzed acylation of *t*-butanol with acetic anhydride might proceed through nucleophilic attack of the DMAP on an Ac_2O-*t*-BuOH complex formed in a preequilibrium. Guibe-Jampel, E.; Le Corre, G.; Wakselman, M. *Tetrahedron Lett.* **1979**, *13*, 1157-1160.

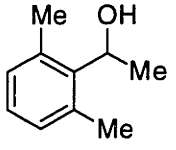
from 14 to 43.[27] As was the case in ether, the selectivity improves with the steric bulk of the alkyl group; under the new conditions 2,2-dimethyl-1-phenylpropanol gave a selectivity of 95. Again, the presence of a 2-substituent on the aryl group results in increased selectivity and rate. Thus, α-methyl-1-naphthalenemethanol and 1-(2-methylphenyl)ethanol gave selectivities of 65 and 71, respectively, and both undergo acylation faster than 1-phenylethanol (entries 5 and 6).

Table 2.4. Selectivities of Kinetic Resolutions in *t*-Amyl Alcohol Compared to those in Ether for a Range of Arylalkylcarbinols.

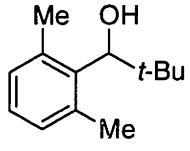
entry	unreacted alcohol, major enantiomer	s (selectivity factor)	
		Et_2O 2% catalyst r.t.	***t*-amyl alcohol** 1% catalyst 0 °C
1		14	**43** *99% ee @ 55% conv.*
2		52	**95** *96% ee @ 51% conv.*
3		12	**32** *98% ee @ 56% conv.*
4		18	**68** *99% ee @ 54% conv.*
5		22	**65** *95% ee @ 52% conv.*
6		22	**71** *99% ee @ 53% conv.*

27 The ruthenium analog of catalyst **2.9** gives an s of 10 for 1-phenylethanol under the improved conditions. Garrett, C. E.; Lo, M. M.-C.; Fu, G. C. *J. Am. Chem. Soc.* **1998**, *120*, 7479-7483.

Because we might have expected the added steric bulk of substrates bearing a 2-substituent on the aryl group to result in a *slower* reaction, this observation led us to explore the effect further by examining substrates with substituents in both the 2- and 6-positions of the aryl group. Kinetic resolution of 1-(2,6-dimethylphenyl)ethanol, **2.10**, under the same conditions used in Table 2.4 resulted in a selectivity of >100, and the acylation was again *faster* than with 1-phenylethanol. For substrates with bulk on the alkyl group and 2-substituents on the aryl group, the effects are additive. Thus, 2,2-dimethyl-1-(2,6-dimethylphenyl)propanol, **2.11**, was resolved with a selectivity of >200. In fact, the selectivity of this substrate was so high that we have used it as a test of the enantiomeric purity of our catalyst. The possible mechanistic implications of these observations will be discussed later.

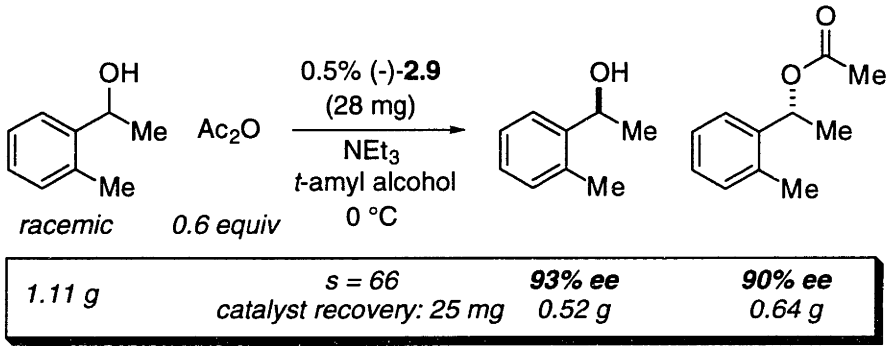


2.10



2.11

To demonstrate the practical utility of **2.9** for kinetic resolutions of arylalkylcarbinols, a large scale resolution of 1-(2-methylphenyl)ethanol was conducted (eq 2B.13). When 1.11 g of racemic alcohol was resolved with 28 mg (0.5 mol%) of (-)-**2.9** as the catalyst, 0.52 g of unreacted alcohol was recovered with 93% ee, while 0.64 g of acetate was recovered with 90% ee. Of the original 28 mg of catalyst, 25 mg were recovered at the end of the reaction. The practical utility of **2.9** was further demonstrated by the observation that a resolution of 1-phenylethanol conducted under air using commercial reagents and solvents that had not been purified resulted in the same selectivity as when carefully purified materials were used in the absence of air.



(2B.13)

Selectivities as high as ours allow for particularly impressive results to be obtained if symmetric, difunctional substrates (meso or racemic diols) are employed.[28] In the case of a racemic diol, each molecule has two carbinol centers with the same absolute configuration. Diol of the "wrong" enantiomer can be present at the end of the reaction only if both of the carbinol centers in the molecule were missed by the catalyst. In contrast, diacetate of the "wrong" enantiomer is only formed if the catalyst mistakenly acylates the same molecule twice. Therefore, most of the mistakes are left as monoacetate at the end of the reaction, in what can be called sequential kinetic resolutions.

A slightly different situation arises with meso diols. The carbinol centers of a meso secondary diol have opposite absolute configurations, so an enantioselective acylating agent will preferentially react at one of those sites over the other, resulting in the chiral monoacetate. At very low conversion, the enantiomer ratio of the monoacetate should just reflect the selectivity of the first acylation. As the reaction progresses, however, the monoacetate can undergo a kinetic resolution since the "wrong" enantiomer of monoacetate still has a free carbinol of the configuration that is preferentially acylated. Asymmetrization-kinetic resolutions, as reactions of this sort are called, have the advantage of a theoretical 100% yield of the desired enantiomer (as opposed to 50% in the case of simple kinetic resolutions).

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28 For discussions on the theory of such processes, see: (a) Kroutil, W.; Kleewein, A.; Faber, K. *Tetrahedron: Asymmetry* **1997**, *8*, 3251-3261, 3263-3274. (b) Reference 2.

Although examples of highly selective enzymatic acylations of diols are well-known,[29] were were aware of only one report of highly enantioselective acylations of diols by a non-enzymatic catalyst. That report was by Oriyama and described the use of a catalytic amount of a proline-derived diamine to effect the asymmetrization of certain *meso*-1,2-diols by acylation with benzoyl chloride.[15] In the case of *cis*-1,2-cyclohexanediol, the best reported substrate, monobenzoate was isolated in 87% yield and with 97% ee using only 0.5 mol% of the catalyst. The isolated yield of dibenzoate in this case was reported to be 0%, suggesting that the first acylation (asymmetrization) was quite selective. Presumably the second benzoylation (kinetic resolution) did not take place because of the bulk of the monobenzoate.

We chose racemic diol **2.12** and its meso diastereomer, **2.13,** as substrates to test **2.9** as a catalyst for the asymmetric acylation of diols. This choice was primarily based on practical concerns. We were reluctant to try 1,2-diols because of concerns of possible racemization in the meso case due to intramolecular acyl transfer,[12] and we wanted a substrate, the diastereomers of which could be easily separated. Fortunately, **2.12** and **2.13** can be separated by recrystallization and/or flash chromatography.

When racemic diol **2.12** was acylated with acetic anhydride under our optimized conditions using (-)-**2.9** as the catalyst, a very selective reaction took place (eq 2B.14). The unreacted diol was isolated in 43% yield (out of 50% theoretical for a single enantiomer) and shown to have a 98% ee. A 39% yield of the diacetate was isolated, and we were delighted to find that it had a 99% ee. An additional 16% of the material was isolated as monoacetate.

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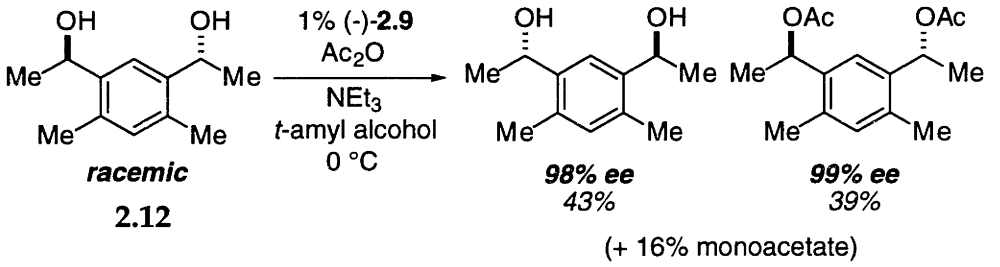
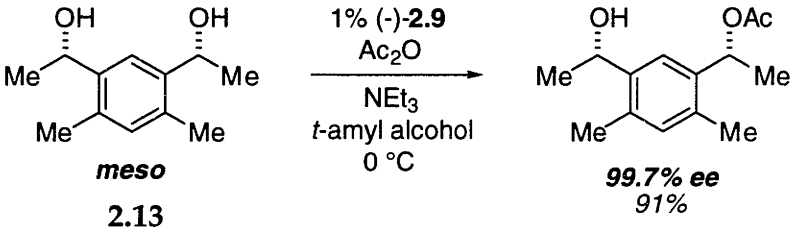
29 For recent examples, see: (a) Guo, Z.-W.; Wu, S.-H.; Chen, C.-S.; Girdaukas, G.; Sih, C. J. *J. Am. Chem. Soc.* **1990**, *112*, 4942-4945. (b) Wallace, J. S.; Baldwin, B. W.; Morrow, C. J. *J. Org. Chem.* **1992**, *57*, 5231-5239.



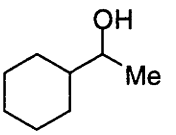
(2B.14)

The meso diastereomer, **2.13**, also underwent very selective acylation catalyzed by (-)-**2.9** (eq 2B.15). The monoacetate was isolated in 91% yield as essentially a single enantiomer. Diacetate was observed in this reaction, but it was not isolated.



(2B.15)

While quite pleased with the selectivities that **2.9** had given in the kinetic resolution of secondary arylalkylcarbinols and cinnamyl alcohols, we were also interested in exploring the possibility that other classes of alcohols might undergo kinetic resolution with our system. In an effort to determine the importance of the unsaturated group attached to the carbinol carbon, we examined the kinetic resolution of 1-cyclohexylethanol, **2.14**. This substrate was acylated only very slowly under our optimized conditions, and with an s of 2.3. Thus, changing a phenyl ring to a cyclohexyl ring resulted in the selectivity dropping from 43 to 2.3 and in a dramatic slowing of the reaction rate.



2.14

Although effective kinetic resolution of dialkylcarbinols such as **2.14** with **2.9** does not seem possible at this point, several other classes of alcohols in which there is an sp^2-hybridized carbon attached to the carbinol carbon are being investigated by other members of our group. Beata Tao has achieved double digit selectivities for a variety of propargylic alcohols,[30] while Dr. Stephane Bellemin-Laponnaz and Frank Breitling have recently observed excellent selectivities for appropriately substituted allylic alcohols, including non-cinnamyl derivatives. The resolution of heteroarylalkylcarbinols has been investigated by Jen Tweddell and is currently being undertaken by Adriane Stebbins, with good preliminary results for some furan derivatives.

In addition to screening substrates, we have conducted some experiments aimed at elucidating the mechanism of asymmetric acylations catalyzed by **2.9**. Assuming by analogy with DMAP that the active acylating agent present in reactions catalyzed by **2.9** is an *N*-acylpyridinium salt, we have prepared and structurally characterized salt **2.15**. As is the case with DMAP, the acylpyridinium salt cannot be isolated directly from mixtures of **2.9** and acetic anhydride because the equilibrium favors free catalyst and acetic anhydride.[31] It is the case, however, with both **2.9** and DMAP that reaction with acetyl chloride proceeds quickly to give the desired salt.[32] The counterion in **2.15** is SbF_6 because this was the first salt for which X-ray quality crystals were obtained.

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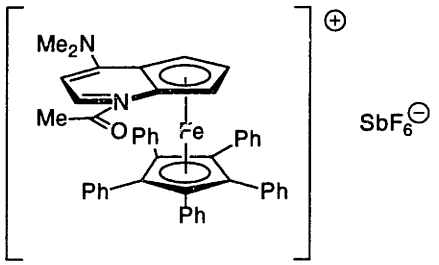
30 Tao, B.; Ruble, J. C.; Hoic, D. A.; Fu, G. C. *submitted for publication.*

31 Höfle, G.; Steglich, W.; Vorbrüggen, H. *Angew. Chem. Int. Ed. Engl.* **1978**, *17*, 569-583.

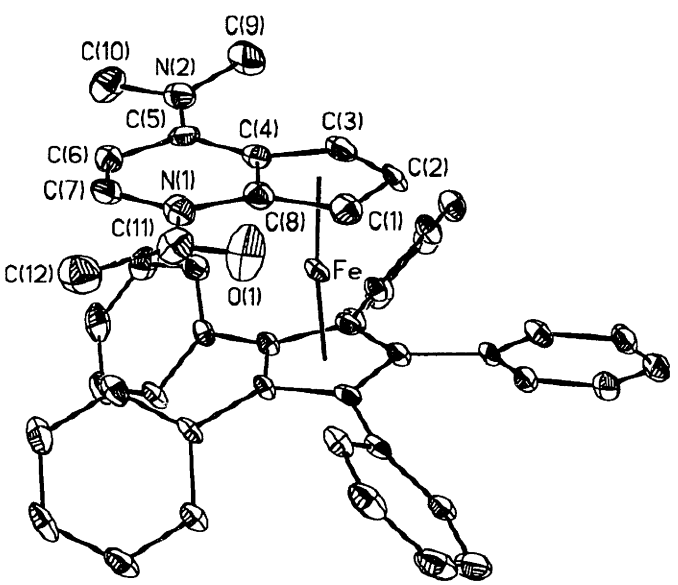
32 For a crystal structure of acetylated DMAP, see: Jones, P. G.; Linoh, K.; Blaschette, A. Z. *Naturforsch.* **1990**, *45b*, 267-270.



2.15

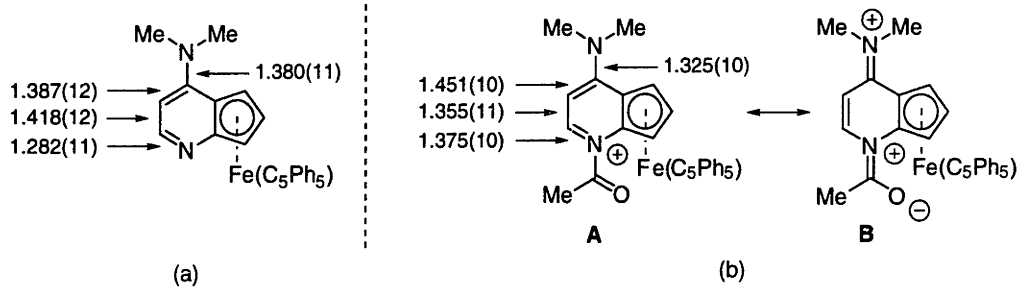
The ORTEP diagram of **2.15** is shown in Figure 2.3. The nearly planar geometry of the dimethylamino group, the pyridine ring, and the acetyl group in the solid state is consistent with extended conjugation, and the changes in bond lengths of the dimethylaminopyridine in going from **2.9** to **2.15** are also consistent with resonance structure **B** (Figure 2.4) having a significant contribution. This extended conjugation is further evidenced by the increased rotational barrier around the Me_2N-C bond upon acetylation ($\Delta G^{\ddagger}$ ~ 10 kcal/mol for **2.9** compared to >21 kcal/mol for **2.15**).[33]

Figure 2.3. ORTEP Representation of Salt 2.15 (the SbF_6 counterion and two THF molecules have been omitted for clarity).



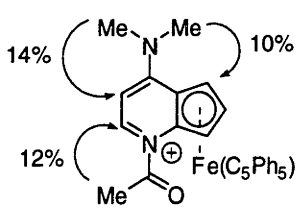
33 The rotational barriers were measured by ^1H NMR in CD_2Cl_2 and in $C_2D_2Cl_4$, respectively.

Figure 2.4. Bond Distances (Å) for the Dimethylaminopyridine Fragment of: (a) Complex 2.9; (b) Acetylated Complex 2.15.



Of the two possible planar orientations of the acetyl group, the crystal structure showed the one in which the oxygen is closer to the fused 5-membered ring, consistent with minimizing steric repulsions. To demonstrate that this is also the preferred conformation in solution, presaturation NOE experiments were performed on complex **2.15** at room temperature in CD_2Cl_2 (Figure 2.5). Saturation of the acetyl methyl group resulted in a 12% enhancement of the proton in the 2-position. When the upfield -NMe signal was saturated, a 14% enhancement of the proton in the 3-position was observed, while saturation of the downfield -NMe signal resulted in a 10% enhancement of the proton in the 5-position. No other enhancements of >1% were observed in any of these three experiments. These data are consistent with the solid-state conformation also predominating in solution.

Figure 2.5. NOE's Observed in CD_2Cl_2 Solution at r.t. for Acylated Complex 2.15.



In considering all of our data on selectivity as a function of substrate in the asymmetric acylation of secondary alcohols catalyzed by **2.9**, we have come to

identify what we believe to be two important factors in achieving high selectivity. We believe that the substrate should be able to have a π-stacking interaction with the acylpyridinium intermediate,[34] and that the alcohol must be able to attain the conformation most favorable in terms of reducing allylic 1,3-strain.[35] That a π-stacking interaction might be important is evidenced by the requirement that an unsaturated group be present in the substrate for a fast, selective reaction. The π-stacking argument is also consistent with the observed rate differences in acylation of arylmethylcarbinols bearing a 4-substituent on the aryl group. Those alcohols bearing an electron-poor arene react faster in acylations catalyzed by **2.9** in *t*-amyl alcohol. Thus 1-(4-fluorophenyl)ethanol and 1-(4-cyanophenyl)ethanol[36] reacted significantly faster than 1-phenylethanol.[37]

In arylmethylcarbinols, allylic 1,3-strain arises from the steric repulsion between a substituent in the 2-position of the arene and the substituents on the carbinol carbon. Of the three rotamers shown in Figure 2.6, rotamer **A** has the least strain, and is thus favored, even for R=H. As the 2-substituent on the arene gets larger, the bias in favor of rotamer **A** grows. The argument for allylic 1,3-strain as a controlling factor in acylations catalyzed by **2.9** relies on our observations with arylmethylcarbinols bearing a 2-substituent on the arene ring (Table 2.4, entries 5 and 6 as well as **2.10**). Not only did these substrates react faster than 1-phenylethanol, they also reacted with higher selectivity. If one assumes that the rotamer of alcohol that reacts preferentially in our asymmetric acylations is rotamer

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34 For a discussion of π-stacking effects in asymmetric synthesis, see: Jones, G. B.; Chapman, B. J. *Synthesis*, **1995**, 475-497.

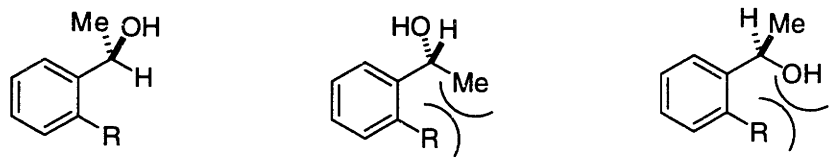
35 For a discussion of allylic 1,3-strain in asymmetric reactions, see: Hoffmann, R. W. *Chem. Rev.* **1989**, *89*, 1841-1860.

36 The s factor for this substrate is 42 under the conditions from Table 2.4.

37 While consistent with a π-stacking interaction, these rate differences might also be caused by small changes in the pK_a of the alcohol as a result of the remote substituent. As evidence that this may be important, we cite the fact that 2-chloro-1-phenylethanol also reacts more quickly than 1-phenylethanol.

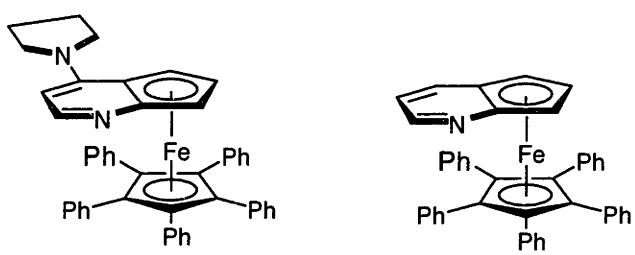
A, then it follows that a faster and more selective reaction might result for a substrate with a larger bias toward **A**.

Figure 2.6. Allylic Strain in Arylmethylcarbinols.



A **B** **C**

Because PPY is known to be more active than DMAP as a catalyst for some acylation reactions,[31] we have prepared and characterized the 4-pyrrolidino derivative, **2.16**. Its synthesis is completely analogous to that of **2.9**, and it is also resolved by chiral HPLC. The *N*-acyl salt of this catalyst has also been prepared and crystallographically characterized.[38] Unfortunately, the reactivity of **2.16** as a catalyst for acylation has not yet been carefully studied, so only its synthesis is presented in this thesis (see experimental section). In the course of optimizing the synthesis of pentaphenylcyclopentadienyl catalysts **2.9** and **2.16**, the parent pyrindinyl complex **2.17** was also synthesized and characterized, although its reactivity has also not been studied.



(-)-**2.16** **2.17**

38 The details of the crystal structure are presented in Appendix II.

Conclusions

We have demonstrated that our planar-chiral π-complexes of nitrogen heterocycles with iron can serve as highly selective catalysts for the kinetic resolution of secondary alcohols by acylation. In the case of azaferrocene derivative **1.16**, acylations were carried out using diketene as the acylating agent because the catalyst is not sufficiently active to promote acylation with more convenient reagents such as anhydrides. These diketene-mediated kinetic resolution reactions resulted in selectivities of 3.7 and 6.5 for 1-phenylethanol and α-methyl-1-naphthalenemethanol, respectively. While these selectivities are quite low compared to the current state-of-the-art, they were the best reported for those substrates at the time.

We were able to begin exploring asymmetric acylations using acetic anhydride after it was discovered that chiral DMAP analog **1.31** can be separated by chiral HPLC. Unfortunately, use of this catalyst resulted in a selectivity of only 1.6 in the kinetic resolution of 1-phenylethanol. This selectivity was improved by increasing the top-bottom differentiation of the catalyst with the use of a bulky pentaphenylcyclopentadienyl ligand in place of the Cp* ligand. The new catalyst, **2.9**, resulted in significantly improved selectivity in acylation reactions with acetic anhydride, giving an s of 14 for 1-phenylethanol when the reaction was conducted in ether. An X-ray crystallographic comparison of **1.31** and **2.9** was performed and confirmed that the latter has a more asymmetric environment around the pyridine nitrogen because of the bulk of the phenyl groups.

The kinetic resolution of secondary arylalkylcarbinols was shown to be particularly efficient using catalyst **2.9** when the reaction was carried out in *t*-amyl alcohols at 0 °C. These second-generation conditions resulted in an s of 43 for 1-phenylethanol. The reactions were quite easy to conduct and could be performed without the need for carefully purified reagents or the exclusion of air. Several

interesting trends were noted in the selectivity of acylations with **2.9**. As the size of the alkyl group of phenylalkylcarbinols was increased, the reaction became slower and more selective, up to an s of 95 when alkyl was *t*-butyl. Also, the selectivity and reaction rate increased when the aryl group bore a 2-substituent. The use of 1-(2-methylphenyl)ethanol resulted in an s of 71. Furthermore, the above two effects are additive; when 2,2-dimethyl-1-(2,6-dimethylphenyl)propanol was the substrate, the observed s was greater than 200!

In an effort to explore the mechanism of asymmetric acylations catalyzed by **2.9**, its *N*-acylpyridinium analog, **2.15**, was synthesized by reaction with acetyl chloride, followed by anion exchange. The X-ray structure of **2.15** was determined and provides evidence for extended conjugation in the system. The acetyl group, the pyridine ring, and the $-NMe_2$ group are nearly coplanar, and the bond lengths of **2.15** have changed relative to **2.9** in a manner consistent with significant donation of electrons from the $-NMe_2$ group. The carbonyl oxygen is oriented closer to the fused 5-membered ring, as would be predicted by steric arguments. The results of NOE experiments on **2.15** were consistent with the structure observed in the solid state also predominating in solution.

The selectivity seen in acylations of secondary arylalkylcarbinols with **2.9** as a catalyst is proposed to stem from two key factors: a π-stacking interaction between substrate and acylpyridinium intermediate and a preferred conformation of the substrate that is determined by allylic 1,3-strain. The π-stacking interaction is postulated because high selectivities have, to date, only been observed for substrates in which an unsaturated group was attached to the carbinol carbon and because the relative rates of reactions for arylmethylcarbinols depends strongly on the electronic nature of the aryl group, although the latter observation may be due to differences in the acidity of the alcohol. The argument in favor of allylic 1,3-strain as a controlling factor is based on the observation that 2-substituents on the aryl groups

of arylmethylcarbinols result in acylations that are both more selective and faster than those of analogous compounds lacking the 2-substituents.

Experimental

General. Iron (II) chloride (Strem), *n*-BuLi (Aldrich, Strem, Alfa Aesar), pyrrolidine (Aldrich) and H_2SO_4were used without further purification. 1,2,3,4,5-Pentaphenyl-1,3-cyclopentadiene was purchased from Aldrich or prepared by the method of Field.[19] Diketene (Aldrich) was distilled prior to use. Ac_2O (Mallinckrodt) was distilled from quinoline prior to use in asymmetric acylations. Triethylamine (Fisher) was distilled from calcium hydride. 1-Phenylethanol (Aldrich), 1-phenyl-1-propanol (Aldrich), α-methyl-1-naphthalenemethanol (Aldrich), 1-cyclohexylethanol (Aldrich) and 1-(4-fluorophenyl)ethanol (Aldrich) were purified by flash chromatography prior to use. 2-Methyl-1-phenyl-1-propanol was made by the reaction of isopropylmagnesium chloride with benzaldehyde and was purified by flash chromatography. 2,2-Dimethyl-1-phenyl-1-propanol was made by the reaction of *t*-butylmagnesium chloride with benzaldehyde and was purified by distillation followed by flash chromatography. 2-Chloro-1-phenylethanol was made by the reaction of sodium borohydride with 2-chloroacetophenone and was purified by distillation. 1-(4-Methoxyphenyl)ethanol was made by the reaction of methyllithium with *p*-anisaldehyde and was purified by distillation followed by flash chromatography. (*E*)-4-Phenyl-3-buten-2-ol was made by the reaction of methylmagnesium iodide with cinnamaldehyde and was purified by distillation followed by flash chromatography. (*E*)-3-Methyl-4-phenyl-3-buten-2-ol was made by the reaction of methylmagnesium iodide with α-methyl-*trans*-cinnamaldehyde and was purified by distillation followed by flash chromatography. 1-(2-Methylphenyl)ethanol was made by the reaction of methylmagnesium chloride with 2-methylbenzaldehyde and was purified by flash chromatography. 1-(4-Cyanophenyl)ethanol was prepared by the reaction of sodium borohydride with 4-cyanoacetophenone and was purified by flash chromatography. 1-(2,6-Dimethylphenyl)ethanol and 2,2-dimethyl-1-(2,6-dimethylphenyl)propanol were

made by the reaction of 2,6-dimethylphenylmagnesium bromide with the appropriate aldehyde and were purified by flash chromatography. 2,4-Dibromo-*m*-xylene was provided by the Buchwald group (M.I.T.).[39] 4-Chloro-6,7-dihydro-1,5-pyrindine-*N*-oxide as well as catalysts **1.16**, and **1.31** were prepared as described in Chapter 1 of this thesis.

The following solvents were distilled from the indicated drying agents: benzene (sodium/benzophenone); tetrahydrofuran (sodium/benzophenone); Et_2O (sodium/benzophenone); toluene (molten sodium); dichloromethane (calcium hydride); *t*-amyl alcohol (sodium); dioxane ($NaBH_4$); acetone (calcium hydride). Ethyl acetate and acetonitrile were distilled. Dimethylformamide (99.8%, anhydrous; Aldrich) was used as received.

Analytical thin layer chromatography was performed using EM Reagents 0.25 mm silica gel 60 plates, and visualization was accomplished with potassium permanganate or with ethanolic phosphomolybdic acid. Flash chromatography was performed on EM Reagents silica gel 60 (230-400 mesh).

^1H and ^{13}C nuclear magnetic resonance spectra were recorded on a Varian XL-300, Varian Mercury 300, Varian Unity 300 or a Varian VXR 500 spectrometer at ambient temperature. ^1H data are reported as follows: chemical shift in parts per million downfield from tetramethylsilane (δ scale), multiplicity (br = broad, s = singlet, d = doublet, t = triplet, q = quartet, and m = multiplet), integration, and coupling constant (Hz). ^{13}C chemical shifts are reported in ppm downfield from tetramethylsilane (δ scale). All ^{13}C spectra were determined with complete proton decoupling.

Infrared spectra were obtained on a Perkin-Elmer Series 1600 FT-IR spectrophotometer. High resolution mass spectra were recorded on a Finnegan

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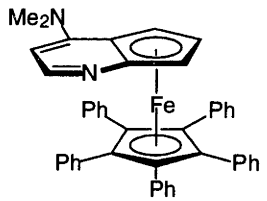
39 For a preparation, see: Datta, R. L.; Chatterjee, N. R. *J. Am. Chem. Soc.* **1916**, *38*, 2545-2552. ^1H NMR ($CDCl_3$) δ 7.67 (s, 1H), 7.08 (s, 1H), 2.30 (s, 6H). ^{13}C NMR ($CDCl_3$) δ 137.0, 135.1, 132.8, 122.2, 22.5. FTIR (KBr) 2984, 2948, 1447, 1350, 1053, 1035, 874 cm^{-1}.

MAT System 8200 spectrometer. Melting points were obtained on a Thomas Hoover Unimelt capillary melting point apparatus.

All reactions were carried out under an atmosphere of nitrogen or argon in oven-dried glassware with magnetic stirring, unless otherwise indicated.

Preparation of New Catalysts



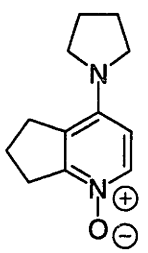
4-Dimethylaminopyrindinyl-pentaphenylcyclopentadienyliron (2.9). *n*-BuLi (2.62 M in hexane, 4.66 mL, 12.2 mmol) was added dropwise by syringe over approximately 5 minutes to a slurry of pentaphenylcyclopentadiene (5.45 g, 12.2 mmol) in 120 mL of THF at r.t.. The mixture was stirred for 2 hours, after which the resulting dark yellow solution was added by cannula over 15 minutes to a slurry of $FeCl_2$ (1.49 g, 11.8 mmol) in 50 mL of THF. The first few drops resulted in the formation of a purple color, but the color changed to green-brown as the addition progressed. After 2 hours, a solution of the lithium salt of 4-dimethylaminopyrindine [made 40 minutes prior to use by the reaction of *n*-BuLi (2.62 M in hexane; 3.58 mL, 9.38 mmol) and 4-dimethylaminopyrindine (1.50 g, 9.39 mmol) in 50 mL of THF at r.t.] was added over 5 minutes by cannula, resulting in a dark purple solution. This solution was stirred in a 60 °C oil bath for 3 hours, after which it was filtered through a short (1") plug of silica gel using aspirator vacuum. The silica gel was washed with 10% NEt_3/45% EtOAc/45% hexanes until no additional purple color was coming through. The resulting solution was concentrated to give a purple solid. This solid was mostly dissolved in CH_2Cl_2 and loaded onto a silica gel column. The column was eluted with CH_2Cl_2 until all of the solids on top of the column (Ph_5C_5H) had dissolved. It was then eluted with

another 2 column volumes of CH_2Cl_2 to elute all of the Ph_5C_5H. The eluant was then changed to 10% NEt_3/90% CH_2Cl_2, and the product was eluted as a tight purple band at the solvent front (care must be taken to release the pressure slowly from the column when using this solvent system to avoid cracking of the silica gel). Removal of the solvent yielded 5.47 g (88%, 21% overall from adipoyl chloride) of purple solid.

^{1}H NMR ($CDCl_3$) δ 8.17 (d, 1H, J = 5.1), 6.9-7.2 (m, 25H), 5.86 (d, 1H, J = 5.4), 5.07 (dd, 1H, J = 2.9, 1.1), 4.92 (dd, 1H, J = 2.9, 1.1), 4.26 (t, 1H, J = 2.9), 2.95 (s, 6H). ^{13}C NMR ($CDCl_3$) δ 158.6, 153.9, 135.3, 132.6, 127.1, 126.2, 113.4, 99.5, 86.0, 77.9, 77.7, 69.6, 66.1, 41.7. FTIR (KBr) 3085, 3056, 2881, 1601, 1537, 1502, 1350, 1028, 908, 740 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{45}H_{36}FeN_2$ (M^+) 660.2228, found 660.2227. Anal. Calcd for $C_{45}H_{36}FeN_2$ (660.6): C, 81.81; H, 5.49; N, 4.24. Found: C, 81.64; H, 5.50; N, 4.23. mp = 231-234 °C.

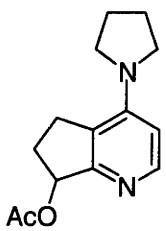
The enantiomers of the product were separated using semi-preparative HPLC (Daicel CHIRALCEL OD, 1 cm x 25 cm, chloroform/hexanes/diethylamine 25:75:0.4, 3.0 mL/min). Enantiomer (-)-**2.9** ($[\alpha]^{20}_D$ = -940° (c = 0.10, $CHCl_3$); enantiomerically pure by analytical chiral HPLC) was collected from 8.25 minutes to 9.25 minutes, and enantiomer (+)-**2.9** ($[\alpha]^{20}_D$ = +890° (c = 0.10, $CHCl_3$)) was collected from 10.0 minutes to 13.0 minutes.

The absolute configuration of (+)-**2.9** has been tentatively assigned on the basis of an X-ray crystallographic study (anomalous dispersion).



4-Pyrrolidino-6,7-dihydro-1,5-pyrindine-*N*-oxide. The following reaction was conducted under air. To a flask containing a stir bar was added 4-chloro-6,7-dihydro-1,5-pyrindine-*N*-oxide (2.52 g, 14.9 mmol), pyrrolidine (7.5 mL, 90 mmol), and water (10.5 mL). The flask was capped and placed into an 80 °C oil bath for 29 hours. K_2CO_3 (2.5 g) was added to the solution, and the water and pyrrolidine were removed by rotary evaporation, leaving a brown solid residue. The product was extracted from this residue with 5 X 50 mL of warm acetone (solid-liquid extraction). The acetone was then dried with Na_2SO_4 and removed by rotary evaporation, leaving the product as 3.02 g (99.5%) of tan solid. This material was used without further purification.

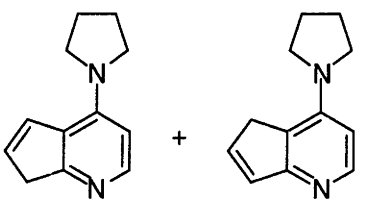
^{1}H NMR (300 MHz, $CDCl_3$) δ 7.84 (d, 1H, J=7.2), 6.20 (d, 1H, J=7.2), 3.44-3.52 (m, 4H), 3.27 (t, 2H, J=7.5), 3.14 (t, 2H, J=7.8), 2.10 (pent, 2H, J=7.7), 1.95-2.01 (m, 4H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 153.3, 144.5, 137.1, 122.6, 107.5, 49.2, 32.8, 29.7, 25.3, 22.0. FTIR (KBr) 3383, 2967, 2869, 1624, 1496, 1457, 1355, 1231, 1172 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{12}H_{16}N_2O$ (M^+) 204.1263, found 204.1262. mp 164-165 °C.



4-Pyrrolidino-7-acetoxy-6,7-dihydro-1,5-pyrindine. Acetic anhydride (25 mL, 270 mmol) was added under air to a round bottom flask containing a stir bar and 4-pyrrolidino-6,7-dihydro-1,5-pyrindine-*N*-oxide (5.64 g, 27.6 mmol) in an ice bath. The resulting mixture was stirred at 0 °C for 20 minutes, and then moved to a 65 °C oil bath for 41 hours. The acetic anhydride was then removed by vacuum. The black residue was dissolved in CH_2Cl_2 and loaded onto a column of silica gel. It was first eluted with 50% EtOAc/50% hexanes and then with 10% NEt_3/45% EtOAc/45%

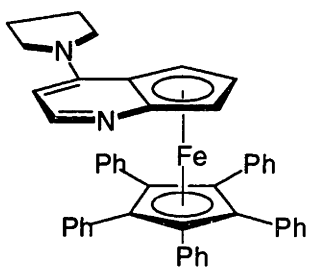
hexanes. Product R_f=0.31 in 10% NEt_3/45% EtOAc/45% hexanes. The product was isolated as 5.00 g (73.6%) of a tan solid. ^1H NMR revealed contamination by about 3% of the reduced material (4-pyrrolidino-6,7-dihydro-1,5-pyrindine, see below). An essentially identical yield was obtained for this reaction when it was carried out at 100 °C for 3 hours, but the chromatography was marginally more tedious.

^1H NMR (300 MHz, $CDCl_3$) δ 8.14 (d, 1H, J=5.7), 6.24 (d, 1H, J=6.0), 5.96 (dd, 1H, J=4.8, 7.5), 3.50-3.55 (m, 4H), 3.28-3.39 (m, 1H), 3.09-3.19 (m, 1H), 2.47-2.59 (m, 1H), 2.12 (s, 3H), 1.94-2.00 (m, 4H), 1.91-2.03 (m, 1H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 171.1, 160.5, 151.2, 149.5, 120.2, 107.1, 78.1, 49.0, 30.4, 29.2, 25.5, 21.4. FTIR (KBr) 2970, 2869, 1728, 1586, 1500, 1370, 1241, 1026 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{14}H_{18}N_2O_2$ (M^+) 246.1368, found 246.1369. mp 108-109 °C.



4-Pyrrolidinopyrindine. Concentrated H_2SO_4 (10 mL) was added under air to a 100 mL flask containing 4-pyrrolidino-7-acetoxy-6,7-dihydro-1,5-pyrindine (6.26 g, 25.4 mmol). The resulting mixture was stirred in a 60 °C oil bath for 90 minutes and then poured over ice. The mixture was adjusted to pH=11 with 6 M NaOH, and the product was extracted into 8 X 100 mL of EtOAc. Approximately 10 mL of NEt_3 were added to the extracts, and they were dried over Na_2SO_4. The volume of solvent was reduced to approximately 10 mL by rotary evaporation, and the mixture was applied to a silica gel column that had been loaded in 10% NEt_3/45% EtOAc/45% hexanes (we have some evidence that the product decomposes on silica gel in the absence of NEt_3). The product was eluted with that solvent system (R_f=0.28) and was isolated as 3.45 g (73%) of a tan, crystalline solid. By ^1H NMR, the product was contaminated with 2-3% of 4-pyrrolidino-6,7-dihydro-1,5-pyrindine (see below).

^{1}H NMR (300 MHz, $CDCl_3$) Major isomer: δ 8.10 (d, 1H, J=6.0), 6.92 (dt, 1H, J=5.7, 1.8), 6.73 (dt, 1H, J=5.7, 2.1), 6.19 (d, 1H, J=6.3), 3.69 (t, 2H, J=1.8), 3.55-3.60 (m, 4H), 1.97-2.04 (m, 4H). Minor isomer: δ 8.03 (d, 1H, J=6.0), 7.16 (dt, 1H, J=6.3, 1.8), 6.31 (dt, 1H, J=6.3, 2.1), 6.28 (d, 1H, J=6.0), 3.53-3.58 (m, 4H), 3.41 (t, 2H, J=2.1), 1.97-2.04 (m, 4H). ^{13}C NMR (75.4 MHz, $CDCl_3$) Major isomer: δ 164.7, 148.5, 146.0, 136.8, 134.2, 118.8, 104.8, 48.7, 39.0, 25.5. Minor isomer: δ 166.9, 149.4, 147.1, 130.7, 128.0, 121.8, 105.8, 49.5, 40.8, 25.7. FTIR (KBr) 2971, 2870, 1694, 1591, 1485, 1394, 1356, 1195, 801, 728 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{12}H_{14}N_2$ (M^+) 186.1157, found 186.1157. mp 87-89 °C.



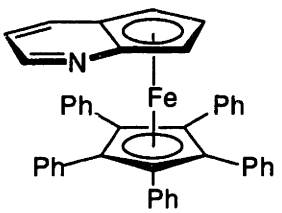
4-Pyrrolidinopyrindinyl-pentaphenylcyclopentadienyliron (2.16). *n*-BuLi (2.62 M in hexane, 2.59 mL, 6.79 mmol) was added by syringe over approximately 3 minutes to a slurry of pentaphenylcyclopentadiene (3.03 g, 6.79 mmol) in 70 mL of THF. The mixture was stirred for 2.5 hours, after which the resulting yellow/orange solution was added by cannula over 3 minutes to a slurry of $FeCl_2$ (0.821 g, 6.48 mmol) in 30 mL of THF. The first few drops resulted in the formation of a purple color, but the color changed to green-brown as the addition progressed. The last of the lithium salt was rinsed into the $FeCl_2$ with an additional 10 mL of THF. After 2 hours, a solution of the lithium salt of 4-pyrrolidinopyrindine [made 1.9 hours prior to use by the reaction of *n*-BuLi (2.62 M in hexane; 2.15 mL, 5.63 mmol) and 4-pyrrolidinopyrindine (1.05 g, 5.63 mmol) in 30 mL of THF at r.t.] was added by cannula, resulting in a dark purple solution. The last of the lithium salt was rinsed in with an additional 5 mL of THF. The resulting dark purple solution was stirred in a 60 °C oil bath for 2.5 hours, after which it was filtered through a short (1") plug

of silica gel using aspirator vacuum. The silica gel was washed with 10% NEt_3/45% EtOAc/45% hexanes until no additional purple color was coming through. The resulting solution was concentrated to give a purple solid. This solid was dissolved in 200 mL of CH_2Cl_2 with sonication and loaded onto a silica gel column for purification by flash chromatography (without sonication, it is very difficult to dissolve all of the recovered Ph_5C_5H). The column was eluted with 3 column volumes of CH_2Cl_2 to elute all of the Ph_5C_5H. The eluant was then changed to 10% NEt_3/90% CH_2Cl_2, and the product was eluted as a tight purple band at the solvent front (care must be taken to release the pressure slowly from the column when using this solvent system to avoid cracking of the silica gel). Removal of the solvent yielded 2.76 g (71%, 15.4% overall from adipoyl chloride) of purple solid.

^1H NMR (300 MHz, $CDCl_3$) δ 8.11 (d, 1H, J=5.1), 7.14 (t, 5H, J=7.2), 7.06 (t, 10H, J=7.2), 6.95 (d, 10H, J=7.2), 5.72 (d, 1H, J=5.1), 5.01 (d, 1H, J=2.7), 4.92 (d, 1H, J=2.7), 4.24 (t, 1H, J=2.7), 3.47 (br, 4H), 2.10 (br, 2H), 1.94 (br, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 155.9, 153.8, 135.3, 132.5, 127.1, 126.2, 113.5, 96.9, 86.0, 78.0, 77.8, 69.3, 66.0, 50.0,. 25.8. FTIR (KBr) 3052, 2974, 2857, 1600, 1539, 1500, 1403, 1338, 1025, 743 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{47}H_{38}FeN_2$ (M^+) 686.2384, found 686.2391. Anal. Calcd for $C_{47}H_{38}FeN_2$ (686.7): C, 82.21; H, 5.58; N, 4.08. Found: C, 81.98; H, 5.30; N, 4.06. mp 261-265 °C (significant darkening above 150 °C).

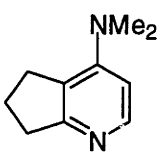
The enantiomers of the product were separated using semi-preparative HPLC (Daicel CHIRALCEL OD, 1 cm x 25 cm, chloroform/hexanes/diethylamine 25:75:0.4, 3.0 mL/min, 10 mg per injection). Enantiomer (-)-**2.16** ($[\alpha]^{20}_D$ = -1800° (c = 0.0069, $CHCl_3$); enantiomerically pure by analytical chiral HPLC) was collected from 10.67 minutes to 13.50 minutes, and enantiomer (+)-**2.16** ($[\alpha]^{20}_D$ = +1700° (c = 0.10, $CHCl_3$)) was collected from 18.00 minutes to 23.50 minutes.

The absolute configuration of (-)-**2.16** has been tentatively assigned by analogy to **2.9** (sign of optical rotation, elution order on chiral HPLC, and sense of selectivity in kinetic resolution of 1-phenylethanol). Ruble, J. C., unpublished results.



Pyrindinyl-pentaphenylcyclopentadienyliron (2.17). This complex was made and purified analogously to **2.16** above. Yield was 32% of a purple solid. This complex has not been resolved.

^{1}H NMR (500 MHz, $CDCl_3$) δ 8.51 (dd, 1H, J=4.0, 1.5), 7.84 (dd, 1H, J=9.0, 1.5), 7.15 (t, 5H, J=7.5), 7.08 (t, 10H, J=7.5), 6.96 (dd, 1H, J=9.0, 4.0), 6.91 (d, 10H, J=7.5), 5.20 (dd, 1H, J=3.0, 1.0), 4.84 (dd, 1H, J=3.0, 1.0), 4.36 (t, 1H, J=3.0). ^{13}C NMR (126 MHz, $CDCl_3$) δ 153.8, 138.3, 135.0, 132.3, 127.3, 126.5, 120.5, 110.3, 86.1, 83.6, 79.6, 70.0, 66.3. FTIR (KBr) 3049, 1600, 1502, 1443, 1315, 1071, 1028, 742, 702 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{43}H_{31}FeN$ (M^+) 617.1806, found 617.1806. mp 231-233 °C.

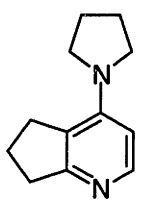


4-Dimethylamino-7-acetoxy-6,7-dihydro-1,5-pyrindine.[40] Acetic acid (1.3 mL) was added under air to a flask containing 4-dimethylamino-6,7-dihydro-1,5-pyrindine-*N*-oxide (563 mg, 3.16 mmol), iron powder (339 mg, 6.07 mmol) and a stir bar. The mixture was heated in a 100 °C oil bath for 2 hours, after which heat was removed and 25 mL of 6 M NaOH was added. The mixture was then filtered through a plug of celite to remove the iron. The plug was washed with 25 mL of water and 25 mL

40 For the reduction of 4-dimethylaminopyridine-1-oxide under these conditions, see: Katritzky, A. R.; Randall, E. W.; Sutton, L. E. *J. Chem. Soc.* **1957**, 1769-1775.

of ether. The filtrate was then added to a sepratory funnel with an additional 25 mL of ether, and the phases were separated. The aqueous phase was extracted with an additional 2 X 50 mL of ether. The combined ether was dried over $MgSO_4$ and evaporated. The residue was purified by flash chromatography using 10% NEt_3/45% EtOAc/45% hexanes (R_f=0.35), resulting in 161 mg (31%) of an off-white, crystalline solid.

^1H NMR (300 MHz, $CDCl_3$) δ 8.07 (d, 1H, J=6.0), 6.34 (d, 1H, J=5.7), 3.04 (t, 2H, J=7.2), 2.96 (s, 3H), 2.92 (t, 2H, J=7.5), 2.04 (pent., 2H, J=7.5). ^{13}C NMR (126 MHz, $CDCl_3$) δ 166.1, 154.4, 148.3, 121.9, 107.0, 41.1, 34.6, 32.3, 23.3. FTIR (KBr) 2952, 2875, 1584, 1499, 1438, 1362, 1021, 810 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{10}H_{14}N_2$ (M^+) 162.1157, found 162.1159. mp 50-51 °C



4-Pyrrolidino-6,7-dihydro-1,5-pyrindine. The procedure used above for the dimethylamino compound was followed starting with 643 mg (3.15 mmol) of *N*-oxide and 326 mg (5.84 mmol) of iron powder. The residue was purified by flash chromatography using 10% NEt_3/45% EtOAc/45% hexanes (R_f=0.28), resulting in 382 mg (64.5%) of an off-white, crystalline solid.

^1H NMR (300 MHz, $CDCl_3$) δ 7.99 (d, 1H, J=6.0), 6.16 (d, 1H, J=5.7), 3.46-3.52 (m, 4H), 3.19 (t, 2H, J=7.5), 2.89 (t, 2H, J=7.8), 2.00 (pent., 2H, J=7.5), 1.92-1.97 (m, 4H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 165.6, 150.8, 148.8, 118.8, 105.7, 48.9, 34.6, 32.0, 25.4, 22.8. FTIR (KBr) 2962, 2868, 1585, 1484, 1459, 1391, 1243, 1085, 833 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{12}H_{16}N_2$ (M^+) 188.1313, found 188.1312. mp 94-95 °C

Kinetic Resolutions With Diketene

Solvent study of the Kinetic Resolution of (±)-1-Phenylethanol (reaction with diketene; Table 2.1). Diketene (4.3 μL, 0.056 mmol) was added by syringe to a solution of 1-phenylethanol (68 μL, 0.56 mmol) and (+)-**1.16** (4.5 mg, 0.011 mmol) in 2.0 mL of the appropriate solvent in a small vial. The resulting solutions were stirred overnight, after which the product was isolated by flash chromatography (10% → 25% Et_2O/pentane). The ee's were measured using analytical chiral HPLC (Daicel CHIRALCEL OD, 4.6 mm X 25 cm, hexane/isopropanol 97.5:2.5, 1.0 mL/min, retention times of enantiomers: (*R*) 19.5 min, (*S*) 22.2 min).[41] Results were as follows: toluene, 30%; THF, 10%; ether, 21%; CH_2Cl_2, 22%, CCl_4, 47% (catalyst decomposed); CH_3CN, 7.6%; MTBE, 33%; benzene, 39%; $PhCF_3$, 38%, hexanes, 22%; dioxane, 2.0%; CH_3NO_2, 2.1%.

Kinetic Resolution of (±)-1-Phenylethanol (reaction with diketene; eq 2B.8). Diketene (52.0 μL, 0.674 mmol) was added by syringe to a vial containing (±)-1-phenylethanol (67.6 μL, 0.561 mmol) in 2.0 mL of C_6D_6. This solution was mixed and evenly divided between two screw cap NMR tubes, one containing (+)-**1.16** (11.2 mg, 0.0279 mmol) and the other containing (-)-**1.16** (11.1 mg, 0.0276 mmol). The reactions were monitored by ^1H NMR and stopped at approximately 58% conversion (~ 4 hours) by placing the NMR tubes into a -78 °C bath. For each reaction, the acetoacetate was separated from the unreacted alcohol using flash chromatography (5% → 25% Et_2O/pentane). Chiral GC (Chiraldex G-TA, 0.25 mm X 30 m, 105 °C, 40 cm/s carrier gas flow, retention times of enantiomers: (*S*) 9.50 min, (*R*) 9.69 min) showed the acetoacetate from the reaction using (+)-**1.16** to have a 38% ee of the *R* enantiomer and the acetoacetate from the reaction using (-)-**1.16** to have a 39% ee of the *S* enantiomer. Chiral GC of the unreacted alcohol (same conditions

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41 The absolute configuration was assigned by comparison with the acetoacetate prepared via acylation of (*R*)-1-phenylethanol (Norse) with diketene.

as above) showed the alcohol from the reaction using (+)-**1.16** to have a 54% ee of the *S* enantiomer and the alcohol from the reaction using (-)-**1.16** to have a 53% ee of the *R* enantiomer.

These values correspond to a selectivity factor (s) of 3.7.

Reactions conducted under identical conditions but stopped at ~15% conversion yielded an s of 3.5.

Kinetic Resolution of (±)-α-Methyl-1-naphthalenemethanol (reaction with diketene; eq 2B.9). Diketene (104 μL, 1.35 mmol) was added by syringe to a vial containing (±)-α-methyl-1-naphthalenemethanol (196 mg, 1.14 mmol) in 4.0 mL of C_6D_6. This solution was mixed, and 2.0 mL of it was placed into a vial containing (-)-**1.16** (22.6 mg, 0.0563 mmol). The resulting solution was transferred to a screw-cap NMR tube. The reaction was monitored by ^1H NMR and stopped at 67% conversion (~ 5 hours) by placing the NMR tube into a -78 °C bath. The acetoacetate was separated from the unreacted alcohol using flash chromatography (5% → 25% MTBE/pentane). Analytical chiral HPLC (Daicel CHIRALCEL OD, 4.6 mm X 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: (*R*) 8.3 min, (*S*) 11.2 min) showed the acetoacetate to have a 43% ee of the *S* enantiomer.[42] Analytical chiral HPLC (Daicel CHIRALCEL OD, 4.6 mm X 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: (*S*) 9.8 min, (*R*) 15.6 min) of the unreacted alcohol showed an 87% ee of the *R* enantiomer.

These values correspond to a selectivity factor (s) of 6.5.

An s of 6.5 was observed under otherwise identical conditions when (+)-**1.16** was used as the catalyst.

Kinetic Resolution of 1-Phenylethanol Catalyzed by (-)-1.31: Reaction with Diketene (eq 2B.10). A solution of diketene (4.8 mg, 0.057 mmol) in 2.0 mL of

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42 The absolute configuration was assigned by comparison with the acetoacetate prepared via acylation of (*R*)-α-methyl-1-naphthalenemethanol (Aldrich) with diketene.

benzene was added dropwise by pipet to a flask containing (-)-**1.31** (4.0 mg, 0.011 mmol) and 1-phenylethanol (70.0 mg, 0.573 mg) in 2.0 mL of benzene. The solution was stirred for three hours, then purified directly by flash chromatography (10% → 25% Et_2O/pentane), which provided 10 mg of the acetoacylated alcohol. HPLC analysis of the acetoacetate showed a racemic mixture.

Kinetic Resolutions Using 2.9 in Ether.

General Procedure for the Kinetic Resolution of Alcohols by Reaction with Acetic Anhydride and Catalyst (-)-2.9 in Ether (Table 2.2). 1-Phenylethanol. Catalyst (-)-**2.9** (6.6 mg, 0.010 mmol), (±)-1-phenylethanol (61.1 mg, 0.500 mmol), ether (1.0 mL), and triethylamine (52.2 μL, 0.375 mmol) were added in turn to a vial, resulting in a dark purple solution. The vial was capped with a septum and removed from the glove box. Acetic anhydride (35.4 μL, 0.375 mmol) was then added by syringe. After 48 minutes, 0.5 mL of the reaction mixture was removed by syringe. This aliquot was filtered through a short plug of silica gel to remove the catalyst (50% → 75% EtOAc/hexane; the catalyst was then collected by flushing the column with 10% NEt_3/EtOAc). The colorless filtrate was concentrated and analyzed by chiral GC, which revealed an 86.7% ee of (*R*) acetate at 5.2% conversion. After 25 hours, the remaining reaction mixture was worked up according to the same procedure. GC analysis showed a 58.7% ee of (*R*) acetate and a 95.2% ee of (*S*) alcohol[43] at 61.2 % conversion. The ee values indicate s = 13.6 at 61.9% conversion.

1-Phenyl-1-propanol. The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 68.6 mg (0.504 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. An aliquot taken after 35 minutes showed a 91.2% ee of (*R*)[44] acetate at 4.3% conversion (GC). The

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43 The absolute configuration was assigned by comparison with (*R*)-1-phenylethanol (Norse).

44 The absolute configurations were assigned by comparison with the acetate derived from acylation of (*R*)-1-phenyl-1-propanol (Lancaster) with acetic anhydride.

remainder of the mixture was worked up after 29 hours; GC showed a 61.7% ee of (*R*) acetate at 62.1% conversion. The unreacted alcohol was purified by flash chromatography and trifluoroacetylated. GC of the trifluoroacetate showed a 98.8% ee of the (*S*) isomer. The ee values indicate s = 19.9 at 61.6% conversion.

2-Methyl-1-phenyl-1-propanol. The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 75.9 mg (0.505 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. An aliquot taken after 73 minutes showed a 92.8% ee of (*R*)[45] acetate at 6.9% conversion (GC). The remainder of the mixture was worked up after 26 hours; GC showed a 78.4% ee of (*R*) acetate at 54.8% conversion. The unreacted alcohol was purified by flash chromatography and trifluoroacetylated. GC of the trifluoroacetate showed a 97.7% ee of the (*S*) isomer. The ee values indicate s = 35.9 at 55.5% conversion.

2,2-Dimethyl-1-phenyl-1-propanol. The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 82.6 mg (0.503 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. An aliquot taken after 120 minutes showed a 96.1% ee of (*R*)[46] acetate at 5.7% conversion (GC). The remainder of the mixture was worked up after 49 hours; GC showed an 88.0% ee of (*R*) acetate and a 92.2% ee of (*S*) alcohol at 51.8 % conversion. The ee values indicate s = 51.6 at 51.2% conversion.

2-Chloro-1-phenylethanol. The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 78.5 mg (0.501 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. An aliquot taken after 25 minutes showed an 80.4% ee of (*S*)[47] acetate at 7.8% conversion (GC). The

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45 The absolute configurations were assigned by comparison with the acetate derived from acylation of (*R*)-2-methyl-1-phenyl-1-propanol (Aldrich) with acetic anhydride.

46 The absolute configurations were determined from the optical rotation of the kinetically resolved alcohol: Clark, D. R.; Mosher, H. S. *J. Org. Chem.* **1970**, *35*, 1114-1118.

47 The absolute configurations were assigned by comparison with commercially available (*S*)-2-chloro-1-phenylethanol (Aldrich).

remainder of the mixture was worked up after 27 hours; GC showed a 44.5% ee of (*S*) acetate and a 98.9% ee of (*R*) alcohol at 68.4% conversion. The ee values indicate s = 11.7 at 68.9% conversion.

1-(4-Fluorophenyl)ethanol. The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 69.8 mg (0.498 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. An aliquot taken after 40 minutes showed a 90.2% ee of (*R*)[48] acetate at 7.2% conversion (GC). The remainder of the mixture was worked up after 29 hours; GC showed a 55.9% ee of (*R*) acetate and a 99.2% ee of (*S*) alcohol at 64.4% conversion. The ee values indicate s = 17.8 at 64.0% conversion.

1-(4-Methoxyphenyl)ethanol. The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 76.6 mg (0.503 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. An aliquot taken after 51 minutes showed an 88.1% ee of (*R*)[49] acetate at 6.3% conversion (GC). The remainder of the mixture was worked up after 25 hours; GC showed a 63.3% ee of (*R*) acetate and a 94.5% ee of (*S*) alcohol at 60.0% conversion. The ee values indicate s = 15.4 at 59.9% conversion.

α-Methyl-1-naphthalenemethanol. The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 86.2 mg (0.500 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. An aliquot taken after 43 minutes showed 9.9% conversion (GC). The acetate was purified by flash chromatography and shown by HPLC to have a 92.2% ee of the (*R*)[50] isomer. The remainder of the mixture was worked up after 27 hours and shown by GC to have

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48 The absolute configurations were determined from the optical rotation of the kinetically resolved alcohol: Nieduzak, T. R.; Margolin, A. L. *Tetrahedron: Asymmetry* **1991**, *2*, 113-122.

49 The absolute configurations were determined from the optical rotation of the kinetically resolved alcohol: Janssen, A. J. M.; Klunder, A. J. H.; Zwanenburg, B. *Tetrahedron* **1991**, *47*, 7645-7662.

50 The absolute configurations were assigned by comparison with commercially available (*R*)-α-methyl-1-naphthalenemethanol (Aldrich).

proceeded to 63.1% conversion. The acetate and alcohol were separated by flash chromatography. HPLC analysis of the acetate showed a 57.7% ee of the (*R*) isomer, and HPLC analysis of the alcohol showed a 99.7% ee of the (*S*) isomer. The ee values indicate s = 21.8 at 63.3% conversion.

(*E*)-4-Phenyl-3-buten-2-ol. The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 74.1 mg (0.500 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. An aliquot taken after 14 minutes showed an 84.9% ee of (*R*)[51] acetate at 2.8% conversion (GC). The remainder of the mixture was worked up after 31 hours; GC showed a 48.9% ee of (*R*) acetate at 67.2% conversion. The unreacted alcohol was purified by flash chromatography, then converted into the acetate using DMAP and acetic anhydride. The acetate was shown to have a 99.1% ee by GC. The ee values indicate s = 13.9 at 67.0% conversion.

(*E*)-3-Methyl-4-phenyl-3-buten-2-ol. The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 81.4 mg (0.502 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. An aliquot taken after 28 minutes showed a 92.1% ee of (*R*) acetate at 3.8% conversion (GC). The remainder of the mixture was worked up after 31 hours; GC showed a 63.3% ee of (*R*)[52] acetate at 63.2% conversion. The unreacted alcohol was purified by flash chromatography, then converted into the acetate using DMAP and acetic anhydride. The acetate was shown to have a 99.0% ee by GC. The ee values indicate s = 22.0 at 61.0% conversion.

1-(2-Methylphenyl)ethanol . The general procedure was followed using 6.6 mg (0.010 mmol) of (-)-**2.9**, 68.1 mg (0.500 mmol) of alcohol, 52.2 μL (0.375 mmol) of

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51 The absolute configurations were determined from the optical rotation of the kinetically resolved alcohol: Schenck, T. G.; Bosnich, B. *J. Am. Chem. Soc.* **1985**, *107*, 2058-2066.

52 The absolute configurations were determined by converting some of the kinetically resolved alcohol into the Mosher's ester: Fuganti, C.; Grasselli, P.; Spreafico, F.; Zirotti, C.; Casati, P. *J. Chem. Res., Synop.* **1985**, 22-23.

triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. The reaction mixture worked up after 24.5 hours. GC analysis revealed a 98.7% ee of (*S*) alcohol.[53] The acetate was isolated by flash chromatography (2% → 10% EtOAc/hexanes), and then it was reduced with $LiAlH_4$ and analyzed by GC, which revealed a 64.9% ee of (*R*) alcohol. These ee values correspond to a selectivity factor (s) of 22.2 at 60.3% conversion.

Solvent Study of the Kinetic Resolution of 1-Phenylethanol Using 2.9 (Table 2.3). General procedure. To a vial containing catalyst (-)-**2.9** (6.6 mg, 0.010 mmol) was added 1-phenylethanol (61.1 mg, 0.500 mmol). Solvent (1.0 mL) and triethylamine (52.2 μl, 0.375 mmol) were then added by syringe, and the vial was capped with a septum. The vial was gently heated to dissolve the catalyst. After the catalyst had dissolved and the solution had been given ample time to return to room temperature, acetic anhydride (35.4 μl, 0.375 mmol) was added by syringe. After exactly one hour, approximately half of the solution was removed from the vial by syringe and added to a large excess of methanol to quench the reaction. The catalyst was removed by passing the mixture through a short plug of silica (50 → 75% EtOAc/hexanes, then triethylamine). The fractions containing the alcohol and the acetate were combined, reduced to approximately 10 mL by rotary evaporation (care was taken not to reduce the samples to dryness, as the acetate is somewhat volatile), and analyzed by GC for conversion (Table 2.5).

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53 Authentic (*S*)-1-(2-methylphenyl)ethanol was made by metallation of (*S*)-1-phenylethanol (Aldrich) with 2.0 equivalents of *t*-BuLi in ether at -78 °C followed by addition of 1.0 equivalents of MeI. The optical rotation was determined for a sample of (*S*)-1-(2-methylphenyl)ethanol made by kinetic resolution: $[\alpha]^{20}_D$ = -63° (c = 0.6, methanol).

Table 2.5. Percent Conversion After 1.0 h as a Function of Solvent.

Solvent	Run 1	Run 2	Average
DMF	6.1	5.5	5.8
CH_3CN	10.7	9.5	10.1
CH_2Cl_2	13.4	14.2	13.8
acetone	8.0	7.5	7.7
THF	4.5	4.3	4.4
EtOAc	6.5	6.0	6.3
toluene	12.6	13.6	13.1
Et_2O	7.3	8.2	7.7
t-amyl alcohol	36.0	35.4	35.7

After an appropriate amount of time, the remainder of the reaction was quenched by the addition of a large excess of methanol. The reaction mixture was worked up as above and then analyzed by chiral GC to determine the selectivity factor (Table 2.6).

Table 2.6. Selectivity as a Function of Solvent.

Solvent	Run #	Acetate ee	Alcohol ee	% conversion	s
DMF	1	35.6	44.2	55.4	3.2
DMF	2	39.4	47.0	54.4	3.5
CH_3CN	1	39.4	50.8	56.3	3.7
CH_3CN	2	37.9	48.5	56.2	3.5
CH_2Cl_2	1	45.3	87.3	65.8	7.0
CH_2Cl_2	2	41.6	91.1	68.6	7.0

acetone	1	62.7	69.2	52.4	8.8
acetone	2	62.6	67.7	52.0	8.6
THF	1	66.1	70.0	51.4	10.1
THF	2	65.1	65.0	50.0	9.1
EtOAc	1	66.9	74.6	52.7	11.0
EtOAc	2	67.3	71.8	51.6	10.8
toluene	1	61.9	88.2	58.8	11.9
toluene	2	59.6	88.2	59.7	11.0
Et_2O	1	54.7	97.2	64.0	13.4
Et_2O	2	56.3	95.6	63.0	13.0
t-amyl alcohol	1	60.5	99.8	62.2	25.5
t-amyl alcohol	2	64.4	99.8	60.8	29.1

Kinetic Resolutions Using 2.9 in *t*-Amyl Alcohol (Table 2.4).

1-Phenylethanol. General Procedure. Catalyst (-)-**2.9** (3.3 mg, 0.0050 mmol), (±)-1-phenylethanol (61.2 mg, 0.501 mmol), *t*-amyl alcohol (1.0 mL), and triethylamine (52.2 μL, 0.375 mmol) were added in turn to a vial. The vial was capped with a septum, removed from the glove box, and gently heated with stirring to dissolve the catalyst. After all of the catalyst had dissolved, the purple solution was cooled in an ice bath, and acetic anhydride (35.4 μL, 0.375 mmol) was added by syringe. After 23.5 hours, the reaction was quenched by the addition of a large excess of methanol. The reaction mixture was passed through a short plug of silica to remove the catalyst (50% → 75% EtOAc/hexanes, then 10% NEt_3/EtOAc). The fractions containing the alcohol and the acetate were concentrated and analyzed by chiral GC, which revealed a 79.2% ee of *R* acetate and a 98.9% ee of *S* alcohol.[43] These ee values correspond to a selectivity factor (s) of 43.2 at 55.5% conversion.

A second run provided an 80.8% ee of acetate and a 97.9% ee of alcohol (s = 42.0 at 54.8% conversion).

2,2-Dimethyl-1-phenyl-1-propanol. The general procedure was followed using 3.3 mg (0.0050 mmol) of (-)-**2.9**, 82.0 mg (0.500 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. Reaction time: 111 hours. GC analysis revealed a 92.2% ee of *R* acetate. The alcohol was purified by flash chromatography and converted into the trifluoroacetate derivative. GC analysis of the trifluoroacetate revealed a 96.1% ee of the *S* enantiomer.[46] These ee values correspond to a selectivity factor (s) of 97.7 at 51.0% conversion.

A second run provided a 95.1% ee of acetate and a 76.7% ee of alcohol (s = 92.7 at 44.6% conversion).

A third run provided a 94.8% ee of acetate and an 80.6% ee of alcohol (s = 94.1 at 45.9% conversion).

1-(4-Fluorophenyl)ethanol. The general procedure was followed using 3.3 mg (0.0050 mmol) of (-)-**2.9**, 70.0 mg (0.500 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. Reaction time: 22 hours. GC analysis revealed a 77.8% ee of *R* acetate and a 99.9% ee of *S* alcohol.[48] These ee values correspond to a selectivity factor (s) of 62.0 at 56.2% conversion.

A second run provided an 82.0% ee of acetate and a 99.9% ee of alcohol (s = 70.7 at 54.9% conversion).

A third run provided an 86.2% ee of acetate and a 99.1% ee of alcohol (s = 71.2 at 53.5% conversion).

2-Chloro-1-phenylethanol. The general procedure was followed using 3.3 mg (0.0050 mmol) of (-)-**2.9**, 78.3 mg (0.500 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. Reaction time: 6 hours. The acetate and the alcohol were separated by flash chromatography (2% → 10% EtOAc/hexanes). GC analysis revealed a 76.1% ee of *S* acetate and a 97.5% ee of *R*

alcohol.[47] These ee values correspond to a selectivity factor (s) of 31.4 at 56.2% conversion.

A second run provided a 77.2% ee of acetate and a 97.1% ee of alcohol (s = 32.0 at 55.7% conversion).

1-(2-Methylphenyl)ethanol. The general procedure was followed using 3.3 mg (0.0050 mmol) of (-)-**2.9**, 68.0 mg (0.499 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. Reaction time: 12 hours. Analysis by GC revealed a 98.6% ee of *S* alcohol.[53] The acetate was then isolated by flash chromatography (2% → 10% EtOAc/hexanes), reduced with $LiAlH_4$, and then analyzed by GC, which revealed an 86.6% ee of *R* alcohol. These ee values correspond to a selectivity factor (s) of 68.2 at 53.2% conversion.

A second run provided a 88.2% ee of acetate and a 98.2% ee of alcohol (s = 73.7 at 52.7% conversion).

α-Methyl-1-naphthalenemethanol. The general procedure was followed using 3.3 mg (0.0050 mmol) of (-)-**2.9**, 86.6 mg (0.503 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. Reaction time: 6 hours. The acetate and the alcohol were separated by flash chromatography (2% → 25% EtOAc/hexanes). HPLC analysis revealed an 89.1% ee of *R* acetate and a 94.9% ee of *S* alcohol.[50] These ee values correspond to a selectivity factor (s) of 64.0 at 51.6% conversion.

A second run provided an 89.3% ee of acetate and a 95.1% ee of alcohol (s = 65.8 at 51.6% conversion).

1-(2,6-Dimethylphenyl)ethanol. The general procedure was followed using 3.3 mg (0.0050 mmol) of (-)-**2.9**, 75.1 mg (0.500 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. Reaction time: 8 hours.

GC analysis revealed a 94.0% ee of acetate and a 92.5% ee of alcohol.[54] These ee values correspond to a selectivity factor (s) of 108 at 49.6% conversion.

A second run provided an 89.7% ee of acetate and a 99.6% ee of alcohol (s = 113 at 52.6% conversion).

2,2-Dimethyl-1-(2,6-dimethylphenyl)propanol. The general procedure was followed using 3.3 mg (0.0050 mmol) of (-)-**2.9**, 96.0 mg (0.504 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. Reaction time: 141 hours. GC analysis revealed a 97.8% ee of acetate and a 95.0% ee of alcohol.[55] These ee values correspond to a selectivity factor (s) of 334 at 49.3% conversion.

A second run provided an 95.1% ee of acetate and a 98.8% ee of alcohol (s = 202 at 50.9% conversion).[56]

1-(4-Cyanophenyl)ethanol. The general procedure was followed using 3.3 mg (0.0050 mmol) of (-)-**2.9**, 73.8 mg (0.501 mmol) of alcohol, 52.2 μL (0.375 mmol) of triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. Reaction time: 3.4 hours. GC analysis revealed a 85.7% ee of acetate and a 91.9% ee of alcohol.[57] These ee values correspond to a selectivity factor (s) of 42.3 at 51.7% conversion.

A second run provided an 81.4% ee of acetate and a 97.3% ee of alcohol (s = 41.0 at 54.4% conversion).

1-Cyclohexylethanol. The general procedure was followed using 3.3 mg (0.0050 mmol) of (-)-**2.9**, 63.9 mg (0.498 mmol) of alcohol, 52.2 μL (0.375 mmol) of

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54 The absolute configuration of the product has not been determined.

55 The absolute configuration of the product has not been determined.

56 In cases of very high selectivity, the observed s is very sensitive to quite small amounts of the other enantiomer of the catalyst. This may explain why such a difference in s was observed between runs in the case of this substrate. For a mathematical treatment of kinetic resolutions using catalysts of less than 100% ee, see: Ismagilov, R. F. *J. Org. Chem.* **1998**, *63*, 3772-3774.

57 The absolute configuration of the product has not been determined.

triethylamine, and 35.4 μL (0.375 mmol) of acetic anhydride. Reaction time: 15 hours. GC analysis revealed a 36.7% ee of acetate at 12.5% conversion (s=2.3).[58,59]

A second run provided an 36.9% ee of acetate at 12.9% conversion (s = 2.3).

Kinetic Resolution in the Presence of Air with Unpurified Reagents.

A vial containing catalyst (-)-**2.9** (3.3 mg, 0.0050 mmol) and 1-phenylethanol (61.4 mg, 0.503 mmol) was removed from the glove box and opened to air. *t*-Amyl alcohol (1.0 mL) and triethylamine (52.2 μL, 0.375 mmol), each from a freshly opened bottle, were added by syringe. The vial was closed with a teflon-lined cap and heated gently with stirring to dissolve the catalyst. After the catalyst had completely dissolved, the vial was cooled in an ice bath. The cap was removed, acetic anhydride (35.4 μL, 0.375 mmol) was added by syringe, and the cap was replaced. After 25 hours, the reaction was quenched with a large excess of methanol. The reaction mixture was passed through a short plug of silica (50% → 75% EtOAc/hexanes, then 10% NEt_3/EtOAc) to separate the alcohol and the acetate from the catalyst. The solution of alcohol and acetate was concentrated and analyzed by chiral GC, which revealed a 79.9% ee of *R* acetate and a 98.5% ee of *S* alcohol. These ee values correspond to a selectivity factor (s) of 42.8 at 55.2% conversion.

Preparative Scale Kinetic Resolution of 1-(2-Methylphenyl)ethanol (eq 2B.13).

1-(2-Methylphenyl)ethanol (1.11 g, 8.14 mmol), *t*-amyl alcohol (16 mL), and triethylamine (0.67 mL, 4.8 mmol) were added to a flask containing (-)-**2.9** (27.7 mg, 0.0419 mmol). A septum was added, and the flask was removed from the glove box. After some gentle heating to dissolve the catalyst, the flask was cooled in an ice bath. Acetic anhydride (0.46 mL, 4.9 mmol) was added by syringe. After 25.5 hours, the

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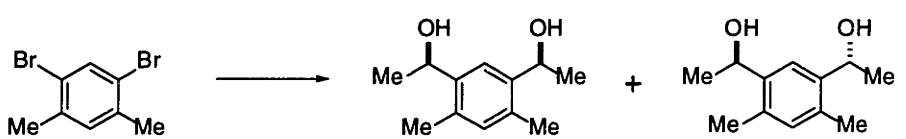
58 Percent conversion was determined using response factors calculated for alcohol and acetate.

59 The absolute configuration of the product has not been determined.

reaction was quenched with 5 mL of methanol. The mixture was passed through a short plug of silica (50% → 100% EtOAc/hexanes, then 10% NEt_3/EtOAc) to separate the alcohol and the acetate from the catalyst. The solution of alcohol and acetate was concentrated, and the residue was purified by flash chromatography (5% → 25% Et_2O/pentane), which yielded 639 mg of acetate and 517 mg of alcohol. GC analysis of the alcohol revealed a 92.9% ee of the *S* enantiomer. A sample of the acetate was reduced with $LiAlH_4$ to the alcohol, which GC analysis showed to have a 90.2% ee of the *R* enantiomer. These ee values correspond to a selectivity factor (s) of 65.9 at 50.7% conversion. The recovered catalyst was purified by flash chromatography (50% EtOAc/hexanes → 10% NEt_3/45% EtOAc/45% hexanes), which provided 24.9 mg of pure catalyst.

A second run using 26.4 mg (0.040 mmol) of (-)-**2.9**, 1.10 g (8.05 mmol) of alcohol, 0.67 mL (4.8 mmol) of triethylamine, and 0.46 mL (4.8 mmol) of acetic anhydride yielded 688 mg of acetate with an 87.4% ee and 475 mg of alcohol with a 97.2% ee. These ee values correspond to a selectivity factor (s) of 62.9 at 52.7% conversion.

Acylation of Diols .



Synthesis of α,α′,4,6-tetramethyl-1,3-benzenedimethanol (rac and meso). 2,4-Dibromo-*m*-xylene (25.6 g, 97.0 mmol) was dissolved in 250 mL of ether in a 500 mL flask. The solution was cooled to 0 °C, and a solution of *n*-BuLi (61 mL, 98 mmol) was added by cannula. The solution was stirred at room temperature for 2 hours. Then, it was cooled to 0 °C, and acetaldehyde (5.5 mL, 97 mmol) was added by syringe. After 30 minutes, another portion of *n*-BuLi (100 mL, 160 mmol) was added by cannula. The solution was stirred at room temperature for 30 minutes, and then

it was cooled to 0 °C, and another portion of acetaldehyde (10.0 mL, 177 mmol) was added. After being allowed to warm to room temperature, the mixture was washed with 300 mL of saturated aqueous $NaHCO_3$. The aqueous layer was extracted with ether (2 x 100 mL). The combined organics were washed with saturated aqueous NaCl, dried over $MgSO_4$, and concentrated. The residue was dissolved in CH_2Cl_2 and passed through a plug of silica to remove less polar impurities. EtOAc was needed to elute the highly polar diol, which was obtained as a yellow solid (7.0 g). GC analysis revealed a 1:1 mixture of diastereomers.

Because the rac diol was much less soluble than the meso diol, the mixture was initially purified by a series of recrystallizations from hot methanol. The crystals of rac diol were freed from the last traces of the more polar meso diastereomer by flash chromatography (50% → 100% Et_2O/pentane). Because of the very low solubility of the racemic diol in this solvent system, the column was dry loaded. The pure racemic diol was obtained as a fluffy, white solid. ^1H NMR (d_6-acetone) δ 7.69 (s, 1H), 6.82 (s, 1H), 5.01 (dq, 2H, J=3.9, 6.6), 3.95 (d, 2H, J=3.9), 2.24 (s, 6H), 1.35 (d, 6H, J=6.3). ^{13}C NMR (d_6-acetone) δ 143.5, 132.7, 132.7, 122.6, 66.8, 25.0, 18.6. FTIR (KBr) 3292, 2964, 1363, 1250, 1096, 897 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{12}H_{18}O_2$ (M^+) 194.1307, found 194.1308. m.p. 155.0-155.5 °C.

The mother liquor from the above recrystallizations was significantly enriched in the meso diol. It was freed from the last traces of the less polar rac diastereomer by flash chromatography (50% → 100% Et_2O/pentane). The pure meso diol was obtained as a white solid. ^1H NMR (d_6-acetone) δ 7.65 (s, 1H), 6.82 (s, 1H), 5.01 (dq, 2H, J=3.9, 6.3), 3.93 (d, 2H, J=3.9), 2.25 (s, 6H), 1.36 (d, 6H, J=6.3). ^{13}C NMR (d_6-acetone) δ 143.2, 132.8, 132.7, 122.5, 66.9, 25.0, 18.6. FTIR (KBr) 3257, 2970, 1500, 1455, 1365, 1260, 1179, 1093, 1010, 901 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{12}H_{18}O_2$ (M^+) 194.1307, found 194.1308. m.p. 97.0-97.5 °C.

Acylation of the rac diol (eq 2B.14). The rac diol (97.5 mg, 0.502 mmol), *t*-amyl alcohol (4.0 mL), and triethylamine (105 μL, 0.755 mmol) were added to a vial containing (-)-**2.9** (3.3 mg, 0.0050 mmol). A septum was added, and the vial was removed from the glove box. After some gentle heating to dissolve the catalyst and the diol, the vial was cooled in an ice bath, and acetic anhydride (71.0 μL, 0.752 mmol) was added by syringe. After 49.5 hours of stirring at 0 °C, the reaction was quenched by the addition of 1 mL of methanol. The mixture was then passed through a short plug of silica (50% → 100% EtOAc/hexanes, then 10% NEt_3/EtOAc) to separate the alcohol and the acetates from the catalyst. The solution of the alcohol and the acetates was concentrated, and the resulting oil was purified by flash chromatography (5% → 100% Et_2O/pentane).

The diacetate was isolated as a colorless oil (54.6 mg, 39%). A small portion was reduced with $LiAlH_4$, and the resulting alcohol was shown by HPLC to have a 98.7% ee (assigned by analogy as the (*R,R*) enantiomer). ^1H NMR (d_6-acetone) δ 7.40 (s, 1H), 6.94 (s, 1H), 5.98 (q, 2H, J=6.6), 2.30 (s, 6H), 2.02 (s, 6H), 1.45 (d, 6H, J=6.9). ^{13}C NMR (d_6-acetone) δ 170.3, 139.3, 134.9, 133.2, 123.3, 69.7, 21.7, 21.2, 18.7. FTIR (KBr) 2984, 2928, 1740, 1727, 1446, 1367, 1253, 1091, 1049, 938 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{16}H_{22}O_4$ (M^+) 278.1518, found 278.1518. $[\alpha]^{20}_D$ = +184° (c=1.0, MeOH).

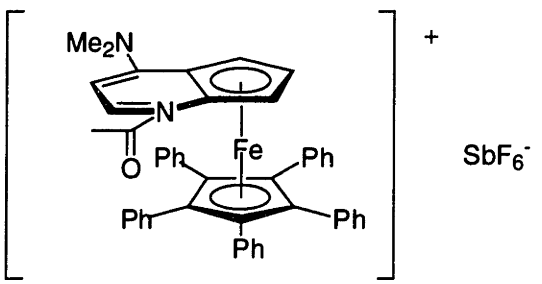
The monoacetate was isolated as a colorless oil (19.3 mg, 16%). It was reduced with $LiAlH_4$, and the resulting alcohol and was shown by GC to have a 35.1% ee of the R,R enantiomer.

The diol was isolated as a white solid (42.3 mg, 43%). It was shown by GC to have a 97.9% ee of the (*S,S*) enantiomer. NMR data for the optically active material matched that of the racemate (see above). $[\alpha]^{20}_D$ = -99° (c=0.8, MeOH).

Acylation of the meso diol (eq 2B.15). The meso diol (97.3 mg, 0.501 mmol), *t*-amyl alcohol (1.0 mL), and triethylamine (105 μL, 0.755 mmol) were added to a vial containing (-)-**2.9** (3.3 mg, 0.0050 mmol). A septum was added, and the vial was

removed from the glove box. After some gentle heating to dissolve the catalyst and the diol, the vial was cooled in an ice bath. Acetic anhydride (71.0 μL, 0.752 mmol) was added by syringe. After 13.25 hours at 0 °C, the reaction was quenched with 1 mL of methanol. The mixture was passed through a short plug of silica (50% → 100% EtOAc/hexanes, followed by 10% NEt_3/EtOAc) to separate the catalyst from the alcohol and the acetates. The solution of the alcohol and the acetates was concentrated, and the resulting oil was purified by flash chromatography (10% → 50% Et_2O/pentane). The monoacetate was collected as a white, crystalline solid (108 mg, 91%). GC analysis revealed a 99.7% ee (acylation of the (*R*) hydroxyl assumed based on analogy). ^1H NMR (d_6-acetone) δ 7.57 (s, 1H), 6.88 (s, 1H), 5.98 (q, 1H, J=6.6), 5.01 (dq, 1H, J=3.9, 6.3), 4.03 (d, 1H, J=3.9), 2.29 (s, 3H), 2.25 (s, 3H), 1.99 (s, 3H), 1.46 (d, 3H, J=6.6), 1.35 (d, 3H, J=6.3). ^{13}C NMR (d_6-acetone) δ 170.3, 144.0, 138.8, 133.9, 133.5, 132.8, 122.8, 69.9, 66.0, 25.0, 21.7, 21.2, 18.6, 18.6. FTIR (KBr) 3420, 2973, 2929, 1738, 1503, 1450, 1371, 1241, 1079, 1020 cm^{-1}. HRMS (EI, *m/e*) calcd for $C_{14}H_{20}O_3$ (M^+) 236.1412, found 236.1412. $[\alpha]^{20}_D$ = +61° (c=2.0, MeOH).

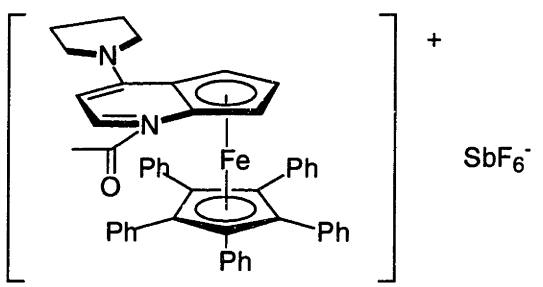
Preparation of Acylated Catalysts.



Acylation of 2.9 (2.15). Acetyl chloride (30 μL, 0.42 mmol) was added by syringe to a purple solution of **2.9** (211 mg, 0.319 mmol) in 5 mL of CH_2Cl_2, resulting in a green solution. After 5 minutes, the solvent and excess acetyl chloride were removed by vacuum, and the residue was dissolved in 4 mL of CH_2Cl_2. To this solution was

added silver hexafluoroantimonate (112 mg, 0.324 mmol) in 1.5 ml of CH_3CN, resulting in the formation of a grainy, white precipitate. After 35 minutes, the solution was filtered to remove the precipitated AgCl, and solvent was removed by vacuum, leaving the product as a green solid. The product was purified by recrystallization from THF/pentane, resulting in 103 mg (34%) of green crystals, one of which was suitable for X-ray analysis.

^{1}H NMR (300 MHz, CD_2Cl_2) δ 8.15 (d, 1H, J = 8.4), 7.26 (t, 5H, J=7.5), 7.12 (t, 10H, J=7.5), 6.85 (d, 10H, J=7.5), 6.44 (dd, 1H, J=3.0, 1.2), 6.35 (d, 1H, J=8.4), 5.14 (dd, 1H, J=3.0, 1.2), 4.94 (t, 1H, J=3.0), 3.51 (s, 3H), 3.34 (s, 3H), 2.47 (s, 3H). ^{13}C NMR (126 MHz, CD_2Cl_2) δ 170.3, 168.6, 140.9, 133.4, 132.4, 128.0, 128.0, 101.2, 100.8, 88.4, 82.9, 71.7, 70.7, 70.2, 46.3, 45.1, 23.6. FTIR (KBr) 3055, 1736, 1606, 1504, 1226, 1168, 1053, 743, 702, 659 cm^{-1}. Anal. Calcd for $C_{47}H_{39}F_6FeN_2OSb$ (939.4): C, 60.09; H, 4.18; N, 2.98. Found: C, 59.79; H, 4.05; N, 2.85. mp = 254-255 °C.

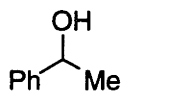
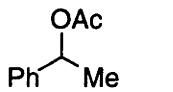
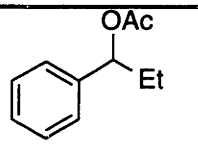
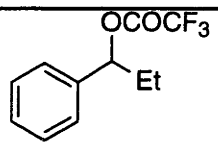
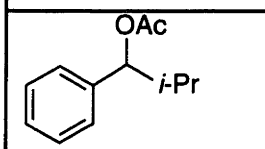
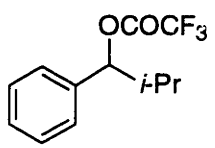


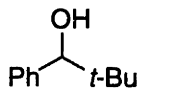
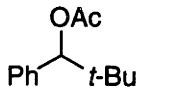
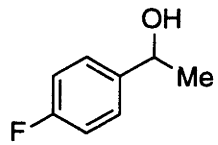
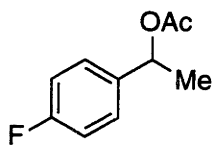
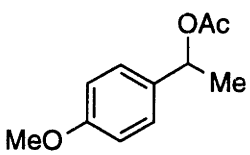
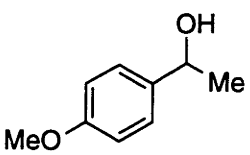
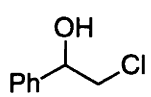
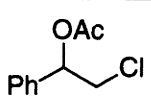
Acylated 2.16. The above procedure was followed starting with 398 mg (0.580 mmol) of **2.16**, 55 μL (0.77 mmol) of acetyl chloride, and 203 mg (0.59 mmol) of silver hexafluoroantimonate. The product was purified by recrystallization from THF/pentane, resulting in 346 mg (62%) of green crystals. X-ray quality crystals were grown by diffusion of ether into a saturated solution of the complex in CD_2Cl_2.

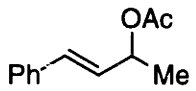
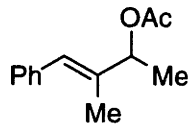
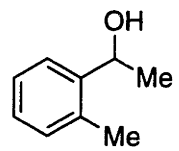
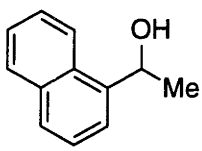
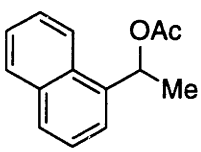
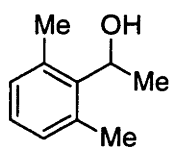
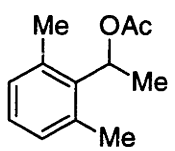
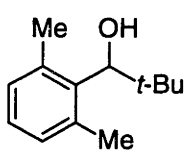
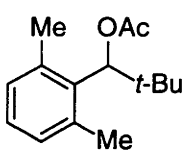
^{1}H NMR (300 MHz, CD_2Cl_2) δ 8.15 (d, 1H, J = 8.1), 7.26 (t, 5H, J=7.5), 7.12 (t, 10H, J=7.5), 6.86 (d, 10H, J=7.5), 6.40 (dd, 1H, J=3.0, 1.2), 6.28 (d, 1H, J=8.4), 5.09 (dd, 1H, J=3.0, 1.2), 4.89 (t, 1H, J=3.0), 3.64-3.89 (m, 4H), 2.45 (s, 3H), 2.05-2.30 (m, 4H). ^{13}C NMR (75

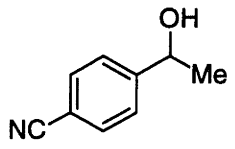
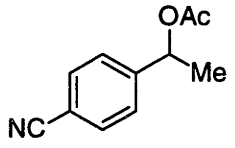
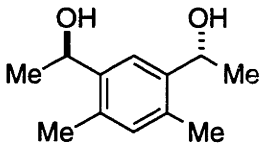
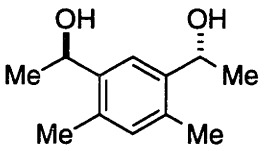
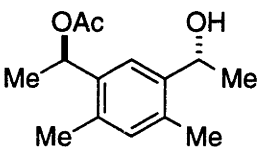
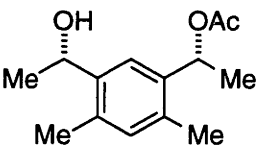
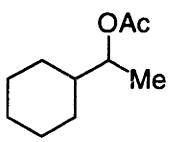
MHz, CD_2Cl_2) δ 170.3, 165.6, 141.1, 133.5, 132.4, 128.0, 127.9, 101.5, 100.4, 88.4, 82.7, 71.8, 70.4, 70.2, 54.5, 53.9, 26.2, 24.8, 23.6. FTIR (KBr) 3056, 1735, 1609, 1560, 1507, 1219, 1173, 990, 702, 658 cm^{-1}. Anal. Calcd for $C_{49}H_{41}F_6FeN_2OSb$ (965.5): C, 60.96; H, 4.28; N, 2.90. Found: C, 60.66; H, 3.90; N, 2.76. mp = 246-247 °C.

Table 2.7. Methods Used to Assay ee's of Alcohols and Acetates

Substrate	ee Assay	Conditions	Retention Time of *R* Isomer (min)	Retention Time of *S* Isomer (min)
	GC Chiraldex B-PH	80 °C 2.0 mL/min carrier gas flow	14.44	14.89
	GC Chiraldex B-PH	80 °C 2.0 mL/min carrier gas flow	7.75	7.46
	GC Chiraldex B-PH	105 °C; 2.0 mL/min carrier gas flow	6.76	6.41
	GC Chiraldex G-TA	65 °C, 10 min; 2 °C/min to 85 °C; 0.8 mL/min carrier gas flow	17.73	18.08
	GC Chiraldex B-PH	105 °C; 2.0 mL/min carrier gas flow	7.80	7.22
	GC Chiraldex G-TA	65 °C, 10 min; 2 °C/min to 85 °C; 0.8 mL/min carrier gas flow	19.17	19.74

	Convert to TFA then GC Chiraldex G-TA	95 °C 0.7 mL/min carrier gas flow	13.2	13.9
	GC Chiraldex B-PH	100 °C 2.0 mL/min carrier gas flow	12.8	11.9
	GC Chiraldex B-PH	105 °C, 10 min; 10 °C/min to 150 °C 2.0 mL/min carrier gas flow	10.8	11.0
	GC Chiraldex B-PH	105 °C, 10 min; 10 °C/min to 150 °C 2.0 mL/min carrier gas flow	5.8	5.5
	GC Chiraldex B-PH	100 °C 2.0 mL/min carrier gas flow	46.52	43.28
	GC Chiraldex B-PH	100 °C 2.0 mL/min carrier gas flow	69.10	71.38
	GC Chiraldex G-TA	105 °C, 10 min; 10 °C/min to 150 °C 0.7 mL/min carrier gas flow	12.30	12.95
	GC Chiraldex G-TA	95 °C 0.7 mL/min carrier gas flow	27.91	30.59

	GC Chiraldex B-PH	115 °C 2.0 mL/min carrier gas flow	19.64	18.65
	GC Chiraldex B-PH	115 °C 2.0 mL/min carrier gas flow	18.56	17.74
	GC Chiraldex G-TA	105 °C 0.7 mL/min carrier gas flow	7.20	8.18
	HPLC Chiralcel OD	10% *i*PrOH/hexane 1.0 mL/min	18.4	11.4
	HPLC Chiralcel OD	10% *i*PrOH/hexane 1.0 mL/min	6.4	8.3
	GC Chiraldex G-TA	100 °C 0.8 mL/min carrier gas flow	17.17	19.92
	GC Chiraldex G-TA	100 °C 0.8 mL/min carrier gas flow	13.91	14.30
	GC Chiraldex G-TA	100 °C 0.8 mL/min carrier gas flow	38.92	40.13
	GC Chiraldex G-TA	100 °C 0.8 mL/min carrier gas flow	34.27	33.06

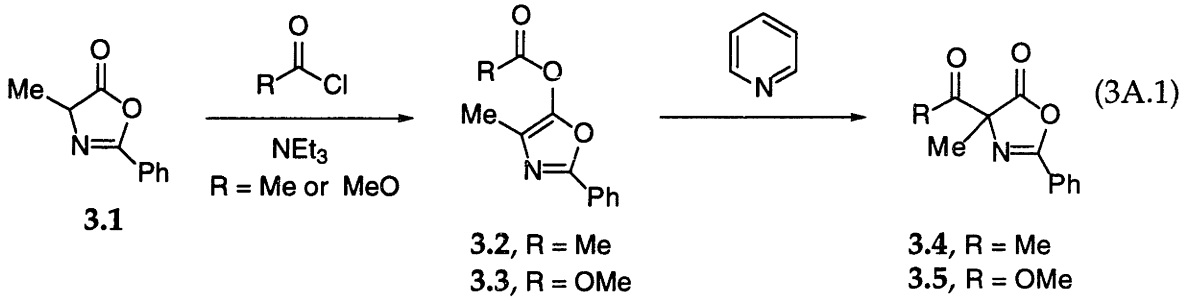
	GC Chiraldex G-TA	135 °C 0.8 mL/min carrier gas flow	14.50	15.12
	GC Chiraldex G-TA	135 °C 0.8 mL/min carrier gas flow	12.80	12.14
	GC Chiraldex B-PH	150 °C 2.0 mL/min carrier gas flow	32.90	34.55
	HPLC Chiralcel OD	10% *i*PrOH/hexane 1.0 mL/min	11.2	8.4
	GC Chiraldex B-PH	150 °C 2.0 mL/min carrier gas flow	14.98	16.95
	GC Chiraldex B-PH	150 °C 2.0 mL/min carrier gas flow	17.46 (R) configuration at acetate	15.10 (S) configuration at acetate
	GC Chiraldex G-TA	65 °C, 10 min; 2 °C/min to 85 °C; 0.8 mL/min carrier gas flow	11.83	11.01

Chapter Three:

Asymmetric Rearrangement of *O*-Acylated Enolates to β-Dicarbonyls Catalyzed by Planar-Chiral π-Complexes

Chapter Three, Part A: Introduction to Nucleophile-Catalyzed *O*-to-*C* Acyl Transfer

Steglich and Höfle reported in 1968 that 4-substituted 2-phenyl-4*H*-oxazol-5-ones (azlactones) react with aliphatic carboxylic acid chlorides, as well as chloroformates, in the presence of triethylamine to give a good yield of the kinetically favored 2,4-disubstituted 5-acyloxyoxazoles.[1,2] They further reported that heating the *O*-acyl compounds in the presence of pyridine results in a rearrangement to the thermodynamically favored *C*-acylated isomers (4-substituted 2-phenyl-4-acyloxazol-5-ones) (eq 3A.1). This observation was significant because of its applicability to the mechanism of the Dakin-West reaction, a conversion of amino acids into amino ketones (Scheme 3.1).[3,4] Although it was known that azlactones could be *C*-acylated under Dakin-West conditions (acetic anhydride/pyridine), the *O*-acylated derivatives had not been isolated under those conditions.[5]



(3A.1)

1 Steglich, W.; Höfle, G. *Angew. Chem. Internat. Edit.* **1968**, *7*, 61.

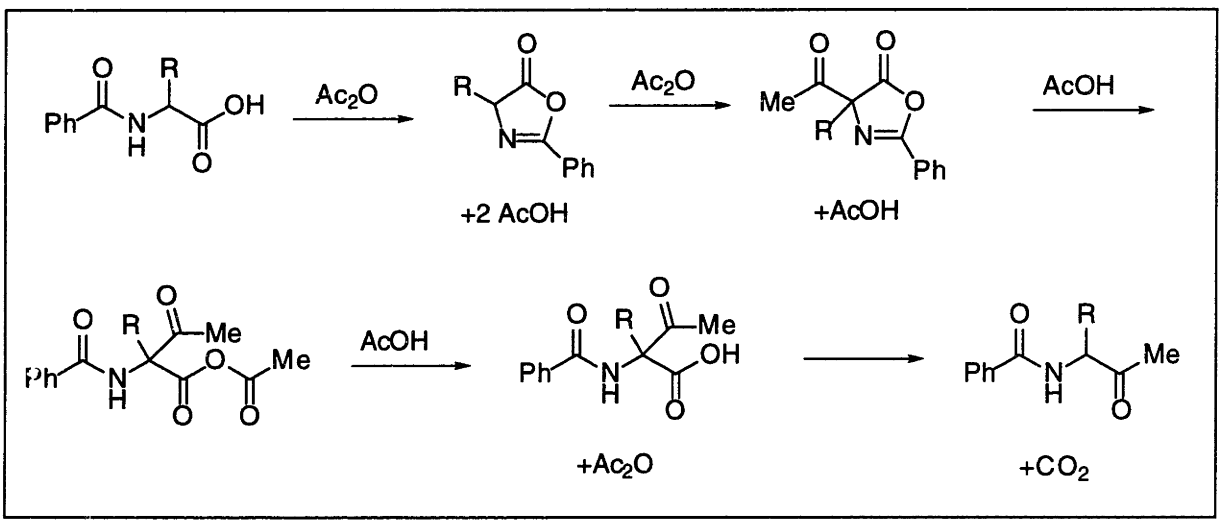
2 The pKa of **3.1** has been reported to be 8.9: de Jersey, J.; Zerner, B. *Biochemistry* **1969**, *8*, 1967-1974.

3 Dakin, H. D.; West, R. *J. Biol. Chem.* **1928**, *78*, 91-105.

4 For a review of the Dakin-West reaction, see: Buchannan, G. L. *Chem. Soc. Rev.* **1988**, *17*, 91-109.

5 Iwakura, Y.; Toda, F.; Suzuki, H. *J. Org, Chem.* **1967**, *32*, 440-443.

Scheme 3.1. Dakin-West Reaction of an *N*-Benzoyl Amino-Acid.



The following year, Steglich and Höfle published a report that the *C*-acylation step of the Dakin-West reaction is greatly accelerated by the use of 5 mol% of DMAP as the catalyst. Whereas the reaction with pyridine takes 5 hours, the DMAP-catalyzed reaction is complete in only 3 minutes.[6] This allows for the Dakin-West reaction to be conveniently conducted at room temperature.

Steglich and Höfle reported in 1970 that both DMAP and PPY are effective catalysts for the rearrangements of the discrete *O*-acylated azlactones to the corresponding β-dicarbonyls as was seen for pyridine in equation 3A.1.[7] Interestingly, they noted that the rearrangements of substrates with a trifluoromethyl substituent in the 2-position (rather than phenyl) resulted in the acyl group rearranging predominantly to that position (eq 3A.2). The same regiochemistry is observed if the 2-substituent is *p*-nitrophenyl and there is a bulky *t*-butyl in the 4-position; the use of a methyl in the 4-position results in the β-dicarbonyl, however (eq 3A.3). PPY is reported to be more active than DMAP as a catalyst for these rearrangements.[8]

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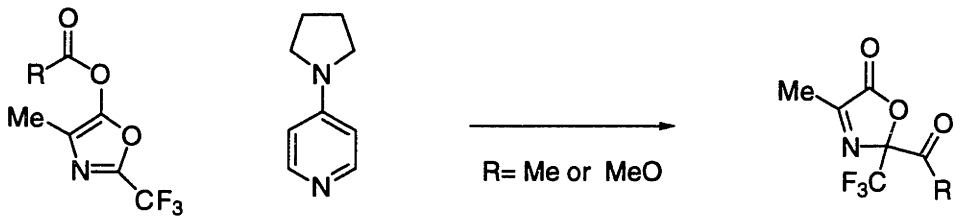
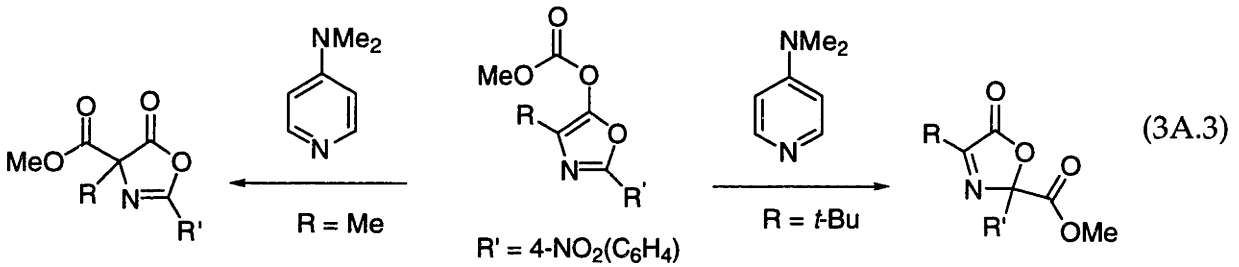
6 Steglich, W.; Höfle, G. *Angew. Chem. Internat. Edit.* **1969**, *8*, 981.
7 Steglich, W.; Höfle, G. *Tetrahedron Lett.* **1970**, 4727-4730.
8 Höfle, G.; Steglich, W.; Vorbrüggen, H. *Angew. Chem. Int. Ed. Engl.* **1978**, *17*, 569-583.



(3A.2)



(3A.3)

A similar DMAP-catalyzed oxygen to carbon acyl transfer reaction has been studied with benzofuran-derived substrates. Black reported in 1986 that 3-phenyl-2-(3*H*)-benzofuranone, **3.6**, is resistant to *C*-acylation with ethyl chloroformate under a wide range of conditions, providing almost exclusively the *O*-acylated derivative, **3.7**.[9] Addition of a small amount of DMAP, however, results in a rapid rearrangement to **3.8**, with the transient formation of a deep-blue color (eq 3A.4). If DMAP is added to the reaction before ethyl chloroformate, **3.8** is formed directly, although it was reported in a subsequent publication by the same authors that this one-step procedure also results in the formation of the blue color.[10] This observation was taken as evidence that the same intermediate, ion pair **3.9**, is present in both cases. The acylation of **3.6** occurs almost exclusively on oxygen with a range of chloroformates (methyl, ethyl, *n*-propyl, *n*-butyl, *sec*-butyl, benzyl, phenyl, allyl, and vinyl), and each of the *O*-acylated derivatives undergoes rapid rearrangement under the influence of DMAP. Of the chloroformates tested, only vinyl chloroformate results in a significant amount of *C*-acylation in the absence of

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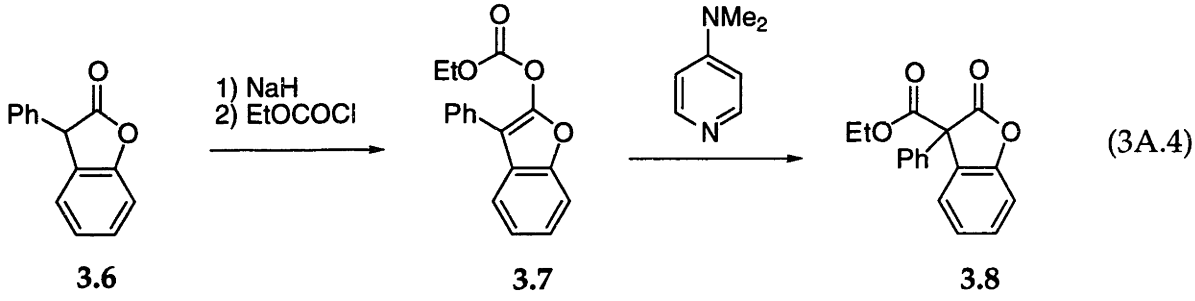
9 Black, T. H.; Arrivo, S. M.; Schumm, J. S.; Knobeloch, J. M. *J. Chem. Soc., Chem. Commun.* **1986**, 1524-1525

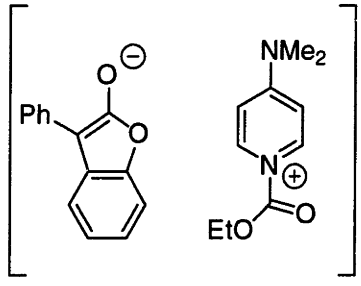
10 Black, T. H.; Arrivo, S. M.; Schumm, J. S.; Knobeloch, J. M. *J. Org. Chem.* **1987**, *52*, 5425-5430.

DMAP. In a later review of control of carbon versus oxygen acylation of enolate ions, Black states that diaryl acetic acid esters are also *C*-acylated in the presence of DMAP and *O*-acylated without it, but no details are given, and the reference is to his own unpublished results.[11]



(3A.4)

3.6 **3.7** **3.8**



3.9

Matthies has shown that this *O*-acylation-rearrangement also works for benzofuranones in which the 3-substituent is an amine protected as either an amide or as a carbonate.[12] In this case, as with Steglich's azlactones, the rearrangement was demonstrated with both enol carbonates and enol acetates (R' = OCH_3 or CH_3, eq 3A.5).

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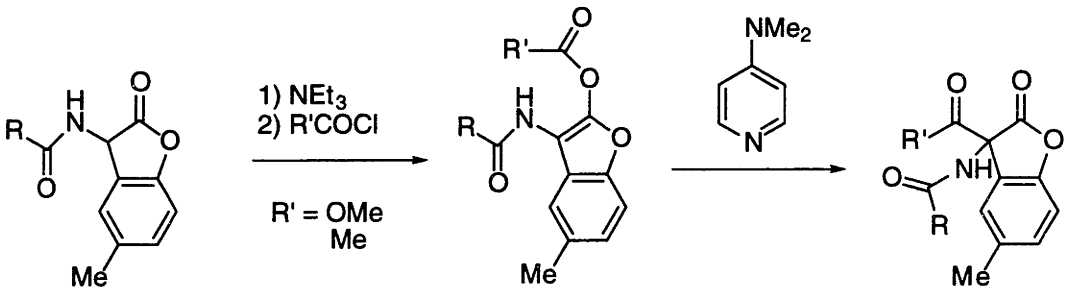
11 Black, T. H. *Org. Prep. Proced. Int.* **1989**, *21*, 179-217.

12 Matthies, D.; Siewers, S.; Vogt, A. *Chem.-Ztg.* **1990**, *114*, 283-287.

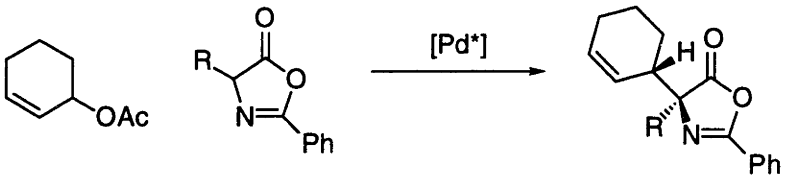


Because these rearrangement reactions result in the formation of a new carbon-carbon bond and quaternary stereocenter, we felt that their investigation with our chiral DMAP derivatives was warranted. This chapter presents our initial results in the asymmetric rearrangement of both *O*-acylated benzofuranones and *O*-acylated azlactones. In the case of azlactone-derived enol carbonates such as **3.3**, our optimization of the rearrangement reaction will be presented in detail, including the preparation of a new catalyst. Some ring-opening reactions of the *C*-acylated products to quaternary amino acid derivatives will be presented, as will initial mechanistic studies.

Chapter Three, Part B: Asymmetric *O*-to-*C* Acyl Transfer Reactions Catalyzed by Planar-Chiral π-Complexes

Background

To the best of our knowledge, there have been no reports of enantioselective or of diastereoselective rearrangements of *O*-acylated enolates to β-dicarbonyls. This is despite the fact that, in the case of the azlactone-derived compounds, the products are α-alkylated-α-amino acid derivatives.[13] In fact, we are only aware of one reported case of catalytic, asymmetric synthesis of α-alkylated-α-amino acids by any method.[14] That approach, published by Trost in 1997, involves the palladium-catalyzed alkylation of allylic acetates with azlactones (eq 3B.1) and results in excellent diastereoselectivity as well as enantioselectivity for several substrates.



(3B.1)

Although the β-dicarbonyls derived from the *O*-to-*C* acyl transfer reaction have not been made asymmetrically, reactivity has been demonstrated for the racemic compounds that suggests the products of these rearrangements might possess synthetic utility. Specifically, the lactone carbonyl group of the products has been shown to react preferentially with nucleophiles to give ring-opened products. In one such case, treatment of benzofuranone **3.10** with ethanol and sulfuric acid results in opening of the benzofuranone ring to give the ethyl ester and the free phenol, and the remainder of the molecule is left intact (eq 3B.2).[15]

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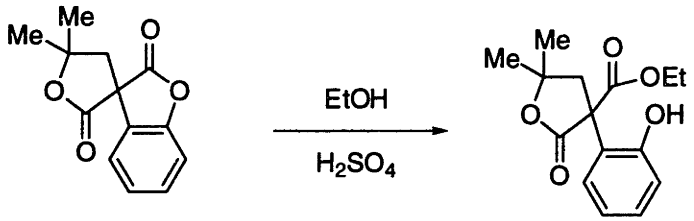
13 For a recent overview of the synthesis of α-alkylated α-amino acids, see: Wirth, T. *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 225-227.

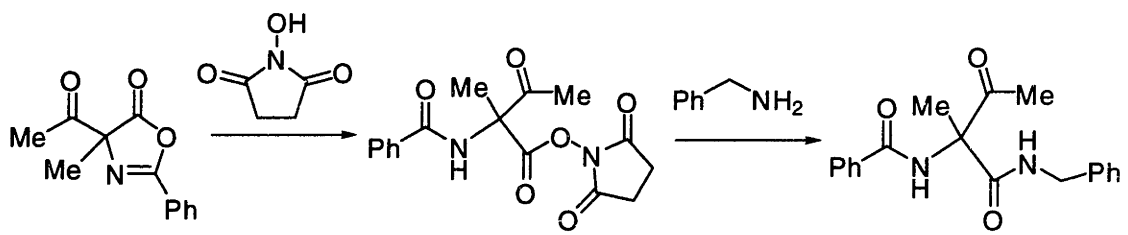
14 Trost, B. M.; Ariza, X. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2635-2637.

15 Setsune, J.-i.; Ueda, T.; Shikata, K.; Matsukawa, K.; Iida, T.; Kitao, T. *Tetrahedron* **1986**, *42*, 2647-2656.



3.10 (3B.2)

The azlactone-derived compounds also show preference for reaction at the lactone carbonyl. One example of this, the third step of the Dakin-West reaction (Scheme 3.1) has already been discussed. In that case, the rearranged molecule is ring opened with a carboxylic acid, but other nucleophiles have also been shown to work. Steglich reported that **3.4** undergoes selective ring opening with *N*-hydroxysuccinimide and that the intermediate can be further reacted with benzylamine (eq 3B.3).[16] The direct reaction of **3.4** with benzylamine or methanol is reported to give a mixture of products, however.



3.4 (3B.3)

The reaction of *C*-acylated azlactones with carbon nucleophiles has also been reported as part of the synthesis of 3-aryl-2-methylserines.[17] Treatment of **3.11** with phenyl Grignard results in a 28% yield of the desired ketoester, **3.12** (eq 3B.4). Subsequent borohydride reduction of the ketone, followed by hydrolysis, gives 3-phenyl-2-methylserine.

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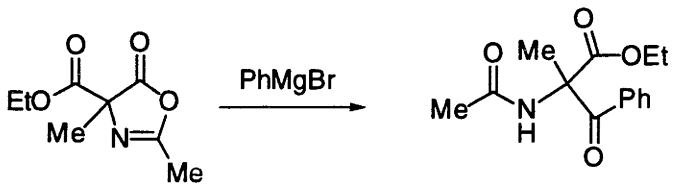
16 Steglich, W.; Höfle, G. *Chem. Ber.* **1969**, *102*, 883-898.

17 Pines, S. H.; Karady, S.; Sletzinger, M. *J. Org. Chem.* **1968**, *33*, 1758-1761.



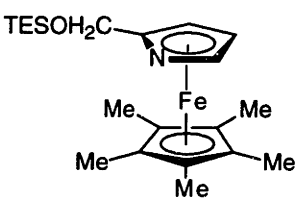
(3B.4)

3.11 **3.12**

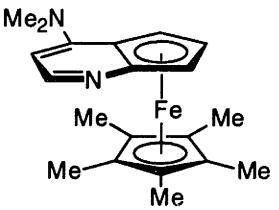
Given the synthetic potential that these β-dicarbonyls hold and the lack of any previous work on asymmetric variants of *O*-to-*C* rearrangements that can be used to form them, we felt that the investigation of this area with our planar-chiral π-complexes was well-justified.

Results and Discussion

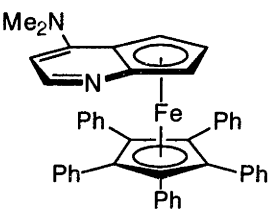
Our initial studies of the asymmetric rearrangement of *O*-acylated enolates to β-dicarbonyls focused on the two original substrates of Steglich, enol acetate **3.2** and enol carbonate **3.3**, as well as Black's *O*-acylated benzofuranone, **3.7**. By the time that we became interested in this work, we had already discovered routes to azaferrocene derivative **1.16** as well as chiral DMAP derivative **1.31** as single enantiomers (Chapter 1), so we were able in several cases to immediately conduct the experiments with optically pure catalysts.



(-)-**1.16**

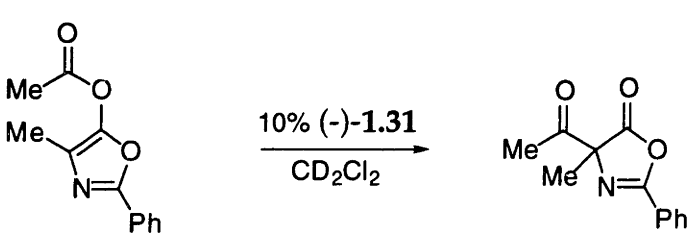


(-)-**1.31**



(-)-**2.9**

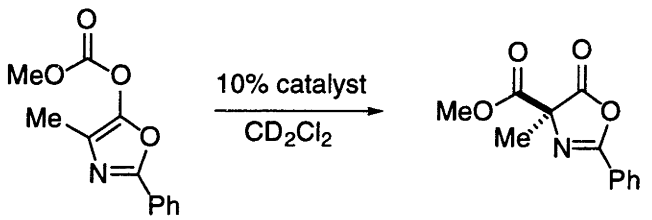
In the case of Steglich's enol acetate, **3.2**, addition of the substrate to 10 mol% of (-)-**1.31** in CD_2Cl_2 resulted in complete rearrangement to the desired β-dicarbonyl in less than 20 minutes and with 50% ee (eq 3B.5)! Under the same conditions, no rearrangement was seen in the absence of catalyst, and the substrate could even be stored neat at room temperature. Unfortunately, the activity of racemic **1.16** as a catalyst in this reaction was quite low, and the corresponding reaction with enantiopure catalyst has not been attempted.



3.2 **3.4**

50% ee (minutes) (3B.5)

Enol carbonate, **3.3**, also underwent a very rapid rearrangement to the corresponding β-dicarbonyl in the presence of 10 mol% of (-)-**1.31** in CD_2Cl_2. Complete conversion took place in less than 50 minutes, and it was accompanied by a transient yellow-green color. At the end of the reaction, the pink color of **1.31** returned, and the product was isolated with a 49% ee. With this substrate, 10 mol% of (-)-**1.16** also catalyzed the desired reaction. Although the reaction was less than 50% complete after 50 hours, the product was formed with a 59% ee.[18]

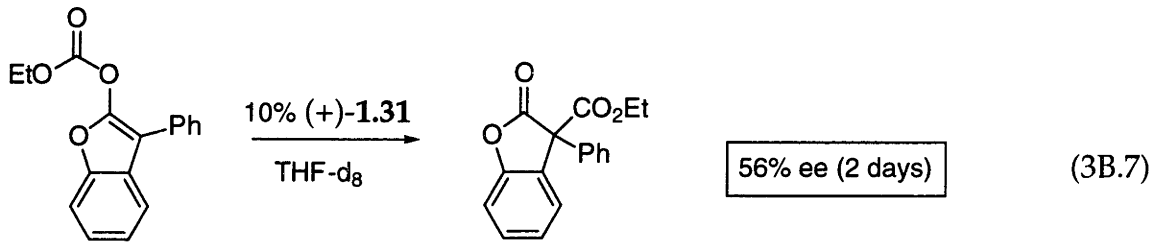


3.3 **3.5**

catalyst	%ee	time
(-)-**1.31**	49	minutes
(-)-**1.16**	59	days

(3B.6)

With benzofuranone derivative **3.7**, even the reaction catalyzed by (-)-**1.31** was sluggish. Mixing **3.7** with 10 mol% of (+)-**1.31** in deuterated THF resulted in an immediate color change to deep blue, but the reaction required approximately 2 days to proceed to completion (eq 3B.7). The product isolated under these conditions had a 56% ee.



3.7 **3.8**

(3B.7)

Although each of the three classes of compounds tested showed significant asymmetric induction in rearrangement reactions catalyzed by **1.31** (eqs 3B.5-3B.7),

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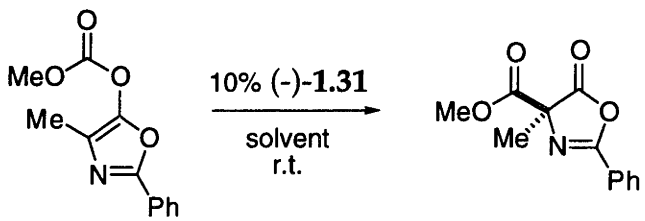
18 The absolute configuration of **3.5** was assumed by analogy to that of other products that will be discussed later in this chapter.

our efforts to date have focused on the optimization of the rearrangement of azlactone-derived enol carbonates, such as **3.5**. Motivated by the large increase in selectivity that we observed for alcohol acylations when the reactions were conducted in *t*-amyl alcohol (see Chapter 2), we conducted a solvent study for this reaction as well. We were again quite pleased to observe a significant solvent effect: When conducted in *t*-amyl alcohol, the (-)-**1.31**-catalyzed rearrangement of **3.3** proceeded to give **3.5** that had 20% higher ee than when the reaction was conducted in any of the other solvents screened (Table 3.1).

Table 3.1. Solvent Effects on Selectivity in the (-)-1.31-Catalyzed Rearrangement of 3.3 to 3.5.



3.3 **3.5**

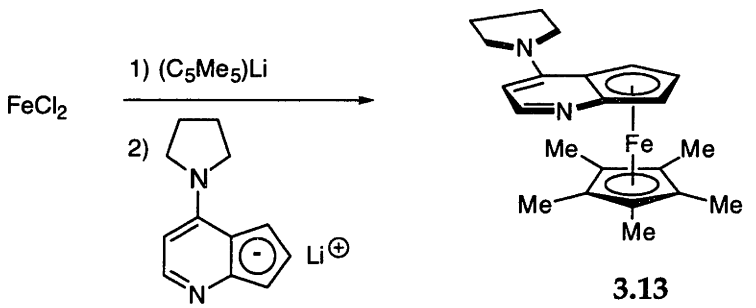
solvent	% ee
CD_2Cl_2	49
THF	36
toluene	44
$PhCF_3$	48
$CHCl_3$	49
ether	37
t-amyl alcohol*	71

* An ee of 78% was observed at 0 °C.

The rearrangement of **3.3** catalyzed by **1.31** in *t*-amyl alcohol was quite fast as well as selective. Upon adding a pink solution of **1.31** in *t*-amyl alcohol to a 10-fold excess of **3.3**, a brown solution was formed. The pink color of the catalyst returned within 30 minutes, signaling the completion of the reaction. Hoping to take advantage of this observation, we lowered the temperature of the reaction to 0 °C. Although the reaction was much slower at 0 °C, the product was formed with an improved ee of

78%. Because pentaphenyl complex **2.9** was so much more selective than **1.31** as a catalyst for alcohol acylation (see Chapter 2), we also tried **2.9** as a catalyst for this reaction. Under conditions where **1.31** gave 78% ee, **2.9** produced the product with 76% ee in a much slower reaction.

Because PPY has been reported to be more active as a catalyst for these rearrangements than DMAP,[8] we became interested in the synthesis of chiral PPY analog **3.13** with the hope of regaining some of the reactivity that was lost by running the rearrangements at 0 °C. The synthesis of **3.13** was completely analogous to that of **1.31**. Treatment of iron(II) chloride with the Cp*-Li followed by the lithium salt of 4-(pyrrolidino)pyrindine resulted in an 84% yield of the desired complex as a burgundy solid (eq 3B.8). This represents an 18% yield over ten steps from adipoyl chloride. The enantiomers of **3.13** were separated by HPLC on a Chiralcel OD column, and the absolute configuration of (+)-**3.13** was determined by X-ray crystallography.[19]



(3B.8)

3.13
(enantiomer shown is (-)-**3.13**)

When we compared the catalytic activity of (-)-**3.13** with that of (-)-**1.31** in the conversion of **3.3** into **3.5**, we were happy to find that the reaction catalyzed by the pyrrolidino derivative was faster by a factor of approximately 4-5. Use of **3.13** instead of **1.31** also resulted in an unexpected, albeit slight, increase in the selectivity of the reaction. When the reaction was conducted with 10 mol% of catalyst at 0 °C in

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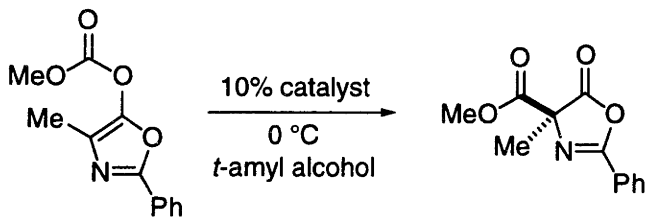
19 The details of the X-ray structure are included in Appendix II.

t-amyl alcohol, (-)-**3.13** gave product with 82% ee, while the product from the reaction with (-)-**1.31** had 77% ee (eq 3B.9). Since **3.13** was both more selective and faster than **1.31**, it became our catalyst of choice for these rearrangement reactions.



3.3 **3.5**

(-)-**3.13**:	82% ee
(-)-**1.31**:	77% ee

(3B.9)

After settling on **3.13** as the catalyst, we began to look systematically at the effects of the substrate's substituents on the rearrangement reaction. We started by looking at the 2-substituent on the azlactone ring. If one ultimately wants to ring open these rearranged molecules into amino acid derivatives, the substituent in the 2-position will simply be part of the nitrogen protecting group. Therefore, we did not have a strong preference for one group over another and conducted a rather extensive survey (Table 3.2). Alkyl substituents (entries 1-3) were inferior to aryl substituents (entries 5-8). Within the subset of aryl substituents, the selectivity was essentially unchanged by electronic effects (entries 5, 7, and 8). The rate of the reaction was, however, affected by electronic changes. A more electron-rich aryl group increased the reaction rate; the substrate in entry 8 reacted faster than than in entry 5, which reacted faster than that in entry 7.[20] Changing the 2-substituent to 2-furyl resulted in a slight lowering of the selectivity, while a *trans*-cinnamyl substituent resulted in a selective but very slow reaction. Because of its high selectivity and rate, the 4-methoxyphenyl group was selected as the 2-substituent of choice.

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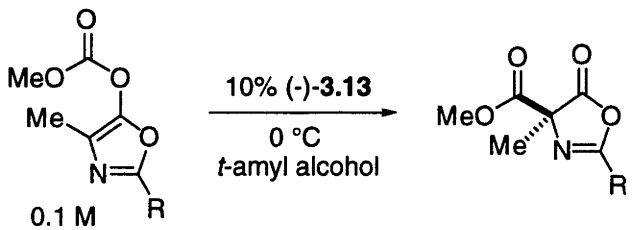
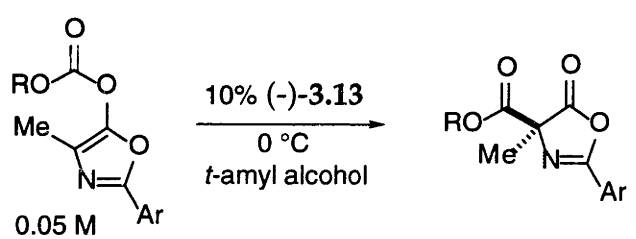
20 The implications of this observation with respect to our proposed mechanism of this reaction will be discussed later.

Table 3.2. Enantioselectivity as a Function of the 2-Substituent of the Azlactone.



Entry	R	% ee
1	Me	54
2	*t*-Bu	42
3	benzyl	17
4	2-furyl	70
5	Ph	82
6	1-naphthyl	81
7	4-Cl-C_6H_4	84
8	4-MeO-C_6H_4	84
9	*trans*-cinnamyl	81

After settling upon 4-methoxyphenyl as the 2-substituent, our attention turned to the choice of the optimal migrating acyl group. We again had no preconceived notions about what this group should be because it should be easily changed (transesterification) after rearrangement and ring opening. The *O*-acylated azlactones derived from commercially available methyl, ethyl, isopropyl, and benzyl chloroformates were prepared and subjected to the rearrangement using 10 mol% of (-)-**3.13** in *t*-amyl alcohol at °C (eq 3B.10). Although a slight decrease in rate and in selectivity was observed in going from methyl to ethyl to isopropyl, the benzyl derivative reacted at approximately the same rate as the methyl derivative and provided the product with slightly enhanced (90%) ee .



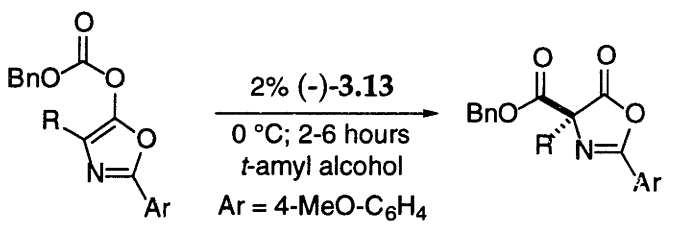
Ar = 4-MeO-C_6H_4

R = Me	86% ee
Et	84% ee
i-Pr	83% ee
Bn	90% ee

(3B.10)

We next investigated the scope of this rearrangement reaction with the optimized groups in the 2-position (4-methoxyphenyl) and on the migrating acyl portion of the substrates (benzyl). The results are shown in Table 3.3. Using only 2 mol% of (-)-**3.13** as the catalyst, a range of substrates (derived from the amino acids alanine, ethylglycine, phenylalanine, allylglycine, leucine, and methionine)[21] were rearranged with excellent ee (88-92%) and in high isolated yield (93-95%). These reactions were conducted on a 0.5 mmol scale and required from 2 to 6 hours to proceed to completion. In each case, the pink color of the catalyst solution changed to deep blue or purple upon mixing and returned quickly to pink at the end of the reaction. The products were purified by flash chromatography to remove the catalyst.

Table 3.3. Rearrangement of a Range of Substrates Catalyzed by (-)-3.13.



R	% ee	% yield
Me	91	94
Et	90	93
CH_2Ph	90	93
allyl	91	93
CH_2CHMe_2	92	95
CH_2CH_2SMe	88	94

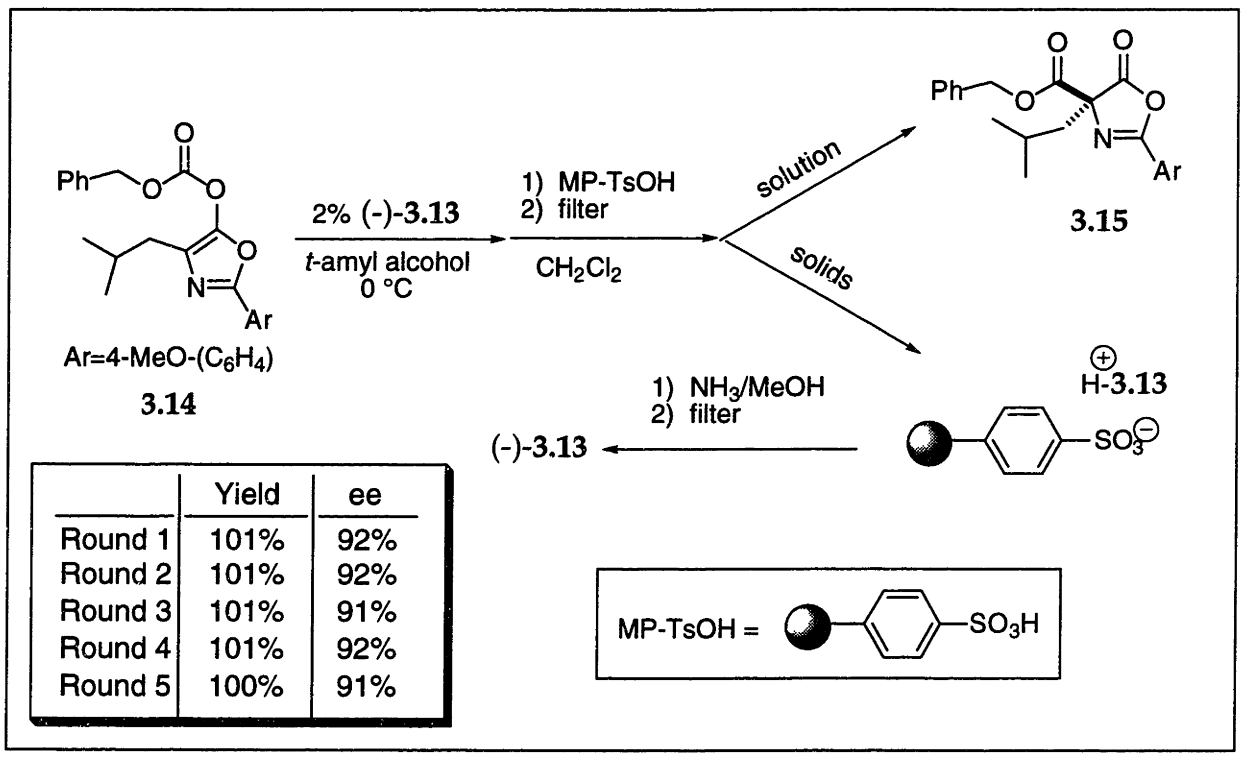
Although the isolated yields of the products from this rearrangement were quite high, we suspected that a small amount of hydrolysis[22] of the products might take place on silica gel and began to search for alternate ways in which the reaction could be worked up. At the end of a reaction, there is only catalyst, product, and *t*-amyl

21 Preliminary experiments with valine-derived substrates (R=isopropyl) indicated the formation of multiple products.

22 The hydroylsis of similar products has been reported, see reference 16.

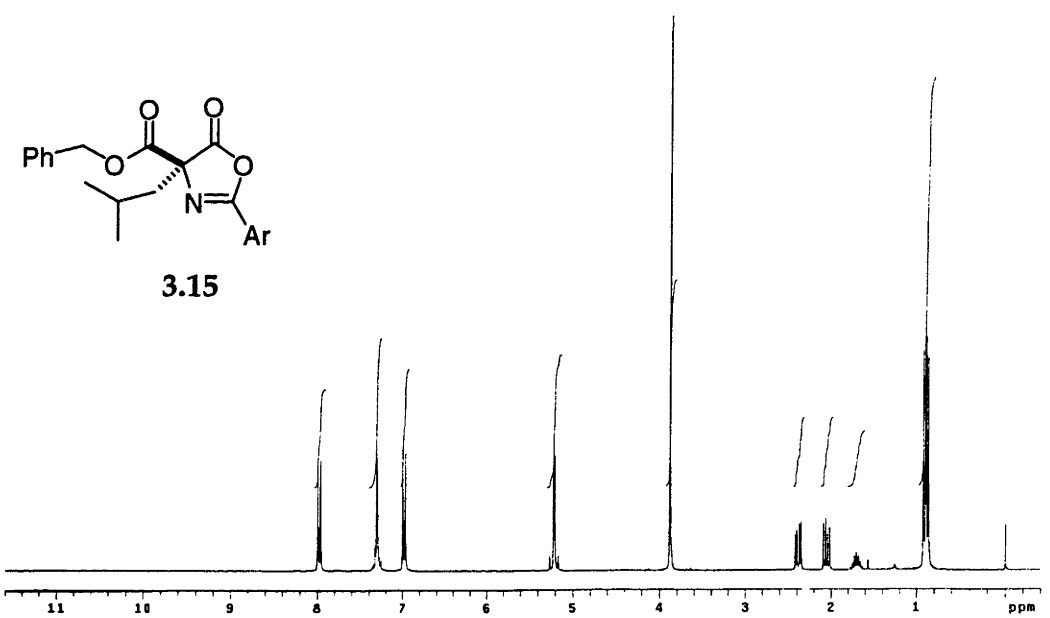
alcohol remaining. Because the catalyst is basic, one might expect that a wash with aqueous acid would be effective, but we were concerned that these conditions might also result in partial hydrolysis of the product. Acting on a suggestion from Jeff Labadie at Argonaut Technologies, we simply added a polymer-bound sulfonic acid (MP-TsOH) after the (-)-**3.13** catalyzed rearrangement of **3.14** (Scheme 3.2). After a few hours of stirring, all of the pink color of the catalyst had been removed from the solution, and the polymer beads had turned from off-white to purple. A simple filtration, followed by removal of the solvent, provided **3.15** in quantitative yield and with very high purity. Figure 3.1 shows the crude ^{1}H NMR of **3.15** that was purified in this manner. The catalyst was then freed from the beads by treatment with ammonia in methanol. Filtration, followed by removal of solvent afforded the catalyst, which was reused without further purification. We have used the same batch of catalyst up to five times in this way. Although the recovery of the catalyst was not quantitative, this only affected the time required for subsequent reactions, not the ee of the **3.15** that was produced.

Scheme 3.2. Catalyst Separation and Recycling Using a Polymer Bound Acid.

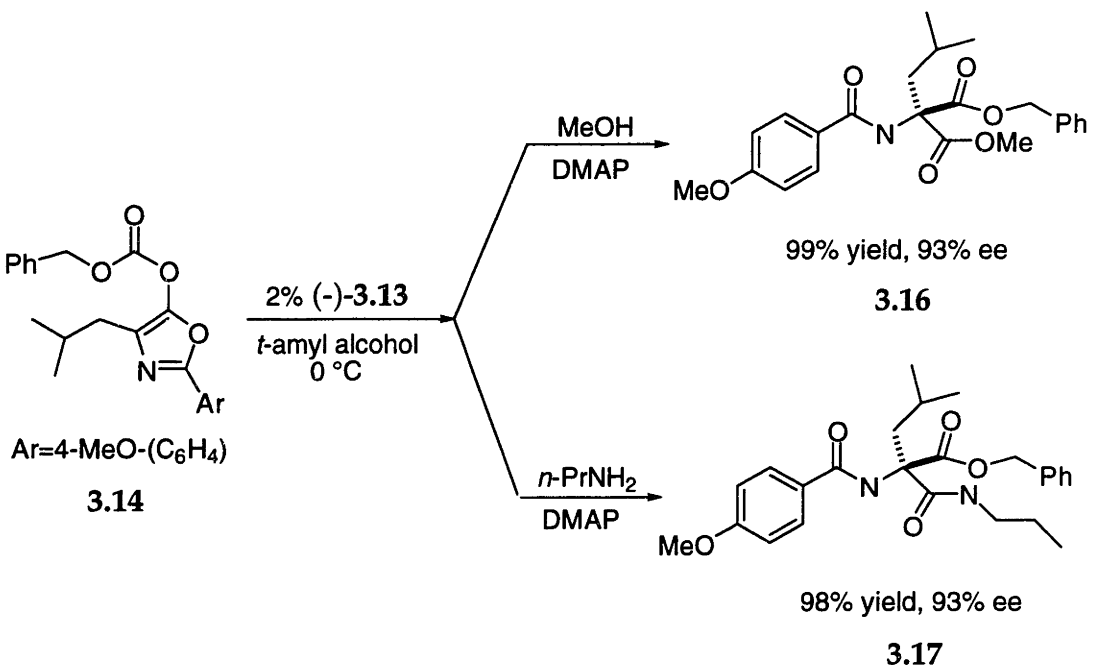


	Yield	ee
Round 1	101%	92%
Round 2	101%	92%
Round 3	101%	91%
Round 4	101%	92%
Round 5	100%	91%

Figure 3.1. Crude NMR of 3.15 After Removal of Catalyst with MP-TsOH Resin.



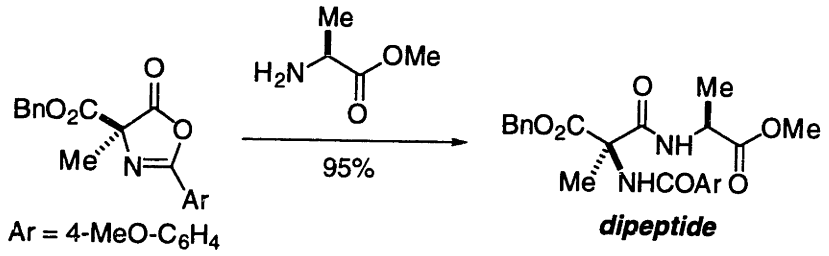
Another approach to preventing the loss in yield of the rearranged products caused by their hydrolysis on silica gel is through their in situ conversion into more stable products. This can be accomplished by the addition of a nucleophile at the end of the reaction to ring open the azlactone. When **3.14** was rearranged under the optimized conditions and, then methanol and DMAP were added, 1,3-diester **3.16** was isolated in 99% yield and in 93% ee after chromatography (eq 3B.11). The use of *n*-proplyamine instead of methanol resulted in a 98% yield of 1,3-amido ester **3.17** in 98% yield and in 93% ee (eq 3B.12). Thus, by avoiding chromatography on **3.15**, either by the use of a polymer bound acid or by in situ ring opening, the yield of the rearrangement reaction of **3.14** catalyzed by (-)-**3.13** was shown to be essentially quantitative.



(3B.11)

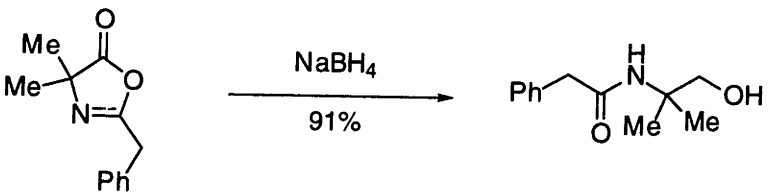
(3B.12)

The ring opening of the rearranged products was also shown to proceed with amino acid derivatives to give dipeptides. The reaction of quaternary alanine derivative **3.18** with (L)-alanine methyl ester hydrochloride, triethylamine, and DMAP resulted in a 95% yield of dipeptide **3.19** (eq 3B.13).

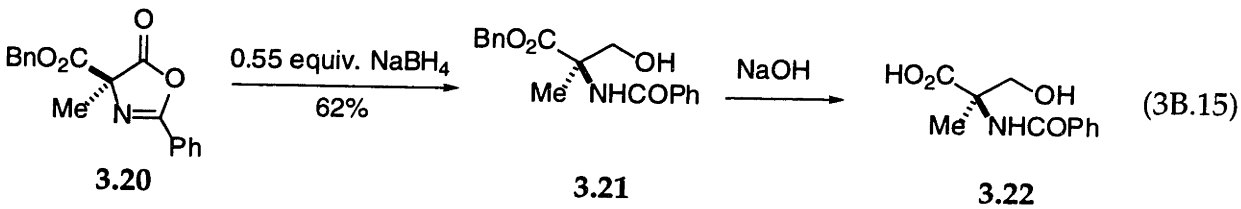


3.18 **3.19** (3B.13)

We have discovered that hydride may also be used as the nucleophile to ring open the rearranged products. Truitt and Chakravarty have shown that azlactones are subject to reduction with sodium borohydride to give the corresponding amidoalcohols in good yield (eq 3B.14),[23] but we were unsure if the presence of the second ester group in our products would be problematic. In fact, the use of excess reducing agent did lead to overreduction to the meso diol in some instances, but reduction of **3.20** with just 0.55 equivalents of sodium borohydride yielded 62% of **3.21**, a protected α-methylserine (eq 3B.15).[24] The absolute configuration of **3.21**, and therefore **3.20**, was determined by hydrolysis to form *N*-benzoyl-α-methylserine, **3.22**, a compound for which the absolute configuration has been reported.[25]



(3B.14)



3.20 **3.21** **3.22** (3B.15)

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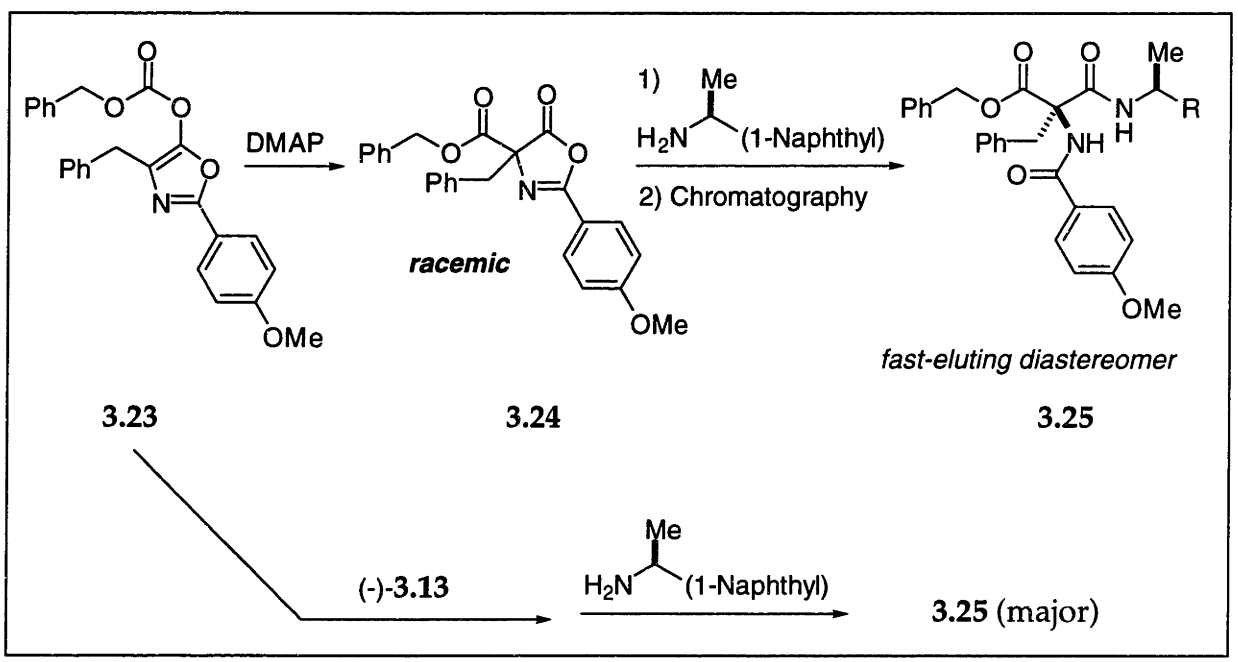
23 Truitt, P.; Chakravarty, J. *J. Org. Chem.* **1970**, *35*, 864-865.

24 For an asymmetric synthesis of α-methylserine and a discussion of its significance, see: Moon, S.-H.; Ohfune, Y. *J. Am. Chem. Soc.* **1994**, *116*, 7405-7406.

25 Leplawy, M. T.; Olma, A. *Polish J. Chem.* **1979**, *53*, 353-357.

The absolute configuration of another one of our rearranged products was determined as shown in Scheme 3.3. *O*-Acylated azlactone **3.23** was rearranged by DMAP to give racemic **3.24**, which was then ring opened using (*S*)-1-(1-naphthyl)ethylamine. The resulting diastereomeric amides were separated by flash chromatography,[26] and the relative stereochemistry of the fast-eluting diastereomer, **3.25**, was determined by X-ray crystallography.[27] When **3.23** was rearranged using (-)-**3.13** as the catalyst and the product was ring opened with (*S*)-1-(1-naphthyl)ethylamine, the major diastereomer of product was identical by ^{1}H NMR and by TLC to **3.25**. The absolute configurations of all other products of azlactone-derived enol carbonate rearrangements were assigned by analogy to **3.20** and **3.24**.

Scheme 3.3. Determination of the Absolute Configuration of the Products.

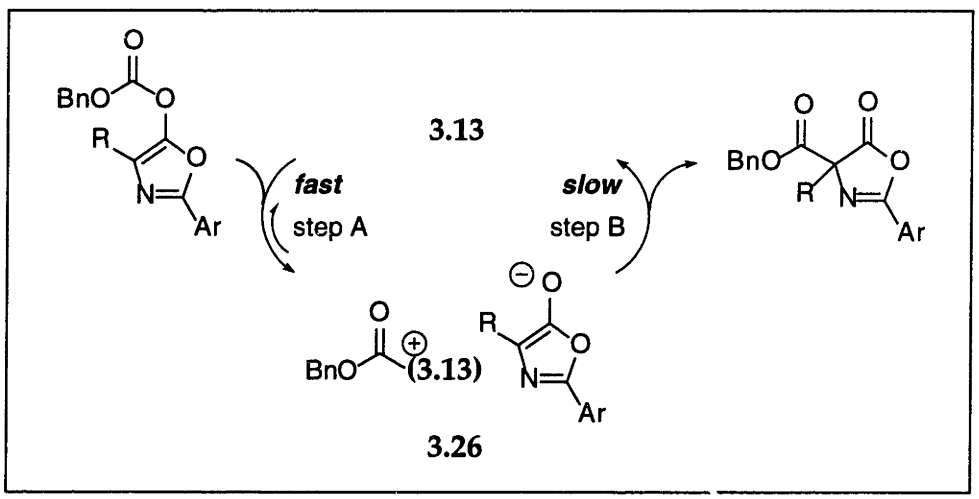


26 For an example of ring opening a disubstituted azlactone with an optically pure amine, followed by separation of the diastereomers as a route to optically pure α,α-disubstituted amino acids, see: Obrecht, D.; Bohdal, U.; Broger, C.; Bur, D.; Lehmann, C.; Ruffieux, R.; Schönholzer, P.; Spiegler, C.; Müller, K. *Helv. Chim. Acta* **1995**, *78*, 563-580.

27 The details of the X-ray structure are presented in Appendix II.

Based on several observations, we believe that the rearrangement of *O*-acylated azlactones catalyzed by **3.13** proceeds through an ion-pair intermediate analogous to **3.9**, which Black proposed for the DMAP-catalyzed rearrangement of *O*-acylated benzofuranones.[10] First of all, we observed that the rate of the reaction was zero-order in substrate and independent of concentration.[28] Also, mixing a solution of **3.13** with a substrate was always accompanied by an immediate color change from the pink color of **3.13** to a transient color[29] that changed quickly back to pink as the reaction approached completion. These observations are consistent with the mechanism shown in Scheme 3.3. The resting state of catalyst is the ion pair **3.26**, so long as there is substrate present in the solution. The rate-determining step is the carbon-carbon bond formation (step B). This is consistent with the electronic effects seen for the aryl group (more electron-rich aryl group resulted in faster reaction).

Scheme 3.3. Proposed Mechanism for the Rearrangement Catalyzed by 3.13.



The crossover experiment shown in eq 3B.16 was done to probe the nature of ion pair **3.26**. The experiment consisted of subjecting equimolar amounts of the

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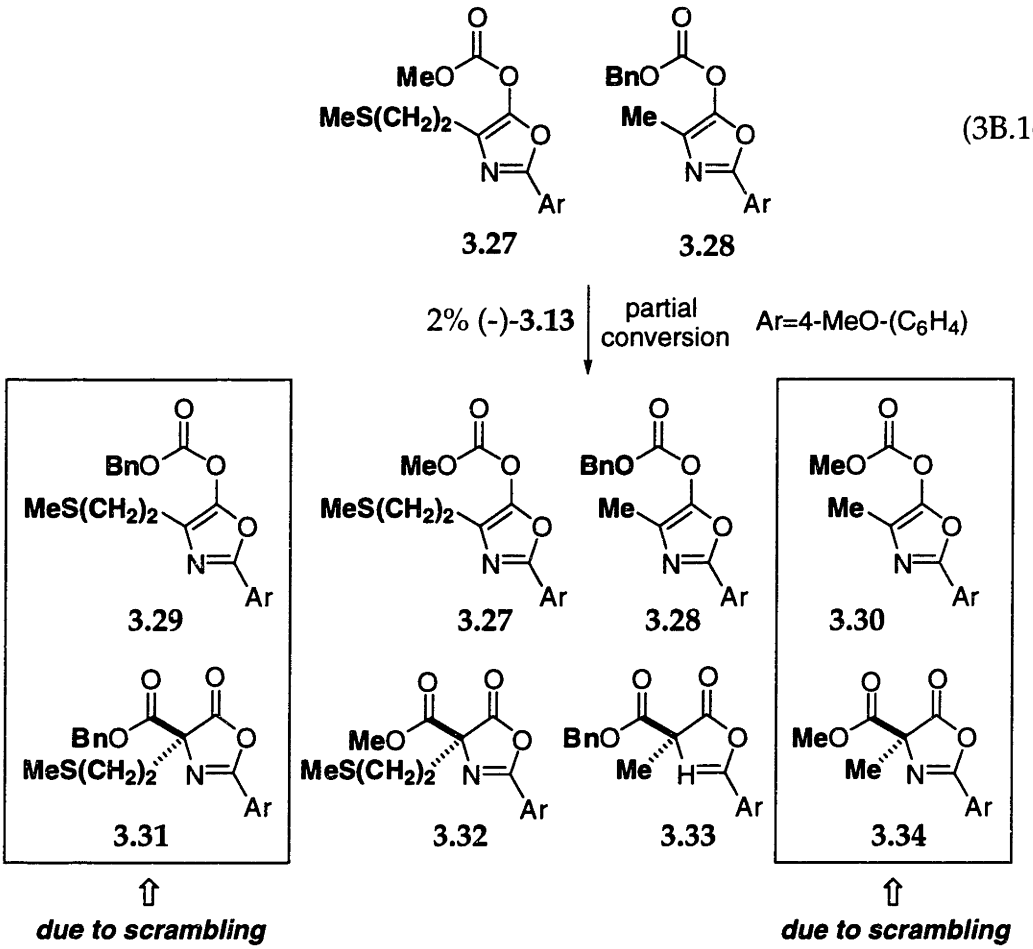
28 For a given amount of catalyst and substrate, the reaction required the same amount of time to proceed to completion, regardless of the amount of solvent used.

29 For the substrates in Table 3.3, the transient color was a deep blue or purple. Other substrates, particularly those with different 2-substituents, resulted in different colors. See the experimental section for more observations.

methionine-derived methyl carbonate, **3.27**, and the alanine-derived benzyl carbonate, **3.28**,[30] to the **3.13**-catalyzed rearrangement conditions and stopping the reaction before it had gone to completion. After removal of solvent, analysis by ^{1}H NMR showed that unreacted starting materials **3.27** and **3.28**, as well as the corresponding products **3.32** and **3.33** were present in the mixture. Also present were significant amounts of "scrambled products" **3.31** and **3.34** and a trace of "scrambled starting materials" **3.29** and **3.30**. In terms of our proposed mechanism, the formation of scrambled products indicated that the counterions of the proposed ion pair **3.26** are able to exchange. The scrambled starting materials also indicated that the counterions of **3.26** can exchange, but they also demonstrated that step A of our mechanism is reversible. A study of the configurational stability of the rearranged products over time suggested that step B of our proposed mechanism is irreversible (no racemization observed).

30 These substrates were selected because of their ease of analysis by ^{1}H NMR (methyl singlets) and because they react at similar rates.


MeO
MeS(CH2)2
BnO
Me
N
Ar
3.27
3.28
2% (-)-3.13
partial conversion
Ar=4-MeO-(C6H4)
3.29
3.27
3.28
3.30
3.31
3.32
3.33
3.34
due to scrambling
due to scrambling

(3B.16)

Conclusions

We have shown that the rearrangement of certain *O*-acylated enolates to β-dicarbonyls is subject to efficient asymmetric catalysis by our planar-chiral π-complexes. After an initial screening of the known nucleophile-catalyzed *O*-to-*C* acyl transfer reactions, we focused on the rearrangement of azlactone-derived enol carbonates, such as **3.3**, with our chiral DMAP derivative **1.31**. A solvent study of this reaction revealed that conducting the reaction in *t*-amyl alcohol results in dramatically improved selectivity, as was seen for alcohol acylation. In contrast to what was seen for alcohol acylation, the use of pentaphenylcyclopentadienyl catalyst **2.9** in place of **1.31** resulted in marginally lower selectivity for the rearrangement reaction. The **1.31**-catalyzed rearrangement of **3.3** was found to give higher ee's at lower temperature, but at the expense of reaction rate. To combat this loss in rate, chiral PPY analog **3.13** was prepared, assuming by analogy to PPY that it would be more reactive than **1.31**. Rearrangement reactions catalyzed by **3.13** were found to be significantly faster and also marginally more selective than those catalyzed by **1.31**.

With improved catalyst **3.13**, the rearrangement reaction was optimized with respect to substrate. Use of a 4-methoxyphenyl substituent in the 2-position of the azlactone ring was shown to be optimal, relative to the other groups studied, in terms of both selectivity and reaction rate. A boost in selectivity was also observed in changing the alkyl group of the migrating acyl portion of the substrates from a methyl into a benzyl. Upon combining these effects, substrates derived from a range of amino acids were shown to rearrange with approximately 90% ee and in excellent isolated yields.

Because the products are somewhat sensitive to hydrolysis on silica gel, a procedure for purifying the reaction mixtures by the use of a polymer-bound acid to scavenge the catalyst was developed. This approach allowed the product to be isolated in high purity and in quantitative yield after a simple filtration and

evaporation of the solvent. The rearranged products could also be ring opened in situ with an alcohol or an amine to prevent loss of product to hydrolysis. The ring opening of one of the rearranged products was demonstrated to proceed in excellent yield with an amino acid derivative to give a dipeptide containing a quaternary residue. Partial reduction of one of the products with sodium borohydride to give a protected α-methyl serine was also demonstrated, although the yield was only moderate.

We propose that the **3.13**-catalyzed rearrangement of azlactone-derived enol carbonates proceeds through the rapid formation of ion pair **3.26**, followed by rate-determining carbon-carbon bond formation. Kinetic observations have indicated that **3.26** is the resting state of the catalyst in this mechanism, and a crossover experiment has demonstrated that the counterions are able to exchange and that the formation of **3.26** is reversible.

Experimental

General

Toluene, THF, *t*-amyl alcohol (caution!), and pentane were distilled from sodium. CH_2Cl_2 and NEt_3 were distilled from calcium hydride.

p-Anisoyl chloride (Aldrich), (D)-phenylalanine (Pfizer), (L)-leucine (Eastman), (±)-2-aminobutyric acid (Aldrich), (±)-2-amino-4-pentenoic acid (ICN), (L)-methionine methyl ester hydrochloride (Aldrich), acetic anhydride (Mallinckrodt), 4-dimethylaminopyridine (DMAP; Aldrich), *n*-BuLi (1.6 M in hexanes; Strem), iron (II) chloride (Strem), 1,2,3,4,5-pentamethyl-1,3-cyclopentadiene (Cp*-H; Strem), 1,3-dicyclohexylcarbodiimide (DCC; Aldrich), 2-hydroxyphenylacetic acid (Aldrich), 4-methylmorpholine (Aldrich), propylamine (Fluka), methanol (Mallinckrodt), methyl chloroformate (Aldrich), ethyl chloroformate (Aldrich), isopropyl chloroformate (1.0 M in toluene; Aldrich), benzyl chloroformate (Aldrich), (L)-alanine ethyl ester hydrochloride (Aldrich), and (L)-alanine methyl ester hydrochloride (Aldrich) were used as received. Catalysts **1.16** and **1.31** were prepared and resolved as reported in Chapter 1. 4-Pyrrolidinopyrindine was prepared as described in Chapter 2. *O*-Acylated azlactones **3.2** and **3.3** were prepared according to the method of Steglich.[1] O-Acylated benzofuranone 3.7 was prepared according to the method of Black.[10]

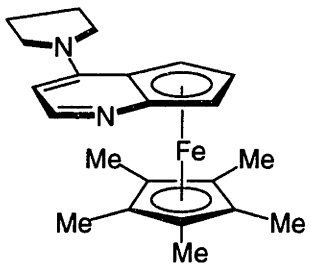
Analytical thin layer chromatography was performed using EM Reagents 0.25 mm silica gel 60 plates, and visualization was accomplished with ultraviolet light and/or phosphomolybdic acid. Flash chromatography was performed on TCI silica gel 60 (230-400 mesh).

Optical rotations were measured on a Perkin-Elmer 241 polarimeter. Infrared spectra were obtained on a Perkin-Elmer Series 1600 FT-IR spectrophotometer. Melting points (uncorrected) were obtained on a Thomas Hoover Unimelt capillary melting point apparatus.

^1H and ^{13}C nuclear magnetic resonance spectra were recorded on a Varian Unity 300, Varian Mercury 300, or a Varian VXR 500 spectrometer at ambient temperature. ^1H data are reported as follows: chemical shift in parts per million downfield from tetramethylsilane (δ scale), multiplicity (br = broad, s = singlet, d = doublet, t = triplet, q = quartet, and m = multiplet), integration, and coupling constant (Hz). ^{13}C chemical shifts are reported in ppm downfield from tetramethylsilane (δ scale). All ^{13}C spectra were determined with complete proton decoupling.

All reactions were carried out under an atmosphere of nitrogen or argon in oven-dried glassware with magnetic stirring, unless otherwise indicated.

Preparation of Catalyst 3.13



4-Pyrrolidinopyrindinyl-pentamethylcyclopentadienyliron (3.13). *n*-BuLi (2.62 M in hexane; 5.27 mL, 13.8 mmol) was added to a solution of Cp*-H (1.88 g, 13.8 mmol) in THF (90 mL), resulting in a milky-white precipitate. This slurry was added by cannula to a slurry of $FeCl_2$ (1.70 g, 13.4 mmol) in THF (30 mL) at 0 °C over 20 minutes (an additional 20 mL of THF was used to rinse leftover Cp*-Li from the flask). A forest green solution resulted. After 2 hours, the ice bath was removed, and a solution of the lithium salt of 4-pyrrolidinopyrindine [made 1.5 hours prior to use by the reaction of *n*-BuLi (2.62 M in hexane; 4.55 mL, 11.9 mmol) and 4-pyrrolidinopyrindine (2.22 g, 11.9 mmol) in 30 mL of THF at r.t.] was added rapidly by cannula, resulting in a burgundy solution (an additional 10 mL of THF was used to rinse the leftover lithium salt from the flask). The reaction mixture was stirred at room temperature for 18.5 hours. It was then filtered through a short plug of silica

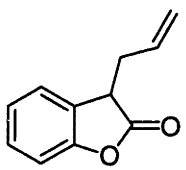
using aspirator vacuum (this operation should be done as quickly as possible, as the crude reaction mixture seems to be rather air sensitive until it is filtered). The silica was washed with 10% NEt_3/90% EtOAc until no more pink color was coming through. The solvent was removed by rotary evaporation, and the residue was purified by flash chromatography (50% MTBE/pentane → 10% NEt_3/70% MTBE/pentane), which provided 3.77 g (84%, 18% overall from adipoyl chloride) of a burgundy crystalline solid. (The NEt_3/MTBE/pentane solvent system give the best separation of the product from the 4-pyrrolidino-6,7-dihydro-1,5-pyrindine that is present as a minor impurity in the 4-pyrrolidinopyrindine, see Chapter 2). Although the product was pure by elemental analysis (see below) a trace of 4-pyrrolidino-6,7-dihydro-1,5-pyrindine could be seen by ^1H NMR. This impurity was removed by a single recrystallization from toluene/Et_20.

^1H NMR (300 MHz, $CDCl_3$) δ 8.19 (d, 1H, J=5.1), 5.56 (d, 1H, J=5.4), 4.51 (dd, 1H, J=2.7, 1.2), 4.31 (dd, J=2.7, 1.2), 3.71 (t, 1H, J=2.7), 3.57 (br s, 4H), 2.03-2.07 (m, 4H), 1.64 (s, 15H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 156.3, 152.1, 111.3, 93.8, 78.4, 74.4, 73.2, 67.1, 64.0, 49.3, 25.7 (br), 9.9. FTIR (KBr) 2966, 2902, 2865, 1538, 1487, 1380, 1338, 1021, 907, 730 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{22}H_{28}FeN_2$ (M^+) 376.1602, found 376.1602. Anal. Calcd for $C_{22}H_{28}FeN_2$ (376.3): C, 70.22; H, 7.50; N, 7.44. Found: C, 70.08; H, 7.82; N, 7.43 (for material purified by chromatography only). mp 163-164°C.

The enantiomers of the product were separated using semi-preparative HPLC (Daicel CHIRALCEL OD, 1 cm x 25 cm, ethanol/hexanes/diethylamine 50:50:0.4, 3.0 mL/min). Injections of 1.0 mL of a 30 mg/mL solution were made. Enantiomer (+)-**3.12** was collected from 7.08 minutes to 8.50 minutes (this enantiomer co-elutes with 4-pyrrolidino-6,7-dihydro-1,5-pyrindine, so it is best to remove the impurity as described above before performing the HPLC), and enantiomer (-)-**3.12** ($[\alpha]^{20}_D$ = -1,850° (c = 0.0075, $CHCl_3$)) was collected from 14.4 minutes to 19.3 minutes.

The absolute configuration of (+)-**3.12** was assigned on the basis of an X-ray crystallographic study (anomalous dispersion).

Preparation and *O*-Acylation of Benzofuranones

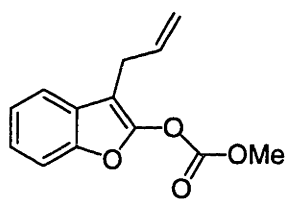


3-Allyl-3*H*-benzofuran-2-one. A solution of 2-hydroxyphenylacetic acid (4.95 g, 32.5 mmol) in 60 mL of THF was added dropwise by cannula at 0 °C to a solution of LDA (10.46 g, 97.6 mmol) in 250 mL of THF. This mixture was then heated to 60 °C for 3.5 hours, after which it was cooled back to 0 °C. Allyl bromide (2.9 mL, 33.5 mmol) was added by syringe, and the mixture was stirred at r.t. overnight. Aqueous 1 M HCl (200 mL) was added, and most of the THF was removed by rotary evaporation. The aqueous layer was then extracted with 3 X 100 mL of ether, which was dried over $MgSO_4$ and evaporated leaving a brown oil (*C*-allylated hydroxy acid). This crude oil was dissolved in 100 mL of CH_2Cl_2 in a flask containing DMAP (20 mg, 0.16 mmol) and a stir bar. The solution was cooled to 0 °C, and a solution of DCC (6.50 g, 31.5 mmol) in 50 mL of CH_2Cl_2 was added by cannula. The ice bath was removed, and the mixture was stirred at r.t. overnight.

The mixture was filtered to remove the precipitated urea, and the precipitate was rinsed with hexane. The filtrate was concentrated by rotary evaporation, leaving an orange oil. This material was purified by flash chromatography using 2% Et_2O/pentane → 10% Et_2O/pentane, resulting in 4.9 g of orange oil which was shown by NMR to still contain DCC. The oil was dissolved in 15 mL of CH_2Cl_2 and treated with 1 mL of acetic acid, 0.2 mL of methanol, and a few mg's of DMAP to destroy the DCC. After stirring overnight, there was a small amount of precipitate. This was filtered away, and the filtrate was concentrated. It was then purified by

flash chromatography as above to give 4.57 g (81%, based on 2-hydroxyphenylacetic acid) of product as a pale, yellow oil.

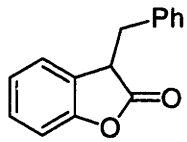
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.30 (t, 1H, J=7.5), 7.30 (d, 1H, J=7.0), 7.14 (t, 1H, J=7.5), 7.10 (d, 1H, J=8.0), 5.7-5.8 (m, 1H), 5.1-5.2 (m, 2H), 3.79 (t, 1H, J=6.5), 2.8-2.9 (m, 1H), 2.6-2.7 (m, 1H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 176.5, 153.8, 132.8, 128.9, 127.0, 124.5, 124.1, 119.1, 110.7, 43.2, 35.3. FTIR (KBr) 3079, 2982, 2914, 1807, 1619, 1479, 1463, 1231, 1126, 1060 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{11}H_{10}O_2$ (M^+) 174.0681, found 174.0681.



Carbonic acid methyl ester 3-allyl-benzofuran-2-yl ester. 3-Allyl-3*H*-benzofuran-2-one (935 mg, 5.37 mmol) was dissolved in 30 mL of THF, and the solution was cooled to 0 °C. Triethylamine (820 µL, 5.89 mmol) and methyl chloroformate (440 µL, 5.69 mmol) were added sequentially by syringe, resulting in a white precipitate. The mixture was kept at 0 °C overnight, after which the solvent was removed by rotary evaporation. The residue was then partitioned between 100 mL of ether and 100 mL of 1 M HCl. The ether was washed with an additional 100 mL of HCl, followed by 100 mL of saturated NaCl. It was then dried over $MgSO_4$ and removed by rotary evcaporation. The residue was purified by flash chromatography using 2% MTBE/pentane → 10% MTBE/pentane, resulting in 1.07 g (86%) of product as a clear, colorless oil.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.47-7.50 (m, 1H), 7.38-7.41 (m, 1H), 7.20-7.30 (m, 2H), 5.89-6.02 (m, 1H), 5.17 (dq, 1H, J=17.1, 1.8), 5.10 (dq, 1H, J=9.9, 1.5), 3.96 (s, 3H), 3.35 (dt, 2H, J=6.0, 1.5). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 152.4, 149.7, 149.7, 134.4, 128.7, 124.2, 123.1, 120.0, 116.5, 111.2, 100.7, 56.4, 26.7. FTIR (KBr) 3063, 2960, 1785, 1659, 1455, 1219,

1176, 1131, 926, 744 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{13}H_{12}O_4$ (M^+) 232.0736, found 232.0736.

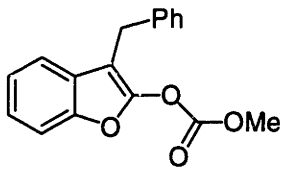


3-Benzyl-3*H*-benzofuran-2-one. A solution of 2-hydroxyphenylacetic acid (4.19 g, 27.5 mmol) in 60 mL of THF was added by cannula at 0 °C to a solution of LDA (8.86 g, 82.7 mmol) in 250 mL of THF. This mixture was then heated to 65 °C for 3 hours, after which it was cooled back to 0 °C. Benzyl bromide (3.4 mL, 28.6 mmol) was added by syringe, and the mixture was stirred at r.t. overnight. Aqueous 1 M HCl (200 mL) was added, and most of the THF was removed by rotary evaporation. The product was then extracted into 3 X 100 mL of ether, which was dried over $MgSO_4$ and evaporated leaving a brown oil (*C*-benzylated hydroxy acid). This crude oil was dissolved in 100 mL of CH_2Cl_2 in a flask containing DMAP (20 mg, 0.16 mmol) and a stir bar. The solution was cooled to 0 °C, and a solution of DCC (5.67 g, 27.5 mmol) in 30 mL of CH_2Cl_2 was added by cannula. The ice bath was removed, and the mixture was stirred at r.t. overnight.

Acetic acid (2 mL) and methanol (0.4 mL) were added to decompose leftover DCC, and the mixture was stirred for an additional 8 hours, after which it was filtered to remove the urea. The filtrate was concentrated to an orange oil which was purified by flash chromatography using pentane → 10% MTBE/pentane, resulting in 4.04 g (66%) of product as a pale yellow oil that solidified upon standing. Several later fractions of product were contaminated with a more polar impurity and were discarded.

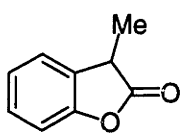
^1H NMR (500 MHz, $CDCl_3$) δ 7.22-7.30 (m, 4H), 7.15 (d, 2H, J=7.0), 7.02 (t, 2H, J=7.5), 6.79 (d, 1H, J=7.5), 4.00 (dd, 1H, J=9.0, 5.0), 3.49 (dd, 1H, J=13.5, 5.0), 3.02 (dd, 1H,

J=13.5, 9.0).[31] ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 176.5, 153.7, 129.4, 129.0, 128.6, 127.2, 126.8, 124.9, 123.9, 110.7, 45.0, 37.2. FTIR (KBr) 3062, 6029, 2925, 1804, 1619, 1478, 1231, 1126, 1061 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{15}H_{12}O_2$ (M^+) 224.0837, found 224.0838.



Carbonic acid methyl ester 3-benzyl-benzofuran-2-yl ester. The above procedure for carbonic acid methyl ester 3-allyl-benzofuran-2-yl ester was followed. Yield was 1.30 g (99%) of pale yellow oil from 1.05 g (4.67 mmol) of 3-benzyl-3*H*-benzofuran-2-one.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.11-7.42 (m, 9H), 3.95 (s, 2H), 3.92 (s, 3H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 152.4, 150.0, 149.8, 138.4, 128.7, 128.6, 126.5, 124.2, 123.1, 120.1, 111.2, 101.9, 56.4, 28.5. FTIR (KBr) 3028, 2959, 2911, 1783, 1658, 1454, 1240, 1126, 926, 746 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{17}H_{14}O_4$ (M^+) 282.0892, found 282.0892.



3-Methyl-3*H*-benzofuran-2-one. The procedure used above for the benzyl compound was used with methyl iodide instead of benzyl bromide. Yield was 3.00 g (65%) of a pale yellow oil from 4.76 g (31.3 mmol) of 2-hydroxyphenylacetic acid.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.30 (t, 1H, J=8.5), 7.26 (d, 1H, J=7.0), 7.15 (t, 1H, J=7.5), 7.10 (d, 1H, J=7.5), 3.73 (q, 1H, J=8.0), 1.58 (d, 3H, J=7.5).[32] ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 177.9, 153.5, 128.8, 128.8, 124.2, 124.0, 110.6, 38.3, 15.9. FTIR (KBr) 3056, 2980, 2937,

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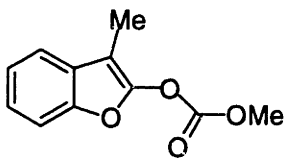
31 The ^{1}H NMR and FTIR data match those previously reported: Yoneda, E.; Sugioka, T.; Hirao, K.; Zhang, S.-W.; Takahashi, S. *J. Chem. Soc., Perkin Trans. 1* **1998**, *3*, 477-484.

32 The 1H NMR data match those previously reported: Rewcastle, G. W.; Atwell, G. J.; Baguley, B. C.; Boyd, M.; Thomsen, L. L.; Zhuang, L.; Denny, W. A. *J. Med. Chem.* **1991**, *34*, 2864-2870.

1806, 1619, 1479, 1232, 1132, 1033, 880 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_9H_{18}O_2$ (M^+) 148.0524, found 148.0524.



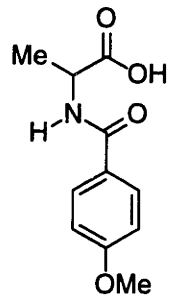
Carbonic acid methyl ester 3-methyl-benzofuran-2-yl ester. The above procedure for carbonic acid methyl ester 3-allyl-benzofuran-2-yl ester was followed. Yield was 1.41 g (94%) of pale yellow oil from 1.07 g (7.25 mmol) of 3-methyl-3*H*-benzofuran-2-one.

^1H NMR (300 MHz, $CDCl_3$) δ 7.21-7.48 (m, 4H), 3.97 (s, 3H), 2.13 (s, 3H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ 152.4, 149.6, 149.5, 129.5, 124.1, 123.0, 119.4, 111.0, 98.5, 56.3, 6.5. FTIR (KBr) 3039, 2960, 1785, 1668, 1456, 1240, 1180, 1132, 928, 743 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{11}H_{10}O_4$ (M^+) 206.0579, found 206.0579.

Synthesis of *N*-(*p*-Anisoyl) Amino Acids

General. We have found that the Schotten-Baumann procedure for *N*-acylation of amino acids (aqueous NaOH) is very unreliable with *p*-anisoyl chloride (*p*-anisic acid is often the major product). Although some of the compounds listed below were prepared by this method (early work), we recommend that the Schotten-Baumann procedure be avoided and that the *N*-acylations be performed in an organic solvent on the amino acid ester. Subsequent hydrolysis of the ester to the desired *N*-anisoyl amino acid is straightforward.

All yields are unoptimized.



***N*-Anisoylalanine.** CH_2Cl_2 (350 mL) and NEt_3 (30 mL, 220 mmol) were added to a flask containing (L)-alanine ethyl ester hydrochloride (14.4 g, 93.8 mmol). The resulting slurry was cooled to 0 °C, and *p*-anisoyl chloride (15.7 g, 92.0 mmol) in CH_2Cl_2 (25 mL) was added by cannula over ~15 minutes. After 75 minutes, the ice bath was removed, and the mixture was stirred at room temperature for 4 hours. The mixture was then washed with 1 M HCl (2 x 300 mL), saturated $NaHCO_3$ (2 x 300 mL), and saturated NaCl (300 mL). The CH_2Cl_2 layer was dried ($MgSO_4$), and the solvent was removed by rotary evaporation, providing the *N*-anisoyl-(L)-alanine ethyl ester as a white solid. This solid was dissolved in methanol (160 mL), and 2 M aqueous NaOH (49 mL) was added. The resulting mixture was stirred for 20 minutes, and then the methanol was removed by rotary evaporation. Water was added until the aqueous solution was homogeneous, and then the aqueous solution was washed with CH_2Cl_2 (2 x 200 mL). The aqueous layer was made acidic with 1 M HCl, which resulted in the formation of a white precipitate, which was filtered, washed with several portions of water, and dried with a flow of air through a filter (15.6 g, 74%; pure according to ^1H NMR).

^1H NMR (300 MHz, DMSO-d_6) δ 12.50 (br s, 1H), 8.51 (d, 1H, J=7.2), 7.88 (d, 2H, J=8.7), 7.00 (d, 2H, J=8.7), 4.41 (pent., 1H, J=7.2), 3.80 (s, 3H), 1.39 (d, 3H, J=7.2).[33] ^{13}C NMR (75 MHz, DMSO-d_6) δ 174.7, 166.0, 161.9, 129.5, 126.3, 113.6, 55.4, 48.4, 17.1. FTIR

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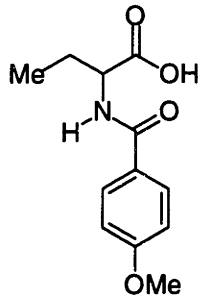
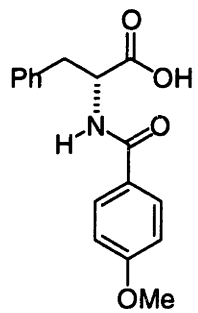
33 The ^1H NMR data match those previously been reported: Davies, J. S.; Hakeem, E. *J. Chem. Soc., Perkin Trans. 2* **1984**, 1387-1392.

(KBr) 3430, 2582, 1726, 1647, 1506 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{11}H_{13}NO_4$ (M^+) 223.0845, found 223.0844. mp 169-170 °C.



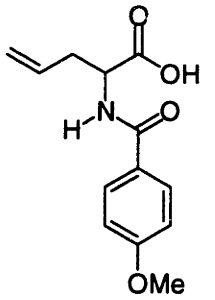
***N*-Anisoyl-2-aminobutyric acid.** (±)-2-Aminobutyric acid (12.8 g, 124 mmol) was added to a Schlenk tube that contained methanol (150 mL) and concentrated aqueous HCl (12.5 mL, 150 mmol). The Schlenk tube was closed, and the mixture was stirred for 25 hours in a 100 °C oil bath. The contents of the Schlenk tube were transferred to a flask, and the solvent was removed by rotary evaporation, providing the 2-aminobutyric acid methyl ester hydrochloride as a white solid. To this flask was added CH_2Cl_2 (250 mL) and NEt_3 (40 mL, 290 mmol). The resulting slurry was cooled to 0 °C, and *p*-anisoyl chloride (21.0 g, 123 mmol) in CH_2Cl_2 (20 mL) was added by cannula over ~15 minutes. The mixture was allowed to warm to room temperature and stirred overnight. It was then washed with 1 M HCl (2 x 250 mL), saturated $NaHCO_3$ (2 x 250 mL), and saturated NaCl (250 mL). The organic layer was dried ($MgSO_4$), and the solvent was removed by rotary evaporation, thereby providing the *N*-anisoyl-2-aminobutyric acid methyl ester as a pale yellow oil. This material was dissolved in methanol (200 mL), and 2 M aqueous NaOH (55 mL) was added. The mixture was stirred for 20 minutes, after which the methanol was removed by rotary evaporation. Water was added, and the resulting homogeneous solution was washed with CH_2Cl_2 (2 x 100 mL). The aqueous layer was then made acidic with 1 M HCl. The resulting white precipitate was collected by filtration, washed with water (500 mL), and recrystallized from 800 mL of boiling water, thereby providing the desired product (15.9 g, 54%).

^{1}H NMR (500 MHz, DMSO-d_6) δ 12.53 (br s, 1H), 8.41 (d, 1H, J=8.0), 7.89 (d, 2H, J=9.0), 7.00 (d, 2H, J=9.0), 4.25-4.31 (m, 1H), 3.81 (s, 3H), 1.72-1.90 (m, 2H), 0.95 (t, 3H, J=7.5). ^{13}C NMR (75 MHz, DMSO-d_6) δ 173.8, 166.2, 161.7, 129.4, 126.4, 113.4, 55.3, 54.2, 24.1, 10.8. FTIR (KBr) 3431, 2555, 1723, 1649, 1606 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{12}H_{15}NO_4$ (M^+) 237.1001, found 237.1001. mp 149-150 °C.



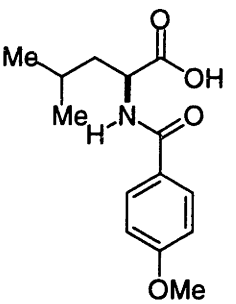
***N*-Anisoyl-(D)-phenylalanine.** (D)-Phenylalanine (27.0 g, 163 mmol) and NaOH (6.6 g, 170 mmol) were dissolved in water (50 mL). Ether (250 mL) was added, and the flask was cooled to 0 °C with rapid stirring. *p*-Anisoyl chloride (28.0 g, 164 mmol) and a solution of NaOH (6.6 g, 170 mmol) in 20 mL of water were added alternately, in portions, over 90 minutes. The mixture was allowed to warm to room temperature overnight. The ether was removed by rotary evaporation, and concentrated HCl (14 mL) was added. The resulting white precipitate was collected by filtration and recrystallized from hot acetone (400 mL), providing the product as white crystals (39.4 g, 81%).

^{1}H NMR (500 MHz, DMSO-d_6) δ 12.76 (br s, 1H), 8.57 (d, 1H, J=8.5), 7.81 (d, 2H, J=9.0), 7.32 (d, 2H, J=7.5), 7.26 (t, 2H, J=7.5), 7.17 (t, 1H, J=7.5), 6.98 (d, 2H, J=9.0), 4.59-4.64 (m, 1H), 3.79 (s, 3H), 3.19 (dd, 1H, J=14.0, 4.0), 3.08 (dd, 1H, J=14.0, 11.0). ^{13}C NMR (75 MHz, DMSO-d_6) δ 173.5, 166.1, 161.8, 138.4, 129.4, 129.2, 128.3, 126.4, 126.3, 113.5, 55.4, 54.4, 36.5. FTIR (KBr) 3425, 2564, 1721, 1648, 1606 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{17}H_{17}NO_4$ (M^+) 299.1158, found 299.1158. mp 171-172 °C.



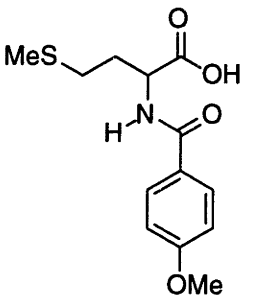
***N*-Anisoyl-2-amino-4-pentenoic acid.** (±)-2-Amino-4-pentenoic acid (4.95 g, 43.0 mmol) and NaOH (1.75 g, 43.8 mmol) were dissolved in water (15 mL). Ether (200 mL) was added, and the flask was cooled to 0 °C with rapid stirring. *p*-Anisoyl chloride (7.36 g, 43.1 mmol) and a solution of NaOH (1.75 g, 43.8 mmol) in 15 mL of water were added alternately, in portions, over 60 minutes. After the additions were complete, the mixture was allowed to warm to room temperature and was stirred overnight. The ether was then removed by rotary evaporation, and concentrated HCl (4 mL) was added. The resulting white precipitate was collected by filtration and recrystallized from hot acetone, which provided the product as white crystals (2.80 g, 26%).

^{1}H NMR (500 MHz, DMSO-d_6) δ 12.52 (br s, 1H), 8.46 (d, 1H, J=8.0), 7.87 (d, 2H, J=9.0), 7.00 (d, 2H, J=9.0), 5.78-5.86 (m, 1H), 5.14 (dd, 1H, J=17.0, 1.5), 5.03 (d, 1H, J=10.0), 4.41-4.47 (m, 1H), 3.80 (s, 3H), 2.49-2.62 (m, 2H). ^{13}C NMR (75 MHz, DMSO-d_6) δ 173.4, 165.9, 161.8, 134.7, 129.4, 126.3, 117.4, 113.5, 55.4, 52.4, 35.1. FTIR (KBr) 3438, 2588, 1724, 1648, 1606, 1507 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{13}H_{15}NO_4$ (M^+) 249.1001, found 249.1001. mp 124-125 °C.



***N*-Anisoyl-(L)-leucine.** (L)-Leucine (20.0 g, 153 mmol) and NaOH (6.2 g, 160 mmol) were dissolved in water (50 mL). Ether (250 mL) was added, and the flask was cooled to 0 °C with rapid stirring. *p*-Anisoyl chloride (26.1 g, 153 mmol) and a solution of NaOH (6.2 g, 160 mmol) in 20 mL of water were added alternately, in portions, over 90 minutes. The mixture was allowed to warm to room temperature overnight. The ether was removed by rotary evaporation, and concentrated HCl (13 mL) was added. The resulting white precipitate was collected by filtration and recrystallized from boiling water (~1 L), providing the product as white crystals (9.73 g, 24%).

^{1}H NMR (300 MHz, DMSO-d_6) δ 12.53 (br s, 1H), 8.43 (d, 1H, J=8.1), 7.88 (d, 2H, J=8.7), 7.00 (d, 2H, J=8.7), 4.38-4.50 (m, 1H), 3.80 (s, 3H), 1.52-1.83 (m, 3H), 0.91 (d, 3H, J=6.3), 0.87 (d, 3H, J=6.0). ^{13}C NMR (75 MHz, DMSO-d_6) δ 174.5, 166.1, 161.8, 129.4, 126.3, 113.5, 55.4, 50.9, 39.6, 24.6, 23.0, 21.2. FTIR (KBr) 3422, 2567, 1719, 1648, 1606 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{14}H_{19}NO_4$ (M^+) 265.1314, found 265.1314. mp 151-152 °C (lit. 172-174 °C).[34]



***N*-Anisoylmethionine.** CH_2Cl_2 (300 mL) and NEt_3 (22 mL, 160 mmol) were added to a flask containing (L)-methionine methyl ester hydrochloride (15.1 g, 75.5 mmol). The resulting slurry was cooled to 0 °C, and *p*-anisoyl chloride (13.1 g, 76.5 mmol) in CH_2Cl_2 (25 mL) was added by cannula over 28 minutes. After 10 minutes, the ice bath was removed, and the mixture was stirred at room temperature for 3

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34 Leone-Bay, A.; McInnes, C.; Wang, N.; DeMorin, F.; Achan, D.; Lercara, C.; Sarubbi, D.; Haas, S.; Press, J.; Barantsevich, E.; O'Broin, B.; Milstein, S.; Paton, D. *J. Med. Chem.* **1995**, *38*, 4257-4262.

hours. The mixture was then washed with 1 M HCl (2 x 200 mL), saturated $NaHCO_3$ (2 x 200 mL), and saturated NaCl (200 mL). The CH_2Cl_2 solution was dried ($MgSO_4$), and the CH_2Cl_2 was removed by rotary evaporation, leaving the *N*-anisoyl-(L)-methionine methyl ester as a white solid. This solid was dissolved in methanol (140 mL), and 2 M aqueous NaOH (44 mL) was added. This mixture was stirred for 15 minutes, and then the methanol was removed by rotary evaporation. Water was added, and the resulting homogeneous solution was washed with CH_2Cl_2 (2 x 200 mL). The aqueous layer was then made acidic with 1 M HCl (100 mL). The resulting white precipitate was collected by filtration, washed with several portions of water, and recrystallized from hot acetone/water, which provided the product as a white solid (18.8 g, 88%).

^1H NMR (500 MHz, DMSO-d_6) δ 12.63 (br s, 1H), 8.48 (d, 1H, J=7.5), 7.87 (d, 2H, J=9.0), 7.00 (d, 2H, J=9.0), 4.50 (q, 1H, J=8.0), 3.81 (s, 3H), 2.49-2.62 (m, 2H), 2.02-2.08 (m, 2H), 2.05 (s, 3H). ^{13}C NMR (75 MHz, DMSO-d_6) δ 173.7, 166.2, 161.8, 129.4, 126.2, 113.5, 55.4, 51.7, 30.4, 30.2, 14.6. FTIR (KBr) 3425, 2516, 1704, 1629, 1505 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{13}H_{17}NO_4S$ (M^+) 283.0878, found 283.0879. mp 122-123 °C.

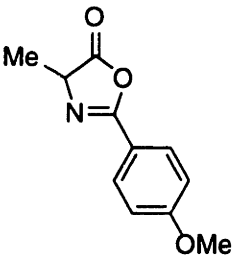
Synthesis of Azlactones

General. We had initially planned to synthesize all of the azlactones using the method of Benoiton, wherein the *N*-acylamino acid is converted to the mixed anhydride by treatment with methyl chloroformate and *N*-methylmorpholine in CH_2Cl_2.[35] Under the reaction conditions, the mixed anhydride quickly cyclizes to the desired azlactone. After a series of aqueous washes, the product is obtained in virtually quantitative yield and in very high purity. Unfortunately, we found that azlactones prepared in this way are sometimes contaminated with a very small amount of the *O*-acylated product from the reaction of the desired azlactone with

35 Chen, F. M. F.; Slebioda, M.; Benoiton, N. L. *Int. J. Peptide Protein Res.* **1988**, *31*, 339-344.

methyl chloroformate. If the ultimate desired product (after *O*-acylation) is the methyl carbonate, this poses no problem. However, if the ultimate desired product is the benzyl carbonate, we have found that it can be very difficult to separate the benzyl and methyl carbonates. Therefore, we recommend that DCC be used for the cyclization.

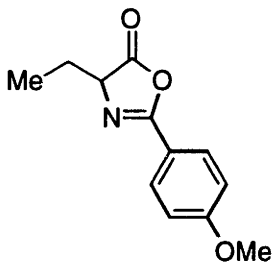
All yields are unoptimized.



2-(4-Methoxyphenyl)-4-methyloxazalone. A solution of DCC (9.28 g, 45.0 mmol) in CH_2Cl_2 (40 mL) was added by cannula to a 0 °C slurry of *N*-anisoylalanine (10.0 g, 45.0 mmol) in CH_2Cl_2 (250 mL). The resulting slurry was allowed to warm to room temperature overnight. The white precipitate (dicyclohexylurea) was then removed by filtration, and the CH_2Cl_2 solution was washed with saturated $NaHCO_3$ (2 x 200 mL), followed by saturated NaCl (200 mL). The CH_2Cl_2 layer was dried ($MgSO_4$), and the CH_2Cl_2 was removed by rotary evaporation. The resulting white solid was dissolved in a minimum amount of CH_2Cl_2, and the solution was passed through an Acrodisc filter, diluted 3 to 1 with pentane, and placed in a -35 °C freezer to crystallize. After 24 hours, the resulting white crystals were collected by filtration, washed with cold pentane, and dried under vacuum (7.09 g, 77%).

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.93 (d, 2H, J=9.0), 6.98 (d, 2H, J=9.0), 4.43 (q, 1H, J=7.5), 3.88 (s, 3H), 1.58 (d, 3H, J=7.5). ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.2, 163.3, 161.3, 129.8, 118.4, 114.3, 61.0, 55.5, 17.1. FTIR (KBr) 2990, 2842, 1811, 1654, 1609, 1512, 1317,

1258, 1111, 997 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{11}H_{11}NO_3$ (M^+) 205.0739, found 205.0739. mp 95-96 °C (lit. 95-97 °C).[36]



2-(4-Methoxyphenyl)-4-ethyloxazalone. A solution of DCC (5.39 g, 26.1 mmol) in CH_2Cl_2 (40 mL) was added by cannula to a 0 °C slurry of *N*-anisoyl-2-aminobutryic acid (6.22 g, 26.2 mmol) in CH_2Cl_2 (200 mL). The resulting slurry was allowed to warm to room temperature overnight. The white precipitate (dicyclohexylurea) was then removed by filtration, and the CH_2Cl_2 solution was washed with $NaHCO_3$ (2 x 200 mL), followed by saturated NaCl (200 mL). The CH_2Cl_2 layer was dried ($MgSO_4$), and the CH_2Cl_2 was removed by rotary evaporation. The resulting white solid was dissolved in a minimum amount of CH_2Cl_2, and the solution was passed through an Acrodisc filter, diluted 3 to 1 with pentane, and placed in a -35 °C freezer to crystallize. After 24 hours, the resulting white crystals were collected by filtration, washed with cold pentane, and dried under vacuum (4.06 g, 71%).

^1H NMR (500 MHz, $CDCl_3$) δ 7.95 (d, 2H, J=9.0), 6.98 (d, 2H, J=9.0), 4.37 (t, 1H, J=6.0), 3.88 (s, 3H), 2.02-2.11 (m, 1H), 1.89-1.98 (m, 1H), 1.04 (t, 3H, J=7.5). ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.6, 163.2, 161.4, 129.8, 118.4, 114.3, 66.4, 55.5, 25.1, 9.6. FTIR (KBr) 2969, 1817, 1654, 1609, 1514, 1325, 1264, 1117, 1025, 882 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{12}H_{13}NO_3$ (M^+) 219.0895, found 219.0896. mp 69-70 °C.

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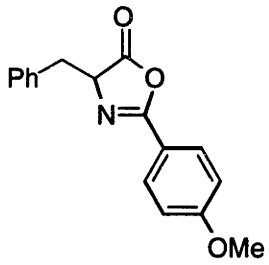
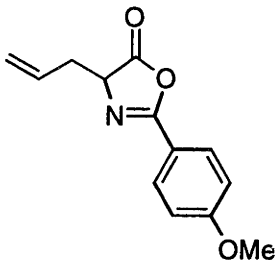
36 The ^1H NMR and FTIR also agree with those previously reported: Marquez, A.; Chuaqui, C.A.; Rodriguez, H.; Zagal, L. *Tetrahedron* **1985**, *41*, 2341-2346.



2-(4-Methoxyphenyl)-4-benzyloxazalone. A solution of DCC (7.73 g, 37.5 mmol) in CH_2Cl_2 (45 mL) was added by cannula to a 0 °C slurry of *N*-anisoyl-(D)-phenylalanine (11.2 g, 37.5 mmol) in CH_2Cl_2 (200 mL). The resulting slurry was allowed to warm to room temperature overnight. The white precipitate (dicyclohexylurea) was then removed by filtration, and the CH_2Cl_2 was removed by rotary evaporation. The resulting white solid was dissolved in a minimum amount of CH_2Cl_2, and the solution was passed through an Acrodisc filter, diluted 4 to 1 with pentane, and placed in a -35 °C freezer to crystallize. After 24 hours, the resulting white crystals were collected by filtration, washed with cold pentane, and dried under vacuum (7.09 g, 67%).

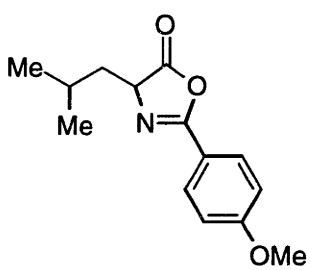
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.88 (d, 2H, J=9.0), 7.18-7.30 (m, 5H), 6.95 (d, 2H, J=9.0), 4.68 (dd,1H, J=6.5, 5.0), 3.87 (s, 3H), 3.37 (dd, 1H, J=14.0, 5.0), 3.19 (dd, 1H, J=14.0, 7.0). ^{13}C NMR (75 MHz, $CDCl_3$) δ 177.9, 163.2, 161.4, 135.6, 129.8, 129.7, 128.4, 127.2, 118.2, 114.2, 66.5, 55.5, 37.5. FTIR (KBr) 3026, 2929, 2840, 1797, 1649, 1608, 1512, 1304, 1261, 1047 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{17}H_{15}NO_3$ (M^+) 281.1052, found 281.1052. mp 114-115 °C.



2-(4-Methoxyphenyl)-4-allyloxazalone. *N*-Methylmorpholine (1.10 mL, 10.0 mmol) and methyl chloroformate (0.73 mL, 9.5 mmol) were added successively by

syringe to *N*-anisoyl-2-amino-4-pentenoic acid (2.47 g, 9.92 mmol) in CH_2Cl_2 (90 mL). After 20 minutes, the solution was washed with 5% citric acid (100 mL), water (100 mL), and saturated $NaHCO_3$ (100 mL). The CH_2Cl_2 solution was dried ($MgSO_4$), and the CH_2Cl_2 was removed by rotary evaporation, yielding a pale yellow solid (2.16 g, 99%), which was used without further purification (>95% purity, according to ^1H NMR).

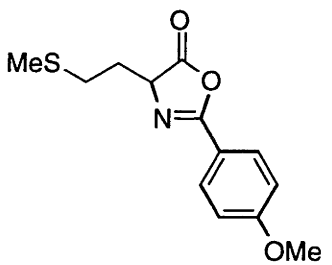
^1H NMR (300 MHz, $CDCl_3$) δ 7.94 (d, 2H, J=9.0), 6.97 (d, 2H, J=9.0), 5.73-5.87 (m, 1H), 5.24 (dq, 1H, J=17.1, 1.5), 5.13-5.19 (m, 1H), 4.47 (dd, 1H, J=6.3, 5.7), 3.88 (s, 3H), 2.75-2.85 (m, 1H), 2.57-2.68 (m, 1H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.1, 163.3, 161.6, 131.8, 129.9, 119.7, 118.3, 114.3, 65.4, 55.6, 35.6. FTIR (KBr) 3080, 2936, 2840, 1820, 1651, 1609, 1513, 1259, 1043, 889 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{13}H_{13}NO_3$ (M^+) 231.0895, found 231.0896. mp 52-53 °C.



2-(4-Methoxyphenyl)-4-isobutyloxazalone. A solution of DCC (2.49 g, 12.1 mmol) in CH_2Cl_2 (25 mL) was added by cannula to a 0 °C slurry of *N*-anisoyl-(L)-leucine (3.21 g, 12.1 mmol) in CH_2Cl_2 (150 mL). The resulting slurry was allowed to warm to room temperature overnight. The white precipitate (dicyclohexylurea) was then removed by filtration, and the CH_2Cl_2 solution was washed with $NaHCO_3$ (2 x 150 mL), followed by saturated NaCl (150 mL). The CH_2Cl_2 layer was dried ($MgSO_4$), and the CH_2Cl_2 was removed by rotary evaporation. The resulting white solid was dissolved in a minimum amount of CH_2Cl_2, and the solution was passed through an Acrodisc filter, diluted 4 to 1 with pentane, and placed in a -35 °C freezer to

crystallize. After 2 days, the resulting fluffy white solid was collected by filtration, washed with cold pentane, and dried under vacuum (1.14 g, 38%).

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.94 (d, 2H, J=9.0), 6.97 (d, 2H, J=9.0), 4.39 (dd, 1H, J=9.0, 6.0), 3.88 (s, 3H), 2.00-2.11 (m, 1H), 1.79-1.85 (m, 1H), 1.64-1.70 (m, 1H), 1.03 (d, 3H, J=6.0), 1.00 (d, 3H, J=7.0). ^{13}C NMR (75 MHz, $CDCl_3$) δ 179.4, 163.2, 161.2, 129.8, 118.5, 114.2, 63.9, 55.6, 41.0, 25.3, 22.9, 22.2. FTIR (KBr) 2960, 1815, 1796, 1652, 1609, 1514, 1307, 1260, 1042, 905 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{14}H_{17}NO_3$ (M^+) 247.1208, found 247.1209. mp 66-67 °C.



2-(4-Methoxyphenyl)-4-(2-methylthio)ethyloxazalone. A solution of DCC (5.02 g, 24.3 mmol) in CH_2Cl_2 (45 mL) was added by cannula to a 0 °C slurry of *N*-anisoylmethionine (6.90 g, 24.4 mmol) in CH_2Cl_2 (200 mL). The resulting slurry was allowed to warm to room temperature overnight. The white precipitate (dicyclohexylurea) was then removed by filtration, and the CH_2Cl_2 solution was washed with $NaHCO_3$ (2 x 250 mL), followed by saturated NaCl (250 mL). The CH_2Cl_2 layer was dried ($MgSO_4$), and the CH_2Cl_2 was removed by rotary evaporation. The residue was dissolved in a minimum amount of CH_2Cl_2, and the solution was passed through an Acrodisc filter, diluted 3 to 1 with pentane, and placed in a -35 °C freezer to crystallize. After 24 hours, the resulting fluffy white solid was collected by filtration, washed with cold pentane, and dried under vacuum (4.88 g, 76%).

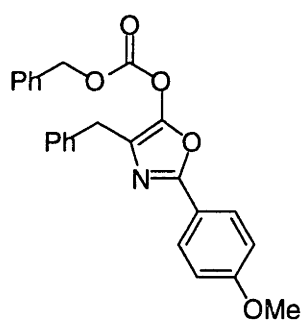
^{1}H NMR (300 MHz, $CDCl_3$) δ 7.94 (d, 2H, J=9.0), 6.98 (d, 2H, J=9.0), 4.57 (t, 1H, J=6.6), 3.88 (s, 3H), 2.73 (t, 2H, J=7.2), 2.23-2.36 (m, 1H), 2.06-2.20 (m, 1H), 2.12 (s, 3H).

^{13}C NMR (75 MHz, $CDCl_3$) δ 178.6, 163.3, 161.7, 129.8, 118.3, 114.3, 63.7, 55.5, 30.7, 30.1, 15.2. FTIR (KBr) 2917, 2839, 1815, 1651, 1609, 1513, 1324, 1258, 1172, 1023 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{13}H_{15}NO_3S$ (M^+) 265.0773, found 265.0772. mp 62-63 °C.

O-Acylation of Azlactones

General. Our procedure closely follows that reported by Steglich and Höfle.[1] The procedure given below for the *O*-acylation of 2-(4-methoxyphenyl)-4-benzyloxazalone with benzyl chloroformate is representative. The *O*-acylation should be followed by TLC to make certain that all of the azlactone is consumed. In each case, DMAP was added to the ^1H NMR sample of the product to ensure that a rearrangement would take place.

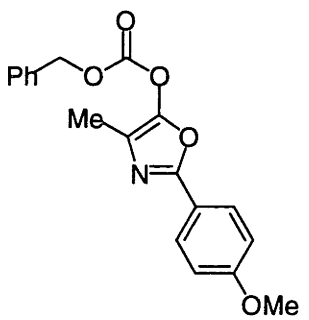
All yields are unoptimized.



5-Benzyloxycarbonyloxy-4-benzyl-2-(4-methoxyphenyl)-oxazole (3.23). NEt_3 (1.15 mL, 8.27 mmol) was added by syringe to a 0 °C solution of 2-(4-methoxyphenyl)-4-benzyloxazalone (2.10 g, 7.47 mmol) in THF (150 mL). Benzyl chloroformate (1.12 mL, 7.85 mmol) was added by syringe, resulting in a white precipitate. The mixture was allowed to stir at 0 °C overnight. The THF was then removed by rotary evaporation, and the residue was partitioned between ether (150 mL) and 1 M HCl (150 mL). The ether layer was washed with 1 M HCl (150 mL), followed by saturated NaCl (150 mL). The organic layer was then dried ($MgSO_4$), and the solvent was removed by rotary evaporation. The residue was purified by flash chromatography

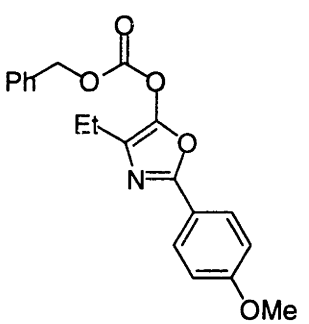
(10% TBME/90% pentane → 25% TBME/75% pentane), which afforded the desired product as a pale yellow oil (2.08 g, 67%).

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.87 (d, 2H, J=9.0), 7.15-7.45 (m, 10H), 6.92 (d, 2H, J=9.0), 5.21 (s, 2H), 3.84 (s, 2H), 3.84 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.5, 155.4, 151.6, 146.1, 137.7, 134.0, 129.2, 129.0, 128.9, 128.8, 128.5, 127.8, 126.6, 123.2, 120.0, 114.2, 71.8, 55.4, 31.7. FTIR (KBr) 3031, 2961, 1784, 1665, 1613, 1499, 1255, 1215, 1169, 1029 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{25}H_{21}NO_5$ (M^+) 415.1420, found 415.1420.



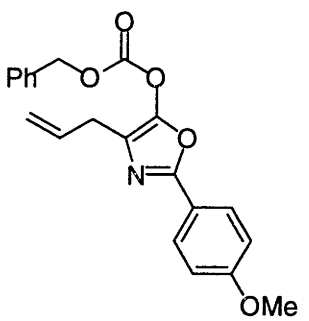
5-Benzyloxycarbonyloxy-4-methyl-2-(4-methoxyphenyl)-oxazole (3.28). The general procedure was followed, except that the product was purified by recrystallization from CH_2Cl_2/pentane after the flash chromatography. Yield of white needles: 35%.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.87 (d, 2H, J=9.0), 7.38-7.48 (m, 5H), 6.93 (d, 2H, J=9.0), 5.32 (s, 2H), 3.85 (s, 3H), 2.11 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.4, 155.1, 151.8, 145.8, 134.0, 129.3, 128.9, 128.8, 127.7, 120.2, 120.1, 114.3, 71.8, 55.5, 10.4. FTIR (KBr) 2988, 1775, 1676, 1615, 1499, 1253, 1217, 1172, 1030, 831 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{19}H_{17}NO_5$ (M^+) 339.1107, found 339.1107. mp 82-83 °C.



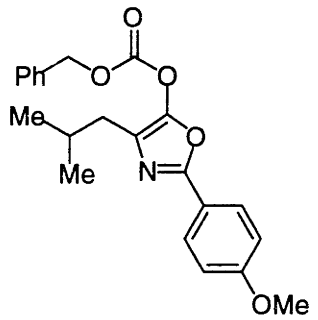
5-Benzyloxycarbonyloxy-4-ethyl-2-(4-methoxyphenyl)-oxazole. The general procedure was followed. Purification by flash chromatography (10% TBME/90% pentane → 25% TBME/75% pentane) provided a 63% yield of a colorless oil. (On one occasion, the product solidified into a crystalline solid with mp 36-37 °C).

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.88 (d, 2H, J=9.0), 7.3-7.5 (m, 5H), 6.93 (d, 2H, J=9.0), 5.32 (s, 2H), 3.85 (s, 3H), 2.49 (q, 2H, J=7.5), 1.22 (t, 3H, J=7.5). ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.4, 155.1, 152.0, 145.1, 134.1, 129.2, 128.9, 128.7, 127.7, 125.5, 120.2, 114.2, 71.8, 55.4, 18.6, 12.5. FTIR (KBr) 2972, 2939, 1784, 1614, 1500, 1255, 1224, 1204, 1172, 1030 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{20}H_{19}NO_5$ (M^+) 353.1263, found 353.1263.



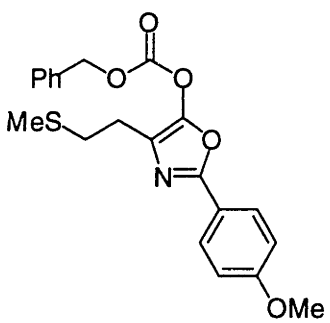
5-Benzyloxycarbonyloxy-4-allyl-2-(4-methoxyphenyl)-oxazole. The general procedure was followed. Purification by flash chromatography (5% TBME/95% pentane → 25% TBME/75% pentane) provided a 65% yield of a cream-colored solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.88 (d, 2H, J=9.0), 7.38-7.46 (m, 5H), 6.93 (d, 2H, J=9.0), 5.86-6.00 (m, 1H), 5.31 (s, 2H), 5.14 (dq, 1H, J=17.1, 1.5), 5.05 (dq, 1H, J=10.1, 1.5), 3.85 (s, 3H), 3.25 (dt, 2H, J=6.3, 1.5). ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.5, 155.3, 151.8, 145.9, 134.0, 133.6, 129.3, 128.9, 128.8, 127.8, 122.3, 120.0, 117.1, 114.2, 71.8, 55.4, 29.7. FTIR (KBr) 3072, 2963, 1785, 1664, 1614, 1500, 1255, 1217, 1171, 1029 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{21}H_{19}NO_5$ (M^+) 365.1263, found 365.1263. mp 50-51 °C.



5-Benzyloxycarbonyloxy-4-(2-methylpropyl)-2-(4-methoxyphenyl)-oxazole (3.14). The general procedure was followed. Purification by flash chromatography (5% TBME/95% pentane -→ 20% TBME/80% pentane) provided an 87% yield of a clear, colorless oil.

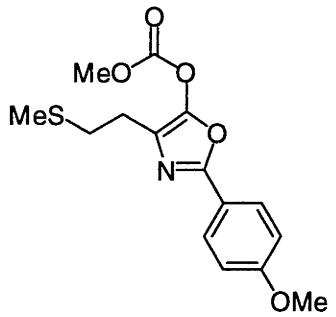
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.88 (d, 2H, J=9.0), 7.39-7.47 (m, 5H), 6.93 (d, 2H, J=9.0), 5.32 (s, 2H), 3.85 (s, 3H), 2.31 (d, 2H, J=7.0), 1.96-2.07 (m, 1H), 0.92 (d, 6H, J=6.5). ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.4, 155.1, 151.9, 146.2, 134.1, 129.2, 128.9, 128.8, 127.7, 123.6, 120.3, 114.3, 71.8, 55.4, 34.0, 27.7, 22.5. FTIR (KBr) 2957, 1785, 1665, 1614, 1500, 1255, 1219, 1172, 1030, 837 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{22}H_{23}NO_5$ (M^+) 381.1576, found 381.1578.



5-Benzyloxycarbonyloxy-4-((2-methylthio)ethyl)-2-(4-methoxyphenyl)-oxazole (3.29). The general procedure was followed. Purification by flash chromatography (10% TBME/90% pentane → 25% TBME/75% pentane) provided a 47% yield of a clear, colorless oil.

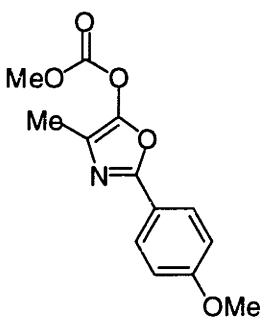
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.87 (d, 2H, J=9.0), 7.3-7.5 (m, 5H), 6.93 (d, 2H, J=9.0), 5.32 (s, 2H), 3.85 (s, 3H), 2.72-2.82 (m, 4H), 2.10 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ

161.5, 155.3, 151.7, 146.0, 134.0, 129.2, 128.9, 128.7, 127.7, 122.6, 120.0, 114.2, 71.8, 55.4, 32.4, 25.4, 15.5. FTIR (KBr) 2916, 1784, 1665, 1614, 1500, 1255, 1209, 1173, 1029, 837 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{21}H_{21}NO_5S$ (M^+) 399.1140, found 399.1140.



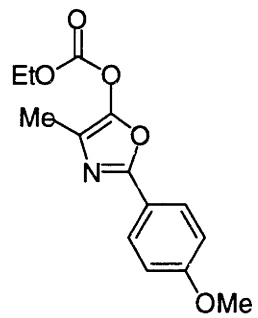
5-Methoxycarbonyloxy-4-((2-methylthio)ethyl)-2-(4-methoxyphenyl)-oxazole (3.27). The general procedure was followed. Purification by flash chromatography (5% TBME/95% pentane → 25% TBME/75% pentane) provided a 97% yield of a pale yellow oil.

^1H NMR (300 MHz, $CDCl_3$) δ 7.88 (d, 2H, J=9.0), 6.94 (d, 2H, J=9.0), 3.98 (s, 3H), 3.85 (s, 3H), 3.73-2.87 (m, 4H), 2.15 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.4, 155.3, 152.3, 145.9, 127.7, 122.5, 119.9, 114.2, 56.6, 55.4, 32.4, 25.3, 15.5. FTIR (KBr) 2959, 2917, 2838, 1789, 1668, 1614, 1500, 1441, 1229, 1028 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{15}H_{17}NO_5S$ (M^+) 323.0827, found 323.0828.



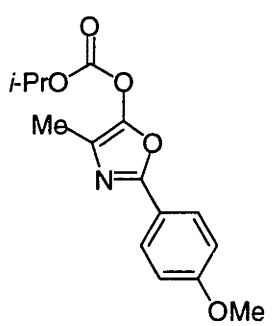
5-Methoxycarbonyloxy-4-methyl-2-(4-methoxyphenyl)-oxazole. The general procedure was followed. Purification by flash chromatography (10% TBME/90% pentane → 50% TBME/50% pentane) provided a 92% yield of a white solid.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.87 (d, 2H, J=9.0), 6.93 (d, 2H, J=9.0), 3.96 (s, 3H), 3.83 (s, 3H), 2.13 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.4, 155.0, 152.3, 145.7, 127.5, 120.0, 120.0, 114.2, 56.5, 55.3, 10.3. FTIR (KBr) 2960, 2839, 1789, 1675, 1614, 1500, 1253, 1220, 1173, 1029 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{13}H_{13}NO_5$ (M^+) 263.0794, found 263.0794. mp 60-61 °C.



5-Ethoxycarbonyloxy-4-methyl-2-(4-methoxyphenyl)-oxazole. The general procedure was followed. Purification by flash chromatography (5% TBME/95% pentane → 25% TBME/75% pentane) provided a 95% yield of a pale yellow oil.

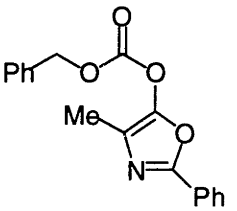
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.88 (d, 2H, J=9.0), 6.94 (d, 2H, J=9.0), 4.39 (q, 2H, J=7.0), 3.85 (s, 3H), 2.13 (s, 3H), 1.42 (t, 3H, J=7.0). ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.3, 154.8, 151.6, 145.7, 127.5, 120.0, 120.0, 114.1, 66.3, 55.2, 14.0, 10.2. FTIR (KBr) 2984, 2839, 1785, 1673, 1615, 1500, 1253, 1215, 1173, 1030 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{14}H_{15}NO_5$ (M^+) 277.0950, found 277.0950.



5-(2-Methyl)ethyloxycarbonyloxy-4-methyl-2-(4-methoxyphenyl)-oxazole. The general procedure was followed. Purification by flash chromatography (10%

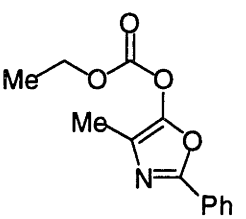
TBME/90% pentane → 25% TBME/75% pentane) provided a 94% yield of a white solid.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.88 (d, 2H, J=9.0), 6.94 (d, 2H, J=9.0), 5.02 (sept, 1H, J=6.0), 3.85 (s, 3H), 2.13 (s, 3H), 1.41 (s, 6H, J=6.0). ^{13}C NMR (75 MHz, $CDCl_3$) δ 161.4, 154.9, 151.1, 145.9, 127.6, 120.1, 120.0, 114.2, 75.1, 55.4, 21.6, 10.4. FTIR (KBr) 2985, 2839, 1782, 1672, 1614, 1499, 1253, 1216, 1173, 1101 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{15}H_{17}NO_5$ (M^+) 291.1107, found 291.1108. mp 66-67 °C.



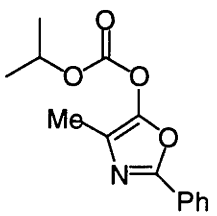
5-Benzyloxycarbonyloxy-4-methyl-2-phenyl-oxazole. The general procedure was followed for the *O*-acylation. Purification by flash chromatography (5% TBME/95% pentane → 10% TBME/90% pentane) afforded an 89% yield of a white solid.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.91-7.96 (m, 2H), 7.39-7.46 (m, 8H), 5.33 (s, 2H), 2.14 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 154.8, 151.6, 146.1, 133.9, 130.3, 129.1, 128.8, 128.7, 128.7, 127.2, 125.9, 120.5, 71.8, 10.4. FTIR (KBr) 3065, 3036, 2928, 1785, 1669, 1553, 1450, 1211, 1082, 1068 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{18}H_{15}NO_4$ (M^+) 309.1001, found 309.1000. mp 56-57 °C.



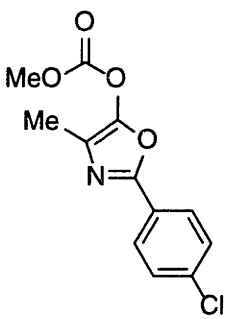
5-Ethoxycarbonyloxy-4-methyl-2-phenyl-oxazole. The general procedure was followed for the *O*-acylation. Purification by flash chromatography (pentane → 25% TBME/75% pentane) afforded an 56% yield of colorless oil.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.91-7.98 (m, 2H), 7.40-7.46 (m, 3H), 5.03 (sept., 1H, J=6.3), 2.15 (s, 3H), 1.42 (d, 6H, J=6.3). ^{13}C NMR (75 MHz, $CDCl_3$) δ 154.6, 150.9, 146.2, 130.2, 128.7, 127.2, 125.8, 120.3, 75.1, 21.5, 10.3. FTIR (KBr) 2985, 2931, 1782, 1670, 1554, 1251, 1219, 1101, 908, 774 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{14}H_{15}NO_4$ (M^+) 261.1001, found 261.1001.



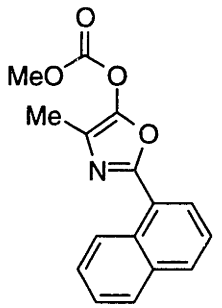
5-Isopropyloxycarbonyloxy-4-methyl-2-phenyl-oxazole. The general procedure was followed for the *O*-acylation. Purification by flash chromatography (pentane → 25% TBME/75% pentane) afforded an 87% yield of colorless oil.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.91-7.98 (m, 2H), 7.39-7.46 (m, 3H), 4.39 (q, 2H, J=7.2), 2.15 (s, 3H), 1.43 (t, 3H, J=7.2). ^{13}C NMR (75 MHz, $CDCl_3$) δ 154.7, 151.5, 146.1, 130.2, 128.7, 127.2, 125.8, 120.4, 66.3, 14.0, 10.3. FTIR (KBr) 2985, 2930, 1786, 1671, 1553, 1214, 1069, 774, 692 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{13}H_{13}NO_4$ (M^+) 247.0845, found 247.0845.



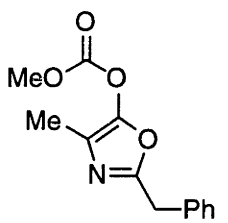
5-Methoxycarbonyloxy-4-methyl-2-(4-chlorophenyl)-oxazole. The general procedure was followed for the *O*-acylation. Purification by flash chromatography (10% TBME/90% pentane → 25% TBME/75% pentane) provided a 93% yield of a white solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.87 (d, 2H, J=8.4), 7.41 (d, 2H, J=8.4), 3.99 (s, 3H), 2.14 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 153.9, 152.2, 146.2, 136.5, 129.2, 127.2, 125.7, 120.8, 56.7, 10.4. FTIR (KBr) 2960, 2930, 1789, 1671, 1484, 1253, 1219, 1092, 925, 836 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{12}H_{10}ClNO_4$ (M^+) 267.0298, found 267.0301. mp 75-76 °C.



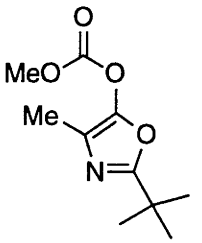
5-Methoxycarbonyloxy-4-methyl-2-(1-naphthyl)-oxazole. The general procedure was followed for the *O*-acylation. Purification by flash chromatography (5% TBME/95% pentane → 25% TBME/75% pentane) provided a 91% yield of a white solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ 9.18 (d, 1H, J=8.7), 8.09 (d, 1H, J=7.2), 7.93 (d, 1H, J=8.4), 7.89 (d, 1H, J=8.1), 7.63 (t, 1H, J=6.9), 7.54 (t, 1H, J=6.9), 7.51 (t, 1H, J=7.8), 4.00 (s, 3H), 2.24 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 154.9, 152.4, 146.2, 134.0, 131.2, 130.1, 128.6, 127.7, 127.7, 126.4, 126.1, 125.0, 123.6, 120.4, 56.7, 10.6. FTIR (KBr) 3053, 2959, 1788, 1673, 1440, 1252, 1221, 924, 774 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{16}H_{13}NO_4$ (M^+) 283.0845, found 283.0842. mp 73-74 °C.



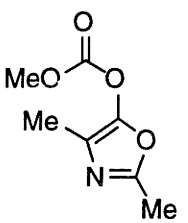
5-Methoxycarbonyloxy-4-methyl-2-benzyloxazole. The general procedure was followed for the *O*-acylation. Purification by flash chromatography (10% TBME/90% pentane → 50% TBME/50% pentane) provided a 62% yield of a pale yellow oil. This compound was not perfectly pure by ^{1}H NMR, but the impurity was not the rearranged material.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.22-7.36 (m, 5H), 4.00 (s, 2H), 3.93 (s, 3H), 2.04 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 156.3, 152.3, 146.0, 135.2, 128.8, 127.2, 118.9, 56.5, 35.0, 10.2. FTIR (neat) 3032, 2960, 1789, 1680, 1752, 1441, 1252, 1217, 925, 723 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{13}H_{13}NO_4$ (M^+) 247.0845, found 247.0840.



5-Methoxycarbonyloxy-4-methyl-2-*t*-butyloxazole. The general procedure was followed for the *O*-acylation. Purification by flash chromatography (10% TBME/90% pentane → 25% TBME/75% pentane) provided the desired product as a colorless oil.

^{1}H NMR (300 MHz, $CDCl_3$) δ 3.95 (s, 3H), 2.04 (s, 3H), 1.34 (s, 9H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 164.3, 152.4, 145.4, 118.0, 56.4, 33.8, 28.4, 10.2. FTIR (neat) 2974, 2932, 1790, 1683, 1565, 1442, 1255, 1223, 1175, 1117, 926 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{10}H_{15}NO_4$ (M^+) 213.1001, found 213.0998.



5-Methoxycarbonyloxy-4-methyl-2-methyloxazole. Due to the likely instability and volatility of the requisite azlactone, the general procedure was not used.[37] To a flask containing a solution of *N*-acetyl-dl-alanine (1.29 g, 9.84 mmol) and 4-methylmorpholine (2.3 mL, 21 mmol) in THF (50 mL) at 0 °C was added methyl chloroformate (1.6 mL, 21 mmol) dropwise by syringe, resulting in a white precipitate. After stirring for 35 minutes at 0 °C, the mixture was warmed to r.t. for 75 minutes, after which the precipitate was filtered away. The THF was then

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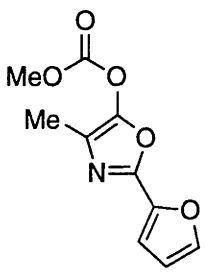
37 For a similar reaction, see: Murakami, M.; Iwanami, M. *Bull. Chem. Soc. Jpn.* **1968**, *41*, 726-727.

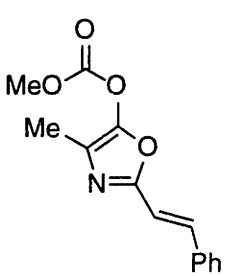
removed by rotary evaporation, and the residue was purified by flash chromatography (25% TBME/75% pentane → 50% TBME/50% pentane). Two spots were observed (use $KMnO_4$ to stain). The top spot (R_f=0.47 in 50% TBME/50% pentane) yielded 170 mg (10%) of the desired product as a colorless oil.

^1H NMR (300 MHz, $CDCl_3$) δ 3.95 (s, 3H), 2.37 (s, 3H), 2.03 (s, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 154.7, 152.4, 145.6, 118.6, 56.5, 14.2, 10.0. FTIR (neat) 2963, 2931, 1788, 1683, 1585, 1442, 1252, 1214, 925 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_7H_9NO_4$ (M^+) 171.0532, found 171.0530.



5-Methoxycarbonyloxy-4-methyl-2-(2-furyl)-oxazole. The general procedure was followed for the *O*-acylation. Purification by flash chromatography (10% TBME/90% pentane → 20% TBME/80% pentane) provided an 85% yield of a pale yellow oil.

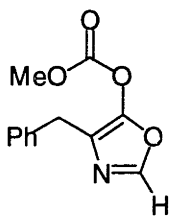
^1H NMR (300 MHz, $CDCl_3$) δ 7.53 (dd, 1H, J=2.1, 0.6), 6.94 (dd, 1H, J=3.3, 0.6), 6.52 (dd, 1H, J=3.3, 1.8), 3.98 (s, 3H), 2.14 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 151.9, 147.6, 145.4, 144.2, 142.2, 120.2, 111.6, 110.9, 56.4, 10.0. FTIR (neat) 3130, 2962, 2931, 1790, 1672, 1539, 1442, 1255, 1218, 1098 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{10}H_9NO_5$ (M^+) 223.0481, found 223.0482.



5-Methoxycarbonyloxy-4-methyl-2-(2-phenylethenyl)-oxazole. The general procedure was followed for the *O*-acylation. Purification by flash chromatography

(10% TBME/90% pentane → 50% TBME/50% pentane) provided a 75% yield of a white solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.28-7.52 (m, 6H), 6.78 (d, 1H, J=16.5), 3.98 (s, 3H), 2.11 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 154.8, 152.2, 145.6, 135.6, 135.4, 129.2, 128.9, 127.1, 120.6, 113.6, 56.5, 10.2. FTIR (KBr) 3027, 2960, 1785, 1668, 1529, 1441, 1255, 1227, 964, 924 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{14}H_{13}NO_4$ (M^+) 259.0845, found 259.0845. mp 74-75 °C.

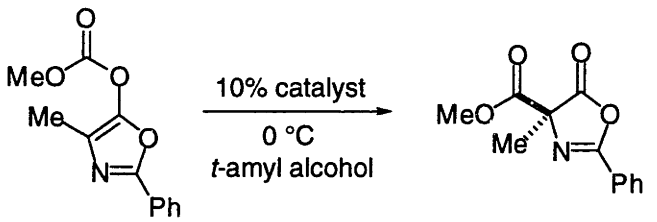


5-Methoxycarbonyloxy-4-benzyloxazole. The general procedure was followed for the *O*-acylation, but the starting azlactone was not pure. Purification of the product by flash chromatography (10% TBME/90% pentane → 50% TBME/50% pentane) provided a 45% yield of a colorless oil.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.57 (s, 1H), 7.19-7.34 (m, 5H), 3.88 (s, 3H), 3.81 (s, 2H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 151.9, 146.7, 144.9, 137.4, 128.9, 128.5, 126.6, 121.7, 56.5, 31.2. FTIR (neat) 3137, 3030, 2960, 1788, 1670, 1511, 1441, 1232, 1109, 924 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{12}H_{11}NO_4$ (M^+) 233.0688, found 233.0689.

Comparison of 3.13 and 1.31 (eq 3B.9)

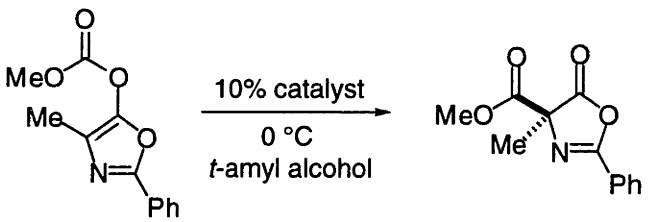
Note: We routinely transfer reagents in a glove box, for reasons of convenience (they are stored there, as a precautionary measure). It is important to note that neither **3.13** nor the *O*-acylated azlactones are unusually air- or moisture-sensitive (they are purified by chromatography in air).



Inside a glove box, the 5-methoxycarbonyloxy-4-methyl-2-phenyl-oxazole (23.3 mg, 0.100 mmol) was dissolved in 0.40 mL of *t*-amyl alcohol in a small vial containing a stir bar. Catalyst (-)-**3.13** (3.8 mg, 0.010 mmol) was dissolved in 0.60 mL of *t*-amyl alcohol in a separate small vial. Each vial was capped with a rubber septum and taken out of the glove box and placed into an ice bath. The catalyst solution was added by cannula to the substrate solution, resulting in a dark blue solution. When the pink color of the catalyst had returned, the mixture was filtered through a short plug of silica using EtOAc (the catalyst remains on the silica). The product was shown by GC (Chiraldex G-TA, 120 °C, 0.7 mL/min, retention times of enantiomers: 32.2 min (major), 35.0 min (minor)) to have an 81.7% ee.

When the above procedure was repeated using catalyst (-)-**1.31**, product having a 77.4% ee was isolated.

Comparison of 1.31 and 2.9

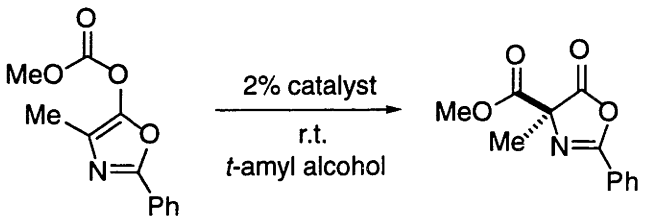


Inside a glove box, the 5-methoxycarbonyloxy-4-methyl-2-phenyl-oxazole (23.3 mg, 0.100 mmol) was dissolved in 0.40 mL of *t*-amyl alcohol in a small vial containing a stir bar. Catalyst (-)-**1.31** (3.5 mg, 0.010 mmol) was dissolved in 1.60 mL of *t*-amyl alcohol in a separate small vial. Each vial was capped with a rubber septum and taken out of the glove box and placed into an ice bath. The catalyst

solution was added by cannula to the substrate solution, resulting in a black solution. When the pink color of the catalyst had returned (6 hours), the mixture was filtered through a short plug of silica using 50% EtOAc/50% hexanes (the catalyst remains on the silica). The product was shown by GC (see previous section) to have a 77.5% ee.

When the above procedure was repeated using catalyst (-)-**2.9**, product having a 75.9% ee was isolated (gentle heating was needed to dissolve the catalyst before it was placed in the ice bath). The reaction turned red-brown upon mixing, and the purple color of the catalyst did not return for more than 22 hours.

Comparing the Rates of 1.31 and 3.13 as Catalysts



Inside a glove box, a solution of 5-methoxycarbonyloxy-4-methyl-2-phenyl-oxazole was made in *t*-amyl alcohol at a concentration of 58 mg/mL. Catalysts (-)-**1.31** (3.5 mg, 0.010 mmol) and (-)-**3.13** (3.8 mg, 0.010 mmol) were each dissolved in 2.0 mL of *t*-amyl alcohol in separate flasks equipped with stir bars. The substrate solution (2.0 mL, 0.50 mmol) was added by syringe to each of the catalyst solutions (a yellow-brown solution resulted for **1.31**, and a dark blue solution resulted for **3.13**). The flasks were removed from the glove box and stirred at room temperature. Aliquots were removed by syringe and filtered thru a plug of silica using EtOAc to remove the catalyst and stop the progress of the reaction. Solvent was removed on by rotary evaporation, and the percent conversion was determined by ^{1}H NMR.

(-)-**3.13**	
Time (min)	% Conversion
0	0
4.0	17.7
10.0	38.9
20.0	69.7

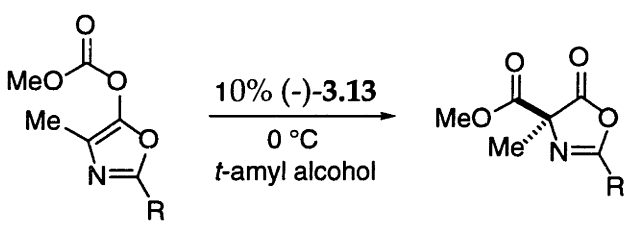
(-)-**1.31**	
Time (min)	% Conversion
0	0
4.5	5.5
10	10.3
20	18.0

A linear curve fit of the data followed by taking the ratio of the slopes suggests that (-)-**3.13** is 3.9 times faster that (-)-**1.31**.

After the reactions were complete (return of pink color), a final aliquot was worked up as above and analyzed by chiral GC to determine the ee of the product. (-)-**1.31** gave a 70.7% ee, and (-)-**3.13** gave a 74.7 % ee.

When this experiment was repeated using independently purified (-)-**3.13** and (+)-**1.31**, the relative rate was calculated to be 4.7.

Dependence of Enantioselectivity on the 2-Substituent (Table 3.2)



General procedure. Inside a glove box, the substrate (0.079 mmol-0.10 mmol) was added to a 4 mL vial containing a stir bar. *t*-Amyl alcohol (0.40 mL) was added, and the vial was capped with a rubber septum. Catalyst (-)-**3.13** (3.8 mg, 0.010 mmol) was dissolved in 0.60 mL of *t*-amyl alcohol in a separate vial. This vial was also capped with a rubber septum. Both vials were removed from the glove box and cooled in an ice bath. The pink catalyst solution was then added by cannula to the substrate

solution, resulting in a color change. This solution was stirred at 0 °C until the pink color of the catalyst had returned (In some cases, the pink color did not return in a reasonable amount of time, and the reaction was worked up anyway (vide infra); unfortunately, in many cases the starting material and the product co-elute on TLC). After the reaction was complete, the catalyst was removed by filtration through a 1" plug of silica using EtOAc as the eluant. The solvent was then removed by rotary evaporation, and the ee of the product was analyzed (In some cases, the product had to be further purified before the ee could be measured; vide infra).

R=Me. The reaction mixture turned yellow upon mixing, and it returned to pink. The product was shown by GC (Chiraldex G-TA, 150 °C, 0.7 mL/min, retention times of enantiomers: 1.25 min (major), 1.53 min (minor)) to have a 54.3% ee.

R=*t*-Bu. The reaction mixture turned yellow upon mixing. After 3 days, the mixture had turned brown and was worked up. The product had to be purified by flash chromatography to remove an impurity (probably starting material) before the ee could be measured. GC of the purified product (Chiraldex G-TA, 100 °C, 0.7 mL/min, retention times of enantiomers: 5.5 min (major), 6.4 min (minor)) showed a 42.2% ee.

R=Benzyl. The reaction mixture turned yellow upon mixing. It changed to dark brown, but ultimately to dark pink. A purple band at the top of the silica gel indicated some decomposition of catalyst. The product was shown by GC (Chiraldex G-TA, 120 °C, 0.7 mL/min, retention times of enantiomers: 19.6 min (major), 21.8 min (minor)) to have an 17.1% ee.

R=2-Furyl. The reaction mixture turned dark purple upon mixing, and it returned to pink after 5-17 hours. The product was shown by GC (Chiraldex G-TA, 120 °C, 0.7 mL/min, retention times of enantiomers: 20.7 min (major), 24.5 min (minor)) to have a 70.2% ee.

R=Ph: The reaction mixture turned dark blue upon mixing, and it returned to pink when the reaction was complete. The product was shown by GC (Chiraldex G-TA, 120 °C, 0.7 mL/min, retention times of enantiomers: 32.2 min (major), 35.0 min (minor)) to have an 81.7% ee.

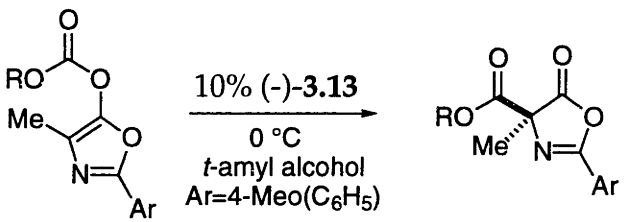
R=1-Naphthyl. The reaction mixture turned yellow-brown upon mixing, and it returned to pink when complete. The product was shown by HPLC (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 9.8 min (minor), 11.3 min (major)) to have an 81.4% ee.

R=4-Cl(C_6H_4). The reaction mixture turned dark blue (almost black) upon mixing, and it returned to pink when the reaction was complete. The product was shown by GC (Chiraldex G-TA, 150 °C, 0.7 mL/min, retention times of enantiomers: 14.9 min (major), 15.9 min (minor)) to have an 84.1% ee.

R=4-MeO(C_6H_4). The reaction mixture turned dark blue upon mixing, and it returned to pink when the reaction was complete. The product was shown by HPLC (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 7.2 min (minor), 9.8 min (major)) to have an 84.0% ee.

R=*trans*-Cinnamyl. The reaction mixture turned dark yellow upon mixing and had changed to brown after 2 days. The still brown mixture was worked up, despite the presence of unreacted starting material. The product had to be purified by flash chromatography to remove an impurity (in addition to the starting material) before the ee could be measured. GC of the purified product (Chiraldex G-TA, 150 °C, 0.7 mL/min, retention times of enantiomers: 38.4 min (major), 41.4 min (minor)) showed an 80.5% ee.

Dependence of Enantioselectivity on the Migrating Acyl Group (eq 3B.10)



General procedure. Inside a glove box, the substrate (0.10 mmol) was added to a 4 mL vial containing a stir bar. *t*-Amyl alcohol (1.4 mL) was added, and the vial was capped with a rubber septum. Catalyst (-)-**3.13** (3.8 mg, 0.010 mmol) was placed in a separate vial containing 0.60 mL of *t*-amyl alcohol. This vial was also capped with a rubber septum, and both vials were removed from the glove box. The substrate was heated gently until it dissolved, and both vials were then cooled in an ice bath. The catalyst solution was added by cannula to the substrate solution, resulting in a dark purple solution. This solution was stirred at 0 °C until the pink color of the catalyst had returned. The catalyst was removed by filtration through a 1" plug of silica using EtOAc as the eluant. The solvent was then removed by rotary evaporation, and the product was analyzed by chiral HPLC.

R=Me. 86.3% ee (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 6.7 min (minor), 8.7 min (major)).

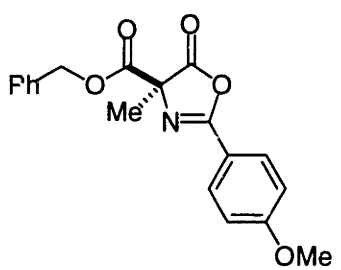
R=Et. 84.2% ee (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 8.4 min (minor), 10.2 min (major)).

R=*i*-Pr. 82.5% ee (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 98:2, 1.0 mL/min, retention times of enantiomers: 9.4 min (minor), 10.8 min (major)).

R=Bn. 90.1% ee (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 12.1 min (minor), 14.5 min (major)).

Enantioselective Rearrangements Under the Optimized Conditions (Table 3.3)

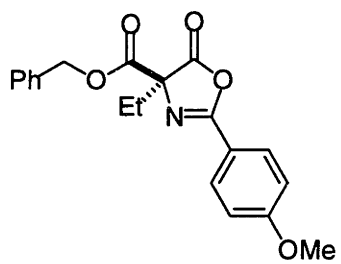
General procedure. Inside a glove box, 6.0 mL of *t*-amyl alcohol was added to a 25 mL flask containing a stir bar and the *O*-acylated azlactone (0.50 mmol). In a separate 5 mL flask, catalyst (-)-**3.13** (3.8 mg, 0.010 mmol) was dissolved in 4.0 mL of *t*-amyl alcohol, resulting in a pink solution. Each flask was capped with a rubber septum and removed from the glove box. The flask containing the substrate was sometimes heated gently to help dissolve the substrate. Both flasks were cooled in an ice bath, and the catalyst solution was added by cannula to the substrate solution, resulting in a deep blue or purple solution. When the pink color of the catalyst returned (2-6 hours), the mixture was passed through a 1" plug of silica (EtOAc as the eluant) to remove the catalyst (the catalyst is recovered by using 10% NEt_3/90% EtOAc as the eluant). The EtOAc and *t*-amyl alcohol were then removed by rotary evaporation, and the residue was purified by flash chromatography (5% ether/95% pentane → 25% ether/75% pentane).



4-Methyl-5-oxo-2-(4-methoxyphenyl)-4,5-dihydro-oxazole-4-carboxylic acid benzyl ester (3.32). The general procedure was followed. The product is a clear, colorless oil. Run 1 gave a 94.4% yield of material that was shown by HPLC (Daicel

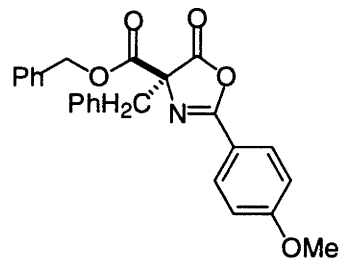
CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 11.7 min (minor), 15.0 min (major)) to have a 90.8% ee. Run 2 gave a 93.6% yield of material that was shown by HPLC to have a 90.6% ee.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.96 (d, 2H, J=9.0), 7.27-7.35 (m, 5H), 6.98 (d, 2H, J=9.0), 5.25 (d, 1H, J=12.5), 5.19 (d, 1H, J=12.5), 3.88 (s, 3H), 1.78 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 175.3, 166.2, 163.8, 163.1, 134.9, 130.3, 128.7, 128.6, 127.9, 117.6, 114.4, 73.0, 68.2, 55.6, 20.7. FTIR (KBr) 2938, 1827, 1754, 1646, 1608, 1513, 1262, 1172, 1019, 1002 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{19}H_{17}NO_5$ (M^+) 339.1107, found 339.1107. $[\alpha]^{20}_D$ = -55° (c=0.95, $CHCl_3$; for product with 90.6% ee).



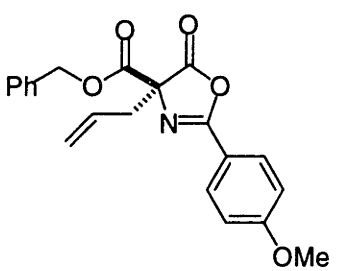
4-Ethyl-5-oxo-2-(4-methoxyphenyl)-4,5-dihydro-oxazole-4-carboxylic acid benzyl ester. The general procedure was followed. The product is a clear, colorless oil. Run 1 gave a 93.8% yield of material that was shown by HPLC (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 10.6 min (minor), 13.3 min (major)) to have a 90.1% ee. Run 2 gave a 91.2% yield of material that was shown by HPLC to have an 89.8% ee.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.98 (d, 2H, J=9.5), 7.2-7.4 (m, 5H), 6.99 (d, 2H, J=9.5), 5.26 (d, 1H, J=12.5), 5.21 (d, 1H, J=12.5), 3.88 (s, 3H), 2.21-2.37 (m, 2H), 0.91 (t, 3H, J=7.5). ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.5, 166.0, 163.8, 163.0, 135.0, 130.4, 128.7, 128.5, 128.0, 117.5, 114.4, 77.3, 68.1, 55.6, 28.0, 7.8. FTIR (KBr) 2974, 2938, 1818, 1754, 1647, 1608, 1513, 1262, 1025 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{20}H_{19}NO_5$ (M^+) 353.1263, found 353.1263. $[\alpha]^{20}_D$ = -48° (c=0.98, $CHCl_3$; for product with 90.1% ee).



4-Benzyl-5-oxo-2-(4-methoxyphenyl)-4,5-dihydro-oxazole-4-carboxylic acid benzyl ester (3.24). The general procedure was followed. The product is a clear, colorless oil. Run 1 gave a 93.0% yield of material that was shown by HPLC (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 12.1 min (minor), 14.5 min (major)) to have an 89.6% ee. Run 2 gave a 92.9% yield of material that was shown by HPLC to have an 89.7% ee.

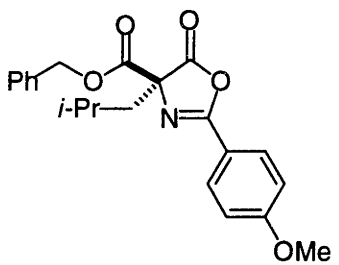
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.81 (d, 2H, J=9.0), 7.29-7.37 (m, 5H), 7.12-7.20 (m, 5H), 6.91 (d, 2H, J=9.0), 5.29 (d, 1H, J=12.5), 5.24 (d, 1H, J=12.5), 3.85 (s, 3H), 3.63 (d, 1H, J=13.5), 3.49 (d, 1H, J=13.5). ^{13}C NMR (75 MHz, $CDCl_3$) δ 173.9, 165.9, 163.7, 162.8, 134.9, 133.1, 130.5, 130.2, 128.7, 128.6, 128.3, 128.1, 127.6, 117.3, 114.3, 77.7, 68.3, 55.6, 40.3. FTIR (KBr) 3032, 2936, 1821, 1753, 1645, 1513, 1261, 1225, 1173, 980 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{25}H_{21}NO_5$ (M^+) 415.1420, found 415.1420. $[\alpha]^{20}_D$ = -169° (c=1.03, $CHCl_3$; for product with 89.6% ee).



4-Allyl-5-oxo-2-(4-methoxyphenyl)-4,5-dihydro-oxazole-4-carboxylic acid benzyl ester. The general procedure was followed. The product is a clear, colorless oil. Run 1 gave a 93.5% yield of material that was shown by HPLC (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of

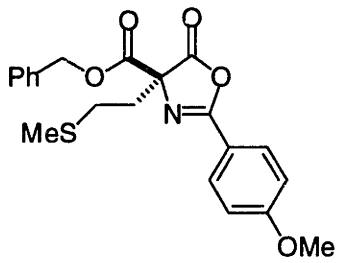
enantiomers: 10.2 min (minor), 13.4 min (major)) to have a 90.6% ee. Run 2 gave a 92.1% yield of material that was shown by HPLC to have a 90.5% ee.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.96 (d, 2H, J=9.0), 7.2-7.4 (m, 5H), 6.98 (d, 2H, J=9.0), 5.55-5.69 (m, 1H), 5.11-5.29 (m, 4H), 3.88 (s, 3H), 3.06 (dd, 1H, J=13.8, 6.6), 2.91 (dd, 1H, J=13.8, 7.8). ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.0, 165.7, 163.8, 163.0, 134.9, 130.4, 129.5, 128.7, 128.6, 128.0, 121.7, 117.5, 114.4, 76.8, 68.3, 55.7, 38.5. FTIR (KBr) 3080, 2937, 1823, 1754, 1645, 1608, 1513, 1261, 1226, 977 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{21}H_{19}NO_5$ (M^+) 365.1263, found 365.1264. $[\alpha]^{20}_D$ = -92° (c=0.97, $CHCl_3$; for product with 90.5% ee).



4-(2-Methylpropyl)-5-oxo-2-(4-methoxyphenyl)-4,5-dihydro-oxazole-4-carboxylic acid benzyl ester (3.14). The general procedure was followed. The product is a pale yellow oil. Run 1 gave a 95.0% yield of material that was shown by HPLC (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 8.8 min (minor), 10.6 min (major)) to have a 92.0% ee. Run 2 gave a 94.8% yield of material that was shown by HPLC to have a 92.8% ee.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.98 (d, 2H, J=9.0), 7.2-7.4 (m, 5H), 6.99 (d, 2H, J=9.0), 5.24 (d, 1H, J=12.5), 5.20 (d, 1H, J=12.0), 3.88 (s, 3H), 2.38 (dd, 1H, J=14.5, 6.0), 2.06 (dd, 1H, J=14.5, 7.5), 1.65-1.76 (m, 1H), 0.92 (d, 3H, J=6.5), 0.88 (d, 3H, J=7.0). ^{13}C NMR (75 MHz, $CDCl_3$) δ 175.2, 166.2, 163.8, 162.6, 135.0, 130.4, 128.6, 128.5, 128.0, 117.8, 114.5, 76.5, 68.2, 55.7, 42.9, 24.8, 23.9, 23.2. FTIR (KBr) 2960, 1820, 1753, 1647, 1608, 1513, 1261, 1222, 1173, 970 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{22}H_{23}NO_5$ (M^+) 381.1576, found 381.1578. $[\alpha]^{20}_D$ = -71° (c=1.1, $CHCl_3$; for product with 92.8% ee).



4-(2-Methylthio)ethyl-5-oxo-2-(4-methoxyphenyl)-4,5-dihydro-oxazole-4-carboxylic acid benzyl ester (3.30). The general procedure was followed. The product is a pale yellow oil. Run 1 gave a 94.1% yield of material that was shown by HPLC (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 12.2 min (minor), 16.2 min (major)) to have an 88.4% ee. Run 2 gave a 94.2% yield of material that was shown by HPLC to have an 88.0% ee.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.97 (d, 2H, J=9.0), 7.28-7.35 (m, 5H), 6.98 (d, 2H, J=9.0), 5.25 (d, 1H, J=12.5), 5.20 (d, 1H, J=12.5), 3.89 (s, 3H), 2.43-2.67 (m, 4H), 2.04 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 174.5, 165.7, 163.9, 163.6, 134.9, 130.4, 128.7, 128.6, 128.0, 117.6, 114.5, 75.8, 68.3, 55.7, 33.5, 28.4, 15.2. FTIR (KBr) 2917, 2840, 1819, 1752, 1644, 1608, 1512, 1307, 1262, 1020 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{21}H_{21}NO_5S$ (M^+) 399.1140, found 399.1140. $[\alpha]^{20}_D$ = -98° (c=1.05, $CHCl_3$; for product with 88.4% ee).

Purification or Reaction Mixture with MP-TsOH Resin

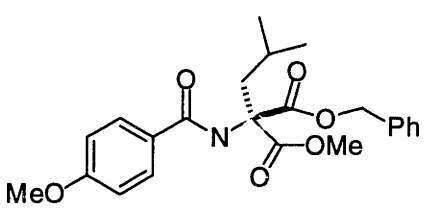
A pink solution of (-)-**3.13** (8.4 mg, 0.022 mmol) in 4 mL of *t*-amyl alcohol was added by cannula at 0 °C to a solution of the *O*-acylated azlactone (**3.14**, 384 mg, 1.01 mmol) in 6 mL of *t*-amyl alcohol, resulting in a deep blue solution. After 135 minutes, the pink color of the catalyst had returned, and the reaction mixture was added by cannula to a slurry of MP-TsOH resin (57 mg, 0.067 mmol) in 5 mL of CH_2Cl_2. The reaction flask was rinsed with an additional 5 mL of CH_2Cl_2. After 17 hours, the colorless solution was decanted away from the purple resin beads. The

resin beads were washed with 2 X 5 mL of Et_2O, and the washes were added to the *t*-amyl alcohol solution. The solvents were removed from the product by rotary evaporation. Pentane was added, and the mixture was again dried by rotary evaporation to remove the last of the *t*-amyl alcohol. The product was left as 387 mg (101%) of light tan oil that was essentially pure by ^1H NMR (see Figure 3.1). HPLC analysis of the product revealed a 92.2% ee (see above for conditions).

The resin beads were slurried in 10 mL of CH_2Cl_2 and treated with 1 mL of 2.0 M NH_3 in methanol. After 75 minutes, the pink solution was filtered to remove the beads. The beads were washed with 10 mL of CH_2Cl_2 and the solvent was removed, leaving the recycled catalyst which was used again without further purification.

This sequence was repeated four additional times with the same batch of catalyst. Although the yield and ee of product was essentially constant, the reaction time required increased with each successive run, presumably due to non-quantitative recovery of the catalyst.

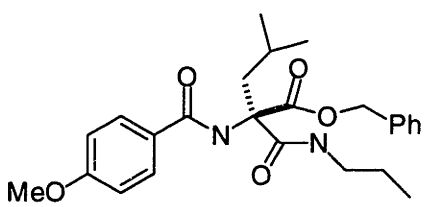
Derivatization of the Rearranged Products



(3.16). The leucine-derived substrate (**3.14**, 193 mg, 0.505 mmol) was rearranged under the optimized conditions as described above using 3.8 mg (0.010 mmol) of catalyst (-)-**3.13**. After the pink color of the catalyst had returned (approximately 3 hours), the ice bath was removed, and the solution was allowed to warm to room temperature. A solution of methanol (100 μL, 2.5 mmol) and DMAP (6 mg, 0.05 mmol) in 1 mL of CH_2Cl_2 was added by syringe. After 42 hours, TLC showed ring opened product as well as a trace of the rearranged material. After 75.5 hours, the

mixture was filtered thru a plug of silica using EtOAc to remove the catalysts. Solvent was removed on the rotovap, and the residue was purified by flash chromatography using 25% ether/75% pentane → 50% ether/50% pentane. The product was collected as 206 mg (99%) of colorless glass. The product was shown by HPLC (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 98:2, 1.0 mL/min, retention times of enantiomers: 39.9 min (minor), 42.5 min (major)) to have a 93.1% ee.

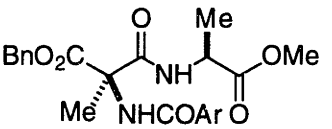
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.79 (d, 2H, J=9.0), 7.47 (s, 1H), 7.28-7.35 (m, 5H), 6.94 (d, 2H, J=9.0), 5.24 (d, 1H, J=12.5), 5.21 (d, 1H, J=12.5), 3.85 (s, 3H), 3.69 (s, 3H), 2.40-2.50 (m, 2H), 1.50-1.61 (m, 1H), 0.85 (d, 3H, J=7.0), 0.83 (d, 3H, J=6.5). ^{13}C NMR ($CDCl_3$) δ 169.3, 168.6, 165.5, 162.7, 135.1, 129.0, 128.6, 128.5, 128.3, 125.8, 113.9, 68.0, 66.5, 55.5, 53.3, 40.2, 24.3, 23.5, 23.3. FTIR (KBr) 3422, 2956, 1739, 1662, 1607, 1487, 1305, 1256, 1203 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{23}H_{27}NO_6$ (M^+) 413.1838, found 413.1837. $[\alpha]^{20}_D$ = +18° (c=1.12, $CHCl_3$, 93.1% ee)



(3.17). The leucine-derived substrate (**3.14**, 191 mg, 0.502 mmol) was rearranged under the optimized conditions as described above using 3.8 mg (0.010 mmol) of catalyst (-)-**3.13**. After the pink color of the catalyst had returned (approximately 3 hours), the ice bath was removed, and the solution was allowed to warm to room temperature. A solution of *n*-propylamine (200 μL, 2.3 mmol) and DMAP (6 mg, 0.05 mmol) in 1 mL of CH_2Cl_2 was added by syringe. After 3.5 hours, TLC showed ring opened product as well as rearranged material. After 42 hours, TLC showed complete conversion to ring opened product. The mixture was filtered thru a plug of silica using EtOAc to remove the catalysts. Solvent was removed on the rotovap,

and the residue was purified by flash chromatography using 25% ether/75% pentane → 50% ether/50% pentane. The product was collected as 217 mg (98%) of colorless glass. The product was shown by HPLC (Daicel CHIRALCEL OD, 4.6 mm x 25 cm, hexane/isopropanol 90:10, 1.0 mL/min, retention times of enantiomers: 17.7 min (minor), 19.5 min (major)) to have a 92.5% ee.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.85 (br s, 1H), 7.80 (d, 2H, J=8.5), 7.25-7.29 (m, 5H), 6.93 (d, 2H, J=8.5), 6.21 (br t, 1H), 5.19 (d, 1H, J=12.5), 5.16 (d, 1H, J=12.5), 3.85 (s, 3H), 3.08-3.24 (m, 2H), 2.70 (dd, 1H, J=15.0, 6.5), 2.15 (dd, 1H, J=15.0, 6.5), 1.58-1.66 (m, 1H), 1.36-1.48 (m, 2H), 0.88 (d, 3H, J=7.0), 0.87 (d, 3H, J=7.0), 0.84 (t, 3H, J=7.5). ^{13}C NMR ($CDCl_3$) δ 171.0, 167.3, 165.7, 162.5, 135.2, 129.0, 128.5, 128.3, 128.2, 126.2, 113.8, 67.9, 66.4, 55.4, 42.0, 41.6, 24.5, 23.7, 23.4, 22.5, 11.3. FTIR (KBr) 3376, 2960, 2873, 1739, 1652, 1607, 1523, 1482, 1254, 1216 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{25}H_{32}N_2O_5$ (M^+) 440.2311, found 440.2310. $[\alpha]^{20}_D$ = +8.7° (c=1.15, $CHCl_3$, 92.5% ee).

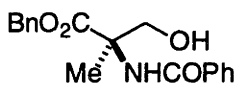


Ar = 4-MeO-C_6H_4

(3.19). The alanine-derived substrate (**3.27**, 170 mg, 0.500 mmol) was rearranged under the optimized conditions using 3.8 mg (0.010 mmol) of catalyst (-)-**3.13**. After the pink color of the catalyst had returned (~ 3 hours), the mixture was passed through a 1" plug of silica (EtOAc as eluant) to remove the catalyst. The EtOAc and the *t*-amyl alcohol were then removed by rotary evaporation. HPLC analysis of the residue revealed a 90.4% ee. The residue was then dissolved in CH_2Cl_2 (5 mL) and added to a mixture of (L)-alanine methyl ester hydrochloride (105 mg, 0.752 mmol), NEt_3 (140 μL, 1.01 mmol), and DMAP (30 mg, 0.25 mmol) in CH_2Cl_2 (3 mL). The resulting clear, colorless solution was stirred for three days, after which the product was purified by flash chromatography using 50% Et_2O/50% pentane → 100% Et_2O as

the eluant. The product was a colorless, viscous oil (210 mg, 95%). By ^{1}H NMR, the product was shown to be contaminated with a small amount of the ethyl ester. Analysis of the (L)-alanine methyl ester hydrochloride used for the ring opening confirmed that it was the source of the impurity.

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.78 (d, 2H, J=9.0), 7.65 (br s, 1H), 7.26-7.32 (m, 5H), 6.92 (d, 2H, J=9.0), 6.89 (d, 1H, J=7.0), 5.25 (d, 1H, J=12.0), 5.21 (d, 1H, J=12.0), 4.50 (pent, 1H, J=7.0), 3.85 (s, 3H), 3.70 (s, 3H), 1.93 (s, 3H), 1.40 (d, 3H, J=7.0). ^{13}C NMR (75 MHz, $CDCl_3$) δ 172.4, 170.4, 167.8, 166.1, 162.5, 135.2, 129.1, 128.4, 128.3, 128.1, 125.9, 113.7, 68.1, 63.2, 55.4, 52.5, 48.8, 22.1, 17.9. FTIR (KBr) 3370, 2951, 1743, 1678, 1654, 1607, 1526, 1485, 1258, 1126 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{23}H_{26}N_2O_7$ (M^+) 442.1740, found 442.1740.



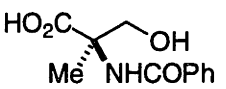
***N*-Benzoyl-α-methylserine benzyl ester (3.21).** The azlactone (**3.20**, 504 mg, 1.63 mmol; 80.6% ee of the (-)-enantiomer, from a rearrangement conducted with (-)-**3.13** at room temperature) was dissolved in THF (10 mL) in a round-bottom flask with a stir bar. Solid $NaBH_4$ (34 mg, 0.90 mmol) was added in one portion to the solution; the last traces of the $NaBH_4$ were rinsed into the flask with additional THF (2 mL). The reaction mixture quickly turned bright yellow. The solution was stirred for 3 hours, after which saturated aqueous $NaHCO_3$ (30 mL) was added. The THF was removed by rotary evaporation, and the product was extracted with CH_2Cl_2 (3 x 30 mL). The CH_2Cl_2 solution was then dried ($MgSO_4$), and the CH_2Cl_2 was removed by rotary evaporation. The product was purified by flash chromatography using 25% EtOAc/75% hexanes → 100% EtOAc as the eluant. The product was a colorless glass (317 mg, 62%).

Starting material (3.20): ^{1}H NMR (300 MHz, $CDCl_3$) δ 8.03 (d, 2H, J=7.5), 7.61 (t, 1H, J=7.2), 7.50 (t, 2H, J=7.2), 7.26-7.38 (m, 5H), 5.26 (d, 1H, J=12.3), 5.20 (d, 1H, J=12.3),

1.80 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 175.0, 166.0, 163.5, 135.1, 133.4, 129.0, 128.8, 128.6, 128.5, 127.9, 125.6, 73.2, 68.3, 20.6. FTIR (KBr) 3034, 2940, 1829, 1756, 1650, 1452, 1296, 1259, 1157, 1010 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{18}H_{15}NO_4$ (M^+) 309.1001, found 309.1001.

Product (3.21): ^1H NMR (500 MHz, $CDCl_3$) δ 7.79 (d, 2H, J=8.0), 7.52 (t, 1H, J=8.5), 7.44 (t, 1H, J=8.0), 7.32-7.38 (m, 5H), 7.18 (br s, 1H), 5.27 (d, 1H, J=12.5), 5.24 (d, 1H, J=12.5), 4.24 (dd, 1H, J=12.0, 6.5), 3.93 (dd, 1H, J=12.0, 6.5), 3.53 (t, 1H, J=6.5), 1.66 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 173.1, 167.8, 135.4, 134.0, 131.8, 128.6, 128.6, 128.4, 128.0, 127.1, 67.6, 66.3, 62.2, 19.9. FTIR (KBr) 3402, 3064, 2945, 1736, 1646, 1530, 1315, 1222, 1129, 1057 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{18}H_{19}NO_4$ (M^+) 313.1314, found 313.1313. $[\alpha]^{20}_D$ = -4.5° (c=1.0, $CHCl_3$; for product with 80.6% ee).[38]

Determination of the Absolute Configuration of the Rearranged Products



***N*-Benzoyl-α-methylserine (3.22).** A 2 M solution of NaOH (0.55 mL, 1.1 mmol) was added by syringe to a solution of (-)-*N*-benzoyl-α-methylserine benzyl ester (284 mg, 0.907 mmol) in methanol (5 mL). After 2 minutes, TLC showed that the starting material had been totally consumed, that benzyl alcohol had been produced, and that a large quantity of a new compound, only slightly more polar than the starting material, had been formed. This compound disappeared after 3.5 hours, replaced by a very polar compound. Approximately 25 mL of water was then added, and the methanol was removed by rotary evaporation. The water layer was washed with CH_2Cl_2 (2 x 25 mL) and then acidified with 1M HCl (1.5 mL). The product was extracted into CH_2Cl_2 (8 x 25 mL). The combined CH_2Cl_2 washings were dried

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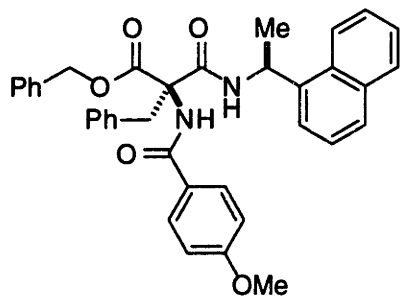
38 It was assumed that the ee of the reduction product was identical to that of the starting azlactone.

($MgSO_4$), and the CH_2Cl_2 was removed by rotary evaporation, leaving the product as a white, crystalline solid (48.9 mg). Comparison of the optical rotation of the product with that reported in the literature confirmed that the absolute configuration is (R).[25]



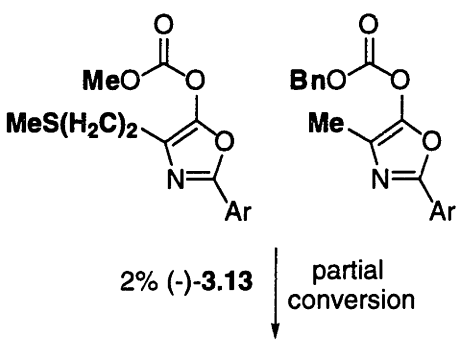
(3.25). A solution of DMAP (50 mg, 0.41 mmol) in CH_2Cl_2 (0.5 mL) was added to a solution of the *O*-acylated azlactone (**3.23**, 194 mg, 0.468 mmol) in CH_2Cl_2 (6 mL). The resulting solution was stirred for 20 minutes, after which (*S*)-1-(1-naphthyl)ethylamine (100 μL, 0.62 mmol) was added by syringe. After 1 day, TLC of the reaction mixture showed a small amount of azlactone and two poorly resolved, more polar spots (the 2 diastereomeric products). After 6 days, the reaction mixture was loaded onto a column of silica and eluted with 10% EtOAc/90% hexanes → 50% EtOAc/50% hexanes. Several fractions of the pure faster-eluting product diastereomer were collected; removal of the solvent provided a white, crystalline solid (113 mg).

^{1}H NMR (500 MHz, $CDCl_3$) δ 7.06-7.90 (m, 20H), 6.87 (d, 2H, J=9.0), 6.54 (d, 1H, J=8.0), 5.82 (pent, 1H, J=7.0), 5.04 (d, 1H, J=12.5), 4.75 (d, 1H, J=12.5), 3.97 (d, 1H, J=14.0), 3.83 (s, 3H), 3.60 (d, 1H, J=14.0), 1.70 (d, 3H, J=7.0). ^{13}C NMR (75 MHz, $CDCl_3$) δ 170.3, 166.3, 165.5, 162.8, 137.7, 135.3, 135.1, 134.3, 131.2, 130.4, 129.2, 129.1, 128.8, 128.6, 128.5, 128.4, 127.5, 126.8, 126.7, 126.0, 125.5, 123.2, 122.8, 114.1, 68.4, 67.7, 55.6, 46.4, 39.2, 20.7. FTIR (KBr) 3379, 3033, 2975, 1730, 1678, 1652, 1606, 1521, 1480, 1257 cm^{-1}. HRMS (EI, *m/e*) calcd. for $C_{37}H_{34}N_2O_5$ (M^+) 586.2468, found 586.2468. mp = 142-143 °C.

X-ray quality crystals of this diastereomer were grown from CH_2Cl_2/hexanes, and the configuration of the quaternary center was determined to be (R) by single crystal X-ray diffraction.[39]

When the same *O*-acylated azlactone was rearranged under the standard conditions using (-)-**3.13** as the catalyst and then subjected to DMAP-catalyzed ring opening with (*S*)-1-(1-naphthyl)ethylamine, the major product was identical (by TLC and ^{1}H NMR) to the faster-eluting diastereomer described above. By ^{1}H NMR, the (*S*)-1-(1-naphthyl)ethylamine-derived methyl resonances of the two diastereomers are well-separated in $CDCl_3$: a doublet at 1.70 ppm for the major (faster-eluting) product and a doublet at 1.46 ppm for the minor (slower-eluting) product.

Crossover Experiment (eq 3B.16)



Reaction taken to completion. Inside a glove box, the *methyl* carbonate of the methionine derivative, **3.27**, (23 mg, 0.071 mol) and the *benzyl* carbonate of the alanine derivative, **3.28**, (24 mg, 0.072 mmol) were added to a 5 mL flask with a stir bar and 2.5 mL of *t*-amyl alcohol. The catalyst ((-)-**3.13**, 0.94 mg, 0.0025 mmol) was dissolved in 1.0 mL of *t*-amyl alcohol in a separate flask, resulting in a pink solution. Each flask was capped with a septum and removed from the glove box. The flask containing the substrates was gently heated until the substrates had dissolved. Both

39 Details of the crystal structure appear in Appendix II.

flasks were cooled in an ice bath, and the catalyst solution was added by cannula to the substrates, resulting in a purple solution. The pink color of **3.13** returned after approximately 4 hours. The mixture was then passed through a 1" plug of silica (EtOAc as eluant) to remove the catalyst. The solvents were removed, leaving 48 mg of a colorless oil. The ^{1}H NMR spectrum of this material revealed the presence of each of the four possible products in a 1.0: 1.0: 1.2: 1.3 ratio.

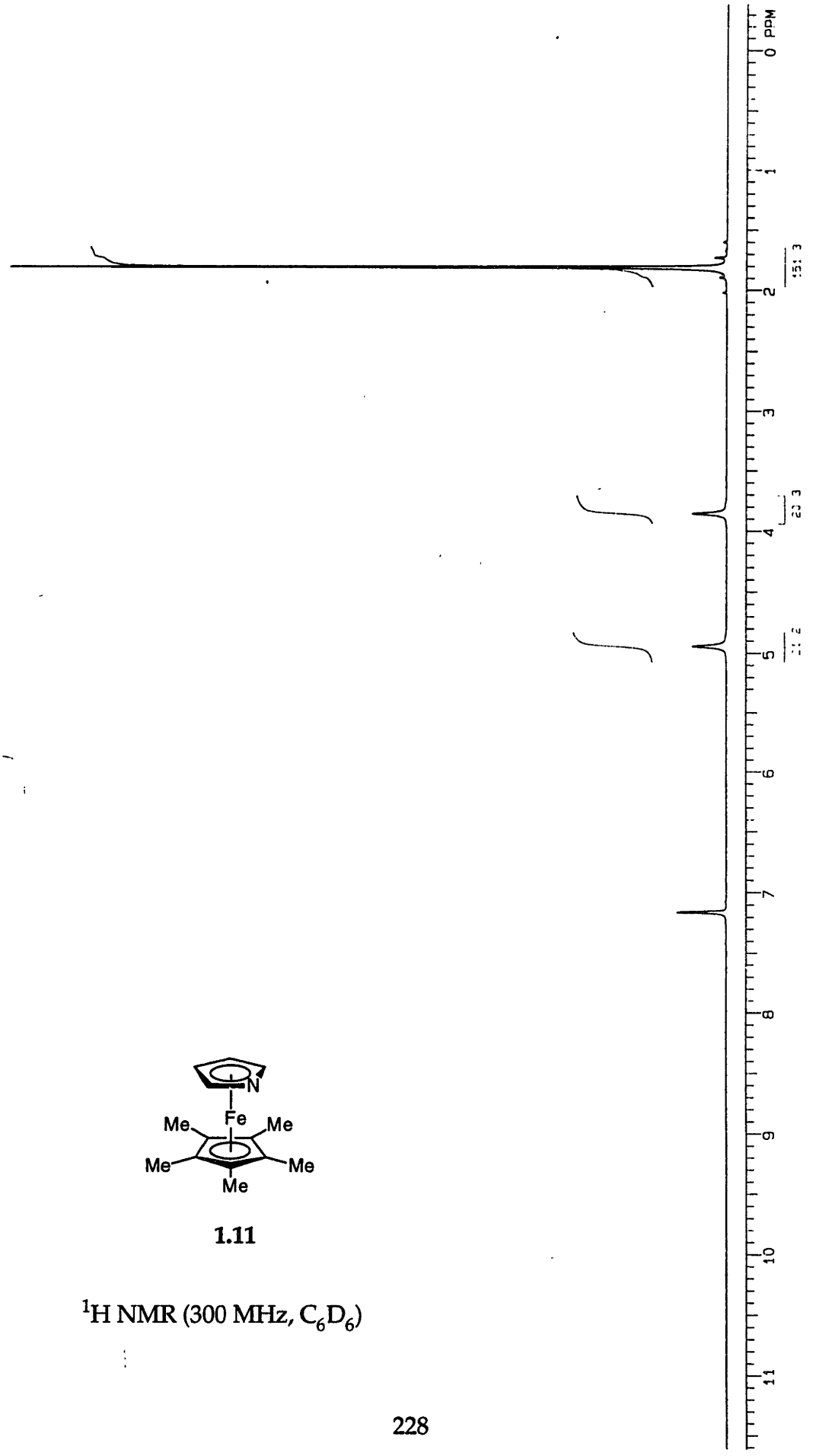
Reaction taken to partial conversion. When a similar experiment was set up and worked up after only 1.8 hours (still purple), the ^{1}H NMR spectrum of the resulting material revealed not only the four products and the two starting materials, but also small amounts of the other two *O*-acylated azlactones (the *benzyl* carbonate of the methionine derivative (**3.29**) and the *methyl* carbonate of the alanine derivative (**3.30**)).

Configurational Stability of the Rearranged Products over Time

The *O*-acylated phenylalanine derivative, **3.23**, was rearranged under the optimized conditions (0 °C, *t*-amyl alcohol, 2% (-)-**3.13**). After the return of the pink color (5.5 hours), a 1 mL portion of the reaction mixture was removed and filtered through silica to remove the catalyst; HPLC analysis revealed an 89.4% ee of product. After an additional 15.5 hours at 0 °C, a second aliquot was removed and shown to have an 89.2% ee of product. The mixture was then stirred for 4 days at room temperature, and then a final aliquot was removed and shown to have an 88.9% ee of product. From these data, we conclude that under the reaction conditions there is no significant deterioration of the ee of the rearranged products.

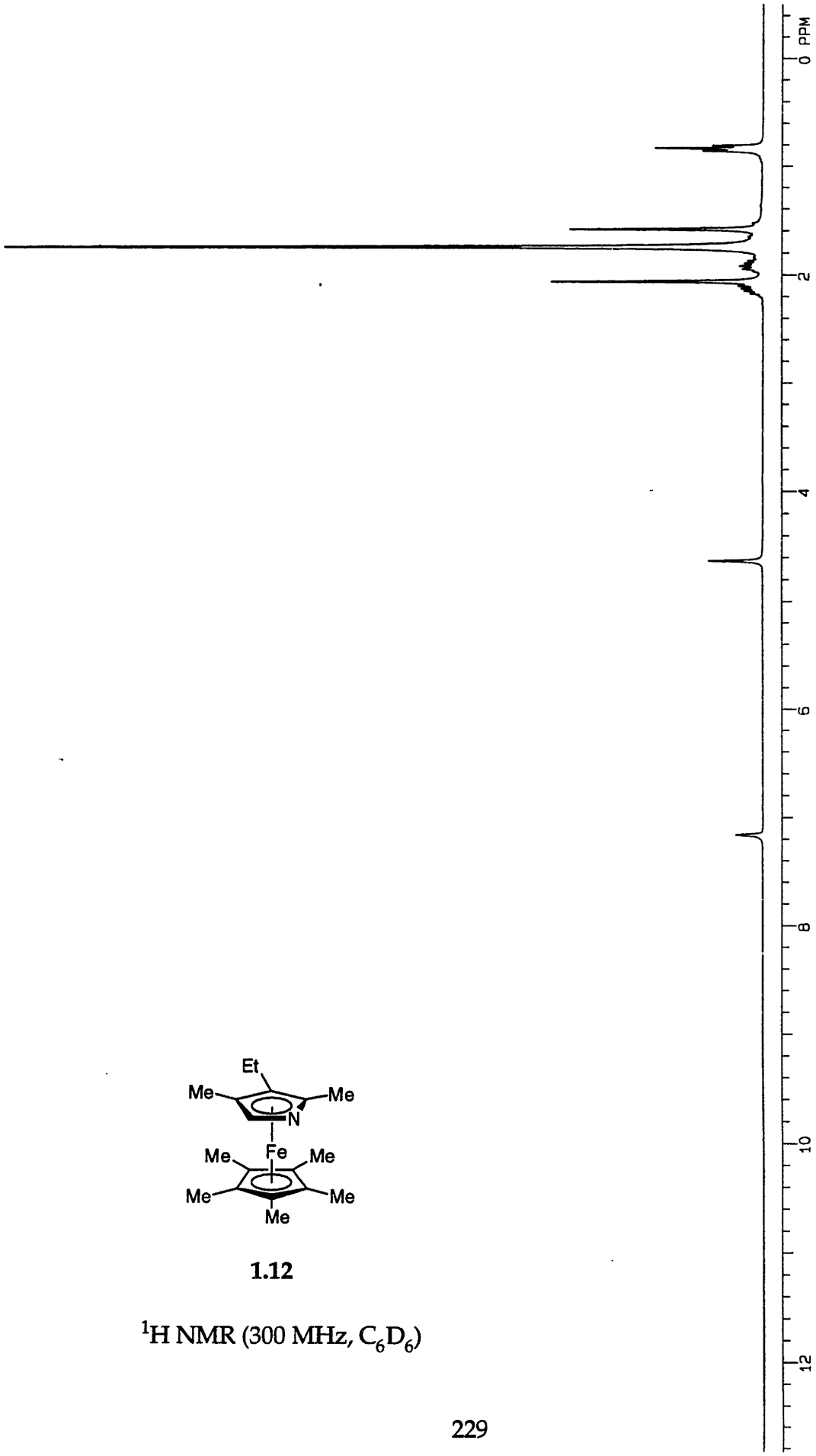
Appendix I:

NMR Spectra for Selected Compounds



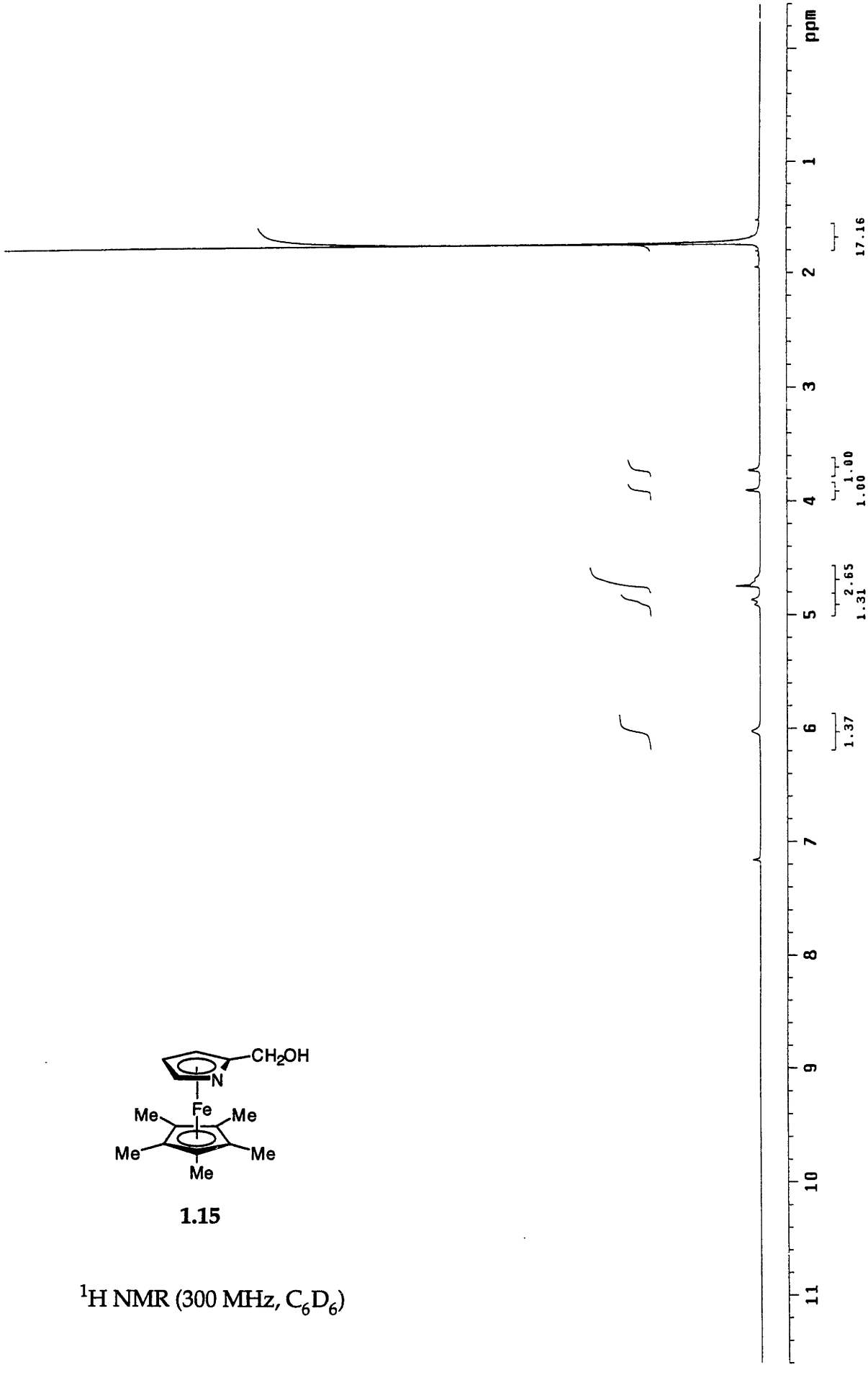
1.11

^{1}H NMR (300 MHz, C_6D_6)



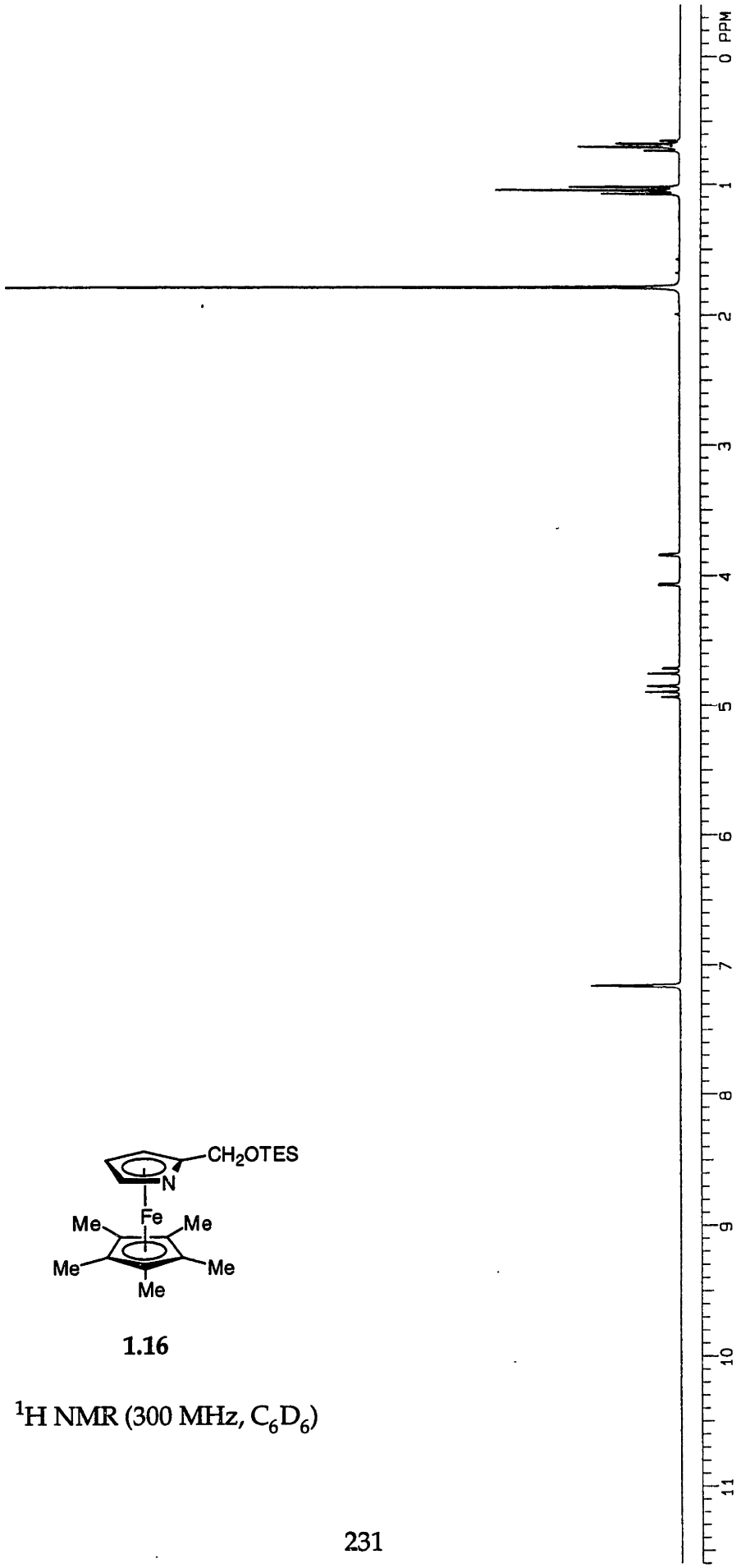
1.12

^{1}H NMR (300 MHz, C_6D_6)



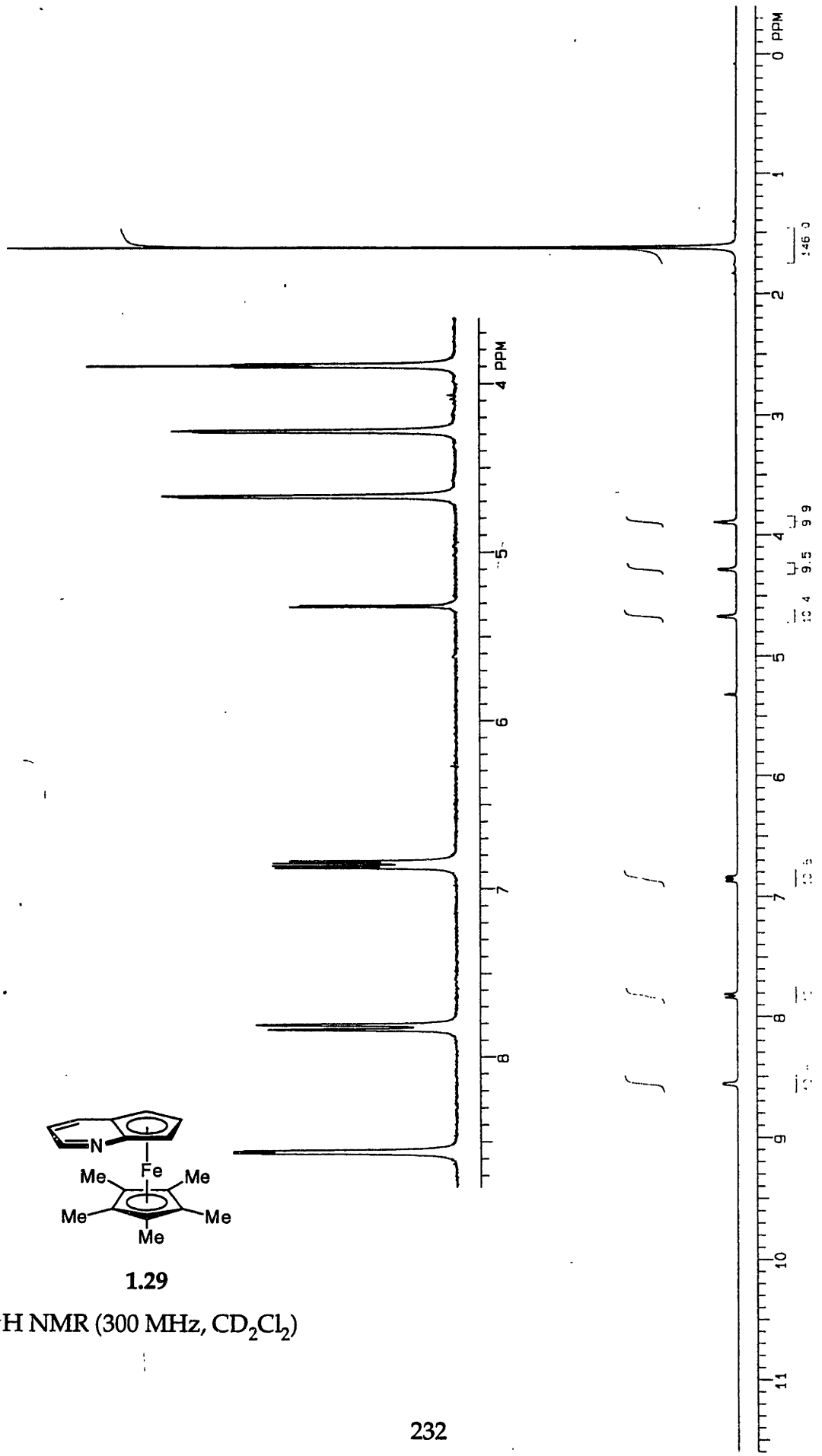
1.15

^{1}H NMR (300 MHz, C_6D_6)



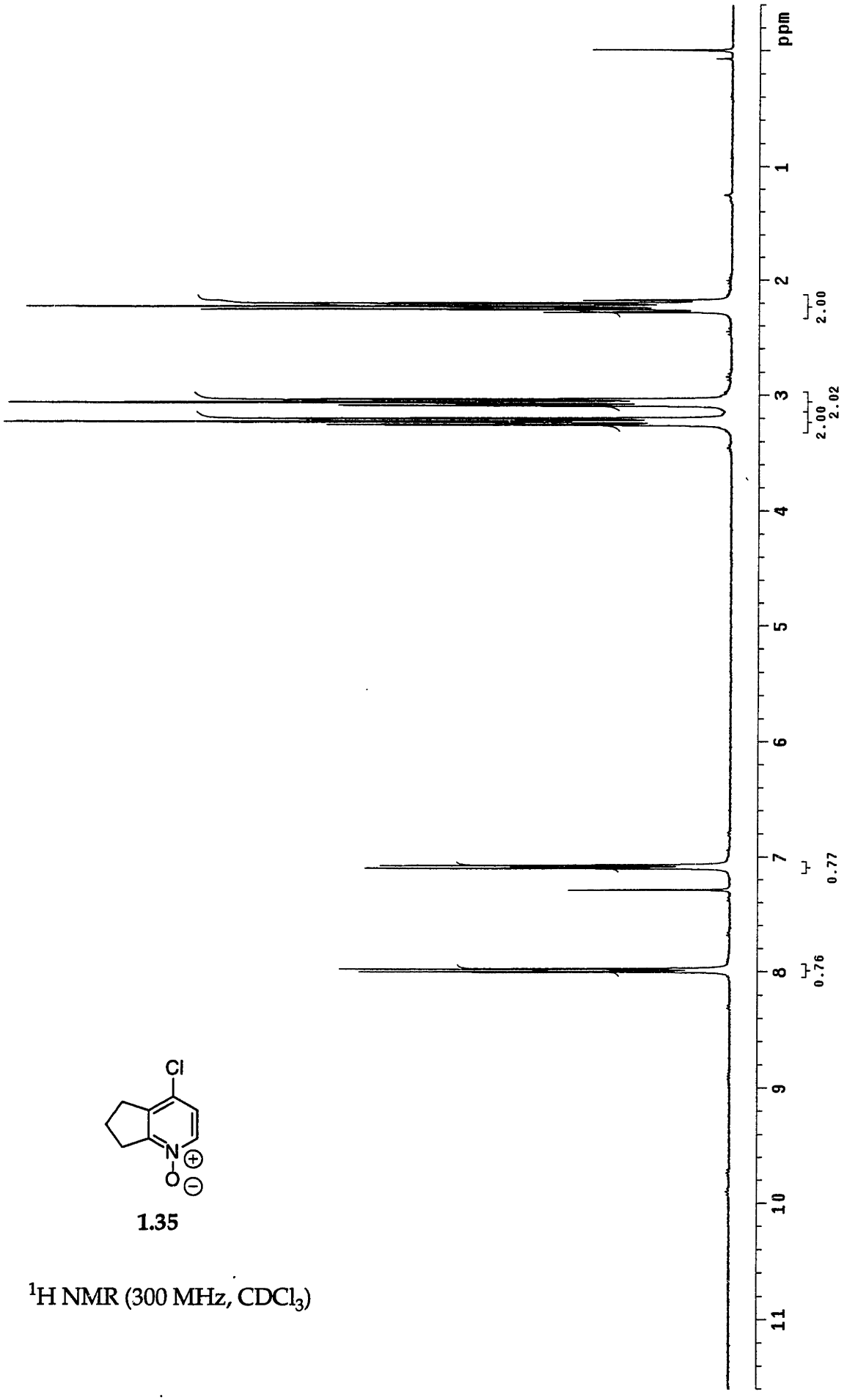
1.16

^{1}H NMR (300 MHz, C_6D_6)



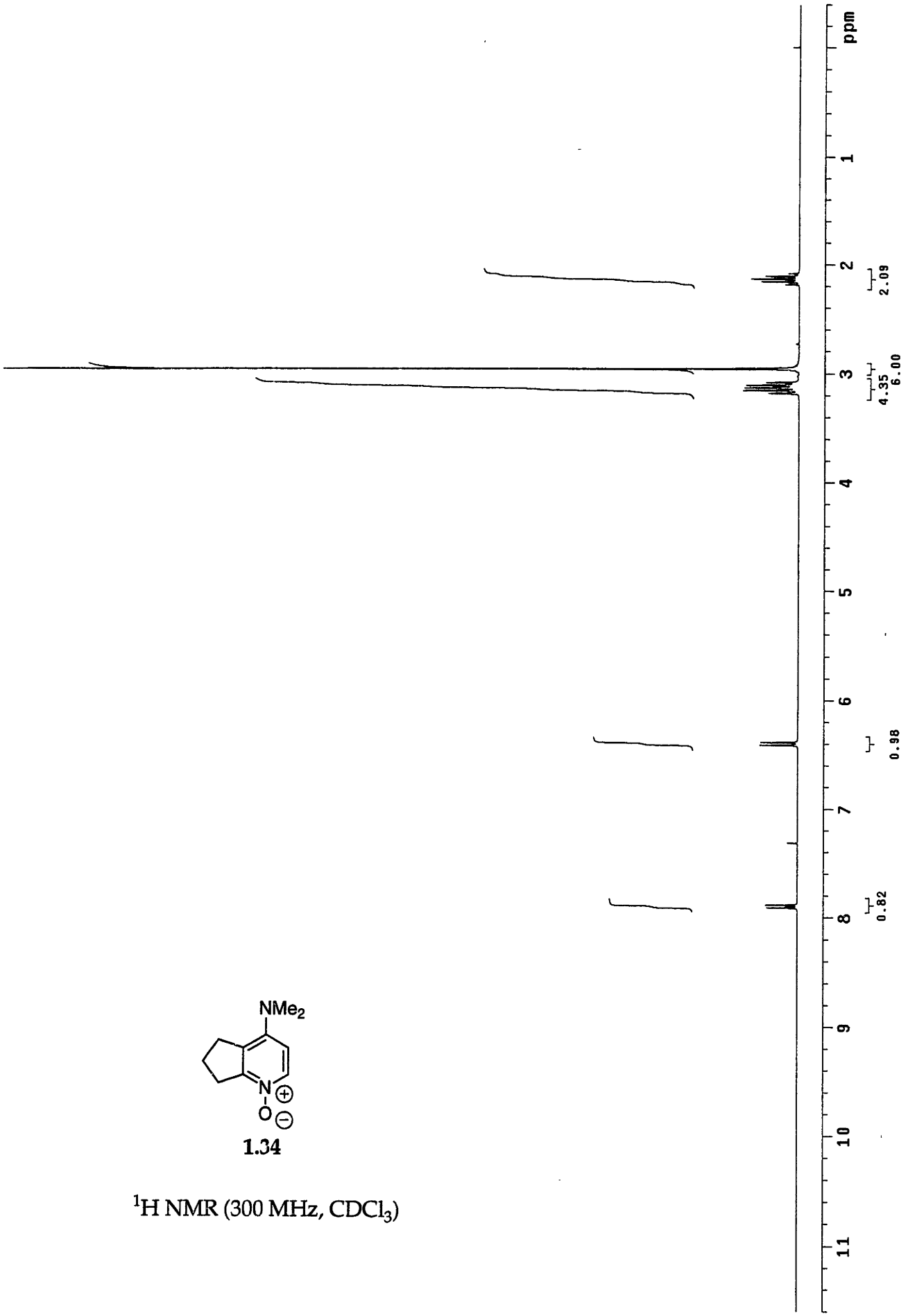
1.29

^{1}H NMR (300 MHz, CD_2Cl_2)



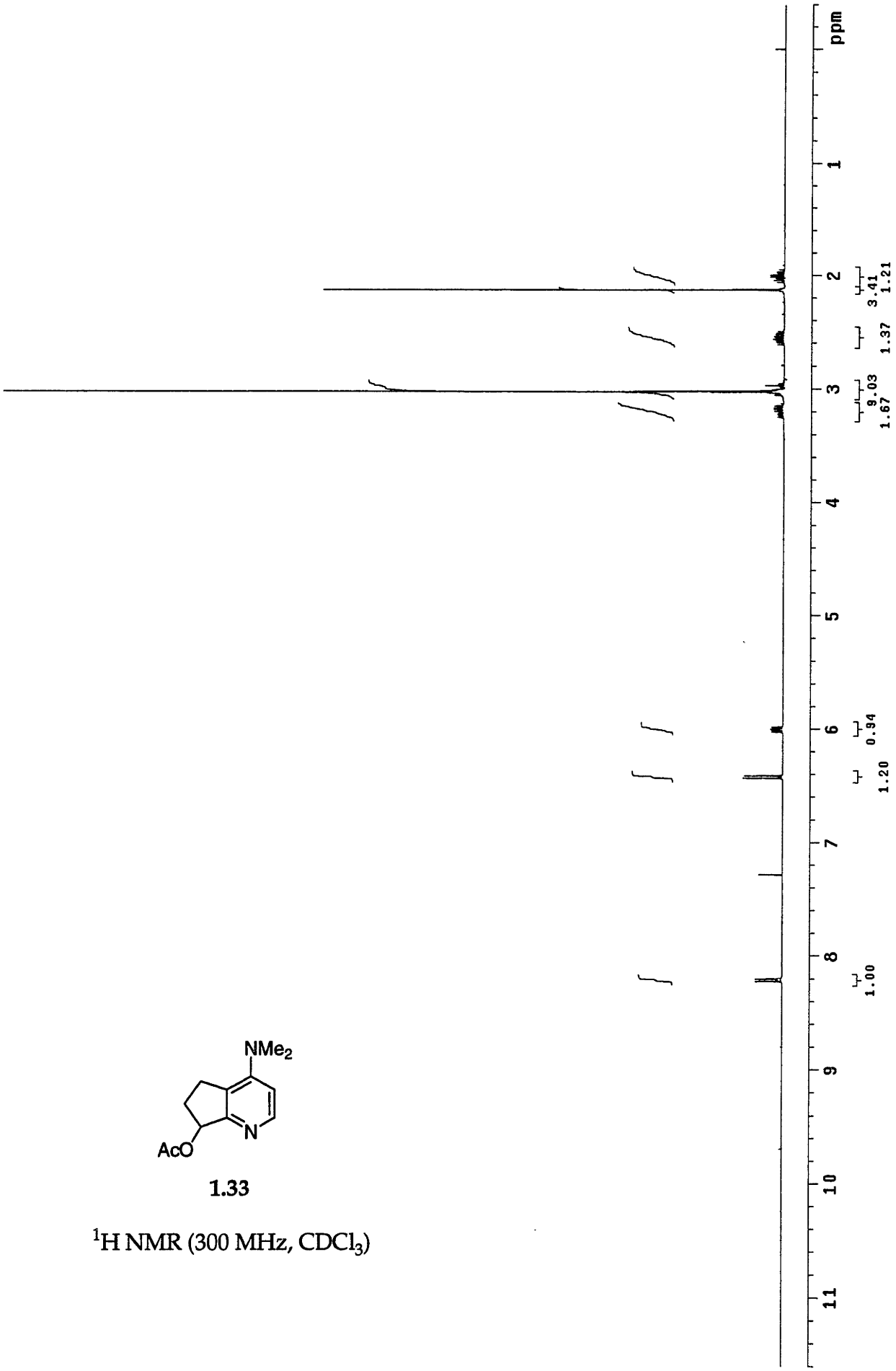
1.35

^{1}H NMR (300 MHz, $CDCl_3$)



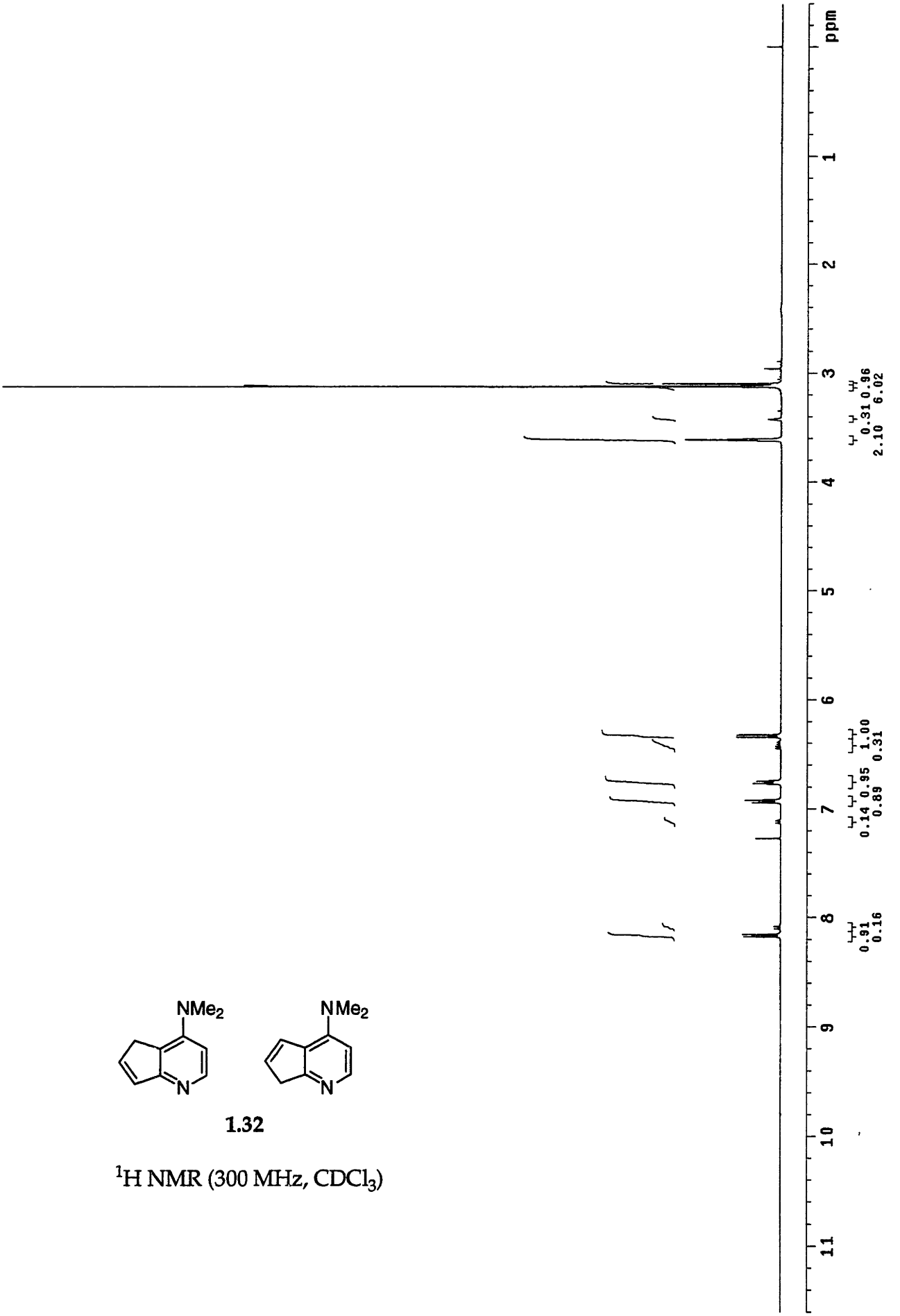
1.34

^{1}H NMR (300 MHz, $CDCl_3$)



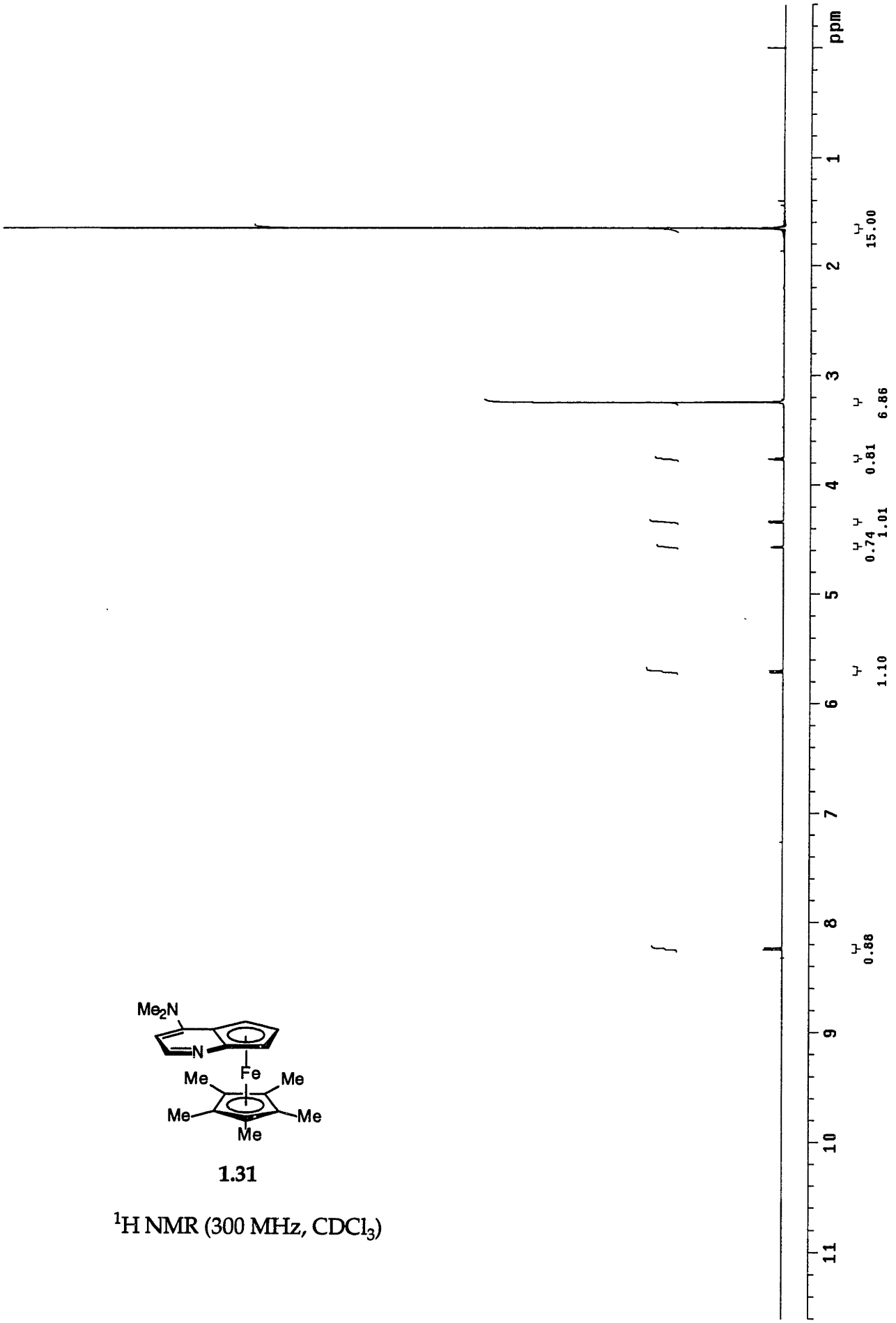
1.33

^{1}H NMR (300 MHz, $CDCl_3$)



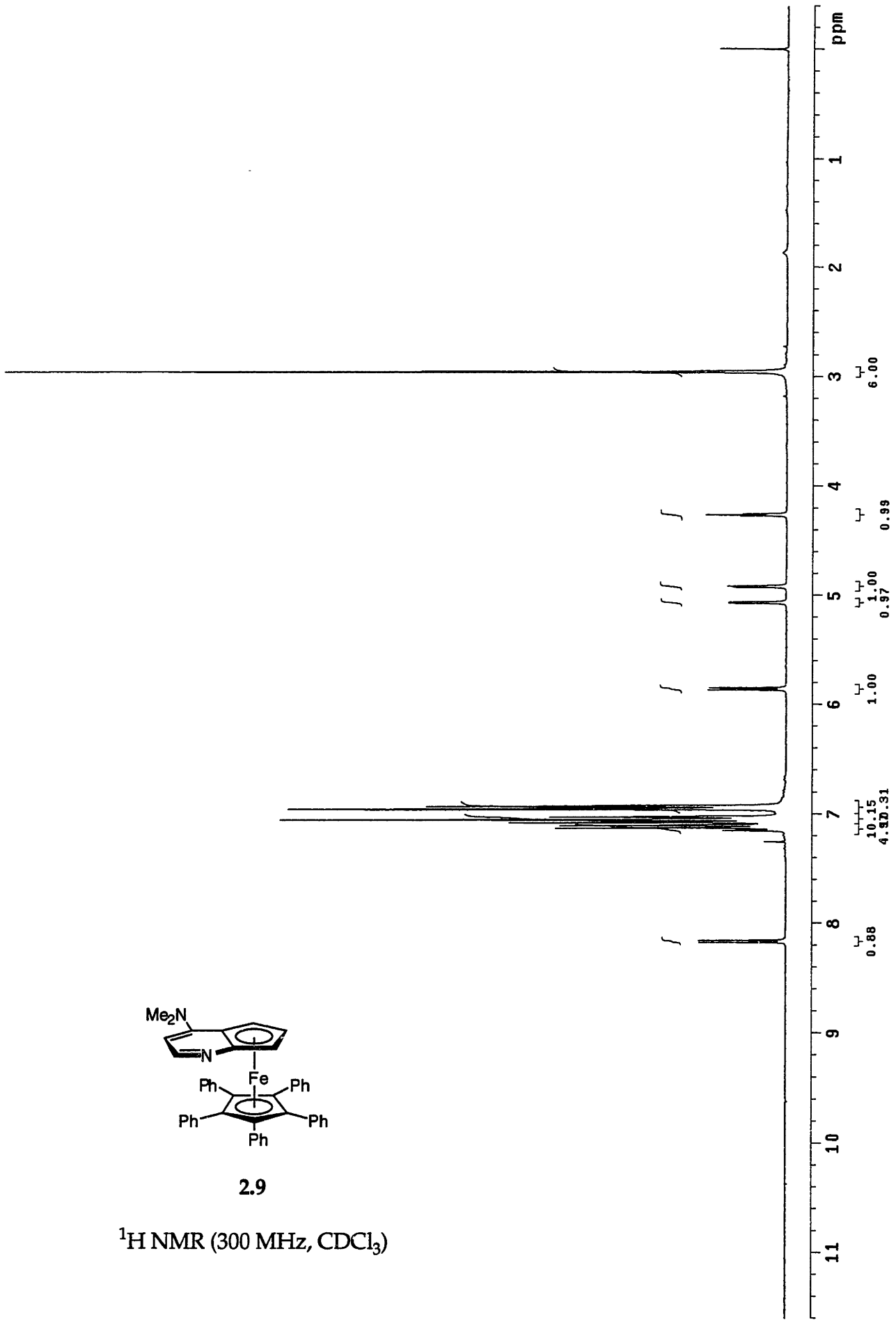
1.32

^{1}H NMR (300 MHz, $CDCl_3$)



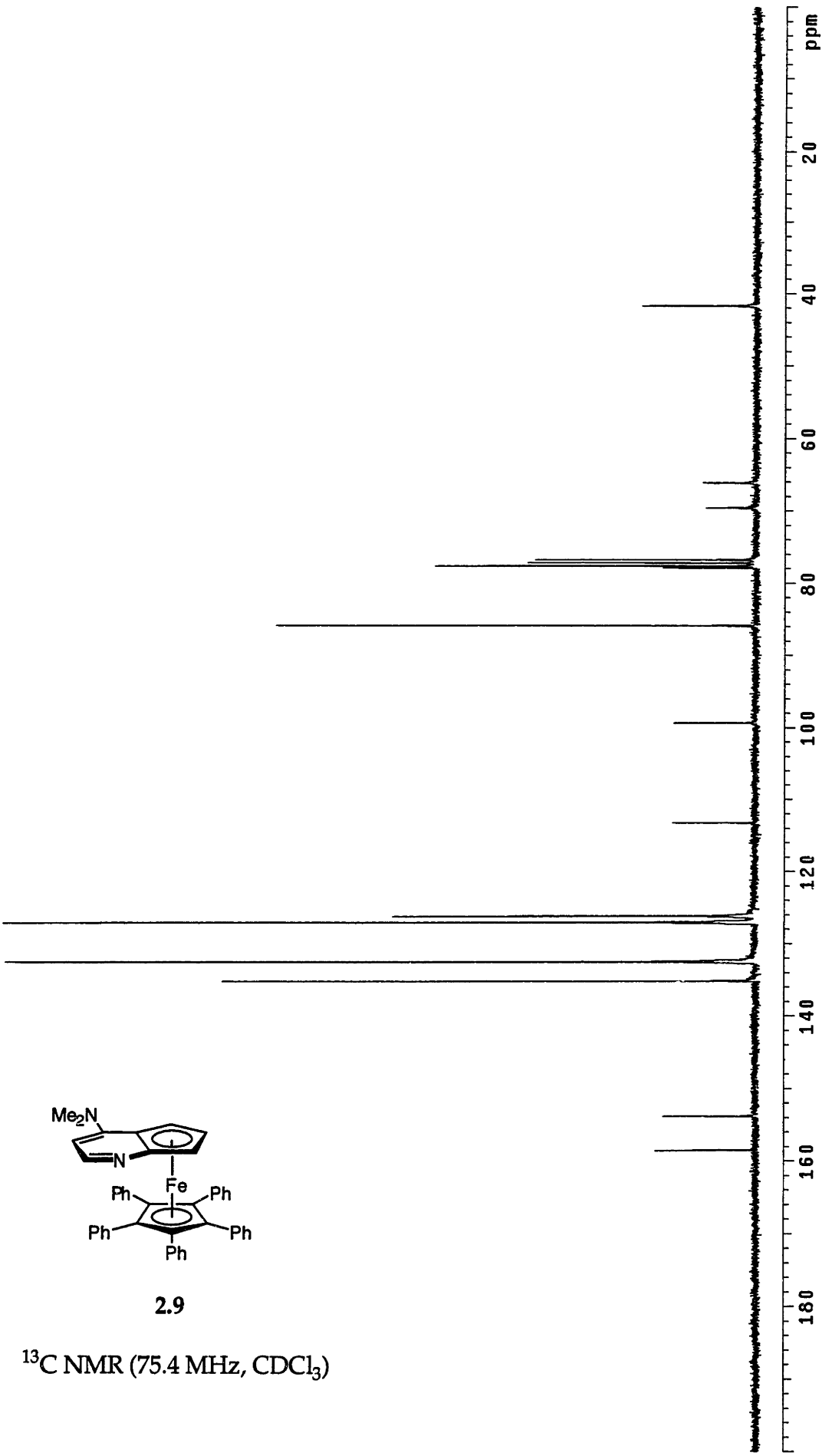
1.31

^{1}H NMR (300 MHz, $CDCl_3$)



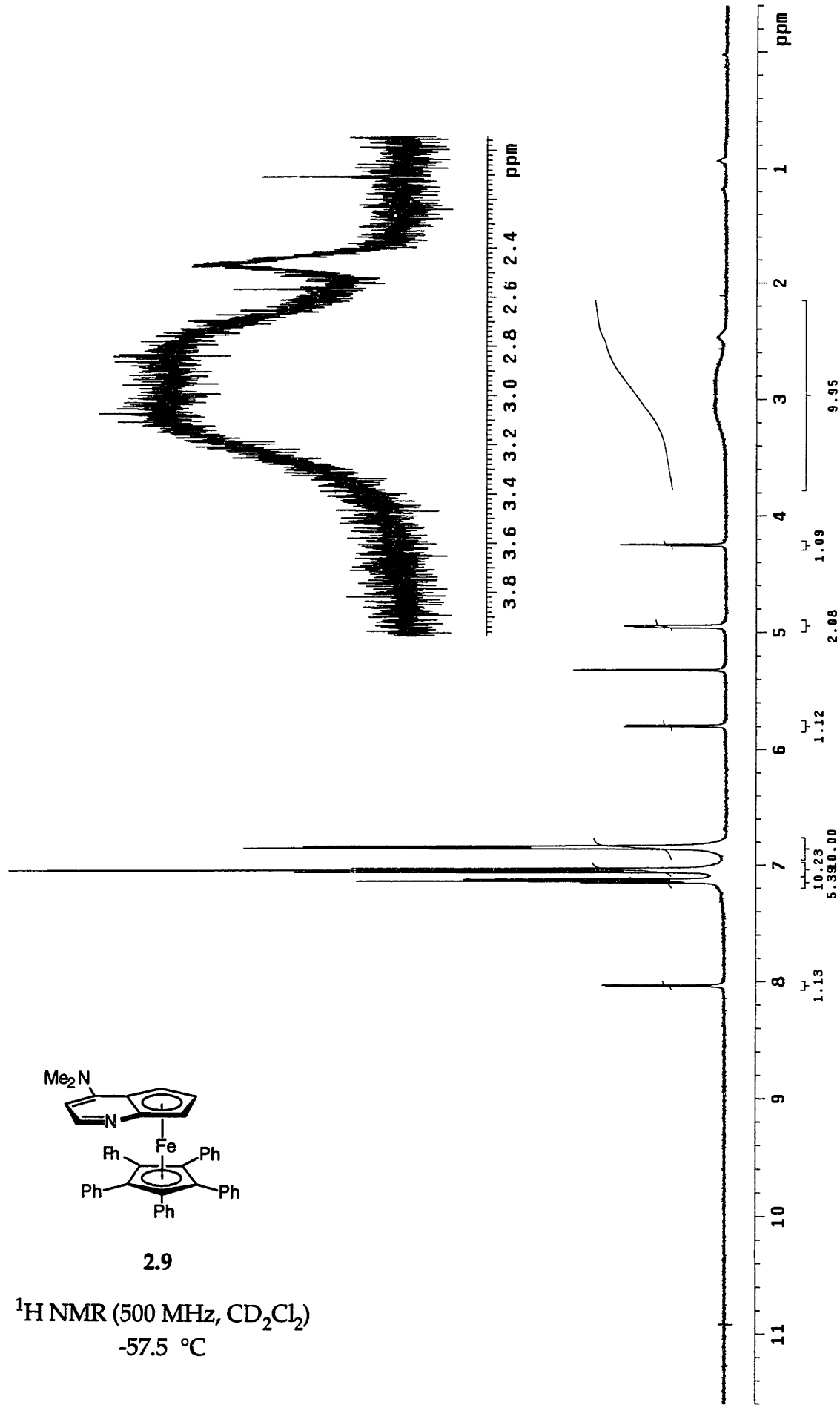
2.9

^{1}H NMR (300 MHz, $CDCl_3$)



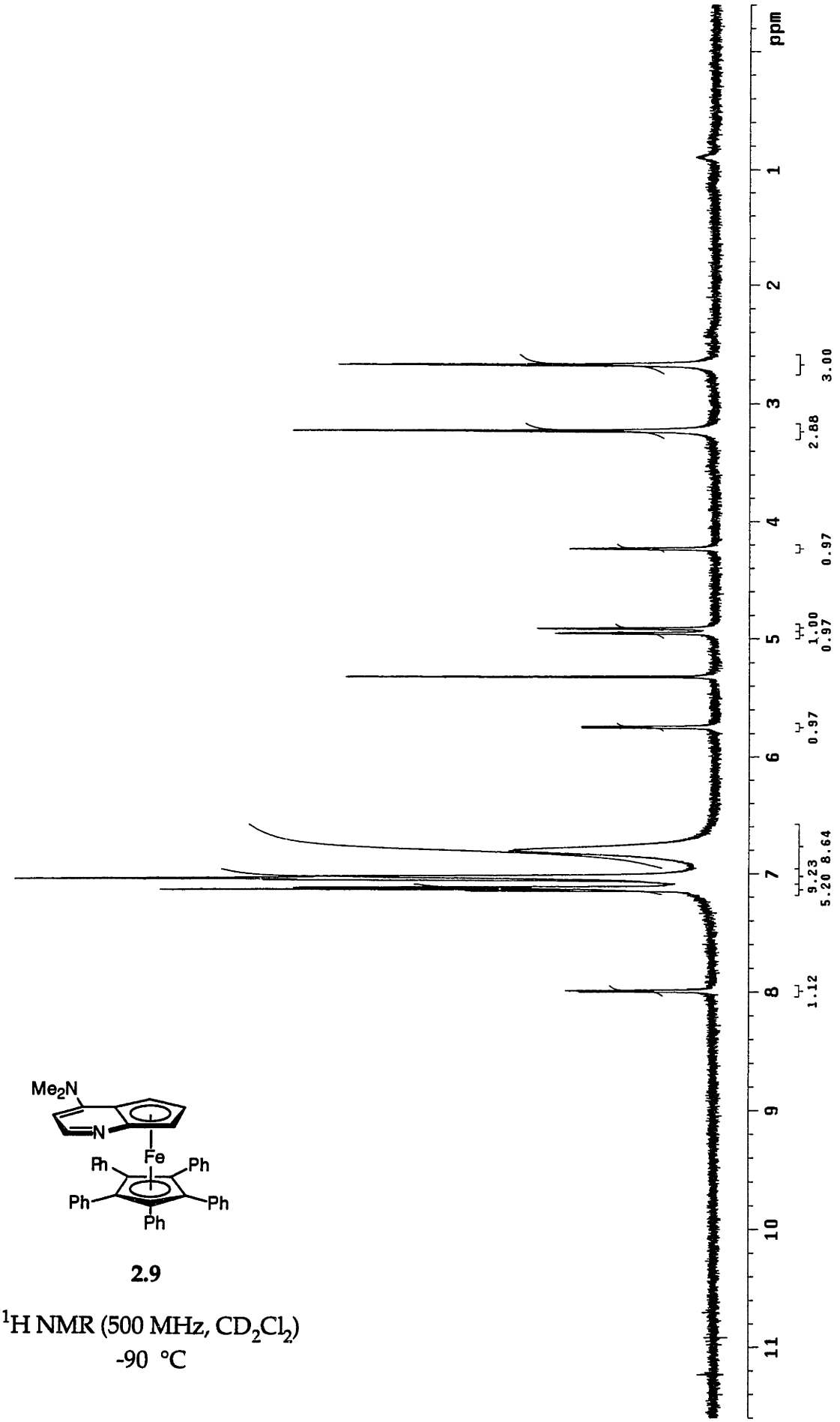
2.9

^{13}C NMR (75.4 MHz, $CDCl_3$)



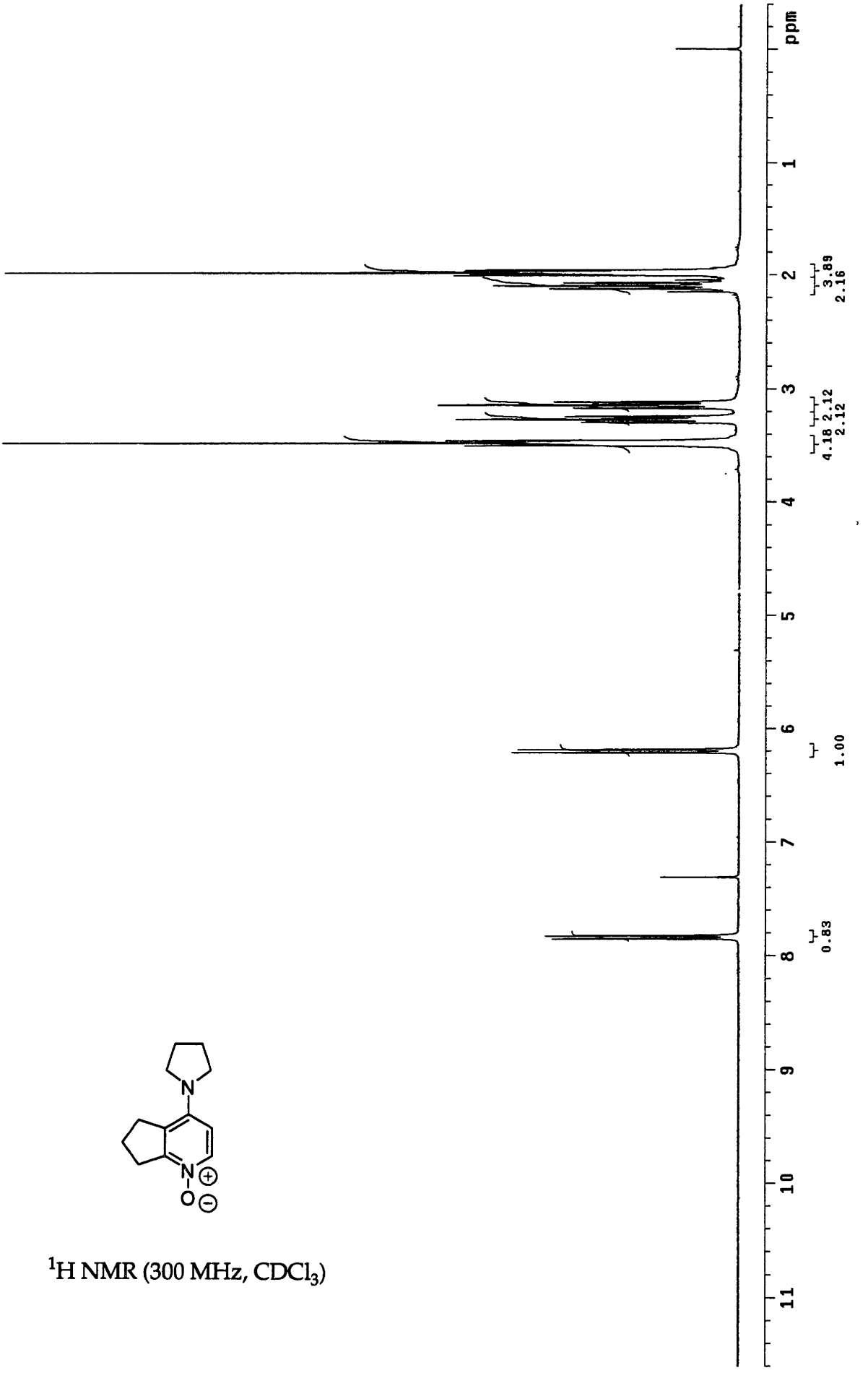
2.9

^{1}H NMR (500 MHz, CD_2Cl_2)
-57.5 °C

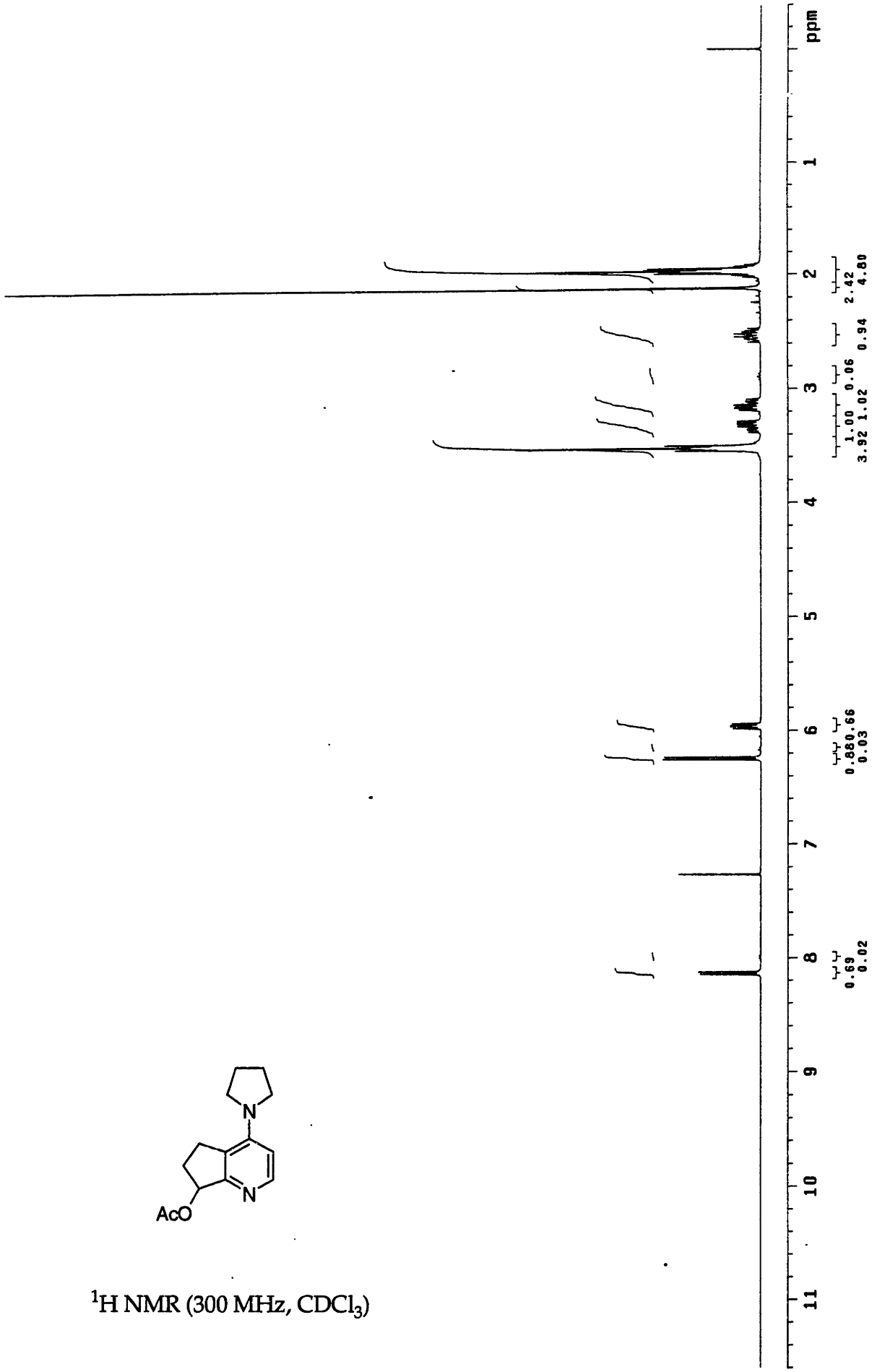


2.9

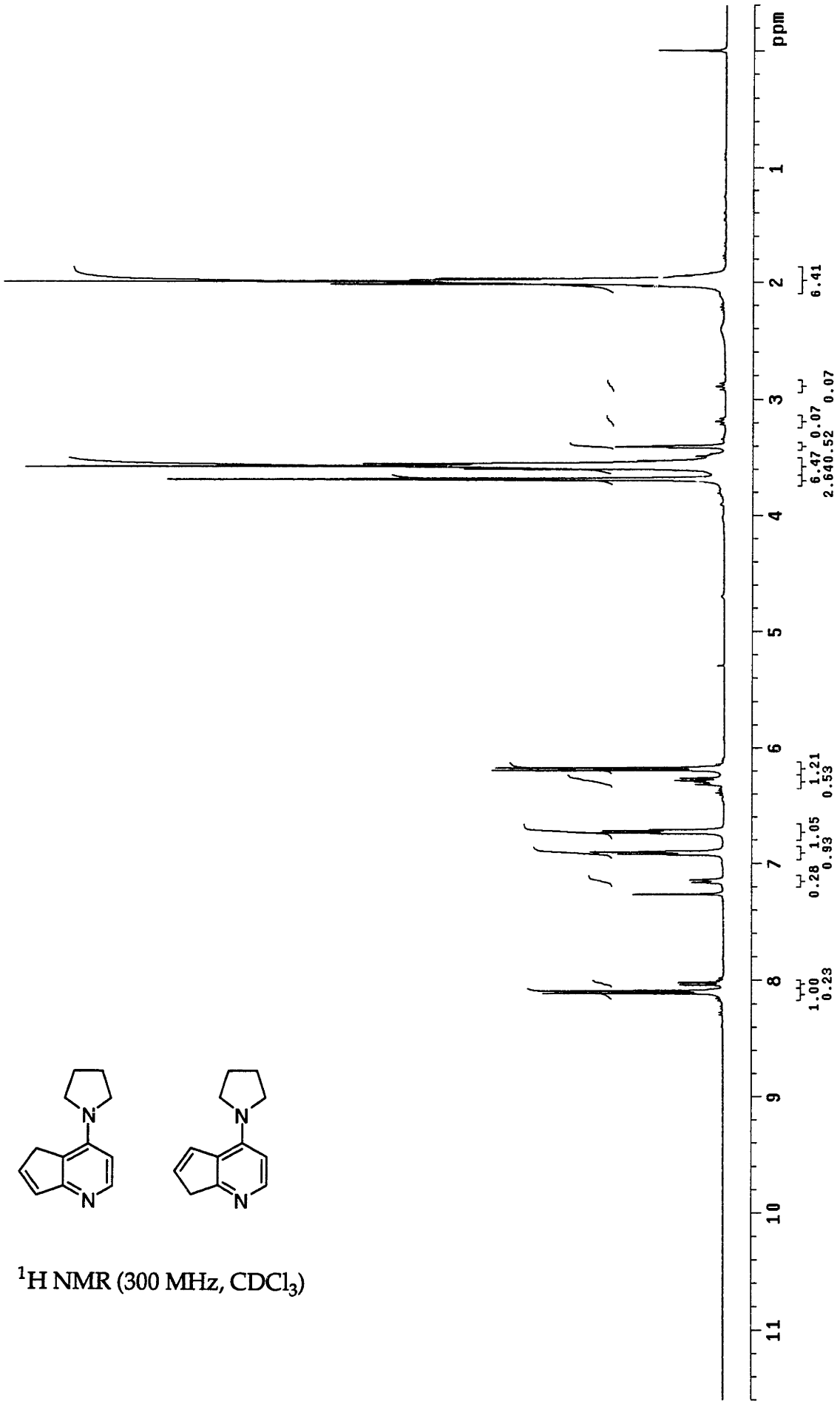
^{1}H NMR (500 MHz, CD_2Cl_2)
-90 °C



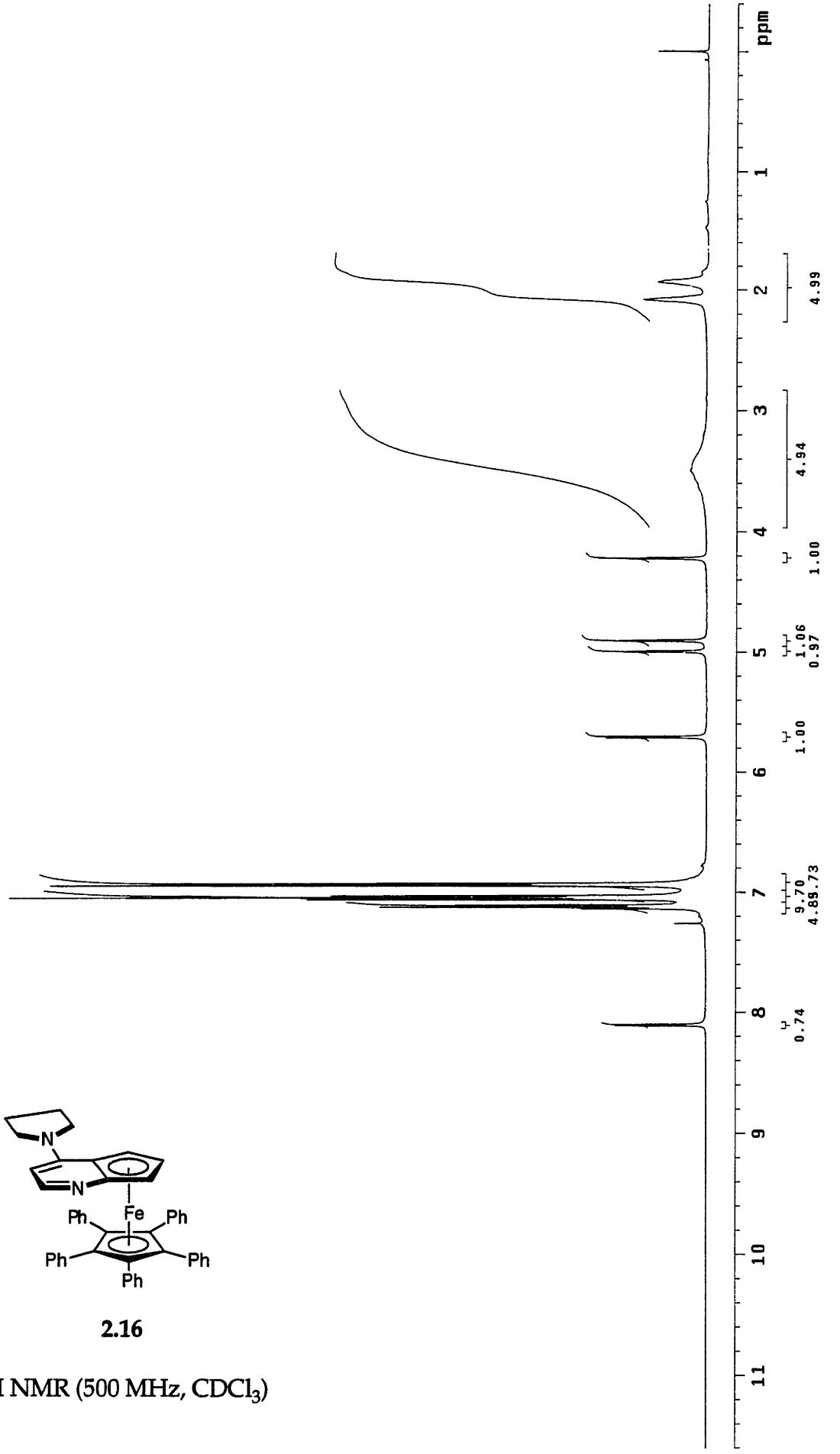
^{1}H NMR (300 MHz, $CDCl_3$)



^{1}H NMR (300 MHz, $CDCl_3$)

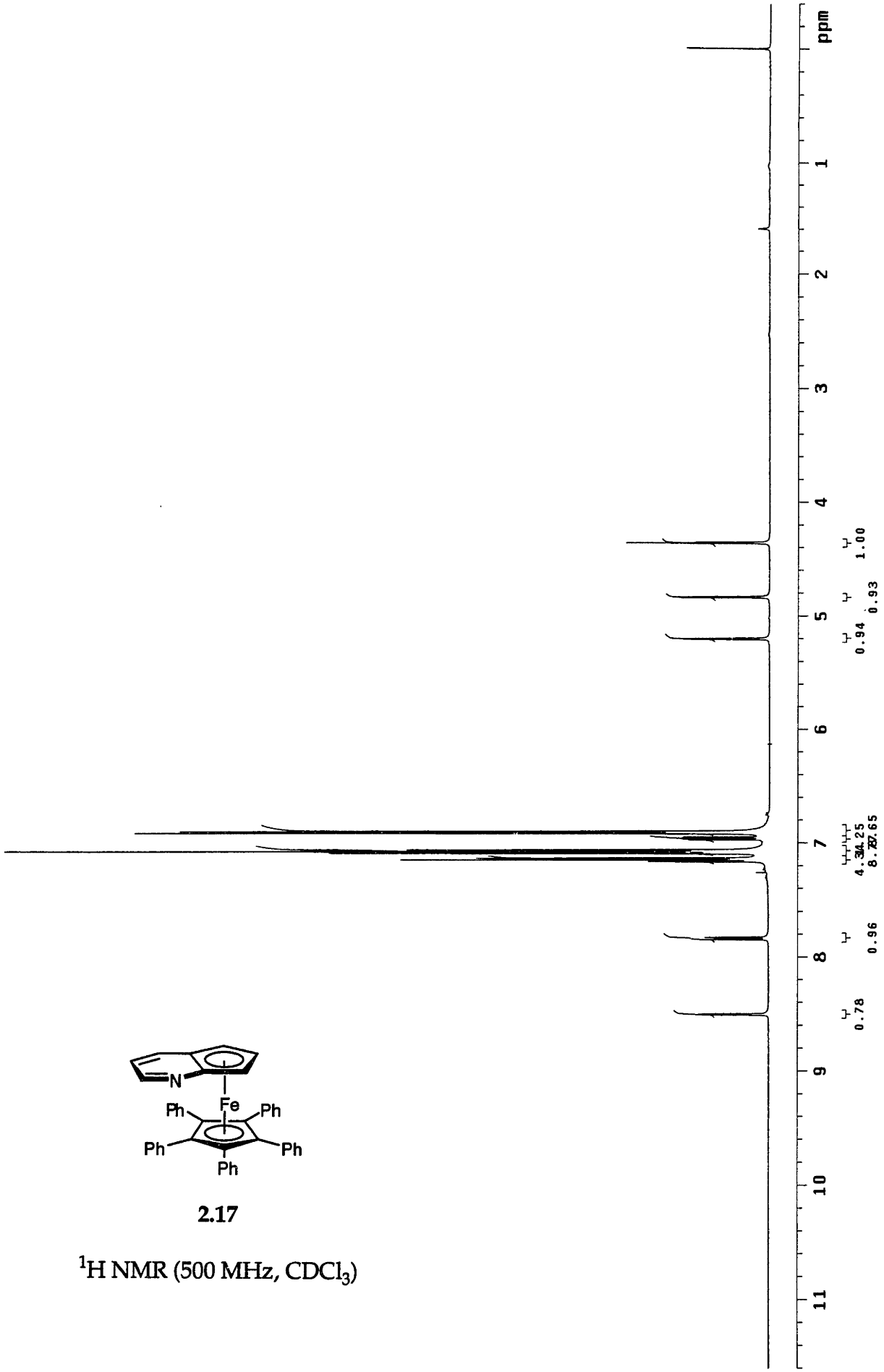


^{1}H NMR (300 MHz, $CDCl_3$)



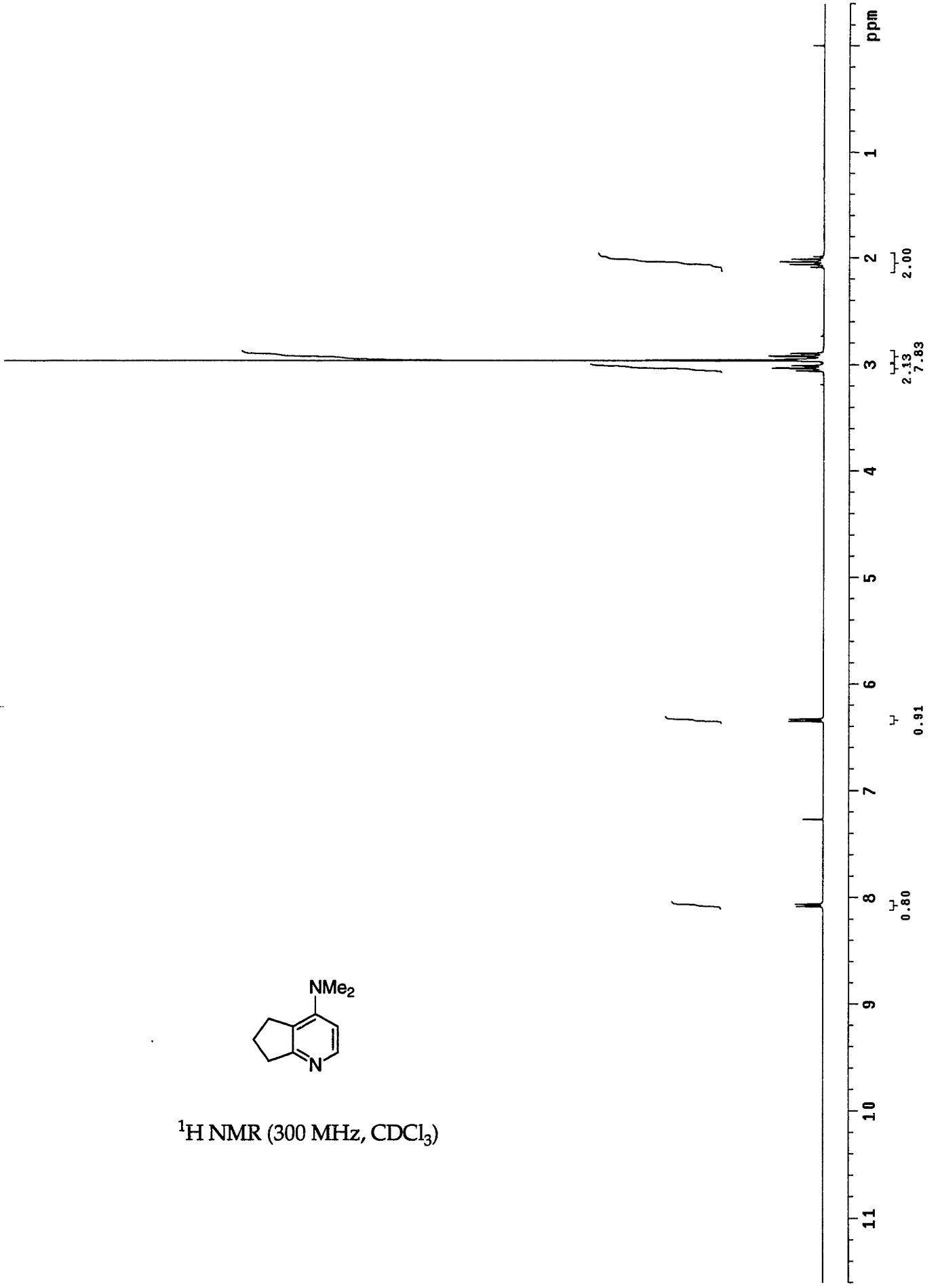
2.16

^{1}H NMR (500 MHz, $CDCl_3$)

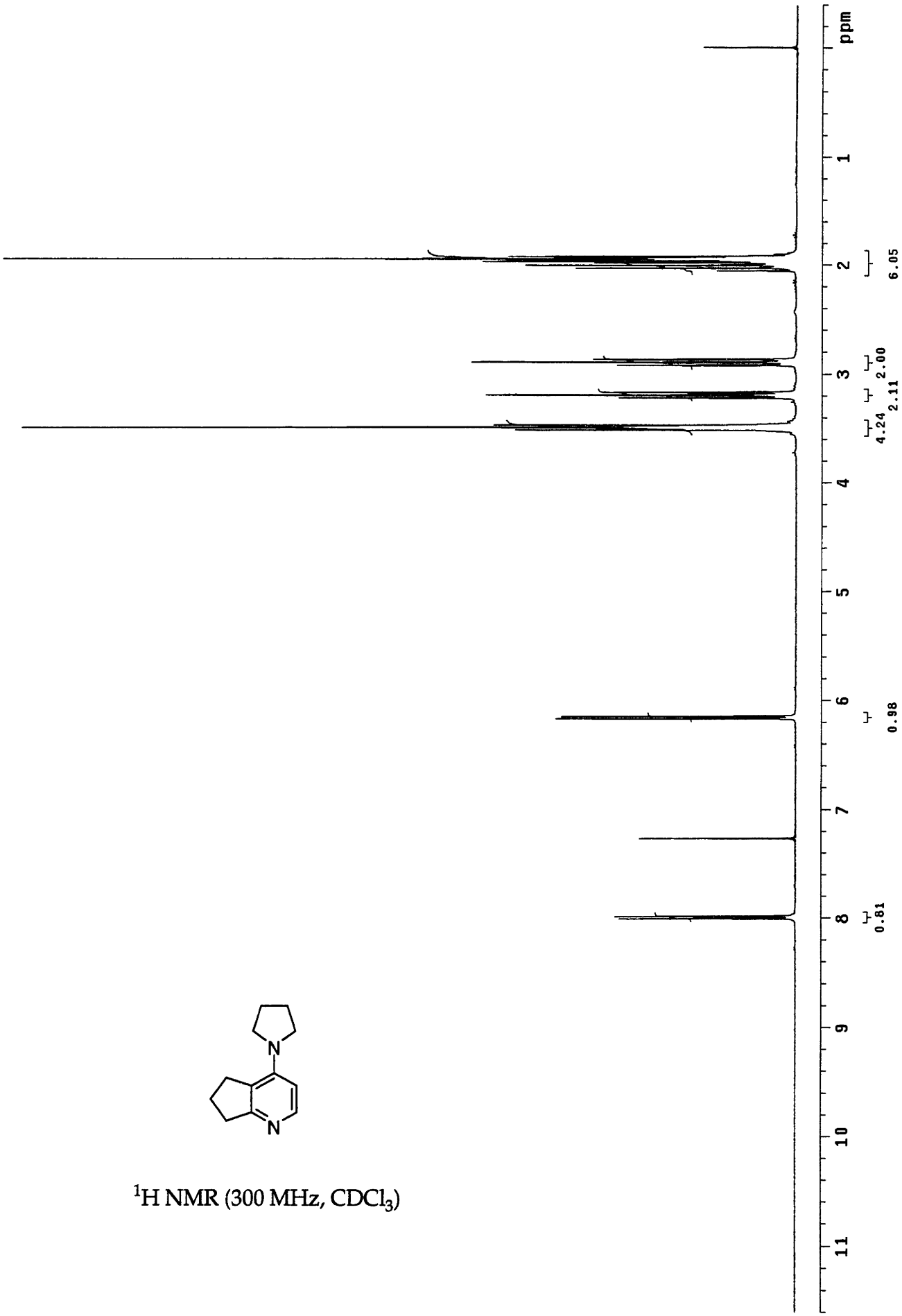


2.17

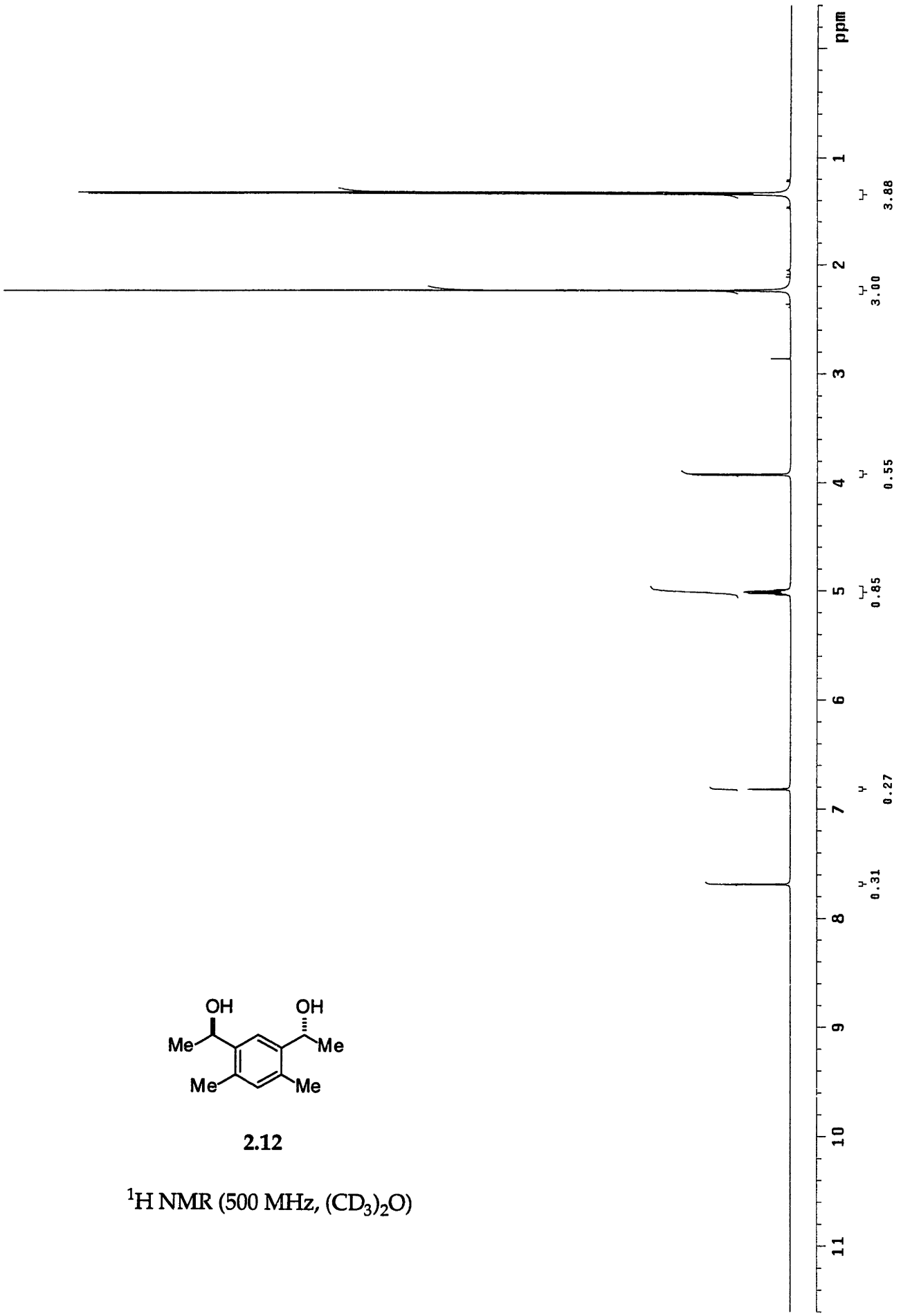
^{1}H NMR (500 MHz, $CDCl_3$)



^{1}H NMR (300 MHz, $CDCl_3$)

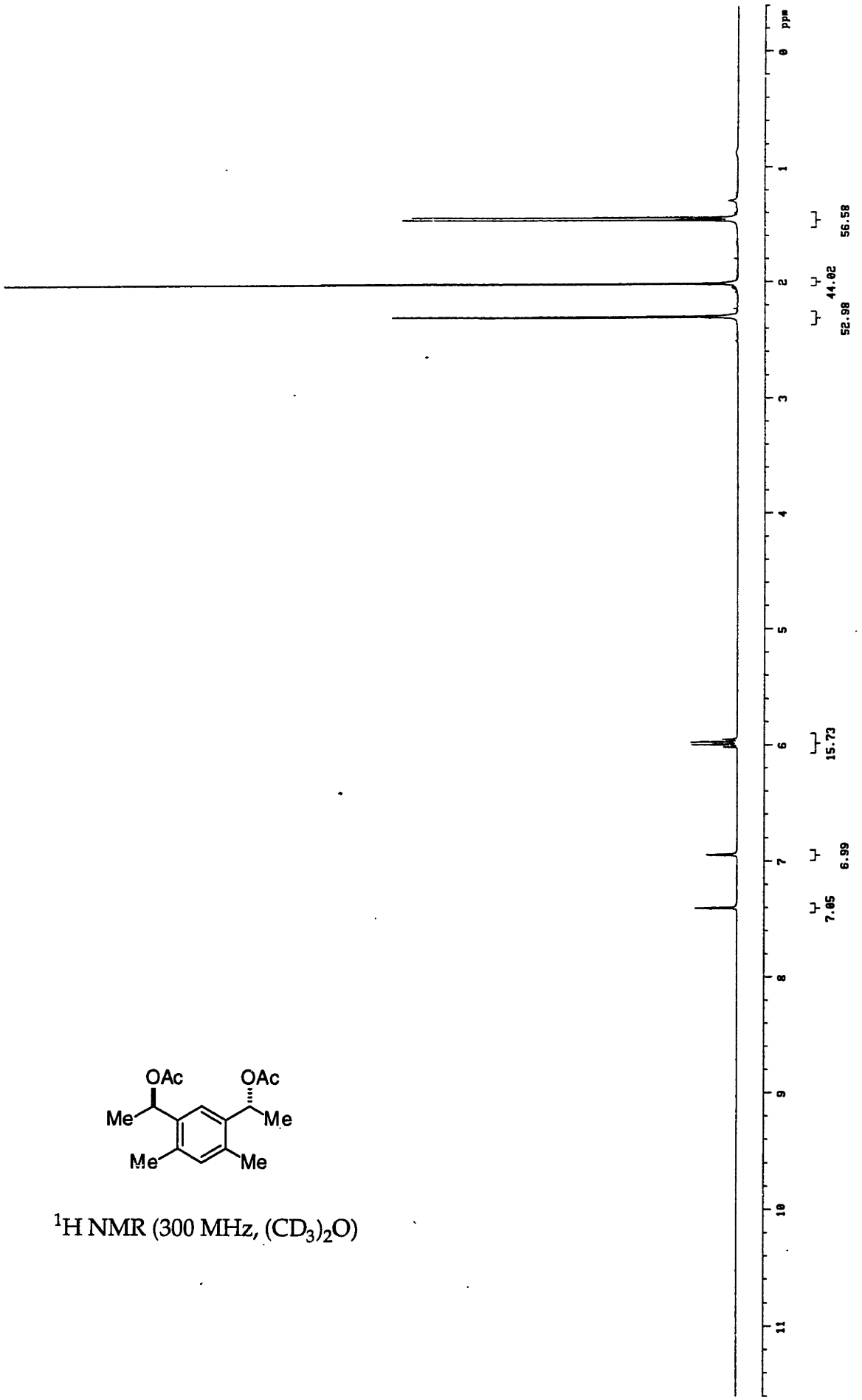


^{1}H NMR (300 MHz, $CDCl_3$)

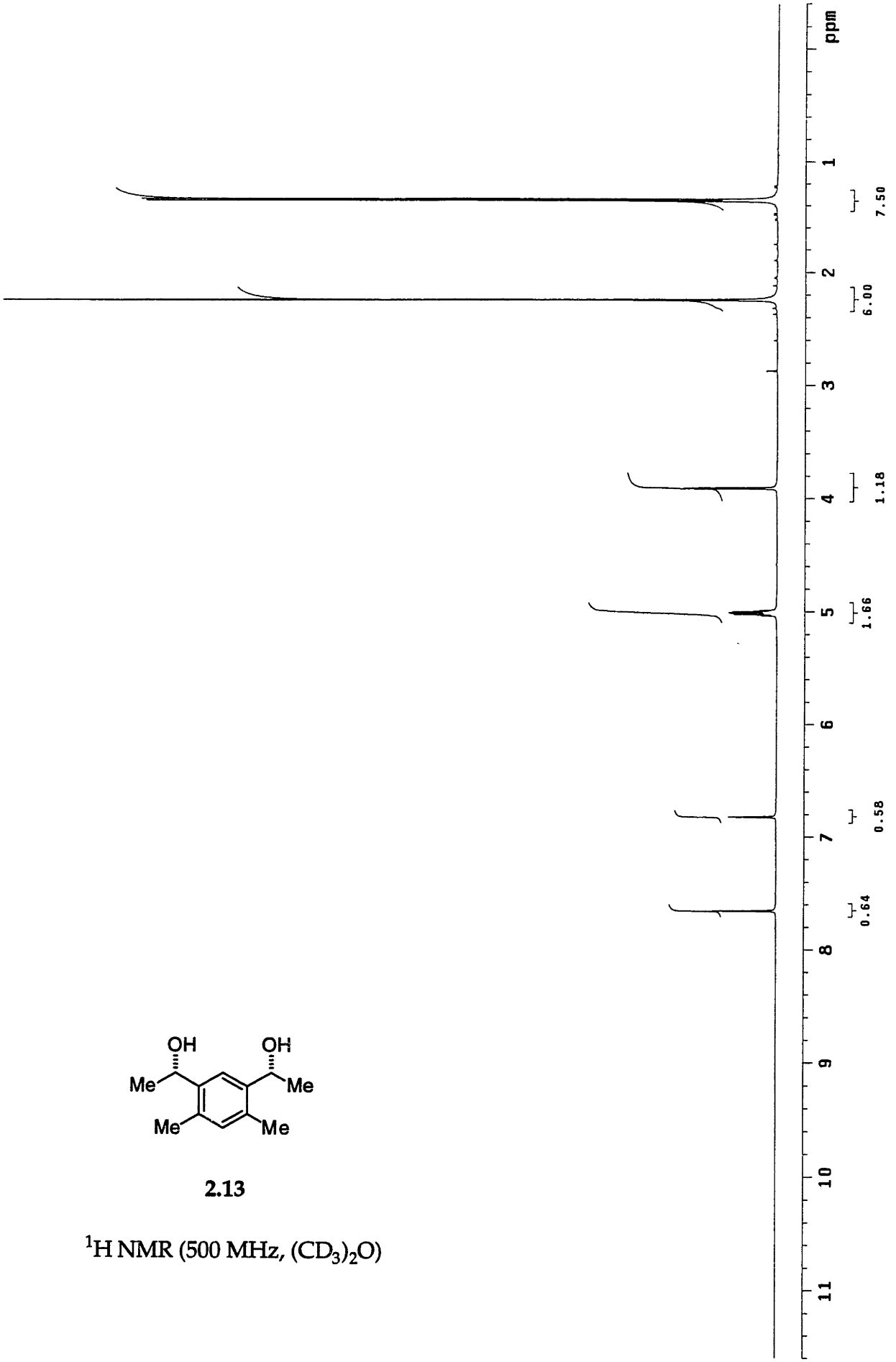


2.12

^{1}H NMR (500 MHz, $(CD_3)_2O$)

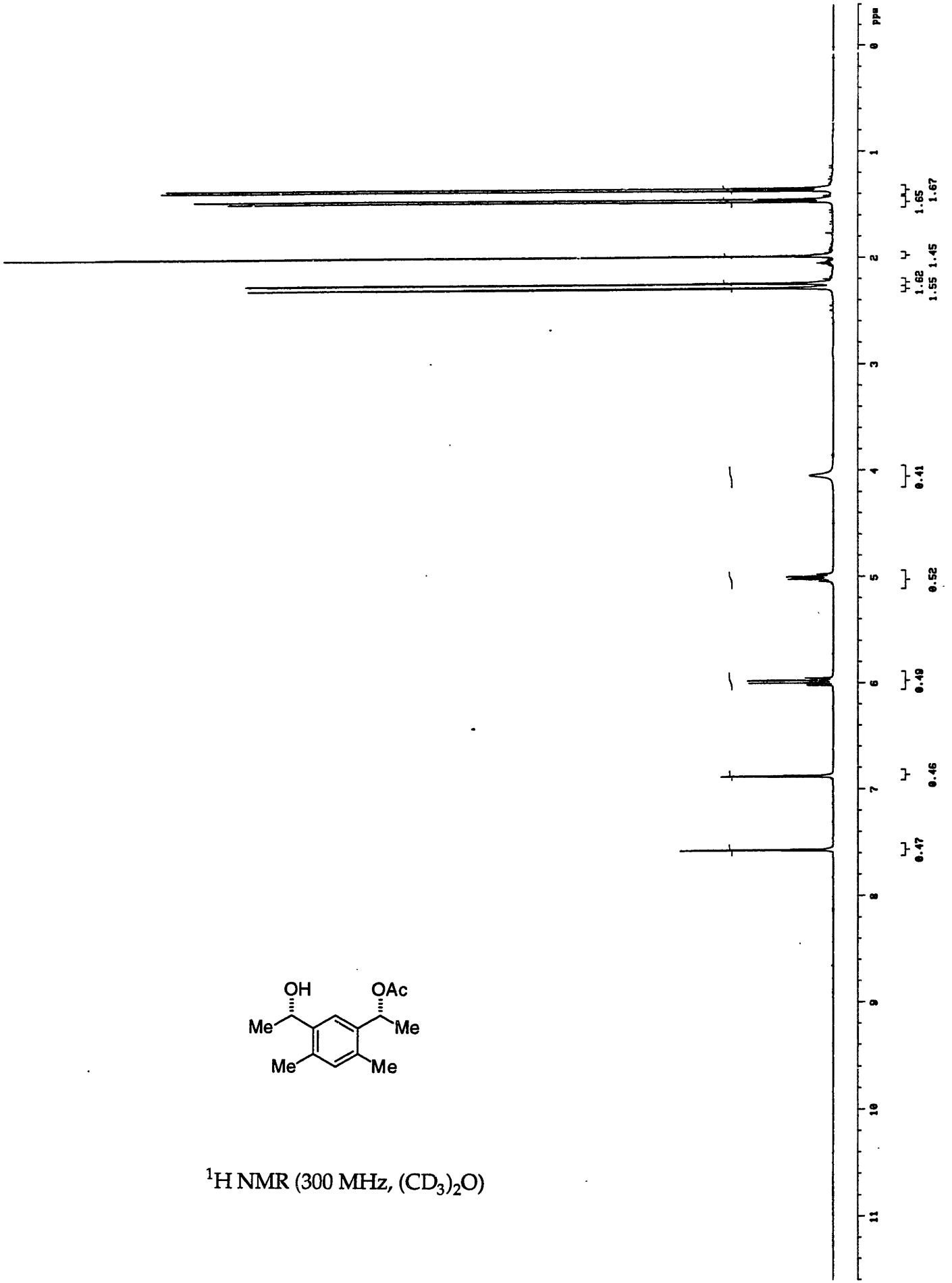


^{1}H NMR (300 MHz, $(CD_3)_2O$)

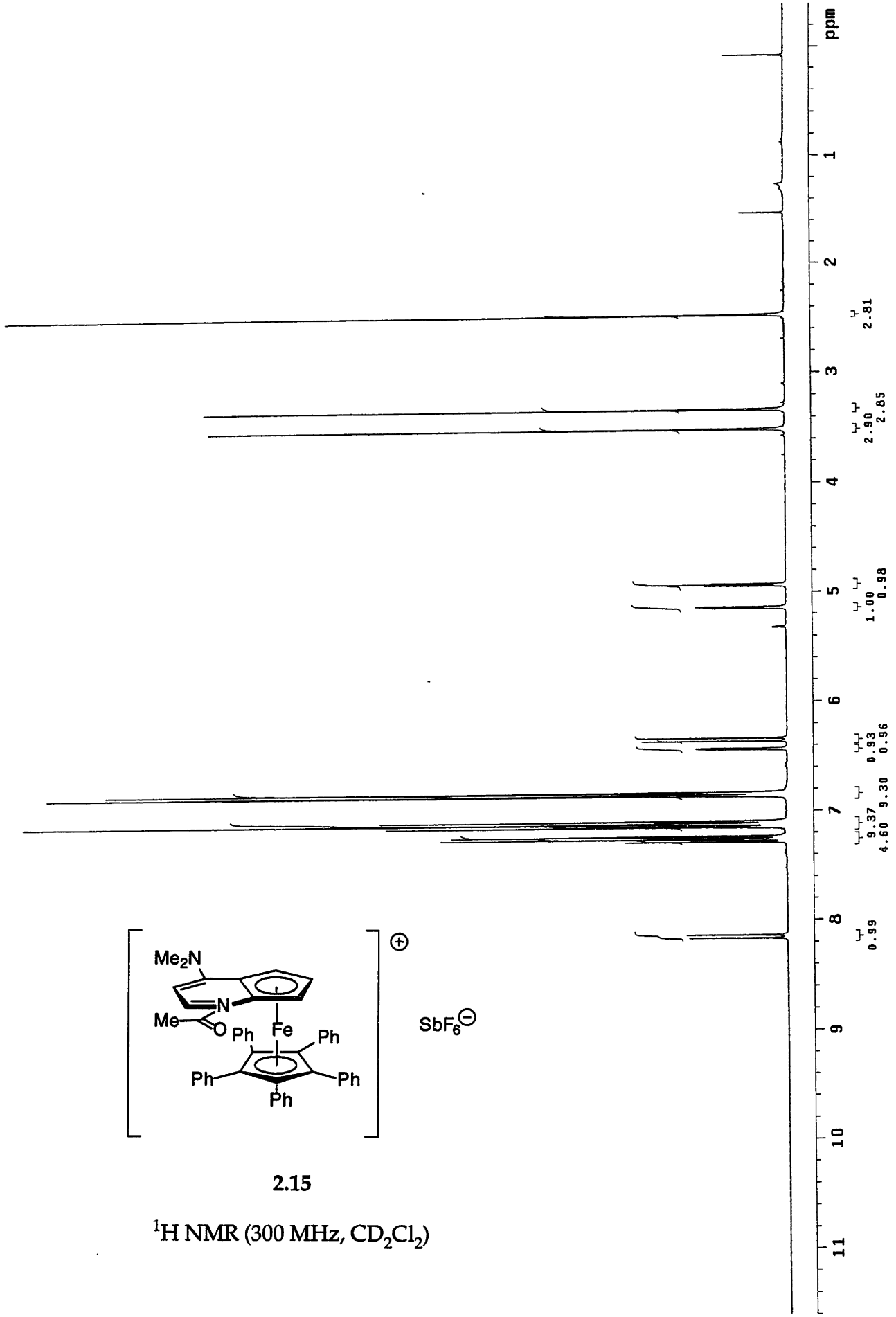


2.13

^{1}H NMR (500 MHz, $(CD_3)_2O$)

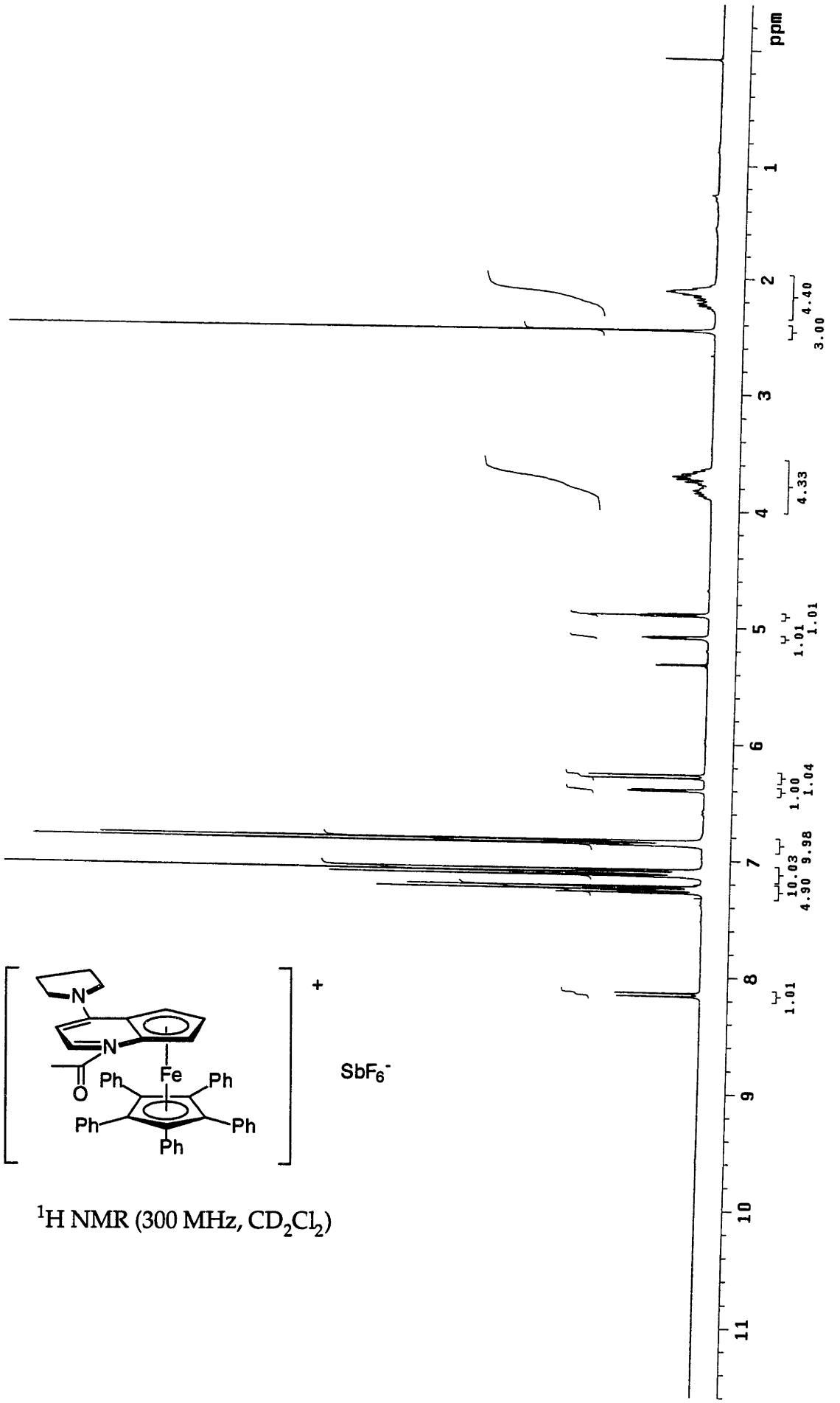


^{1}H NMR (300 MHz, $(CD_3)_2O$)

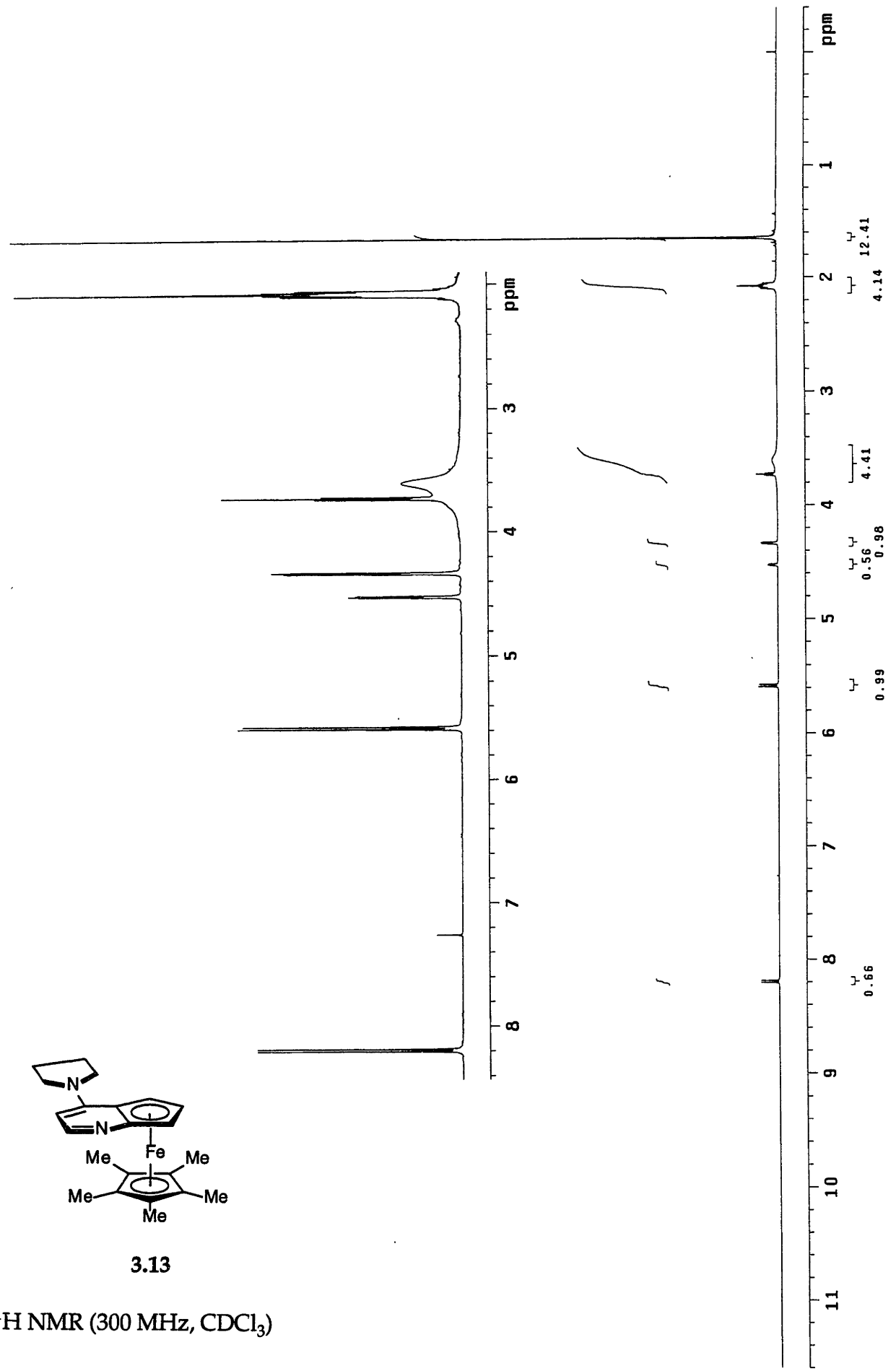


2.15

^{1}H NMR (300 MHz, CD_2Cl_2)

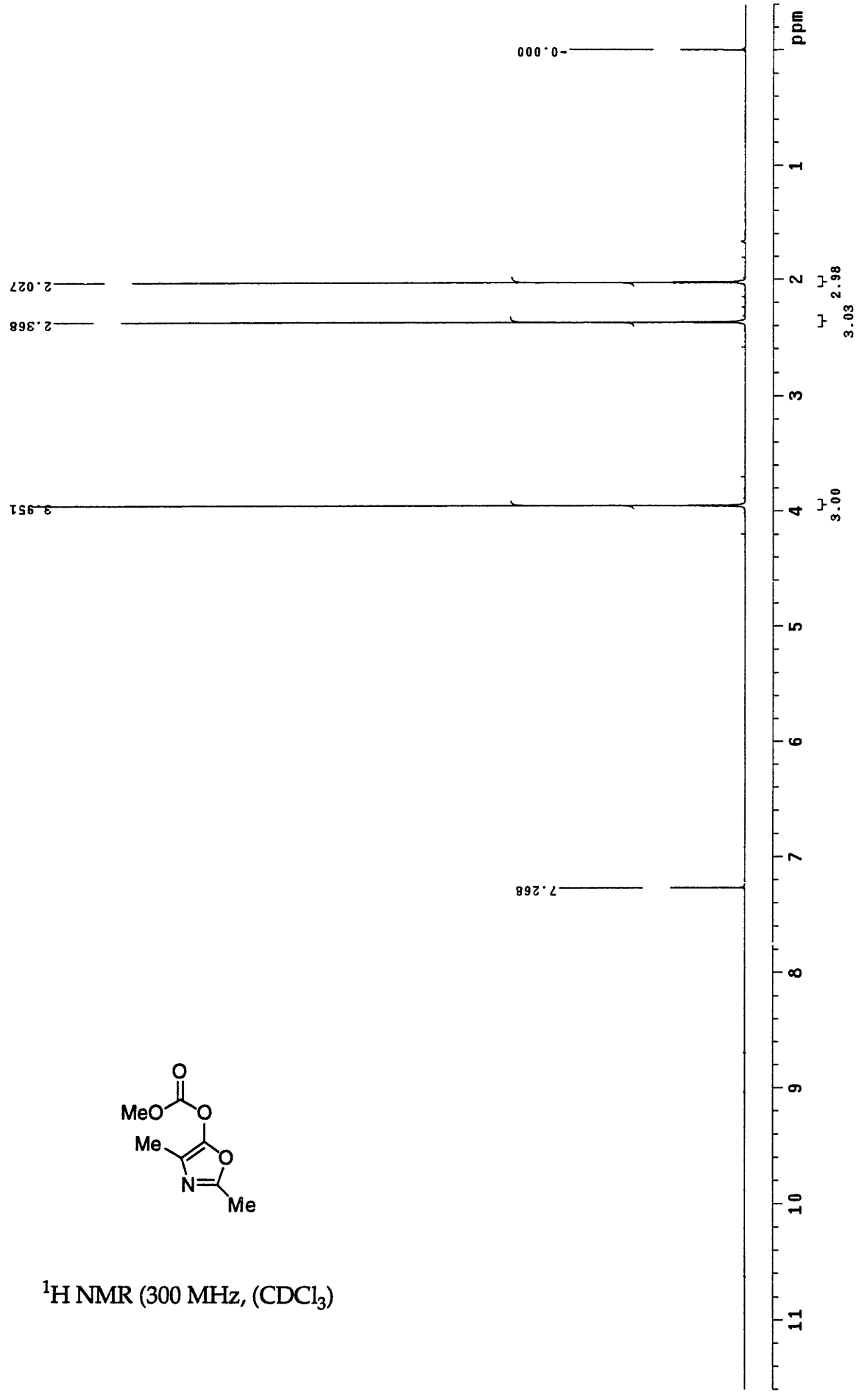


^{1}H NMR (300 MHz, CD_2Cl_2)

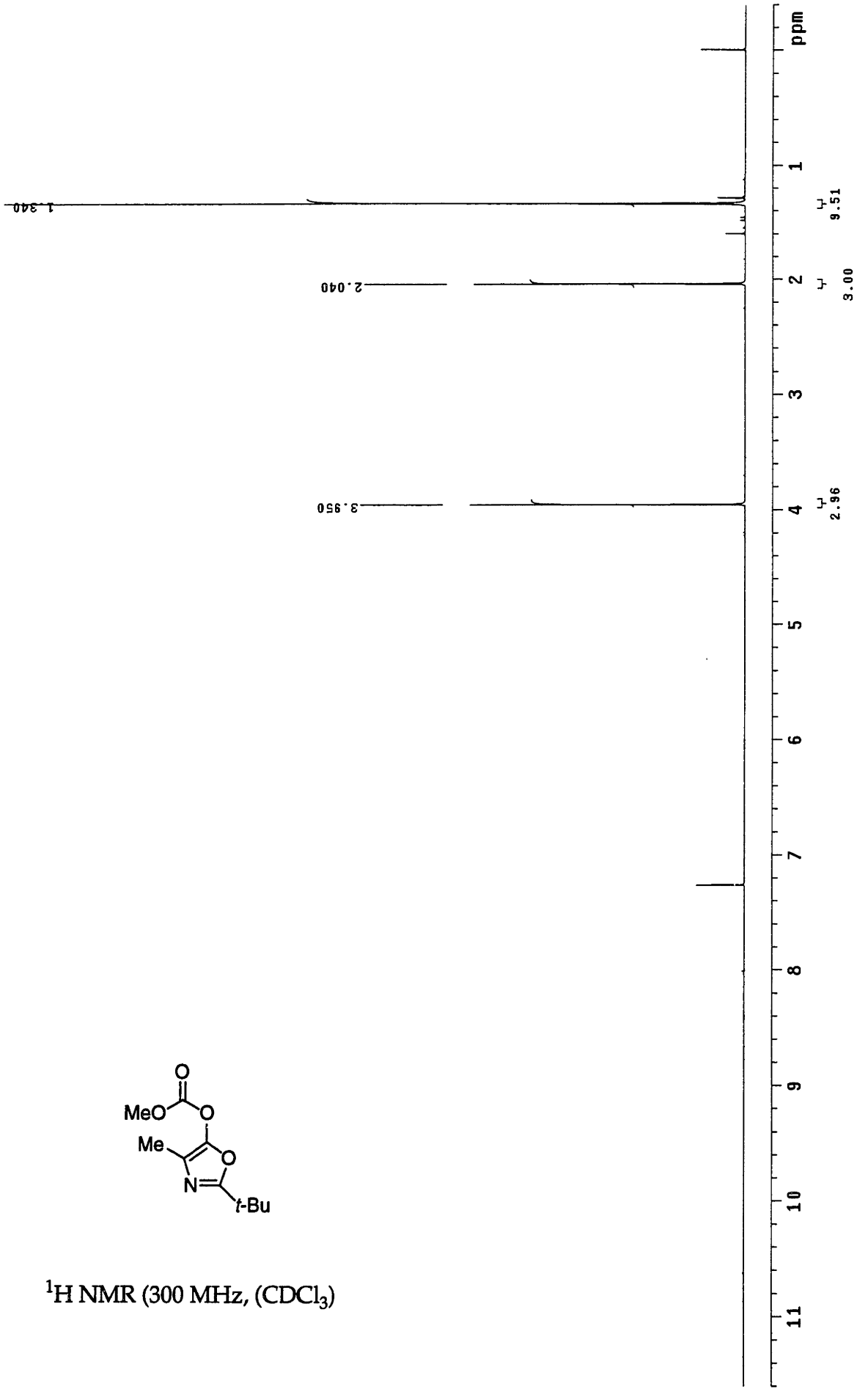


3.13

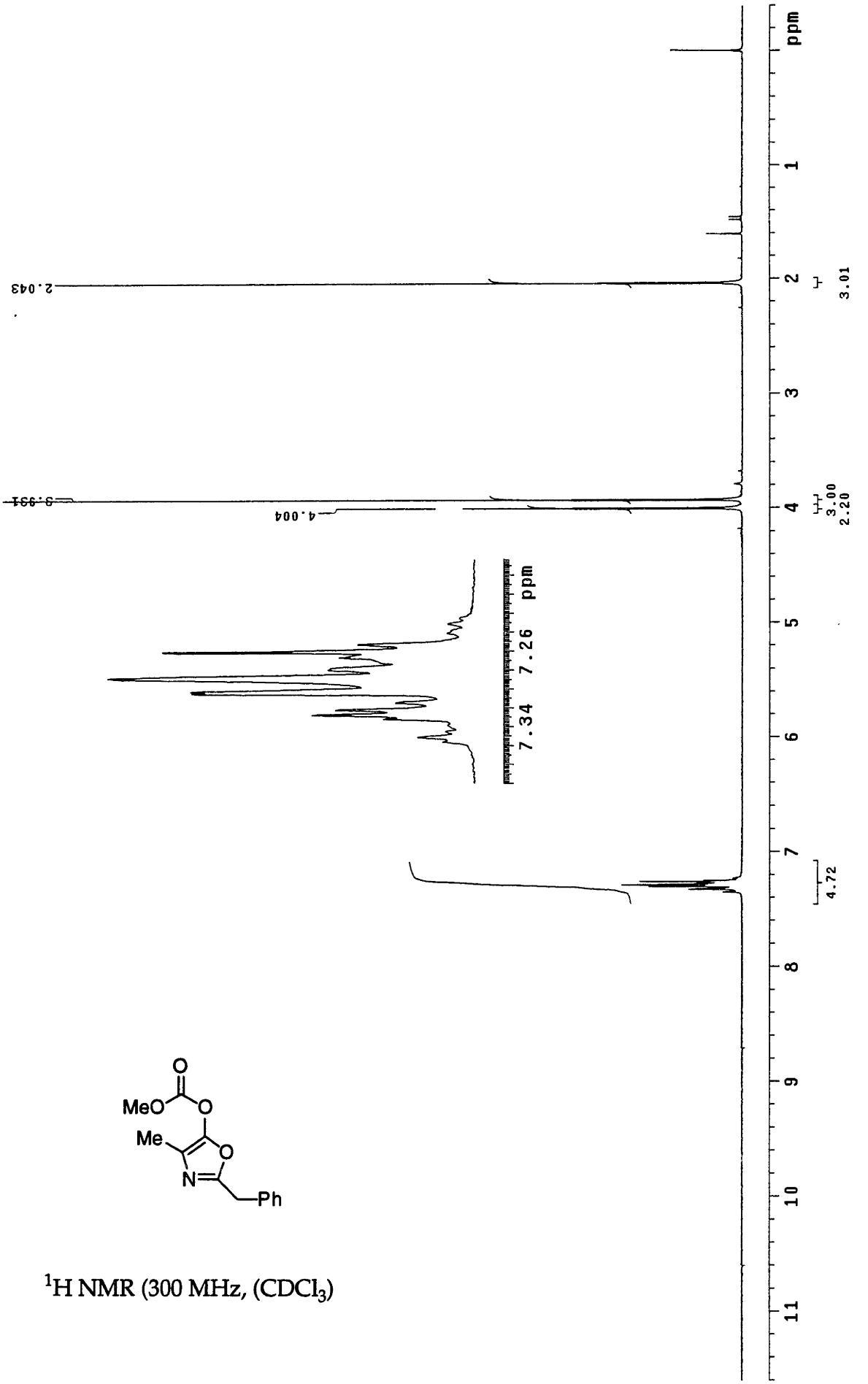
^{1}H NMR (300 MHz, $CDCl_3$)



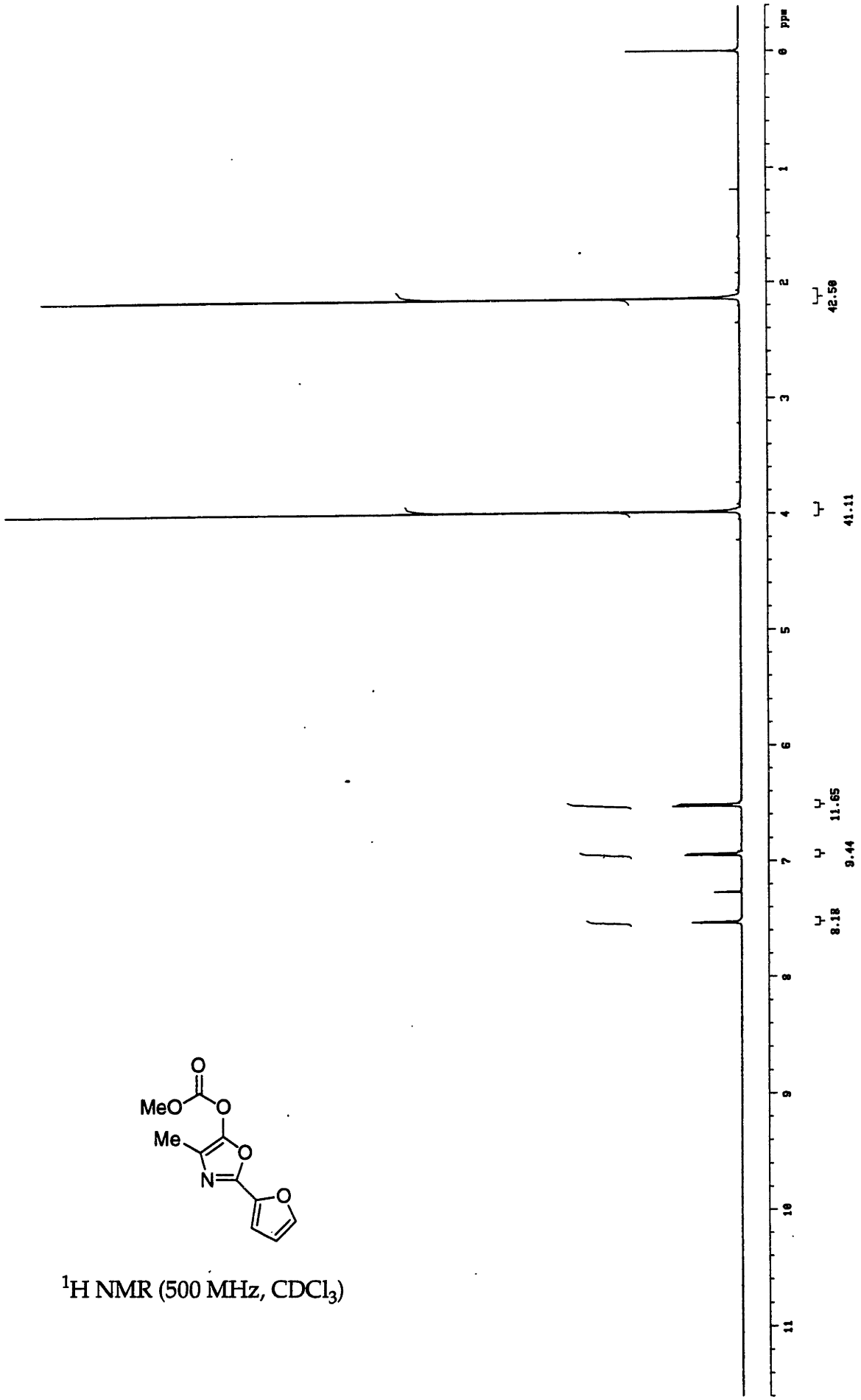
^{1}H NMR (300 MHz, ($CDCl_3$)



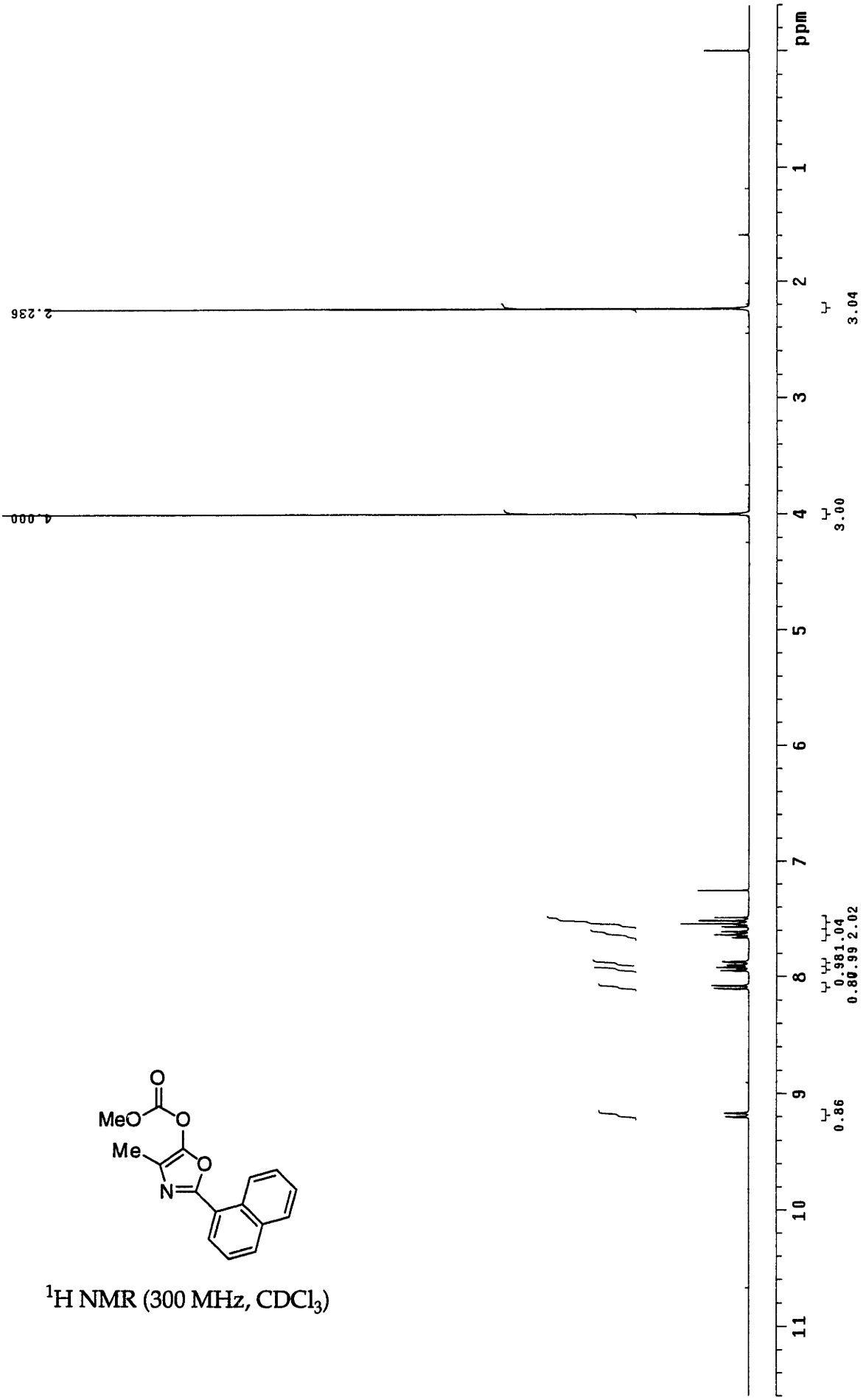
^{1}H NMR (300 MHz, ($CDCl_3$)



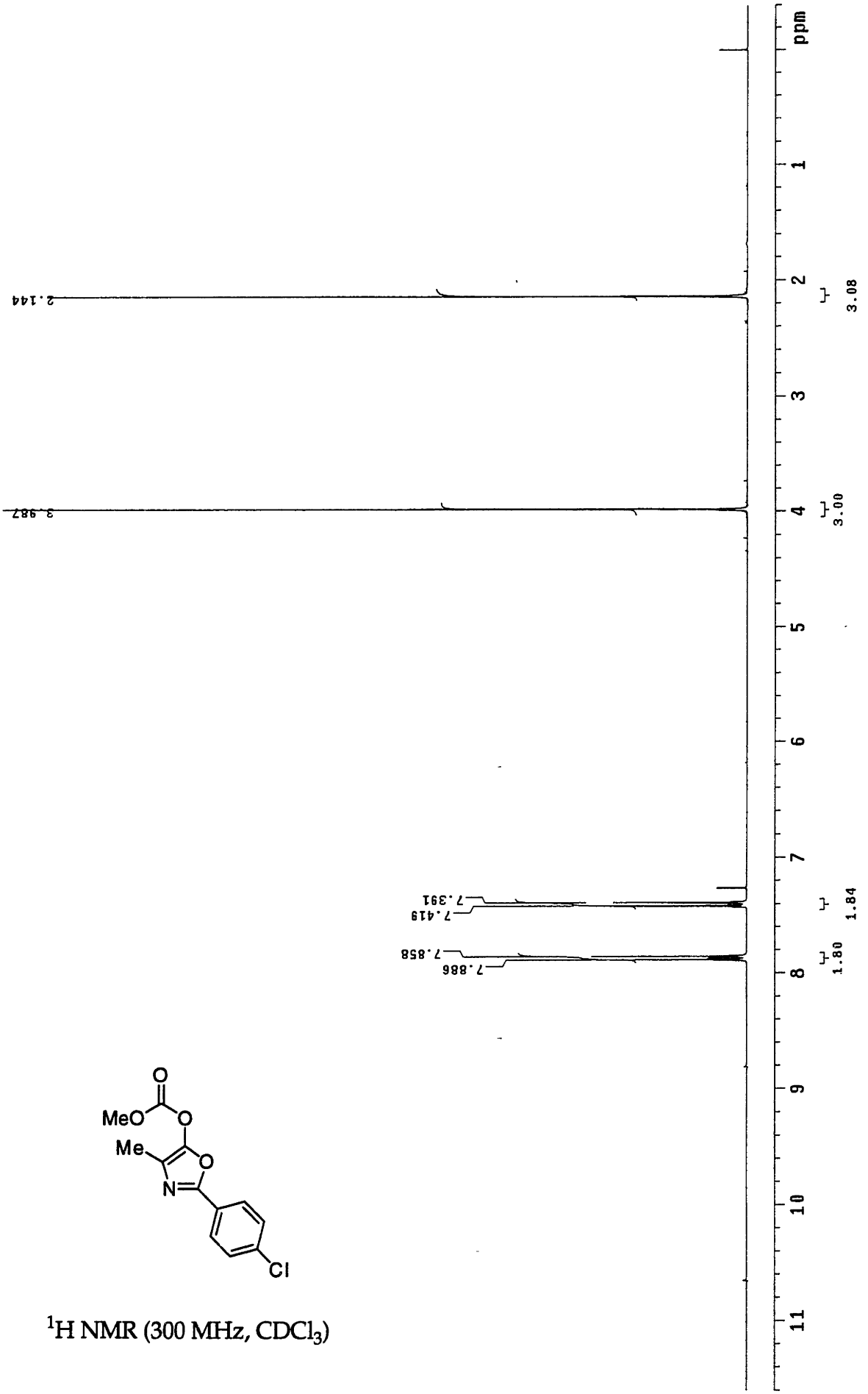
^{1}H NMR (300 MHz, ($CDCl_3$)



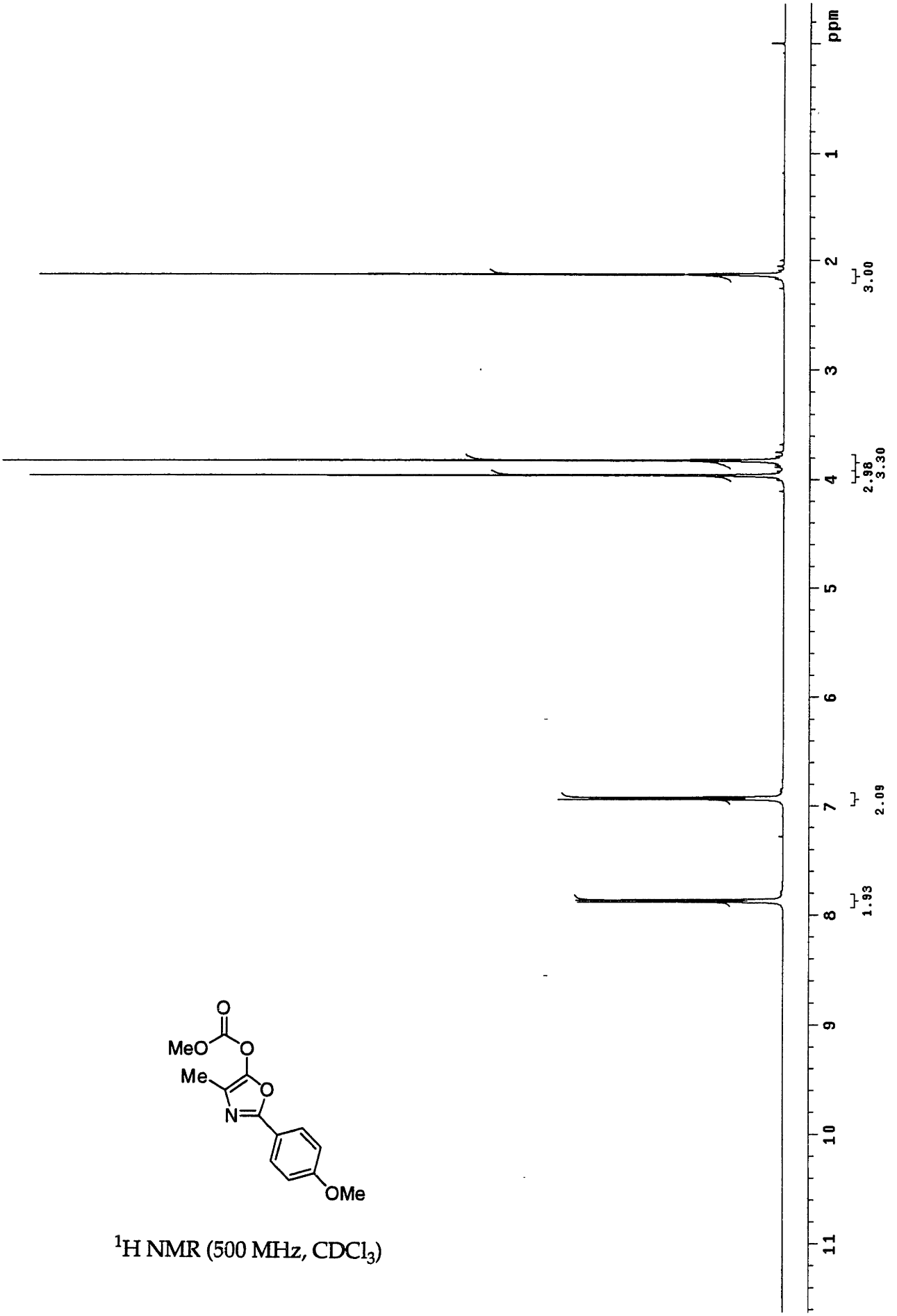
^{1}H NMR (500 MHz, $CDCl_3$)



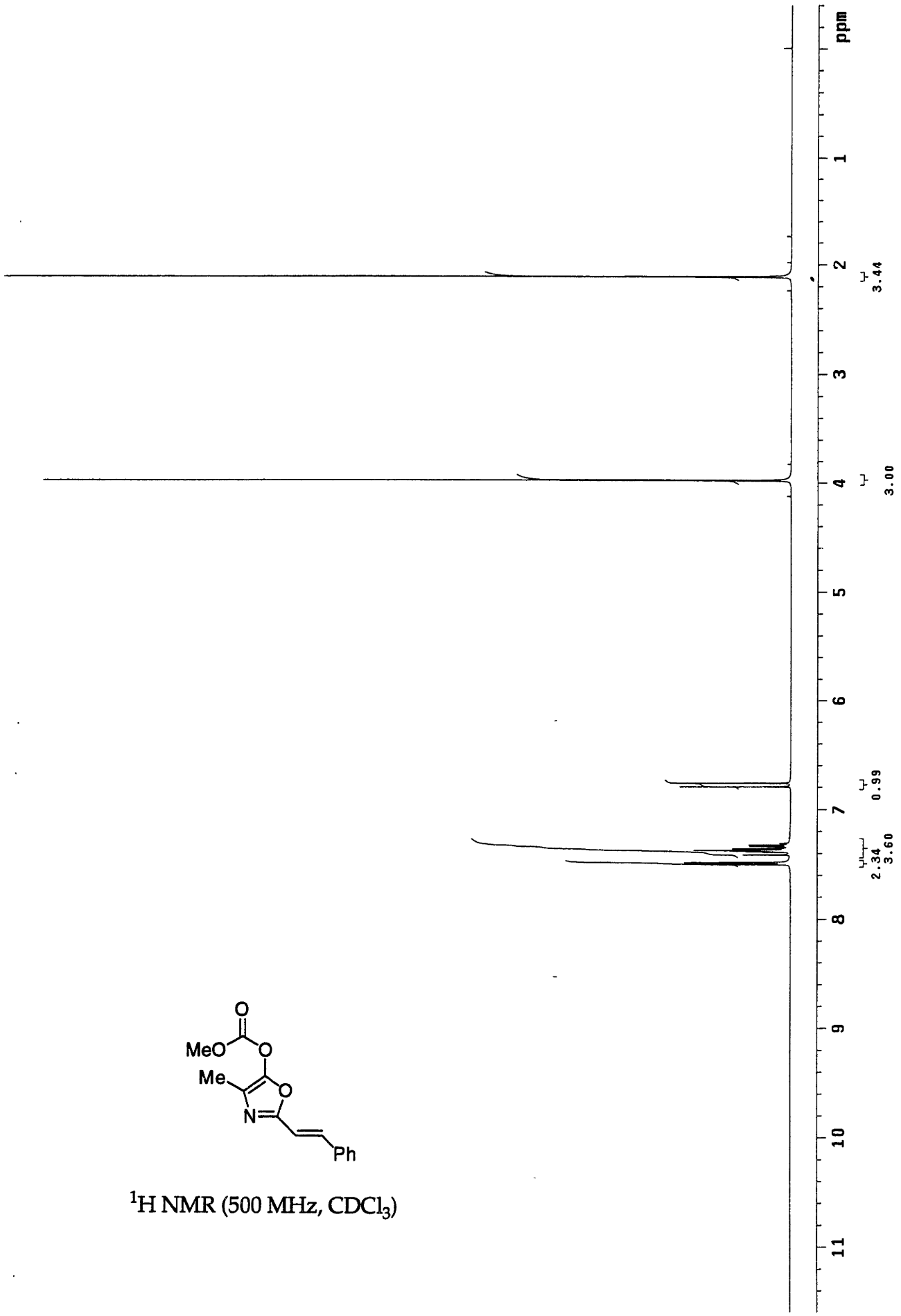
^{1}H NMR (300 MHz, $CDCl_3$)



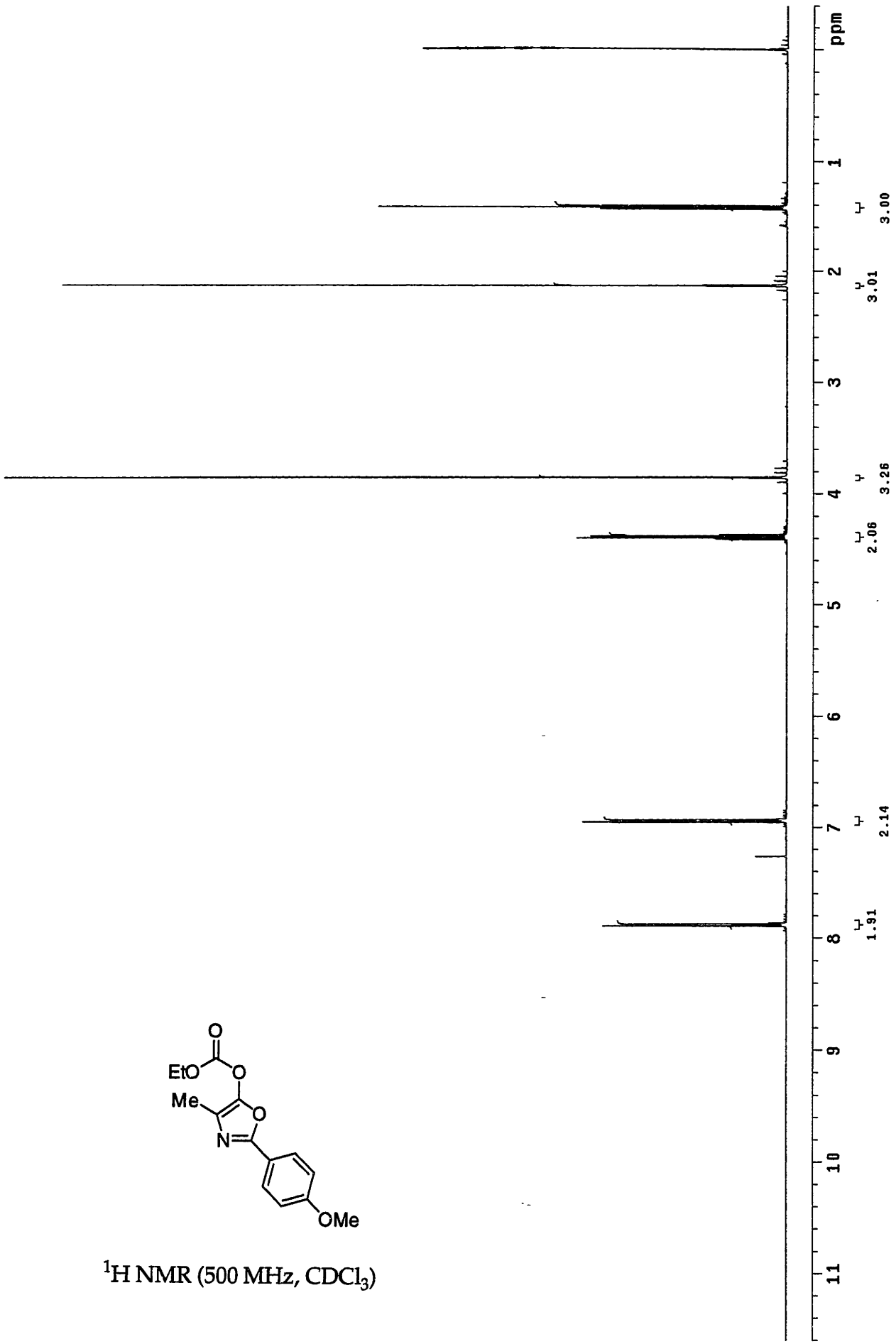
^{1}H NMR (300 MHz, $CDCl_3$)



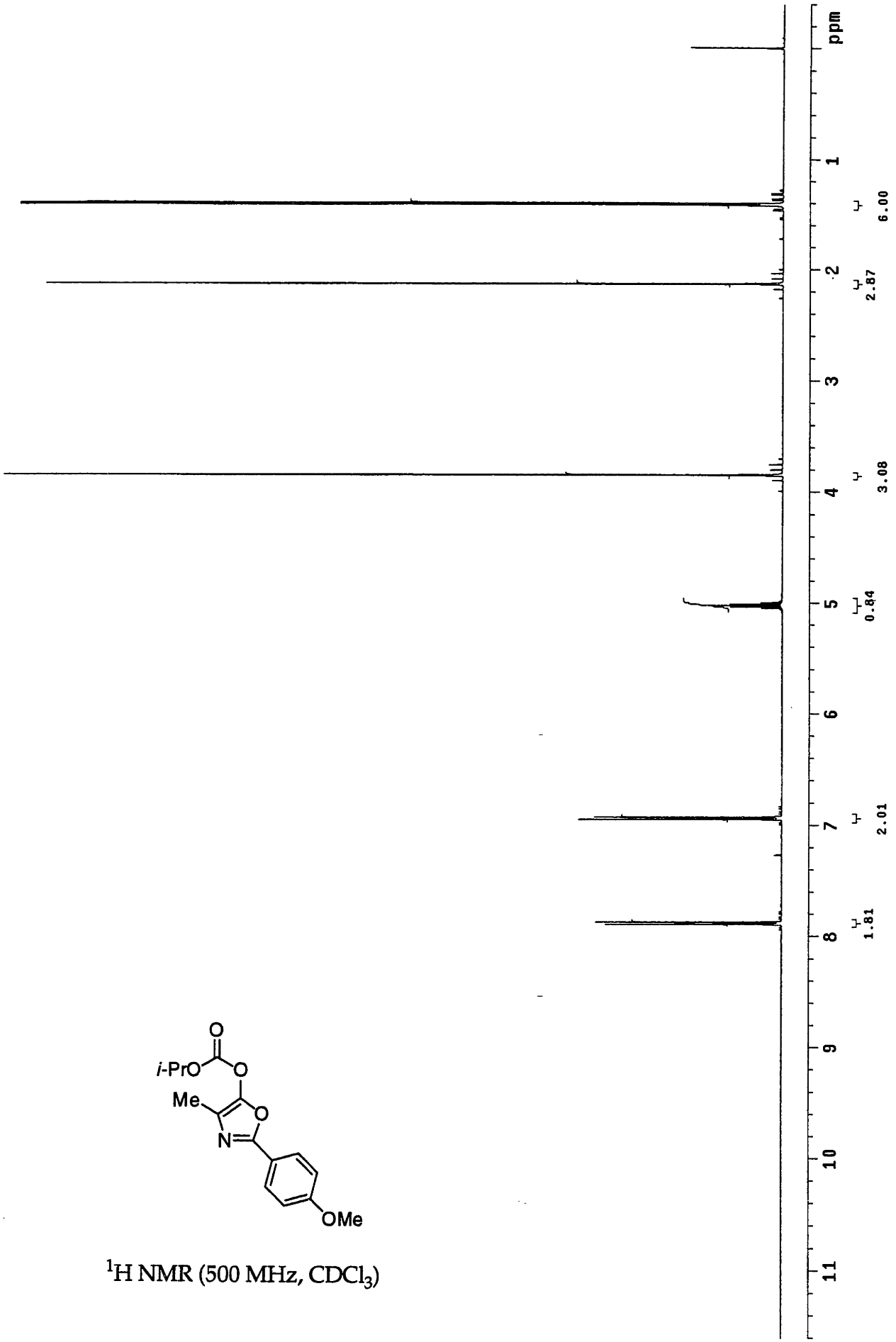
^{1}H NMR (500 MHz, $CDCl_3$)



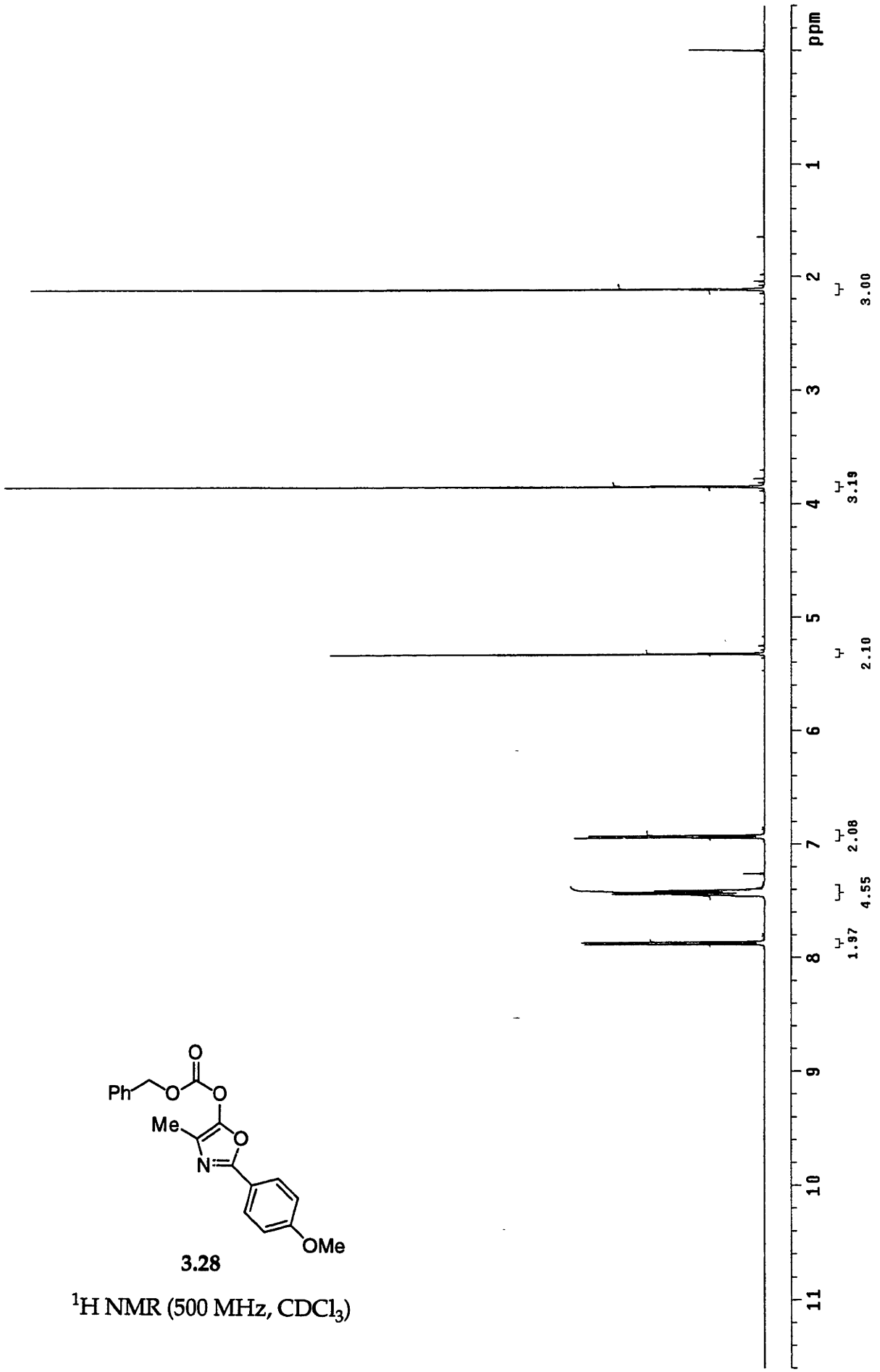
^{1}H NMR (500 MHz, $CDCl_3$)



^{1}H NMR (500 MHz, $CDCl_3$)

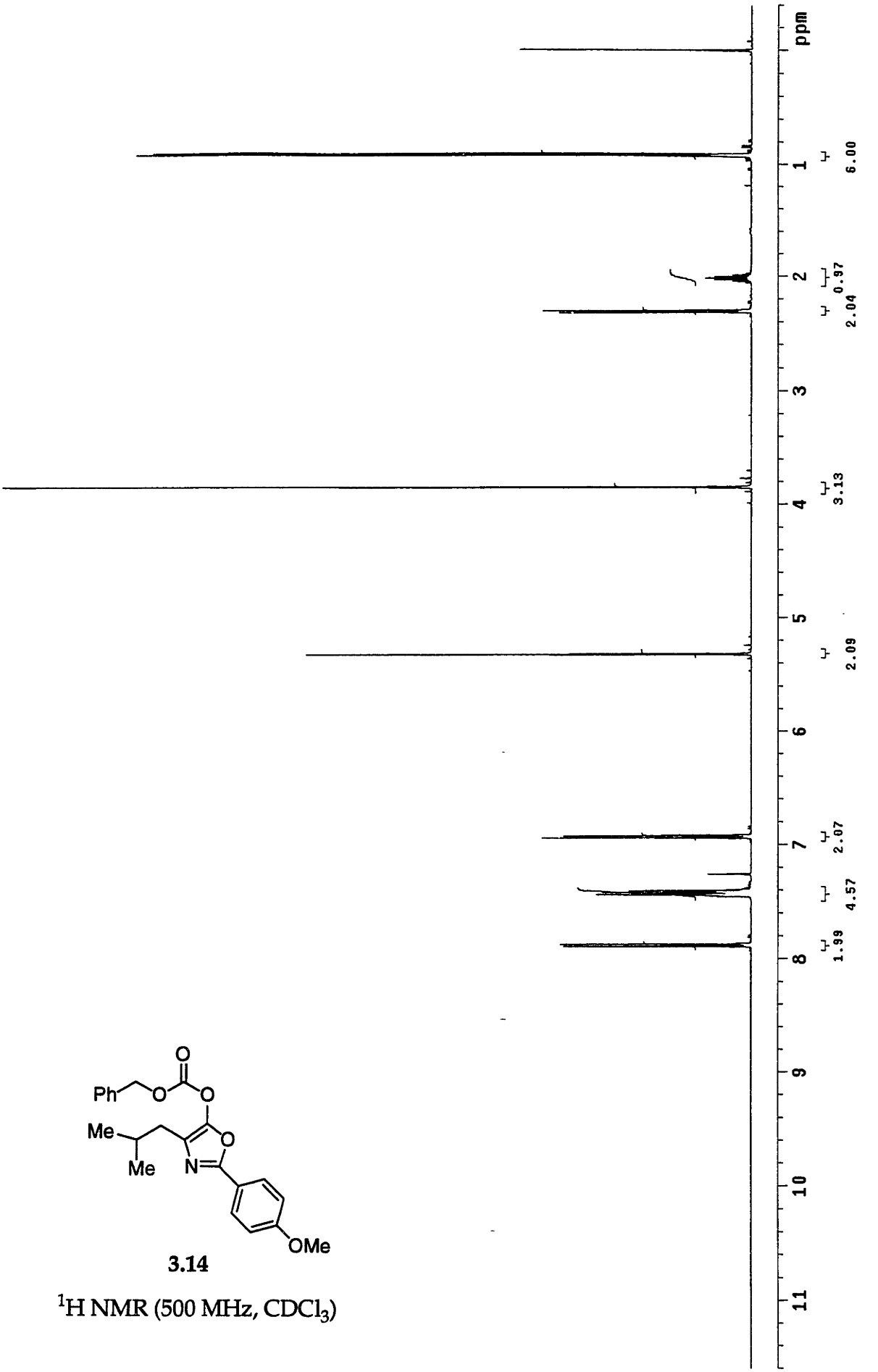


^{1}H NMR (500 MHz, $CDCl_3$)



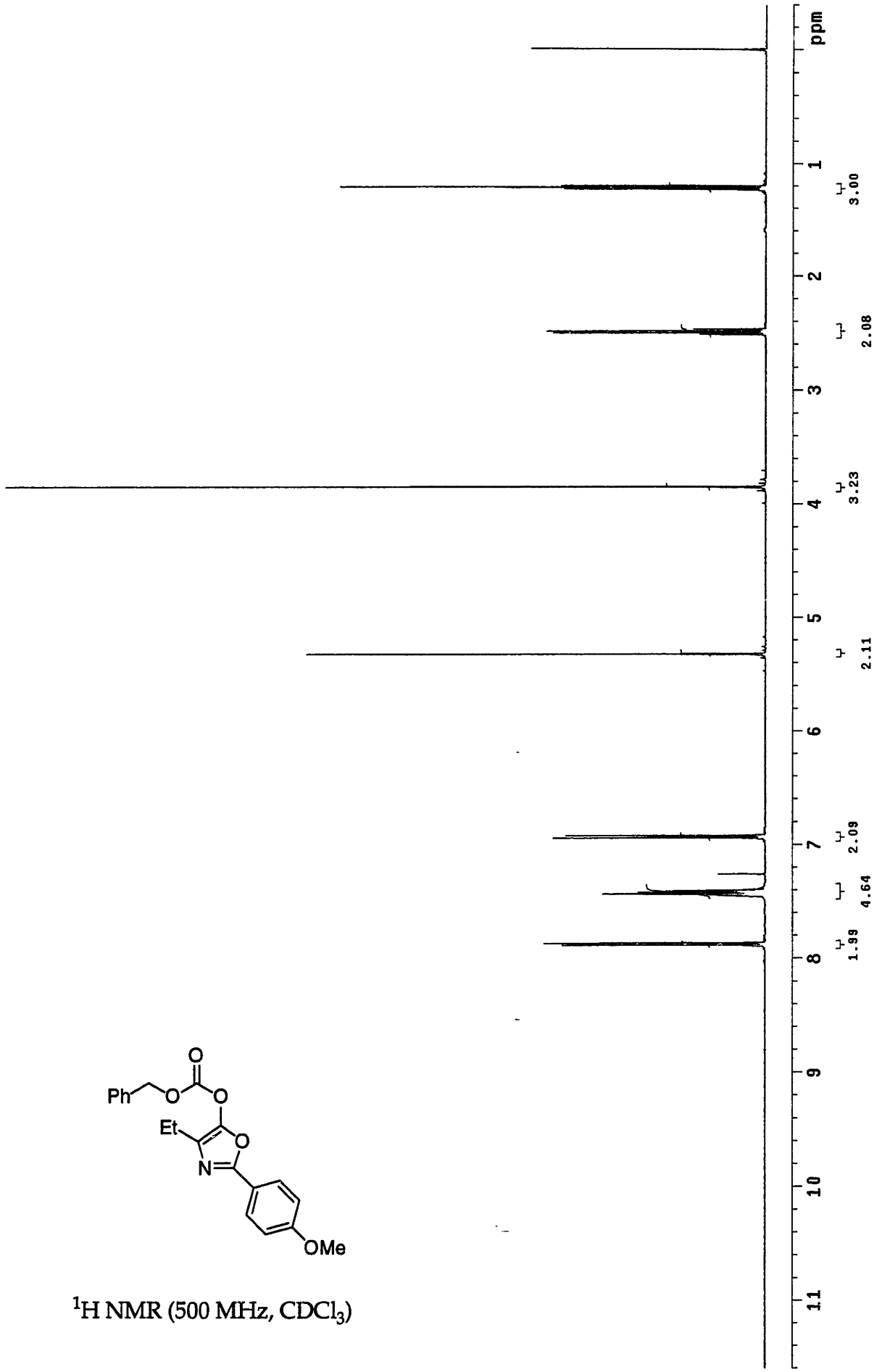
3.28

^{1}H NMR (500 MHz, $CDCl_3$)

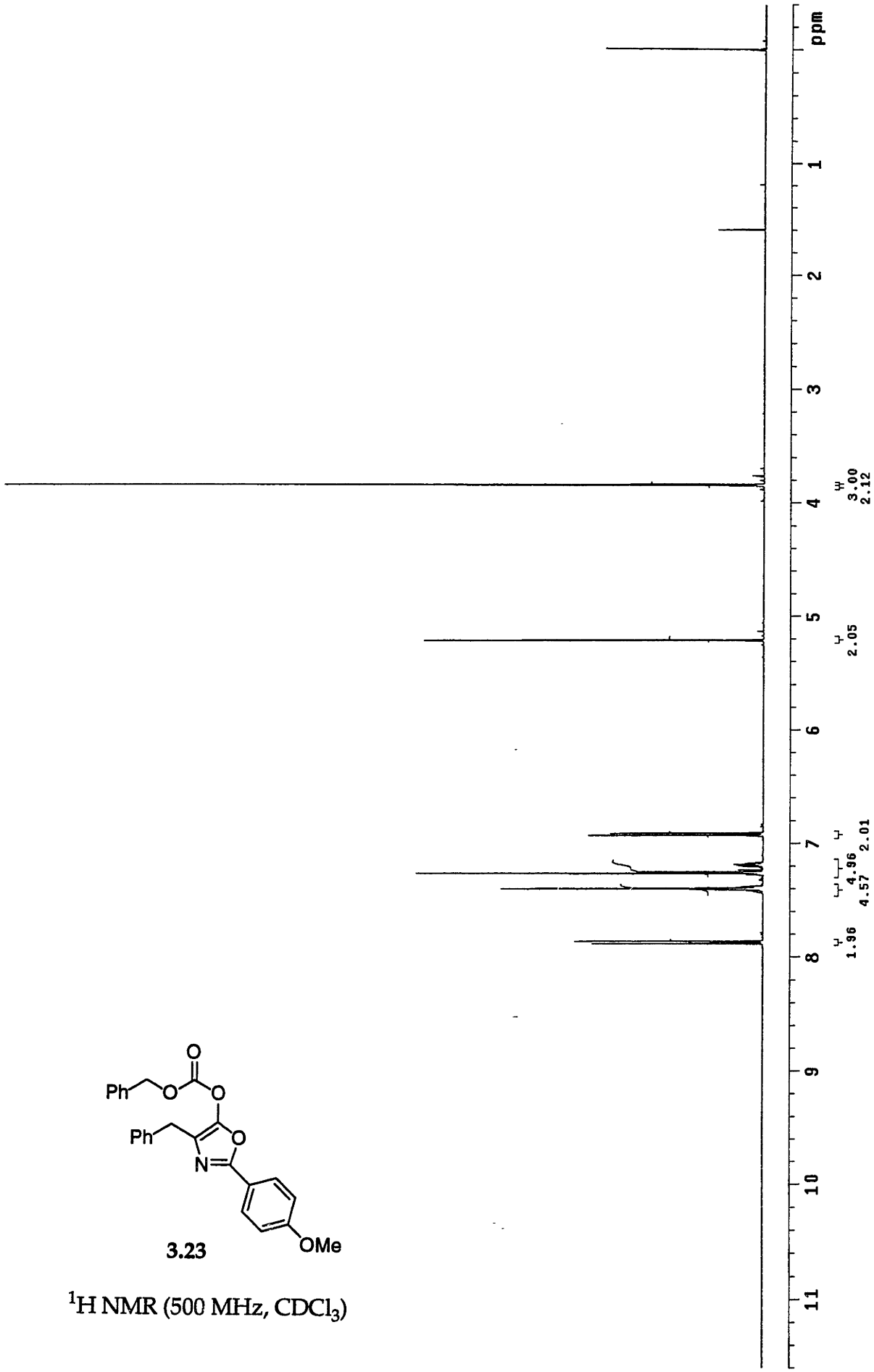


3.14

^{1}H NMR (500 MHz, $CDCl_3$)

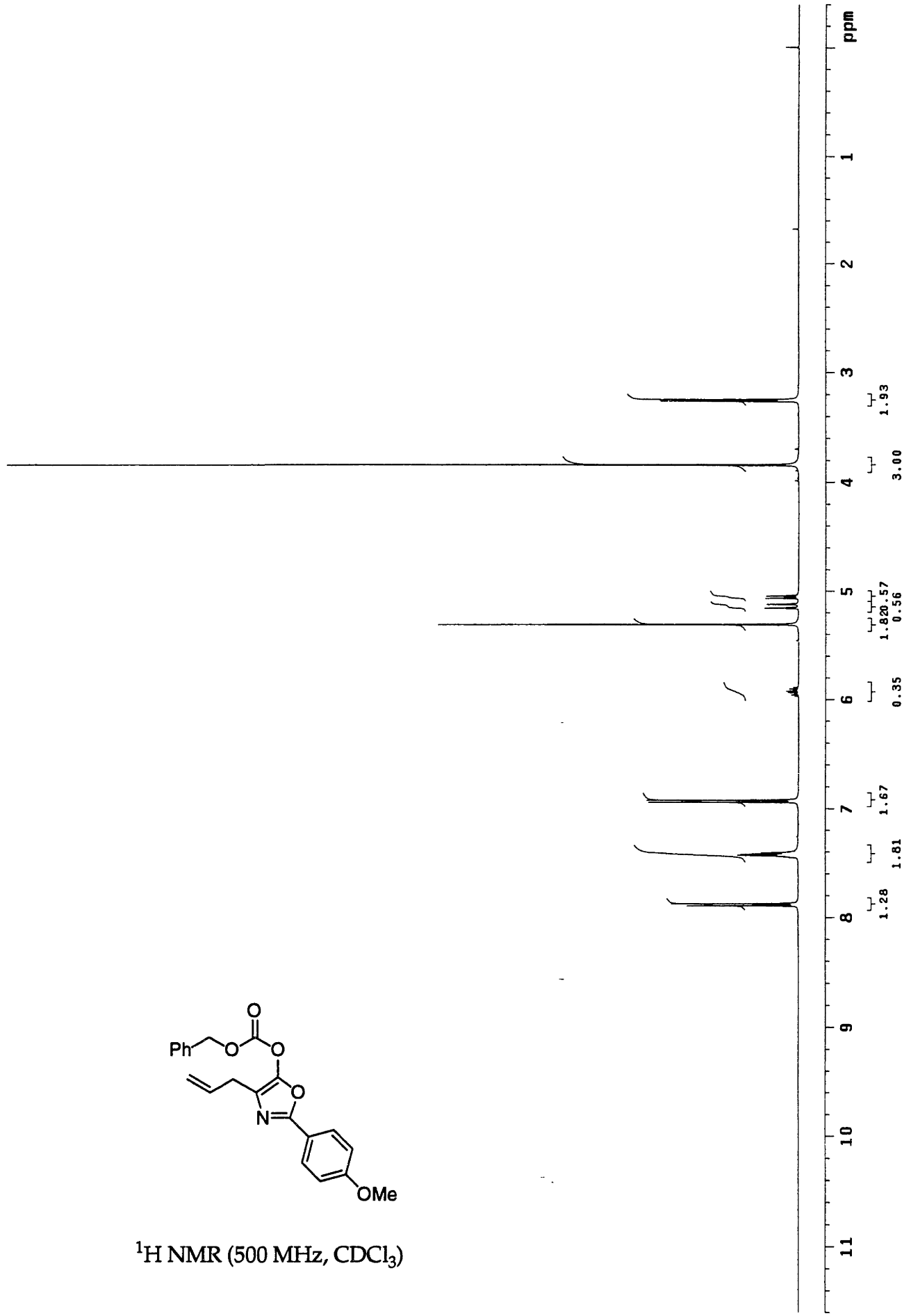


^{1}H NMR (500 MHz, $CDCl_3$)

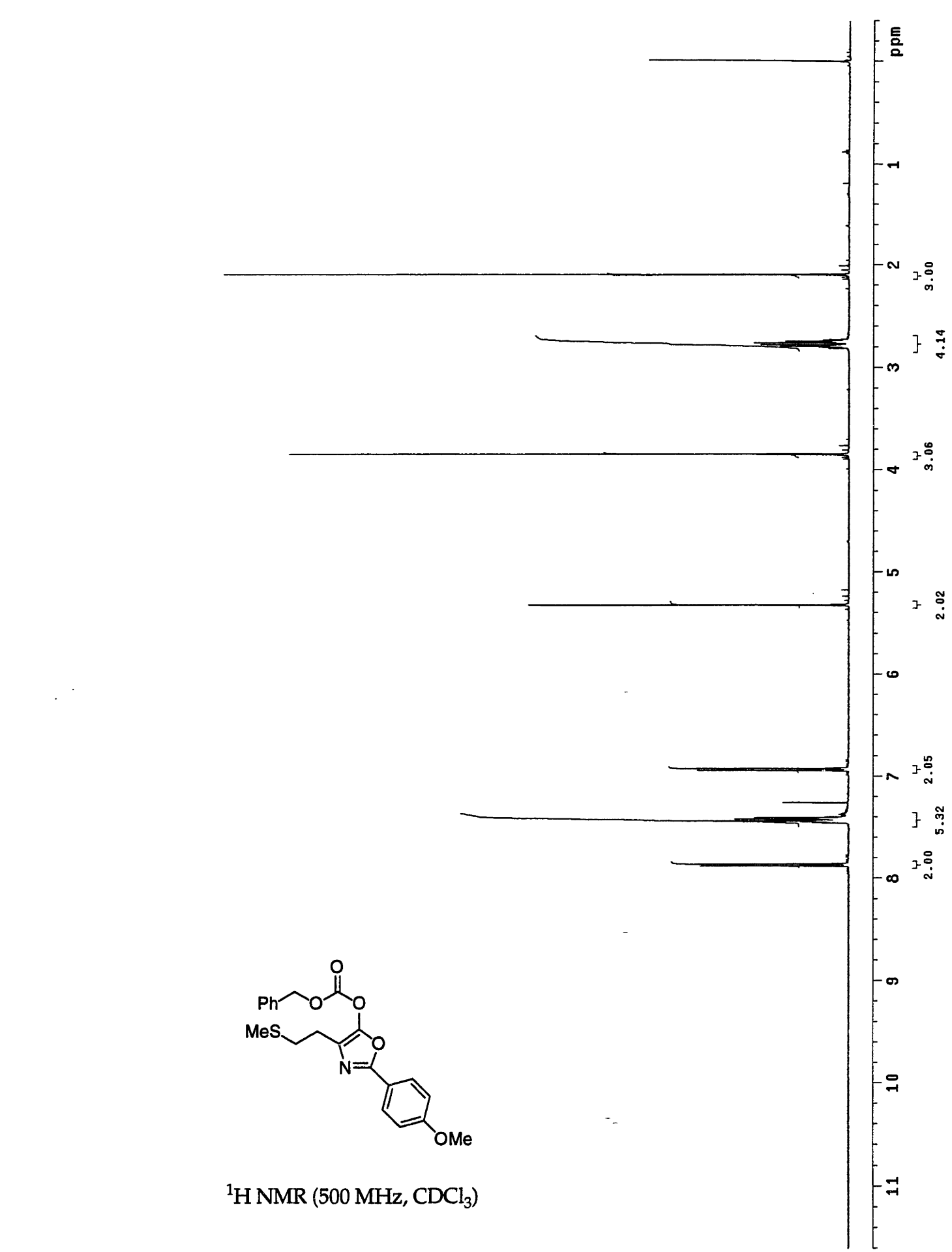


3.23

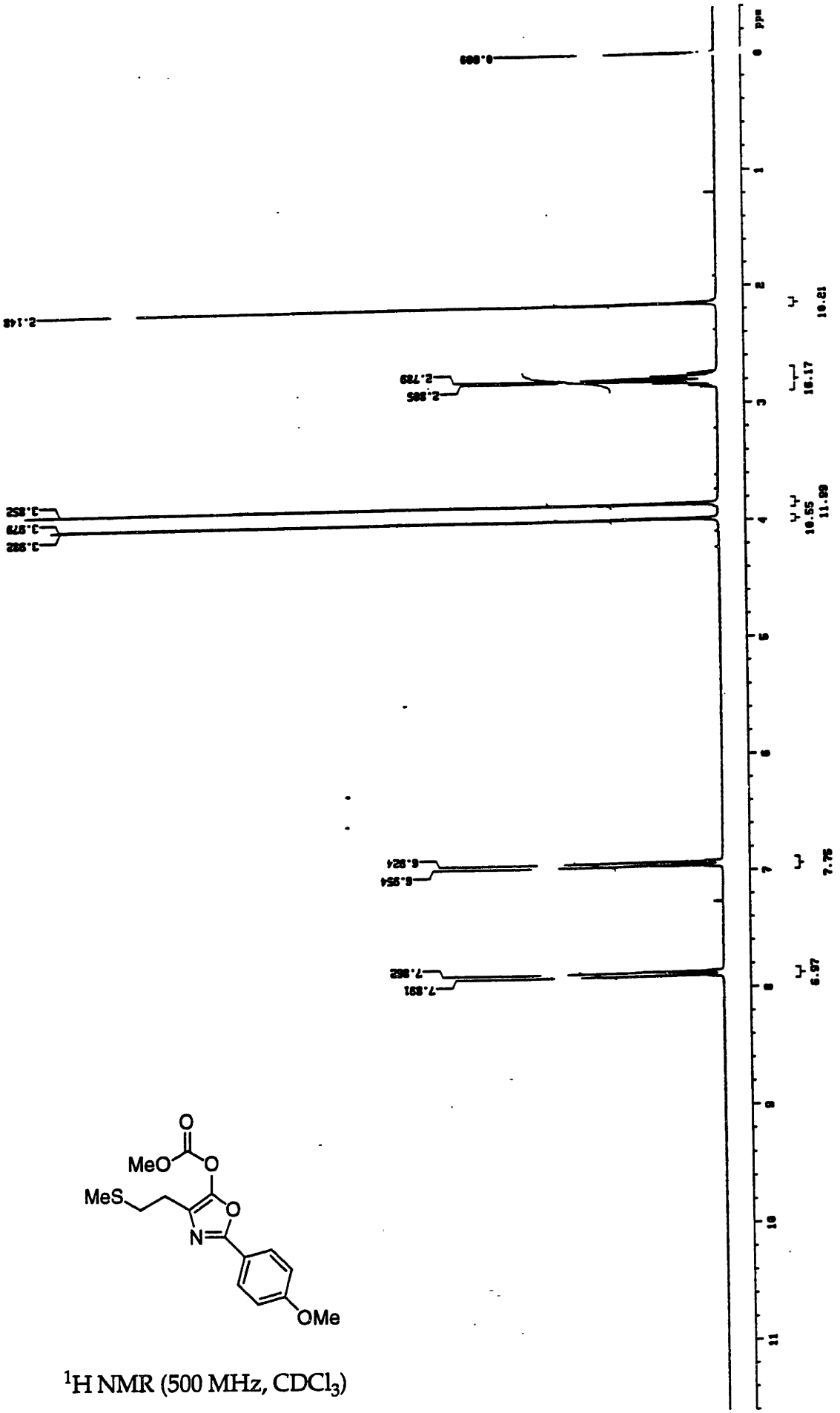
^{1}H NMR (500 MHz, $CDCl_3$)



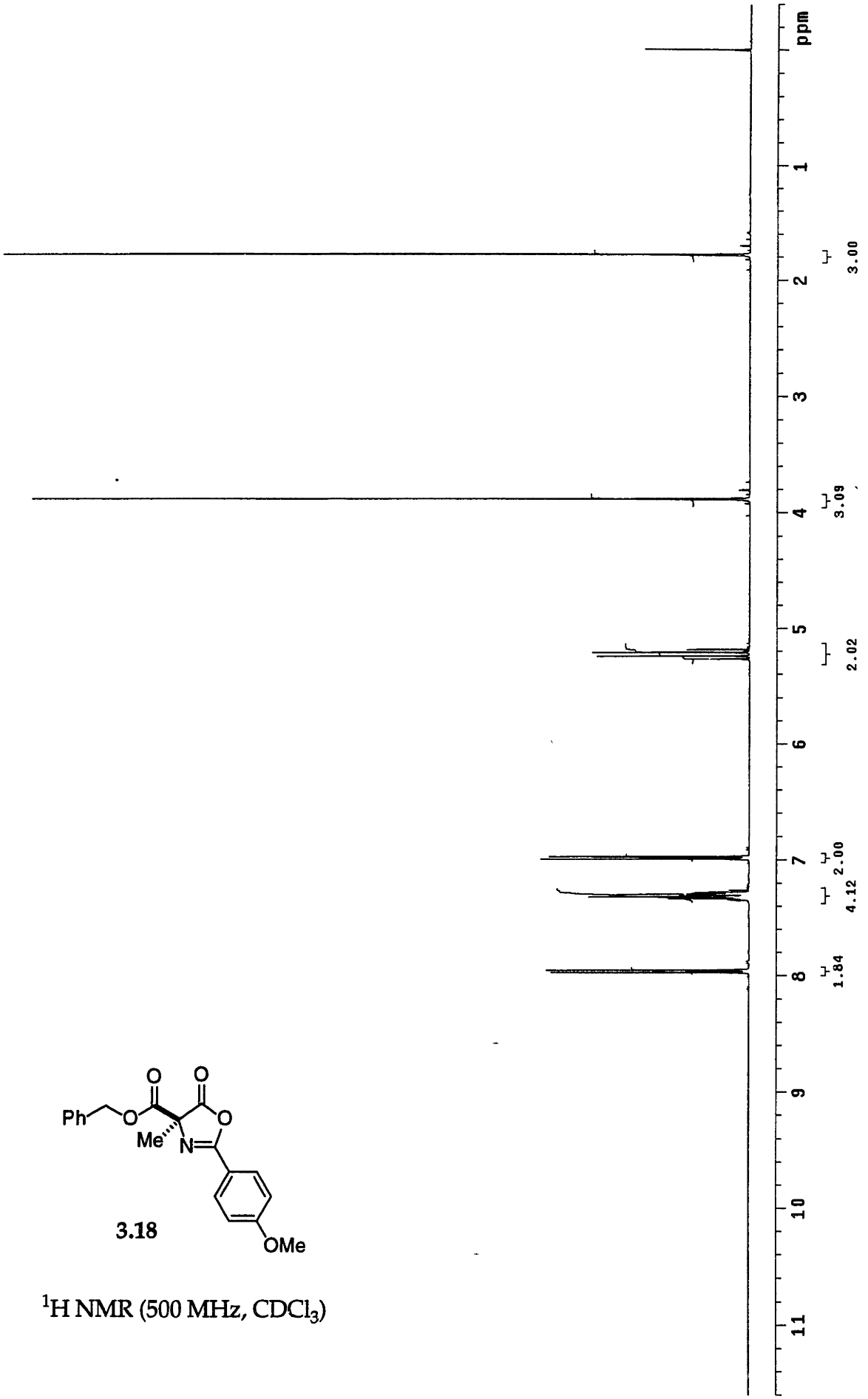
^{1}H NMR (500 MHz, $CDCl_3$)



^{1}H NMR (500 MHz, $CDCl_3$)

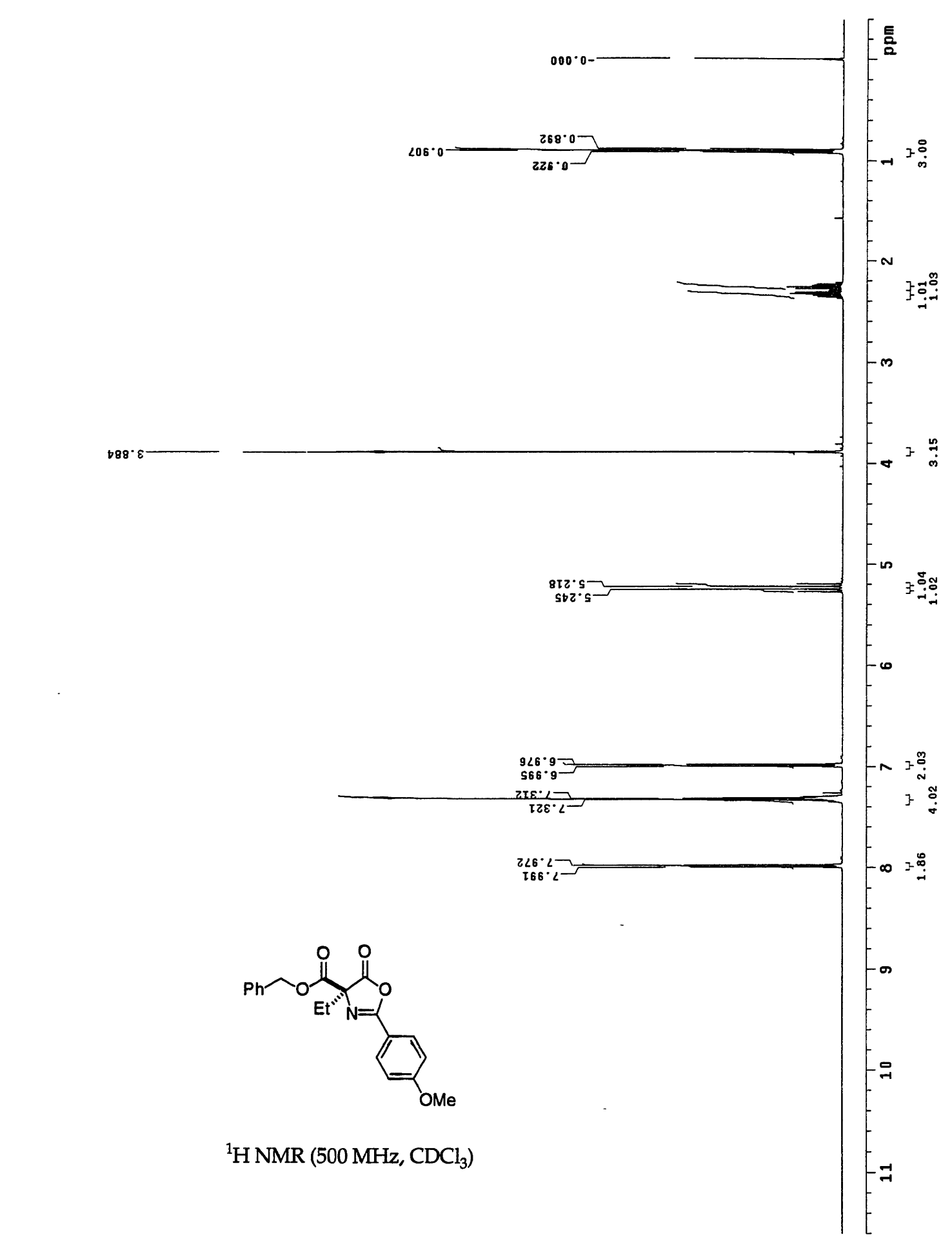


^{1}H NMR (500 MHz, $CDCl_3$)

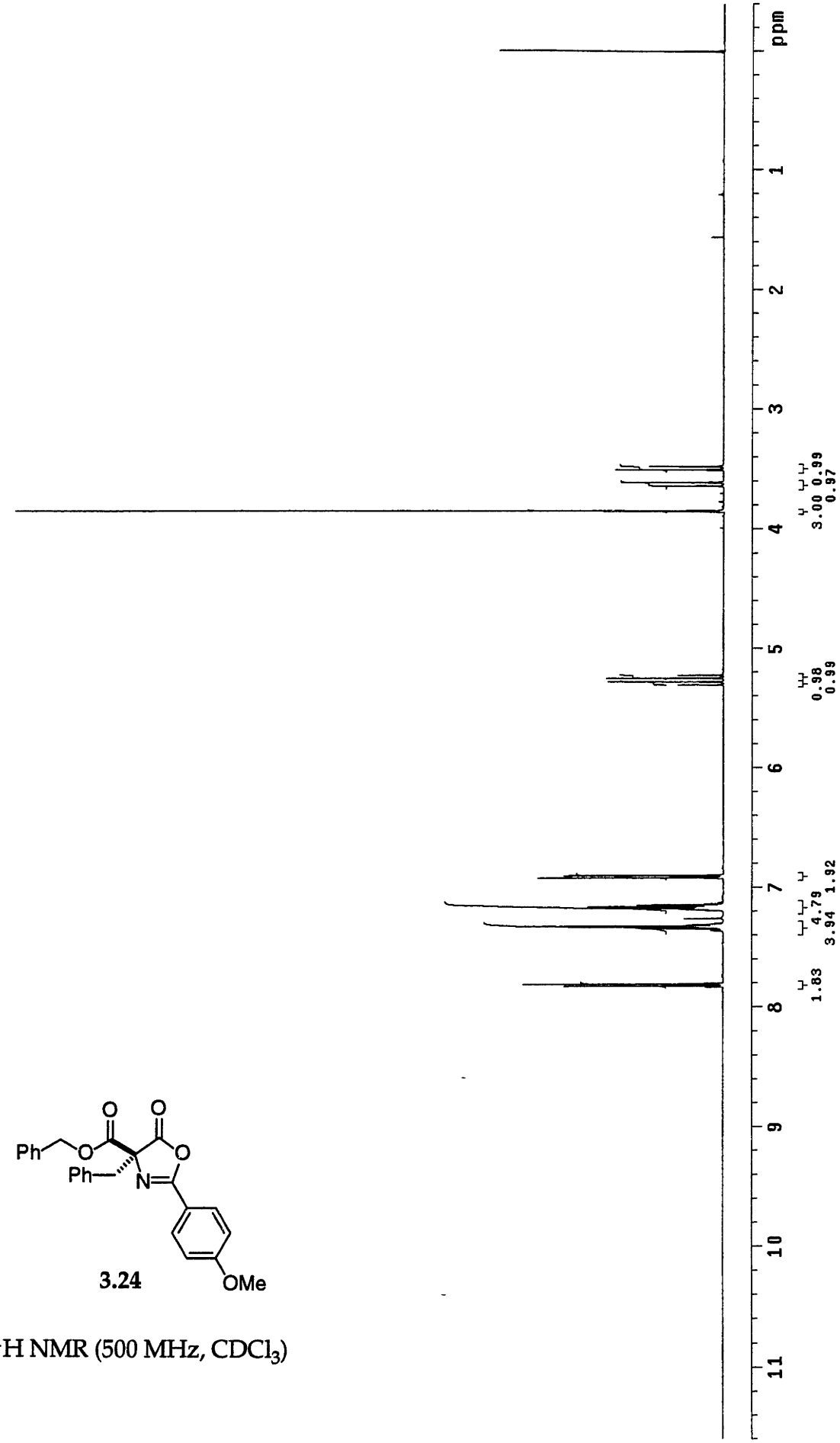


3.18

^{1}H NMR (500 MHz, $CDCl_3$)

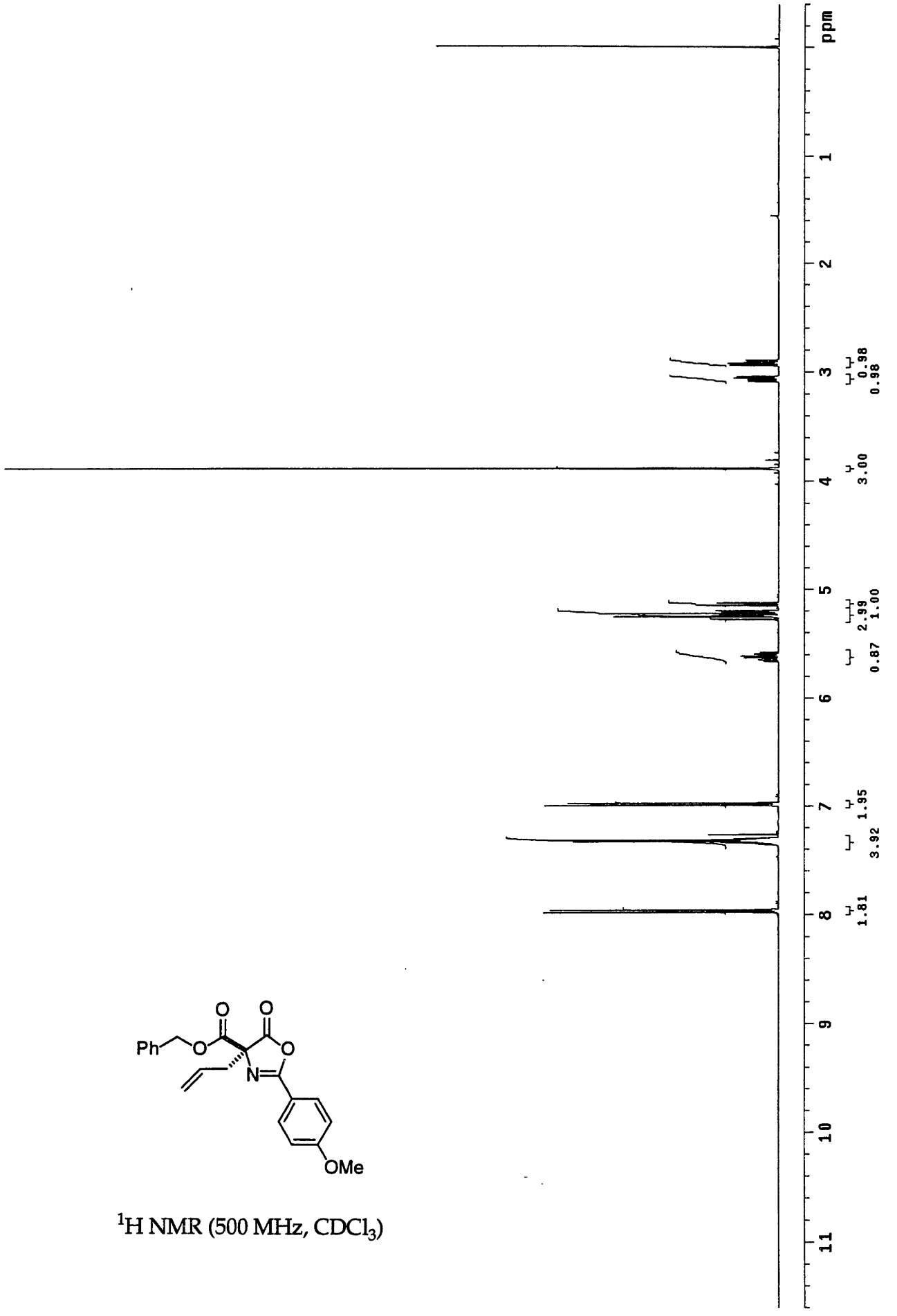


^{1}H NMR (500 MHz, $CDCl_3$)

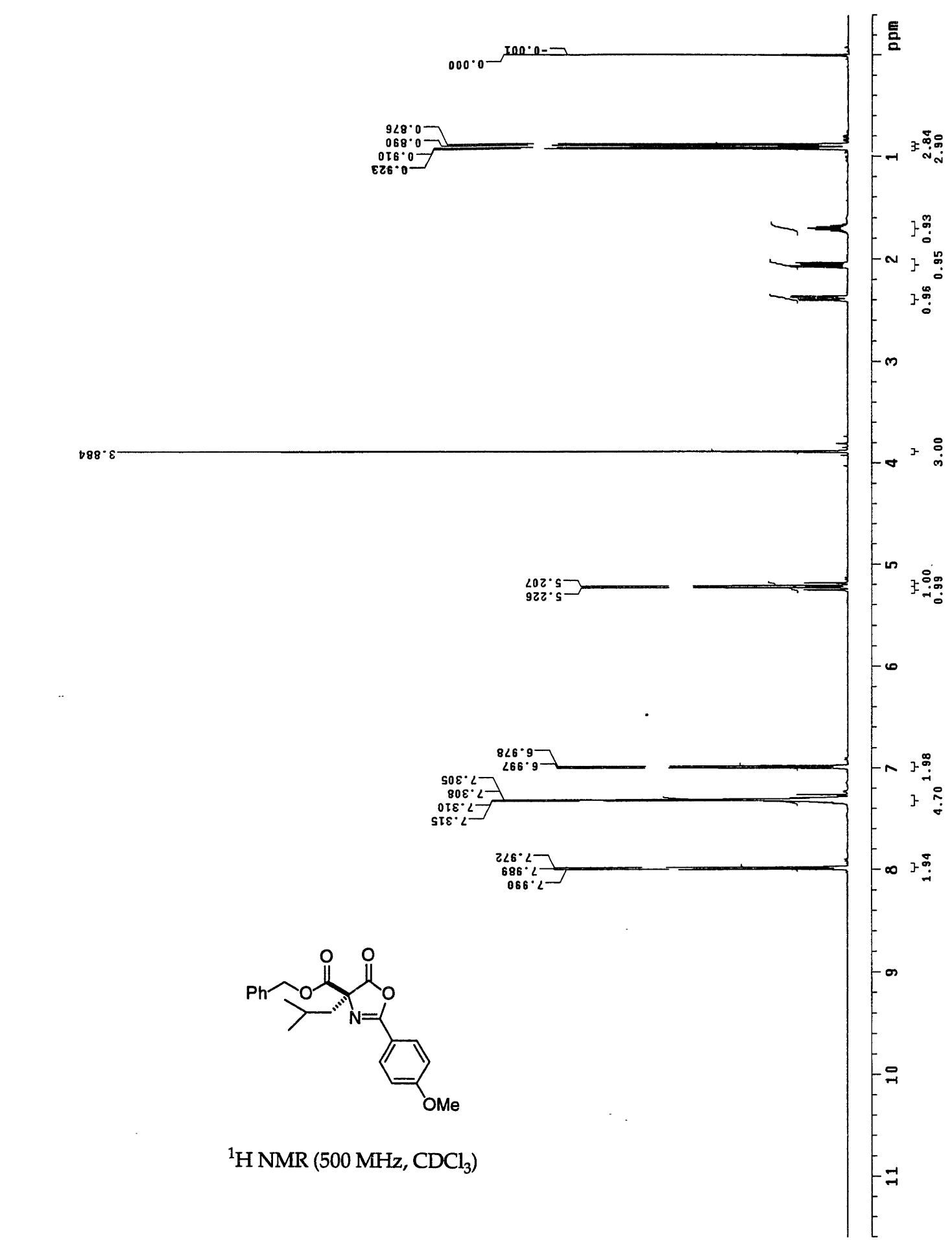


3.24

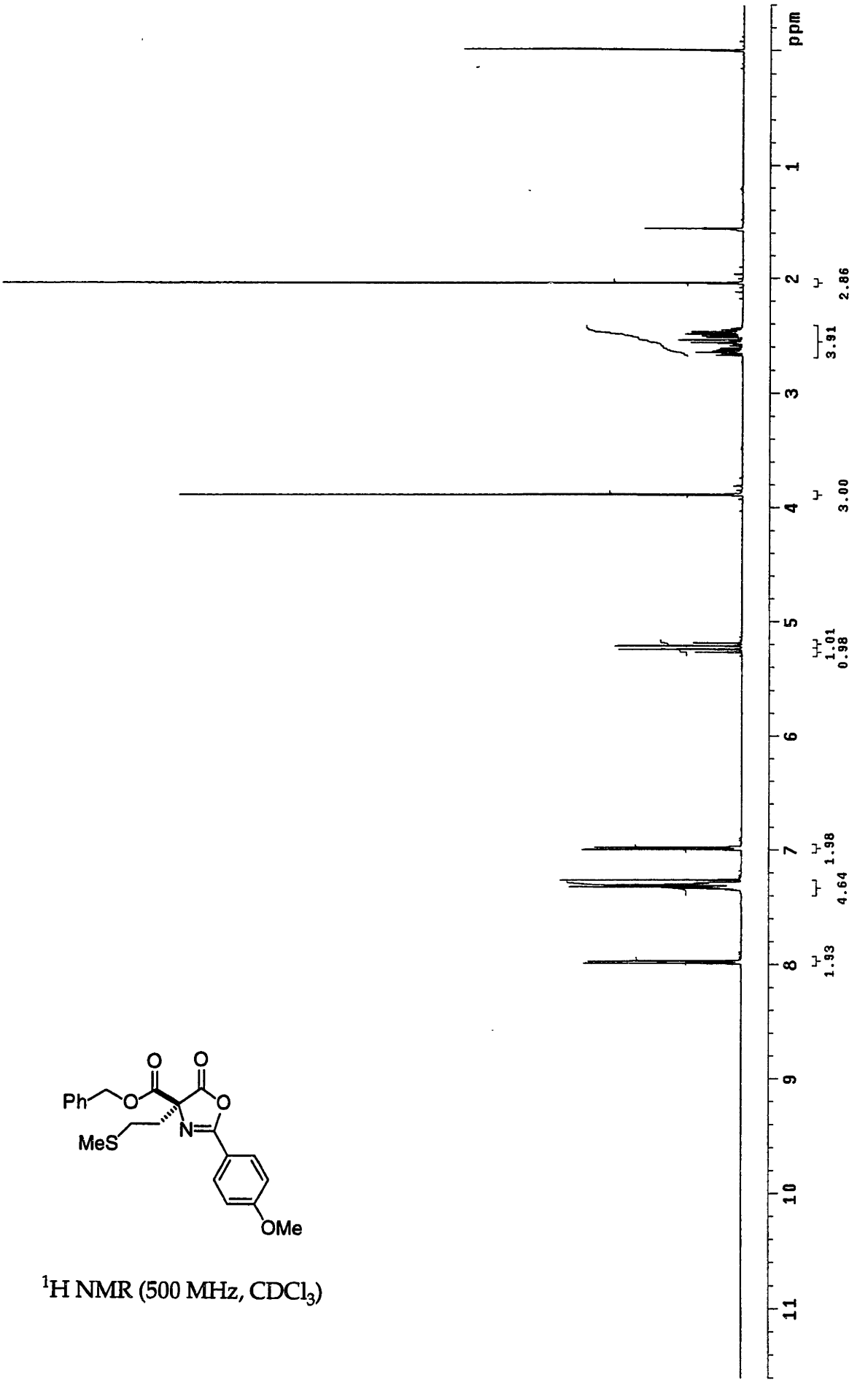
^{1}H NMR (500 MHz, $CDCl_3$)



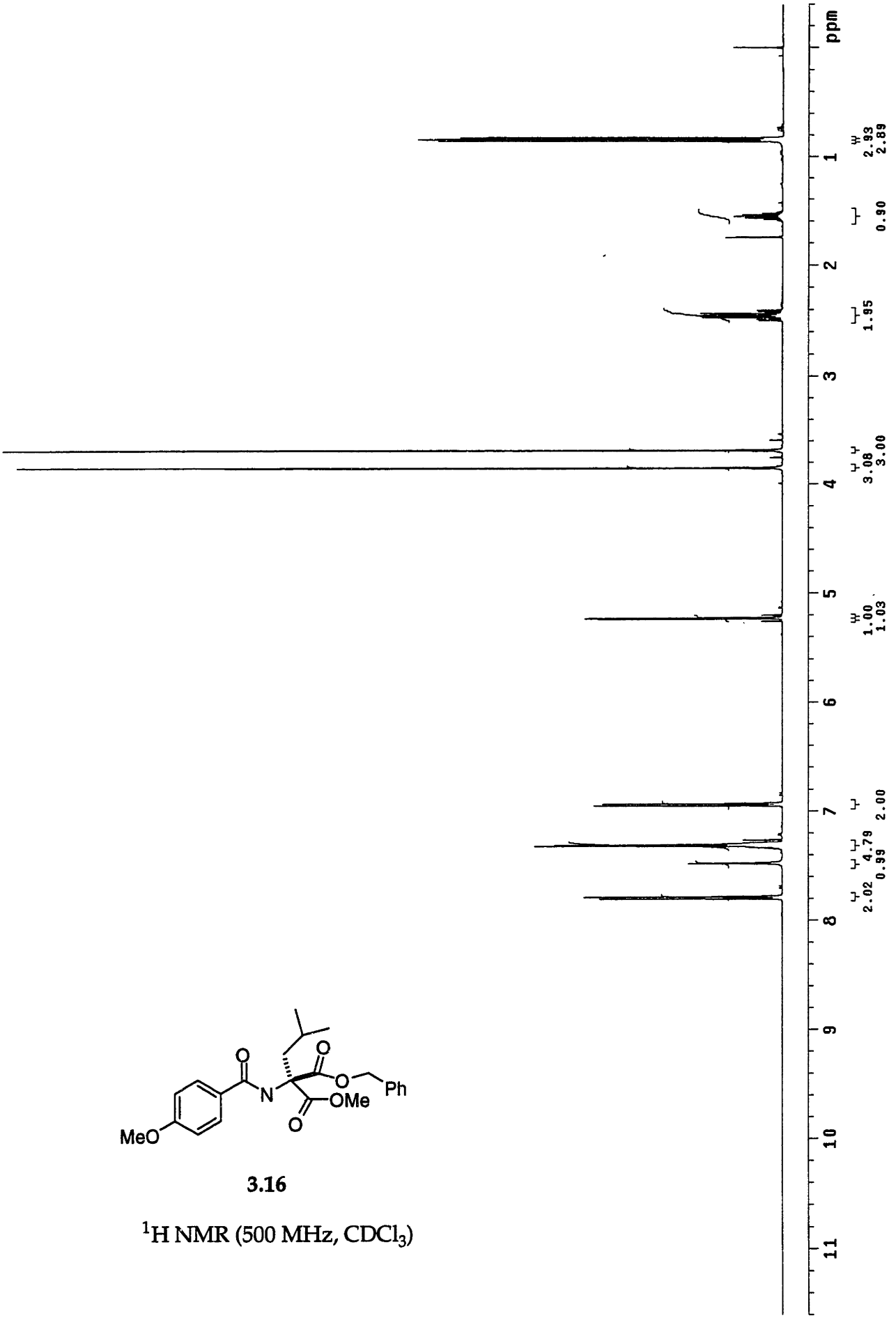
^{1}H NMR (500 MHz, $CDCl_3$)



^{1}H NMR (500 MHz, $CDCl_3$)

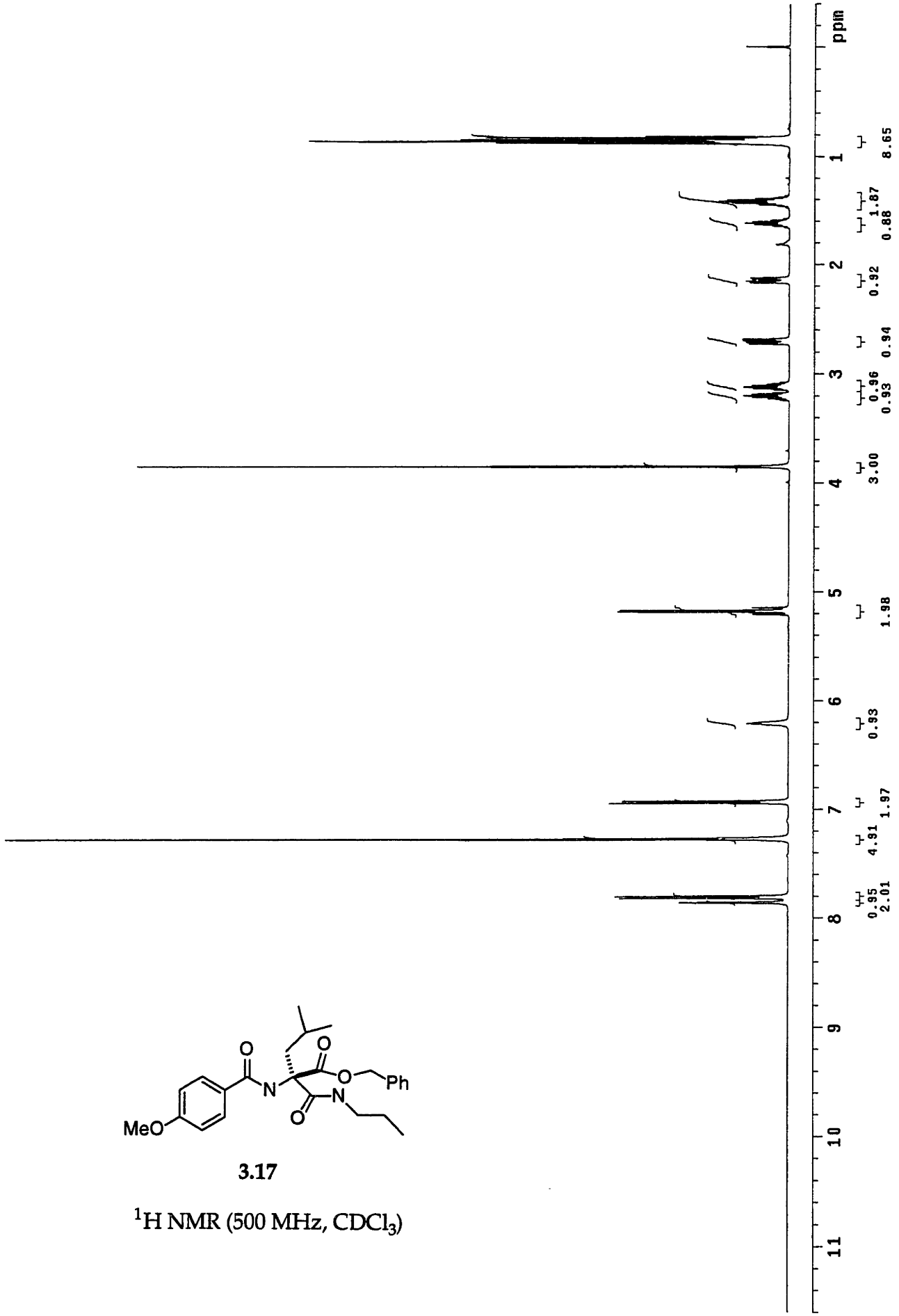


^{1}H NMR (500 MHz, $CDCl_3$)



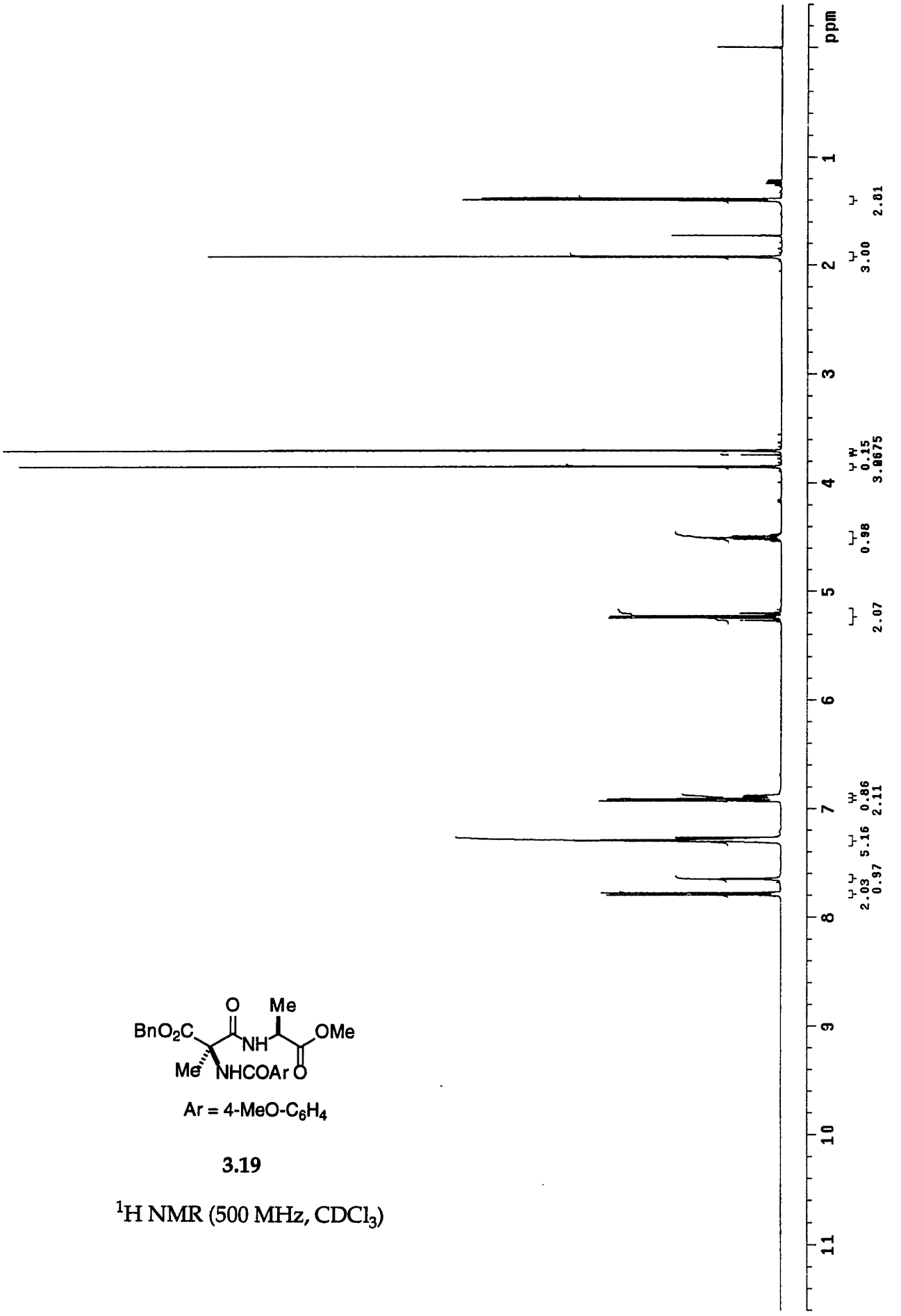
3.16

^{1}H NMR (500 MHz, $CDCl_3$)



3.17

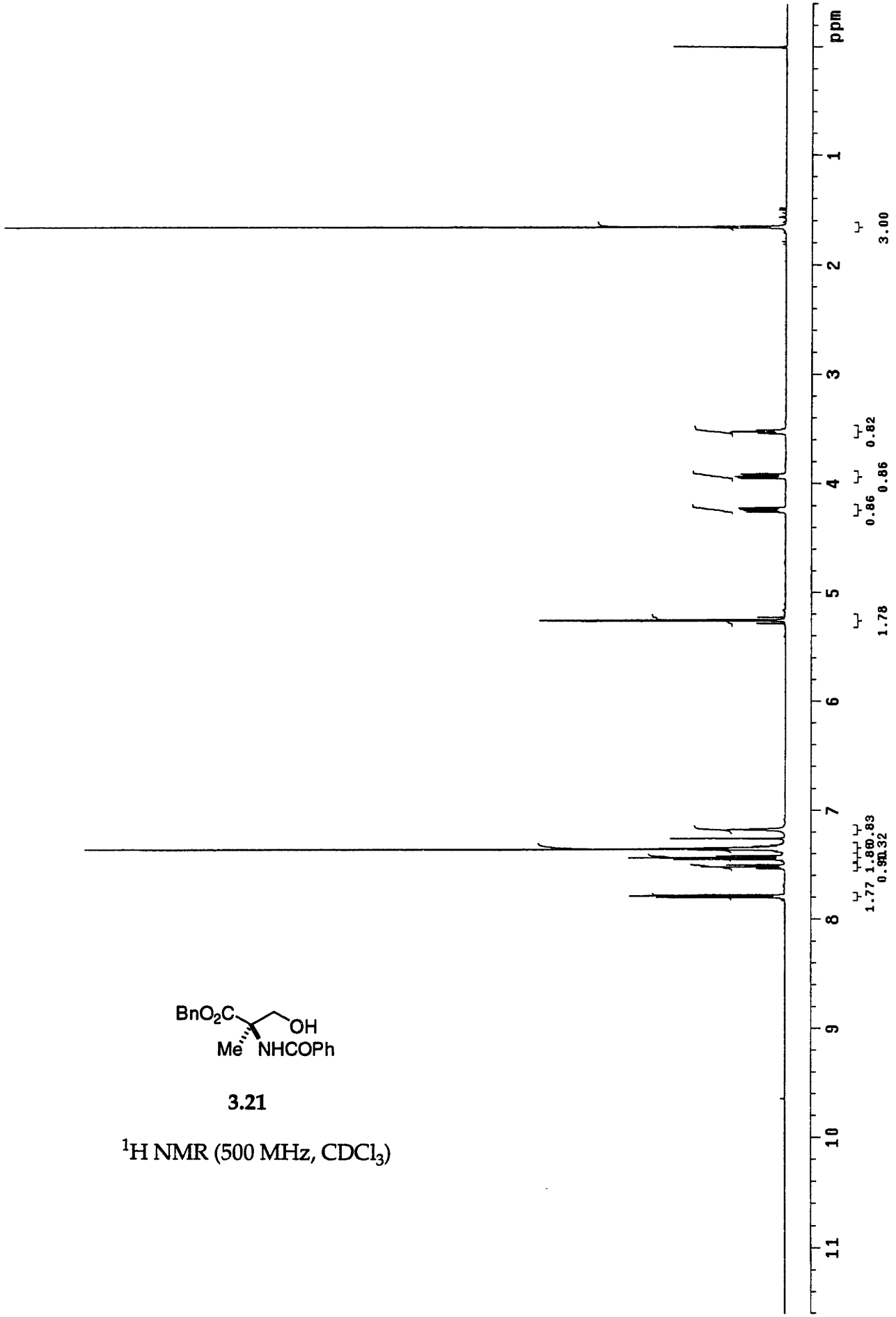
^{1}H NMR (500 MHz, $CDCl_3$)



Ar = 4-MeO-C_6H_4

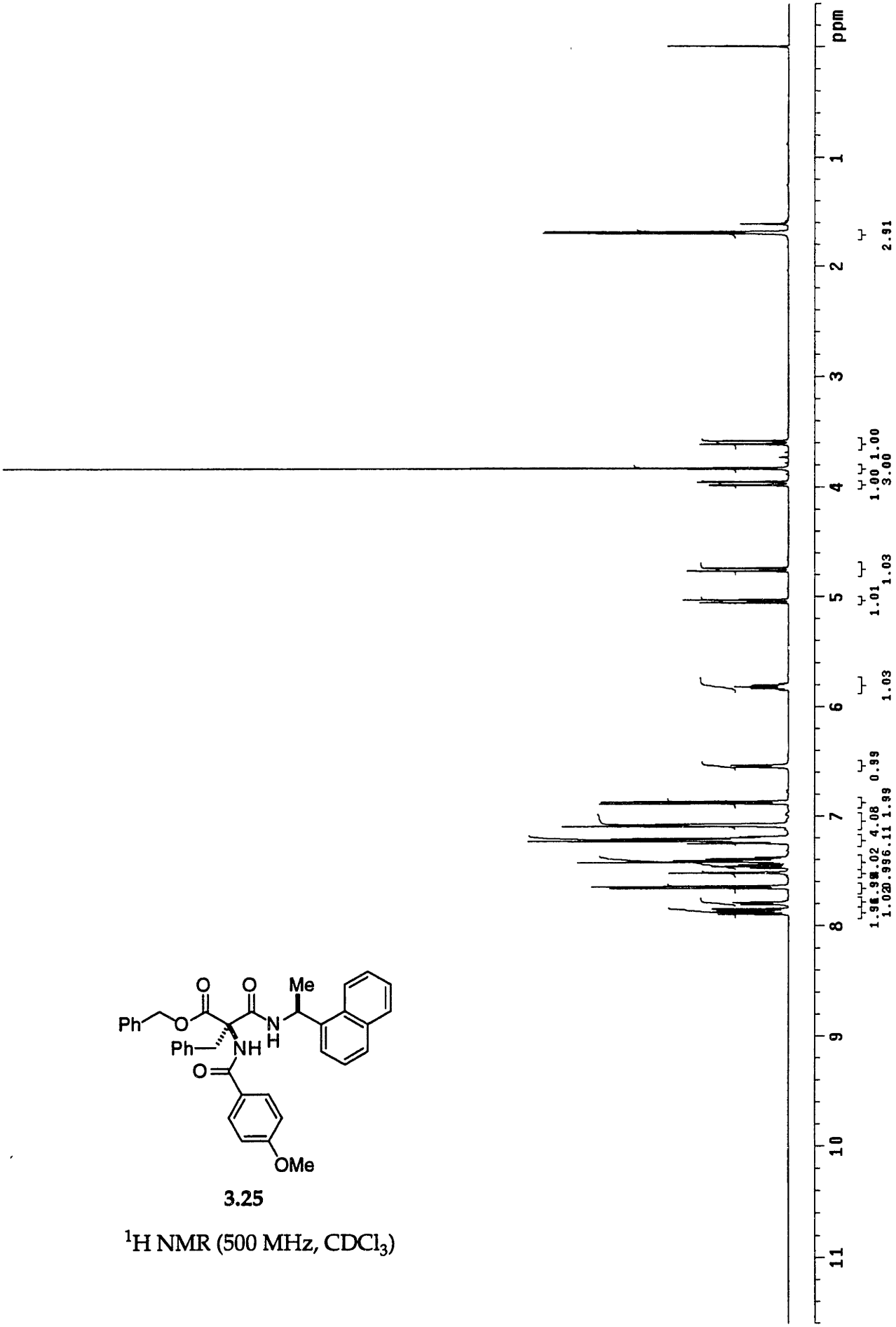
3.19

^{1}H NMR (500 MHz, $CDCl_3$)



3.21

^{1}H NMR (500 MHz, $CDCl_3$)

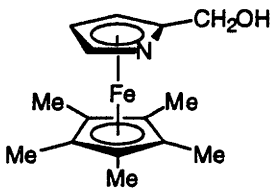


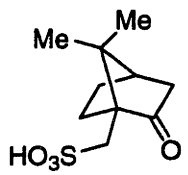
3.25

^{1}H NMR (500 MHz, $CDCl_3$)

Appendix II:

X-Ray Crystal Structure Data

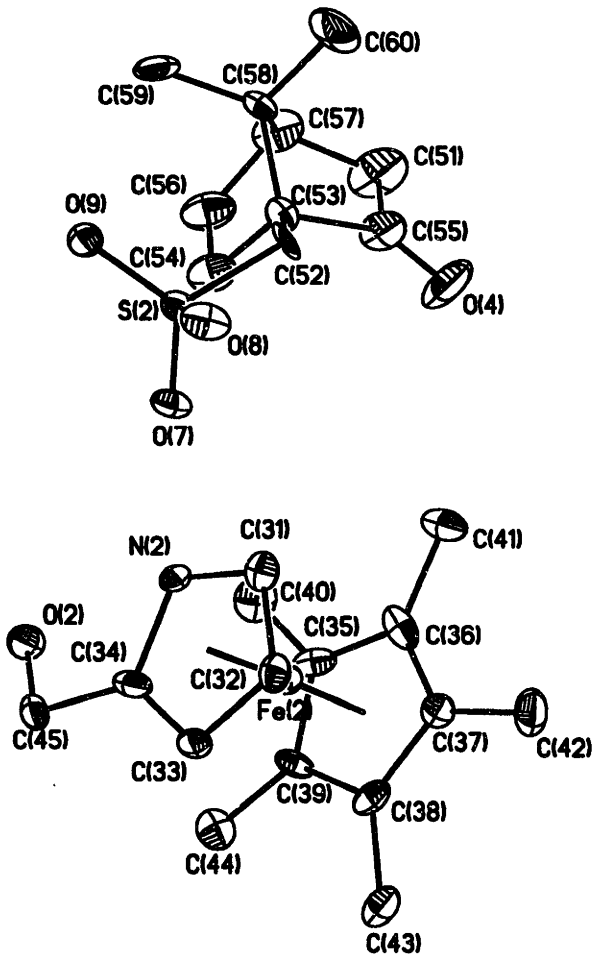




1:1 salt of (+)-**1.15** and (*S*)-(+)-camphor-10-sulphonic acid.

A solvent molecule (toluene) is also present in the crystal lattice.

Structure solved by Diego Hoic.


C(60)
C(58)
C(59)
C(57)
C(51)
C(56)
C(53)
O(9)
C(55)
C(54)
C(52)
O(4)
S(2)
O(8)
O(7)
C(31)
C(41)
N(2)
C(40)
O(2)
C(35)
C(36)
C(34)
C(32)
Fe(2)
C(37)
C(42)
C(45)
C(33)
C(39)
C(38)
C(44)
C(43)

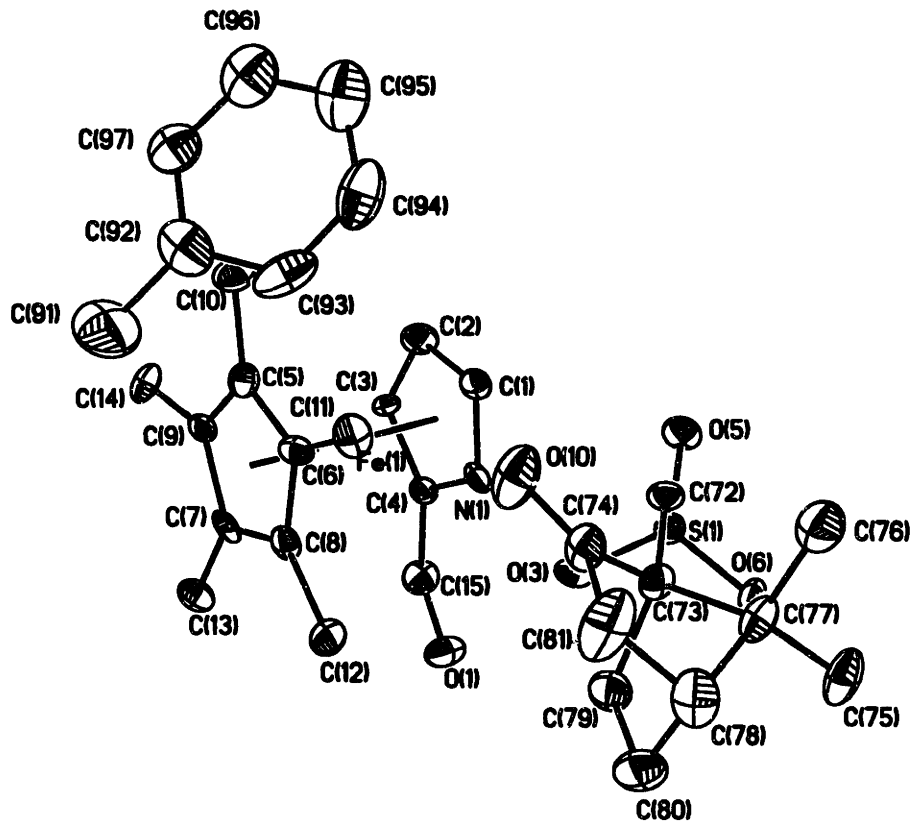

C(96)
C(95)
C(97)
C(94)
C(92)
C(10)
C(93)
C(91)
C(2)
C(5)
C(3)
C(1)
C(14)
C(11)
C(9)
O(5)
Fe(1)
C(6)
O(10)
C(72)
C(4)
N(1)
C(74)
C(7)
S(1)
C(76)
C(8)
O(3)
O(6)
C(15)
C(73)
C(77)
C(13)
C(81)
C(12)
O(1)
C(79)
C(75)
C(78)
C(80)

Table 1. Crystal data and structure refinement for 1.

A. Crystal Data

Identification code	~~expt1a~~ 96110
Empirical formula	$C_{57}H_{82}Fe_2N_2O_{10}S_2$
Formula weight	1131.07
Temperature	153(2) K
Wavelength	0.71073 Å
Crystal morphology	plate
Crystal size	0.05 x 0.15 x 0.21 mm
Crystal system	Monoclinic
Space group	$P2_1$
Unit cell dimensions	a = 7.916(3) Å alpha = 90° b = 13.493(11) Å beta = 91.69(4)° c = 26.52(2) Å gamma = 90°
Volume, Z	2832(3) $Å^3$, 2
Density (calculated)	1.327 Mg/m^3
Absorption coefficient	0.644 mm^{-1}
F(000)	1204

B. Data Collection and Reduction

Diffractometer	Siemens SMART/CCD
Scan Type	ω Scans
Scan angle	0.30°
θ range for data collection	1.54 to 23.29°
Limiting indices	$-8 \le h \le 7$, $-14 \le k \le 7$, $-29 \le l \le 27$

Reflections collected	9230
Independent reflections	5987 (R_{int} = 0.0833)
Absorption correction	Semi-empirical from psi-scans
Max. and min. transmission	0.2777 and 0.2152

C. Solution and Refinement

Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	5982 / 1 / 659
Goodness-of-fit on F^2	1.119
Final R indices [I>2σ(I)]	R1 = 0.0727, wR2 = 0.1518
R indices (all data)	R1 = 0.1026, wR2 = 0.1908
Absolute structure parameter	0.01(4)
Extinction coefficient	0.0026(5)
Largest diff. peak and hole	0.860 and -0.458 $e\text{Å}^{-3}$

Table 2. Atomic coordinates [x 10^4] and equivalent isotropic displacement parameters [$Å^2$ x 10^3] for 1. U(eq) is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U(eq)
Fe(1)	5478(2)	3757(1)	4385(1)	23(1)
Fe(2)	722(2)	877(1)	648(1)	22(1)
S(1)	8935(3)	6879(2)	4508(1)	25(1)
S(2)	4036(3)	-2278(2)	489(1)	25(1)
O(1)	3191(9)	5755(7)	4973(3)	40(2)
O(2)	-1712(9)	-1111(7)	92(3)	40(2)
O(3)	7215(8)	6528(6)	4373(3)	27(2)
O(4)	5019(19)	-1888(10)	2108(4)	98(5)
O(5)	9858(9)	6155(6)	4820(3)	36(2)
O(6)	8948(9)	7869(6)	4711(3)	30(2)
O(7)	2392(8)	-1918(6)	621(3)	31(2)
O(8)	4956(9)	-1529(6)	207(3)	38(2)
O(9)	3985(9)	-3243(6)	245(3)	31(2)
O(10)	9932(14)	6274(8)	2910(4)	64(3)
N(1)	6257(10)	4826(8)	4853(3)	26(2)
N(2)	1404(11)	-199(7)	173(3)	23(2)
C(1)	7584(15)	4171(9)	4784(4)	30(3)
C(2)	7080(16)	3236(11)	4966(5)	39(3)
C(3)	5363(13)	3327(9)	5129(4)	23(3)
C(4)	4879(14)	4327(10)	5071(4)	25(3)
C(5)	5821(14)	2897(10)	3762(4)	32(3)
C(6)	5930(13)	3927(10)	3629(4)	28(3)
C(9)	4162(13)	2717(10)	3968(4)	26(3)
C(7)	3256(12)	3644(10)	3948(4)	28(3)
C(10)	7172(15)	2118(11)	3701(5)	45(4)
C(8)	4343(14)	4391(10)	3755(4)	30(3)
C(11)	7363(15)	4457(11)	3391(5)	42(4)
C(12)	3914(15)	5444(10)	3679(5)	38(3)
C(13)	1492(12)	3755(11)	4116(4)	34(3)
C(14)	3535(15)	1737(9)	4145(4)	36(3)
C(15)	3344(14)	4842(10)	5243(5)	37(3)
C(31)	2745(14)	479(9)	227(4)	27(3)
C(32)	2152(14)	1401(10)	62(4)	27(3)
C(33)	450(14)	1306(9)	-100(4)	28(3)
C(34)	-50(14)	317(10)	-34(4)	27(3)
C(35)	-272(14)	294(10)	1294(4)	31(3)
C(36)	1340(12)	740(12)	1412(4)	34(3)
C(37)	1271(13)	1768(10)	1260(4)	25(3)
C(38)	-455(14)	1933(10)	1070(4)	29(3)
C(39)	-1373(11)	1007(10)	1080(4)	25(3)
C(40)	-698(17)	-793(10)	1385(5)	43(4)
C(41)	2846(14)	208(10)	1645(5)	40(4)
C(42)	2594(15)	2520(11)	1320(5)	46(4)
C(43)	-1133(16)	2900(9)	876(4)	39(3)
C(44)	-3179(12)	875(11)	921(4)	36(3)
C(45)	-1636(14)	-231(9)	-183(4)	29(3)
C(51)	4925(27)	-3640(13)	2342(6)	87(6)
C(52)	5238(15)	2414(10)	1064(4)	39(3)

C(53)	4660(14)	-3162(11)	1457(4)	34(3)
C(54)	2767(16)	-3487(10)	1446(5)	46(4)
C(55)	4935(21)	-2739(14)	1992(5)	61(5)
C(56)	2760(18)	-4423(12)	1788(6)	59(4)
C(57)	4608(19)	-4488(12)	1976(4)	55(4)
C(58)	5620(12)	-4181(11)	1513(4)	33(3)
C(59)	5417(15)	-4851(10)	1071(5)	41(4)
C(60)	7561(16)	-4021(14)	1607(6)	66(5)
C(72)	10117(13)	6915(10)	3943(4)	28(3)
C(73)	9607(14)	7618(9)	3524(4)	29(3)
C(74)	9865(17)	7155(11)	3010(5)	41(3)
C(79)	7746(16)	8019(11)	3484(5)	46(4)
C(80)	7838(17)	8900(12)	3116(6)	59(4)
C(81)	9869(25)	7977(12)	2629(5)	74(5)
C(91)	7275(21)	2674(18)	2199(7)	108(8)
C(92)	9052(19)	2641(16)	2387(5)	64(5)
C(93)	9985(24)	3547(13)	2457(6)	66(5)
C(94)	11636(25)	3487(15)	2645(6)	72(5)
C(95)	12358(25)	2610(18)	2784(6)	78(6)
C(96)	11460(25)	1777(17)	2720(6)	76(5)
C(97)	9867(21)	1786(14)	2531(6)	65(5)
C(77)	10630(15)	8592(10)	3451(5)	39(3)
C(78)	9669(19)	8870(13)	2954(5)	58(4)
C(76)	12532(17)	8433(12)	3402(6)	63(5)
C(75)	10433(19)	9358(10)	3882(5)	51(4)

Table 3. Bond lengths [Å] and angles [°] for 1.

Fe(1)-N(1)	1.990(10)	Fe(1)-C(1)	2.026(12)
Fe(1)-C(5)	2.044(12)	Fe(1)-C(4)	2.045(11)
Fe(1)-C(9)	2.051(12)	Fe(1)-C(8)	2.059(11)
Fe(1)-C(6)	2.058(11)	Fe(1)-C(3)	2.063(11)
Fe(1)-C(7)	2.083(10)	Fe(1)-C(2)	2.088(12)
Fe(2)-N(2)	2.006(9)	Fe(2)-C(34)	2.038(12)
Fe(2)-C(39)	2.051(10)	Fe(2)-C(38)	2.053(12)
Fe(2)-C(31)	2.050(11)	Fe(2)-C(37)	2.056(12)
Fe(2)-C(35)	2.062(11)	Fe(2)-C(33)	2.071(12)
Fe(2)-C(32)	2.075(11)	Fe(2)-C(36)	2.079(10)
S(1)-O(6)	1.440(8)	S(1)-O(5)	1.461(8)
S(1)-O(3)	1.476(7)	S(1)-C(72)	1.792(11)
S(2)-O(7)	1.442(7)	S(2)-O(9)	1.453(9)
S(2)-O(8)	1.464(8)	S(2)-C(52)	1.785(10)
O(1)-C(15)	1.43(2)	O(2)-C(45)	1.394(14)
O(4)-C(55)	1.19(2)	O(10)-C(74)	1.22(2)
N(1)-C(1)	1.389(14)	N(1)-C(4)	1.420(14)
N(2)-C(31)	1.405(14)	N(2)-C(34)	1.440(14)
C(1)-C(2)	1.41(2)	C(2)-C(3)	1.44(2)
C(3)-C(4)	1.41(2)	C(4)-C(15)	1.48(2)
C(5)-C(6)	1.44(2)	C(5)-C(9)	1.46(2)
C(5)-C(10)	1.51(2)	C(6)-C(8)	1.45(2)
C(6)-C(11)	1.50(2)	C(9)-C(7)	1.44(2)
C(9)-C(14)	1.49(2)	C(7)-C(8)	1.43(2)
C(7)-C(13)	1.485(13)	C(8)-C(12)	1.47(2)
C(31)-C(32)	1.40(2)	C(32)-C(33)	1.41(2)
C(33)-C(34)	1.40(2)	C(34)-C(45)	1.50(2)
C(35)-C(39)	1.41(2)	C(35)-C(36)	1.44(2)
C(35)-C(40)	1.53(2)	C(36)-C(37)	1.44(2)
C(36)-C(41)	1.51(2)	C(37)-C(38)	1.46(2)
C(37)-C(42)	1.46(2)	C(38)-C(39)	1.45(2)
C(38)-C(43)	1.50(2)	C(39)-C(44)	1.489(13)
C(51)-C(57)	1.52(2)	C(51)-C(55)	1.53(2)
C(52)-C(53)	1.53(2)	C(53)-C(55)	1.54(2)
C(53)-C(54)	1.56(2)	C(53)-C(58)	1.58(2)
C(54)-C(56)	1.55(2)	C(56)-C(57)	1.53(2)
C(57)-C(58)	1.54(2)	C(58)-C(59)	1.48(2)
C(58)-C(60)	1.56(2)	C(72)-C(73)	1.51(2)
C(73)-C(74)	1.52(2)	C(73)-C(79)	1.57(2)
C(73)-C(77)	1.56(2)	C(74)-C(81)	1.50(2)
C(79)-C(80)	1.54(2)	C(80)-C(78)	1.52(2)
C(81)-C(78)	1.49(2)	C(91)-C(92)	1.48(2)
C(92)-C(97)	1.37(2)	C(92)-C(93)	1.44(2)
C(93)-C(94)	1.39(2)	C(94)-C(95)	1.36(2)
C(95)-C(96)	1.34(2)	C(96)-C(97)	1.34(2)
C(77)-C(76)	1.53(2)	C(77)-C(78)	1.55(2)
C(77)-C(75)	1.55(2)		

N(1)-Fe(1)-C(1)	40.5(4)	N(1)-Fe(1)-C(5)	150.5(4)
C(1)-Fe(1)-C(5)	116.9(5)	N(1)-Fe(1)-C(4)	41.2(4)
C(1)-Fe(1)-C(4)	68.9(5)	C(5)-Fe(1)-C(4)	166.7(5)
N(1)-Fe(1)-C(9)	167.3(4)	C(1)-Fe(1)-C(9)	150.1(5)
C(5)-Fe(1)-C(9)	41.7(4)	C(4)-Fe(1)-C(9)	127.6(5)
N(1)-Fe(1)-C(8)	108.9(5)	C(1)-Fe(1)-C(8)	129.9(5)
C(5)-Fe(1)-C(8)	69.2(5)	C(4)-Fe(1)-C(8)	117.3(5)

C(9)-Fe(1)-C(8)	69.2(5)	N(1)-Fe(1)-C(6)	117.8(5)
C(1)-Fe(1)-C(6)	108.3(5)	C(5)-Fe(1)-C(6)	41.0(5)
C(4)-Fe(1)-C(6)	151.2(5)	C(9)-Fe(1)-C(6)	69.6(5)
C(8)-Fe(1)-C(6)	41.3(4)	N(1)-Fe(1)-C(3)	68.2(4)
C(1)-Fe(1)-C(3)	68.7(5)	C(5)-Fe(1)-C(3)	128.7(5)
C(4)-Fe(1)-C(3)	40.2(4)	C(9)-Fe(1)-C(3)	106.7(5)
C(8)-Fe(1)-C(3)	149.6(4)	C(6)-Fe(1)-C(3)	167.7(5)
N(1)-Fe(1)-C(7)	129.9(5)	C(1)-Fe(1)-C(7)	168.1(5)
C(5)-Fe(1)-C(7)	68.8(5)	C(4)-Fe(1)-C(7)	107.9(4)
C(9)-Fe(1)-C(7)	40.8(5)	C(8)-Fe(1)-C(7)	40.4(5)
C(6)-Fe(1)-C(7)	68.6(4)	C(3)-Fe(1)-C(7)	116.8(4)
N(1)-Fe(1)-C(2)	67.2(5)	C(1)-Fe(1)-C(2)	40.1(5)
C(5)-Fe(1)-C(2)	108.3(5)	C(4)-Fe(1)-C(2)	67.7(5)
C(9)-Fe(1)-C(2)	117.1(5)	C(8)-Fe(1)-C(2)	168.3(5)
C(6)-Fe(1)-C(2)	129.5(5)	C(3)-Fe(1)-C(2)	40.7(4)
C(7)-Fe(1)-C(2)	150.5(5)	N(2)-Fe(2)-C(34)	41.7(4)
N(2)-Fe(2)-C(39)	130.5(4)	C(34)-Fe(2)-C(39)	107.6(4)
N(2)-Fe(2)-C(38)	168.4(4)	C(34)-Fe(2)-C(38)	127.8(5)
C(39)-Fe(2)-C(38)	41.3(5)	N(2)-Fe(2)-C(31)	40.5(4)
C(34)-Fe(2)-C(31)	68.8(5)	C(39)-Fe(2)-C(31)	169.7(5)
C(38)-Fe(2)-C(31)	148.5(5)	N(2)-Fe(2)-C(37)	149.8(4)
C(34)-Fe(2)-C(37)	165.6(5)	C(39)-Fe(2)-C(37)	70.4(4)
C(38)-Fe(2)-C(37)	41.6(4)	C(31)-Fe(2)-C(37)	115.6(4)
N(2)-Fe(2)-C(35)	111.3(5)	C(34)-Fe(2)-C(35)	119.0(5)
C(39)-Fe(2)-C(35)	40.0(4)	C(38)-Fe(2)-C(35)	67.7(5)
C(31)-Fe(2)-C(35)	132.5(5)	C(37)-Fe(2)-C(35)	69.1(5)
N(2)-Fe(2)-C(33)	67.9(4)	C(34)-Fe(2)-C(33)	40.0(5)
C(39)-Fe(2)-C(33)	116.6(4)	C(38)-Fe(2)-C(33)	107.0(5)
C(31)-Fe(2)-C(33)	67.2(5)	C(37)-Fe(2)-C(33)	127.3(5)
C(35)-Fe(2)-C(33)	150.6(5)	N(2)-Fe(2)-C(32)	67.2(5)
C(34)-Fe(2)-C(32)	67.5(5)	C(39)-Fe(2)-C(32)	149.0(5)
C(38)-Fe(2)-C(32)	116.0(5)	C(31)-Fe(2)-C(32)	39.6(4)
C(37)-Fe(2)-C(32)	106.5(5)	C(35)-Fe(2)-C(32)	169.4(5)
C(33)-Fe(2)-C(32)	39.7(4)	N(2)-Fe(2)-C(36)	119.2(5)
C(34)-Fe(2)-C(36)	152.7(6)	C(39)-Fe(2)-C(36)	68.5(4)
C(38)-Fe(2)-C(36)	68.1(5)	C(31)-Fe(2)-C(36)	110.0(4)
C(37)-Fe(2)-C(36)	40.9(5)	C(35)-Fe(2)-C(36)	40.6(5)
C(33)-Fe(2)-C(36)	166.6(5)	C(32)-Fe(2)-C(36)	130.0(4)
O(6)-S(1)-O(5)	114.3(5)	O(6)-S(1)-O(3)	112.6(5)
O(5)-S(1)-O(3)	111.5(5)	O(6)-S(1)-C(72)	106.8(5)
O(5)-S(1)-C(72)	103.1(5)	O(3)-S(1)-C(72)	107.8(5)
O(7)-S(2)-O(9)	113.4(5)	O(7)-S(2)-O(8)	110.9(5)
O(9)-S(2)-O(8)	113.5(5)	O(7)-S(2)-C(52)	106.8(5)
O(9)-S(2)-C(52)	107.2(6)	O(8)-S(2)-C(52)	104.3(5)
C(1)-N(1)-C(4)	110.2(10)	C(1)-N(1)-Fe(1)	71.2(6)
C(4)-N(1)-Fe(1)	71.5(6)	C(31)-N(2)-C(34)	108.5(10)
C(31)-N(2)-Fe(2)	71.4(6)	C(34)-N(2)-Fe(2)	70.3(6)
N(1)-C(1)-C(2)	107.5(10)	N(1)-C(1)-Fe(1)	68.4(6)
C(2)-C(1)-Fe(1)	72.3(7)	C(1)-C(2)-C(3)	107.8(11)
C(1)-C(2)-Fe(1)	67.6(7)	C(3)-C(2)-Fe(1)	68.7(6)
C(4)-C(3)-C(2)	107.6(11)	C(4)-C(3)-Fe(1)	69.2(7)
C(2)-C(3)-Fe(1)	70.6(7)	C(3)-C(4)-N(1)	106.8(10)
C(3)-C(4)-C(15)	129.6(11)	N(1)-C(4)-C(15)	123.3(11)
C(3)-C(4)-Fe(1)	70.6(7)	N(1)-C(4)-Fe(1)	67.3(6)
C(15)-C(4)-Fe(1)	131.5(8)	C(6)-C(5)-C(9)	108.3(10)
C(6)-C(5)-C(10)	126.8(11)	C(9)-C(5)-C(10)	124.9(12)
C(6)-C(5)-Fe(1)	70.0(7)	C(9)-C(5)-Fe(1)	69.4(6)
C(10)-C(5)-Fe(1)	126.3(8)	C(5)-C(6)-C(8)	107.6(10)
C(5)-C(6)-C(11)	128.1(11)	C(8)-C(6)-C(11)	124.3(12)

C(5)-C(6)-Fe(1)	68.9(6)	C(8)-C(6)-Fe(1)	69.4(6)
C(11)-C(6)-Fe(1)	128.3(8)	C(7)-C(9)-C(5)	107.2(11)
C(7)-C(9)-C(14)	127.6(10)	C(5)-C(9)-C(14)	125.2(11)
C(7)-C(9)-Fe(1)	70.8(7)	C(5)-C(9)-Fe(1)	68.9(6)
C(14)-C(9)-Fe(1)	127.2(8)	C(8)-C(7)-C(9)	108.7(10)
C(8)-C(7)-C(13)	128.1(12)	C(9)-C(7)-C(13)	123.2(12)
C(8)-C(7)-Fe(1)	68.9(6)	C(9)-C(7)-Fe(1)	68.4(6)
C(13)-C(7)-Fe(1)	127.8(7)	C(7)-C(8)-C(6)	108.2(11)
C(7)-C(8)-C(12)	126.2(11)	C(6)-C(8)-C(12)	125.6(11)

C(7)-C(8)-Fe(1)	70.7(6)	C(6)-C(8)-Fe(1)	69.3(6)
C(12)-C(8)-Fe(1)	127.3(9)	O(1)-C(15)-C(4)	108.0(9)
C(32)-C(31)-N(2)	107.6(10)	C(32)-C(31)-Fe(2)	71.2(7)
N(2)-C(31)-Fe(2)	68.1(6)	C(31)-C(32)-C(33)	108.9(11)
C(31)-C(32)-Fe(2)	69.3(7)	C(33)-C(32)-Fe(2)	70.0(6)
C(32)-C(33)-C(34)	108.6(11)	C(32)-C(33)-Fe(2)	70.3(7)
C(34)-C(33)-Fe(2)	68.7(7)	C(33)-C(34)-N(2)	106.4(10)
C(33)-C(34)-C(45)	132.3(11)	N(2)-C(34)-C(45)	121.0(11)
C(33)-C(34)-Fe(2)	71.3(8)	N(2)-C(34)-Fe(2)	68.0(6)
C(45)-C(34)-Fe(2)	130.0(8)	C(39)-C(35)-C(36)	109.7(12)
C(39)-C(35)-C(40)	125.7(11)	C(36)-C(35)-C(40)	124.6(12)
C(39)-C(35)-Fe(2)	69.6(6)	C(36)-C(35)-Fe(2)	70.3(6)
C(40)-C(35)-Fe(2)	126.1(9)	C(35)-C(36)-C(37)	108.4(10)
C(35)-C(36)-C(41)	125.2(13)	C(37)-C(36)-C(41)	126.4(11)
C(35)-C(36)-Fe(2)	69.1(6)	C(37)-C(36)-Fe(2)	68.7(6)
C(41)-C(36)-Fe(2)	127.0(8)	C(38)-C(37)-C(36)	105.7(10)
C(38)-C(37)-C(42)	126.3(12)	C(36)-C(37)-C(42)	127.9(10)
C(38)-C(37)-Fe(2)	69.1(6)	C(36)-C(37)-Fe(2)	70.4(7)
C(42)-C(37)-Fe(2)	128.8(8)	C(39)-C(38)-C(37)	109.2(11)
C(39)-C(38)-C(43)	125.8(10)	C(37)-C(38)-C(43)	125.0(11)
C(39)-C(38)-Fe(2)	69.3(7)	C(37)-C(38)-Fe(2)	69.3(6)
C(43)-C(38)-Fe(2)	125.6(8)	C(35)-C(39)-C(38)	107.0(9)
C(35)-C(39)-C(44)	127.7(12)	C(38)-C(39)-C(44)	125.2(11)
C(35)-C(39)-Fe(2)	70.4(6)	C(38)-C(39)-Fe(2)	69.4(6)
C(44)-C(39)-Fe(2)	128.0(8)	O(2)-C(45)-C(34)	109.4(9)
C(57)-C(51)-C(55)	102.4(12)	C(53)-C(52)-S(2)	119.1(8)
C(52)-C(53)-C(55)	110.2(12)	C(52)-C(53)-C(54)	118.6(10)
C(55)-C(53)-C(54)	103.3(11)	C(52)-C(53)-C(58)	119.2(10)
C(55)-C(53)-C(58)	100.5(10)	C(54)-C(53)-C(58)	102.5(10)
C(56)-C(54)-C(53)	103.7(11)	O(4)-C(55)-C(51)	127.8(14)
O(4)-C(55)-C(53)	126.9(14)	C(51)-C(55)-C(53)	105.1(14)
C(57)-C(56)-C(54)	102.5(12)	C(51)-C(57)-C(56)	107.7(13)
C(51)-C(57)-C(58)	103.1(13)	C(56)-C(57)-C(58)	103.8(10)
C(59)-C(58)-C(57)	114.8(12)	C(59)-C(58)-C(60)	107.0(10)
C(57)-C(58)-C(60)	116.2(10)	C(59)-C(58)-C(53)	114.5(9)
C(57)-C(58)-C(53)	92.8(10)	C(60)-C(58)-C(53)	111.3(12)
C(73)-C(72)-S(1)	119.9(8)	C(72)-C(73)-C(74)	111.2(11)
C(72)-C(73)-C(79)	119.9(9)	C(74)-C(73)-C(79)	103.3(10)
C(72)-C(73)-C(77)	119.6(10)	C(74)-C(73)-C(77)	98.7(10)
C(79)-C(73)-C(77)	101.0(10)	O(10)-C(74)-C(81)	125.0(13)
O(10)-C(74)-C(73)	127.1(12)	C(81)-C(74)-C(73)	107.7(12)
C(80)-C(79)-C(73)	104.3(10)	C(78)-C(80)-C(79)	102.8(11)
C(74)-C(81)-C(78)	101.8(12)	C(97)-C(92)-C(93)	116(2)
C(97)-C(92)-C(91)	124(2)	C(93)-C(92)-C(91)	120(2)
C(94)-C(93)-C(92)	118(2)	C(95)-C(94)-C(93)	122(2)
C(96)-C(95)-C(94)	119(2)	C(95)-C(96)-C(97)	122(2)
C(96)-C(97)-C(92)	123(2)	C(76)-C(77)-C(78)	114.9(11)
C(76)-C(77)-C(75)	106.0(11)	C(78)-C(77)-C(75)	114.0(12)
C(76)-C(77)-C(73)	114.2(11)	C(78)-C(77)-C(73)	93.8(10)
C(75)-C(77)-C(73)	114.0(10)	C(81)-C(78)-C(80)	107.6(14)
C(81)-C(78)-C(77)	103.8(13)	C(80)-C(78)-C(77)	102.4(10)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters [$Å^2$ x 10^3] for 1.

The anisotropic displacement factor exponent takes the form:

$-2\pi^2 [(ha^*)^2 U_{11} + ... + 2hka^* b^* U_{12}]$

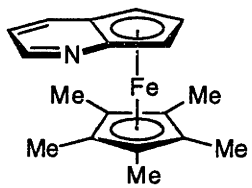
	U11	U22	U33	U23	U13	U12
Fe(1)	23(1)	22(1)	23(1)	0(1)	-4(1)	0(1)
Fe(2)	22(1)	21(1)	23(1)	1(1)	1(1)	0(1)
S(1)	25(2)	22(2)	28(2)	0(1)	2(1)	-1(1)
S(2)	22(1)	22(2)	31(2)	4(2)	-3(1)	-1(1)
O(1)	39(5)	29(6)	53(5)	3(5)	9(4)	9(5)
O(2)	35(5)	20(5)	65(6)	0(5)	-15(4)	-5(4)
O(3)	18(4)	31(5)	33(4)	12(4)	6(3)	2(4)
O(4)	181(14)	53(9)	57(7)	-28(7)	-41(8)	57(9)
O(5)	35(4)	31(6)	41(5)	18(4)	-6(4)	0(4)
O(6)	31(4)	22(5)	38(5)	-6(4)	2(3)	-7(4)
O(7)	19(4)	32(5)	41(5)	6(4)	1(3)	5(4)
O(8)	28(4)	37(6)	49(5)	16(5)	8(4)	0(4)
O(9)	31(4)	23(5)	40(5)	0(4)	-5(3)	1(4)
O(10)	107(9)	52(8)	33(5)	-6(5)	5(5)	-17(7)
N(1)	17(5)	34(7)	27(5)	-2(5)	-7(4)	-1(5)
N(2)	24(5)	24(6)	23(5)	-7(5)	2(4)	8(5)
C(1)	34(7)	23(8)	33(7)	13(6)	-12(5)	-3(6)
C(2)	49(8)	34(9)	33(7)	7(7)	-14(6)	11(7)
C(3)	21(6)	16(7)	31(7)	-2(5)	0(5)	5(5)
C(4)	22(6)	28(8)	24(6)	-4(6)	-3(5)	3(6)
C(5)	37(7)	35(9)	24(6)	-8(6)	-3(5)	1(7)
C(6)	27(6)	31(9)	25(6)	4(6)	-1(5)	6(6)
C(9)	25(6)	21(7)	31(7)	6(6)	-10(5)	0(6)
C(7)	26(6)	38(8)	18(5)	6(6)	-14(4)	-1(6)
C(10)	44(8)	47(10)	44(8)	-12(7)	5(6)	17(7)
C(8)	33(7)	27(8)	29(7)	11(6)	-13(5)	-7(6)
C(11)	43(8)	45(10)	38(7)	6(7)	-1(6)	-7(7)
C(12)	43(7)	27(8)	43(8)	3(7)	-2(6)	-2(6)
C(13)	22(6)	44(9)	38(7)	5(7)	2(5)	1(7)
C(14)	49(7)	23(8)	36(7)	-6(6)	9(6)	-12(6)
C(15)	29(7)	39(9)	43(8)	-1(7)	13(5)	0(6)
C(31)	36(7)	34(8)	12(6)	0(6)	6(5)	-2(6)
C(32)	26(6)	26(8)	29(7)	-4(6)	1(5)	-6(6)
C(33)	34(7)	14(7)	34(7)	7(6)	-10(5)	1(6)
C(34)	25(6)	34(9)	23(6)	3(6)	0(5)	13(6)
C(35)	36(7)	28(8)	28(7)	9(6)	14(5)	12(6)
C(36)	21(6)	63(11)	19(6)	2(7)	3(4)	-6(7)
C(37)	32(6)	24(8)	20(6)	4(6)	1(5)	-1(6)
C(38)	40(7)	22(8)	26(7)	-3(6)	12(5)	3(6)
C(39)	11(5)	34(8)	32(6)	10(6)	3(4)	3(6)
C(40)	59(9)	33(9)	38(7)	16(7)	5(6)	-11(7)
C(41)	33(7)	52(10)	34(7)	8(7)	3(5)	15(7)
C(42)	48(8)	49(10)	40(8)	-16(7)	-7(6)	-5(7)
C(43)	55(8)	26(8)	34(7)	-5(6)	5(6)	0(7)
C(44)	25(6)	50(9)	33(6)	0(7)	9(5)	-2(7)
C(45)	31(6)	25(8)	30(6)	-1(6)	-11(5)	-3(6)
C(51)	158(18)	66(13)	36(9)	20(9)	-8(10)	43(12)
C(52)	36(7)	37(9)	51(7)	2(7)	-35(6)	2(6)

C(53)	33(7)	37(8)	31(7)	-1(7)	-8(5)	3(7)
C(54)	58(9)	33(9)	49(8)	15(7)	12(7)	6(7)
C(55)	103(13)	56(12)	22(7)	3(8)	-21(8)	39(10)
C(56)	71(10)	46(11)	62(10)	15(8)	15(8)	17(8)
C(57)	89(11)	63(12)	14(6)	12(7)	13(7)	26(9)
C(58)	25(6)	36(8)	37(7)	2(7)	-12(5)	8(6)
C(59)	33(7)	23(8)	67(9)	0(7)	3(6)	14(6)
C(60)	62(9)	64(12)	69(10)	21(10)	-31(7)	16(9)
C(72)	32(6)	25(7)	27(6)	5(6)	-4(5)	7(6)
C(73)	36(6)	21(7)	31(6)	8(6)	2(5)	-5(6)
C(74)	58(9)	42(10)	24(7)	-1(7)	-5(6)	-4(7)
C(79)	50(8)	41(10)	46(8)	10(7)	-14(6)	2(7)
C(80)	67(10)	43(10)	65(10)	23(9)	-10(7)	7(8)
C(81)	140(16)	46(11)	37(9)	19(8)	9(9)	-30(11)
C(91)	71(12)	153(24)	101(15)	-38(16)	15(11)	34(14)
C(92)	63(10)	103(17)	25(7)	0(10)	6(7)	7(11)
C(93)	93(13)	43(12)	63(11)	0(9)	35(10)	19(11)
C(94)	102(15)	62(15)	53(10)	-9(10)	18(10)	-32(12)
C(95)	108(15)	93(17)	33(9)	-3(11)	6(9)	-20(14)
C(96)	106(15)	84(16)	38(9)	-2(10)	7(9)	-1(13)
C(97)	73(11)	50(12)	71(11)	3(10)	2(9)	3(10)
C(77)	52(8)	26(9)	40(7)	-2(7)	9(6)	-9(7)
C(78)	86(11)	55(12)	33(7)	25(8)	-18(7)	-19(10)
C(76)	57(9)	47(11)	84(11)	-2(9)	3(8)	-4(8)
C(75)	84(11)	31(9)	38(8)	5(7)	0(7)	-23(8)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

	x	y	z	U(eq)
H(1A)	2329(9)	6060(7)	5066(3)	60
H(2A)	-2599(9)	-1420(7)	8(3)	61
H(3B)	6625(8)	6528(6)	4631(3)	41
H(7A)	1775(8)	-1867(6)	359(3)	46
H(1B)	8706(15)	4337(9)	4642(4)	36
H(2B)	7762(16)	2613(11)	4960(5)	47
H(3A)	4651(13)	2780(9)	5264(4)	27
H(10A)	6763(15)	1480(11)	3825(5)	67
H(10B)	8192(15)	2312(11)	3895(5)	67
H(10C)	7437(15)	2057(11)	3344(5)	67
H(11A)	7067(15)	5157(11)	3344(5)	64
H(11B)	7582(15)	4156(11)	3063(5)	64
H(11C)	8378(15)	4405(11)	3610(5)	64
H(12A)	4889(15)	5794(10)	3545(5)	57
H(12B)	3614(15)	5740(10)	4001(5)	57
H(12C)	2952(15)	5499(10)	3439(5)	57
H(13A)	1068(12)	3111(11)	4227(4)	52
H(13B)	777(12)	4001(11)	3835(4)	52
H(13C)	1466(12)	4227(11)	4396(4)	52
H(14A)	4433(15)	1241(9)	4118(4)	53
H(14B)	2555(15)	1534(9)	3935(4)	53
H(14C)	3205(15)	1791(9)	4497(4)	53
H(15A)	2333(14)	4425(10)	5175(5)	44
H(15B)	3441(14)	4972(10)	5610(5)	44
H(31A)	3913(14)	327(9)	360(4)	33
H(32A)	2819(14)	2031(10)	66(4)	32
H(33A)	-289(14)	1856(9)	-230(4)	33
H(40A)	285(17)	-1128(10)	1540(5)	65
H(40B)	-999(17)	-1111(10)	1062(5)	65
H(40C)	-1654(17)	-837(10)	1610(5)	65
H(41A)	3793(14)	673(10)	1685(5)	60
H(41B)	3172(14)	-339(10)	1425(5)	60
H(41C)	2554(14)	-54(10)	1975(5)	60
H(42A)	3629(15)	2212(11)	1458(5)	68
H(42B)	2220(15)	3037(11)	1552(5)	68
H(42C)	2819(15)	2816(11)	992(5)	68
H(43A)	-256(16)	3410(9)	912(4)	58
H(43B)	-2115(16)	3093(9)	1070(4)	58
H(43C)	-1472(16)	2830(9)	519(4)	58
H(44A)	-3622(12)	1499(11)	782(4)	54
H(44B)	-3834(12)	681(11)	1212(4)	54
H(44C)	-3268(12)	357(11)	662(4)	54
H(45A)	-2634(14)	184(9)	-114(4)	35
H(45B)	-1644(14)	-381(9)	-548(4)	35
H(51A)	6023(27)	-3718(13)	2526(6)	104
H(51B)	4013(27)	-3591(13)	2588(6)	104
H(52A)	6407(15)	-2591(10)	976(4)	46
H(52B)	5292(15)	-1756(10)	1229(4)	46
H(54A)	2041(16)	-2959(10)	1583(5)	55

H(54B)	2366(16)	-3647(10)	1099(5)	55
H(56A)	1988(18)	-4339(12)	2072(6)	71
H(56B)	2423(18)	-5021(12)	1593(6)	71
H(57A)	4931(19)	-5151(12)	2116(4)	66
H(59A)	6099(15)	-4604(10)	796(5)	62
H(59B)	4225(15)	-4871(10)	961(5)	62
H(59C)	5793(15)	-5519(10)	1166(5)	62
H(60A)	7748(16)	-3579(14)	1897(6)	98
H(60B)	8046(16)	-3723(14)	1307(6)	98
H(60C)	8106(16)	-4661(14)	1676(6)	98
H(72A)	11305(13)	7065(10)	4042(4)	34
H(72B)	10104(13)	6238(10)	3799(4)	34
H(79A)	6965(16)	7503(11)	3350(5)	55
H(79B)	7359(16)	8239(11)	3817(5)	55
H(80A)	7046(17)	8811(12)	2823(6)	70
H(80B)	7581(17)	9533(12)	3286(6)	70
H(81A)	8916(25)	7911(12)	2381(5)	89
H(81B)	10945(25)	7997(12)	2448(5)	89
H(91A)	6963(21)	3361(18)	2120(7)	162
H(91B)	6536(21)	2417(18)	2458(7)	162
H(91C)	7150(21)	2268(18)	1894(7)	162
H(93A)	9484(24)	4169(13)	2377(6)	79
H(94A)	12284(25)	4077(15)	2677(6)	87
H(95A)	13477(25)	2589(18)	2923(6)	94
H(96A)	11964(25)	1161(17)	2812(6)	91
H(97A)	9281(21)	1174(14)	2495(6)	78
H(78A)	10065(19)	9499(13)	2798(5)	70
H(76A)	13038(17)	8264(12)	3733(6)	94
H(76B)	13049(17)	9043(12)	3278(6)	94
H(76C)	12728(17)	7892(12)	3164(6)	94
H(75A)	9230(19)	9489(10)	3929(5)	77
H(75B)	11002(19)	9976(10)	3793(5)	77
H(75C)	10942(19)	9094(10)	4195(5)	77



1.29

Structure solved by Dr. Bill Davis.

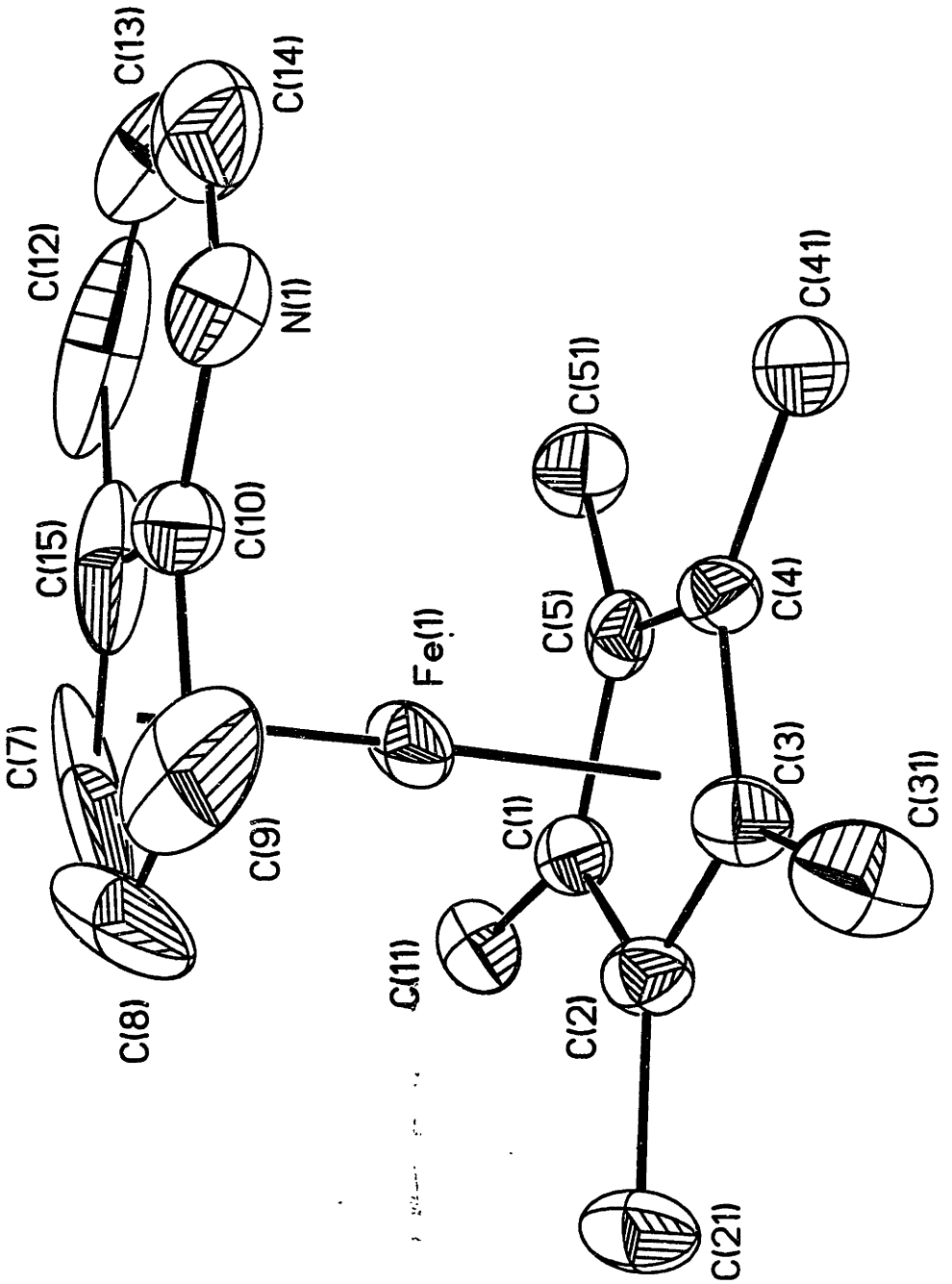

C(13)
C(14)
C(12)
N(1)
C(15)
C(10)
C(7)
Fe(1)
C(5)
C(51)
C(41)
C(4)
C(9)
C(1)
C(3)
C(31)
C(11)
C(2)
C(8)
C(21)

Table 1. Crystal data and structure refinement for 1.

A. Crystal data

Identification code	95096
Empirical formula	$C_{18}H_{21}FeN$
Formula weight	307.21
Temperature	293(2) K
Wavelength	0.71073 Å
Crystal system	Orthorhombic
Space group	$P2_12_12_1$
Unit cell dimensions	a = 9.4545(7) Å α = 90°
	b = 12.5740(10) Å β = 90°
	c = 12.6985(10) Å γ = 90°
Volume, Z	1509.6(2) $Å^3$, 4
Density (calculated)	1.352 Mg/m^3
Absorption coefficient	0.988 mm^{-1}
F(000)	648
Crystal morphology	?
Crystal size	? x ? x ? mm

B. Data Collection and Reduction

Diffractometer	Siemens SMART/CCD
Crystal-Detector distance	6.0 cm
Scan type	ω Scans
Scan angle	0.30°
θ range for data collection	2.28 to 23.32°
Limiting indices	$-10 \le h \le 9$, $-8 \le k \le 13$, $-14 \le l \le 14$
Reflections collected	5979
Independent reflections	2181 (R_{int} = 0.0874)
Absorption correction	None

C. Structure Solution and Refinement

Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	2181 / 0 / 178
Goodness-of-fit on F^2	1.081
Final R indices [$I>2\sigma(I)$]	R_1 = 0.0653, wR_2 = 0.1714
R indices (all data)	R_1 = 0.0674, wR_2 = 0.1751
Maximum shift/esd	-0.163
Absolute structure parameter	0.52(5)
Largest diff. peak and hole	0.886 and -0.480 $e\text{Å}^{-3}$

Notes: E

$$R_1 = \sum|F_o|-|F_c|/\sum|F_o|$$

$$wR_2=[\sum[w(F_o^2-F_c^2)^2/[\sum(F_o^2)^2]]^{1/2}$$

Weighting scheme

calc w=1/[\s^2^(Fo^2^)+(0.1040P)^2^+2.3012P] where P=(Fo^2^+2Fc^2^)/3

Refinement on F^2 for ALL reflections. Weighted R-factors wR and all goodnesses of fit S are based on F^2, conventional R-factors R are based on F, with F set to zero for negative F^2. The observed criterion of $F^2 > 2\sigma(F^2)$ is used only for calculating R_1 and is not relevant to the choice of reflections for refinement. R-factors based on F^2 are statistically about twice as large as those based on F, and R- factors based on ALL data will be even larger.

Table 2. Atomic coordinates [x 10^4] and equivalent isotropic displacement parameters [$Å^2$ x 10^3] for 1. U(eq) is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U(eq)
Fe(1)	1111(1)	4659(1)	5283(1)	45(1)
N(1)	2096(7)	6319(5)	3652(6)	66(2)
C(1)	-466(6)	3929(5)	6094(5)	37(1)
C(2)	476(7)	3158(5)	5651(5)	40(1)
C(3)	497(6)	3293(5)	4551(5)	42(1)
C(4)	-449(6)	4164(5)	4283(5)	36(1)
C(5)	-1052(5)	4527(4)	5251(5)	38(1)
C(7)	2094(23)	5581(20)	6337(10)	212(14)
C(8)	2975(15)	4913(16)	6012(17)	185(13)
C(9)	3135(8)	4999(8)	4908(12)	107(4)
C(10)	2260(6)	5894(5)	4601(5)	41(1)
C(11)	-793(7)	4065(6)	7251(5)	51(2)
C(15)	1609(11)	6266(8)	5549(6)	86(4)
C(12)	573(10)	7215(9)	5331(14)	118(6)
C(13)	510(11)	7490(7)	4305(10)	79(3)
C(14)	1225(6)	7065(4)	3558(5)	80(3)
C(21)	1274(6)	2330(4)	6255(5)	57(2)
C(31)	1333(9)	2653(7)	3776(6)	67(2)
C(41)	-766(7)	4574(5)	3216(5)	51(2)
C(51)	-2142(7)	5405(5)	5335(6)	56(2)

Table 3. Bond lengths [Å] and angles [°] for 1.

Fe(1)-C(7)	1.999(13)	Fe(1)-C(1)	2.032(6)
Fe(1)-C(9)	2.017(8)	Fe(1)-C(8)	2.016(11)
Fe(1)-C(2)	2.034(6)	Fe(1)-C(3)	2.037(7)
Fe(1)-C(4)	2.043(6)	Fe(1)-C(5)	2.053(5)
Fe(1)-C(10)	2.083(6)	Fe(1)-C(15)	2.103(9)
N(1)-C(14)	1.254(9)	N(1)-C(10)	1.328(9)
C(1)-C(5)	1.421(8)	C(1)-C(2)	1.432(9)
C(1)-C(11)	1.510(8)	C(2)-C(3)	1.407(9)
C(2)-C(21)	1.498(8)	C(3)-C(4)	1.454(8)
C(3)-C(31)	1.497(9)	C(4)-C(5)	1.430(8)
C(4)-C(41)	1.481(9)	C(5)-C(51)	1.513(8)
C(7)-C(8)	1.25(3)	C(7)-C(15)	1.40(2)
C(8)-C(9)	1.41(2)	C(9)-C(10)	1.450(12)
C(10)-C(15)	1.430(10)	C(15)-C(12)	1.57(2)
C(12)-C(13)	1.35(2)	C(13)-C(14)	1.281(12)

C(7)-Fe(1)-C(1)	105.3(5)	C(7)-Fe(1)-C(9)	66.1(7)
C(1)-Fe(1)-C(9)	155.7(4)	C(7)-Fe(1)-C(8)	36.4(9)
C(1)-Fe(1)-C(8)	118.7(5)	C(9)-Fe(1)-C(8)	41.0(7)
C(7)-Fe(1)-C(2)	121.4(5)	C(1)-Fe(1)-C(2)	41.2(3)
C(9)-Fe(1)-C(2)	122.1(3)	C(8)-Fe(1)-C(2)	107.5(4)
C(7)-Fe(1)-C(3)	157.9(8)	C(1)-Fe(1)-C(3)	69.0(3)
C(9)-Fe(1)-C(3)	110.0(4)	C(8)-Fe(1)-C(3)	126.3(7)
C(2)-Fe(1)-C(3)	40.4(3)	C(7)-Fe(1)-C(4)	158.1(9)
C(1)-Fe(1)-C(4)	69.4(2)	C(9)-Fe(1)-C(4)	127.1(5)
C(8)-Fe(1)-C(4)	164.7(8)	C(2)-Fe(1)-C(4)	69.3(2)
C(3)-Fe(1)-C(4)	41.8(2)	C(7)-Fe(1)-C(5)	121.5(8)
C(1)-Fe(1)-C(5)	40.7(2)	C(9)-Fe(1)-C(5)	163.2(5)
C(8)-Fe(1)-C(5)	153.2(7)	C(2)-Fe(1)-C(5)	68.6(2)
C(3)-Fe(1)-C(5)	68.9(2)	C(4)-Fe(1)-C(5)	40.9(2)
C(7)-Fe(1)-C(10)	66.7(4)	C(1)-Fe(1)-C(10)	158.4(2)
C(9)-Fe(1)-C(10)	41.4(3)	C(8)-Fe(1)-C(10)	67.5(4)
C(2)-Fe(1)-C(10)	160.2(2)	C(3)-Fe(1)-C(10)	126.0(3)
C(4)-Fe(1)-C(10)	110.2(2)	C(5)-Fe(1)-C(10)	124.8(2)
C(7)-Fe(1)-C(15)	39.8(7)	C(1)-Fe(1)-C(15)	121.1(3)
C(9)-Fe(1)-C(15)	67.8(4)	C(8)-Fe(1)-C(15)	65.0(6)
C(2)-Fe(1)-C(15)	157.0(3)	C(3)-Fe(1)-C(15)	161.3(3)
C(4)-Fe(1)-C(15)	123.6(3)	C(5)-Fe(1)-C(15)	107.7(3)
C(10)-Fe(1)-C(15)	39.9(3)	C(14)-N(1)-C(10)	117.6(7)
C(5)-C(1)-C(2)	107.7(5)	C(5)-C(1)-C(11)	126.4(6)
C(2)-C(1)-C(11)	125.9(6)	C(5)-C(1)-Fe(1)	70.4(3)
C(2)-C(1)-Fe(1)	69.5(3)	C(11)-C(1)-Fe(1)	126.3(4)
C(3)-C(2)-C(1)	108.5(5)	C(3)-C(2)-C(21)	125.8(6)
C(1)-C(2)-C(21)	125.7(6)	C(3)-C(2)-Fe(1)	69.9(4)
C(1)-C(2)-Fe(1)	69.3(3)	C(21)-C(2)-Fe(1)	127.8(4)
C(2)-C(3)-C(4)	108.3(6)	C(2)-C(3)-C(31)	126.6(6)
C(4)-C(3)-C(31)	125.1(6)	C(2)-C(3)-Fe(1)	69.7(4)
C(4)-C(3)-Fe(1)	69.4(3)	C(31)-C(3)-Fe(1)	127.0(5)
C(5)-C(4)-C(3)	106.6(5)	C(5)-C(4)-C(41)	126.5(5)
C(3)-C(4)-C(41)	126.9(6)	C(5)-C(4)-Fe(1)	69.9(3)
C(3)-C(4)-Fe(1)	68.9(3)	C(41)-C(4)-Fe(1)	127.5(4)
C(1)-C(5)-C(4)	108.8(4)	C(1)-C(5)-C(51)	126.8(6)
C(4)-C(5)-C(51)	124.4(6)	C(1)-C(5)-Fe(1)	68.9(3)
C(4)-C(5)-Fe(1)	69.2(3)	C(51)-C(5)-Fe(1)	128.2(4)
C(8)-C(7)-C(15)	113.3(14)	C(8)-C(7)-Fe(1)	72.5(12)

C(15)-C(7)-Fe(1)	74.1(5)	C(7)-C(8)-C(9)	110.3(12)
C(7)-C(8)-Fe(1)	71.1(7)	C(9)-C(8)-Fe(1)	69.5(6)
C(8)-C(9)-C(10)	105.4(11)	C(8)-C(9)-Fe(1)	69.4(6)
C(10)-C(9)-Fe(1)	71.8(4)	N(1)-C(10)-C(15)	125.6(7)
N(1)-C(10)-C(9)	128.5(8)	C(15)-C(10)-C(9)	105.9(9)
N(1)-C(10)-Fe(1)	128.1(5)	C(15)-C(10)-Fe(1)	70.8(4)
C(9)-C(10)-Fe(1)	66.9(4)	C(7)-C(15)-C(10)	105.0(13)
C(7)-C(15)-C(12)	143.1(14)	C(10)-C(15)-C(12)	111.7(9)
C(7)-C(15)-Fe(1)	66.1(8)	C(10)-C(15)-Fe(1)	69.3(5)
C(12)-C(15)-Fe(1)	124.2(6)	C(13)-C(12)-C(15)	113.1(8)
C(14)-C(13)-C(12)	125.8(10)	N(1)-C(14)-C(13)	126.1(8)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters [$Å^2$ x 10^3] for 1.

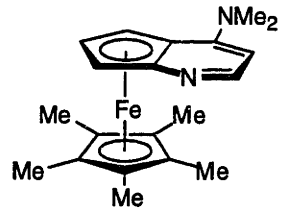
The anisotropic displacement factor exponent takes the form:

$-2\pi^2 [(ha^*)^2 U_{11} + ... + 2hka^* b^* U_{12}]$

	U11	U22	U33	U23	U13	U12
Fe(1)	26(1)	57(1)	52(1)	17(1)	-10(1)	-12(1)
N(1)	66(4)	55(4)	78(4)	7(3)	-5(3)	-19(3)
C(1)	26(3)	37(3)	47(3)	4(3)	-1(2)	-4(2)
C(2)	30(3)	40(3)	51(4)	7(3)	-2(3)	5(3)
C(3)	30(3)	47(3)	49(4)	2(3)	2(3)	9(3)
C(4)	25(3)	36(3)	47(3)	6(3)	-4(2)	1(2)
C(5)	24(3)	34(3)	54(3)	-6(3)	-3(3)	-5(3)
C(7)	240(21)	342(30)	55(6)	45(12)	-69(10)	-247(22)
C(8)	97(10)	216(19)	243(22)	190(18)	-124(12)	-121(11)
C(9)	28(4)	77(6)	215(13)	19(8)	27(6)	-14(4)
C(10)	36(3)	43(3)	46(3)	6(3)	0(3)	-3(3)
C(11)	47(4)	63(4)	44(3)	0(3)	-2(3)	-6(3)
C(15)	92(7)	112(8)	54(5)	-30(5)	23(5)	-75(6)
C(12)	66(5)	84(7)	204(15)	-100(9)	79(8)	-35(5)
C(13)	70(6)	47(4)	119(8)	0(5)	26(6)	-8(4)
C(14)	47(4)	78(6)	114(7)	3(5)	-7(5)	-14(5)
C(21)	42(4)	62(4)	67(4)	14(4)	-4(4)	17(3)
C(31)	65(5)	81(5)	54(4)	0(4)	7(4)	26(4)
C(41)	41(3)	51(4)	60(4)	7(3)	-7(3)	-9(3)
C(51)	45(4)	47(3)	76(4)	-5(4)	-6(3)	14(3)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

	x	y	z	U(eq)
H(7A)	1792(23)	5617(20)	7033(10)	255
H(8A)	3456(15)	4430(16)	6436(17)	223
H(9A)	3684(8)	4573(8)	4472(12)	128
H(11A)	-248(7)	3566(6)	7653(5)	77
H(11B)	-1782(7)	3942(6)	7369(5)	77
H(11C)	-556(7)	4776(6)	7465(5)	77
H(12A)	53(10)	7553(9)	5855(14)	141
H(13A)	-105(11)	8037(7)	4124(10)	94
H(14A)	1084(6)	7335(4)	2884(5)	95
H(21A)	1081(6)	2407(4)	6993(5)	85
H(21B)	2270(6)	2415(4)	6132(5)	85
H(21C)	984(6)	1636(4)	6026(5)	85
H(31A)	1151(9)	2910(7)	3077(6)	100
H(31B)	1061(9)	1920(7)	3823(6)	100
H(31C)	2323(9)	2721(7)	3930(6)	100
H(41A)	-214(7)	4193(5)	2706(5)	76
H(41B)	-536(7)	5317(5)	3182(5)	76
H(41C)	-1753(7)	4478(5)	3067(5)	76
H(51A)	-2358(7)	5669(5)	4645(6)	84
H(51B)	-1772(7)	5972(5)	5760(6)	84
H(51C)	-2987(7)	5129(5)	5654(6)	84



(+)-**1.31**

Structure solved by Diego Hoic.

C(28)
C(27)
C(23)
C(24)
C(29)
C(22)
Fe(2)
C(25)
C(21)
C(30)
C(26)
C(32)
C(33)
C(40)
C(31)
C(38)
C(37)
C(34)
N(3)
N(4)
C(36)
C(39)
C(35)
C(16)
C(15)
C(19)
N(1)
C(14)
C(17)
N(2)
C(18)
C(20)
C(11)
C(7)
C(6)
C(13)
Fe(1)
C(2)
C(12)
C(3)
C(1)
C(8)
C(5)
C(10)
C(4)
C(9)

Table 1. Crystal data and structure refinement for 1.

CA. Crystal Data

Identification code	96192
Empirical formula	$C_{20}H_{26}FeN_2$
Formula weight	350.28
Temperature	183(2) K
Wavelength	0.71073 Å
Crystal size	.15 x .23 x .26 mm
Crystal system	Monoclinic
Space group	$P2_1$
Unit cell dimensions	a = 8.1624(2) Å alpha = 90°
	b = 25.2907(3) Å beta = 92.1110(10)°
	c = 8.5483(2) Å gamma = 90°
Volume, Z	1763.45(6) $Å^3$, 4
Density (calculated)	1.319 Mg/m^3
Absorption coefficient	0.856 mm^{-1}
F(000)	744

CB. Data Collection and Reduction

Diffractometer	Siemens SMART/CCD
Scan Type	ω Scans
Scan angle	0.30°
θ range for data collection	1.61 to 23.27°
Limiting indices	$-9 \le h \le 8$, $-28 \le k \le 21$, $-9 \le l \le 9$
Reflections collected	7132
Independent reflections	3901 (R_{int} = 0.0349)
Absorption correction	None
Refinement method	Full-matrix least-squares on F^2

Data / restraints / parameters	3900 / 1 / 415
Goodness-of-fit on F^2	1.072
Final R indices [$I>2\sigma(I)$]	R1 = 0.0359, wR2 = 0.0957
R indices (all data)	R1 = 0.0371, wR2 = 0.1004
Absolute structure parameter	0.00(2)
Largest diff. peak and hole	0.594 and -0.298 $e\text{Å}^{-3}$

Table 2. Atomic coordinates [x 10^4] and equivalent isotropic displacement parameters [$Å^2$ x 10^3] for 1. U(eq) is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U(eq)
Fe(2)	-9355(1)	-3932(1)	-7188(1)	22(1)
Fe(1)	-14421(1)	-7005(1)	-7960(1)	22(1)
C(1)	-16697(6)	-7097(2)	-7063(6)	30(1)
N(1)	-14222(5)	-5891(2)	-9563(5)	30(1)
N(3)	-9130(5)	-5040(2)	-5519(5)	33(1)
C(25)	-11620(6)	-3847(2)	-6238(6)	34(1)
C(21)	-11788(5)	-3889(3)	-7925(6)	32(1)
N(2)	-14248(5)	-5905(2)	-4551(4)	33(1)
C(34)	-9292(6)	-5026(2)	-8947(5)	26(1)
C(14)	-14241(5)	-5914(2)	-6147(5)	25(1)
N(4)	-9412(5)	-5036(2)	-10543(4)	32(1)
C(38)	-8378(6)	-4627(2)	-8069(5)	26(1)
C(12)	-11917(5)	-7023(3)	-8029(5)	31(1)
C(15)	-15004(6)	-5536(2)	-7066(6)	32(1)
C(18)	-13364(5)	-6322(2)	-7006(5)	22(1)
C(11)	-12572(5)	-6726(2)	-9302(6)	29(1)
C(4)	-15241(6)	-7767(2)	-8237(6)	30(1)
C(35)	-10054(6)	-5401(2)	-8029(6)	29(1)
C(2)	-16828(5)	-7027(3)	-8739(5)	32(1)
C(3)	-15927(6)	-7430(2)	-9440(6)	32(1)
C(32)	-6846(5)	-3932(3)	-7055(5)	29(1)
C(36)	-9937(6)	-5388(2)	-6376(6)	33(1)
C(22)	-10851(6)	-3468(2)	-8591(5)	32(1)
C(17)	-13437(5)	-6286(2)	-8700(5)	22(1)
C(33)	-7437(6)	-4172(2)	-8458(6)	28(1)
C(13)	-12417(5)	-6791(2)	-6615(6)	26(1)
C(24)	-10599(6)	-3397(2)	-5898(6)	31(1)
C(23)	-10126(6)	-3169(2)	-7329(6)	31(1)
C(31)	-7462(6)	-4217(2)	-5779(6)	29(1)
C(16)	-14959(6)	-5534(2)	-8698(6)	31(1)
C(19)	-15163(8)	-5482(3)	-3785(7)	54(2)
C(37)	-8378(5)	-4659(2)	-6371(5)	26(1)
C(5)	-15730(6)	-7555(2)	-6766(6)	30(1)
C(10)	-15304(8)	-7792(3)	-5193(6)	51(2)
C(27)	-10714(7)	-3359(3)	-10310(6)	46(2)
C(9)	-14268(7)	-8253(2)	-8471(8)	52(2)
C(39)	-10455(8)	-5437(3)	-11308(6)	53(2)
C(30)	-12381(7)	-4201(3)	-5088(8)	54(2)
C(7)	-17747(6)	-6586(3)	-9556(7)	51(2)
C(28)	-9124(7)	-2675(3)	-7541(8)	51(2)
C(26)	-12785(7)	-4293(3)	-8798(8)	49(2)
C(8)	-15760(8)	-7506(3)	-11167(6)	54(2)
C(6)	-17530(7)	-6759(3)	-5866(7)	50(2)
C(40)	-8455(8)	-4705(3)	-11533(6)	50(2)
C(29)	-10083(8)	-3193(3)	-4299(6)	54(2)
C(20)	-13414(8)	-6293(3)	-3551(6)	48(2)

Table 3. Bond lengths [Å] and angles [°] for 1.

Fe(2)-C(33)	2.031(5)	Fe(2)-C(23)	2.033(5)
Fe(2)-C(24)	2.040(5)	Fe(2)-C(32)	2.047(4)
Fe(2)-C(31)	2.055(5)	Fe(2)-C(22)	2.048(5)
Fe(2)-C(25)	2.057(5)	Fe(2)-C(21)	2.064(4)
Fe(2)-C(38)	2.083(5)	Fe(2)-C(37)	2.113(5)
Fe(1)-C(3)	2.037(5)	Fe(1)-C(13)	2.037(5)
Fe(1)-C(5)	2.048(5)	Fe(1)-C(12)	2.047(4)
Fe(1)-C(4)	2.051(5)	Fe(1)-C(1)	2.049(5)
Fe(1)-C(2)	2.052(4)	Fe(1)-C(11)	2.054(5)
Fe(1)-C(18)	2.083(5)	Fe(1)-C(17)	2.094(5)
C(1)-C(5)	1.419(8)	C(1)-C(2)	1.444(7)
C(1)-C(6)	1.513(7)	N(1)-C(16)	1.327(7)
N(1)-C(17)	1.385(6)	N(3)-C(36)	1.308(7)
N(3)-C(37)	1.366(7)	C(25)-C(24)	1.434(8)
C(25)-C(21)	1.448(7)	C(25)-C(30)	1.484(8)
C(21)-C(22)	1.440(9)	C(21)-C(26)	1.490(8)
N(2)-C(14)	1.365(6)	N(2)-C(20)	1.453(7)
N(2)-C(19)	1.473(7)	C(34)-N(4)	1.365(6)
C(34)-C(35)	1.392(7)	C(34)-C(38)	1.448(7)
C(14)-C(15)	1.373(7)	C(14)-C(18)	1.468(7)
N(4)-C(40)	1.441(7)	N(4)-C(39)	1.462(7)
C(38)-C(33)	1.429(7)	C(38)-C(37)	1.454(6)
C(12)-C(11)	1.411(7)	C(12)-C(13)	1.417(7)
C(15)-C(16)	1.397(7)	C(18)-C(13)	1.447(7)
C(18)-C(17)	1.450(7)	C(11)-C(17)	1.424(7)
C(4)-C(3)	1.434(7)	C(4)-C(5)	1.437(7)
C(4)-C(9)	1.482(8)	C(35)-C(36)	1.413(7)
C(2)-C(3)	1.404(8)	C(2)-C(7)	1.502(8)
C(3)-C(8)	1.500(7)	C(32)-C(31)	1.414(7)
C(32)-C(33)	1.413(7)	C(22)-C(23)	1.428(8)
C(22)-C(27)	1.504(7)	C(24)-C(23)	1.419(7)
C(24)-C(29)	1.506(7)	C(23)-C(28)	1.507(8)
C(31)-C(37)	1.428(7)	C(5)-C(10)	1.503(7)

C(33)-Fe(2)-C(23)	119.7(2)	C(33)-Fe(2)-C(24)	153.7(2)
C(23)-Fe(2)-C(24)	40.8(2)	C(33)-Fe(2)-C(32)	40.5(2)
C(23)-Fe(2)-C(32)	108.1(2)	C(24)-Fe(2)-C(32)	119.2(2)
C(33)-Fe(2)-C(31)	68.3(2)	C(23)-Fe(2)-C(31)	126.3(2)
C(24)-Fe(2)-C(31)	107.1(2)	C(32)-Fe(2)-C(31)	40.3(2)
C(33)-Fe(2)-C(22)	108.3(2)	C(23)-Fe(2)-C(22)	41.0(2)
C(24)-Fe(2)-C(22)	68.8(2)	C(32)-Fe(2)-C(22)	127.3(2)
C(31)-Fe(2)-C(22)	164.4(2)	C(33)-Fe(2)-C(25)	164.6(2)
C(23)-Fe(2)-C(25)	69.1(2)	C(24)-Fe(2)-C(25)	41.0(2)
C(32)-Fe(2)-C(25)	152.8(2)	C(31)-Fe(2)-C(25)	118.2(2)
C(22)-Fe(2)-C(25)	69.3(2)	C(33)-Fe(2)-C(21)	127.2(2)
C(23)-Fe(2)-C(21)	68.9(2)	C(24)-Fe(2)-C(21)	68.7(2)
C(32)-Fe(2)-C(21)	165.1(2)	C(31)-Fe(2)-C(21)	153.1(2)
C(22)-Fe(2)-C(21)	41.0(2)	C(25)-Fe(2)-C(21)	41.1(2)
C(33)-Fe(2)-C(38)	40.6(2)	C(23)-Fe(2)-C(38)	154.4(2)
C(24)-Fe(2)-C(38)	163.8(2)	C(32)-Fe(2)-C(38)	67.9(2)
C(31)-Fe(2)-C(38)	68.0(2)	C(22)-Fe(2)-C(38)	120.0(2)
C(25)-Fe(2)-C(38)	126.4(2)	C(21)-Fe(2)-C(38)	108.1(2)
C(33)-Fe(2)-C(37)	68.1(2)	C(23)-Fe(2)-C(37)	163.4(2)
C(24)-Fe(2)-C(37)	126.0(2)	C(32)-Fe(2)-C(37)	67.5(2)
C(31)-Fe(2)-C(37)	40.0(2)	C(22)-Fe(2)-C(37)	154.4(2)

C(25)-Fe(2)-C(37)	107.1(2)	C(21)-Fe(2)-C(37)	119.6(2)
C(38)-Fe(2)-C(37)	40.5(2)	C(3)-Fe(1)-C(13)	160.7(2)
C(3)-Fe(1)-C(5)	68.8(2)	C(13)-Fe(1)-C(5)	108.8(2)
C(3)-Fe(1)-C(12)	123.4(2)	C(13)-Fe(1)-C(12)	40.6(2)
C(5)-Fe(1)-C(12)	122.6(2)	C(3)-Fe(1)-C(4)	41.1(2)
C(13)-Fe(1)-C(4)	124.5(2)	C(5)-Fe(1)-C(4)	41.1(2)
C(12)-Fe(1)-C(4)	107.3(2)	C(3)-Fe(1)-C(1)	68.8(2)
C(13)-Fe(1)-C(1)	122.6(2)	C(5)-Fe(1)-C(1)	40.5(2)
C(12)-Fe(1)-C(1)	158.2(2)	C(4)-Fe(1)-C(1)	68.9(2)
C(3)-Fe(1)-C(2)	40.2(2)	C(13)-Fe(1)-C(2)	158.3(2)
C(5)-Fe(1)-C(2)	68.5(2)	C(12)-Fe(1)-C(2)	159.2(2)
C(4)-Fe(1)-C(2)	68.5(2)	C(1)-Fe(1)-C(2)	41.2(2)
C(3)-Fe(1)-C(11)	105.8(2)	C(13)-Fe(1)-C(11)	68.5(2)
C(5)-Fe(1)-C(11)	156.7(2)	C(12)-Fe(1)-C(11)	40.2(2)
C(4)-Fe(1)-C(11)	120.1(2)	C(1)-Fe(1)-C(11)	160.6(2)
C(2)-Fe(1)-C(11)	122.8(2)	C(3)-Fe(1)-C(18)	155.8(2)
C(13)-Fe(1)-C(18)	41.1(2)	C(5)-Fe(1)-C(18)	125.7(2)
C(12)-Fe(1)-C(18)	68.3(2)	C(4)-Fe(1)-C(18)	162.3(2)
C(1)-Fe(1)-C(18)	108.4(2)	C(2)-Fe(1)-C(18)	121.8(2)
C(11)-Fe(1)-C(18)	68.4(2)	C(3)-Fe(1)-C(17)	119.9(2)
C(13)-Fe(1)-C(17)	68.3(2)	C(5)-Fe(1)-C(17)	162.3(2)
C(12)-Fe(1)-C(17)	67.4(2)	C(4)-Fe(1)-C(17)	155.2(2)
C(1)-Fe(1)-C(17)	125.1(2)	C(2)-Fe(1)-C(17)	107.4(2)
C(11)-Fe(1)-C(17)	40.1(2)	C(18)-Fe(1)-C(17)	40.6(2)
C(5)-C(1)-C(2)	107.3(5)	C(5)-C(1)-C(6)	126.9(5)
C(2)-C(1)-C(6)	125.7(5)	C(5)-C(1)-Fe(1)	69.7(3)
C(2)-C(1)-Fe(1)	69.5(2)	C(6)-C(1)-Fe(1)	128.7(4)
C(16)-N(1)-C(17)	113.9(4)	C(36)-N(3)-C(37)	113.7(4)
C(24)-C(25)-C(21)	107.0(5)	C(24)-C(25)-C(30)	126.9(5)
C(21)-C(25)-C(30)	126.1(6)	C(24)-C(25)-Fe(2)	68.9(3)
C(21)-C(25)-Fe(2)	69.7(2)	C(30)-C(25)-Fe(2)	127.0(4)
C(22)-C(21)-C(25)	107.9(5)	C(22)-C(21)-C(26)	126.7(5)
C(25)-C(21)-C(26)	125.4(5)	C(22)-C(21)-Fe(2)	68.9(3)
C(25)-C(21)-Fe(2)	69.2(3)	C(26)-C(21)-Fe(2)	128.2(4)
C(14)-N(2)-C(20)	123.9(4)	C(14)-N(2)-C(19)	118.5(4)
C(20)-N(2)-C(19)	117.6(4)	N(4)-C(34)-C(35)	122.3(5)
N(4)-C(34)-C(38)	123.2(4)	C(35)-C(34)-C(38)	114.5(4)
N(2)-C(14)-C(15)	122.9(5)	N(2)-C(14)-C(18)	122.1(4)
C(15)-C(14)-C(18)	115.0(4)	C(34)-N(4)-C(40)	123.8(4)
C(34)-N(4)-C(39)	118.6(4)	C(40)-N(4)-C(39)	117.4(4)
C(33)-C(38)-C(34)	135.4(4)	C(33)-C(38)-C(37)	107.2(4)
C(34)-C(38)-C(37)	117.4(4)	C(33)-C(38)-Fe(2)	67.7(3)
C(34)-C(38)-Fe(2)	125.4(3)	C(37)-C(38)-Fe(2)	70.8(3)
C(11)-C(12)-C(13)	108.9(5)	C(11)-C(12)-Fe(1)	70.1(3)
C(13)-C(12)-Fe(1)	69.3(3)	C(14)-C(15)-C(16)	123.1(5)
C(13)-C(18)-C(17)	106.5(4)	C(13)-C(18)-C(14)	136.6(4)
C(17)-C(18)-C(14)	116.9(4)	C(13)-C(18)-Fe(1)	67.7(3)
C(17)-C(18)-Fe(1)	70.1(3)	C(14)-C(18)-Fe(1)	125.2(3)
C(12)-C(11)-C(17)	108.4(4)	C(12)-C(11)-Fe(1)	69.6(3)
C(17)-C(11)-Fe(1)	71.5(3)	C(3)-C(4)-C(5)	107.0(5)
C(3)-C(4)-C(9)	126.5(5)	C(5)-C(4)-C(9)	126.5(5)
C(3)-C(4)-Fe(1)	69.0(3)	C(5)-C(4)-Fe(1)	69.4(3)
C(9)-C(4)-Fe(1)	128.5(4)	C(34)-C(35)-C(36)	122.1(5)
C(3)-C(2)-C(1)	108.3(5)	C(3)-C(2)-C(7)	126.9(5)
C(1)-C(2)-C(7)	124.8(5)	C(3)-C(2)-Fe(1)	69.4(3)
C(1)-C(2)-Fe(1)	69.3(2)	C(7)-C(2)-Fe(1)	125.9(4)
C(2)-C(3)-C(4)	108.8(4)	C(2)-C(3)-C(8)	125.5(5)
C(4)-C(3)-C(8)	125.6(5)	C(2)-C(3)-Fe(1)	70.5(3)
C(4)-C(3)-Fe(1)	70.0(3)	C(8)-C(3)-Fe(1)	127.2(4)

C(31)-C(32)-C(33)	108.4(5)	C(31)-C(32)-Fe(2)	70.1(3)
C(33)-C(32)-Fe(2)	69.1(3)	N(3)-C(36)-C(35)	126.2(5)
C(23)-C(22)-C(21)	107.7(4)	C(23)-C(22)-C(27)	126.7(5)
C(21)-C(22)-C(27)	125.5(5)	C(23)-C(22)-Fe(2)	68.9(3)
C(21)-C(22)-Fe(2)	70.1(3)	C(27)-C(22)-Fe(2)	127.8(3)
N(1)-C(17)-C(11)	126.6(4)	N(1)-C(17)-C(18)	125.3(4)
C(11)-C(17)-C(18)	108.1(4)	N(1)-C(17)-Fe(1)	127.7(3)
C(11)-C(17)-Fe(1)	68.4(3)	C(18)-C(17)-Fe(1)	69.3(3)
C(32)-C(33)-C(38)	108.6(4)	C(32)-C(33)-Fe(2)	70.3(2)

C(38)-C(33)-Fe(2)	71.6(3)	C(12)-C(13)-C(18)	108.1(5)
C(12)-C(13)-Fe(1)	70.1(3)	C(18)-C(13)-Fe(1)	71.2(3)
C(23)-C(24)-C(25)	108.8(4)	C(23)-C(24)-C(29)	124.6(6)
C(25)-C(24)-C(29)	126.6(5)	C(23)-C(24)-Fe(2)	69.3(3)
C(25)-C(24)-Fe(2)	70.2(3)	C(29)-C(24)-Fe(2)	126.1(4)
C(24)-C(23)-C(22)	108.5(5)	C(24)-C(23)-C(28)	127.4(5)
C(22)-C(23)-C(28)	124.0(5)	C(24)-C(23)-Fe(2)	69.9(3)
C(22)-C(23)-Fe(2)	70.1(3)	C(28)-C(23)-Fe(2)	128.8(4)
C(32)-C(31)-C(37)	108.8(4)	C(32)-C(31)-Fe(2)	69.6(3)
C(37)-C(31)-Fe(2)	72.2(3)	N(1)-C(16)-C(15)	125.7(5)
N(3)-C(37)-C(31)	127.1(4)	N(3)-C(37)-C(38)	126.0(5)
C(31)-C(37)-C(38)	106.9(4)	N(3)-C(37)-Fe(2)	128.2(3)
C(31)-C(37)-Fe(2)	67.8(3)	C(38)-C(37)-Fe(2)	68.6(3)
C(1)-C(5)-C(4)	108.6(4)	C(1)-C(5)-C(10)	126.5(5)
C(4)-C(5)-C(10)	124.8(6)	C(1)-C(5)-Fe(1)	69.8(3)
C(4)-C(5)-Fe(1)	69.6(3)	C(10)-C(5)-Fe(1)	127.6(4)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters [$Å^2$ x 10^3] for 1.

The anisotropic displacement factor exponent takes the form:

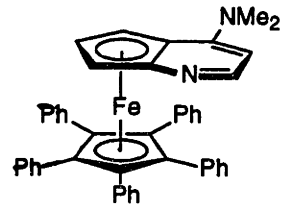
$-2\pi^2 [(ha^*)^2 U_{11} + ... + 2hka^* b^* U_{12}]$

	U11	U22	U33	U23	U13	U12
Fe(2)	20(1)	22(1)	24(1)	-1(1)	1(1)	3(1)
Fe(1)	20(1)	22(1)	23(1)	-1(1)	1(1)	-2(1)
C(1)	23(2)	31(4)	36(3)	-9(3)	3(2)	-6(2)
N(1)	32(2)	26(3)	32(2)	4(2)	-2(2)	-4(2)
N(3)	40(2)	31(3)	30(2)	4(2)	0(2)	3(2)
C(25)	32(3)	36(4)	35(3)	7(3)	9(2)	10(3)
C(21)	22(2)	30(3)	43(3)	-6(3)	0(2)	6(3)
N(2)	40(2)	32(3)	25(2)	-5(2)	-2(2)	9(2)
C(34)	25(2)	25(3)	26(2)	-6(2)	-1(2)	6(2)
C(14)	22(2)	25(3)	27(2)	-4(2)	-2(2)	-4(2)
N(4)	35(2)	33(3)	28(2)	-4(2)	0(2)	-6(2)
C(38)	21(2)	30(3)	27(3)	0(2)	2(2)	5(2)
C(12)	26(2)	28(3)	40(3)	-4(3)	3(2)	-9(3)
C(15)	27(3)	27(3)	41(3)	-6(2)	4(2)	5(2)
C(18)	16(2)	18(3)	33(3)	0(2)	-1(2)	-5(2)
C(11)	26(2)	34(3)	27(2)	0(2)	5(2)	-1(2)
C(4)	29(2)	23(3)	39(3)	-4(2)	1(2)	-7(2)
C(35)	31(3)	19(3)	37(3)	-3(2)	-4(2)	-3(2)
C(2)	22(2)	34(3)	39(3)	-2(3)	-2(2)	-5(3)
C(3)	28(3)	35(3)	32(3)	-3(3)	-2(2)	-9(2)
C(32)	16(2)	25(3)	46(3)	-5(3)	-3(2)	0(3)
C(36)	37(3)	28(3)	35(3)	4(2)	4(2)	-1(2)
C(22)	35(3)	36(3)	23(2)	1(2)	1(2)	13(2)
C(17)	20(2)	16(3)	31(3)	0(2)	0(2)	-2(2)
C(33)	29(3)	24(3)	31(2)	1(2)	4(2)	5(2)
C(13)	21(2)	23(3)	33(3)	1(2)	-4(2)	3(2)
C(24)	34(3)	27(3)	32(3)	-5(2)	-2(2)	15(2)
C(23)	28(3)	25(3)	39(3)	1(2)	0(2)	8(2)
C(31)	28(2)	29(3)	31(2)	-5(2)	-5(2)	7(2)
C(16)	30(3)	27(3)	35(3)	5(2)	0(2)	6(2)
C(19)	71(4)	55(4)	38(3)	-14(3)	7(3)	11(3)
C(37)	23(2)	31(3)	24(2)	0(2)	-2(2)	2(2)
C(5)	30(3)	36(4)	25(3)	5(2)	-3(2)	-14(2)
C(10)	65(4)	52(4)	35(3)	16(3)	-8(3)	-22(3)
C(27)	43(3)	59(4)	34(3)	12(3)	-1(2)	20(3)
C(9)	50(4)	28(4)	79(4)	-12(3)	2(3)	1(3)
C(39)	67(4)	54(4)	37(3)	-12(3)	-11(3)	-8(3)
C(30)	41(3)	57(4)	66(4)	18(3)	19(3)	11(3)
C(7)	29(3)	50(4)	72(4)	15(3)	-15(3)	-1(3)
C(28)	46(3)	30(4)	76(4)	6(3)	0(3)	1(3)
C(26)	31(3)	46(4)	70(4)	-18(3)	-13(3)	6(3)
C(8)	53(4)	76(5)	32(3)	-12(3)	5(3)	-25(4)
C(6)	32(3)	57(4)	62(4)	-18(3)	19(3)	-3(3)
C(40)	59(4)	63(5)	29(3)	-5(3)	5(2)	1(3)
C(29)	63(4)	63(5)	36(3)	-16(3)	0(3)	31(4)
C(20)	73(4)	48(4)	23(2)	1(3)	-2(2)	9(3)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

	x	y	z	U(eq)
H(12A)	-11233(5)	-7349(3)	-8112(5)	38
H(15A)	-15590(6)	-5262(2)	-6569(6)	38
H(11A)	-12431(5)	-6806(2)	-10435(6)	35
H(35A)	-10673(6)	-5675(2)	-8531(6)	35
H(32A)	-6129(5)	-3612(3)	-6978(5)	35
H(36A)	-10498(6)	-5657(2)	-5836(6)	40
H(33A)	-7199(6)	-4053(2)	-9541(6)	33
H(13A)	-12134(5)	-6921(2)	-5535(6)	31
H(31A)	-7260(6)	-4129(2)	-4648(6)	35
H(16A)	-15503(6)	-5251(2)	-9235(6)	37
H(19A)	-15061(8)	-5525(3)	-2647(7)	82
H(19B)	-16322(8)	-5501(3)	-4123(7)	82
H(19C)	-14715(8)	-5137(3)	-4076(7)	82
H(10A)	-14617(8)	-8106(3)	-5327(6)	77
H(10B)	-16312(8)	-7894(3)	-4682(6)	77
H(10C)	-14704(8)	-7532(3)	-4542(6)	77
H(27A)	-11331(7)	-3627(3)	-10914(6)	68
H(27B)	-9559(7)	-3371(3)	-10582(6)	68
H(27C)	-11163(7)	-3008(3)	-10554(6)	68
H(9A)	-13958(7)	-8408(2)	-7452(8)	78
H(9B)	-13278(7)	-8166(2)	-9031(8)	78
H(9C)	-14927(7)	-8508(2)	-9086(8)	78
H(39A)	-10421(8)	-5396(3)	-12447(6)	79
H(39B)	-11585(8)	-5393(3)	-10981(6)	79
H(39C)	-10058(8)	-5790(3)	-11010(6)	79
H(30A)	-13011(7)	-4477(3)	-5646(8)	81
H(30B)	-13112(7)	-3996(3)	-4438(8)	81
H(30C)	-11521(7)	-4366(3)	-4422(8)	81
H(7A)	-18265(6)	-6362(3)	-8779(7)	76
H(7B)	-18591(6)	-6734(3)	-10273(7)	76
H(7C)	-16983(6)	-6373(3)	-10151(7)	76
H(28A)	-8985(7)	-2613(3)	-8660(8)	76
H(28B)	-8047(7)	-2718(3)	-7013(8)	76
H(28C)	-9690(7)	-2373(3)	-7089(8)	76
H(26A)	-13290(7)	-4532(3)	-8054(8)	74
H(26B)	-12077(7)	-4496(3)	-9478(8)	74
H(26C)	-13644(7)	-4117(3)	-9437(8)	74
H(8A)	-15066(8)	-7814(3)	-11349(6)	81
H(8B)	-15260(8)	-7190(3)	-11614(6)	81
H(8C)	-16847(8)	-7563(3)	-11665(6)	81
H(6A)	-18119(7)	-6469(3)	-6398(7)	75
H(6B)	-16703(7)	-6614(3)	-5124(7)	75
H(6C)	-18307(7)	-6976(3)	-5299(7)	75
H(40A)	-8746(8)	-4780(3)	-12633(6)	75
H(40B)	-7287(8)	-4777(3)	-11330(6)	75
H(40C)	-8682(8)	-4333(3)	-11308(6)	75
H(29A)	-10566(8)	-3415(3)	-3497(6)	81
H(29B)	-10461(8)	-2828(3)	-4185(6)	81
H(29C)	-8885(8)	-3205(3)	-4175(6)	81

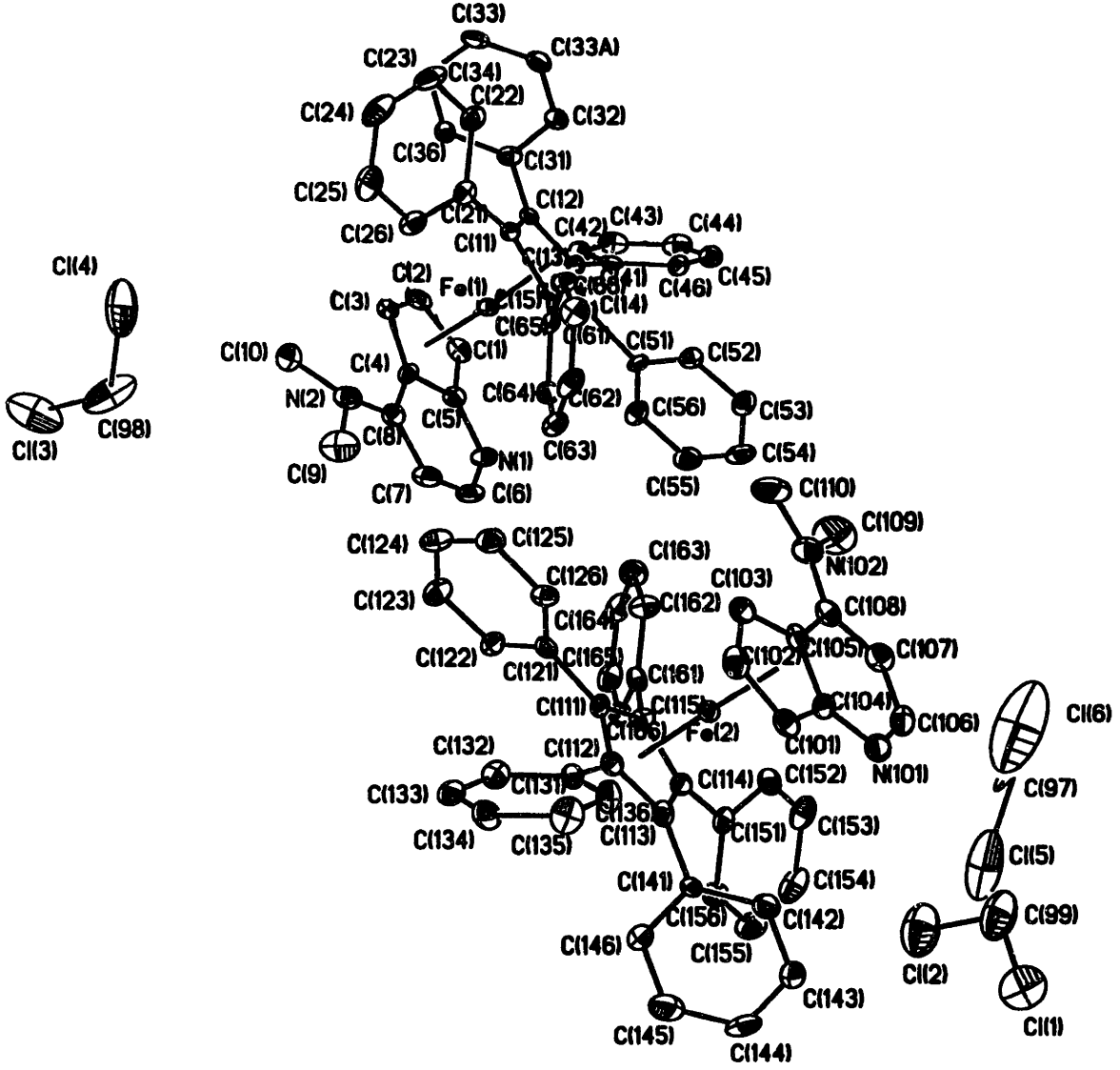
H(20A)	-13590(8)	-6207(3)	-2452(6)	72
H(20B)	-12237(8)	-6286(3)	-3740(6)	72
H(20C)	-13852(8)	-6646(3)	-3788(6)	72



(+)-**2.9**

Solvent molecules (methylene chloride) are included in the crystal lattice.

Structure solved by Diego Hoic and Michael Lo.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C(34)
C(22)
C(24)
C(32)
C(36)
C(31)
C(25)
C(12)
C(21)
C(26)
C(11)
C(42)
C(43)
C(44)
C(46)
C(45)
C(2)
Fe(1)
C(3)
C(14)
C(61)
C(51)
C(52)
C(10)
C(1)
C(4)
C(64)
C(62)
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C(53)
N(2)
C(5)
C(8)
C(63)
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N(1)
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Cl(4)
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Cl(3)
C(6)
C(97)
Cl(5)
C(99)
Cl(2)
Cl(1)

Table 1. Crystal data and structure refinement for 97153.

A. Crystal Data

Identification code	97153
Empirical formula	$C_{46}H_{38}Cl_2FeN_2$
Formula weight	745.53
Temperature	166(2) K
Wavelength	0.71073 Å
Crystal morphology	purple
Crystal size	.12 x .32 x .45 mm
Crystal system	Monoclinic
Space group	$P2_1$
Unit cell dimensions	a = 12.2830(2) Å alpha = 90°
	b = 27.3450(5) Å beta = 113.9990(10)°
	c = 12.4471(2) Å gamma = 90°
Volume, Z	3819.30(11) $Å^3$, 4
Density (calculated)	1.297 Mg/m^3
Absorption coefficient	0.570 mm^{-1}
F(000)	1552

B. Data Collection and Reduction

Diffractometer	Siemens SMART/CCD
Scan Type	ω Scans
Scan angle	0.30°
θ range for data collection	1.49 to 23.30°
Limiting indices	$-13 \le h \le 13$, $-30 \le k \le 24$, $-13 \le l \le 10$

Reflections collected	15879
Independent reflections	8236 (R_{int} = 0.0625)
Absorption correction	Semi-empirical from psi-scans
Max. and min. transmission	0.7643 and 0.5818

C. Solution and Refinement

Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	8234 / 1 / 947
Goodness-of-fit on F^2	1.151
Final R indices [I>2σ(I)]	R1 = 0.0655, wR2 = 0.1747
R indices (all data)	R1 = 0.0746, wR2 = 0.1886
Absolute structure parameter	0.01(3)
Extinction coefficient	0.0030(6)
Largest diff. peak and hole	1.064 and -0.393 $eÅ^{-3}$

Table 2. Atomic coordinates [x 10^4] and equivalent isotropic displacement parameters [$Å^2$ x 10^3] for 97153. U(eq) is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U(eq)
Fe(1)	2110(1)	4271(1)	3304(1)	22(1)
Fe(2)	9005(1)	1656(1)	9155(1)	23(1)
Cl(1)	9974(3)	-315(2)	13629(3)	83(1)
Cl(2)	8717(4)	606(2)	13259(4)	100(1)
Cl(3)	8938(6)	6285(4)	4009(7)	99(3)
Cl(4)	7978(9)	5520(3)	2246(9)	104(3)
Cl(5)	5617(11)	688(4)	13200(13)	152(5)
Cl(6)	4490(21)	388(7)	10728(21)	248(12)
N(1)	3219(6)	4428(3)	6081(5)	32(2)
N(2)	5600(6)	4700(3)	4401(6)	36(2)
N(101)	8212(7)	671(3)	9965(6)	34(2)
N(102)	5490(7)	1417(3)	7126(7)	49(2)
C(1)	1640(7)	4784(3)	4254(7)	29(2)
C(2)	1639(8)	4986(3)	3222(7)	35(2)
C(3)	2797(8)	4944(3)	3214(7)	32(2)
C(4)	3564(8)	4734(3)	4342(6)	25(2)
C(5)	2806(7)	4629(3)	4966(6)	26(2)
C(6)	4333(8)	4324(4)	6524(6)	35(2)
C(7)	5160(8)	4399(4)	6010(7)	36(2)
C(8)	4807(7)	4611(3)	4908(7)	28(2)
C(9)	6823(8)	4530(5)	5054(9)	58(3)
C(10)	5451(9)	5122(4)	3659(8)	46(3)
C(11)	2093(7)	3880(3)	1857(6)	21(2)
C(12)	896(7)	4003(3)	1737(6)	21(2)
C(13)	726(7)	3787(3)	2721(6)	19(2)
C(14)	1785(7)	3538(3)	3434(6)	20(2)
C(15)	2643(7)	3589(3)	2918(6)	22(2)
C(21)	2635(7)	4000(3)	1051(7)	25(2)
C(22)	1993(8)	3917(3)	-180(7)	33(2)
C(23)	2526(10)	4013(4)	-947(8)	44(3)
C(24)	3665(10)	4194(4)	-543(8)	48(3)
C(25)	4302(9)	4282(4)	629(8)	47(3)
C(26)	3797(7)	4180(4)	1419(7)	34(2)
C(31)	-27(7)	4255(3)	720(6)	26(2)
C(32)	-1176(7)	4065(3)	194(6)	26(2)
C(33A)	-2029(8)	4288(4)	-795(7)	35(2)
C(33)	-1750(8)	4698(4)	-1296(7)	37(2)
C(34)	-621(8)	4890(4)	-774(7)	33(2)
C(36)	239(8)	4670(3)	211(6)	27(2)
C(41)	-419(7)	3777(3)	2864(6)	25(2)
C(42)	-1119(7)	4199(3)	2743(7)	30(2)
C(43)	-2231(8)	4165(4)	2741(7)	36(2)
C(44)	-2690(8)	3721(4)	2877(7)	39(2)
C(45)	-2015(8)	3299(4)	3020(7)	32(2)
C(46)	-889(7)	3323(3)	3013(6)	28(2)
C(51)	1951(7)	3205(3)	4458(6)	21(2)
C(52)	2112(7)	2713(3)	4325(7)	25(2)
C(53)	2172(8)	2378(4)	5187(7)	33(2)

C(54)	2097(8)	2547(4)	6211(7)	38(2)
C(55)	1956(8)	3032(4)	6349(7)	37(2)
C(56)	1866(7)	3367(4)	5464(7)	31(2)
C(61)	3787(7)	3331(3)	3317(6)	23(2)
C(62)	4604(8)	3319(3)	4495(7)	31(2)
C(63)	5651(7)	3053(3)	4857(7)	31(2)
C(64)	5860(8)	2771(4)	4049(8)	35(2)
C(65)	5075(8)	2769(4)	2890(8)	36(2)
C(66)	4042(7)	3049(3)	2521(7)	28(2)
C(97)	4316(34)	470(22)	11388(59)	249(45)
C(98)	8874(25)	5596(10)	3664(21)	82(10)
C(99)	8718(14)	-3(5)	12832(12)	82(4)
C(101)	9577(8)	958(3)	9091(8)	32(2)
C(102)	9439(9)	1225(4)	8045(8)	40(2)
C(103)	8215(9)	1373(3)	7476(7)	35(2)
C(104)	8459(8)	921(3)	9132(7)	28(2)
C(105)	7578(8)	1181(3)	8145(7)	31(2)
C(106)	7085(9)	692(3)	9812(8)	39(2)
C(107)	6164(8)	939(4)	8897(8)	38(2)
C(108)	6377(9)	1185(3)	8025(7)	38(2)
C(109)	4304(11)	1454(6)	7154(13)	85(5)
C(110)	5584(11)	1544(6)	6021(9)	81(5)
C(111)	9320(8)	2391(3)	9053(7)	26(2)
C(112)	10413(8)	2136(3)	9762(6)	26(2)
C(113)	10228(8)	1918(3)	10736(7)	26(2)
C(114)	9041(7)	2033(3)	10617(6)	24(2)
C(115)	8479(7)	2331(3)	9565(6)	24(2)
C(121)	9150(7)	2707(3)	8030(6)	24(2)
C(122)	8902(8)	3195(3)	8090(7)	30(2)
C(123)	8802(8)	3524(4)	7189(7)	38(2)
C(124)	8929(8)	3351(4)	6198(7)	38(2)
C(125)	9166(8)	2856(4)	6108(7)	33(2)
C(126)	9302(7)	2541(3)	7027(6)	27(2)
C(131)	11538(7)	2143(3)	9613(6)	24(2)
C(132)	12009(8)	2582(3)	9497(7)	31(2)
C(133)	13117(8)	2620(4)	9459(7)	33(2)
C(134)	13790(8)	2201(4)	9541(7)	37(2)
C(135)	13306(9)	1756(4)	9635(8)	44(3)
C(136)	12217(8)	1723(4)	9679(8)	38(2)
C(141)	11138(7)	1627(3)	11715(6)	24(2)
C(142)	10826(8)	1186(3)	12094(7)	31(2)
C(143)	11681(9)	920(4)	12981(7)	39(2)
C(144)	12841(10)	1091(4)	13506(8)	52(3)
C(145)	13162(9)	1531(4)	13131(8)	50(3)
C(146)	12300(8)	1805(4)	12233(7)	37(2)
C(151)	8523(8)	1928(3)	11484(7)	28(2)
C(152)	7317(8)	1789(3)	11115(7)	32(2)
C(153)	6817(9)	1725(4)	11910(8)	43(2)
C(154)	7515(10)	1788(4)	13115(8)	45(3)
C(155)	8702(10)	1915(4)	13492(7)	45(3)
C(156)	9208(8)	1987(3)	12686(6)	31(2)
C(161)	7326(7)	2589(3)	9179(7)	26(2)
C(162)	6479(7)	2574(4)	8021(7)	31(2)
C(163)	5467(8)	2849(4)	7681(8)	41(2)
C(164)	5218(8)	3133(4)	8449(8)	39(2)
C(165)	6048(9)	3160(4)	9603(8)	37(2)
C(166)	7087(8)	2886(3)	9984(7)	28(2)

Table 3. Bond lengths [Å] and angles [°] for 97153.

Fe(1)-C(2)	2.029(9)	Fe(1)-C(13)	2.040(8)
Fe(1)-C(3)	2.045(9)	Fe(1)-C(12)	2.049(7)
Fe(1)-C(1)	2.062(8)	Fe(1)-C(14)	2.063(9)
Fe(1)-C(11)	2.087(7)	Fe(1)-C(15)	2.097(8)
Fe(1)-C(5)	2.127(8)	Fe(1)-C(4)	2.141(8)
Fe(2)-C(102)	2.044(9)	Fe(2)-C(101)	2.047(9)
Fe(2)-C(112)	2.055(9)	Fe(2)-C(111)	2.061(8)
Fe(2)-C(113)	2.059(8)	Fe(2)-C(103)	2.063(8)
Fe(2)-C(114)	2.077(7)	Fe(2)-C(115)	2.086(8)
Fe(2)-C(104)	2.116(9)	Fe(2)-C(105)	2.131(9)
Cl(1)-C(99)	1.69(2)	Cl(2)-C(99)	1.747(14)
Cl(3)-C(98)	1.93(3)	Cl(4)-C(98)	1.67(3)
Cl(5)-C(97)	2.25(7)	Cl(6)-C(97)	0.96(8)
N(1)-C(6)	1.282(11)	N(1)-C(5)	1.384(10)
N(2)-C(8)	1.380(11)	N(2)-C(10)	1.443(13)
N(2)-C(9)	1.464(12)	N(101)-C(106)	1.319(11)
N(101)-C(104)	1.374(11)	N(102)-C(108)	1.360(12)
N(102)-C(110)	1.47(2)	N(102)-C(109)	1.47(2)
C(1)-C(2)	1.397(12)	C(1)-C(5)	1.408(12)
C(2)-C(3)	1.431(14)	C(3)-C(4)	1.454(12)
C(4)-C(8)	1.437(12)	C(4)-C(5)	1.463(11)
C(6)-C(7)	1.418(12)	C(7)-C(8)	1.387(12)
C(11)-C(21)	1.449(11)	C(11)-C(15)	1.452(11)
C(11)-C(12)	1.455(11)	C(12)-C(13)	1.450(11)
C(12)-C(31)	1.481(11)	C(13)-C(14)	1.416(11)
C(13)-C(41)	1.487(11)	C(14)-C(15)	1.446(11)
C(14)-C(51)	1.512(10)	C(15)-C(61)	1.467(11)
C(21)-C(26)	1.400(12)	C(21)-C(22)	1.428(12)
C(22)-C(23)	1.384(13)	C(23)-C(24)	1.37(2)
C(24)-C(25)	1.368(14)	C(25)-C(26)	1.388(12)
C(31)-C(32)	1.392(12)	C(31)-C(36)	1.402(13)
C(32)-C(33A)	1.391(12)	C(33A)-C(33)	1.392(14)
C(33)-C(34)	1.374(13)	C(34)-C(36)	1.387(12)
C(41)-C(42)	1.411(12)	C(41)-C(46)	1.413(12)
C(42)-C(43)	1.368(12)	C(43)-C(44)	1.378(14)
C(44)-C(45)	1.390(14)	C(45)-C(46)	1.389(12)
C(51)-C(56)	1.373(11)	C(51)-C(52)	1.377(12)
C(52)-C(53)	1.390(12)	C(53)-C(54)	1.394(13)
C(54)-C(55)	1.358(14)	C(55)-C(56)	1.402(13)
C(61)-C(66)	1.389(12)	C(61)-C(62)	1.400(11)
C(62)-C(63)	1.384(12)	C(63)-C(64)	1.372(13)
C(64)-C(65)	1.371(13)	C(65)-C(66)	1.390(12)
C(101)-C(104)	1.398(13)	C(101)-C(102)	1.442(13)
C(102)-C(103)	1.435(14)	C(103)-C(105)	1.452(13)
C(104)-C(105)	1.451(12)	C(105)-C(108)	1.421(13)
C(106)-C(107)	1.408(13)	C(107)-C(108)	1.390(13)
C(111)-C(115)	1.426(12)	C(111)-C(112)	1.451(12)
C(111)-C(121)	1.482(11)	C(112)-C(113)	1.449(11)
C(112)-C(131)	1.466(11)	C(113)-C(114)	1.439(11)
C(113)-C(141)	1.505(12)	C(114)-C(115)	1.455(11)
C(114)-C(151)	1.488(11)	C(115)-C(161)	1.478(12)
C(121)-C(122)	1.377(13)	C(121)-C(126)	1.410(11)
C(122)-C(123)	1.404(12)	C(123)-C(124)	1.389(13)
C(124)-C(125)	1.399(14)	C(125)-C(126)	1.386(12)
C(131)-C(132)	1.365(12)	C(131)-C(136)	1.402(13)

C(132)-C(133)	1.385(12)	C(133)-C(134)	1.392(14)
C(134)-C(135)	1.381(14)	C(135)-C(136)	1.364(13)
C(141)-C(146)	1.394(12)	C(141)-C(142)	1.403(12)
C(142)-C(143)	1.381(13)	C(143)-C(144)	1.39(2)
C(144)-C(145)	1.40(2)	C(145)-C(146)	1.404(14)
C(151)-C(156)	1.396(11)	C(151)-C(152)	1.412(12)
C(152)-C(153)	1.372(12)	C(153)-C(154)	1.403(1)
C(154)-C(155)	1.38(2)	C(155)-C(156)	1.393(13)
C(161)-C(162)	1.394(11)	C(161)-C(166)	1.410(11)
C(162)-C(163)	1.365(13)	C(163)-C(164)	1.360(14)
C(164)-C(165)	1.385(13)	C(165)-C(166)	1.386(13)

C(2)-Fe(1)-C(13)	115.3(3)	C(2)-Fe(1)-C(3)	41.1(4)
C(13)-Fe(1)-C(3)	150.0(3)	C(2)-Fe(1)-C(12)	102.4(3)
C(13)-Fe(1)-C(12)	41.5(3)	C(3)-Fe(1)-C(12)	115.2(3)
C(2)-Fe(1)-C(1)	39.9(4)	C(13)-Fe(1)-C(1)	105.0(3)
C(3)-Fe(1)-C(1)	68.8(4)	C(12)-Fe(1)-C(1)	121.6(3)
C(2)-Fe(1)-C(14)	151.6(3)	C(13)-Fe(1)-C(14)	40.4(3)
C(3)-Fe(1)-C(14)	167.2(4)	C(12)-Fe(1)-C(14)	68.8(3)
C(1)-Fe(1)-C(14)	120.5(3)	C(2)-Fe(1)-C(11)	123.2(3)
C(13)-Fe(1)-C(11)	69.3(3)	C(3)-Fe(1)-C(11)	105.8(3)
C(12)-Fe(1)-C(11)	41.2(3)	C(1)-Fe(1)-C(11)	159.4(3)
C(14)-Fe(1)-C(11)	68.6(3)	C(2)-Fe(1)-C(15)	162.7(3)
C(13)-Fe(1)-C(15)	68.5(3)	C(3)-Fe(1)-C(15)	127.8(3)
C(12)-Fe(1)-C(15)	68.8(3)	C(1)-Fe(1)-C(15)	157.3(3)
C(14)-Fe(1)-C(15)	40.7(3)	C(11)-Fe(1)-C(15)	40.6(3)
C(2)-Fe(1)-C(5)	66.4(3)	C(13)-Fe(1)-C(5)	126.2(3)
C(3)-Fe(1)-C(5)	68.2(3)	C(12)-Fe(1)-C(5)	159.9(3)
C(1)-Fe(1)-C(5)	39.2(3)	C(14)-Fe(1)-C(5)	112.6(3)
C(11)-Fe(1)-C(5)	158.9(3)	C(15)-Fe(1)-C(5)	126.3(3)
C(2)-Fe(1)-C(4)	67.2(3)	C(13)-Fe(1)-C(4)	165.4(3)
C(3)-Fe(1)-C(4)	40.6(3)	C(12)-Fe(1)-C(4)	153.0(3)
C(1)-Fe(1)-C(4)	67.1(3)	C(14)-Fe(1)-C(4)	131.8(3)
C(11)-Fe(1)-C(4)	122.4(3)	C(15)-Fe(1)-C(4)	113.7(3)
C(5)-Fe(1)-C(4)	40.1(3)	C(102)-Fe(2)-C(101)	41.3(4)
C(102)-Fe(2)-C(112)	101.8(4)	C(101)-Fe(2)-C(112)	111.0(4)
C(102)-Fe(2)-C(111)	114.4(4)	C(101)-Fe(2)-C(111)	146.3(4)
C(112)-Fe(2)-C(111)	41.3(3)	C(102)-Fe(2)-C(113)	123.8(4)
C(101)-Fe(2)-C(113)	103.5(3)	C(112)-Fe(2)-C(113)	41.2(3)
C(111)-Fe(2)-C(113)	68.7(3)	C(102)-Fe(2)-C(103)	40.9(4)
C(101)-Fe(2)-C(103)	68.8(4)	C(112)-Fe(2)-C(103)	126.2(3)
C(111)-Fe(2)-C(103)	109.1(3)	C(113)-Fe(2)-C(103)	163.4(4)
C(102)-Fe(2)-C(114)	163.7(4)	C(101)-Fe(2)-C(114)	127.7(3)
C(112)-Fe(2)-C(114)	69.3(3)	C(111)-Fe(2)-C(114)	68.4(3)
C(113)-Fe(2)-C(114)	40.7(3)	C(103)-Fe(2)-C(114)	155.2(4)
C(102)-Fe(2)-C(115)	150.1(3)	C(101)-Fe(2)-C(115)	168.4(3)
C(112)-Fe(2)-C(115)	69.1(3)	C(111)-Fe(2)-C(115)	40.2(3)
C(113)-Fe(2)-C(115)	68.6(3)	C(103)-Fe(2)-C(115)	121.0(3)
C(114)-Fe(2)-C(115)	40.9(3)	C(102)-Fe(2)-C(104)	67.2(4)
C(101)-Fe(2)-C(104)	39.2(4)	C(112)-Fe(2)-C(104)	145.7(3)
C(111)-Fe(2)-C(104)	173.0(4)	C(113)-Fe(2)-C(104)	116.6(3)
C(103)-Fe(2)-C(104)	67.3(3)	C(114)-Fe(2)-C(104)	112.2(3)
C(115)-Fe(2)-C(104)	135.7(3)	C(102)-Fe(2)-C(105)	68.2(4)
C(101)-Fe(2)-C(105)	67.8(4)	C(112)-Fe(2)-C(105)	166.6(3)
C(111)-Fe(2)-C(105)	133.5(3)	C(113)-Fe(2)-C(105)	151.8(3)
C(103)-Fe(2)-C(105)	40.5(4)	C(114)-Fe(2)-C(105)	122.6(3)
C(115)-Fe(2)-C(105)	114.9(3)	C(104)-Fe(2)-C(105)	40.0(3)
C(6)-N(1)-C(5)	114.3(7)	C(8)-N(2)-C(10)	120.4(8)
C(8)-N(2)-C(9)	116.5(7)	C(10)-N(2)-C(9)	116.3(8)

C(106)-N(101)-C(104)	114.2(7)	C(108)-N(102)-C(110)	122.6(9)
C(108)-N(102)-C(109)	118.8(9)	C(110)-N(102)-C(109)	117.4(9)
C(2)-C(1)-C(5)	108.5(7)	C(2)-C(1)-Fe(1)	68.7(5)
C(5)-C(1)-Fe(1)	72.9(5)	C(1)-C(2)-C(3)	110.2(8)
C(1)-C(2)-Fe(1)	71.3(5)	C(3)-C(2)-Fe(1)	70.1(5)
C(2)-C(3)-C(4)	106.3(8)	C(2)-C(3)-Fe(1)	68.8(5)
C(4)-C(3)-Fe(1)	73.3(5)	C(8)-C(4)-C(3)	135.0(7)
C(8)-C(4)-C(5)	118.3(7)	C(3)-C(4)-C(5)	106.7(7)
C(8)-C(4)-Fe(1)	128.1(6)	C(3)-C(4)-Fe(1)	66.2(5)

C(5)-C(4)-Fe(1)	69.5(5)	N(1)-C(5)-C(1)	128.0(7)
N(1)-C(5)-C(4)	123.9(7)	C(1)-C(5)-C(4)	108.1(7)
N(1)-C(5)-Fe(1)	129.2(6)	C(1)-C(5)-Fe(1)	67.9(4)
C(4)-C(5)-Fe(1)	70.5(4)	N(1)-C(6)-C(7)	127.5(7)
C(8)-C(7)-C(6)	120.9(8)	N(2)-C(8)-C(7)	122.1(8)
N(2)-C(8)-C(4)	122.8(7)	C(7)-C(8)-C(4)	115.1(7)
C(21)-C(11)-C(15)	125.4(7)	C(21)-C(11)-C(12)	127.3(7)
C(15)-C(11)-C(12)	107.3(6)	C(21)-C(11)-Fe(1)	129.5(6)
C(15)-C(11)-Fe(1)	70.0(4)	C(12)-C(11)-Fe(1)	68.0(4)
C(13)-C(12)-C(11)	107.8(6)	C(13)-C(12)-C(31)	126.0(7)
C(11)-C(12)-C(31)	125.9(7)	C(13)-C(12)-Fe(1)	68.9(4)
C(11)-C(12)-Fe(1)	70.8(4)	C(31)-C(12)-Fe(1)	130.9(6)
C(14)-C(13)-C(12)	108.3(7)	C(14)-C(13)-C(41)	126.0(7)
C(12)-C(13)-C(41)	125.2(7)	C(14)-C(13)-Fe(1)	70.7(5)
C(12)-C(13)-Fe(1)	69.6(4)	C(41)-C(13)-Fe(1)	131.4(6)
C(13)-C(14)-C(15)	109.0(7)	C(13)-C(14)-C(51)	126.4(7)
C(15)-C(14)-C(51)	124.0(7)	C(13)-C(14)-Fe(1)	68.9(5)
C(15)-C(14)-Fe(1)	70.9(5)	C(51)-C(14)-Fe(1)	133.5(5)
C(14)-C(15)-C(11)	107.7(7)	C(14)-C(15)-C(61)	125.1(7)
C(11)-C(15)-C(61)	126.8(7)	C(14)-C(15)-Fe(1)	68.4(5)
C(11)-C(15)-Fe(1)	69.3(5)	C(61)-C(15)-Fe(1)	134.1(6)
C(26)-C(21)-C(22)	116.8(7)	C(26)-C(21)-C(11)	123.2(7)
C(22)-C(21)-C(11)	120.0(8)	C(23)-C(22)-C(21)	120.0(9)
C(24)-C(23)-C(22)	120.9(9)	C(25)-C(24)-C(23)	120.6(8)
C(24)-C(25)-C(26)	119.6(9)	C(25)-C(26)-C(21)	121.9(8)
C(32)-C(31)-C(36)	117.9(7)	C(32)-C(31)-C(12)	120.4(8)
C(36)-C(31)-C(12)	121.6(7)	C(31)-C(32)-C(33A)	120.5(8)
C(32)-C(33A)-C(33)	121.0(8)	C(34)-C(33)-C(33A)	118.7(8)
C(33)-C(34)-C(36)	120.8(9)	C(34)-C(36)-C(31)	121.1(8)
C(42)-C(41)-C(46)	117.9(7)	C(42)-C(41)-C(13)	122.5(8)
C(46)-C(41)-C(13)	119.3(8)	C(43)-C(42)-C(41)	120.7(9)
C(42)-C(43)-C(44)	121.1(9)	C(43)-C(44)-C(45)	119.7(8)
C(46)-C(45)-C(44)	120.3(9)	C(45)-C(46)-C(41)	120.2(8)
C(56)-C(51)-C(52)	119.6(7)	C(56)-C(51)-C(14)	122.6(8)
C(52)-C(51)-C(14)	117.6(7)	C(51)-C(52)-C(53)	121.0(7)
C(52)-C(53)-C(54)	119.1(9)	C(55)-C(54)-C(53)	119.9(8)
C(54)-C(55)-C(56)	120.8(8)	C(51)-C(56)-C(55)	119.6(9)
C(66)-C(61)-C(62)	117.4(8)	C(66)-C(61)-C(15)	119.3(7)
C(62)-C(61)-C(15)	123.1(7)	C(63)-C(62)-C(61)	121.9(8)
C(64)-C(63)-C(62)	118.9(8)	C(65)-C(64)-C(63)	120.8(8)
C(64)-C(65)-C(66)	120.2(8)	C(61)-C(66)-C(65)	120.7(7)
Cl(6)-C(97)-Cl(5)	127(4)	Cl(4)-C(98)-Cl(3)	107.9(11)
Cl(1)-C(99)-Cl(2)	114.7(9)	C(104)-C(101)-C(102)	108.2(8)
C(104)-C(101)-Fe(2)	73.0(5)	C(102)-C(101)-Fe(2)	69.2(5)
C(103)-C(102)-C(101)	107.7(8)	C(103)-C(102)-Fe(2)	70.3(5)
C(101)-C(102)-Fe(2)	69.5(5)	C(102)-C(103)-C(105)	108.4(8)
C(102)-C(103)-Fe(2)	68.8(5)	C(105)-C(103)-Fe(2)	72.3(5)
N(101)-C(104)-C(101)	125.8(8)	N(101)-C(104)-C(105)	124.4(8)
C(101)-C(104)-C(105)	109.8(8)	N(101)-C(104)-Fe(2)	128.9(6)
C(101)-C(104)-Fe(2)	67.8(5)	C(105)-C(104)-Fe(2)	70.6(5)
C(108)-C(105)-C(103)	135.7(8)	C(108)-C(105)-C(104)	118.5(8)
C(103)-C(105)-C(104)	105.8(8)	C(108)-C(105)-Fe(2)	128.8(6)
C(103)-C(105)-Fe(2)	67.2(5)	C(104)-C(105)-Fe(2)	69.4(5)
N(101)-C(106)-C(107)	126.0(8)	C(108)-C(107)-C(106)	121.3(9)
N(102)-C(108)-C(107)	121.7(9)	N(102)-C(108)-C(105)	122.7(8)
C(107)-C(108)-C(105)	115.6(8)	C(115)-C(111)-C(112)	109.4(7)
C(115)-C(111)-C(121)	125.2(8)	C(112)-C(111)-C(121)	125.1(8)
C(115)-C(111)-Fe(2)	70.8(5)	C(112)-C(111)-Fe(2)	69.1(5)
C(121)-C(111)-Fe(2)	131.1(6)	C(113)-C(112)-C(111)	106.5(7)

C(113)-C(112)-C(131)	126.0(7)	C(111)-C(112)-C(131)	127.1(7)
C(113)-C(112)-Fe(2)	69.6(5)	C(111)-C(112)-Fe(2)	69.6(5)
C(131)-C(112)-Fe(2)	131.1(6)	C(114)-C(113)-C(112)	108.8(7)
C(114)-C(113)-C(141)	125.9(7)	C(112)-C(113)-C(141)	125.3(8)
C(114)-C(113)-Fe(2)	70.3(4)	C(112)-C(113)-Fe(2)	69.2(4)
C(141)-C(113)-Fe(2)	127.1(6)	C(113)-C(114)-C(115)	107.7(7)
C(113)-C(114)-C(151)	126.7(7)	C(115)-C(114)-C(151)	125.1(7)
C(113)-C(114)-Fe(2)	69.0(4)	C(115)-C(114)-Fe(2)	69.9(4)
C(151)-C(114)-Fe(2)	132.6(6)	C(111)-C(115)-C(114)	107.6(7)
C(111)-C(115)-C(161)	124.9(7)	C(114)-C(115)-C(161)	126.9(7)
C(111)-C(115)-Fe(2)	68.9(5)	C(114)-C(115)-Fe(2)	69.2(5)
C(161)-C(115)-Fe(2)	134.0(6)	C(122)-C(121)-C(126)	118.2(7)
C(122)-C(121)-C(111)	118.4(7)	C(126)-C(121)-C(111)	123.3(8)
C(121)-C(122)-C(123)	121.8(8)	C(124)-C(123)-C(122)	119.1(9)
C(123)-C(124)-C(125)	120.2(8)	C(126)-C(125)-C(124)	119.6(8)
C(125)-C(126)-C(121)	121.0(9)	C(132)-C(131)-C(136)	117.3(8)
C(132)-C(131)-C(112)	119.2(8)	C(136)-C(131)-C(112)	123.3(8)
C(131)-C(132)-C(133)	122.3(9)	C(132)-C(133)-C(134)	119.9(9)
C(135)-C(134)-C(133)	118.0(8)	C(136)-C(135)-C(134)	121.6(9)
C(135)-C(136)-C(131)	120.9(9)	C(146)-C(141)-C(142)	120.9(7)
C(146)-C(141)-C(113)	118.2(8)	C(142)-C(141)-C(113)	120.9(7)
C(143)-C(142)-C(141)	119.9(8)	C(142)-C(143)-C(144)	120.1(9)
C(143)-C(144)-C(145)	120.5(9)	C(146)-C(145)-C(144)	120.0(9)
C(141)-C(146)-C(145)	118.6(9)	C(156)-C(151)-C(152)	118.4(8)
C(156)-C(151)-C(114)	120.4(8)	C(152)-C(151)-C(114)	121.1(7)
C(153)-C(152)-C(151)	121.1(8)	C(152)-C(153)-C(154)	119.8(9)
C(155)-C(154)-C(153)	119.7(8)	C(154)-C(155)-C(156)	120.6(8)
C(151)-C(156)-C(155)	120.3(9)	C(162)-C(161)-C(166)	118.0(8)
C(162)-C(161)-C(115)	122.3(7)	C(166)-C(161)-C(115)	119.6(7)
C(163)-C(162)-C(161)	120.4(8)	C(162)-C(163)-C(164)	122.3(9)
C(163)-C(164)-C(165)	118.6(9)	C(166)-C(165)-C(164)	120.9(8)
C(165)-C(166)-C(161)	119.8(8)		

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters [$Å^2$ x 10^3] for 97153.

The anisotropic displacement factor exponent takes the form:

$-2\pi^2 [(ha^*)^2 U_{11} + ... + 2hka^*b^* U_{12}]$

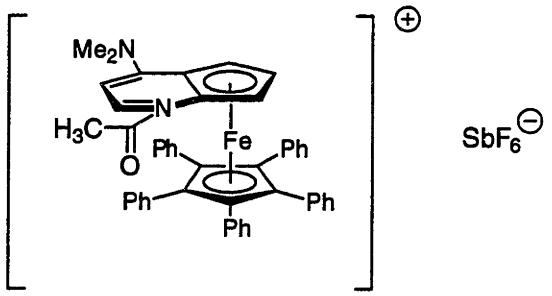
	U11	U22	U33	U23	U13	U12
Fe(1)	22(1)	24(1)	19(1)	0(1)	8(1)	1(1)
Fe(2)	26(1)	22(1)	23(1)	-3(1)	10(1)	-2(1)
Cl(1)	74(2)	98(3)	88(2)	6(2)	42(2)	17(2)
Cl(2)	146(4)	65(3)	116(3)	-3(2)	80(3)	0(2)
Cl(3)	55(4)	148(8)	91(5)	-56(5)	25(4)	15(5)
Cl(4)	128(7)	39(4)	178(8)	-3(4)	96(7)	-9(4)
Cl(5)	160(10)	78(7)	270(15)	45(8)	143(11)	18(7)
Cl(6)	376(25)	157(15)	408(26)	79(14)	360(24)	87(15)
N(1)	38(4)	42(5)	17(3)	-2(3)	12(3)	1(4)
N(2)	24(4)	54(5)	30(4)	-3(3)	9(3)	-4(4)
N(101)	35(4)	31(4)	37(4)	-1(3)	15(3)	-3(3)
N(102)	35(5)	49(6)	43(4)	5(4)	-3(4)	-2(4)
C(1)	23(4)	35(5)	36(4)	-11(4)	19(4)	-1(4)
C(2)	37(6)	26(5)	30(5)	-7(4)	-1(4)	2(4)
C(3)	33(5)	30(5)	25(4)	-2(4)	5(4)	-9(4)
C(4)	42(5)	18(5)	21(4)	0(3)	17(4)	1(4)
C(5)	27(5)	32(5)	24(4)	-6(3)	15(4)	-1(4)
C(6)	43(5)	42(6)	15(3)	-3(4)	7(4)	3(5)
C(7)	32(5)	53(7)	21(4)	-6(4)	7(4)	-2(4)
C(8)	22(5)	30(5)	30(4)	-1(4)	9(4)	1(4)
C(9)	29(6)	104(11)	48(6)	1(6)	25(5)	6(6)
C(10)	49(6)	49(7)	41(5)	2(4)	20(5)	-12(5)
C(11)	25(4)	19(4)	18(4)	0(3)	7(3)	-1(4)
C(12)	18(4)	19(4)	17(4)	0(3)	-1(3)	-2(3)
C(13)	23(4)	13(4)	21(4)	-1(3)	9(3)	3(3)
C(14)	23(4)	23(5)	16(4)	0(3)	8(3)	2(4)
C(15)	20(4)	21(5)	20(4)	-4(3)	1(3)	-7(4)
C(21)	30(5)	21(5)	30(4)	2(3)	16(4)	8(4)
C(22)	39(5)	28(5)	30(4)	7(4)	13(4)	6(4)
C(23)	71(8)	43(6)	23(4)	7(4)	22(5)	12(6)
C(24)	71(7)	48(7)	43(5)	13(5)	43(5)	17(6)
C(25)	40(6)	52(7)	61(6)	11(5)	34(5)	-1(6)
C(26)	20(4)	52(7)	31(4)	13(4)	12(4)	2(4)
C(31)	28(4)	27(5)	21(3)	-2(4)	7(3)	8(4)
C(32)	18(4)	32(5)	24(4)	-3(3)	7(3)	1(4)
C(33A)	32(5)	38(6)	28(4)	-6(4)	4(4)	-5(5)
C(33)	42(6)	37(6)	20(4)	-7(4)	0(4)	3(5)
C(34)	47(6)	33(5)	20(4)	3(4)	16(4)	0(5)
C(36)	34(5)	20(5)	24(4)	-1(3)	8(4)	-1(4)
C(41)	18(4)	42(6)	12(3)	-4(3)	2(3)	-4(4)
C(42)	24(4)	33(6)	31(4)	0(4)	9(4)	-1(4)
C(43)	28(5)	48(7)	31(4)	-5(4)	10(4)	13(5)
C(44)	29(5)	63(8)	30(5)	1(4)	17(4)	2(5)
C(45)	32(5)	36(6)	29(4)	-1(4)	14(4)	0(5)
C(46)	29(5)	30(5)	24(4)	4(3)	10(4)	-3(4)
C(51)	17(4)	28(5)	15(4)	8(3)	5(3)	2(4)
C(52)	25(4)	24(5)	24(4)	2(3)	9(4)	8(4)
C(53)	30(5)	29(5)	38(5)	9(4)	11(4)	7(4)

C(54)	25(5)	59(7)	22(4)	12(4)	2(4)	5(5)
C(55)	39(6)	51(7)	25(4)	-1(4)	16(4)	-3(5)
C(56)	27(5)	32(5)	35(4)	9(4)	15(4)	5(4)
C(61)	22(4)	22(5)	27(4)	8(3)	11(3)	2(4)
C(62)	36(5)	33(5)	25(4)	-4(4)	15(4)	-7(4)
C(63)	25(5)	37(6)	30(4)	12(4)	12(4)	5(4)
C(64)	30(5)	35(6)	45(5)	19(4)	20(4)	13(4)
C(65)	28(5)	43(6)	44(5)	0(4)	23(4)	7(5)
C(66)	26(5)	36(5)	21(4)	4(3)	10(4)	3(4)
C(97)	58(24)	272(70)	390(86)	309(72)	64(39)	37(32)
C(98)	97(20)	86(20)	73(16)	48(14)	46(15)	88(18)
C(99)	118(12)	52(9)	98(10)	8(7)	67(9)	13(8)
C(101)	32(5)	26(5)	38(5)	-9(4)	12(4)	-2(4)
C(102)	53(6)	33(6)	43(5)	-9(4)	30(5)	-9(5)
C(103)	49(6)	27(5)	26(4)	-8(4)	13(4)	-6(5)
C(104)	35(5)	17(5)	30(4)	-2(3)	13(4)	3(4)
C(105)	35(5)	26(5)	35(5)	-9(4)	16(4)	-10(4)
C(106)	50(6)	30(5)	43(5)	-2(4)	25(5)	-7(5)
C(107)	30(5)	37(6)	45(5)	-2(4)	12(4)	3(4)
C(108)	48(6)	28(5)	32(5)	-10(4)	11(4)	-8(5)
C(109)	48(8)	81(11)	94(10)	7(7)	-2(7)	27(7)
C(110)	56(8)	108(13)	43(6)	14(6)	-15(5)	-25(8)
C(111)	41(5)	13(4)	23(4)	-2(3)	13(4)	-3(4)
C(112)	34(5)	19(5)	24(4)	-6(3)	11(4)	-3(4)
C(113)	35(5)	18(5)	29(4)	-5(3)	17(4)	-3(4)
C(114)	30(5)	21(5)	21(4)	-2(3)	11(3)	-2(4)
C(115)	31(5)	24(5)	19(4)	-2(3)	14(4)	8(4)
C(121)	17(4)	29(5)	24(4)	-3(3)	6(3)	-6(4)
C(122)	36(5)	28(5)	25(4)	4(3)	12(4)	-1(4)
C(123)	42(6)	36(6)	34(5)	11(4)	13(4)	8(5)
C(124)	44(6)	49(7)	20(4)	2(4)	11(4)	6(5)
C(125)	32(5)	46(6)	23(4)	-1(4)	13(4)	-2(5)
C(126)	22(4)	38(5)	19(4)	-3(3)	8(3)	0(4)
C(131)	25(5)	20(5)	27(4)	-3(3)	13(4)	-2(4)
C(132)	39(5)	29(5)	30(4)	-3(4)	19(4)	3(4)
C(133)	31(5)	46(6)	24(4)	6(4)	14(4)	-5(5)
C(134)	23(5)	49(7)	38(5)	0(4)	11(4)	-10(5)
C(135)	44(6)	41(7)	56(6)	1(4)	29(5)	10(5)
C(136)	38(5)	32(6)	47(5)	2(4)	21(4)	-6(5)
C(141)	29(5)	19(4)	18(3)	-3(3)	2(3)	-4(4)
C(142)	25(5)	37(6)	27(4)	0(4)	7(4)	-2(4)
C(143)	50(6)	28(5)	31(5)	1(4)	10(4)	-6(5)
C(144)	51(7)	54(7)	30(5)	17(5)	-5(5)	10(6)
C(145)	36(6)	62(8)	40(5)	2(5)	3(4)	-1(5)
C(146)	44(6)	31(6)	29(4)	5(4)	8(4)	-3(4)
C(151)	35(5)	19(5)	33(4)	3(3)	15(4)	2(4)
C(152)	37(5)	25(5)	35(4)	-7(3)	17(4)	-4(4)
C(153)	44(6)	41(6)	58(6)	15(5)	34(5)	4(5)
C(154)	69(7)	41(7)	50(6)	11(4)	49(6)	13(5)
C(155)	70(8)	42(6)	24(4)	-5(4)	20(5)	4(6)
C(156)	41(5)	28(5)	24(4)	-6(3)	14(4)	2(4)
C(161)	28(5)	18(4)	31(4)	-6(3)	13(4)	-3(4)
C(162)	28(5)	44(6)	24(4)	1(4)	13(4)	11(4)
C(163)	31(5)	50(7)	37(5)	4(4)	10(4)	-4(5)
C(164)	25(5)	46(7)	51(6)	21(5)	19(5)	8(5)
C(165)	50(6)	31(6)	42(5)	2(4)	32(5)	3(5)
C(166)	33(5)	25(5)	26(4)	-2(3)	13(4)	0(4)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 97153.

	x	y	z	U(eq)
H(1B)	938(7)	4764(3)	4464(7)	35
H(2A)	930(8)	5136(3)	2579(7)	42
H(3A)	3045(8)	5062(3)	2588(7)	38
H(6A)	4641(8)	4181(4)	7285(6)	42
H(7A)	5967(8)	4302(4)	6427(7)	44
H(9A)	7304(8)	4612(5)	4615(9)	87
H(9B)	6823(8)	4175(5)	5159(9)	87
H(9C)	7162(8)	4690(5)	5826(9)	87
H(10A)	6087(9)	5129(4)	3375(8)	69
H(10B)	5489(9)	5420(4)	4111(8)	69
H(10C)	4676(9)	5105(4)	2987(8)	69
H(22A)	1199(8)	3797(3)	-474(7)	39
H(23A)	2098(10)	3952(4)	-1763(8)	53
H(24A)	4014(10)	4260(4)	-1084(8)	57
H(25A)	5086(9)	4411(4)	902(8)	56
H(26A)	4253(7)	4234(4)	2234(7)	41
H(32A)	-1378(7)	3781(3)	512(6)	31
H(33A)	-2814(8)	4158(4)	-1133(7)	42
H(33B)	-2329(8)	4843(4)	-1986(7)	45
H(34A)	-426(8)	5176(4)	-1091(7)	39
H(36A)	1020(8)	4803(3)	545(6)	33
H(42A)	-815(7)	4510(3)	2663(7)	37
H(43A)	-2695(8)	4453(4)	2643(7)	44
H(44A)	-3464(8)	3704(4)	2874(7)	47
H(45A)	-2326(8)	2993(4)	3122(7)	38
H(46A)	-433(7)	3033(3)	3109(6)	33
H(52A)	2182(7)	2602(3)	3633(7)	29
H(53A)	2263(8)	2039(4)	5080(7)	40
H(54A)	2144(8)	2323(4)	6812(7)	45
H(55A)	1918(8)	3146(4)	7054(7)	45
H(56A)	1747(7)	3705(4)	5561(7)	37
H(62A)	4433(8)	3498(3)	5062(7)	37
H(63A)	6216(7)	3066(3)	5651(7)	37
H(64A)	6556(8)	2574(4)	4296(8)	42
H(65A)	5237(8)	2576(4)	2338(8)	43
H(66A)	3506(7)	3047(3)	1715(7)	33
H(97A)	3880(34)	185(22)	11506(59)	299
H(97B)	3730(34)	740(22)	11116(59)	299
H(98A)	9682(25)	5472(10)	3822(21)	98
H(98B)	8561(25)	5413(10)	4164(21)	98
H(99A)	8034(14)	-173(5)	12892(12)	98
H(99B)	8597(14)	-9(5)	11996(12)	98
H(10D)	10334(8)	809(3)	9666(8)	39
H(10G)	10079(9)	1292(4)	7763(8)	48
H(10H)	7857(9)	1568(3)	6734(7)	42
H(10F)	6876(9)	525(3)	10370(8)	46
H(10I)	5382(8)	937(4)	8876(8)	46
H(10J)	3762(11)	1630(6)	6454(13)	127
H(10K)	4371(11)	1633(6)	7861(13)	127

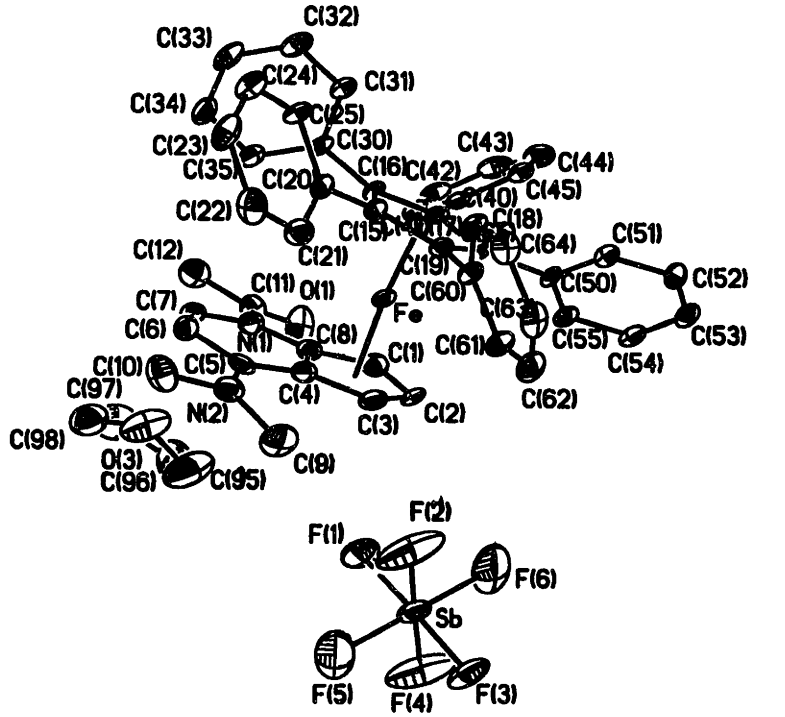
H(10L)	3992(11)	1126(6)	7166(13)	127
H(11A)	4851(11)	1708(6)	5495(9)	121
H(11B)	5697(11)	1245(6)	5643(9)	121
H(11C)	6265(11)	1763(6)	6186(9)	121
H(12C)	8796(8)	3312(3)	8760(7)	36
H(12D)	8649(8)	3861(4)	7257(7)	46
H(12E)	8854(8)	3570(4)	5578(7)	46
H(12B)	9234(8)	2736(4)	5422(7)	40
H(12A)	9500(7)	2208(3)	6980(6)	32
H(13C)	11561(8)	2872(3)	9441(7)	38
H(13E)	13417(8)	2932(4)	9376(7)	40
H(13A)	14558(8)	2221(4)	9532(7)	44
H(13B)	13743(9)	1465(4)	9671(8)	53
H(13D)	11914(8)	1412(4)	9756(8)	46
H(14D)	10027(8)	1071(3)	11742(7)	37
H(14B)	11473(9)	619(4)	13230(7)	47
H(14E)	13423(10)	910(4)	14125(8)	63
H(14A)	13963(9)	1643(4)	13485(8)	60
H(14C)	12505(8)	2107(4)	11984(7)	44
H(15E)	6844(8)	1739(3)	10301(7)	38
H(15B)	6000(9)	1638(4)	11645(8)	52
H(15C)	7173(10)	1743(4)	13669(8)	54
H(15A)	9176(10)	1954(4)	14309(7)	54
H(15D)	10023(8)	2077(3)	12955(6)	37
H(16D)	6607(7)	2370(4)	7464(7)	38
H(16E)	4919(8)	2843(4)	6879(8)	49
H(16C)	4489(8)	3309(4)	8200(8)	47
H(16B)	5904(9)	3369(4)	10141(8)	44
H(16A)	7636(8)	2899(3)	10784(7)	33



2.15

Solvent Molecules (THF) are included in the crystal lattice.

Structure solved by Diego Hoic.


C(32)
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C(54)
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O(3)
C(9)
C(96)
C(95)
F(2)
F(1)
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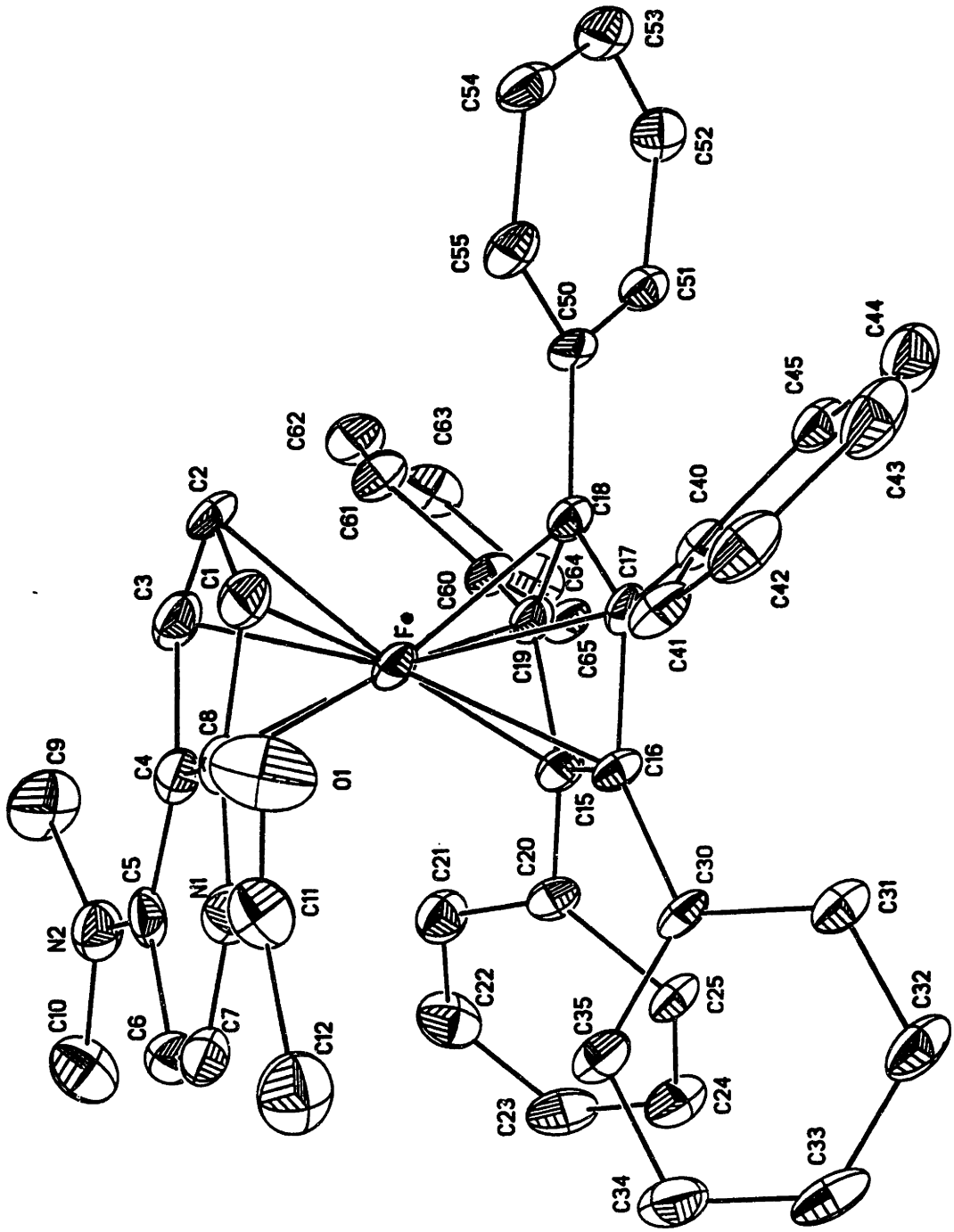
F(5)
F(4)
F(3)
C(93)
C(94)
C(92)
O(2)
C(91)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C1
C60
C64
C17
C42
F
C19
C65
C41
C8
C9
C4
O1
C16
C15
C5
C21
C20
C30
C31
N1
C11
N2
C22
C25
C32
C10
C6
C7
C12
C35
C24
C23
C33
C34

Table 1. Crystal data and structure refinement for 1.

A. Crystal Data

Identification code	97120
Empirical formula	$C_{55}H_{55}F_6FeN_2O_3Sb$
Formula weight	1083.61
Temperature	176(2) K
Wavelength	0.71073 Å
Crystal morphology	morph
Crystal size	0.15 x 0.35 x 0.41 mm
Crystal system	Triclinic
Space group	$P\bar{1}$
Unit cell dimensions	a = 12.142(2) Å alpha = 98.585(4)°
	b = 12.854(2) Å beta = 98.113(4)°
	c = 18.763(3) Å gamma = 117.433(4)°
Volume, Z	2495.4(7) $Å^3$, 2
Density (calculated)	1.442 Mg/m^3
Absorption coefficient	0.899 mm^{-1}
F(000)	1108

B. Data Collection and Reduction

Diffractometer	Siemens SMART/CCD
Scan Type	ω Scans
Scan angle	0.30°
θ range for data collection	1.13 to 23.39°
Limiting indices	$-13 \le h \le 6$, $-13 \le k \le 14$, $-19 \le l \le 20$

Reflections collected	9647
Independent reflections	6807 (R_{int} = 0.1024)
Absorption correction	None

C. Solution and Refinement

Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	6801 / 0 / 613
Goodness-of-fit on F^2	1.222
Final R indices [I>2σ(I)]	R1 = 0.0735, wR2 = 0.1704
R indices (all data)	R1 = 0.0893, wR2 = 0.1891
Largest diff. peak and hole	0.847 and -1.223 eÅ^{-3}

Table 2. Atomic coordinates [x 10^4] and equivalent isotropic displacement parameters [$Å^2$ x 10^3] for 1. U(eq) is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U(eq)
Sb	3967(1)	7318(1)	3756(1)	48(1)
Fe	329(1)	8402(1)	1856(1)	25(1)
F(1)	2227(5)	6789(6)	3632(4)	78(2)
F(2)	4275(6)	8785(7)	3591(6)	132(4)
F(3)	5733(5)	7858(5)	3906(3)	72(2)
F(4)	3721(7)	5873(7)	3910(6)	140(4)
F(5)	4240(7)	7926(10)	4752(4)	132(4)
F(6)	3706(7)	6737(10)	2774(4)	140(4)
O(1)	-2845(6)	5302(5)	2084(4)	60(2)
O(2)	8641(7)	1010(6)	4718(5)	76(2)
O(3)	-2618(8)	5816(8)	4147(6)	98(3)
N(1)	-1717(6)	7230(6)	2797(4)	34(2)
N(2)	1708(6)	10377(6)	4012(4)	38(2)
C(1)	-267(7)	6727(7)	2093(4)	34(2)
C(2)	1062(7)	7333(7)	2169(4)	35(2)
C(3)	1624(7)	8433(7)	2701(4)	37(2)
C(4)	643(7)	8535(6)	3015(4)	29(2)
C(5)	667(7)	9424(7)	3572(4)	32(2)
C(6)	-584(7)	9186(7)	3671(4)	34(2)
C(7)	-1664(7)	8137(7)	3318(4)	33(2)
C(8)	-536(7)	7453(7)	2610(4)	31(2)
C(9)	3008(8)	10541(9)	4051(6)	60(3)
C(10)	1667(9)	11315(8)	4534(5)	51(2)
C(11)	-2870(7)	6130(7)	2468(4)	39(2)
C(12)	-4070(8)	6074(8)	2623(5)	50(2)
C(15)	382(6)	9936(6)	1581(4)	25(2)
C(16)	-832(6)	8879(6)	1219(4)	23(2)
C(17)	-590(6)	8039(6)	760(4)	24(2)
C(18)	774(6)	8581(6)	845(4)	25(2)
C(19)	1366(6)	9739(6)	1354(4)	26(2)
C(20)	572(6)	11089(6)	2035(4)	27(2)
C(21)	1557(7)	11779(7)	2667(4)	37(2)
C(22)	1788(8)	12908(8)	3034(5)	47(2)
C(23)	1000(9)	13352(8)	2782(5)	49(2)
C(24)	12(8)	12686(7)	2146(5)	44(2)
C(25)	-198(7)	11584(7)	1783(4)	33(2)
C(30)	-2130(6)	8739(6)	1231(4)	28(2)
C(31)	-3011(6)	8390(6)	551(4)	30(2)
C(32)	-4197(7)	8305(7)	540(5)	40(2)
C(33)	-4518(7)	8559(7)	1184(5)	42(2)
C(34)	-3678(7)	8903(7)	1854(5)	41(2)
C(35)	-2458(7)	9009(7)	1874(4)	33(2)
C(40)	-1587(6)	6878(6)	227(4)	29(2)
C(41)	-2642(6)	6030(6)	437(4)	30(2)
C(42)	-3579(7)	4992(7)	-86(5)	39(2)
C(43)	-3498(7)	4785(7)	-805(5)	44(2)
C(44)	-2467(8)	5611(7)	-1026(5)	43(2)
C(45)	-1515(6)	6661(6)	-504(4)	29(2)

C(50)	1412(6)	8045(6)	414(4)	23(2)
C(51)	2259(6)	8735(6)	26(4)	27(2)
C(52)	2791(7)	8226(7)	-432(4)	35(2)
C(53)	2484(6)	7040(7)	-503(4)	35(2)
C(54)	1661(7)	6351(7)	-109(4)	33(2)
C(55)	1122(6)	6857(6)	340(4)	30(2)
C(60)	2761(6)	10639(6)	1539(4)	25(2)
C(61)	3694(6)	10316(7)	1778(4)	32(2)
C(62)	4985(7)	11168(8)	1915(5)	43(2)
C(63)	5362(7)	12303(7)	1814(5)	39(2)
C(64)	4459(7)	12628(7)	1569(4)	37(2)
C(65)	3175(7)	11792(7)	1431(4)	33(2)
C(91)	9295(12)	2256(11)	5076(6)	73(3)
C(92)	9282(17)	2892(13)	4469(9)	123(6)
C(93)	8274(17)	1894(13)	3810(9)	120(6)
C(94)	7670(13)	874(13)	4137(9)	106(5)
C(95)	-2359(16)	4845(15)	3995(11)	122(6)
C(96)	-3553(17)	3725(15)	3868(9)	115(5)
C(97)	-4520(12)	4084(12)	4087(8)	95(4)
C(98)	-3678(12)	5397(11)	4479(7)	81(3)

Table 3. Bond lengths [Å] and angles [°] for 1.

Sb-F(6)	1.805(8)	Sb-F(4)	1.817(7)
Sb-F(2)	1.829(7)	Sb-F(5)	1.835(8)
Sb-F(1)	1.862(5)	Sb-F(3)	1.887(5)
Fe-C(3)	2.051(7)	Fe-C(2)	2.061(7)
Fe-C(18)	2.062(7)	Fe-C(19)	2.062(7)
Fe-C(17)	2.069(7)	Fe-C(1)	2.073(7)
Fe-C(16)	2.081(6)	Fe-C(8)	2.084(7)
Fe-C(15)	2.087(7)	Fe-C(4)	2.121(7)
O(1)-C(11)	1.209(10)	O(2)-C(94)	1.414(14)
O(2)-C(91)	1.415(13)	O(3)-C(95)	1.42(2)
O(3)-C(98)	1.422(14)	N(1)-C(7)	1.375(10)
N(1)-C(11)	1.419(10)	N(1)-C(8)	1.434(9)
N(2)-C(5)	1.325(10)	N(2)-C(10)	1.460(11)
N(2)-C(9)	1.482(10)	C(1)-C(2)	1.405(11)
C(1)-C(8)	1.420(11)	C(2)-C(3)	1.400(11)
C(3)-C(4)	1.450(10)	C(4)-C(5)	1.414(11)
C(4)-C(8)	1.451(10)	C(5)-C(6)	1.451(10)
C(6)-C(7)	1.355(11)	C(11)-C(12)	1.497(11)
C(15)-C(19)	1.437(9)	C(15)-C(16)	1.441(9)
C(15)-C(20)	1.492(10)	C(16)-C(17)	1.441(9)
C(16)-C(30)	1.505(9)	C(17)-C(18)	1.444(9)
C(17)-C(40)	1.497(10)	C(18)-C(19)	1.428(10)
C(18)-C(50)	1.493(9)	C(19)-C(60)	1.496(9)
C(20)-C(21)	1.390(11)	C(20)-C(25)	1.419(10)
C(21)-C(22)	1.390(11)	C(22)-C(23)	1.386(13)
C(23)-C(24)	1.393(12)	C(24)-C(25)	1.366(11)
C(30)-C(35)	1.369(10)	C(30)-C(31)	1.406(10)
C(31)-C(32)	1.390(10)	C(32)-C(33)	1.361(12)
C(33)-C(34)	1.367(12)	C(34)-C(35)	1.418(10)
C(40)-C(45)	1.381(10)	C(40)-C(41)	1.403(10)
C(41)-C(42)	1.390(11)	C(42)-C(43)	1.362(12)
C(43)-C(44)	1.385(12)	C(44)-C(45)	1.402(11)
C(50)-C(55)	1.379(10)	C(50)-C(51)	1.393(10)
C(51)-C(52)	1.400(10)	C(52)-C(53)	1.373(11)
C(53)-C(54)	1.384(11)	C(54)-C(55)	1.394(10)
C(60)-C(65)	1.386(10)	C(60)-C(61)	1.415(10)
C(61)-C(62)	1.393(10)	C(62)-C(63)	1.366(12)
C(63)-C(64)	1.387(12)	C(64)-C(65)	1.382(10)
C(91)-C(92)	1.50(2)	C(92)-C(93)	1.52(2)
C(93)-C(94)	1.45(2)	C(95)-C(96)	1.45(2)
C(96)-C(97)	1.53(2)	C(97)-C(98)	1.50(2)

F(6)-Sb-F(4)	89.5(5)	F(6)-Sb-F(2)	89.8(5)
F(4)-Sb-F(2)	177.7(4)	F(6)-Sb-F(5)	179.3(5)
F(4)-Sb-F(5)	91.1(5)	F(2)-Sb-F(5)	89.6(5)
F(6)-Sb-F(1)	89.9(3)	F(4)-Sb-F(1)	90.6(3)
F(2)-Sb-F(1)	91.6(3)	F(5)-Sb-F(1)	90.3(3)
F(6)-Sb-F(3)	91.4(3)	F(4)-Sb-F(3)	89.0(3)
F(2)-Sb-F(3)	88.8(3)	F(5)-Sb-F(3)	88.4(3)
F(1)-Sb-F(3)	178.6(3)	C(3)-Fe-C(2)	39.8(3)
C(3)-Fe-C(18)	119.3(3)	C(2)-Fe-C(18)	102.4(3)
C(3)-Fe-C(19)	106.3(3)	C(2)-Fe-C(19)	118.5(3)
C(18)-Fe-C(19)	40.5(3)	C(3)-Fe-C(17)	155.0(3)
C(2)-Fe-C(17)	119.6(3)	C(18)-Fe-C(17)	40.9(3)
C(19)-Fe-C(17)	68.5(3)	C(3)-Fe-C(1)	67.6(3)

C(2)-Fe-C(1)	39.7(3)	C(18)-Fe-C(1)	117.4(3)
C(19)-Fe-C(1)	152.7(3)	C(17)-Fe-C(1)	105.3(3)
C(3)-Fe-C(16)	162.1(3)	C(2)-Fe-C(16)	157.9(3)
C(18)-Fe-C(16)	68.5(3)	C(19)-Fe-C(16)	68.3(3)
C(17)-Fe-C(16)	40.6(3)	C(1)-Fe-C(16)	125.1(3)
C(3)-Fe-C(8)	67.3(3)	C(2)-Fe-C(8)	66.5(3)
C(18)-Fe-C(8)	155.1(3)	C(19)-Fe-C(8)	164.4(3)
C(17)-Fe-C(8)	123.5(3)	C(1)-Fe-C(8)	40.0(3)
C(16)-Fe-C(8)	113.1(3)	C(3)-Fe-C(15)	124.6(3)
C(2)-Fe-C(15)	156.5(3)	C(18)-Fe-C(15)	68.2(3)
C(19)-Fe-C(15)	40.5(3)	C(17)-Fe-C(15)	68.2(3)
C(1)-Fe-C(15)	163.8(3)	C(16)-Fe-C(15)	40.5(3)
C(8)-Fe-C(15)	130.3(3)	C(3)-Fe-C(4)	40.6(3)
C(2)-Fe-C(4)	67.4(3)	C(18)-Fe-C(4)	158.0(3)
C(19)-Fe-C(4)	125.6(3)	C(17)-Fe-C(4)	161.1(3)
C(1)-Fe-C(4)	68.1(3)	C(16)-Fe-C(4)	127.7(3)
C(8)-Fe-C(4)	40.4(3)	C(15)-Fe-C(4)	113.0(3)
C(94)-O(2)-C(91)	104.6(9)	C(95)-O(3)-C(98)	106.0(10)
C(7)-N(1)-C(11)	122.0(6)	C(7)-N(1)-C(8)	116.3(6)
C(11)-N(1)-C(8)	121.7(6)	C(5)-N(2)-C(10)	123.0(7)
C(5)-N(2)-C(9)	122.7(7)	C(10)-N(2)-C(9)	114.2(7)
C(2)-C(1)-C(8)	107.0(7)	C(2)-C(1)-Fe	69.7(4)
C(8)-C(1)-Fe	70.4(4)	C(3)-C(2)-C(1)	109.7(6)
C(3)-C(2)-Fe	69.7(4)	C(1)-C(2)-Fe	70.6(4)
C(2)-C(3)-C(4)	109.1(7)	C(2)-C(3)-Fe	70.5(4)
C(4)-C(3)-Fe	72.3(4)	C(5)-C(4)-C(8)	122.2(6)
C(5)-C(4)-C(3)	133.3(7)	C(8)-C(4)-C(3)	104.5(6)
C(5)-C(4)-Fe	127.2(5)	C(8)-C(4)-Fe	68.5(4)
C(3)-C(4)-Fe	67.1(4)	N(2)-C(5)-C(4)	125.8(7)
N(2)-C(5)-C(6)	119.8(7)	C(4)-C(5)-C(6)	114.3(7)
C(7)-C(6)-C(5)	122.3(7)	C(6)-C(7)-N(1)	124.7(7)
C(1)-C(8)-N(1)	130.4(7)	C(1)-C(8)-C(4)	109.7(6)
N(1)-C(8)-C(4)	119.7(6)	C(1)-C(8)-Fe	69.6(4)
N(1)-C(8)-Fe	128.7(5)	C(4)-C(8)-Fe	71.2(4)
O(1)-C(11)-N(1)	119.8(7)	O(1)-C(11)-C(12)	123.6(7)
N(1)-C(11)-C(12)	116.6(7)	C(19)-C(15)-C(16)	107.9(6)
C(19)-C(15)-C(20)	125.9(6)	C(16)-C(15)-C(20)	125.8(6)
C(19)-C(15)-Fe	68.8(4)	C(16)-C(15)-Fe	69.6(4)
C(20)-C(15)-Fe	132.8(5)	C(15)-C(16)-C(17)	107.8(5)
C(15)-C(16)-C(30)	126.2(6)	C(17)-C(16)-C(30)	125.4(6)
C(15)-C(16)-Fe	70.0(4)	C(17)-C(16)-Fe	69.2(4)
C(30)-C(16)-Fe	132.5(5)	C(18)-C(17)-C(16)	107.8(6)
C(18)-C(17)-C(40)	126.1(6)	C(16)-C(17)-C(40)	125.7(6)
C(18)-C(17)-Fe	69.3(4)	C(16)-C(17)-Fe	70.1(4)
C(40)-C(17)-Fe	131.2(5)	C(19)-C(18)-C(17)	108.0(6)
C(19)-C(18)-C(50)	127.2(6)	C(17)-C(18)-C(50)	124.6(6)
C(19)-C(18)-Fe	69.7(4)	C(17)-C(18)-Fe	69.8(4)
C(50)-C(18)-Fe	130.2(5)	C(18)-C(19)-C(15)	108.4(6)
C(18)-C(19)-C(60)	124.9(6)	C(15)-C(19)-C(60)	126.3(6)
C(18)-C(19)-Fe	69.7(4)	C(15)-C(19)-Fe	70.7(4)
C(60)-C(19)-Fe	130.9(5)	C(21)-C(20)-C(25)	117.1(7)
C(21)-C(20)-C(15)	123.0(6)	C(25)-C(20)-C(15)	119.6(6)
C(22)-C(21)-C(20)	121.6(7)	C(23)-C(22)-C(21)	119.8(8)
C(22)-C(23)-C(24)	119.8(8)	C(25)-C(24)-C(23)	120.0(7)
C(24)-C(25)-C(20)	121.7(7)	C(35)-C(30)-C(31)	118.7(6)
C(35)-C(30)-C(16)	122.7(6)	C(31)-C(30)-C(16)	118.5(6)
C(32)-C(31)-C(30)	120.1(7)	C(33)-C(32)-C(31)	120.6(7)
C(32)-C(33)-C(34)	120.6(7)	C(33)-C(34)-C(35)	119.5(8)
C(30)-C(35)-C(34)	120.5(7)	C(45)-C(40)-C(41)	118.6(7)

C(45)-C(40)-C(17)	119.5(6)	C(41)-C(40)-C(17)	121.8(7)
C(42)-C(41)-C(40)	119.9(7)	C(43)-C(42)-C(41)	121.1(7)
C(42)-C(43)-C(44)	120.1(7)	C(43)-C(44)-C(45)	119.4(8)
C(40)-C(45)-C(44)	120.9(7)	C(55)-C(50)-C(51)	118.3(6)
C(55)-C(50)-C(18)	122.4(6)	C(51)-C(50)-C(18)	119.1(6)
C(50)-C(51)-C(52)	120.5(7)	C(53)-C(52)-C(51)	120.3(7)
C(52)-C(53)-C(54)	119.6(7)	C(53)-C(54)-C(55)	119.8(7)
C(50)-C(55)-C(54)	121.4(7)	C(65)-C(60)-C(61)	118.1(6)
C(65)-C(60)-C(19)	120.6(6)	C(61)-C(60)-C(19)	121.2(6)

C(62)-C(61)-C(60)	119.4(7)	C(63)-C(62)-C(61)	121.0(7)
C(62)-C(63)-C(64)	120.3(7)	C(65)-C(64)-C(63)	119.3(7)
C(60)-C(65)-C(64)	121.9(7)	O(2)-C(91)-C(92)	105.4(10)
C(91)-C(92)-C(93)	104.2(12)	C(94)-C(93)-C(92)	103.1(12)
O(2)-C(94)-C(93)	105.7(11)	O(3)-C(95)-C(96)	107.8(12)
C(95)-C(96)-C(97)	106.1(13)	C(98)-C(97)-C(96)	102.1(11)
O(3)-C(98)-C(97)	105.4(10)		

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters [$Å^2$ x 10^3] for 1.

The anisotropic displacement factor exponent takes the form:

$-2\pi^2 [(ha^*)^2 U_{11} + ... + 2hka^* b^* U_{12}]$

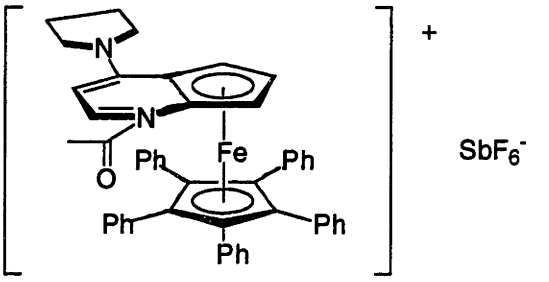
	U11	U22	U33	U23	U13	U12
Sb	36(1)	60(1)	54(1)	9(1)	-4(1)	33(1)
Fe	18(1)	31(1)	31(1)	10(1)	3(1)	16(1)
F(1)	37(3)	123(5)	86(4)	35(4)	11(3)	49(3)
F(2)	45(4)	83(5)	265(12)	63(6)	-1(5)	32(4)
F(3)	42(3)	82(4)	91(4)	-6(3)	-12(3)	45(3)
F(4)	57(4)	78(5)	260(12)	62(6)	-26(5)	25(4)
F(5)	77(5)	213(10)	80(5)	-16(6)	-1(4)	71(6)
F(6)	56(4)	251(11)	85(5)	-21(6)	-7(4)	79(6)
O(1)	50(4)	38(4)	76(5)	3(3)	31(3)	7(3)
O(2)	78(5)	59(5)	99(6)	16(4)	5(4)	45(4)
O(3)	63(5)	82(6)	152(9)	44(6)	5(5)	39(5)
N(1)	30(3)	37(4)	39(4)	17(3)	11(3)	18(3)
N(2)	33(4)	45(4)	35(4)	11(3)	2(3)	19(3)
C(1)	44(5)	27(4)	36(4)	12(3)	10(4)	21(4)
C(2)	35(4)	52(5)	40(5)	19(4)	11(3)	37(4)
C(3)	29(4)	50(5)	43(5)	22(4)	8(3)	26(4)
C(4)	28(4)	33(4)	31(4)	13(3)	5(3)	17(3)
C(5)	30(4)	45(5)	18(4)	12(3)	-1(3)	17(4)
C(6)	29(4)	43(5)	30(4)	5(3)	4(3)	20(4)
C(7)	34(4)	40(4)	33(4)	16(4)	8(3)	23(4)
C(8)	33(4)	34(4)	34(4)	19(3)	11(3)	19(3)
C(9)	28(5)	74(7)	61(6)	2(5)	-10(4)	22(5)
C(10)	49(5)	46(5)	36(5)	-4(4)	2(4)	13(4)
C(11)	37(5)	36(5)	37(5)	8(4)	10(4)	13(4)
C(12)	34(5)	54(5)	53(6)	15(4)	6(4)	16(4)
C(15)	16(3)	31(4)	28(4)	7(3)	4(3)	13(3)
C(16)	15(3)	27(4)	31(4)	6(3)	4(3)	14(3)
C(17)	15(3)	30(4)	27(4)	10(3)	0(3)	12(3)
C(18)	21(3)	33(4)	28(4)	9(3)	6(3)	18(3)
C(19)	19(3)	32(4)	28(4)	9(3)	2(3)	14(3)
C(20)	15(3)	31(4)	37(4)	9(3)	9(3)	12(3)
C(21)	33(4)	40(5)	38(5)	7(4)	3(3)	20(4)
C(22)	45(5)	41(5)	40(5)	-5(4)	5(4)	15(4)
C(23)	57(6)	39(5)	63(6)	3(4)	20(5)	33(4)
C(24)	41(5)	42(5)	57(6)	8(4)	8(4)	29(4)
C(25)	25(4)	39(4)	43(5)	10(3)	3(3)	23(3)
C(30)	17(3)	35(4)	39(4)	11(3)	4(3)	18(3)
C(31)	22(4)	30(4)	41(4)	7(3)	2(3)	16(3)
C(32)	24(4)	41(5)	51(5)	1(4)	-9(4)	20(4)
C(33)	17(4)	42(5)	69(6)	11(4)	10(4)	19(3)
C(34)	38(4)	48(5)	56(5)	22(4)	24(4)	30(4)
C(35)	31(4)	34(4)	45(5)	15(3)	10(3)	22(3)
C(40)	27(4)	35(4)	34(4)	11(3)	4(3)	24(3)
C(41)	22(4)	30(4)	46(5)	14(3)	9(3)	17(3)
C(42)	20(4)	31(4)	62(6)	11(4)	2(4)	13(3)
C(43)	31(4)	33(4)	56(6)	0(4)	-16(4)	16(4)
C(44)	39(5)	46(5)	39(5)	3(4)	-8(4)	25(4)
C(45)	21(4)	32(4)	36(4)	6(3)	0(3)	17(3)

C(50)	9(3)	31(4)	28(4)	3(3)	2(3)	12(3)
C(51)	23(4)	26(4)	32(4)	3(3)	3(3)	14(3)
C(52)	23(4)	48(5)	40(5)	16(4)	14(3)	19(4)
C(53)	20(4)	45(5)	40(5)	5(4)	3(3)	19(3)
C(54)	28(4)	35(4)	41(4)	3(3)	1(3)	22(3)
C(55)	17(3)	36(4)	41(4)	13(3)	6(3)	15(3)
C(60)	14(3)	25(4)	34(4)	2(3)	1(3)	9(3)
C(61)	14(3)	33(4)	46(5)	8(3)	3(3)	10(3)
C(62)	24(4)	57(6)	50(5)	11(4)	11(4)	22(4)
C(63)	13(4)	40(5)	47(5)	4(4)	12(3)	-1(3)
C(64)	29(4)	28(4)	42(5)	4(3)	9(4)	4(3)
C(65)	26(4)	44(5)	38(4)	9(3)	6(3)	24(4)
C(91)	87(8)	79(8)	70(7)	17(6)	14(6)	57(7)
C(92)	139(14)	77(9)	128(13)	33(9)	-26(11)	48(9)
C(93)	144(14)	85(10)	96(11)	33(8)	-14(10)	38(10)
C(94)	80(9)	88(10)	124(12)	10(9)	-29(8)	38(8)
C(95)	108(12)	117(13)	193(19)	80(12)	46(12)	81(11)
C(96)	152(15)	104(12)	83(10)	6(8)	29(10)	64(12)
C(97)	75(8)	82(9)	112(11)	36(8)	9(8)	27(7)
C(98)	93(9)	78(8)	87(9)	24(7)	15(7)	57(7)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

	x	y	z	U(eq)
H(1A)	-901(7)	5924(7)	1751(4)	40
H(2A)	1533(7)	7031(7)	1880(4)	41
H(3A)	2558(7)	9035(7)	2856(4)	44
H(6A)	-648(7)	9788(7)	3995(4)	41
H(7A)	-2441(7)	8019(7)	3439(4)	39
H(9A)	3636(8)	11302(9)	4408(6)	90
H(9B)	3194(8)	10563(9)	3560(6)	90
H(9C)	3053(8)	9867(9)	4210(6)	90
H(10A)	2540(9)	11933(8)	4801(5)	76
H(10B)	1179(9)	10956(8)	4889(5)	76
H(10C)	1256(9)	11688(8)	4261(5)	76
H(12A)	-3862(8)	6845(8)	2947(5)	74
H(12B)	-4476(8)	5421(8)	2869(5)	74
H(12C)	-4657(8)	5920(8)	2155(5)	74
H(21A)	2086(7)	11471(7)	2852(4)	44
H(22A)	2483(8)	13373(8)	3456(5)	56
H(23A)	1134(9)	14110(8)	3042(5)	59
H(24A)	-516(8)	12997(7)	1965(5)	53
H(25A)	-876(7)	11137(7)	1351(4)	40
H(31A)	-2796(6)	8212(6)	98(4)	36
H(32A)	-4789(7)	8068(7)	79(5)	48
H(33A)	-5332(7)	8496(7)	1169(5)	50
H(34A)	-3911(7)	9069(7)	2302(5)	49
H(35A)	-1864(7)	9269(7)	2338(4)	40
H(41A)	-2716(6)	6164(6)	935(4)	36
H(42A)	-4287(7)	4417(7)	61(5)	47
H(43A)	-4151(7)	4074(7)	-1156(5)	53
H(44A)	-2405(8)	5466(7)	-1526(5)	51
H(45A)	-811(6)	7232(6)	-655(4)	35
H(51A)	2479(6)	9558(6)	73(4)	33
H(52A)	3366(7)	8705(7)	-695(4)	42
H(53A)	2835(6)	6693(7)	-820(4)	42
H(54A)	1463(7)	5536(7)	-145(4)	40
H(55A)	544(6)	6374(6)	600(4)	36
H(61A)	3443(6)	9526(7)	1843(4)	39
H(62A)	5613(7)	10956(8)	2082(5)	52
H(63A)	6246(7)	12872(7)	1911(5)	47
H(64A)	4720(7)	13417(7)	1498(4)	45
H(65A)	2559(7)	12014(7)	1258(4)	40
H(91A)	10183(12)	2516(11)	5333(6)	88
H(91B)	8855(12)	2429(11)	5445(6)	88
H(92A)	10129(17)	3274(13)	4350(9)	147
H(92B)	9046(17)	3522(13)	4614(9)	147
H(93A)	7650(17)	2122(13)	3594(9)	143
H(93B)	8673(17)	1709(13)	3420(9)	143
H(94A)	6959(13)	885(13)	4332(9)	128
H(94B)	7330(13)	102(13)	3763(9)	128
H(95A)	-1727(16)	4912(15)	4421(11)	147
H(95B)	-2004(16)	4866(15)	3551(11)	147

H(96A)	-3445(17)	3200(15)	4176(9)	138
H(96B)	-3842(17)	3283(15)	3340(9)	138
H(97A)	-5149(12)	3976(12)	3645(8)	114
H(97B)	-4980(12)	3609(12)	4423(8)	114
H(98A)	-4140(12)	5853(11)	4411(7)	97
H(98B)	-3391(12)	5492(11)	5017(7)	97



A solvent molecule (methylene chloride) is included in the crystal lattice.

Structure solved by Michael Lo.

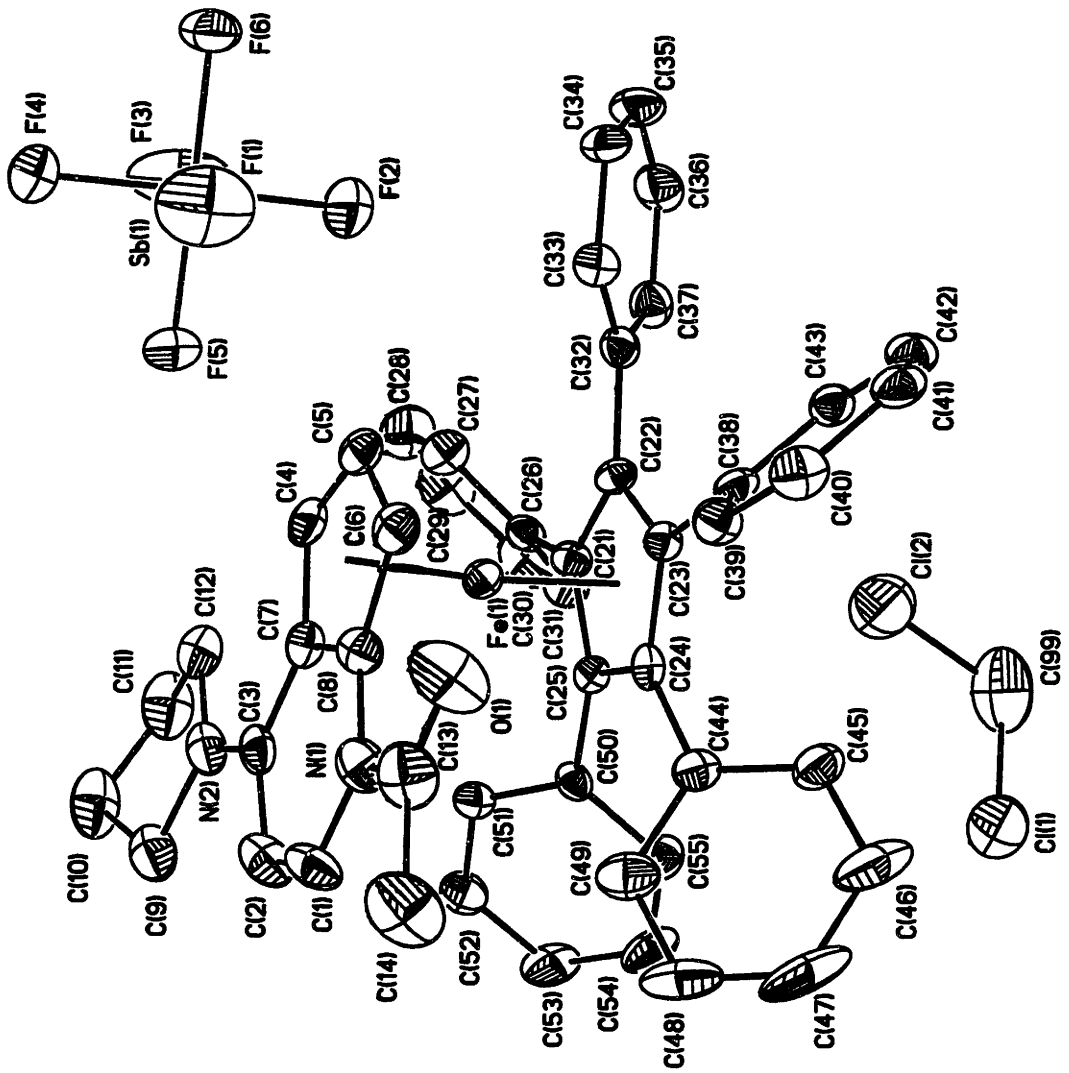

F(6)
F(4)
F(3)
F(1)
F(2)
Sb(1)
F(5)
C(34)
C(35)
C(33)
C(36)
C(37)
C(32)
C(43)
C(42)
C(41)
C(28)
C(27)
C(5)
C(22)
C(38)
C(4)
C(26)
C(40)
C(6)
C(29)
C(21)
C(23)
C(39)
C(12)
C(7)
Fe(1)
C(30)
C(31)
C(24)
C(11)
C(8)
O(1)
C(25)
C(3)
C(44)
C(45)
N(1)
C(13)
C(50)
N(2)
C(51)
C(49)
C(55)
C(10)
C(9)
C(2)
C(1)
C(14)
C(52)
C(46)
C(53)
C(54)
C(48)
C(47)
Cl(2)
C(99)
Cl(1)

Table 1. Crystal data and structure refinement for 1.

A. Crystal Data

Identification code	99037
Empirical formula	$C_{50}H_{43}Cl_2F_6FeN_2OSb$
Formula weight	1050.36
Temperature	160(2) K
Wavelength	0.71073 Å
Crystal morphology	needle
Crystal size	0.09 x 0.18 x 0.24 mm
Crystal system	Monoclinic
Space group	$P2_1/n$
Unit cell dimensions	a = 18.488(3) Å alpha = 90°
	b = 12.781(3) Å beta = 112.09(2)°
	c = 22.351(6) Å gamma = 90°
Volume, Z	4894(2) $Å^3$, 4
Density (calculated)	1.426 Mg/m^3
Absorption coefficient	1.018 mm^{-1}
F(000)	2120

B. Data Collection and Reduction

Diffractometer	Siemens SMART/CCD
Scan Type	ω Scans
Scan angle	0.30°
θ range for data collection	1.22 to 23.25°
Limiting indices	$-20 \le h \le 18$, $-10 \le k \le 14$, $-16 \le l \le 24$

Reflections collected	15342
Independent reflections	6985 (R_{int} = 0.0654)
Absorption correction	Semi-empirical from psi-scans
Max. and min. transmission	0.9174 and 0.6896

C. Solution and Refinement

Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	6985 / 0 / 569
Goodness-of-fit on F^2	1.236
Final R indices [I>2σ(I)]	R1 = 0.0687, wR2 = 0.1637
R indices (all data)	R1 = 0.0843, wR2 = 0.1708
Extinction coefficient	0.0009(2)
Largest diff. peak and hole	0.667 and -0.591 $eÅ^{-3}$

Table 2. Atomic coordinates [x 10^4] and equivalent isotropic displacement parameters [$Å^2$ x 10^3] for 99037. U(eq) is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U(eq)
Sb(1)	4185(1)	8034(1)	7493(1)	41(1)
Fe(1)	6346(1)	11280(1)	9155(1)	28(1)
Cl(1)	9989(2)	13233(3)	9650(2)	114(1)
Cl(2)	8781(2)	12105(3)	8633(2)	92(1)
F(1)	3840(5)	9331(5)	7649(4)	124(3)
F(2)	4974(4)	8689(8)	7327(3)	135(4)
F(3)	4526(5)	6745(6)	7355(3)	118(3)
F(4)	3383(3)	7429(6)	7677(3)	93(2)
F(5)	4826(3)	7923(5)	8374(2)	70(2)
F(6)	3555(3)	8077(5)	6618(2)	71(2)
O(1)	5305(5)	13749(5)	9706(3)	71(2)
N(1)	5887(4)	12292(5)	10269(3)	45(2)
N(2)	6399(4)	9062(5)	10481(3)	44(2)
C(1)	6276(5)	11802(7)	10855(4)	48(2)
C(2)	6464(5)	10784(8)	10928(4)	51(2)
C(3)	6255(4)	10077(6)	10385(4)	36(2)
C(4)	5524(4)	10137(7)	9125(4)	40(2)
C(5)	5167(4)	10964(6)	8702(4)	36(2)
C(6)	5274(4)	11912(7)	9054(4)	40(2)
C(7)	5861(4)	10553(6)	9765(4)	36(2)
C(8)	5696(4)	11667(6)	9712(4)	35(2)
C(9)	6757(5)	8585(7)	11143(4)	55(2)
C(10)	6680(6)	7412(8)	11001(6)	69(3)
C(11)	6734(6)	7327(8)	10344(6)	69(3)
C(12)	6271(5)	8263(6)	9980(4)	50(2)
C(13)	5660(6)	13368(7)	10233(5)	55(2)
C(14)	5873(7)	13968(8)	10848(5)	77(3)
C(21)	7199(4)	10607(6)	8886(3)	28(2)
C(22)	6736(4)	11322(5)	8395(3)	27(2)
C(23)	6809(4)	12344(5)	8690(3)	26(2)
C(24)	7324(4)	12255(5)	9355(3)	28(2)
C(25)	7564(4)	11189(6)	9474(3)	29(2)
C(26)	7337(4)	9474(6)	8791(3)	31(2)
C(27)	6717(5)	8805(6)	8470(4)	41(2)
C(28)	6844(6)	7765(7)	8384(5)	61(3)
C(29)	7582(7)	7365(8)	8600(5)	65(3)
C(30)	8214(6)	8034(8)	8904(4)	57(3)
C(31)	8094(4)	9075(6)	9002(4)	38(2)
C(32)	6287(4)	11087(6)	7699(3)	32(2)
C(33)	5547(4)	11527(6)	7363(4)	40(2)
C(34)	5161(5)	11327(7)	6710(4)	47(2)
C(35)	5489(6)	10693(7)	6380(4)	56(2)
C(36)	6209(6)	10264(7)	6705(4)	50(2)
C(37)	6615(5)	10459(6)	7362(4)	40(2)
C(38)	6491(4)	13339(5)	8333(3)	30(2)
C(39)	6112(4)	14084(6)	8575(4)	37(2)
C(40)	5881(5)	15033(6)	8263(4)	43(2)
C(41)	6013(5)	15240(6)	7703(4)	42(2)

C(42)	6382(4)	14505(6)	7460(4)	38(2)
C(43)	6633(4)	13564(6)	7777(3)	33(2)
C(44)	7605(4)	13148(6)	9812(4)	36(2)
C(45)	7866(5)	14053(6)	9614(4)	45(2)
C(46)	8147(6)	14878(8)	10023(5)	78(3)
C(47)	8196(6)	14829(8)	10645(6)	84(4)
C(48)	7954(5)	13939(9)	10866(4)	65(3)
C(49)	7659(5)	13074(7)	10449(4)	50(2)
C(50)	8173(4)	10782(6)	10080(3)	29(2)
C(51)	8079(4)	9835(6)	10354(3)	35(2)
C(52)	8667(5)	9452(7)	10904(4)	46(2)
C(53)	9356(5)	9988(7)	11166(4)	55(2)
C(54)	9475(5)	10913(7)	10899(4)	55(2)
C(55)	8879(4)	11303(6)	10355(4)	40(2)
C(99)	9715(7)	12694(10)	8890(7)	97(4)

Table 3. Bond lengths [Å] and angles [°] for 99037.

Sb(1)-F(3)	1.831(6)	Sb(1)-F(2)	1.837(6)
Sb(1)-F(4)	1.850(6)	Sb(1)-F(1)	1.856(6)
Sb(1)-F(6)	1.864(5)	Sb(1)-F(5)	1.883(5)
Fe(1)-C(5)	2.069(7)	Fe(1)-C(21)	2.073(7)
Fe(1)-C(6)	2.073(7)	Fe(1)-C(22)	2.079(7)
Fe(1)-C(23)	2.080(7)	Fe(1)-C(4)	2.091(8)
Fe(1)-C(8)	2.090(7)	Fe(1)-C(25)	2.093(7)
Fe(1)-C(24)	2.100(7)	Fe(1)-C(7)	2.110(7)
Cl(1)-C(99)	1.723(14)	Cl(2)-C(99)	1.770(13)
O(1)-C(13)	1.214(11)	N(1)-C(1)	1.385(10)
N(1)-C(8)	1.407(10)	N(1)-C(13)	1.432(11)
N(2)-C(3)	1.325(10)	N(2)-C(12)	1.467(11)
N(2)-C(9)	1.505(10)	C(1)-C(2)	1.341(12)
C(2)-C(3)	1.443(12)	C(3)-C(7)	1.437(11)
C(4)-C(5)	1.406(11)	C(4)-C(7)	1.431(11)
C(5)-C(6)	1.416(11)	C(6)-C(8)	1.417(11)
C(7)-C(8)	1.451(11)	C(9)-C(10)	1.529(13)
C(10)-C(11)	1.513(14)	C(11)-C(12)	1.518(12)
C(13)-C(14)	1.493(13)	C(21)-C(25)	1.438(10)
C(21)-C(22)	1.438(10)	C(21)-C(26)	1.499(10)
C(22)-C(23)	1.446(9)	C(22)-C(32)	1.493(10)
C(23)-C(24)	1.436(10)	C(23)-C(38)	1.499(10)
C(24)-C(25)	1.427(10)	C(24)-C(44)	1.489(10)
C(25)-C(50)	1.492(9)	C(26)-C(27)	1.393(11)
C(26)-C(31)	1.396(10)	C(27)-C(28)	1.376(12)
C(28)-C(29)	1.363(14)	C(29)-C(30)	1.401(14)
C(30)-C(31)	1.379(12)	C(32)-C(37)	1.387(10)
C(32)-C(33)	1.407(11)	C(33)-C(34)	1.386(11)
C(34)-C(35)	1.380(12)	C(35)-C(36)	1.370(13)
C(36)-C(37)	1.396(11)	C(38)-C(43)	1.394(10)
C(38)-C(39)	1.406(10)	C(39)-C(40)	1.385(11)
C(40)-C(41)	1.388(11)	C(41)-C(42)	1.386(11)
C(42)-C(43)	1.384(10)	C(44)-C(45)	1.389(11)
C(44)-C(49)	1.393(11)	C(45)-C(46)	1.363(12)
C(46)-C(47)	1.36(2)	C(47)-C(48)	1.38(2)
C(48)-C(49)	1.416(12)	C(50)-C(55)	1.386(10)
C(50)-C(51)	1.397(10)	C(51)-C(52)	1.389(10)
C(52)-C(53)	1.368(12)	C(53)-C(54)	1.378(12)
C(54)-C(55)	1.391(11)		

F(3)-Sb(1)-F(2)	91.5(5)	F(3)-Sb(1)-F(4)	91.0(4)
F(2)-Sb(1)-F(4)	177.4(4)	F(3)-Sb(1)-F(1)	178.9(4)
F(2)-Sb(1)-F(1)	89.2(4)	F(4)-Sb(1)-F(1)	88.3(4)
F(3)-Sb(1)-F(6)	88.2(3)	F(2)-Sb(1)-F(6)	90.2(3)
F(4)-Sb(1)-F(6)	90.5(3)	F(1)-Sb(1)-F(6)	92.7(3)
F(3)-Sb(1)-F(5)	89.3(3)	F(2)-Sb(1)-F(5)	90.6(3)
F(4)-Sb(1)-F(5)	88.8(2)	F(1)-Sb(1)-F(5)	89.8(3)
F(6)-Sb(1)-F(5)	177.4(3)	C(5)-Fe(1)-C(21)	123.7(3)
C(5)-Fe(1)-C(6)	40.0(3)	C(21)-Fe(1)-C(6)	158.5(3)
C(5)-Fe(1)-C(22)	103.3(3)	C(21)-Fe(1)-C(22)	40.5(3)
C(6)-Fe(1)-C(22)	120.8(3)	C(5)-Fe(1)-C(23)	116.1(3)
C(21)-Fe(1)-C(23)	68.1(3)	C(6)-Fe(1)-C(23)	104.3(3)
C(22)-Fe(1)-C(23)	40.7(3)	C(5)-Fe(1)-C(4)	39.5(3)
C(21)-Fe(1)-C(4)	108.9(3)	C(6)-Fe(1)-C(4)	67.3(3)
C(22)-Fe(1)-C(4)	117.6(3)	C(23)-Fe(1)-C(4)	150.6(3)

C(5)-Fe(1)-C(8)	66.5(3)	C(21)-Fe(1)-C(8)	160.3(3)
C(6)-Fe(1)-C(8)	39.8(3)	C(22)-Fe(1)-C(8)	159.0(3)
C(23)-Fe(1)-C(8)	125.4(3)	C(4)-Fe(1)-C(8)	67.1(3)
C(5)-Fe(1)-C(25)	163.0(3)	C(21)-Fe(1)-C(25)	40.4(3)
C(6)-Fe(1)-C(25)	157.0(3)	C(22)-Fe(1)-C(25)	67.8(3)
C(23)-Fe(1)-C(25)	67.4(3)	C(4)-Fe(1)-C(25)	130.4(3)
C(8)-Fe(1)-C(25)	126.5(3)	C(5)-Fe(1)-C(24)	152.1(3)
C(21)-Fe(1)-C(24)	67.7(3)	C(6)-Fe(1)-C(24)	120.2(3)
C(22)-Fe(1)-C(24)	67.9(3)	C(23)-Fe(1)-C(24)	40.2(3)
C(4)-Fe(1)-C(24)	168.0(3)	C(8)-Fe(1)-C(24)	111.9(3)
C(25)-Fe(1)-C(24)	39.8(3)	C(5)-Fe(1)-C(7)	66.7(3)
C(21)-Fe(1)-C(7)	124.0(3)	C(6)-Fe(1)-C(7)	67.6(3)
C(22)-Fe(1)-C(7)	154.4(3)	C(23)-Fe(1)-C(7)	164.9(3)
C(4)-Fe(1)-C(7)	39.8(3)	C(8)-Fe(1)-C(7)	40.4(3)
C(25)-Fe(1)-C(7)	114.8(3)	C(24)-Fe(1)-C(7)	131.6(3)
C(1)-N(1)-C(8)	116.7(7)	C(1)-N(1)-C(13)	121.6(8)
C(8)-N(1)-C(13)	121.7(7)	C(3)-N(2)-C(12)	126.4(7)
C(3)-N(2)-C(9)	122.8(7)	C(12)-N(2)-C(9)	110.7(7)
C(2)-C(1)-N(1)	124.9(8)	C(1)-C(2)-C(3)	122.1(8)
N(2)-C(3)-C(7)	124.6(8)	N(2)-C(3)-C(2)	120.2(7)
C(7)-C(3)-C(2)	115.0(7)	C(5)-C(4)-C(7)	108.1(7)
C(5)-C(4)-Fe(1)	69.4(4)	C(7)-C(4)-Fe(1)	70.8(4)
C(4)-C(5)-C(6)	109.8(7)	C(4)-C(5)-Fe(1)	71.1(4)
C(6)-C(5)-Fe(1)	70.2(4)	C(8)-C(6)-C(5)	107.2(7)
C(8)-C(6)-Fe(1)	70.8(4)	C(5)-C(6)-Fe(1)	69.8(4)
C(4)-C(7)-C(3)	132.8(8)	C(4)-C(7)-C(8)	106.5(7)
C(3)-C(7)-C(8)	120.6(7)	C(4)-C(7)-Fe(1)	69.4(4)
C(3)-C(7)-Fe(1)	128.7(5)	C(8)-C(7)-Fe(1)	69.1(4)
N(1)-C(8)-C(6)	130.6(7)	N(1)-C(8)-C(7)	120.6(7)
C(6)-C(8)-C(7)	108.5(7)	N(1)-C(8)-Fe(1)	130.7(5)
C(6)-C(8)-Fe(1)	69.4(4)	C(7)-C(8)-Fe(1)	70.5(4)
N(2)-C(9)-C(10)	102.7(8)	C(11)-C(10)-C(9)	103.7(8)
C(10)-C(11)-C(12)	103.6(8)	N(2)-C(12)-C(11)	104.1(8)
O(1)-C(13)-N(1)	118.7(8)	O(1)-C(13)-C(14)	123.1(9)
N(1)-C(13)-C(14)	118.2(9)	C(25)-C(21)-C(22)	108.0(6)
C(25)-C(21)-C(26)	125.6(6)	C(22)-C(21)-C(26)	126.2(6)
C(25)-C(21)-Fe(1)	70.6(4)	C(22)-C(21)-Fe(1)	70.0(4)
C(26)-C(21)-Fe(1)	129.0(5)	C(21)-C(22)-C(23)	107.4(6)
C(21)-C(22)-C(32)	127.3(6)	C(23)-C(22)-C(32)	125.3(6)
C(21)-C(22)-Fe(1)	69.5(4)	C(23)-C(22)-Fe(1)	69.7(4)
C(32)-C(22)-Fe(1)	128.2(5)	C(24)-C(23)-C(22)	108.2(6)
C(24)-C(23)-C(38)	126.3(6)	C(22)-C(23)-C(38)	124.9(6)
C(24)-C(23)-Fe(1)	70.7(4)	C(22)-C(23)-Fe(1)	69.6(4)
C(38)-C(23)-Fe(1)	131.9(5)	C(25)-C(24)-C(23)	107.9(6)
C(25)-C(24)-C(44)	126.9(6)	C(23)-C(24)-C(44)	125.0(6)
C(25)-C(24)-Fe(1)	69.8(4)	C(23)-C(24)-Fe(1)	69.1(4)
C(44)-C(24)-Fe(1)	130.7(5)	C(24)-C(25)-C(21)	108.5(6)
C(24)-C(25)-C(50)	125.3(6)	C(21)-C(25)-C(50)	125.7(6)
C(24)-C(25)-Fe(1)	70.4(4)	C(21)-C(25)-Fe(1)	69.1(4)
C(50)-C(25)-Fe(1)	132.6(5)	C(27)-C(26)-C(31)	118.4(7)
C(27)-C(26)-C(21)	121.1(7)	C(31)-C(26)-C(21)	120.5(7)
C(28)-C(27)-C(26)	121.0(8)	C(29)-C(28)-C(27)	120.9(9)
C(28)-C(29)-C(30)	119.0(9)	C(31)-C(30)-C(29)	120.7(8)
C(30)-C(31)-C(26)	120.0(8)	C(37)-C(32)-C(33)	118.5(7)
C(37)-C(32)-C(22)	119.9(7)	C(33)-C(32)-C(22)	121.6(7)
C(34)-C(33)-C(32)	120.1(8)	C(35)-C(34)-C(33)	121.0(8)
C(36)-C(35)-C(34)	119.1(8)	C(35)-C(36)-C(37)	121.1(8)
C(32)-C(37)-C(36)	120.2(8)	C(43)-C(38)-C(39)	119.5(7)
C(43)-C(38)-C(23)	118.9(6)	C(39)-C(38)-C(23)	121.4(6)

C(40)-C(39)-C(38)	120.2(7)	C(39)-C(40)-C(41)	119.8(7)
C(40)-C(41)-C(42)	120.2(7)	C(43)-C(42)-C(41)	120.6(7)
C(42)-C(43)-C(38)	119.7(7)	C(45)-C(44)-C(49)	118.8(8)
C(45)-C(44)-C(24)	119.6(7)	C(49)-C(44)-C(24)	121.4(7)
C(46)-C(45)-C(44)	121.4(9)	C(47)-C(46)-C(45)	120.8(10)
C(46)-C(47)-C(48)	119.8(9)	C(47)-C(48)-C(49)	120.4(9)
C(44)-C(49)-C(48)	118.8(9)	C(55)-C(50)-C(51)	118.3(6)
C(55)-C(50)-C(25)	119.9(6)	C(51)-C(50)-C(25)	121.6(6)
C(52)-C(51)-C(50)	120.6(7)	C(53)-C(52)-C(51)	119.6(8)

C(52)-C(53)-C(54)	121.3(8)	C(53)-C(54)-C(55)	118.8(8)
C(50)-C(55)-C(54)	121.3(8)	Cl(1)-C(99)-Cl(2)	112.3(6)

Symmetry transformations used to generate equivalent atoms:

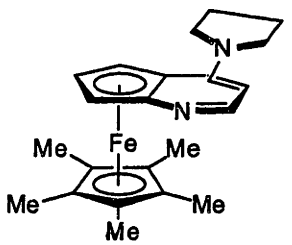
Table 4. Anisotropic displacement parameters [$Å^2 \times 10^3$] for 99037.
The anisotropic displacement factor exponent takes the form:
$-2\pi^2 [(ha^*)^2 U_{11} + ... + 2hka^*b^* U_{12}]$

	U11	U22	U33	U23	U13	U12
Sb(1)	41(1)	46(1)	37(1)	-4(1)	13(1)	-5(1)
Fe(1)	24(1)	29(1)	29(1)	0(1)	8(1)	1(1)
Cl(1)	111(3)	126(3)	83(2)	19(2)	11(2)	-46(2)
Cl(2)	88(2)	110(3)	86(2)	-23(2)	44(2)	-18(2)
F(1)	172(8)	61(4)	123(6)	-27(4)	38(6)	22(5)
F(2)	89(5)	247(11)	71(4)	2(5)	32(4)	-85(6)
F(3)	134(6)	106(5)	76(4)	-31(4)	-2(4)	71(5)
F(4)	56(3)	150(6)	71(4)	11(4)	21(3)	-32(4)
F(5)	62(3)	98(4)	40(3)	-7(3)	7(2)	-17(3)
F(6)	71(4)	81(4)	42(3)	10(3)	-1(3)	-8(3)
O(1)	108(6)	49(4)	64(5)	8(4)	41(4)	30(4)
N(1)	48(4)	47(4)	46(4)	1(3)	25(3)	6(3)
N(2)	38(4)	47(4)	50(4)	15(4)	22(3)	5(3)
C(1)	53(5)	66(6)	29(4)	0(4)	22(4)	10(5)
C(2)	49(5)	68(7)	42(5)	13(5)	24(4)	16(5)
C(3)	29(4)	44(5)	44(5)	7(4)	21(4)	0(4)
C(4)	25(4)	51(5)	47(5)	-3(4)	16(4)	-9(4)
C(5)	21(4)	44(5)	42(5)	0(4)	10(3)	0(3)
C(6)	25(4)	51(5)	46(5)	4(4)	15(4)	4(4)
C(7)	29(4)	41(5)	40(5)	0(4)	16(4)	-4(4)
C(8)	31(4)	40(5)	35(4)	1(4)	14(3)	6(3)
C(9)	41(5)	68(6)	59(6)	21(5)	20(4)	9(5)
C(10)	58(6)	52(6)	102(9)	33(6)	34(6)	12(5)
C(11)	61(6)	51(6)	98(8)	27(6)	32(6)	14(5)
C(12)	45(5)	44(5)	61(6)	0(4)	20(4)	-5(4)
C(13)	64(6)	47(6)	66(7)	-6(5)	39(5)	8(5)
C(14)	115(9)	55(6)	77(7)	-10(6)	55(7)	17(6)
C(21)	25(4)	32(4)	25(4)	1(3)	8(3)	5(3)
C(22)	24(4)	28(4)	27(4)	-6(3)	7(3)	1(3)
C(23)	25(4)	24(4)	29(4)	2(3)	10(3)	1(3)
C(24)	28(4)	26(4)	36(4)	4(3)	18(3)	0(3)
C(25)	26(4)	32(4)	27(4)	2(3)	8(3)	-4(3)
C(26)	39(4)	28(4)	25(4)	4(3)	11(3)	1(3)
C(27)	43(5)	36(5)	46(5)	-9(4)	17(4)	2(4)
C(28)	76(7)	41(5)	67(6)	-20(5)	29(6)	-5(5)
C(29)	92(8)	37(5)	75(7)	1(5)	41(6)	16(6)
C(30)	59(6)	58(6)	60(6)	17(5)	30(5)	36(5)
C(31)	35(4)	37(5)	41(5)	5(4)	12(4)	12(4)
C(32)	39(4)	27(4)	31(4)	1(3)	13(3)	-3(3)
C(33)	39(4)	44(5)	34(4)	2(4)	11(4)	-1(4)
C(34)	41(5)	52(5)	32(5)	6(4)	-3(4)	-7(4)
C(35)	70(7)	56(6)	29(4)	-12(4)	5(5)	-18(5)
C(36)	71(6)	46(5)	38(5)	-11(4)	27(5)	-9(5)
C(37)	45(5)	39(5)	41(5)	-1(4)	21(4)	-2(4)
C(38)	30(4)	27(4)	26(4)	-7(3)	3(3)	-5(3)
C(39)	42(4)	32(4)	35(4)	-2(4)	14(4)	0(4)
C(40)	47(5)	31(4)	47(5)	-4(4)	13(4)	6(4)
C(41)	42(5)	30(4)	37(5)	6(4)	-5(4)	-4(4)

C(42)	36(4)	37(5)	32(4)	4(4)	4(3)	4(4)
C(43)	33(4)	36(4)	31(4)	-7(3)	12(3)	-4(4)
C(44)	37(4)	33(4)	33(4)	-2(4)	8(3)	0(4)
C(45)	46(5)	37(5)	43(5)	-5(4)	6(4)	-9(4)
C(46)	77(7)	47(6)	68(7)	-12(5)	-21(6)	-12(5)
C(47)	73(7)	47(7)	87(9)	-40(6)	-20(6)	-3(6)
C(48)	56(6)	82(8)	40(5)	-32(5)	0(4)	16(6)
C(49)	44(5)	58(6)	43(5)	-7(5)	8(4)	11(4)
C(50)	27(4)	34(4)	26(4)	9(3)	10(3)	5(3)
C(51)	33(4)	42(5)	28(4)	1(4)	8(3)	-1(4)
C(52)	47(5)	48(5)	37(5)	10(4)	10(4)	4(4)
C(53)	43(5)	53(6)	44(5)	9(4)	-13(4)	9(5)
C(54)	30(5)	51(6)	57(6)	1(5)	-15(4)	-1(4)
C(55)	33(4)	38(5)	44(5)	6(4)	7(4)	-2(4)
C(99)	93(9)	83(9)	145(13)	9(8)	78(9)	15(7)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 1.

	x	y	z	U(eq)
H(1A)	6419(5)	12218(7)	11234(4)	57
H(2A)	6743(5)	10520(8)	11349(4)	62
H(4A)	5535(4)	9387(7)	9000(4)	49
H(5A)	4882(4)	10894(6)	8225(4)	43
H(6A)	5071(4)	12616(7)	8873(4)	48
H(9A)	6468(5)	8793(7)	11418(4)	66
H(9B)	7311(5)	8792(7)	11359(4)	66
H(10A)	7106(6)	7018(8)	11330(6)	83
H(10B)	6172(6)	7144(8)	10990(6)	83
H(11A)	6501(6)	6664(8)	10129(6)	83
H(11B)	7283(6)	7364(8)	10380(6)	83
H(12A)	6466(5)	8503(6)	9647(4)	60
H(12B)	5710(5)	8090(6)	9770(4)	60
H(14A)	6157(7)	13511(8)	11213(5)	115
H(14B)	5397(7)	14225(8)	10894(5)	115
H(14C)	6204(7)	14563(8)	10841(5)	115
H(27A)	6199(5)	9071(6)	8308(4)	50
H(28A)	6412(6)	7319(7)	8172(5)	73
H(29A)	7665(7)	6645(8)	8544(5)	78
H(30A)	8731(6)	7768(8)	9043(4)	68
H(31A)	8528(4)	9519(6)	9213(4)	46
H(33A)	5312(4)	11962(6)	7583(4)	47
H(34A)	4662(5)	11630(7)	6487(4)	56
H(35A)	5218(6)	10557(7)	5933(4)	67
H(36A)	6437(6)	9825(7)	6480(4)	60
H(37A)	7117(5)	10161(6)	7578(4)	48
H(39A)	6015(4)	13936(6)	8955(4)	44
H(40A)	5632(5)	15540(6)	8431(4)	52
H(41A)	5850(5)	15888(6)	7485(4)	51
H(42A)	6463(4)	14648(6)	7073(4)	45
H(43A)	6901(4)	13074(6)	7616(3)	40
H(45A)	7849(5)	14099(6)	9185(4)	54
H(46A)	8310(6)	15494(8)	9872(5)	93
H(47A)	8397(6)	15406(8)	10927(6)	101
H(48A)	7986(5)	13906(9)	11300(4)	77
H(49A)	7502(5)	12454(7)	10602(4)	61
H(51A)	7608(4)	9450(6)	10163(3)	42
H(52A)	8592(5)	8820(7)	11098(4)	55
H(53A)	9759(5)	9717(7)	11538(4)	66
H(54A)	9957(5)	11277(7)	11084(4)	66
H(55A)	8957(4)	11940(6)	10169(4)	49
H(99A)	10104(7)	12161(10)	8892(7)	117
H(99B)	9711(7)	13247(10)	8579(7)	117



(+)-**3.13**

Structure solved by Michael Lo.

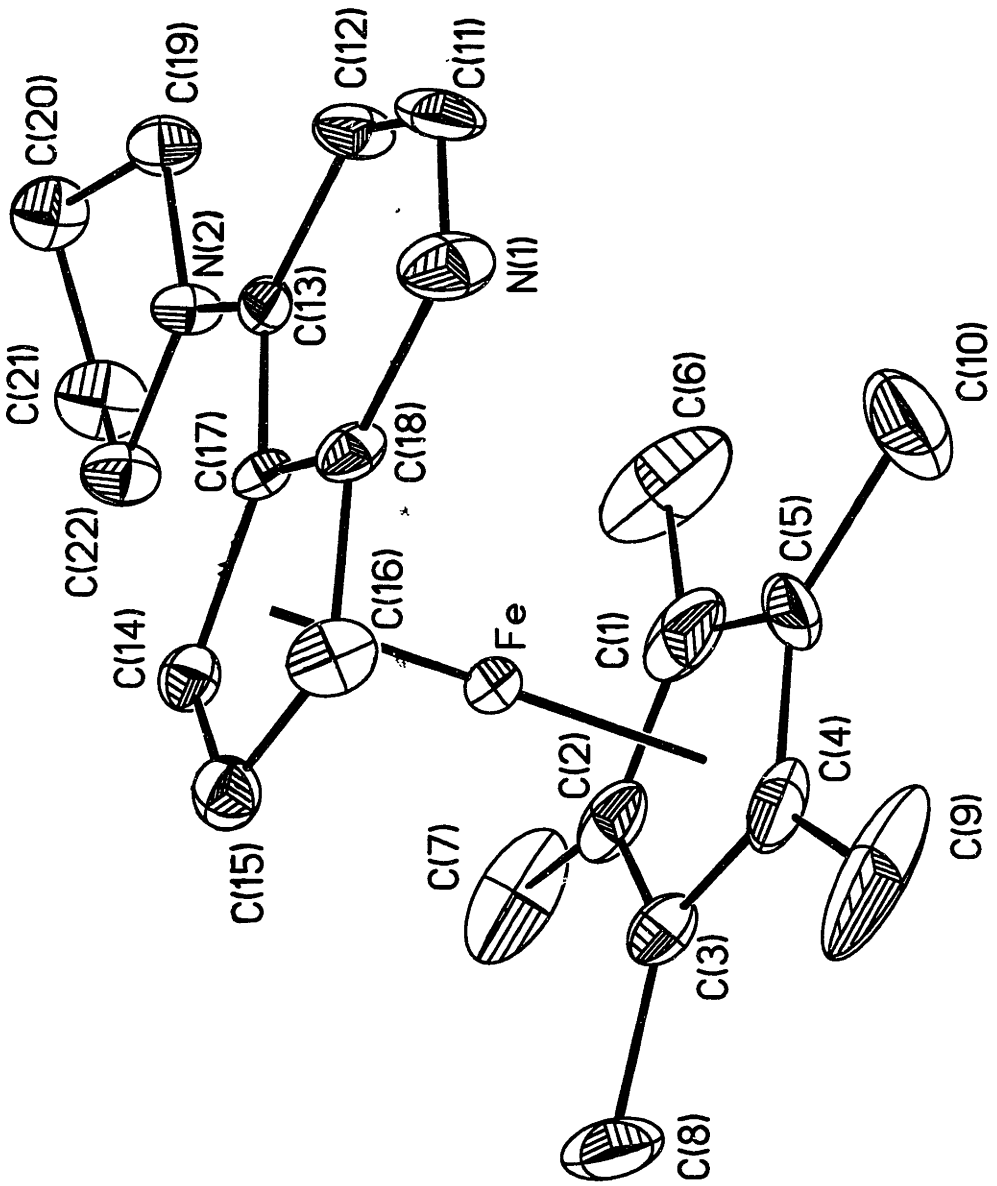

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Table 1. Crystal data and structure refinement for 1.

A. Crystal Data

Identification code	98067
Empirical formula	$C_{22}H_{28}FeN_2$
Formula weight	376.31
Temperature	293(2) K
Wavelength	0.71073 Å
Crystal morphology	irregular block
Crystal size	0.26 x 0.20 x 0.17 mm
Crystal system	Orthorhombic
Space group	$P2_12_12_1$
Unit cell dimensions	a = 7.89550(10) Å alpha = 90° b = 14.21130(10) Å beta = 90° c = 16.7968(3) Å gamma = 90°
Volume, Z	1884.69(4) $Å^3$, 4
Density (calculated)	1.326 Mg/m^3
Absorption coefficient	0.806 mm^{-1}
F(000)	800

B. Data Collection and Reduction

Diffractometer	Siemens SMART/CCD
Scan Type	ω Scans
Scan angle	0.30°
θ range for data collection	1.88 to 23.25°
Limiting indices	$-8 \le h \le 6$, $-15 \le k \le 15$, $-18 \le l \le 17$

Reflections collected	7657
Independent reflections	2698 (R_{int} = 0.0448)
Absorption correction	Semi-empirical from psi-scans
Max. and min. transmission	0.8890 and 0.7527

C. Solution and Refinement

Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	2697 / 0 / 227
Goodness-of-fit on F^2	1.291
Final R indices [I>2σ(I)]	R1 = 0.0533, wR2 = 0.1059
R indices (all data)	R1 = 0.0562, wR2 = 0.1123
Absolute structure parameter	0.02(4)
Extinction coefficient	0.0006(5)
Largest diff. peak and hole	0.250 and -0.509 eÅ^{-3}

Table 2. Atomic coordinates [x 10^4] and equivalent isotropic displacement parameters [$Å^2$ x 10^3] for 98067. U(eq) is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U(eq)
Fe	1358(1)	2877(1)	3142(1)	25(1)
N(1)	138(7)	4647(3)	2201(3)	40(1)
N(2)	1389(6)	2249(3)	785(2)	28(1)
C(1)	3917(7)	2729(7)	3002(4)	63(2)
C(2)	3296(7)	1990(5)	3474(3)	41(2)
C(3)	2488(7)	2390(4)	4145(3)	32(2)
C(4)	2606(9)	3383(4)	4118(4)	47(2)
C(5)	3547(11)	3594(6)	3387(5)	68(3)
C(6)	4855(9)	2653(10)	2222(5)	139(6)
C(7)	3514(11)	964(5)	3311(5)	84(3)
C(8)	1681(9)	1837(5)	4804(3)	54(2)
C(9)	1912(14)	4053(6)	4729(5)	108(4)
C(10)	3987(14)	4583(7)	3124(7)	157(6)
C(11)	912(8)	4674(4)	1504(4)	41(2)
C(12)	1366(9)	3905(3)	1024(3)	33(1)
C(13)	1021(6)	2987(4)	1265(3)	25(1)
C(14)	-378(6)	2121(5)	2508(3)	27(1)
C(15)	-1128(7)	2492(3)	3209(4)	30(1)
C(16)	-1008(7)	3484(4)	3185(4)	35(1)
C(17)	214(6)	2889(4)	2024(3)	23(1)
C(18)	-210(7)	3746(4)	2452(3)	24(1)
C(19)	1953(7)	2351(4)	-45(3)	34(2)
C(20)	1850(8)	1363(4)	-382(3)	44(2)
C(21)	2215(9)	762(5)	326(4)	54(2)
C(22)	1280(9)	1247(4)	1012(3)	40(1)

Table 3. Bond lengths [Å] and angles [°] for 98067.

Fe-C(3)	2.029(5)	Fe-C(15)	2.041(5)
Fe-C(14)	2.042(5)	Fe-C(1)	2.044(6)
Fe-C(4)	2.044(6)	Fe-C(5)	2.048(7)
Fe-C(2)	2.060(6)	Fe-C(16)	2.059(5)
Fe-C(17)	2.083(4)	Fe-C(18)	2.097(5)
N(1)-C(11)	1.321(7)	N(1)-C(18)	1.375(7)
N(2)-C(13)	1.354(6)	N(2)-C(19)	1.471(6)
N(2)-C(22)	1.477(6)	C(1)-C(2)	1.403(10)
C(1)-C(5)	1.420(11)	C(1)-C(6)	1.510(10)
C(2)-C(3)	1.415(8)	C(2)-C(7)	1.494(9)
C(3)-C(4)	1.416(7)	C(3)-C(8)	1.498(8)
C(4)-C(5)	1.466(11)	C(4)-C(9)	1.503(10)
C(5)-C(10)	1.514(10)	C(11)-C(12)	1.404(8)
C(12)-C(13)	1.392(7)	C(13)-C(17)	1.433(6)
C(14)-C(15)	1.419(7)	C(14)-C(17)	1.439(8)
C(15)-C(16)	1.414(7)	C(16)-C(18)	1.433(8)
C(17)-C(18)	1.452(7)	C(19)-C(20)	1.516(8)
C(20)-C(21)	1.493(9)	C(21)-C(22)	1.532(8)

C(3)-Fe-C(15)	106.6(2)	C(3)-Fe-C(14)	123.2(2)
C(15)-Fe-C(14)	40.7(2)	C(3)-Fe-C(1)	68.0(2)
C(15)-Fe-C(1)	158.3(3)	C(14)-Fe-C(1)	123.3(3)
C(3)-Fe-C(4)	40.7(2)	C(15)-Fe-C(4)	120.9(3)
C(14)-Fe-C(4)	158.0(2)	C(1)-Fe-C(4)	69.6(3)
C(3)-Fe-C(5)	68.4(2)	C(15)-Fe-C(5)	159.1(3)
C(14)-Fe-C(5)	159.0(3)	C(1)-Fe-C(5)	40.6(3)
C(4)-Fe-C(5)	42.0(3)	C(3)-Fe-C(2)	40.5(2)
C(15)-Fe-C(2)	122.4(3)	C(14)-Fe-C(2)	108.5(2)
C(1)-Fe-C(2)	40.0(3)	C(4)-Fe-C(2)	68.9(3)
C(5)-Fe-C(2)	67.9(3)	C(3)-Fe-C(16)	120.8(2)
C(15)-Fe-C(16)	40.3(2)	C(14)-Fe-C(16)	68.3(2)
C(1)-Fe-C(16)	160.7(3)	C(4)-Fe-C(16)	105.2(3)
C(5)-Fe-C(16)	123.4(3)	C(2)-Fe-C(16)	157.1(2)
C(3)-Fe-C(17)	160.4(2)	C(15)-Fe-C(17)	68.6(2)
C(14)-Fe-C(17)	40.8(2)	C(1)-Fe-C(17)	109.0(2)
C(4)-Fe-C(17)	158.3(2)	C(5)-Fe-C(17)	122.9(2)
C(2)-Fe-C(17)	124.8(2)	C(16)-Fe-C(17)	68.6(2)
C(3)-Fe-C(18)	156.9(2)	C(15)-Fe-C(18)	67.7(2)
C(14)-Fe-C(18)	68.0(2)	C(1)-Fe-C(18)	125.5(3)
C(4)-Fe-C(18)	121.4(2)	C(5)-Fe-C(18)	108.4(3)
C(2)-Fe-C(18)	161.5(2)	C(16)-Fe-C(18)	40.3(2)
C(17)-Fe-C(18)	40.6(2)	C(11)-N(1)-C(18)	113.0(5)
C(13)-N(2)-C(19)	123.5(4)	C(13)-N(2)-C(22)	125.6(4)
C(19)-N(2)-C(22)	110.9(4)	C(2)-C(1)-C(5)	108.6(6)
C(2)-C(1)-C(6)	127.5(9)	C(5)-C(1)-C(6)	123.9(9)
C(2)-C(1)-Fe	70.6(3)	C(5)-C(1)-Fe	69.8(4)
C(6)-C(1)-Fe	126.3(4)	C(1)-C(2)-C(3)	107.9(6)
C(1)-C(2)-C(7)	125.9(7)	C(3)-C(2)-C(7)	126.1(7)
C(1)-C(2)-Fe	69.4(4)	C(3)-C(2)-Fe	68.6(3)
C(7)-C(2)-Fe	129.3(5)	C(2)-C(3)-C(4)	110.1(6)
C(2)-C(3)-C(8)	124.8(6)	C(4)-C(3)-C(8)	125.1(6)
C(2)-C(3)-Fe	70.9(3)	C(4)-C(3)-Fe	70.2(4)
C(8)-C(3)-Fe	127.2(4)	C(3)-C(4)-C(5)	105.3(6)
C(3)-C(4)-C(9)	125.8(8)	C(5)-C(4)-C(9)	128.8(7)
C(3)-C(4)-Fe	69.1(4)	C(5)-C(4)-Fe	69.2(4)

C(9)-C(4)-Fe	126.5(5)	C(1)-C(5)-C(4)	108.0(6)
C(1)-C(5)-C(10)	128.6(9)	C(4)-C(5)-C(10)	123.4(9)
C(1)-C(5)-Fe	69.6(4)	C(4)-C(5)-Fe	68.9(4)
C(10)-C(5)-Fe	126.6(6)	N(1)-C(11)-C(12)	127.1(5)
C(13)-C(12)-C(11)	120.8(5)	N(2)-C(13)-C(12)	120.7(4)
N(2)-C(13)-C(17)	123.3(5)	C(12)-C(13)-C(17)	115.9(5)
C(15)-C(14)-C(17)	108.7(5)	C(15)-C(14)-Fe	69.6(3)
C(17)-C(14)-Fe	71.1(3)	C(16)-C(15)-C(14)	108.7(6)
C(16)-C(15)-Fe	70.5(3)	C(14)-C(15)-Fe	69.7(3)
C(15)-C(16)-C(18)	108.2(6)	C(15)-C(16)-Fe	69.1(3)
C(18)-C(16)-Fe	71.3(3)	C(13)-C(17)-C(14)	136.1(5)
C(13)-C(17)-C(18)	117.4(5)	C(14)-C(17)-C(18)	106.4(4)
C(13)-C(17)-Fe	127.6(3)	C(14)-C(17)-Fe	68.0(3)
C(18)-C(17)-Fe	70.2(3)	N(1)-C(18)-C(16)	126.3(5)
N(1)-C(18)-C(17)	125.7(5)	C(16)-C(18)-C(17)	108.0(4)
N(1)-C(18)-Fe	126.8(4)	C(16)-C(18)-Fe	68.4(3)
C(17)-C(18)-Fe	69.1(3)	N(2)-C(19)-C(20)	104.3(4)
C(21)-C(20)-C(19)	102.8(5)	C(20)-C(21)-C(22)	104.4(5)
N(2)-C(22)-C(21)	102.2(4)		

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters [$Å^2$ x 10^3] for 98067.

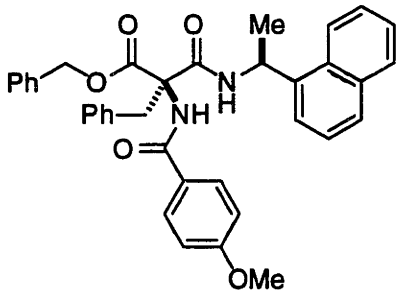
The anisotropic displacement factor exponent takes the form:

$-2\pi^2 [(ha^*)^2 U_{11} + ... + 2hka^*b^* U_{12}]$

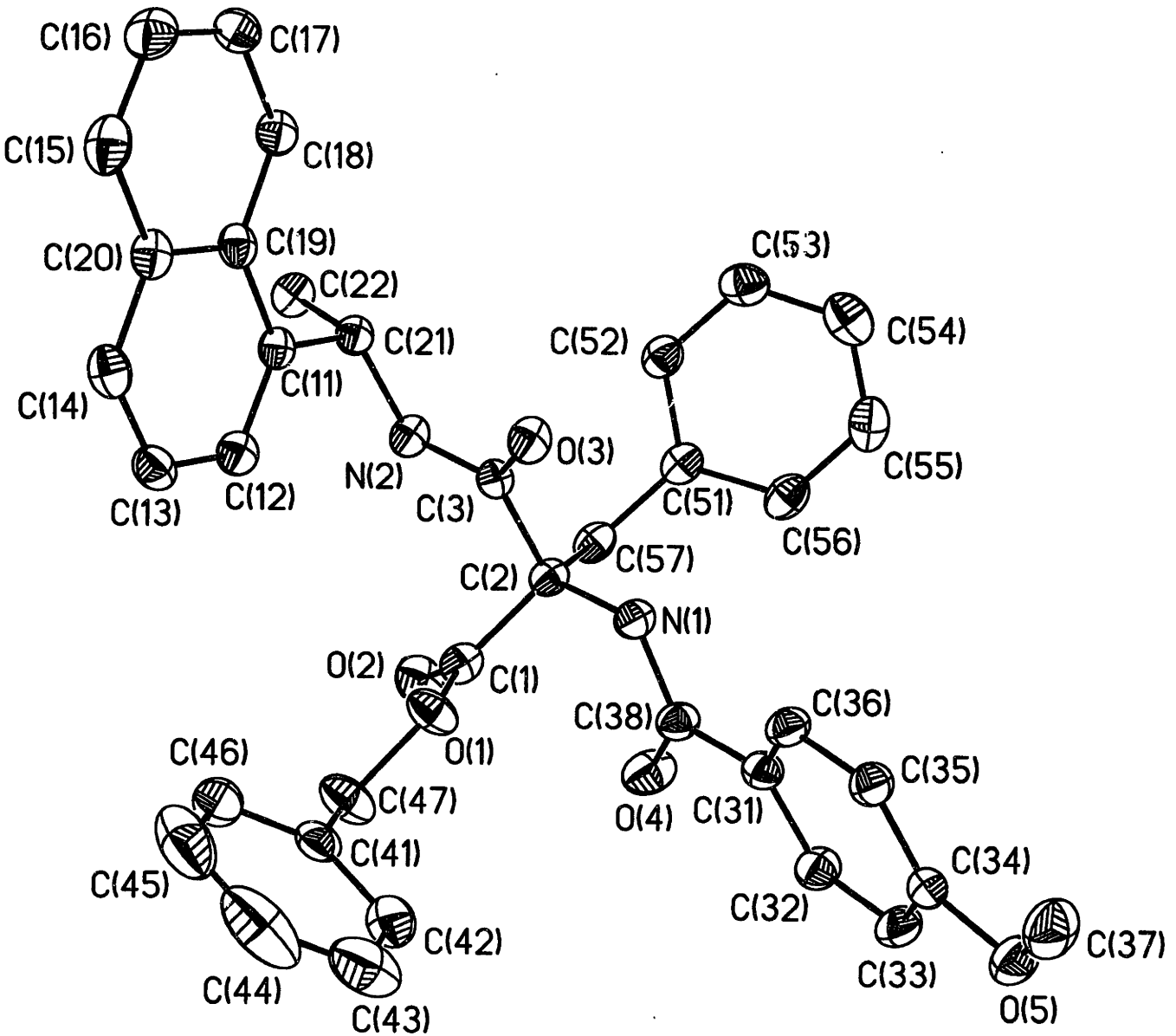
	U11	U22	U33	U23	U13	U12
Fe	27(1)	27(1)	22(1)	4(1)	-5(1)	-4(1)
N(1)	61(4)	23(3)	36(3)	6(2)	-3(3)	9(2)
N(2)	38(2)	24(2)	23(2)	4(2)	5(2)	2(3)
C(1)	23(3)	127(7)	40(4)	7(5)	-10(3)	-4(4)
C(2)	25(3)	65(5)	32(3)	-4(3)	-9(2)	10(3)
C(3)	30(3)	37(4)	29(3)	1(3)	-10(3)	8(3)
C(4)	58(5)	36(4)	46(4)	-5(3)	-33(4)	-2(3)
C(5)	55(5)	73(5)	77(6)	41(4)	-42(5)	-47(5)
C(6)	28(4)	334(19)	55(5)	51(8)	10(4)	-8(7)
C(7)	87(6)	80(5)	85(6)	-43(5)	-40(6)	68(5)
C(8)	58(5)	70(5)	33(3)	24(3)	-3(3)	4(4)
C(9)	158(10)	72(6)	94(7)	-54(5)	-91(7)	49(6)
C(10)	148(10)	136(9)	187(12)	98(9)	-110(10)	-112(8)
C(11)	60(5)	24(3)	38(3)	16(3)	1(3)	-7(3)
C(12)	49(3)	27(3)	22(3)	4(2)	9(3)	-3(3)
C(13)	26(3)	21(3)	28(3)	2(2)	-8(2)	-2(3)
C(14)	25(3)	28(3)	28(3)	0(3)	-4(2)	3(3)
C(15)	25(3)	37(3)	29(3)	-2(2)	2(3)	-1(2)
C(16)	40(4)	34(3)	30(3)	-1(3)	2(3)	10(3)
C(17)	25(2)	25(3)	20(3)	7(3)	-8(2)	0(3)
C(18)	33(3)	19(3)	21(3)	1(2)	-6(2)	7(3)
C(19)	37(3)	37(4)	27(3)	3(3)	8(2)	3(2)
C(20)	51(4)	47(4)	34(3)	-8(3)	7(3)	3(3)
C(21)	64(5)	49(4)	48(4)	-9(3)	19(4)	12(4)
C(22)	50(4)	36(3)	33(3)	2(3)	7(3)	1(4)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 98067.

	x	y	z	U(eq)
H(6A)	5125(9)	3272(10)	2031(5)	209
H(6B)	4156(9)	2337(10)	1839(5)	209
H(6C)	5881(9)	2303(10)	2299(5)	209
H(7A)	2973(11)	606(5)	3724(5)	126
H(7B)	4699(11)	814(5)	3298(5)	126
H(7C)	3011(11)	812(5)	2807(5)	126
H(8A)	1217(9)	2262(5)	5191(3)	80
H(8B)	2517(9)	1444(5)	5052(3)	80
H(8C)	792(9)	1452(5)	4590(3)	80
H(9A)	2161(14)	4688(6)	4573(5)	162
H(9B)	2424(14)	3926(6)	5236(5)	162
H(9C)	708(14)	3973(6)	4769(5)	162
H(10A)	3571(14)	5026(7)	3509(7)	236
H(10B)	3474(14)	4708(7)	2617(7)	236
H(10C)	5194(14)	4644(7)	3080(7)	236
H(11A)	1187(8)	5267(4)	1310(4)	49
H(12A)	1903(9)	4010(3)	539(3)	39
H(14A)	-288(6)	1451(5)	2374(3)	32
H(15A)	-1642(7)	2122(3)	3637(4)	36
H(16A)	-1415(7)	3919(4)	3596(4)	42
H(19A)	3104(7)	2588(4)	-69(3)	40
H(19B)	1217(7)	2776(4)	-336(3)	40
H(20A)	732(8)	1234(4)	-596(3)	53
H(20B)	2687(8)	1267(4)	-798(3)	53
H(21A)	3422(9)	734(5)	430(4)	64
H(21B)	1794(9)	127(5)	247(4)	64
H(22A)	112(9)	1039(4)	1044(3)	48
H(22B)	1836(9)	1130(4)	1517(3)	48



Structure solved by Michael Lo.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C(43)
O(5)

Table 1. Crystal data and structure refinement for 98166.

A. Crystal Data

Identification code	98166
Empirical formula	$C_{37}H_{34}N_2O_5$
Formula weight	586.66
Temperature	185(2) K
Wavelength	0.71073 Å
Crystal morphology	block
Crystal size	0.15 x 0.24 x 0.51 mm
Crystal system	Monoclinic
Space group	$P2_1$
Unit cell dimensions	a = 11.9260(7) Å alpha = 90°
	b = 11.6175(6) Å beta = 116.3320(10)°
	c = 12.8071(7) Å gamma = 90°
Volume, Z	1590.3(2) $Å^3$, 2
Density (calculated)	1.225 Mg/m^3
Absorption coefficient	0.082 mm^{-1}
F(000)	620

B. Data Collection and Reduction

Diffractometer	Siemens SMART/CCD
Scan Type	ω Scans
Scan angle	0.30°
θ range for data collection	1.77 to 23.24°
Limiting indices	$-13 \le h \le 13$, $-12 \le k \le 11$, $-14 \le l \le 12$

Reflections collected	6460
Independent reflections	3781 (R_{int} = 0.0342)
Absorption correction	None

C. Solution and Refinement

Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	3778 / 1 / 398
Goodness-of-fit on F^2	0.999
Final R indices [I>2σ(I)]	R1 = 0.0332, wR2 = 0.0907
R indices (all data)	R1 = 0.0407, wR2 = 0.1131
Absolute structure parameter	-1.2(11)
Extinction coefficient	0.035(3)
Largest diff. peak and hole	0.159 and -0.163 $eÅ^{-3}$

Table 2. Atomic coordinates [x 10^4] and equivalent isotropic displacement parameters [$Å^2$ x 10^3] for 98166. U(eq) is defined as one third of the trace of the orthogonalized U_{ij} tensor.

	x	y	z	U(eq)
O(1)	761(2)	4464(2)	-379(1)	51(1)
O(2)	2565(2)	5259(2)	908(1)	46(1)
O(3)	3137(2)	3385(2)	3252(1)	38(1)
O(4)	474(2)	6497(2)	1208(1)	53(1)
O(5)	3078(2)	10141(2)	5211(2)	48(1)
N(1)	1742(2)	5236(2)	2542(2)	34(1)
N(2)	2193(2)	2414(2)	1557(2)	33(1)
C(1)	1485(2)	4699(2)	604(2)	37(1)
C(2)	1373(2)	4308(2)	1696(2)	32(1)
C(3)	2325(2)	3330(2)	2248(2)	30(1)
C(11)	4306(2)	1560(2)	2193(2)	29(1)
C(12)	4638(2)	2440(2)	1675(2)	35(1)
C(13)	5873(2)	2563(2)	1823(2)	38(1)
C(14)	6772(2)	1806(2)	2482(2)	38(1)
C(15)	7417(2)	93(3)	3773(2)	45(1)
C(16)	7141(3)	-774(3)	4334(2)	48(1)
C(17)	5910(2)	-910(2)	4202(2)	41(1)
C(18)	4992(2)	-165(2)	3517(2)	35(1)
C(19)	5244(2)	759(2)	2914(2)	32(1)
C(20)	6488(2)	884(2)	3052(2)	34(1)
C(21)	2960(2)	1383(2)	1997(2)	31(1)
C(22)	2325(2)	403(2)	1148(2)	39(1)
C(31)	1793(2)	7257(2)	3085(2)	34(1)
C(32)	1188(2)	8312(2)	2793(2)	41(1)
C(33)	1629(3)	9243(2)	3527(2)	44(1)
C(34)	2707(2)	9148(2)	4570(2)	35(1)
C(35)	3328(2)	8107(2)	4890(2)	36(1)
C(36)	2861(2)	7168(2)	4142(2)	37(1)
C(37)	4209(3)	10122(3)	6267(2)	57(1)
C(38)	1284(2)	6310(2)	2214(2)	37(1)
C(41)	4080(3)	6210(2)	504(2)	41(1)
C(42)	4284(3)	7290(3)	1008(2)	57(1)
C(43)	5469(4)	7762(4)	1525(3)	77(1)
C(44)	6447(4)	7157(5)	1549(3)	91(2)
C(45)	6273(4)	6078(5)	1066(3)	82(1)
C(46)	5087(3)	5607(3)	539(2)	56(1)
C(47)	2807(3)	5699(3)	-41(2)	57(1)
C(51)	-118(2)	3528(2)	2450(2)	36(1)
C(52)	257(2)	2453(2)	2971(2)	40(1)
C(53)	177(2)	2173(3)	3984(2)	48(1)
C(54)	-314(2)	2951(3)	4486(2)	53(1)
C(55)	-705(3)	4001(3)	3983(3)	53(1)
C(56)	-601(2)	4304(3)	2978(2)	46(1)
C(57)	28(2)	3872(2)	1382(2)	37(1)

Table 3. Bond lengths [Å] and angles [°] for 98166.

O(1)-C(1)	1.200(3)	O(2)-C(1)	1.337(3)
O(2)-C(47)	1.460(3)	O(3)-C(3)	1.220(3)
O(4)-C(38)	1.239(3)	O(5)-C(34)	1.371(3)
O(5)-C(37)	1.426(3)	N(1)-C(38)	1.352(3)
N(1)-C(2)	1.451(3)	N(2)-C(3)	1.348(3)
N(2)-C(21)	1.460(3)	C(1)-C(2)	1.532(3)
C(2)-C(3)	1.539(3)	C(2)-C(57)	1.556(3)
C(11)-C(12)	1.369(3)	C(11)-C(19)	1.434(3)
C(11)-C(21)	1.524(3)	C(12)-C(13)	1.406(3)
C(13)-C(14)	1.354(3)	C(14)-C(20)	1.419(3)
C(15)-C(16)	1.360(4)	C(15)-C(20)	1.420(4)
C(16)-C(17)	1.410(4)	C(17)-C(18)	1.366(3)
C(18)-C(19)	1.430(3)	C(19)-C(20)	1.422(3)
C(21)-C(22)	1.523(3)	C(31)-C(32)	1.387(3)
C(31)-C(36)	1.391(3)	C(31)-C(38)	1.491(4)
C(32)-C(33)	1.376(4)	C(33)-C(34)	1.388(4)
C(34)-C(35)	1.382(3)	C(35)-C(36)	1.394(3)
C(41)-C(46)	1.374(4)	C(41)-C(42)	1.382(4)
C(41)-C(47)	1.485(4)	C(42)-C(43)	1.380(5)
C(43)-C(44)	1.350(6)	C(44)-C(45)	1.372(6)
C(45)-C(46)	1.381(5)	C(51)-C(56)	1.396(4)
C(51)-C(52)	1.394(4)	C(51)-C(57)	1.507(4)
C(52)-C(53)	1.380(4)	C(53)-C(54)	1.381(4)
C(54)-C(55)	1.361(4)	C(55)-C(56)	1.392(4)

C(1)-O(2)-C(47)	116.6(2)	C(34)-O(5)-C(37)	118.2(2)
C(38)-N(1)-C(2)	120.4(2)	C(3)-N(2)-C(21)	121.5(2)
O(1)-C(1)-O(2)	124.6(2)	O(1)-C(1)-C(2)	125.2(2)
O(2)-C(1)-C(2)	109.9(2)	N(1)-C(2)-C(1)	109.9(2)
N(1)-C(2)-C(3)	106.7(2)	C(1)-C(2)-C(3)	107.0(2)
N(1)-C(2)-C(57)	111.8(2)	C(1)-C(2)-C(57)	111.0(2)
C(3)-C(2)-C(57)	110.1(2)	O(3)-C(3)-N(2)	122.7(2)
O(3)-C(3)-C(2)	121.6(2)	N(2)-C(3)-C(2)	115.7(2)
C(12)-C(11)-C(19)	119.1(2)	C(12)-C(11)-C(21)	122.1(2)
C(19)-C(11)-C(21)	118.8(2)	C(11)-C(12)-C(13)	121.4(2)
C(14)-C(13)-C(12)	120.7(2)	C(13)-C(14)-C(20)	120.4(2)
C(16)-C(15)-C(20)	121.4(2)	C(15)-C(16)-C(17)	120.2(2)
C(18)-C(17)-C(16)	120.1(2)	C(17)-C(18)-C(19)	121.5(2)
C(20)-C(19)-C(18)	117.9(2)	C(20)-C(19)-C(11)	119.1(2)
C(18)-C(19)-C(11)	123.0(2)	C(14)-C(20)-C(15)	121.8(2)
C(14)-C(20)-C(19)	119.2(2)	C(15)-C(20)-C(19)	119.0(2)
N(2)-C(21)-C(22)	108.0(2)	N(2)-C(21)-C(11)	112.7(2)
C(22)-C(21)-C(11)	111.9(2)	C(32)-C(31)-C(36)	118.1(2)
C(32)-C(31)-C(38)	117.3(2)	C(36)-C(31)-C(38)	124.5(2)
C(33)-C(32)-C(31)	121.0(2)	C(32)-C(33)-C(34)	120.3(2)
O(5)-C(34)-C(35)	124.8(2)	O(5)-C(34)-C(33)	115.1(2)
C(35)-C(34)-C(33)	120.1(2)	C(34)-C(35)-C(36)	118.9(2)
C(31)-C(36)-C(35)	121.6(2)	O(4)-C(38)-N(1)	120.4(2)
O(4)-C(38)-C(31)	121.3(2)	N(1)-C(38)-C(31)	118.3(2)
C(46)-C(41)-C(42)	118.5(3)	C(46)-C(41)-C(47)	120.6(3)
C(42)-C(41)-C(47)	121.0(3)	C(43)-C(42)-C(41)	121.1(3)
C(44)-C(43)-C(42)	119.6(4)	C(43)-C(44)-C(45)	120.6(4)
C(44)-C(45)-C(46)	119.9(4)	C(41)-C(46)-C(45)	120.3(3)
O(2)-C(47)-C(41)	106.7(2)	C(56)-C(51)-C(52)	117.4(2)
C(56)-C(51)-C(57)	120.5(2)	C(52)-C(51)-C(57)	122.1(2)

C(53)-C(52)-C(51)	121.3(2)	C(54)-C(53)-C(52)	120.3(3)
C(55)-C(54)-C(53)	119.6(3)	C(54)-C(55)-C(56)	120.8(3)
C(55)-C(56)-C(51)	120.7(3)	C(51)-C(57)-C(2)	111.9(2)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters [$Å^2$ x 10^3] for 98166.
The anisotropic displacement factor exponent takes the form:
$-2\pi^2$ [$(ha^*)^2U_{11}$ + ... + $2hka^*b^*U_{12}$]

	U11	U22	U33	U23	U13	U12
O(1)	53(1)	60(1)	29(1)	-6(1)	9(1)	-7(1)
O(2)	50(1)	57(1)	29(1)	2(1)	14(1)	-14(1)
O(3)	34(1)	44(1)	27(1)	-5(1)	5(1)	2(1)
O(4)	60(1)	42(1)	35(1)	1(1)	1(1)	6(1)
O(5)	60(1)	35(1)	44(1)	-8(1)	20(1)	-2(1)
N(1)	38(1)	31(1)	27(1)	-1(1)	9(1)	2(1)
N(2)	29(1)	36(1)	26(1)	-5(1)	5(1)	2(1)
C(1)	36(1)	34(2)	32(1)	-3(1)	7(1)	1(1)
C(2)	32(1)	30(1)	29(1)	-1(1)	8(1)	2(1)
C(3)	29(1)	33(2)	28(1)	-2(1)	12(1)	-2(1)
C(11)	27(1)	33(2)	26(1)	-5(1)	10(1)	-1(1)
C(12)	34(1)	39(2)	28(1)	-2(1)	10(1)	2(1)
C(13)	41(2)	39(2)	37(1)	-2(1)	22(1)	-7(1)
C(14)	30(1)	50(2)	37(1)	-8(1)	16(1)	-9(1)
C(15)	27(1)	60(2)	42(1)	-9(1)	11(1)	3(1)
C(16)	38(2)	58(2)	39(1)	6(1)	8(1)	14(1)
C(17)	45(2)	46(2)	30(1)	4(1)	14(1)	5(1)
C(18)	32(1)	43(2)	28(1)	-1(1)	10(1)	3(1)
C(19)	31(1)	40(2)	25(1)	-4(1)	11(1)	1(1)
C(20)	27(1)	44(2)	27(1)	-7(1)	8(1)	0(1)
C(21)	30(1)	35(1)	26(1)	0(1)	10(1)	2(1)
C(22)	34(1)	39(2)	40(1)	-6(1)	12(1)	-4(1)
C(31)	40(1)	32(2)	29(1)	4(1)	14(1)	3(1)
C(32)	45(2)	39(2)	31(1)	5(1)	10(1)	9(1)
C(33)	56(2)	31(2)	42(1)	6(1)	20(1)	11(1)
C(34)	47(2)	30(2)	35(1)	-1(1)	24(1)	-2(1)
C(35)	40(1)	33(2)	32(1)	0(1)	14(1)	2(1)
C(36)	41(1)	29(2)	37(1)	3(1)	15(1)	6(1)
C(37)	68(2)	48(2)	47(2)	-14(1)	18(2)	-7(2)
C(38)	41(1)	32(2)	32(1)	3(1)	11(1)	3(1)
C(41)	58(2)	40(2)	29(1)	5(1)	23(1)	-3(1)
C(42)	79(2)	51(2)	49(2)	-2(2)	37(2)	-2(2)
C(43)	111(3)	74(3)	45(2)	-13(2)	34(2)	-44(3)
C(44)	71(3)	149(5)	52(2)	3(3)	25(2)	-46(3)
C(45)	67(2)	130(4)	59(2)	33(3)	37(2)	25(3)
C(46)	75(2)	53(2)	44(2)	12(1)	32(2)	15(2)
C(47)	68(2)	68(2)	35(1)	6(1)	23(1)	-15(2)
C(51)	24(1)	37(2)	44(1)	-3(1)	10(1)	-1(1)
C(52)	34(1)	37(2)	52(2)	-1(1)	21(1)	0(1)
C(53)	40(2)	44(2)	60(2)	7(1)	24(1)	-4(1)
C(54)	43(2)	68(2)	49(2)	-4(2)	21(1)	-18(2)
C(55)	50(2)	57(2)	62(2)	-20(2)	33(2)	-12(2)
C(56)	35(2)	41(2)	59(2)	-5(1)	18(1)	3(1)
C(57)	29(1)	35(2)	40(1)	-2(1)	7(1)	5(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x 10^3) for 98166.

	x	y	z	U(eq)
H(1A)	2267(2)	5099(2)	3273(2)	41
H(2A)	1631(2)	2438(2)	823(2)	40
H(12A)	4021(2)	2978(2)	1205(2)	42
H(13A)	6078(2)	3184(2)	1456(2)	45
H(14A)	7599(2)	1894(2)	2565(2)	46
H(15A)	8248(2)	172(3)	3865(2)	53
H(16A)	7780(3)	-1289(3)	4816(2)	58
H(17A)	5720(2)	-1521(2)	4590(2)	50
H(18A)	4168(2)	-262(2)	3440(2)	42
H(21A)	2977(2)	1179(2)	2762(2)	37
H(22A)	1464(2)	317(2)	1044(2)	59
H(22B)	2786(2)	-314(2)	1459(2)	59
H(22C)	2316(2)	577(2)	396(2)	59
H(32A)	458(2)	8392(2)	2075(2)	49
H(33A)	1193(3)	9955(2)	3319(2)	52
H(35A)	4060(2)	8032(2)	5607(2)	43
H(36A)	3284(2)	6450(2)	4359(2)	44
H(37A)	4359(3)	10884(3)	6632(2)	85
H(37B)	4908(3)	9917(3)	6096(2)	85
H(37C)	4139(3)	9551(3)	6798(2)	85
H(42A)	3599(3)	7714(3)	999(2)	68
H(43A)	5595(4)	8509(4)	1861(3)	92
H(44A)	7262(4)	7481(5)	1905(3)	110
H(45A)	6968(4)	5656(5)	1093(3)	99
H(46A)	4968(3)	4862(3)	200(2)	67
H(47A)	2179(3)	6289(3)	-491(2)	69
H(47B)	2765(3)	5067(3)	-575(2)	69
H(52A)	574(2)	1901(2)	2623(2)	48
H(53A)	462(2)	1443(3)	4337(2)	57
H(54A)	-379(2)	2755(3)	5177(2)	64
H(55A)	-1053(3)	4533(3)	4322(3)	64
H(56A)	-861(2)	5047(3)	2649(2)	55
H(57A)	-581(2)	4487(2)	964(2)	45
H(57B)	-162(2)	3202(2)	853(2)	45

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