Nickel-Catalyzed Asymmetric Arylations of α-Halocarbonyl Compounds
and
Studies of Boratabenzene-Containing Transition Metal Complexes

by

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Submitted to the Department of Chemistry on Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY IN ORGANIC CHEMISTRY
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September 2010

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Nickel-Catalyzed Asymmetric Arylations of α-Halocarbonyl Compounds and Studies of Boratabenzene-Containing Transition Metal Complexes

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Submitted to the Department of Chemistry on August 26, 2010
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ABSTRACT

Chapter 1 begins with a review of the current literature on cross-coupling methods to generate α-arylcarbonyl compounds, with a special emphasis on asymmetric arylations. The second section of chapter 1 describes the development of an asymmetric Negishi arylation of α-bromoketones using a nickel/pybox catalyst. The third section details the development of a Suzuki arylation of α-bromo- and α-chloroamides using aryl-(9-BBN) reagents. Both of these cross-coupling procedures are stereoconvergent, as they convert the racemic starting electrophile to an enantioenriched product.

Chapter 2 describes new studies into the chemistry of boratabenzene-containing transition-metal complexes. In particular, a new method for preparing complexes bearing a diphenylphosphidoboratabenzene ligand is disclosed, starting from a transition metal–diphenylphosphide and a boracycle, which is an intermediate in the synthetic route previously used in the preparation of these complexes. In addition, the preparation and characterization of a new, tri-ortho-substituted variant of potassium diphenylphosphidoboratabenzene is described. This new species is used as a ligand in an iron complex, which is characterized. In addition, preliminary studies towards the synthesis of palladium complex bearing this new ligand are disclosed.

Thesis Supervisor: Gregory C. Fu
Title: Firmenich Professor of Chemistry

Preface

Portions of this thesis have appeared in the previous publications:

"Catalytic Asymmetric Cross-Couplings of Racemic α-Bromoketones with Arylzinc Reagents"
Lundin, P. M.; Esquivias, J.; Fu, G. C. *Angew. Chem., Int. Ed.* **2009**, *48*, 154–156.

"Asymmetric Suzuki Cross-Couplings of Activated Secondary Alkyl Electrophiles: Arylations of Racemic α–Chloroamides"
Lundin, P. M.; Fu, G. C. *J. Am. Chem. Soc.* **2010**, *132*, 11027–11029.

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There are many people whom I wish to thank for their encouragement and support in my pursuit of my PhD degree.

First, many thanks to Greg. I am very fortunate to have had the opportunity to work in your lab on interesting projects and to be surrounded by other people doing great chemistry. I don't think I could have picked a lab better suited for my goals for graduate school, and for that I am grateful. Your scientific integrity and dedication to the research in our lab is great model to aspire to as a researcher. Furthermore, I appreciate your willingness to make time for me whenever I've need to chat about my projects or my career goals and everything in between. I've usually walked out of your office feeling better than when I walked in, and I feel fortunate to have had a research advisor who has taken the word "advisor" to heart.

Second, I would like to thank Prof. Maurice Brookhart, my undergraduate research advisor. His belief in me and what I could achieve was something that I held onto during my graduate career, especially when I was having doubts. Undoubtedly, his invitation to talk about his research group was a pivotal moment in my undergraduate career. Little did I know what a great group I was being invited to join. Another pivotal moment was when he told me that I needed to go to the best graduate school possible. If we had not had that conversation, I would never have considered applying to MIT. On my visits home to NC, his door is always open and he's always had plenty of encouraging words. Without a doubt, I lucked out in starting my research career under his guidance.

I've benefited from the tutelage of many great mentors over the years. In Brook's lab, Alison Cartwright Sykes had so much patience with me, and was always willing to take time to fix a glovebox that was wigging out, go over NMR spectra with me, help me find potential subjects for class projects-- really anything that would crop up. Amy Roy MacArthur was also always willing to answer my questions with an infinite amount of patience.

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Thanks to Jorge Esquivias, from whom I took over the Negishi project. His organization really made that transition to the project much easier than it could have been, and I appreciate his continued enthusiasm and support after he had left.

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The number of colleagues from whom I have learned much about chemistry, both in the abstract and in practice, is too large for me to name everyone, but a few people do deserve special mention. Jackie Murphy's knowledge of inorganic techniques has been priceless, and she has always been willing to help out without a hint of hesitation or irritation, even when I have asked the question three times already. Xing Dai's advice on organic technique was equally valuable, as well as his advice on life. My benefit from being his benchmate during my second and third years is immeasurable. Neil Strotman, Bunnai Saito and Sha Lou were also incredibly helpful resources for me, and I thank them. Thanks as well to Sunghee Son for being a great role model of a positive graduate student, and to her, Jacob Berlin, and Catharine Larsen for being there to help me take a

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Lastly, I could not possibly be where I am today without my family. I couldn't have asked for more supportive parents who always remind me of how loved I am, often going above and beyond the call of duty. Thank you for the phone calls, the care packages, the flowers, and the unwavering confidence in my abilities. My grandparents have been great role models in what it means to be good people, and the pride they have taken in my accomplishments has been inspirational. My brother David and my sister Karen have made sure all this love and pride hasn't gone to my head, and they have also stepped in with many a comic strip, wall post, and obscure movie (and Stan Freberg) quote to keep me laughing. I am also the fortunate beneficiary of a large network of aunts, uncles, cousins, great-aunts, great-uncles, etc. who have always been there for me with visits, heart-to-heart talks, encouraging emails, and love. Even though we've been far apart, you've meant the world to me.

To close, as someone who has found inspiration from the acknowledgments pages of former group members who had successfully made it, I'd like to offer these words to anyone finding themselves in a similar situation. The path through graduate school is not easy and not graceful, and it's easy to get bogged done with the frustration inherent in life in the lab. Don't forget to take a breather once in a while—go for a walk, get some exercise, clear your head. You aren't alone; between the lines of the theses on these shelves are the stories of people who have been there, too. If I can do it, so can you.

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Chapter 1

Cross-Coupling Strategies for the Asymmetric Arylation of α-Halocarbonyl Compounds

Section 1.1

Precedents for α-Arylation of Carbonyl Compounds

A: Introduction

α-Aryl carbonyl compounds are an important class of molecules due to their interesting biological properties. The subclass of α-aryl carboxylic acids are particularly well-known due to their use as non-steroidal anti-inflammatory agents, including naproxen and ibuprofen.[1] Other examples of such compounds include rotenone,[2] ketobemidone,[3] and tropicamide.[4]

Arylation of carbonyl compounds to access such α-aryl carbonyl scaffolds is an attractive strategy as it provides the opportunity to prepare these useful compounds from simple precursors in one step. However, twenty years ago, the direct arylation of a carbonyl compound or its enolate was limited to nucleophilic aromatic substitutions or protocols employing stoichiometric quantities of metal reagents with preformed enolates.[5] The development of cross-coupling technology has greatly improved access to α-aryl carbonyl compounds through the formation of a new bond between the α-carbon of the carbonyl and an aryl ring. Thus, two strategies, opposing in polarity, are possible: 1. the coupling of a metal enolate with an aryl halide or pseudo halide, and 2. the coupling of an α-halocarbonyl compound with an aryl organometallic reagent (Scheme 1).

---

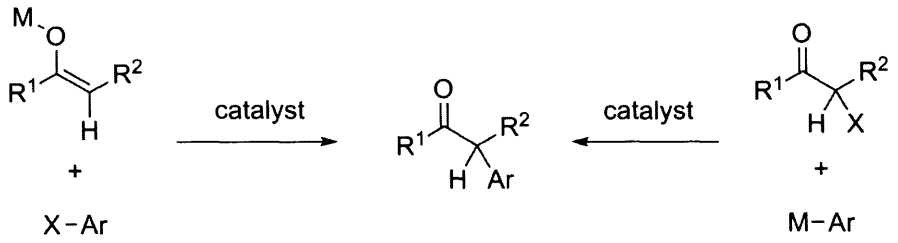
[1] (a) Shen, T. Y. *Angew. Chem. Int. Ed. Eng.* **1972**, *11*, 460–472. (b) Wright, W. B., Jr.; Press, J. B.; Chan, P. S.; Marsico, J. W.; Haug, M. F.; Lucas, J.; Tauber, J.; Tomcufcik, A. S. *J. Med. Chem.* **1986**, *29*, 523–530. (c) Landoni, M. F.; Soraci, A. *Curr. Drug Metab.* **2001**, *2*, 37–51.

[2] For leading references, see: Caboni, P.; Sherer, T. B.; Zhang, N.; Taylor, G.; Na, H. M.; Greenamyre, J. T.; Casida, J. E. *Chem. Res. Toxicol.* **2004**, *17*, 1540–1548.

[3] For leading references, see: Jylli, L.; Lundeberg, S.; Langius-Eklöf, Olsson, G. L. *Acta Anaesthesiol. Scand.* **2004**, *48*, 1256–1259.

[4] *The Merck Index*; O'Neil, M. J., Ed.; Merck: Whitehouse Station, N.J., 2006.

[5] Johansson, C. C. C.; Colacot, T. J. *Angew. Chem. Int. Ed.* **2010**, *49*, 676–707.



Scheme 1: Strategies for the α-arylation of carbonyl compounds

The former strategy, the coupling enolates with aryl halides, is by far the more well developed. The groups of Miura,[6] Buchwald,[7] and Hartwig[8] individually reported the initial examples, which used palladium catalysts to arylate ketone enolates. Subsequently, this field has rapidly expanded in scope to now encompass enolate arylation of esters, amides, aldehydes, and other related compounds such as nitriles; this topic has recently been reviewed.[5,9] Of particular relevance to the contents of this thesis are the examples of the asymmetric arylation of enolates, which will be the focus of part B.[10]

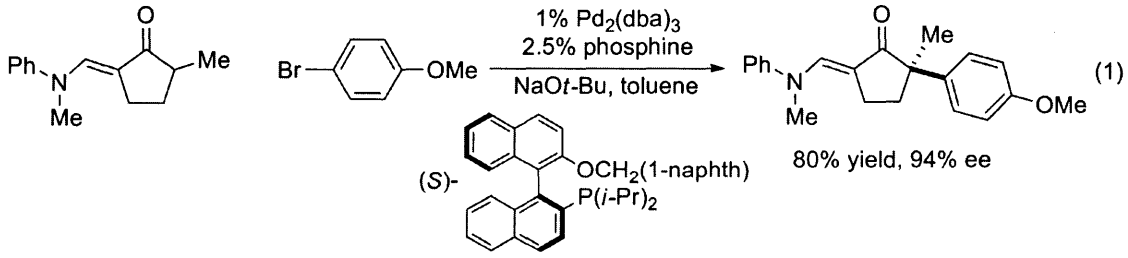
Less work has been done on the umpolung approach, that is the coupling of an α-halocarbonyl compound with an aryl organometallic reagent, and there have been no specialized reviews of this area. Therefore, to contextualize the research presented in sections 1.2 and 1.3 of this thesis chapter, the work in this area to date will be summarized in part C.

---

[6] Satoh, T.; Kawamura, Y.; Miura, M.; Nomura, M. *Angew. Chem., Int. Ed. Eng.* **1997**, *36*, 1740–1742.
[7] Palucki, M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1997**, *119*, 11108–11109.
[8] Hamann, B. C.; Hartwig, J. F. *J. Am. Chem. Soc.* **1997**, *119*, 12382–12383.
[9] Bellina, F.; Rossi, R. *Chem. Rev.* **2010**, *110*, 1082–1146.
[10] For a recent review, see: Burtoloso, A. C. B. *Synlett* **2009**, 320–327.

B: Transition-Metal Catalyzed Asymmetric Arylations of Metal Enolates with Aryl Halides

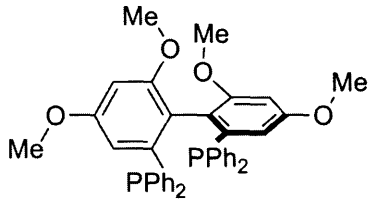
Buchwald was the first to report an asymmetric version of the enolate/aryl halide coupling strategy, using a Pd(0)/BINAP catalyst to effect the coupling of cyclic ketone enolates bearing a tertiary α-carbon with aryl bromides in good yield and modest to good enantioselectivity.[11] However, to control the site of enolate generation, the substrate scope was limited to cyclic ketones containing one non-enolizable α-carbon. A few years later, the same group published a second report that improved upon some of the limitations of the earlier protocol. The reaction temperature and catalyst loading were both lowered substantially, and an easily installed and removed blocking group was now employed to control the arylation regioselectivity (Equation 1).[12] Similar conditions have also been used for the asymmetric α-vinylation of ketones.[13]



Subsequent to these studies, similar protocols have been reported. Chan and coworkers described a nickel/P-Phos catalyst that effects the asymmetric α-arylation of α-substituted tetralones, 2-methyl-1-indanone, and 2-methyl-1-benzosuberoneone with

[11] Åhman, J.; Wolfe, J. P.; Troutman, M. V.; Palucki, M.; Buchwald, S. L. *J. Am. Chem. Soc.* **1998**, *120*, 1918–1919.
[12] Hamada, T.; Chieffi, A.; Åhman, J.; Buchwald, S. L. *J. Am. Chem. Soc.* **2002**, *124*, 1261–1268.
[13] Chieffi, A.; Kamikawa, K.; Åhman, J.; Fox, J. M.; Buchwald, S. L. *Org. Lett.* **2001**, *3*, 1897–1900.

aryl halides.[14] Hartwig and coworkers extended the electrophile scope of ketone arylation to include aryl triflates, which offer the advantage of easy preparation from phenols.[15] The electronic properties of the aryl triflate heavily influence the optimal reaction conditions and whether a nickel- or palladium-based catalyst is better suited to perform the desired transformation. One limitation of all of the protocols for the asymmetric arylation of ketones to date is that only cyclic ketones undergo α-arylation with good selectivity.

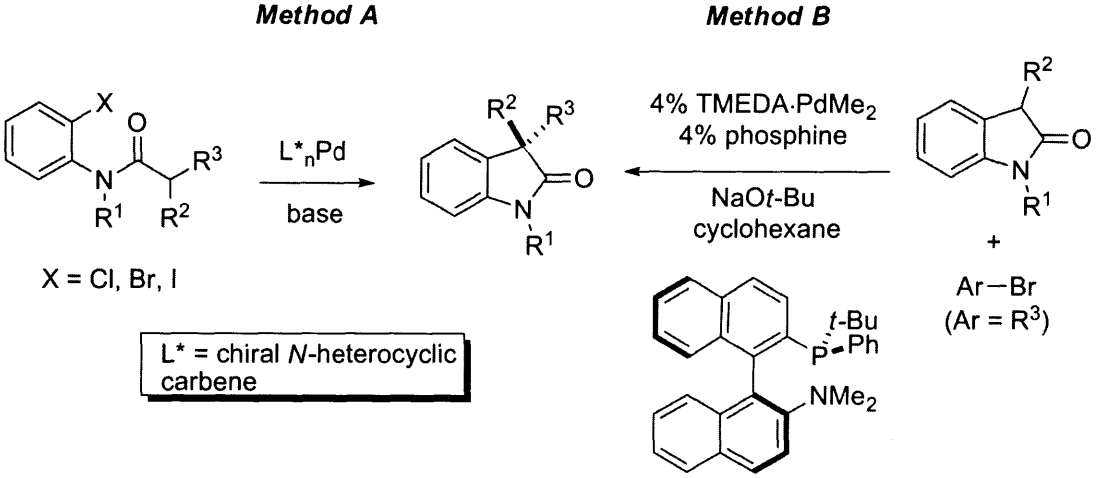


(*R*)-P-Phos

Asymmetric arylation of enolates has also been applied to carboxylic acid derivatives. For amides, much of the work has focused on intramolecular arylations to form oxindoles (Scheme 2, Method A), which was first reported by Hartwig et al. using chiral *N*-heterocyclic carbene ligands for the palladium catalyst.[16] Coupling was feasible with aryl chlorides, bromides, and iodides, but the enantioselectivities were only moderate. Following this report, this reaction was used to evaluate the performance of several new carbene ligands,[17] though, of these, only two articles show

[14] Chen, G.; Kwong, F. Y.; Chan, H. O.; Yu, W.-Y.; Chan, A. S. C. *Chem. Commun.* **2006**, 1413–1415.
[15] Liao, X.; Weng, Z.; Hartwig, J. F. *J. Am. Chem. Soc.* **2008**, *130*, 195–200.
[16] Lee, S.; Hartwig, J. F. *J. Org. Chem.* **2001**, *66*, 3402–3415.
[17] (a) Glorius, F.; Altenhoff, G.; Goddard, R.; Lehman, C. *Chem. Commun.* **2002**, 2704–2705. (b) Arao, T.; Kondo, K.; Aoyama, T. *Tetrahedron Lett.* **2006**, *47*, 1417–1420. (c) Arao, T.; Sato, K.; Kondo, K.; Aoyama, T. *Chem. Pharm. Bull.* **2006**, *54*, 1576–1581. (d) Kündig, E. P.; Seidel, T. M.; Jia, Y.; Bernardinelli, G. *Angew. Chem., Int. Ed.* **2007**, *46*, 8484–8447. (e) Malkov, A. V.; Stewart-Liddon, A. J. P.; Teplý, F.; Kobr, L.; Muir, K. W.; Haigh, D.; Kočovský, P. *Tetrahedron* **2008**, *64*, 4011–4025. (f) Luan, X.; Mariz, R.; Rober, C.; Gatti, M.; Blumentritt, S.; Linden, A.; Dorta, R. *Org. Lett.* **2008**, *10*,

examples with high enantioselectivity.[17d,17g] Accessing these quaternary-center-bearing oxindole products in a complementary fashion, Buchwald and co-workers recently reported an *intermolecular* α-arylation (and α –vinylation) of oxindoles (Scheme 2, Method B).[18] This work is the first example of a catalytic asymmetric intermolecular arylation of a non-ketone enolate.



Scheme 2: Methods for generating α,α' -substituted oxindoles

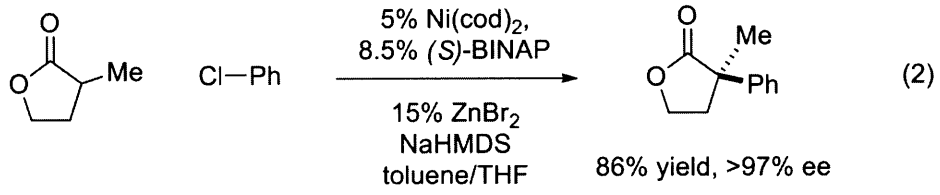
α-Substituted γ-lactones have also been reported by Buchwald and coworkers to be competent reaction partners for coupling with aryl bromides and chlorides using a nickel-BINAP catalyst (Equation 2).[19] Interestingly, this method employs a zinc salt additive to improve the reaction rate and efficiency; the authors postulate these effects are due to zinc-promoted abstraction of the bromide from the oxidative addition adduct to form a cationic species that undergoes transmetallation more easily than its precursor.

5569–5572. (g) Würtz, S.; Lohre, C.; Fröhlich, R.; Bergander, K.; Glorius, F. *J. Am. Chem. Soc.* **2009**, *131*, 8344–8345.

[18] Taylor, A. M.; Altman, R. A.; Buchwald, S. L. *J. Am. Chem. Soc.* **2009**, *131*, 9900–9901.

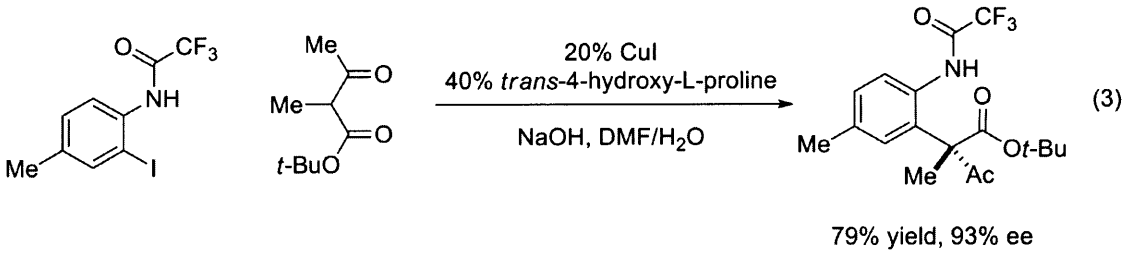
[19] Spielvogel, D. J.; Buchwald, S. L. *J. Am. Chem. Soc.* **2002**, *124*, 3500–3501.

This methodology has since found employment in the preparation of chiral 4,4'-disubstituted hexahydroazepines.[20]



(2)

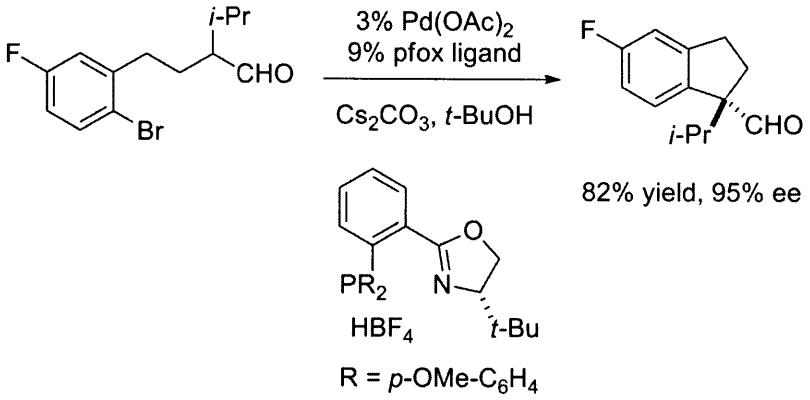
β-Ketoesters are another substrate class that have been proven competent in catalytic asymmetric α-arylation. Ma and coworkers have shown that 2-methylacetoacetate esters can be coupled with 2-iodotrifluoroacetanilides to give enantioselectivity values ranging from 60-93% ee (Equation 3).[21] This Ullmann-type process utilizes a copper/*trans*-4-hydroxy-L-proline catalyst in contrast with the other α-arylation procedures, which rely upon palladium and nickel catalysts. The electronic parameters of the anilide coupling partner strongly influence the coupling yield and enantioselectivity, and this method suffers from limited substrate scope. However, the products can be converted to chiral α-hydroxyindoles, thus making this method complementary to those methods of generating oxindoles discussed above.



(3)

[20] Delhaye, L.; Merschaert, A.; Diker, K.; Houpis, I. N. *Synthesis* **2006**, 1437–1442.
[21] Xie, X.; Chen, Y.; Ma, D. *J. Am. Chem. Soc.* **2006**, *128*, 16050–16051.

Aldehydes have also recently been utilized in catalytic asymmetric α-arylation by Buchwald and co-workers.[22] Using a palladium catalyst bearing phosphanyl-oxazoline ligands, in several cases the intramolecular arylation proceeded in good yield and with enantioselectivity values over 90% ee (Equation 4). This methodology is particularly remarkable in that the aldehyde enolate preferentially undergoes transmetallation with the palladium catalyst rather than participation in an aldol reaction.[23]

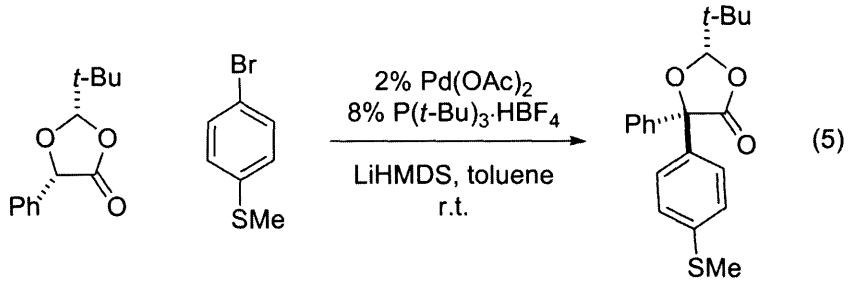


(4)

In addition to the catalytic *enantioselective* examples already discussed, a few catalytic *diastereoselective* examples of α-arylation have also been reported. Hartwig and coworkers appended both Evans and Ley chiral auxiliaries to silyl enolates for palladium-catalyzed coupling with aryl bromides, which was mediated by zinc additives.[24] The authors postulate that the presence of these zinc additives attenuate the basicity of the reaction, thus allowing tertiary α-aryl stereocenters to be formed; however the exact role of the zinc additive is unknown. More recently, Jansat and

[22] García-Fortanet, J.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2008**, *47*, 8108–8111.
[23] For organocatalytic procedures for the α-arylation of aldehydes, see: (a) Conrad, J. C.; Kong, J.; Laforteza, B. N.; MacMillan, D. W. C. *J. Am. Chem. Soc.* **2009**, *131*, 11640–11641. (b) Jensen, K. L.; Franke, P. T.; Nielsen, L. T.; Daasbjerg, K.; Jørgensen, K. A. *Angew. Chem., Int. Ed.* **2010**, *49*, 129–133.
[24] Liu, X.; Hartwig, J. F. *J. Am. Chem. Soc.* **2004**, *126*, 5182–5191.

coworkers have also developed a diastereoselective α-arylation (and α-vinylation) by using a chiral dioxolane derived from chiral mandelic acid and a palladium/phosphine catalyst (Equation 5).[25]



(5)

95% yield, 98% ee

The catalytic asymmetric α-arylation of enolates has been applied to a variety of carbonyl compounds to generate products containing enantioenriched α-aryl stereocenters, which are difficult to access via other synthetic methods. This method is especially good for generating quaternary centers, which remain a particular challenge in synthetic chemistry. However, this approach does have its limitations. With the exception of the report by Hartwig that employs zinc additives to arylate silyl enol ethers, the basic reaction conditions required to generate the enolate preclude the formation of tertiary α-aryl stereocenters, which are more acidic than their precursors and thus are quickly racemized. Furthermore, the product scope of these arylations is often limited to cyclic molecules, either through intermolecular couplings with cyclic enolates, or by intramolecular couplings. In some cases of intermolecular couplings, a large excess (2 or more equivalents) of the enolate precursor is often needed to offset loss of reagent due to competitive aldol and Claisen condensation reactions.

[25] Jiang, L.; Weist, S.; Jansat, S. *Org. Lett.* **2009**, *11*, 1543–1546.

Nevertheless, the protocols described represent substantial advances in the ability to prepare enantiomerically enriched α-arylcarbonyl compounds.

C: Transition-Metal Catalyzed Cross-Couplings between α-Halocarbonyl Compounds and Aryl Metal Reagents

The coupling of aryl metal reagents with α-halocarbonyl compounds is the umpolung approach to α-arylation of enolates in the effort to generate enantioenriched α–aryl stereocenters. This process has been much less explored due in part to the challenges posed in the cross-coupling of β-hydrogen-containing, sp^3-hybridized electrophiles. The oxidative addition of these electrophiles may be slow in comparison to sp^2-hybridized electrophiles, and once an oxidative addition adduct has been formed, there is a strong propensity of this complex to undergo β-hydride elimination.[26] Recently, however, advances in cross-coupling methodology have overcome these obstacles and the arylation of α–halocarbonyl compounds has become a much more feasible undertaking.

The first reports of this mode of coupling appeared in 1986 by Amano, Fujita, and coworkers in which they effected nickel-catalyzed Kumada couplings of aryl Grignard reagents with α-bromopropionates in moderate yields (Equation 6).[27]

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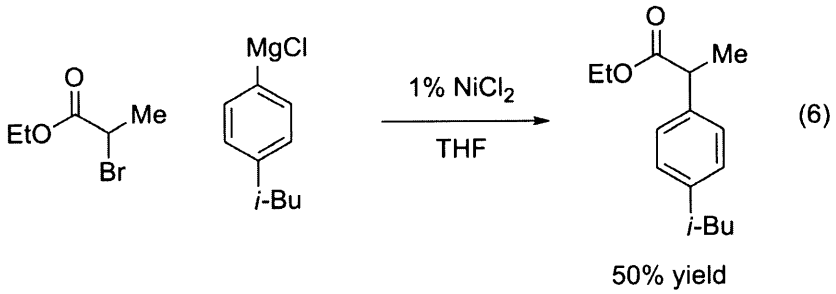
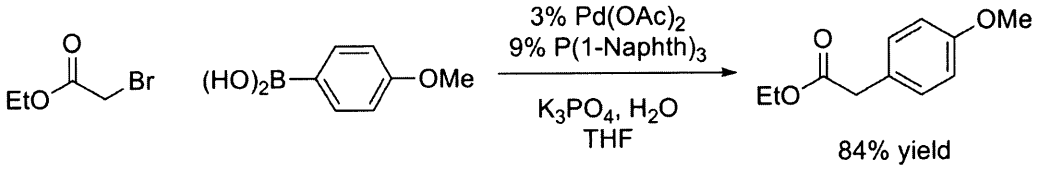
[26] (a) Cárdenas, D. J. *Angew. Chem., Int. Ed. Eng.* **1999**, *38*, 3018–3020. (b) Luh, T.-Y. L., M.-k.; Wong, K.-T. *Chem. Rev.* **2000**, *100*, 3187–3204.

[27] Amano, T.; Yoshikawa, K.; Sano, T.; Ohuchi, Y.; Shiono, M.; Ishiguro, M.; Fujita, Y. *Synth. Commun.* **1986**, *16*, 499–507.



(6)

In 1989, Suzuki and coworkers reported that they used a $Pd(PPh_3)_4$ catalyst to couple ethyl bromoacetate with dibutyl phenylboronate;[28] because base alone did not facilitate the transmetallation, the additive thallium carbonate was used. This chemistry was revived in 2001 by Gooßen, who reported a more practical Suzuki arylation that did not require toxic thallium additives to couple α-bromoacetates (and one α-bromoacetamide) with arylboronic acids and aryl pinacol boronates. This protocol used a palladium/phosphine catalyst to give the products in modest to very good yields (Equation 7; 1-Naphth = 1-naphthalene).[29]

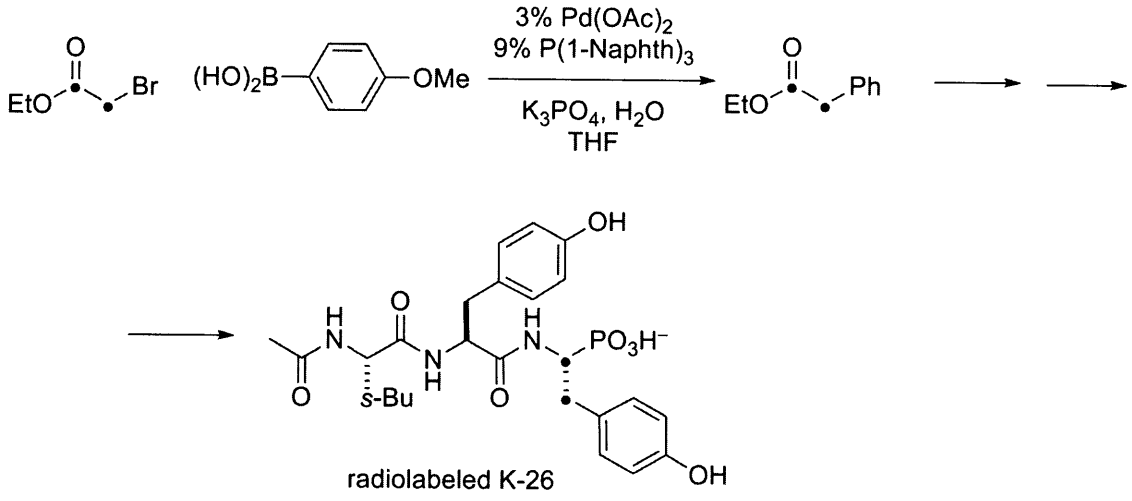


(7)

This methodology was incorporated into two syntheses of novel molecules for the purpose of probing biological problems. The first example used this coupling procedure to prepare an isotopically labeled nonproteinogenic amino acid in order to elucidate the biosynthetic pathway to make the angiotensin converting enzyme inhibitor

[28] Sato, M.; Miyaura, N.; Suzuki, A. *Chem. Lett.* **1989**, 1405–1408.
[29] Gooßen, L. *Chem. Commun.* **2001**, 669–670.

K-26 (Scheme 3).[30] In the second synthesis, a novel bifunctional poly(amino carboxylate) chelating agent was prepared that contained functionality for site-specific labeling of biomolecules to be used in biodistribution studies.[31]



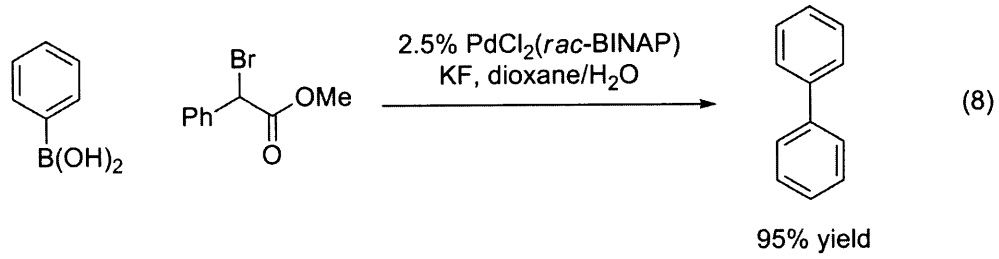
Scheme 3: Application of Gooßen's Suzuki arylation of α-bromoacetates

Subsequent to Gooßen's report, a similar procedure for the coupling of arylboronic acids to ethyl bromoacetate was reported by Deng and coworkers.[32] This process used $Pd(PPh_3)_4$ as the pre-catalyst in combination with a copper(I) oxide co-catalyst. The same group also reported a coupling procedure for *N,N*-dibutyl bromoacetamide with arylboronic acids, although this protocol did not require the copper co-catalyst.[33]

Concurrent with these studies, Lei and Zhang noted the presence of two competing pathways in the catalytic cycle while studying the α-arylation of primary and

[30] Ntai, I.; Phelan, V. V.; Bachmann, B. O. *Chem. Commun.* **2006**, 4518–4520.
[31] Knör, S.; Modlinger, A.; Poethko, T.; Schottelius, M.; Wester, H.-J.; Kessler, H. *Chem.–Eur. J.* **2007**, *13*.
[32] Liu, X.-X.; Deng, M.-Z. *Chem. Commun.* **2002**, 622–623.
[33] Duan, Y.-Z.; Deng, M.-Z. *Tetrahedron Lett.* **2003**, *44*, 3423–3426.

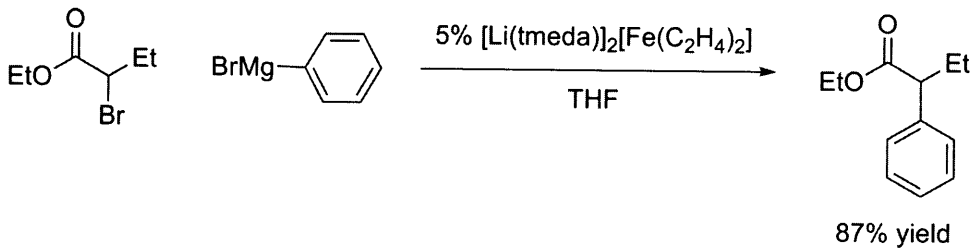
secondary α-bromoesters.[34] One pathway gave rise to the desired cross-coupling product, while the second led to homocoupling of the nucleophile, presumably through a double transmetallation of the oxidative addition adduct by the nucleophile. In the case of α-bromoacetate, this group was able to obtain a 7:3 ratio of the cross-coupling product to the homocoupling product. However, in the end, they decided to optimize for the selective formation of the homocoupling product mediated by the α-bromoester reagent (Equation 8).



95% yield (8)

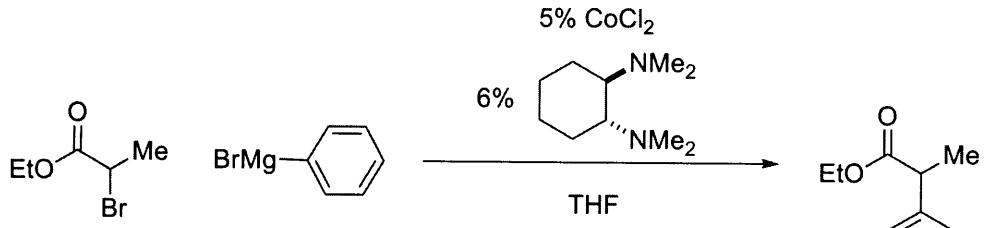
The first example of selective α-arylation of a secondary α-halocarbonyl compound following Amano and Fujita's 1986 report was in 2004 by Fürstner and coworkers.[35,36] Here they were able to use a well-defined iron catalyst to couple, amongst other substrates, ethyl α-bromobutyrate with phenylmagnesium bromide in high yield (Equation 9). However, this particular reaction was the only example of such an α-arylation included.

[34] Lei, A.; Zhang, X. *Tetrahedron Lett.* **2002**, *43*, 2525–2528.
[35] Martin, R.; Fürstner, A. *Angew. Chem., Int. Ed.* **2004**, *43*, 3955–3957. For a more detailed report of these experimental findings, see Fürstner, A.; Martin, R.; Krause, H.; Seidel, G.; Goddard, R.; Lehmann, C. W. *J. Am. Chem. Soc.* **2008**, *130*, 8773–8787.
[36] For a review of transition metal-catalyzed cross-couplings of secondary alkyl electrophiles, see: Rudolph, A.; Lautens, M. *Angew. Chem., Int. Ed.* **2009**, *48*, 2656–2670.



87% yield (9)

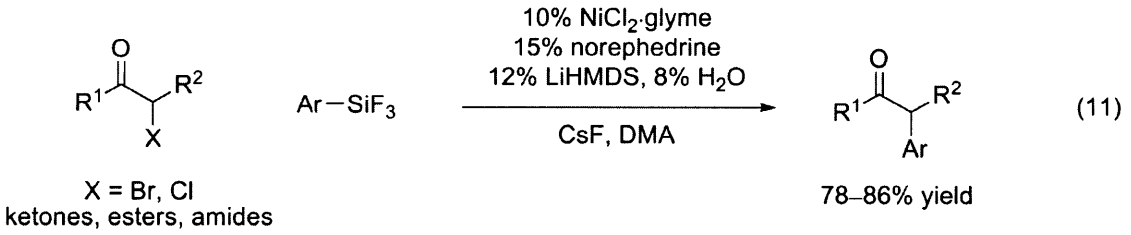
This transformation has been demonstrated to be facilitated by other metal catalysts as well. Yorimitsu and Oshima have one example of the use of a cobalt/diamine catalyst for the coupling of ethyl α-bromopropionate with phenylmagnesium bromide (Equation 10).[37]



88% yield (10)

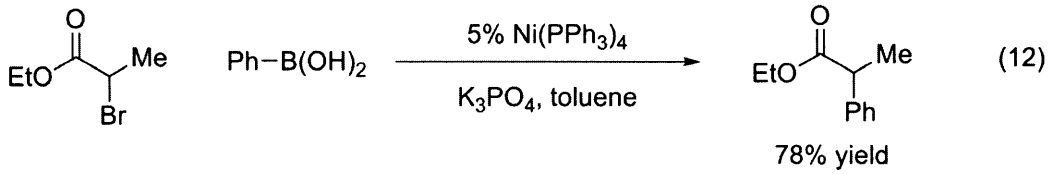
Nickel-catalysis has also been used for the arylation of α-halocarbonyl compounds. In the first such example, Strotman, Sommer and Fu demonstrated a nickel/amino alcohol-mediated Hiyama arylation of α-chloro- and α-bromoketones, esters, and amides, all in good yields (Equation 11).[38] This method was also applicable to α-chloro and α-bromonitriles and phosphonates.

[37] Ohmiya, H.; Yorimitsu, H.; Oshima, K. *J. Am. Chem. Soc.* **2006**, *128*, 1886–1889.
[38] Strotman, N. A.; Sommer, S.; Fu, G. C. *Angew. Chem., Int. Ed.* **2007**, *46*, 3556–3558.



(11)

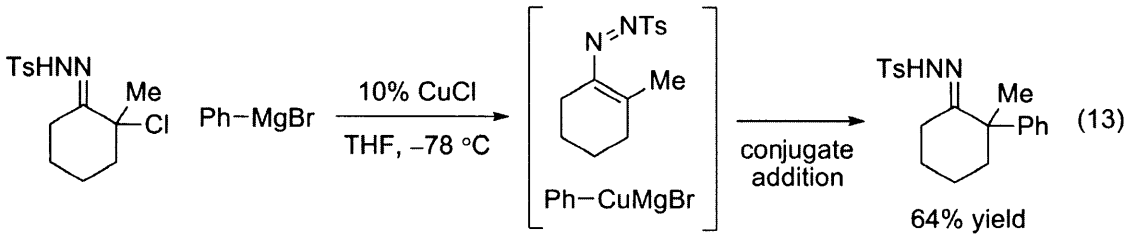
Lei and coworkers have also used nickel catalysis for the Suzuki arylation of α-bromoesters and amides, and both α-bromo- and α-chloroketones.[39] The conditions vary depending on the substrate pair; however, a representative coupling can be found in Equation 12.



(12)

Recently, α-chlorohydrazones have been shown to be suitable electrophiles for copper-catalyzed cross-coupling with Grignard reagents, including one example with phenymagnesium bromide (Equation 13).[40] After the coupling, the α-phenylhydrazone can be hydrolyzed to give the α-phenylketone. This reaction is noteworthy in that it generates an α-quaternary center, which is unique for this polarity of cross-coupling. The mechanism is presumed to proceed through a conjugate addition to an azo-alkene intermediate, whereas other α-arylations of α-halocarbonyls are supposed to occur through radical-mediated or S_N2-type oxidative addition processes. This mechanistic difference may account for this divergency in reactivity.

[39] Liu, C.; He, C.; Shi, W.; Chen, M.; Lei, A. *Org. Lett.* **2007**, *9*, 5601–5604.
[40] Hatcher, J. M.; Coltart, D. M. *J. Am. Chem. Soc.* **2010**, *132*, 4546–4547.



(13)

The arylation of secondary α-halocarbonyl compounds using catalysts bearing chiral ligands under mild conditions provides the opportunity for generating enantioenriched tertiary stereocenters, as the ability to use milder reaction conditions may avoid the epimerization that hinders enolate arylation for these targets. Our group has been very interested in stereoconvergent, asymmetric cross-coupling reactions of racemic secondary alkyl electrophiles for a number of years,[41,42,43] and we were intrigued by the possibility of utilizing this methodology for the synthesis of these difficult tertiary α-arylcarbonyl stereocenters.

The first success in this area was Dai and Strotman's development of an asymmetric Hiyama arylation protocol for use with α-bromoesters.[44] It was found that bulky esters gave the higher levels of enantioselectivity, with a 2,6-di-*tert*-butyl-4-methylphenyl (BHT) ester being optimal (Equation 14). The reaction was sensitive to the steric demand of the α-alkyl substituent, but was fairly tolerant of various functional groups. Interestingly, this methodology was also applicable to asymmetric couplings with alkenylsilanes under the same reaction conditions to afford β,γ-unsaturated ester

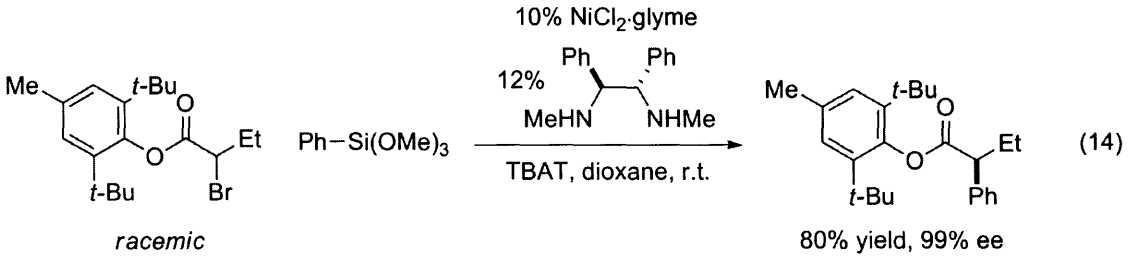
[41] (a) Fischer, C.; Fu, G. C. *J. Am. Chem. Soc.* **2005**, *127*, 4594–4595. (b) Arp, F. O.; Fu, G. C. *J. Am. Chem. Soc.* **2005**, *127*, 10482–10483. (c) Son, S.; Fu, G. C. *J. Am. Chem. Soc.* **2008**, *130*, 2756–2757. (d) Saito, B.; Fu, G. C. *J. Am. Chem. Soc.* **2008**, *130*, 6694–6695. (e) Smith, S. W.; Fu, G. C. *J. Am. Chem. Soc.* **2008**, *130*, 12645–12647. (f) Lou, S.; Fu, G. C. *J. Am. Chem. Soc.* **2010**, *132*, 5010–5011. (g) Owston, N. A.; Fu, G. C. *J. Am. Chem. Soc.* **2010**, *132*, ASAP.

[42] For an example of a nickel-catalyzed asymmetric alkynylation with trialkynylindium reagents, see: Caeiro, J.; Sestelo, J. P.; Sarandeses, L. A. *Chem.–Eur. J.* **2008**, *14*, 741–746.

[43] For a review on asymmetric cross-couplings of secondary alkyl electrophiles, see: Glorius, F. *Angew. Chem., Int. Ed.* **2008**, *47*, 8347–8349.

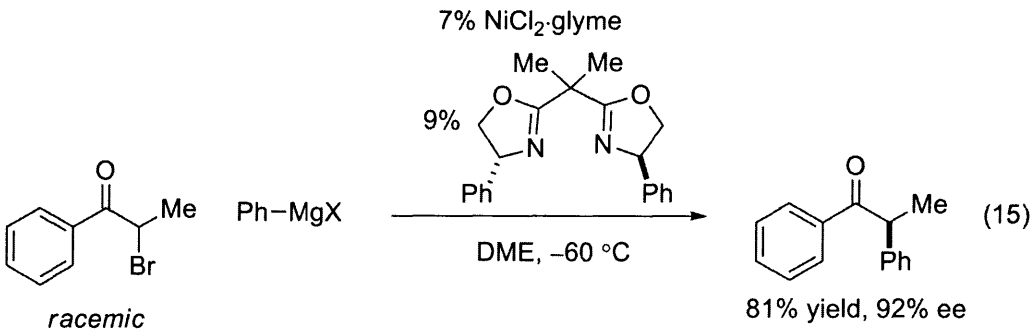
[44] Dai, X.; Strotman, N. A.; Fu, G. C. *J. Am. Chem. Soc.* **2008**, *130*, 3302–3303.

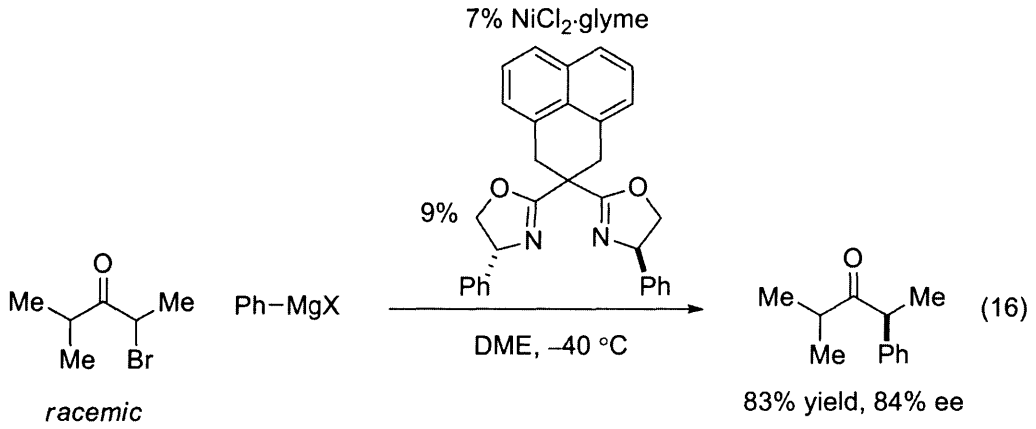
products bearing a tertiary α-stereocenter. These ester products are easily converted into other molecules; if an α-aryl carboxylic acid is desired, an oxidatively cleavable 2,6-di-*tert*-butyl-4-methoxyphenyl ester can also be used with only a modest decrease in enantioselectivity.



Following the development of the Hiyama α-arylation methodology, our group has sought to expand this strategy to other classes of carbonyl compounds and other organometallic reagents. The enantioselective Negishi arylation of α-bromoketones is the subject of section 1.2 of this thesis, and the enantioselective Suzuki arylation of α-haloamides is the subject of section 1.3. In addition to these three reports, Lou has developed an asymmetric Kumada arylation of both aryl-alkyl and dialkyl α-bromoketones (Equations 15 and 16).[45] Despite the strong basicity of the Grignard nucleophiles, racemization of the enantiomerically enriched products is not observed under the reaction conditions. This reaction is also quite tolerant of a number of functional groups, including esters, nitriles, and aromatic heterocycles.

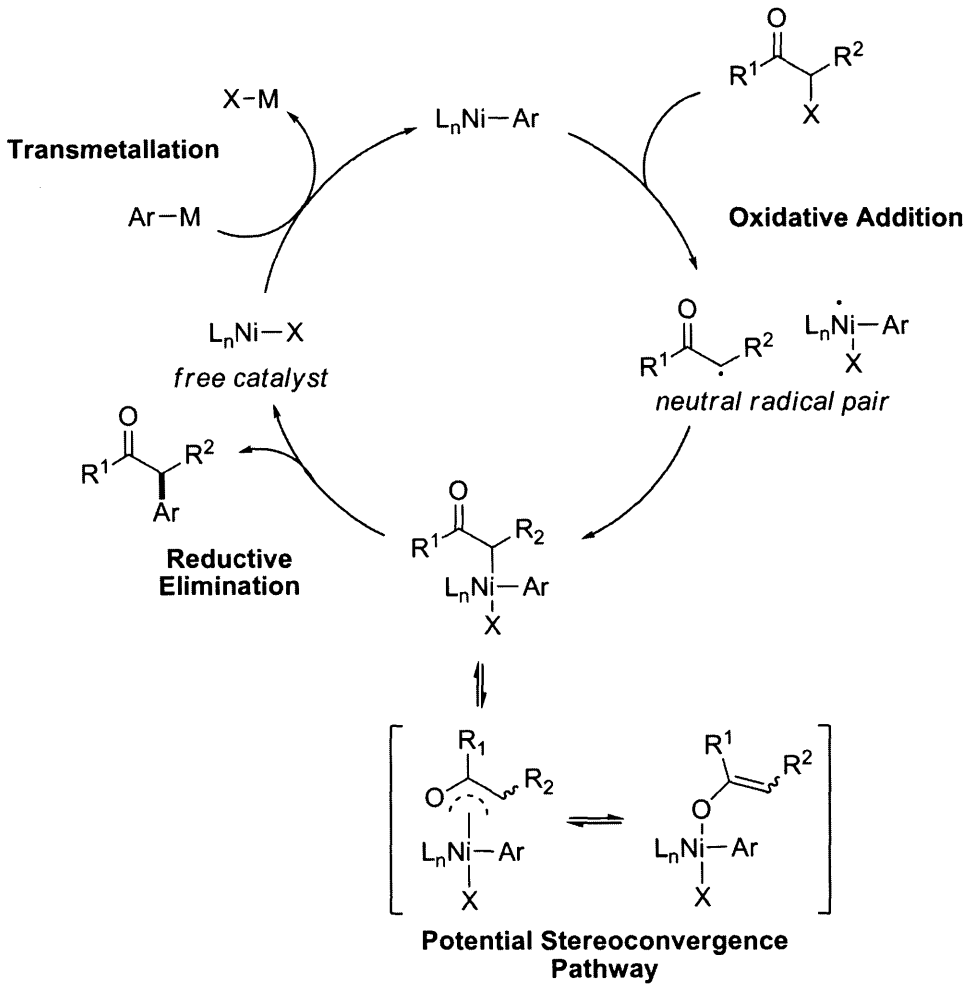
[45] Lou, S.; Fu, G. C. *J. Am. Chem. Soc.* **2010**, *132*, 1264–1266.





Kinetic studies were undertaken to elucidate the mechanism of this reaction. It was found that the reaction is first order in both catalyst and nucleophile, and zero order in electrophile. If the resting state is assumed to be the free catalyst, this data seems to support a pathway in which transmetallation occurs before oxidative addition (Scheme 4). However, to more clearly define the mechanism of this coupling, more information must be gathered. At this point, the exact nature of the stereochemistry-determining step remains unclear; the stereochemistry may be set in the course of initial carbon–nickel bond formation, or it may be determined by reductive elimination after interconversion of the intermediate nickel enolate. Which of these pathways is the most likely would depend on the rate of reductive elimination relative to enolate interconversion. If it is fast, then the former scenario is more likely, but if it is slow,

then the latter pathway is more plausible. However, at this point, the relative rates of the steps in this postulated catalytic cycle are unknown.



Scheme 4: Postulated mechanism for the nickel-catalyzed Kumada coupling of α-bromoketones

D: Conclusions

In the last fifteen years, advances in transition metal-catalyzed cross-coupling technology have made possible remarkable progress in the ability to synthesize α-arylcarbonyl compounds. Within this class of new reactions, methods to generate enantioenriched α-carbonyl compounds are especially promising and exciting. Two

transition-metal catalyzed cross-coupling approaches exist to prepare these products: (1) the arylation of enolates with aryl halides, and (2) the arylation of α-halocarbonyls with aryl organometallic reagents. Each of these strategies has been applied to a number of carbonyl subclasses and offers its own advantages and disadvantages (Figure 1); however, together, these complementary methods combine to considerably strengthen the synthetic chemist's ability to prepare novel and potentially biologically significant molecules.

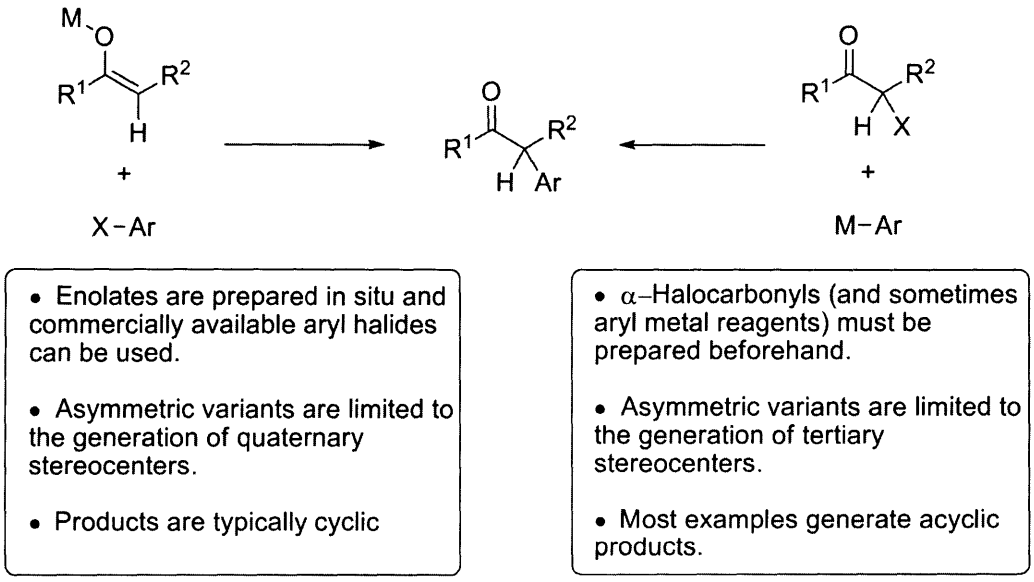


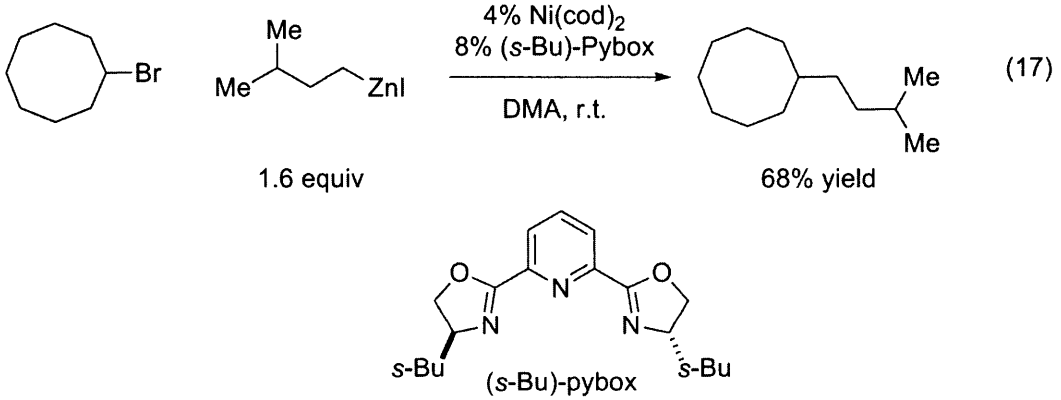
Figure 1: Comparison of strategies for asymmetric arylation of carbonyls

Section 1.2

Asymmetric Negishi Arylation of α-Bromoketones

A: Introduction

The Negishi coupling of organozinc nucleophiles is a functional-group tolerant procedure that proceeds under mild conditions, generally without the use of additives, making it more straightforward than many other cross-coupling reactions.[46] It is not surprising, therefore, that Negishi coupling reactions have played a pivotal role in the Fu group's development of strategies for cross-coupling secondary alkyl electrophiles. The first such example from the group was a Negishi coupling of unactivated secondary and primary alkyl bromides and iodides with a variety of primary alkylzinc iodides developed by Zhou in 2003 (Equation 17).[47] This paper is notable in that it is this group's initial foray into the field of nickel-catalyzed cross-coupling reactions.



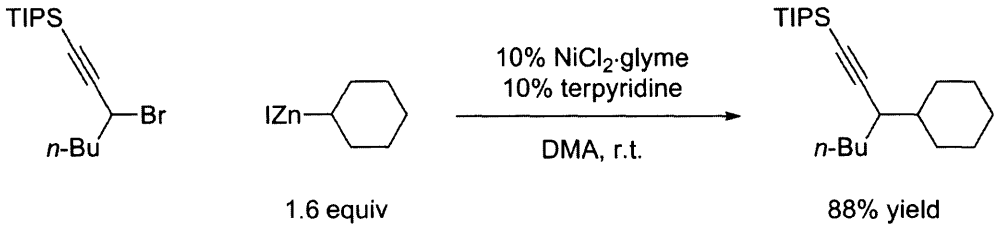
More recently, Smith reported the coupling of secondary alkylzinc iodides and bromides with secondary propargyl bromides and chlorides (Equation 18).[48] This

[46] For a review of the Negishi reaction, see: Negishi, E.-i.; Hu, Q.; Huang, Z.; Wang, G.; Yin, N. In *The Chemistry of Organozinc Compounds*; Rappopport, Z., Marek, I., Eds.; Wiley: New York, 2006; Chapter 11.

[47] Zhou, J.; Fu, G. C. *J. Am. Chem. Soc.* **2003**, *125*, 14726–14727.

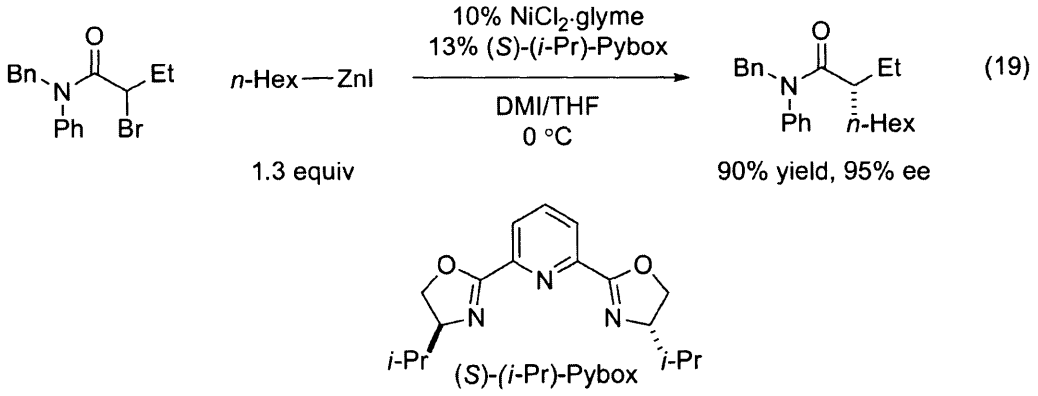
[48] Smith, S. W.; Fu, G. C. *Angew. Chem., Int. Ed.* **2008**, *47*, 9334–9336.

report is the first example of a nickel-catalyzed cross-coupling of a secondary alkyl nucleophile of any type with a secondary alkyl electrophile.[49]



(18)

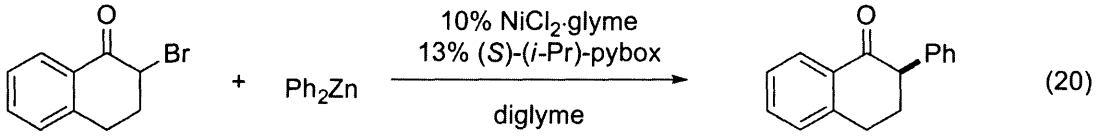
In 2005, Fischer disclosed the *asymmetric* Negishi coupling of α-bromoamides and primary alkylzinc bromide and iodide nucleophiles, again with a nickel/Pybox catalyst (Equation 19), which is the first example of an asymmetric cross-coupling reaction wherein a racemic secondary alkyl electrophile is converted to a highly enantioenriched coupling product.[41a] To expand the scope of this novel transformation, the competency of many new electrophile classes in such transformations were evaluated. Soon afterwards, Arp reported the second example of an asymmetric Negishi alkylation, in this case with benzylic bromides and chlorides as the electrophilic coupling partner.[41b] Subsequently, Son developed a method for Negishi alkylation of allylic chlorides and bromides.[41c]



(19)

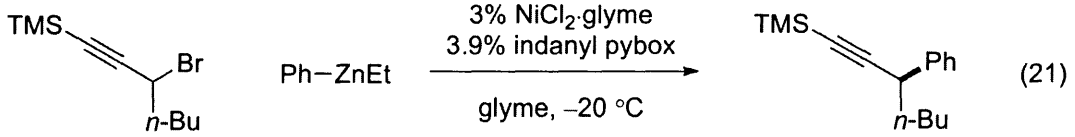
[49] For a copper-catalyzed cross-coupling of secondary alkylzinc halides with α-chloroketones, see: Malosh, C. F.; Ready, J. M. *J. Am. Chem. Soc.* **2004**, *126*, 10240–10241.

Given the success these asymmetric Negishi reactions with alkylzinc nucleophiles, we were interested in whether we could extend this methodology to arylzinc nucleophiles. Jorge Esquivias initially explored this question, finding that diphenylzinc could indeed be coupled with 2-bromo-α-tetralone using a nickel/Pybox catalyst to give the product with 87% yield and 82% ee. Upon cooling of the reaction to –30 °C, these results were improved to 94% yield and 89% ee (Equation 20). It was with this result in hand that the optimization process described in section B was begun to further improve the scope, yield, and enantioselectivity.

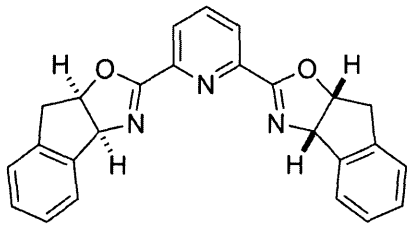


racemic 1.5 equiv r.t.: 87% yield, 82% ee; –30 °C: 94% yield, 89% ee (20)

Concurrent with the studies detailed in this thesis section, Smith developed the asymmetric Negishi arylation of secondary propargylic halides, using ethylphenylzinc as the arylating agent and a nickel/Pybox catalyst (Equation 21).[41e]



racemic 2.0 equiv 90% yield, 92% ee (21)



indanyl-Pybox

B: Results and Discussion[50]

Although the conditions found by Esquivias were very good for coupling 2-bromo-α-tetralone, other classes of ketones did not give comparably high yield and ee, including acyclic ketones. Thus the utility of this method to the synthetic community was very limited. We therefore decided our efforts were best concentrated on optimizing reaction conditions for a more general family of electrophiles, namely, an acyclic scaffold. Under the conditions in Equation 20, 2-bromopropiophenone was found to couple in 59% yield and 74% ee; a simple switch of solvent from diglyme to glyme improved the enantiomeric excess to 79% although the yield decreased to 55%. At this point, a number of Pybox ligands were evaluated in the reaction due to their success in our other asymmetric cross-coupling procedures (Figure 2).[41a-41c] Although a number of these species gave ee values greater or equal to that obtained with (*i*-Pr)-Pybox, the *trans*-4-methoxymethyl-5-phenyl-substituted Pybox ligand, **1**, stood out with the highest ee (93%).

[50] Portions of the work described in this section are published in: Lundin, P. M.; Esquivias, J.; Fu, G. C. *Angew. Chem., Int. Ed.* **2009**, *48*, 154–156.

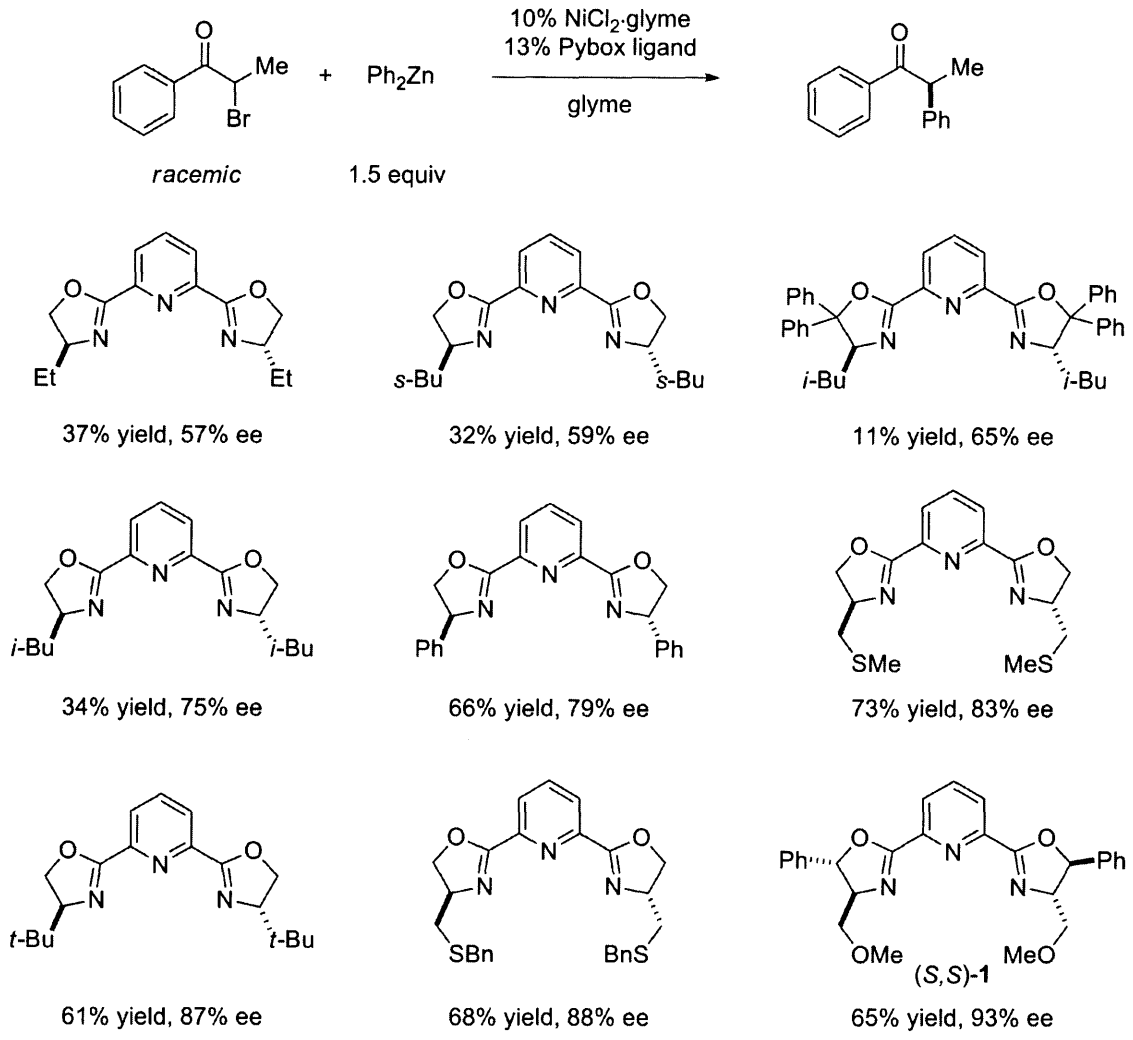
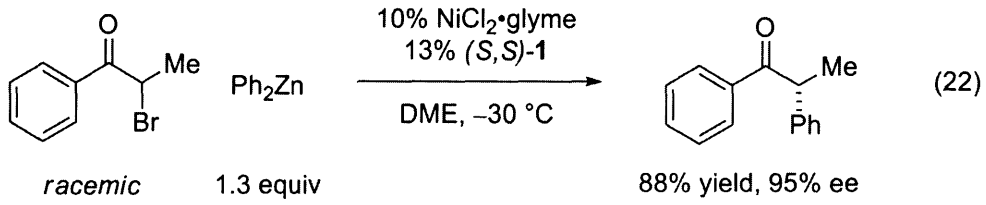


Figure 2: Ligand screen

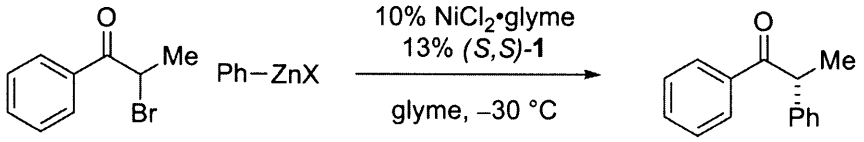
We continued reaction optimization with ligand **1** and were able to improve the system with the conditions in equation 22, which gave the coupling product in 88% yield and 95% ee.



However, the diphenylzinc powder that had been used up to this point as the arylating agent posed two problems to the development of a general coupling procedure. First, diarylzinc solids are air-sensitive compounds and thus are not amenable to handling on the bench top. Secondly, diphenylzinc is one of only two such species that are commercially available. Therefore, to expand the nucleophile scope, it was imperative to find another arylzinc source, and a variety of potential species were tested (Table 1). Ethylphenylzinc[51] and phenylzinc bromide did not provide any coupling product (entries 1 and 2). While phenylzinc chloride gave the desired product with high enantioselectivity, the yield was low (entry 3). A commercially available phenylzinc iodide solution gave only 79% ee (entry 4). The use of phenylzinc iodide generated from phenylmagnesium bromide and zinc iodide led to high yield and ee of the coupling product (entry 5), whereas s phenylzinc iodide synthesized by zinc insertion into iodobenzene gave even higher yield and ee (entry 6). Diphenylzinc generated from phenyl Grignard and of zinc chloride also gave high ee but the yield was lower (entry 7). However, filtration of the nucleophile solution to remove the magnesium salts prior to addition to the reaction significantly improved the yield (entry 8).

[51] Bolm, C.; Rudolph, J. *J. Am. Chem. Soc.* **2002**, *124*, 14850–14851.

Table 1: Arylzinc reagents tested in reaction



racemic 1.3 equiv

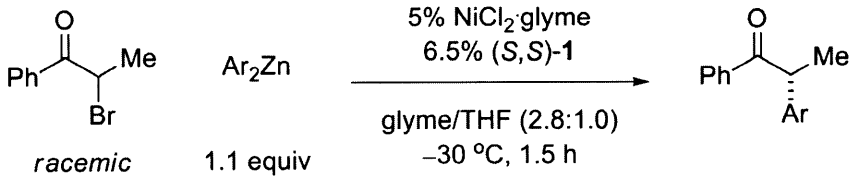
entry	Nucleophile	% yield[a]	% ee
1	Ph–ZnEt	0	–
2	Ph–ZnBr $\Longrightarrow$ PhMgBr + $ZnBr_2$	0	–
3	Ph–ZnCl $\Longrightarrow$ PhMgBr + $ZnCl_2$	14	88
4	Ph–ZnI (0.5 M solution, Aldrich)	51	79
5	Ph–ZnI $\Longrightarrow$ PhMgBr + ZnI_2	84	90
6	Ph–ZnI $\Longrightarrow$ PhI + Zn (dioxane/DMA)	82	95
7	Ph–ZnPh $\Longrightarrow$ PhMgBr + $ZnCl_2$	58	94
8[b]	Ph–ZnPh $\Longrightarrow$ PhMgBr + $ZnCl_2$	92	96

[a]Yields were determined by GC versus *n*-tetradecane as an internal standard. [b]The nucleophile solution was filtered through an Acrodisc prior to use in the reaction.

Reaction optimization was therefore continued using in situ-generated diarylzinc reagents. Testing with a variety of different nucleophile substitution patterns identified the conditions specified in Table 2 as optimal. These reactions can be set up without the use of an inert atmosphere glovebox, as the commercially available nickel salt can be handled in air.[52] Both meta- (entries 2 and 3) and para-substituted (entries 4-7) nucleophiles coupled well. Electron-donating groups in both these positions (entry 3 and entries 5-7) were suitable for coupling.

[52] Ligand **1** is not commercially available, but it can be prepared in 2-3 steps using commercially available amino alcohols and a commercially available pyridine derivative. For experimental information, see part D.

Table 2: Nucleophile scope with diarylzinc reagents



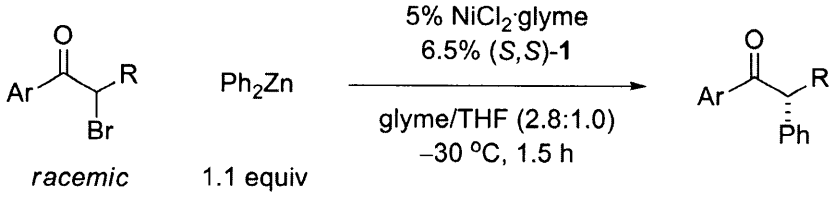
entry	aryl	% yield	% ee
1	Ph	83 (88[a])	93 (95[a])
2	3-Me-C_6H_4	87	92
3	3-OMe-C_6H_4	87	94
4	4-F-C_6H_4	79	95
5	4-OMe-C_6H_4	80	91
6	4-NMe_2-C_6H_4	88	89
7	4-SMe-C_6H_4	82	92

All data are the average of two runs. [a] Diphenylzinc powder was used rather than diphenylzinc generated in situ.

Variations on the electrophile were also tested in the reaction (Table 3). A variety of aryl alkyl ketones[53] couple efficiently with moderate to high ee. Functional groups are tolerated on the alkyl chain (entries 2-3), and branching at the β-position relative to the reaction center does not hinder the reaction (entry 4). Substitution at the ortho position of the aryl ring does result in a decrease in yield and ee (entries 5 and 6). In the para position, the aryl ring can bear either electron-rich (entry 7) or electron-poor (entry 8) substituents. A heteroaromatic ketone is also tolerated in this reaction (entry 9).

[53] 2-Bromocyclohexanone was found to couple with Ph_2Zn powder in 68% yield and 72% ee. However, in general, dialkyl ketones were found to only couple in low yields and enantioselectivities.

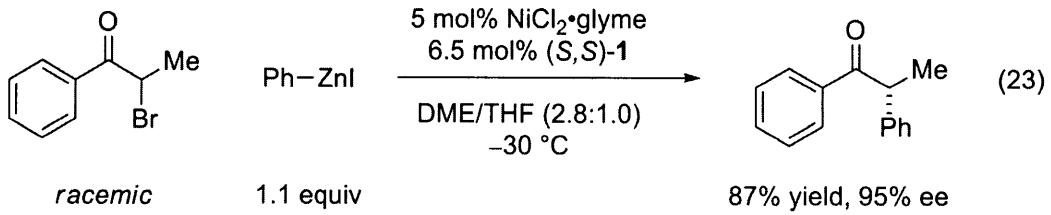
Table 3: Electrophile scope in coupling with diarylzinc nucleophiles



entry	aryl	R	% yield	% ee
1	Ph	Et	91	88
2	Ph	CH_2Ph	86	87
3	Ph	CH_2CH_2Cl	82	86
4	Ph	*i*-Bu	89	95
5	2-F-C_6H_4	Me	68	70
6	2-Et-C_6H_4	Me	43	76
7	4-OMe-C_6H_4	Me	91	94
8	4-CF_3-C_6H_4	Me	82	89
9[a]	2-thienyl	Me	87	93

All data are the average of two runs. [a] Reaction time of 6 h rather than 1.5 h.

With these results in hand, the reaction with phenylzinc iodide in place of diphenylzinc was again tested. Whereas phenylzinc iodide was previously a slightly inferior coupling partner with respect to enantioselectivity (Table 1, entry 5 versus entry 8), under the current reaction conditions it was found that it gave slightly improved enantioselectivity as compared to diphenylzinc (Equation 23 versus Table 2 entry 1).

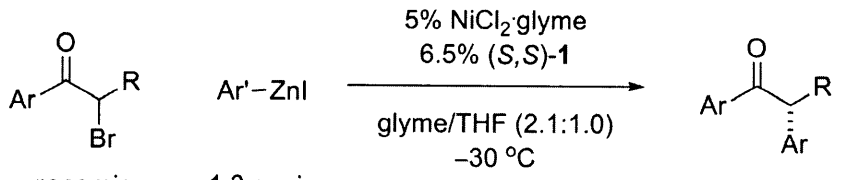


(23)

A variety of other arylzinc iodides were tested under these conditions, and the improvement in enantioselectivity was indeed found to be general. Arylzinc iodides offer an advantage over diarylzinc reagents in that they require one equivalent of Grignard reagent to zinc salt, whereas the diarylzinc reagents require two equivalents.[54] Therefore, the reaction parameters for coupling with arylzinc iodides were optimized, and the couplings analogous to those performed in Tables 2 and 3 were performed with arylzinc iodide nucleophiles (Table 4). Two couplings did not proceed well with the arylzinc iodide nucleophile. In the case of 3-methoxyphenylzinc iodide, the nucleophile solution turned to a thick slurry that was difficult to syringe into the reaction solution. For 2-bromo-4-methyl-1-phenylpentan-1-one, the reaction with phenylzinc iodide was more sluggish as compared to the coupling with diphenylzinc. The ee values obtained in Table 4 are either comparable to or higher than the corresponding entries in Tables 2 and 3; the yields vary from being lower, higher, or comparable.

[54] We preferred to generate arylzinc iodides through transmetalation rather than zinc insertion, as we found the transmetalation procedure to be more reliable.

Table 4. Coupling with arylzinc iodide reagents



entry	Ar	R	Ar'	% yield	% ee
1	Ph	Me	Ph	86	96
2	Ph	Me	3-Me-C_6H_4	88	94
3	Ph	Me	4-F-C_6H_4	74	96
4	Ph	Me	4-OMe-C_6H_4	93	96
5	Ph	Me	4-NMe_2-C_6H_4	85	93
6	Ph	Me	4-SMe-C_6H_4	71	96
7	Ph	Et	Ph	86	94
8	Ph	CH_2Ph	Ph	76	95
9[a]	Ph	CH_2CH_2Cl	Ph	90	92
10	2-F-C_6H_4	Me	Ph	80	72
11	2-Et-C_6H_4	Me	Ph	79	75
12	4-OMe-C_6H_4	Me	Ph	90	96
13	4-CF_3-C_6H_4	Me	Ph	76	87
14	2-thienyl	Me	Ph	81	96

All data are the average of two runs. [a] The reaction temperature was –20 °C rather than –30 °C.

A few other notes should be made regarding this coupling system. Ortho-substituted nucleophiles were not successful in the coupling of either diarylzinc or arylzinc iodide reagents due to low yields. α-Branching on the alkyl side chain was also not tolerated. On a gram-scale at –30 °C, the reaction is sluggish, but at –10 °C the

product (same as Table 4, entry 1) was obtained in 81% yield and 93% ee. In all reactions, the ee of the starting electrophile remains less than 5% over the course of the reaction; therefore, the oxidative addition of the α-bromoketone seems unlikely to proceed through a kinetic resolution. The ee of the product remains essentially constant during the reaction.

C. Conclusions

In conclusion, the first asymmetric cross-coupling of secondary α-haloketones has been developed, specifically, a Negishi arylation of α-bromoketones. This process is a new procedure for the synthesis of enantioenriched α-arylketones, a motif that is difficult to access via other methods. Both diaryl zinc and arylzinc iodide reagents are suitable coupling partners in this stereoconvergent process, which occurs under very mild conditions without the presence of any activators.

D. Experimental

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1. General Information

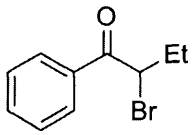
All reactions were carried out in oven-dried glassware under an atmosphere of argon.

The following reagents were purchased and used without purification: ZnI_2 (Alfa), $ZnPh_2$ (Alfa), $NiCl_2$·glyme (Strem), glyme (Fluka), THF (anhydrous; Aldrich), (1*S*,2*S*)-(+)-2-amino-3-methoxy-1-phenyl-1-propanol (Aldrich), and (1*R*,2*R*)-(+)-2-amino-1-phenyl-1,3-propanediol (TCI).

HPLC analyses were carried out on an Agilent 1100 series system with Daicel Chiralpak® columns.

2. Preparation of a-Bromoketones

General Procedure: Bromine (1.0 equiv) was added to a solution of the ketone in Et_2O. The solution was stirred for 30 min, and then the reaction was quenched with 10% aqueous potassium carbonate (10 mL). The organic layer was washed with sodium thiosulfate (10 mL) and brine (10 mL), dried over sodium sulfate, and concentrated. The a-bromoketone was purified by flash chromatography.
These procedures have not been optimized.



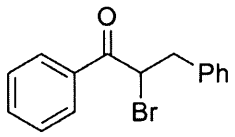
2-Bromo-1-phenylbutan-1-one [877-35-0]. Prepared from butyrophenone (1.49 g, 10 mmol) and bromine (0.51 mL, 10 mmol) in Et_2O (25 mL). Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a yellow oil in 70% yield (1.6 g).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.04-8.02 (m, 2H), 7.62-7.59 (m, 1H), 7.52-7.48 (m, 2H), 5.09 (dd, J = 7.2, 7.6 Hz, 1H), 2.29-2.11 (m, 2H), 1.10 (t, J = 7.6 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 193.4, 134.7 133.9, 129.0, 128.0, 49.3, 27.1, 12.4;

IR (film): 1683, 1597, 1448, 1226, 1002, 899, 802, 703 cm^{-1};

LRMS (EI) for $C_{10}H_{11}O$ (M–Br): calcd 147, found 147.

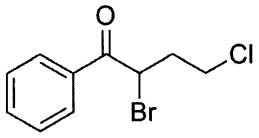


2-Bromo-1,3-diphenylpropan-1-one [51012-66-9]. Prepared from 3-phenylpropiophenone (2.3 g, 10 mmol) and bromine (0.51 mL, 10 mmol) in Et_2O (20 mL). Solvent system for chromatography: 4:1→2:1 hexanes:dichloromethane. The product was isolated as a white solid in 79% yield (2.3 g).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.00-7.97 (m, 2H), 7.61-7.57 (m, 1H), 7.49-7.45 (m, 2H), 7.33-7.24 (m, 5H), 5.34 (t, J = 7.2 Hz, 1H), 3.69 (dd, J = 7.6, 14 Hz, 1H), 3.38 (dd, J = 7.4, 14 Hz, 1H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 193.0, 137.7, 134.6, 134.0, 129.7, 129.04, 128.97, 128.8, 127.3, 46.8, 39.7;

LRMS (EI) for $C_{15}H_{13}O$ (M–Br): calcd 209, found 209.



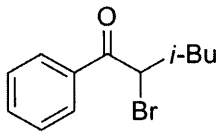
2-Bromo-4-chloro-1-phenylbutan-1-one [52868-15-2]. Prepared from 4-chlorobutyrophenone (1.81 g, 10 mmol) and bromine (0.51 mL, 10 mmol) in Et_2O (20 mL). Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a yellow oil in 89% yield (1.8 g).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.14-8.07 (m, 2H), 7.68-7.64 (m, 1H), 7.58-7.54 (m, 2H), 5.55 (dd, J = 2.4, 7.6 Hz, 1H), 3.85-3.78 (m, 2H), 2.76-2.57 (m, 2H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 192.7, 134.20, 134.17, 129.2, 129.1, 43.9, 42.6, 35.9;

IR (film): 1685, 1596, 1449, 1257, 1178, 851, 707 cm^{-1};

LRMS (EI) for $C_{10}H_{10}BrO$ (M–Cl): calcd 225, found 225.



2-Bromo-4-methyl-1-phenylpentan-1-one [33809-96-0]. Prepared from 4-methylvalerophenone (2.3 g, 13.1 mmol), which was prepared according to a literature procedure,[55] and bromine (0.67 mL, 13.1 mmol) in Et_2O (30 mL). Solvent system for chromatography: 3:1 hexanes:dichloromethane. The product was isolated as a clear, colorless oil in 30% yield (1.0 g).

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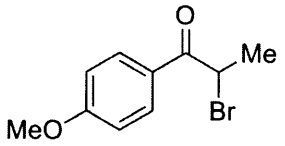
[55] Cho, C. S. *J. Mol. Catal. A: Chem.* **2005**, *240*, 55–60.

^{1}H NMR (400 MHz, $CDCl_3$): d 8.05-8.02 (m, 2H), 7.63-7.59 (m, 1H), 7.53-7.49 (m, 2H), 5.23 (dd, J = 6.4, 8.0 Hz, 1H), 2.12-1.99 (m, 2H), 1.91-1.81 (m, 1H), 0.98 (dd, J = 3.6, 6.8 Hz, 6H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 193.5, 134.7, 133.9, 129.03, 129.00, 45.9, 42.2, 26.5, 22.9, 22.0;

IR (film): 1687, 1597, 1448, 1369, 1278, 705, 686 cm^{-1};

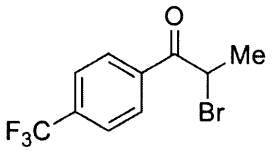
LRMS (EI) for $C_{12}H_{15}O$ (M–Br): calcd 175, found 175.



2-Bromo-1-(4-methoxyphenyl)propan-1-one [21086-33-9]. Prepared from 4-methoxypropiophenone (1.64 g, 10 mmol) and bromine (0.51 mL, 10 mmol) in Et_2O (20 mL). Solvent system for chromatography: 1:1 hexanes:dichloromethane. The product was isolated as a white solid in 61% yield (1.5 g).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.02 (dd, J = 2.4, 8.8 Hz, 2H), 6.96 (dd, J = 2.4, 8.8 Hz, 2H), 5.27 (q, J = 6.8 Hz, 1H), 3.88 (s, 3H), 1.89 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 192.2, 164.1, 131.5, 127.0, 114.1, 55.7, 41.7, 20.4.



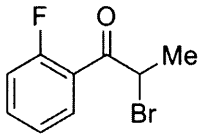
2-Bromo-1-(4-(trifluoromethyl)phenyl)propan-1-one [95728-57-7]. Prepared from 4-(trifluoromethyl)propiophenone (2.02 g, 10 mmol) and bromine (0.51 mL, 10 mmol) in Et_2O (25 mL). Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a white solid in 64% yield (1.8 g).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.14 (d, J = 8.4 Hz, 2H), 7.76 (d, J = 8.4 Hz, 2H), 5.27 (q, J = 6.4 Hz, 1H), 1.93 (d, J = 6.4 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): d 192.3, 136.8, 134.8 (q, J = 132 Hz), 129.3, 125.8 (t, J = 16 Hz), 123.5 (q, J = 1088 Hz), 41.4, 19.8;

IR (film): 1694, 1446, 1410, 1154, 1119, 1056, 999, 861, 768, 701 cm^{-1};

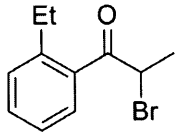
LRMS (EI) for $C_{10}H_8BrF_3O$: calcd 280, found 280.



2-Bromo-1-(2-fluorophenyl)propan-1-one [186036-09-9]. Prepared from 2'-fluoropropiophenone (1.51 g, 10 mmol) and bromine (0.51 mL, 10 mmol) in Et_2O (20

mL). Solvent system for chromatography: 3:1 hexanes:dichloromethane. The product was isolated as a clear, colorless oil in 75% yield (1.7 g).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.91-7.87 (m, 1H), 7.55-7.53 (m, 1H), 7.27-7.24 (m, 1H), 7.12 (ddd, J = 0.8, 8.0, 11.2 Hz, 1H), 5.30 (dq, J = 1.2, 6.8 Hz, 1H), 1.89 (dd, J = 0.8, 6.8 Hz, 3H).



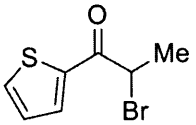
2-Bromo-1-(2-ethylphenyl)propan-1-one. Prepared from 2'-ethylpropiophenone (0.97 g, 6.3 mmol) and bromine (0.32 mL, 6.3 mmol) in Et_2O (12 mL). Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a yellow oil in 75% yield (1.1 g).

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.60-7.58 (m, 1H), 7.47-7.43 (m, 1H), 7.34 (d, J = 7.6 Hz, 1H), 7.30-7.26 (m, 1H), 5.20 (q, J = 6.4 Hz, 1H), 2.88-2.77 (m, 2H), 1.90 (d, J = 6.4 Hz, 3H), 1.27 (t, J = 7.6 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 197.4, 145.4, 135.8, 132.1, 130.7 127.7, 125.8, 45.5, 27.1, 20.6, 16.1;

IR (film): 1688, 1444, 1331, 1222, 941, 754 cm^{-1};

LRMS (EI) for $C_{11}H_{13}O$ (M–Br): calcd 161, found 161.



2-Bromo-1-(thiophen-2-yl)propan-1-one [75815-46-2]. Prepared from 2-propionylthiophene (1.94 g, 13.9 mmol) and bromine (0.71 mL, 13.9 mmol) in Et_2O (20 mL). Solvent system for chromatography: 3:1 hexanes:dichloromethane. The product was isolated as an orange oil in 40% yield (0.88 g).

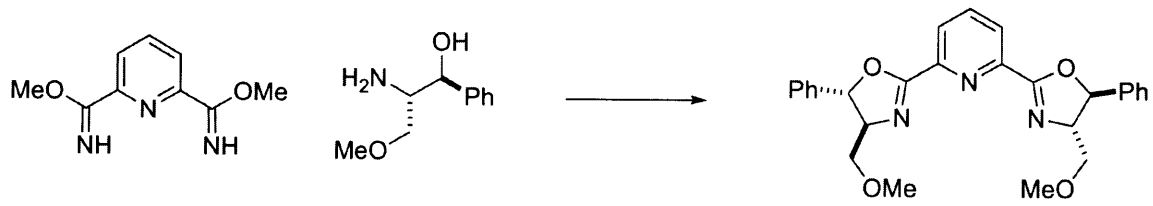
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.85 (dd, J = 1.0, 4.0 Hz, 1H), 7.70 (dd, J = 1.0, 5.2 Hz, 1H), 7.17 (dd, J = 4.0, 5.2 Hz, 1H), 5.15 (q, J = 6.8 Hz, 1H), 1.90 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 187.1, 141.0, 135.2, 133.3, 128.6, 42.7, 20.6;

IR (film): 1666, 1519, 1413, 1246, 1167, 1065, 855, 723, 648 cm^{-1};

LRMS (EI) for C_7H_8BrOS (M+H): calcd 219, found 219.

III. Preparation of Ligand 2



2,6-Bis((4*S*,5*S*)-4-(methoxymethyl)-5-phenyl-4,5-dihydrooxazol-2-yl)pyridine ((+)-2). A solution of (1*S*,2*S*)-(+)-2-amino-3-methoxy-1-phenyl-1-propanol (1.0 g, 5.5 mmol) and 2,6-pyridinedicarboximidic acid, dimethyl ester (531 mg, 2.75 mmol; 0.50 equiv) prepared according to a literature procedure [56] in dichloromethane (10 mL) was heated to reflux in a Schlenk tube for two days. The solvent was then removed, and the residue was purified by flash chromatography (2% triethylamine in ethyl acetate), which afforded the product as a white solid in 60% yield (761 mg; not optimized).

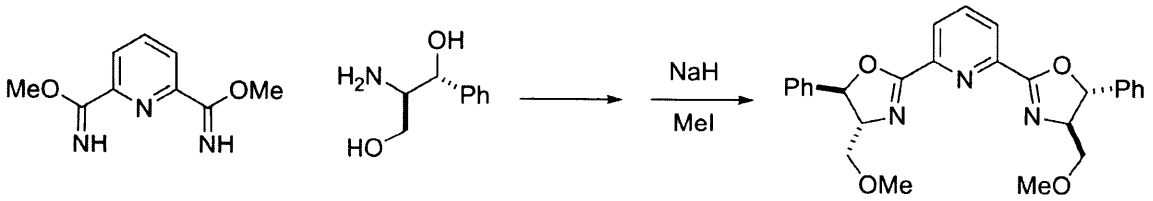
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.24 (d, J = 8.0 Hz, 2H), 7.92 (t, J = 8.0 Hz, 1H), 7.33-7.26 (m, 10H), 5.58 (d, J = 7.6 Hz, 2H), 4.42-4.37 (m, 2H), 3.74-3.70 (m, 2H), 3.63-3.59 (m, 2H), 3.42 (s, 6H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 163.1, 147.2, 140.5, 137.5, 128.9, 128.5, 126.4, 126.2, 84.9, 75.2, 74.3, 59.5;

IR (film): 1645, 1575, 1457, 1385, 1193, 1132, 964, 733, 699 cm^{-1};

HRMS (ESI) for $C_{27}H_{27}N_3O_4$ (M+H): calcd 458.2074, found 258.2063;

$[\alpha]^{22}_D$ +90 (*c* 1.03, $CDCl_3$).



2,6-Bis((4*R*,5*R*)-4-(methoxymethyl)-5-phenyl-4,5-dihydrooxazol-2-yl)pyridine ((–)-2). A solution of (1*R*,2*R*)-2-amino-1-phenyl-1,3-propanediol (2.00 g, 12 mmol) and 2,6-pyridinedicarboximidic acid, dimethyl ester (1.16 g, 6.0 mmol; 0.5 equiv) in dichloromethane (30 mL) was heated to 80 °C in a Schlenk tube for 40 h. The solvent was then removed, and the residue was washed with ethyl acetate to give the Pybox diol (1.8 g), which was dissolved in THF (45 mL) and cooled to 0 °C. NaH (351 mg, 14.7 mmol; 3.5 equiv) was added, and the solution was stirred for 1 h. Next, iodomethane (5.2 mL, 83.5 mmol; 20 equiv) was added. The reaction mixture was stirred overnight at room temperature, and then the reaction was quenched with saturated ammonium chloride (10 mL). The mixture was washed with brine (10 mL), dried over sodium sulfate, and concentrated. The resulting residue was passed through a column of silica gel (eluant: 2% triethylamine in ethyl acetate). The residue was

[56] Müller, P.; Boléa, C. *Helv. Chim. Acta* **2001**, *84*, 1093–1111.

recrystallized from ethyl acetate to give 400 mg of the product as a white solid (15% yield; not optimized).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.24 (d, J = 8.0 Hz, 2H), 7.92 (t, J = 8.0 Hz, 1H), 7.33-7.26 (m, 10H), 5.58 (d, J = 7.6 Hz, 2H), 4.42-4.37 (m, 2H), 3.74-3.70 (m, 2H), 3.63-3.59 (m, 2H), 3.42 (s, 6H);

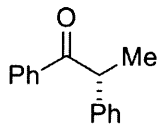
$[\alpha]^{22}_D$ –95 (*c* 1.01, $CDCl_3$).

IV. Asymmetric a-Arylations of Ketones

General Procedure A: Asymmetric a-arylation with ArZnI: A solution of the arylmagnesium bromide (1.6 mmol; 1.6 equiv) was added to a solution of ZnI_2 (510 mg, 1.6 mmol; 1.6 equiv) in THF (final concentration of ArZnI = 0.20 M) under argon. The mixture was stirred for 40 min at room temperature (a precipitate is immediately observed), and then it was cooled to –30 °C. $NiCl_2$·glyme (11.0 mg, 0.050 mmol; 0.050 equiv) and (+)-**2** (29.9 mg, 0.065 mmol; 0.065 equiv) were added to an oven-dried 50-mL flask. The flask was purged with argon, and the a-bromoketone (1.0 mmol; 1.0 equiv) was added, followed by glyme (13.5 mL). This solution was allowed to stir at room temperature for 20 min, and then it was cooled to –30 °C. The suspension of ArZnI (6.5 mL, 1.3 mmol; 1.3 equiv) was added dropwise over 3 min, and the reaction mixture was stirred at –30 °C for 4 h. Then, the reaction was quenched with saturated ammonium chloride (10 mL). The reaction mixture was diluted with Et_2O (50 mL), washed with distilled water (10 mL) and brine (10 mL), dried over magnesium sulfate, and concentrated. The product was purified by flash chromatography.
The second run was conducted with (–)-**2**.

General Procedure B: Asymmetric a-arylation with Ar_2Zn: A solution of $ZnCl_2$ in Et_2O (1.0 M; 1.3 mL, 1.3 mmol; 1.3 equiv) under argon was diluted with THF (5.2 mL) to provide a solution that was 0.20 M in zinc. A solution of the arylmagnesium bromide (2.6 mmol; 2.6 equiv) was added (if a suspension formed, the mixture was filtered through an acrodisc), and the solution was stirred for 20 min at r.t. Then, the reaction mixture was cooled to –30 °C. $NiCl_2$·glyme (11.0 mg, 0.050 mmol; 0.050 equiv) and (+)-**2** (29.9 mg, 0.065 mmol; 0.065 equiv) were added to an oven-dried 50-mL flask. The flask was purged with argon, and the a-bromoketone (1.00 mmol; 1.00 equiv) was added, followed by glyme (14.5 mL). This solution was allowed to stir at room temperature for 20 min, and then it was cooled to –30 °C. The solution of Ar_2Zn (5.5 mL, 1.1 mmol; 1.1 equiv) was added dropwise over ~5 min, and the reaction mixture was stirred at –30 °C for 90 min. Then, the reaction was quenched with saturated ammonium chloride (10 mL). The reaction mixture was diluted with Et_2O (50 mL), washed with distilled water (10 mL) and brine (10 mL), dried over magnesium sulfate, and concentrated. The product was purified by flash chromatography.

The second run was conducted with (–)-**2**.



1,2-Diphenylpropan-1-one (Table 2, entry 1; Table 4, entry 1). 2-Bromopropiophenone (213 mg, 1.0 mmol) and an arylzinc reagent prepared from phenylmagnesium bromide were used. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a clear, colorless oil.

PhZnI: Run 1, 172 mg (82% yield, 96% ee). Run 2, 189 mg (90% yield, 96% ee).

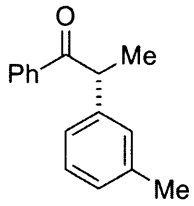
Ph_2Zn (in situ): Run 1, 170 mg (81% yield, 93% ee). Run 2, 178 mg (85% yield, 93% ee).

Ph_2Zn (solid): Run 1, 176 mg (84% yield, 95% ee). Run 2, 191 mg (91% yield, 95% ee).

The ee was determined on an OJ-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 14.7 (minor) and 16.8 (major) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.98-7.96 (m, 2H), 7.51-7.47 (m, 1H), 7.41-7.37 (m, 2H), 7.31-7.26 (m, 4H), 7.24-7.20 (m, 1H), 4.71 (q, J = 6.8 Hz, 1H), 1.55 (d, J = 6.8 Hz, 3H);

$[\alpha]^{22}_D$ +190 (*c* 1.08, $CHCl_3$); 96% ee, from (–)-**2**.



1-Phenyl-2-*m*-tolylpropan-1-one (Table 2, entry 2; Table 4, entry 2). 2-Bromopropiophenone (213 mg, 1.0 mmol) and an arylzinc iodide reagent prepared from *m*-tolylmagnesium bromide were used. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a yellow oil.

Ar_2Zn : Run 1, 201 mg (90% yield, 94% ee). Run 2 192 mg (85% yield, 91% ee).

ArZnI: Run 1, 197 mg (88% yield, 95% ee). Run 2, 195 mg (87% yield, 93% ee).

The ee was determined on an OJ-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 12.6 (major) and 13.7 (minor) min.

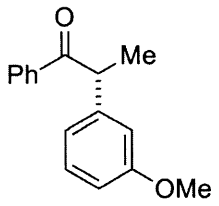
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.99-7.97 (m, 2H), 7.49-7.47 (m, 1H), 7.41-7.37 (m, 2H), 7.22-7.18 (m, 1H), 7.12 (br s, 2H), 7.04-7.02 (m, 1H), 4.67 (q, J = 6.8 Hz, 1H), 2.32 (s, 3H), 1.54 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 200.6, 141.6, 138.9, 136.7, 133.0, 129.04, 129.98, 128.7, 128.5, 127.9, 125.1, 48.0, 21.6, 19.8;

IR (film): 1682, 1597, 1449, 1208, 95.7, 734, 693 cm^{-1};

LRMS (EI) for $C_{16}H_{17}O$ (M+H): calcd 225, found 225;

$[\alpha]^{22}_D$ +182 (*c* 1.13, $CHCl_3$); 93% ee, from (–)-**2**.



2-(3-Methoxyphenyl)-1-phenylpropan-1-one (Table 2, entry 4). 2-Bromopropiophenone (213 mg, 1.0 mmol) and a diarylzinc reagent prepared from 3-methoxyphenylmagnesium bromide were used. Solvent system for chromatography: 1:1 hexanes:dichloromethane. The product was isolated as a clear, colorless oil.

Ar_2Zn (in situ): Run 1, 206 mg (86% yield, 96% ee). Run 2, 211 mg (88% yield, 93% ee).

The ee was determined on an OD-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 7.3 (minor) and 8.8 (major) min.

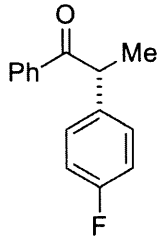
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.95-7.93 (m, 2H), 7.46-7.42 (m, 1H), 7.37-7.33 (m, 2H), 7.21-7.17 (m, 1H), 6.87-6.85 (m, 1H), 6.82-6.81 (m, 1H), 6.73-6.71 (m, 1H), 4.64 (q, J = 6.8 Hz, 1H), 3.73 (s, 3H), 1.51 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 200.3, 160.2, 143.2, 136.7, 133.0, 130.2, 129.0, 128.7, 120.4, 113.7, 112.3, 55.4, 48.1, 19.7;

IR (film): 1682, 1598, 1485, 1448, 1264, 1045, 957, 693 cm^{-1};

LRMS (EI) for $C_{16}H_{17}O_2$ (M+H): calcd 241, found 241;

$[\alpha]^{22}_D$ +166 (*c* 1.04, $CHCl_3$); 93% ee, from (–)-**2**.



2-(4-Fluorophenyl)-1-phenylpropan-1-one (Table 2, entry 4; Table 4, entry 3). 2-Bromopropiophenone (213 mg, 1.0 mmol) and an arylzinc iodide reagent prepared from *p*-fluorophenylmagnesium bromide were used. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a yellow oil.

Ar_2Zn: Run 1, 171 mg (75% yield, 95% ee). Run 2, 190 mg (83% yield, 95% ee).

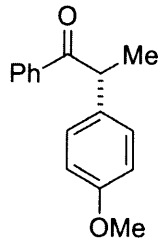
ArZnI: Run 1, 162 mg (71% yield, 96% ee). Run 2, 173 mg (76% yield, 96% ee).

The ee was determined on an OJ-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 12.5 (major) and 14.2 (minor) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.96-7.94 (m, 2H), 7.53-7.48 (m, 1H), 7.42-7.39 (m, 2H), 7.28-7.25 (m, 2H), 7.02-6.97 (m, 2H), 4.71 (q, J = 6.8 Hz, 1H), 1.54 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 200.4, 162.0, 137.3, 136.4, 133.1, 129.5, 128.9, 128.8, 116.0, 47.1, 19.8;

IR (film): 1684, 1507, 1448, 1223, 840, 738 cm^{-1};
LRMS (EI) for $C_{15}H_{14}FO$ (M+H): calcd 229, found 229;
$[\alpha]^{22}_D$ +159 (*c* 1.02, $CHCl_3$); 96% ee, from (–)-**2**.



2-(4-Methoxyphenyl)-1-phenylpropan-1-one (Table 2, entry 5; Table 4, entry 4) [(*S*) enantiomer: 35572-39-5]. 2-Bromopropiophenone (213 mg, 1.0 mmol) and an arylzinc iodide reagent prepared from 4-methoxyphenylmagnesium bromide were used. Solvent system for chromatography: 1:1 hexanes:dichloromethane. The product was isolated as a yellow oil.

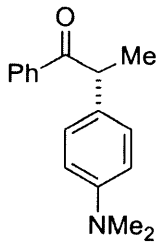
Ar_2Zn: Run 1, 199 mg (83% yield, 93% ee). Run 2, 182 mg (76% yield, 90% ee).

ArZnI: Run 1, 230 mg (96% yield, 96% ee). Run 2, 214 mg (89% yield, 95% ee).

The ee was determined on an AD-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 11.2 (minor) and 14.4 (major) min.

^1H NMR (400 MHz, $CDCl_3$): δ 7.94-7.91 (m, 2H), 7.47-7.43 (m, 1H), 7.37-7.33 (m, 2H), 7.24-7.15 (m, 2H), 6.83-6.79 (m, 2H), 4.65 (q, J = 6.8 Hz, 1H), 3.76 (s, 3H), 1.51 (d, J = 6.8 Hz, 3H);

$[\alpha]^{22}_D$ +161 (*c* 1.00, $CHCl_3$); 95% ee, from (–)-**2**.



2-(4-(Dimethylamino)phenyl)-1-phenylpropan-1-one (Table 2, entry 6; Table 4, entry 5) [740843-43-0]. 2-Bromopropiophenone (213 mg, 1.0 mmol) and an arylzinc iodide reagent prepared from *p*-(*N,N*-dimethylamino)phenylmagnesium bromide were used. Solvent system for chromatography: 49:49:2 hexanes:dichloromethane:triethylamine. The product was isolated as a white solid.

Ar_2Zn: Run 1, 231 mg (91% yield, 88% ee). Run 2, 219 mg (86% yield, 89% ee).

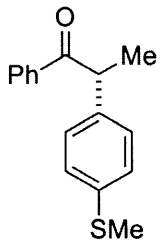
ArZnI: Run 1, 218 mg (86% yield, 93% ee). Run 2, 213 mg (84% yield, 92% ee).

The ee was determined on an AD-H column (hexanes:isopropanol 95:5, flow 1.0 mL/min), with enantiomers eluting at 7.5 (minor) and 10.9 (major) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.03-8.01 (m, 2H), 7.47-7.46 (m, 1H), 7.41-7.37 (m, 2H), 7.21-7.19 (m, 2H), 6.71-6.69 (m, 2H), 4.65 (q, J = 6.8 Hz, 1H), 2.91 (s, 6H), 1.55 (d, J = 6.8 Hz, 3H);

IR (film): 1684, 1653, 1559, 1521, 1507, 1228 cm^{-1};

$[\alpha]^{22}_D$ –162 (*c* 0.98, $CHCl_3$); 93% ee, from (+)-**2**.



2-(4-(Methylthio)phenyl)-1-phenylpropan-1-one (Table 2, entry 7; Table 4, entry 6). 2-Bromopropiophenone (213 mg, 1.0 mmol) and an arylzinc iodide reagent prepared from 4-(methylthio)phenylmagnesium bromide were used. Solvent system for chromatography: 1:1 hexanes:dichloromethane. The product was isolated as a white solid.

Ar_2Zn: Run 1, 217 mg (85% yield, 93% ee). Run 2, 201 mg (78% yield, 91% ee).

ArZnI: Run 1, 182 mg (71% yield, 96% ee). Run 2, 182 mg (71% yield, 95% ee).

The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 7.7 (minor) and 8.9 (major) min.

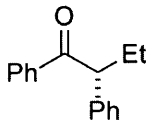
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.96-7.94 (m, 2H), 7.51-7.47 (m, 1H), 7.41-7.37 (m, 2H), 7.23-7.17 (m, 4H), 4.66 (q, J = 6.8 Hz, 1H), 2.44 (s, 3H), 1.52 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 200.4, 138.4, 137.1, 136.6, 133.1, 128.9, 128.7, 128.5, 127.3, 47.5, 19.6, 16.0;

IR (film): 2927, 2361, 1653, 1457, 1131, 971, 699 cm^{-1};

LRMS (EI) for $C_{16}H_{17}OS$ (M+H): calcd 257, found 257;

$[\alpha]^{22}_D$ +125 (*c* 1.00, $CHCl_3$); 95% ee, from (–)-**2**.



1,2-Diphenylbutan-1-one (Table 3, entry 1; Table 4, entry 7) [(*S*) enantiomer: 175274-19-8; (*R*) enantiomer: 175274-18-7]. 2-Bromo-1-phenylbutan-1-one (227 mg, 1.0 mmol) and an arylzinc reagent prepared from phenylmagnesium bromide were used. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a white solid.

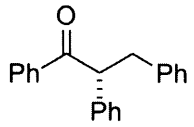
Ph_2Zn (in situ): Run 1, 202 mg (90% yield, 88% ee). Run 2, 209 mg (93% yield, 88% ee).

PhZnI: Run 1, 186 mg (83% yield, 94% ee). Run 2, 197 mg (88% yield, 93% ee).

The ee was determined on an OD-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 5.2 (minor) and 5.8 (major) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.00-7.98 (m, 2H), 7.50-7.47 (m, 1H), 7.42-7.38 (m, 2H), 7.35-7.30 (m, 4H), 7.24-7.22 (m, 1H), 4.47 (t, J = 7.0 Hz, 1H), 2.26-2.19 (m, 1H), 1.92-1.85 (m, 1H), 0.93 (t, J = 7.4 Hz, 3H);

$[\alpha]^{22}_D$ +155 (*c* 1.01, $CHCl_3$); 88% ee, from (–)-**2**.



1,2,3-Triphenylpropan-1-one (Table 3, entry 2; Table 4, entry 8). 2-Bromo-1,3-diphenylpropan-1-one (289 mg, 1.0 mmol) and an arylzinc iodide reagent prepared from phenylmagnesium bromide were used. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a white solid.

Ph_2Zn (in situ): Run 1, 257 mg (90% yield, 86% ee). Run 2, 237 mg (83% yield, 89% ee).

PhZnI: Run 1, 206 mg (72% yield, 95% ee). Run 2, 229 mg (80% yield, 94% ee).

The ee was determined on an OJ-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 17.2 (major) and 20.0 (minor) min.

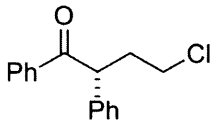
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93-7.89 (m, 2H), 7.48-7.44 (m, 1H), 7.38-7.34 (m, 2H), 7.30-7.19 (m, 7H), 7.17-7.13 (m, 1H), 7.11-7.08 (m, 2H), 4.83 (t, J = 7.2 Hz, 1H), 3.58 (dd, J = 7.2, 13.6 Hz, 1H), 3.08 (dd, J = 7.2, 13.6 Hz, 1H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 199.4, 140.0, 139.3, 136.9, 133.1, 129.3, 129.1, 128.9, 128.7, 128.5, 128.4, 127.4, 126.3, 56.1, 40.3;

IR (film): 1675, 1596, 1447, 1244, 950, 757, 736, 695 cm^{-1};

LRMS (EI) for $C_{21}H_{18}O$: calcd 286, found 286;

$[\alpha]^{22}_D$ +215 (*c* 1.00, $CHCl_3$); 94% ee, from (–)-**2**.



4-Chloro-1,2-diphenylbutan-1-one (Table 3, entry 3; Table 4, entry 9). 2-Bromo-4-chloro-1-phenylbutan-1-one (262 mg, 1.0 mmol) and an arylzinc reagent prepared from phenylmagnesium bromide were used. The reaction was run at –20 °C. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a yellow oil.

Ph_2Zn (in situ): Run 1, 203 mg (78% yield, 87% ee). Run 2, 219 mg (83% yield, 89% ee).

PhZnI: Run 1, 225 mg (87% yield, 93% ee). Run 2, 240 mg (93% yield, 91% ee).

1The ee was determined on an OJ-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 16.0 (minor) and 16.9 (major) min.

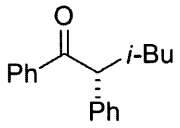
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.00-7.97 (m, 2H), 7.52-7.49 (m, 1H), 7.42-7.38 (m, 2H), 7.34-7.31 (m, 4H), 7.26-7.22 (m, 1H), 4.47 (dd, , J = 6.8, 7.6 Hz, 1H), 3.63-3.58 (m, 1H), 3.47-3.41 (m, 1H), 2.64-2.56 (m, 1H), 2.35-2.27 (m, 1H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 199.2, 138.3, 136.5, 133.3, 129.4, 129.0, 128.8, 128.5, 127.7, 50.3, 43.3, 36.2;

IR (film): 1684, 1653, 1559, 1540, 1507, 1448, 756, 698 cm^{-1};

LRMS (EI) for $C_{16}H_{15}ClO$: calcd 258, found 258;

$[\alpha]^{22}_D$ +233 (*c* 1.02, $CHCl_3$); 91% ee, from (–)-**2**.



4-Methyl-1,2-diphenylpentan-1-one (Table 3, entry 4). 2-Bromo-4-methyl-1-phenylpentan-1-one (191 mg, 0.75 mmol) and an arylzinc reagent prepared from phenylmagnesium bromide were used. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a white solid.

Ph_2Zn (in situ): Run 1, 168 mg (89% yield, 94% ee). Run 2, 166 mg (88% yield, 95% ee).

The ee was determined on an IA-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 5.2 (minor) and 6.2 (major) min.

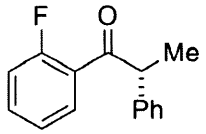
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.99 (d, J = 7.2 Hz, 2H), 7.50 (t, J = 7.2 Hz, 1H), 7.43-7.39 (m, 2H), 7.34-7.27 (m, 4H), 7.23-7.19 (m, 1H), 4.69 (t, J = 7.2 Hz, 1H), 2.13-2.069 (m, 1H), 1.75 (q, J = 6.8 Hz, 1H), 1.51 (s, J = 6.8 Hz, 1H), 0.96 (d, J = 6.8 Hz, 3H), 0.91 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 200.4, 140.0, 137.1, 133.0, 129.1, 128.8, 128.7, 128.4, 127.1, 51.5, 43.2, 26.0, 23.1, 22.7;

IR (film): 1682, 1597, 1448, 1208, 757, 698 cm^{-1};

LRMS (EI) for $C_{18}H_{21}O$ (M+H): calcd 253, found 253;

$[\alpha]^{22}_D$ +144 (*c* 0.98, $CHCl_3$); 95% ee, from (–)-**2**.



1-(2-Fluorophenyl)-2-phenylpropan-1-one (Table 3, entry 5; Table 4, entry 10). 2-Bromo-1-(2-fluorophenyl)propan-1-one (231 mg, 1.0 mmol) and an arylzinc reagent prepared from phenylmagnesium bromide were used. Solvent system for chromatography: 3:1 hexanes:dichloromethane. The product was isolated as a yellow oil.

Ph_2Zn (in situ): Run 1, 151 mg (66% yield, 70% ee). Run 2, 157 mg (69% yield, 71% ee).

PhZnI: Run 1, 182 mg (80% yield, 73% ee). Run 2, 180 mg (79% yield, 70% ee).

The ee was determined on an OJ-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 12.5 (minor) and 16.3 (major) min.

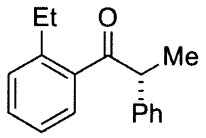
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.75 (td, J = 2.0, 7.6 Hz, 1H), 7.43-7.37 (m, 1H), 7.29-7.27 (m, 4H), 7.22-7.18 (m, 1H), 7.14 (td, J = 1.2, 7.6 Hz, 1H), 7.03 (ddd, J = 1.2, 8.4, 11.2 Hz, 1H), 4.65 (m, 1H), 1.56 (dd, J = 0.8, 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 199.8 (d, J = 16 Hz), 161.1 (d, J = 1000 Hz), 140.7, 134.2 (d, J = 36 Hz), 131.2 (d, J = 12 Hz), 128.9, 128.4, 127.2, 126.3 (d, J = 52 Hz), 124.6 (d, J = 16 Hz), 116.7 (d, J = 96 Hz), 52.1 (d, J = 28 Hz), 19.1;

IR (film): 1687, 1609, 1480, 1450, 1273, 1212, 762, 700 cm^{-1};

LRMS (EI) for $C_{15}H_{13}FO$: calcd 228, found 228;

$[\alpha]^{22}_D$ +175 (*c* 1.04, $CHCl_3$); 70% ee, from (–)-**2**.



1-(2-Ethylphenyl)-2-phenylpropan-1-one (Table 3, entry 6; Table 4, entry 11). 2-Bromo-1-(2-ethylphenyl)propan-1-one (241 mg, 1.0 mmol) and an arylzinc iodide reagent prepared from phenylmagnesium bromide were used. The reaction was run at –20 °C, with a large stir bar. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a yellow oil.

Ph_2Zn (in situ): Run 1, 110 mg (46% yield, 74% ee). Run 2, 93 mg (39% yield, 78% ee).

PhZnI: Run 1, 195 mg (82% yield, 75% ee). Run 2, 181 mg (76% yield, 70% ee).

The ee was determined on an OJ-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 11.6 (major) and 20.1 (minor) min.

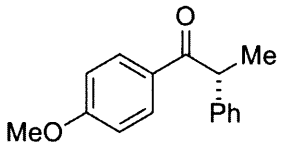
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.54 (dd, J = 1.2, 7.6 Hz, 1H), 7.34-7.21 (m, 8H), 4.58 (q, J = 6.8 Hz, 1H), 2.69-2.59 (m, 2H), 1.63 (d, J = 7.2 Hz, 3H), 1.17 (t, J = 7.6 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 205.3, 144.0. 140.5, 138.9, 131.0, 130.3, 129.0, 128.3, 127.8, 127.2, 125.5, 51.3, 26.9, 18.7, 16.2;

IR (film): 1687, 1600, 1453, 1250, 943, 756, 700 cm^{-1};

LRMS (EI) for $C_{17}H_{18}O$: calcd 238, found 238;

$[\alpha]^{22}_D$ –79 (*c* 1.03, $CHCl_3$); 71% ee, from (+)-**2**.



1-(4-Methoxyphenyl)-2-phenylpropan-1-one (Table 3, entry 7; Table 4, entry 12) [(*S*) enantiomer: 36065-28-8 ; (*R*) enantiomer: 28968-16-3]. 2-Bromo-1-(4-methoxyphenyl)propan-1-one (243 mg, 1.0 mmol) and an arylzinc iodide reagent prepared from phenylmagnesium bromide were used. Solvent system for chromatography: 1:1 dichloromethane:hexanes. The product was isolated as a white solid.

Ph_2Zn (in situ): Run 1, 219 mg (91% yield, 94% ee). Run 2, 221 mg (92% yield, 95% ee).

Run 1, 206 mg (86% yield, 97% ee). Run 2, 223 mg (93% yield, 95% ee).

The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 9.8 (minor) and 11.1 (major) min.

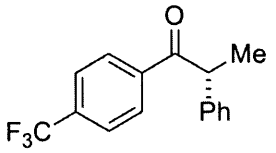
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.95-7.91 (m, 2H), 7.27-7.26 (m, 4H), 7.19-7.16 (m, 1H), 6.86 (d, J = 8.8 Hz, 2H), 4.67 (q, J = 6.8 Hz, 1H), 3.80 (s, 3H), 1.54 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 199.1, 163.4, 142.1, 131.3, 129.6, 129.1, 127.9, 127.0, 113.9, 55.6, 47.7, 19.8;

IR (film): 1674, 1600, 1510, 1251, 1170, 1029, 701 cm^{-1};

LRMS (EI) for $C_{16}H_{17}O_2$ (M+H): calcd 241, found 241;

$[\alpha]^{22}_D$ +117 (*c* 1.03, $CHCl_3$); 95% ee, from (–)-**2**.



2-Phenyl-1-(4-(trifluoromethyl)phenyl)propan-1-one (Table 3, entry 8; Table 4, entry 13). 2-Bromo-1-(4-(trifluoromethyl)phenyl)propan-1-one (281 mg, 1.0 mmol) and an arylzinc reagent prepared from phenylmagnesium bromide were used. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a white solid.

Ph_2Zn (in situ): Run 1, 220 mg (79% yield, 89% ee). Run 2, 234 mg (84% yield, 88% ee).

PhZnI: Run 1, 203 mg (73% yield, 87% ee). Run 2, 217 mg (78% yield, 86% ee).

The ee was determined on an OJ-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 7.1 (minor) and 8.3 (major) min.

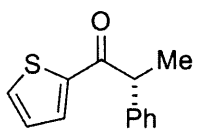
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.04 (d, J = 8.0 Hz, 2H), 7.64 (d, J = 8.0 Hz, 2H), 7.28-7.21 (m, 5H), 4.67 (q, J = 6.8 Hz, 1H), 1.56 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 199.4, 141.0, 139.4, 134.2 (q, J = 128 Hz), 129.4, 129.3, 127.9, 127.4, 125.7 (q, J = 16 Hz), 123.8 (q, J = 1084 Hz), 48.7, 19.6;

IR (film): 1690, 1409, 1323, 1170, 1130, 1067, 700 cm^{-1};

LRMS (EI) for $C_{16}H_{13}F_3O$: calcd 278, found 278;

$[\alpha]^{22}_D$ +145 (*c* 1.05, $CHCl_3$); 86% ee, from (–)-**2**.



2-Phenyl-1-(thiophen-2-yl)propan-1-one (Table 3, entry 9; Table 4, entry 14). 2-Bromo-1-(thiophen-2-yl)propan-1-one (219 mg, 1.0 mmol) and an arylzinc reagent prepared from phenylmagnesium bromide were used. The reaction was run for

six hours. Solvent system for chromatography: 3:1→2:1 hexanes:dichloromethane. The product was isolated as a white solid.

Ph_2Zn (in situ): Run 1, 192 mg (89% yield, 92% ee). Run 2, 186 mg (86% yield, 93% ee).

Run 1, 171 mg (79% yield, 95% ee). Run 2, 179 mg (83% yield, 96% ee).
The ee was determined on an OJ-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 24.5 (minor) and 37.0 (major) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.68 (d, J = 3.6 Hz, 1H), 7.57 (dd, J = 0.8, 4.8 Hz, 1H), 7.35-7.30 (m, 4H), 7.27-7.22 (m, 1H), 7.05 (dd, J = 4.0, 4.4 Hz, 1H), 4.52 (s, J = 6.8 Hz, 1H), 1.55 (d, J = 6.8 Hz, 3H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 193.5, 143.9, 141.5, 133.8, 132.6, 129.1, 128.2, 127.9, 127.3, 49.5, 19.4;

IR (film): 1661, 1414, 1323, 1235, 856, 699 cm^{-1};

LRMS (EI) for $C_{13}H_{13}OS$ (M+H): calcd 217, found 217;

$[\alpha]^{22}_D$ +161 (*c* 1.00, $CHCl_3$); 96% ee, from (–)-**2**.

Gram-scale asymmetric a-arylation of ketones: Negishi reaction of 2-bromopropiophenone with phenylzinc iodide. Because the reaction mixture is heterogeneous, we decided to determine if General Procedure A can be applied without modification to a cross-coupling that is carried out on a larger scale. In a gram-scale experiment, we found that the ee remains the same, but that the reaction is much slower. However, if the cross-coupling is conducted at –10 °C, the desired product is obtained in 93% ee and 81% yield.

V. Assignment of Absolute Configuration

The optical rotations were measured of the products generated in the presence of (–)-**2**.

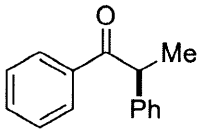


Table 4, entry 1.
[a]$^{22}_D$ +190 (*c* 1.08, $CHCl_3$); 96% ee, from (–)-**2**. Lit.[57] [a]$^{19}_D$ +196 (*c* 1.10, $CHCl_3$).

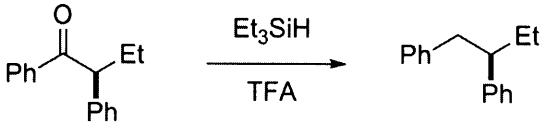


Table 4, entry 7.
[a]$^{22}_D$ –75 (*c* 1.01, $CHCl_3$); 94% ee, from (–)-**2**. Lit.[58] [a]$^{20}_D$ –102 (*c* 1, $CHCl_3$).

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[57] Shionhara, T.; Suzuki, K. *Synthesis* **2003**, 141–146.

[58] Ruano, J. L. G.; Aranda, M. T.; Puente, M. *Tetrahedron* **2005**, *61*, 10099–10104.

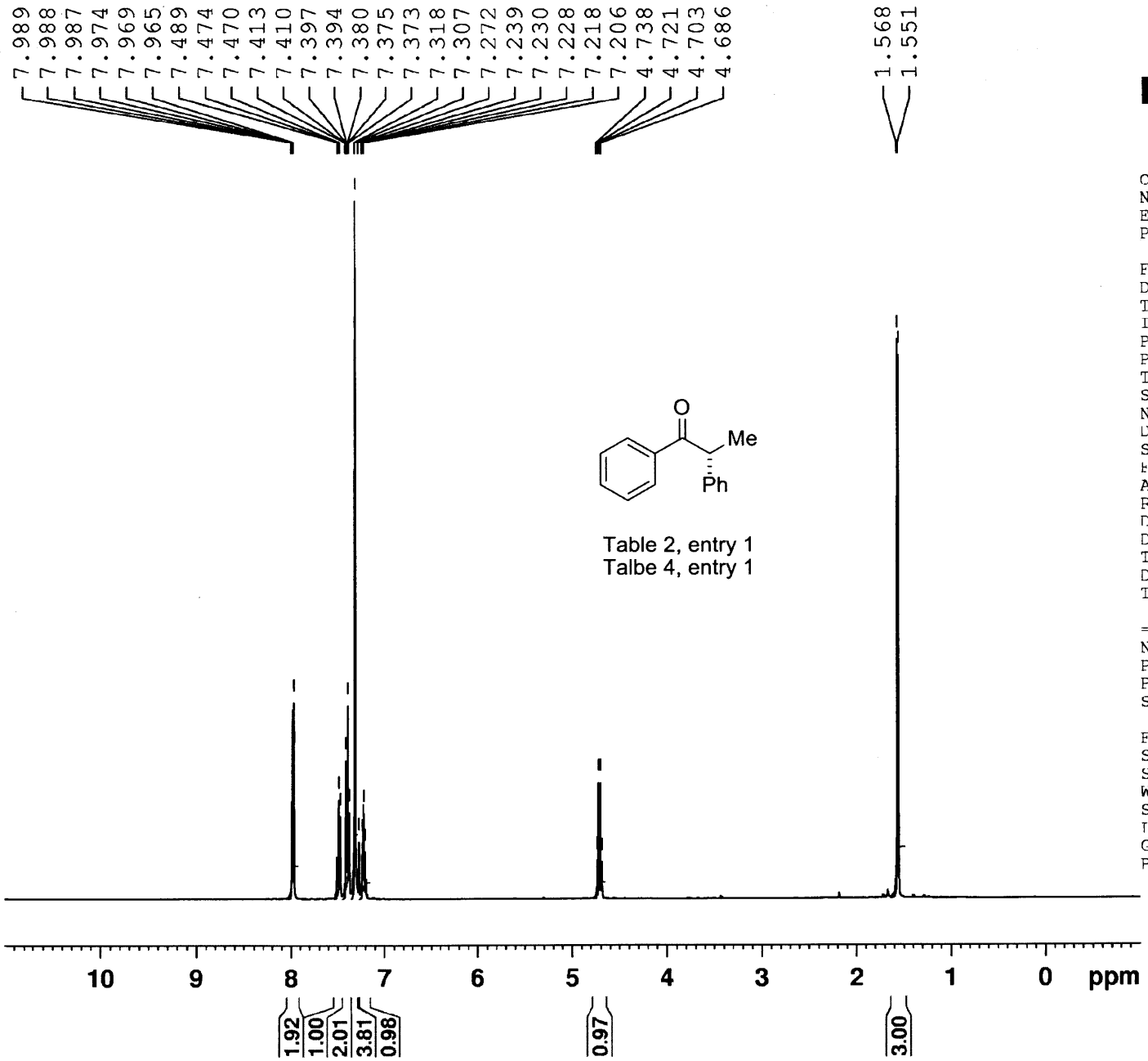


Table 2, entry 1
Talbe 4, entry 1

BRUKER

Current Data Parameters
NAME II-297
EXPNO 3
PROCNO 1

F2 - Acquisition Parameters
Date_ 20070626
Time 9.56
INSTRUM spect
PROBHD 5 mm QNP 1H/13
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 161.3
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 14.00 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300049 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00

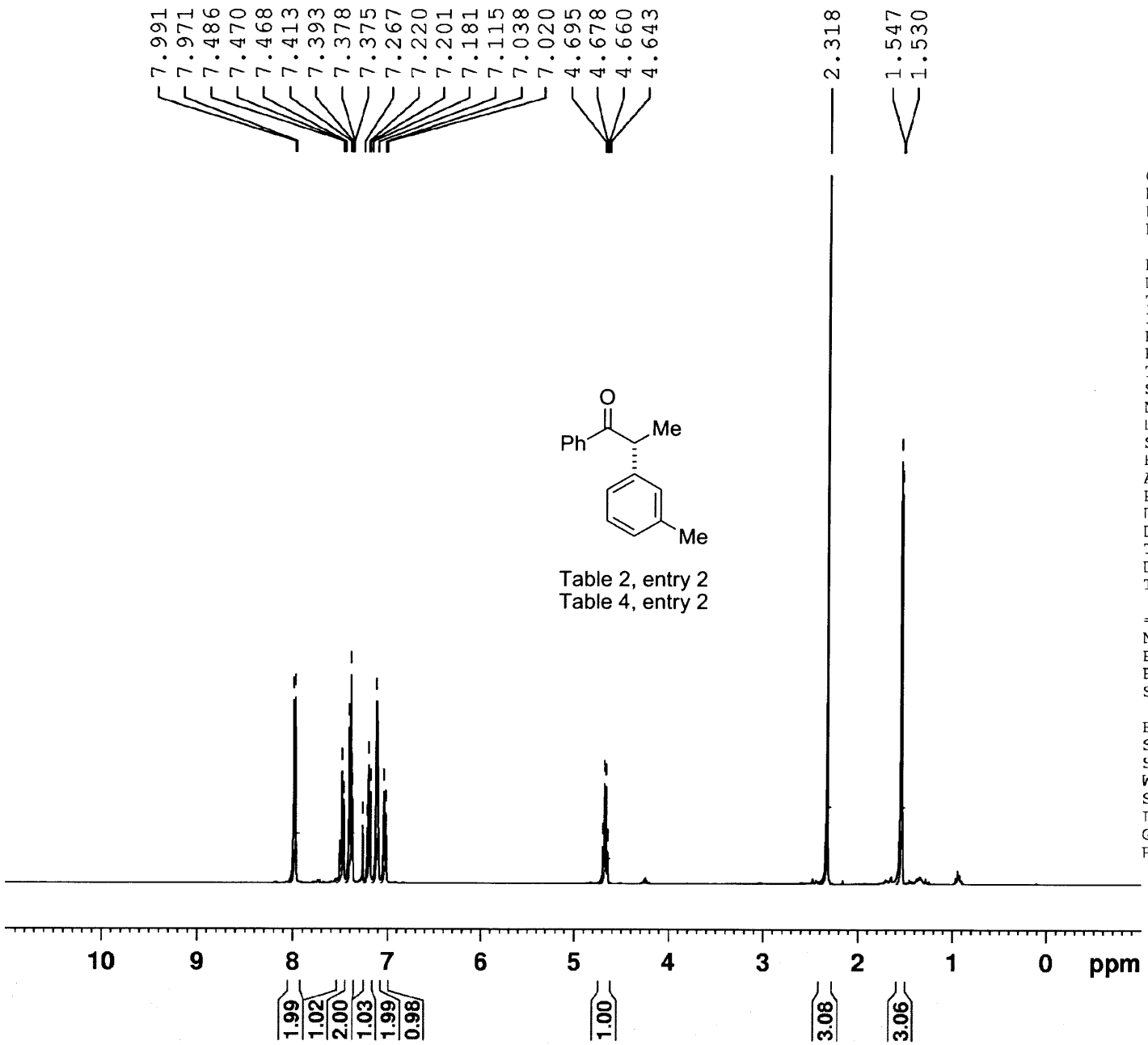


Table 2, entry 2
Table 4, entry 2

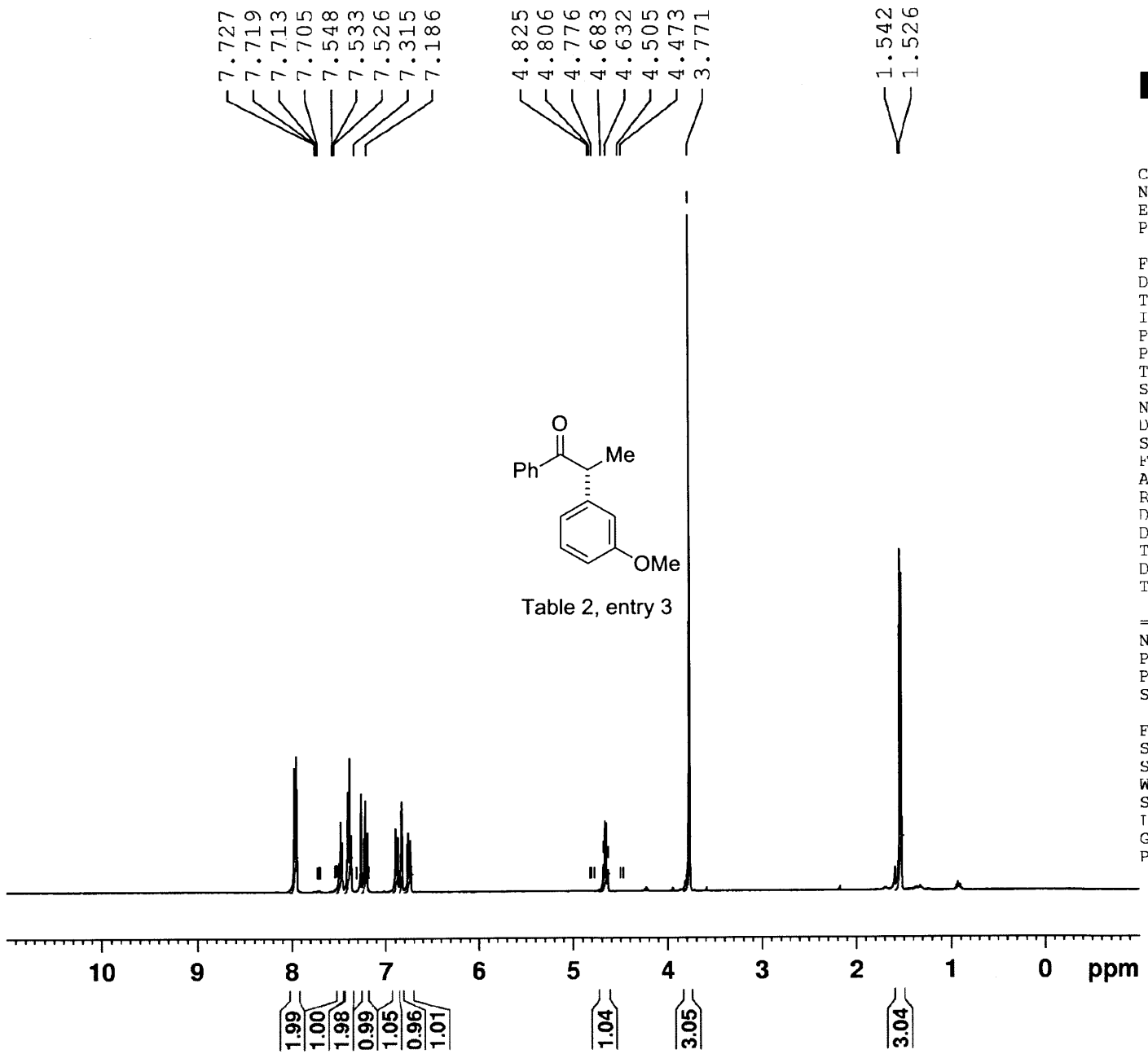
BRUKER

Current Data Parameters
NAME II-289
EXPNO 1
PROCNO 1

F2 - Acquisition Parameters
Date_ 20070619
Time 20.07
INSTRUM spect
PROBHD 5 mm QNP 1H/13
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 143.7
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 14.00 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300069 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00



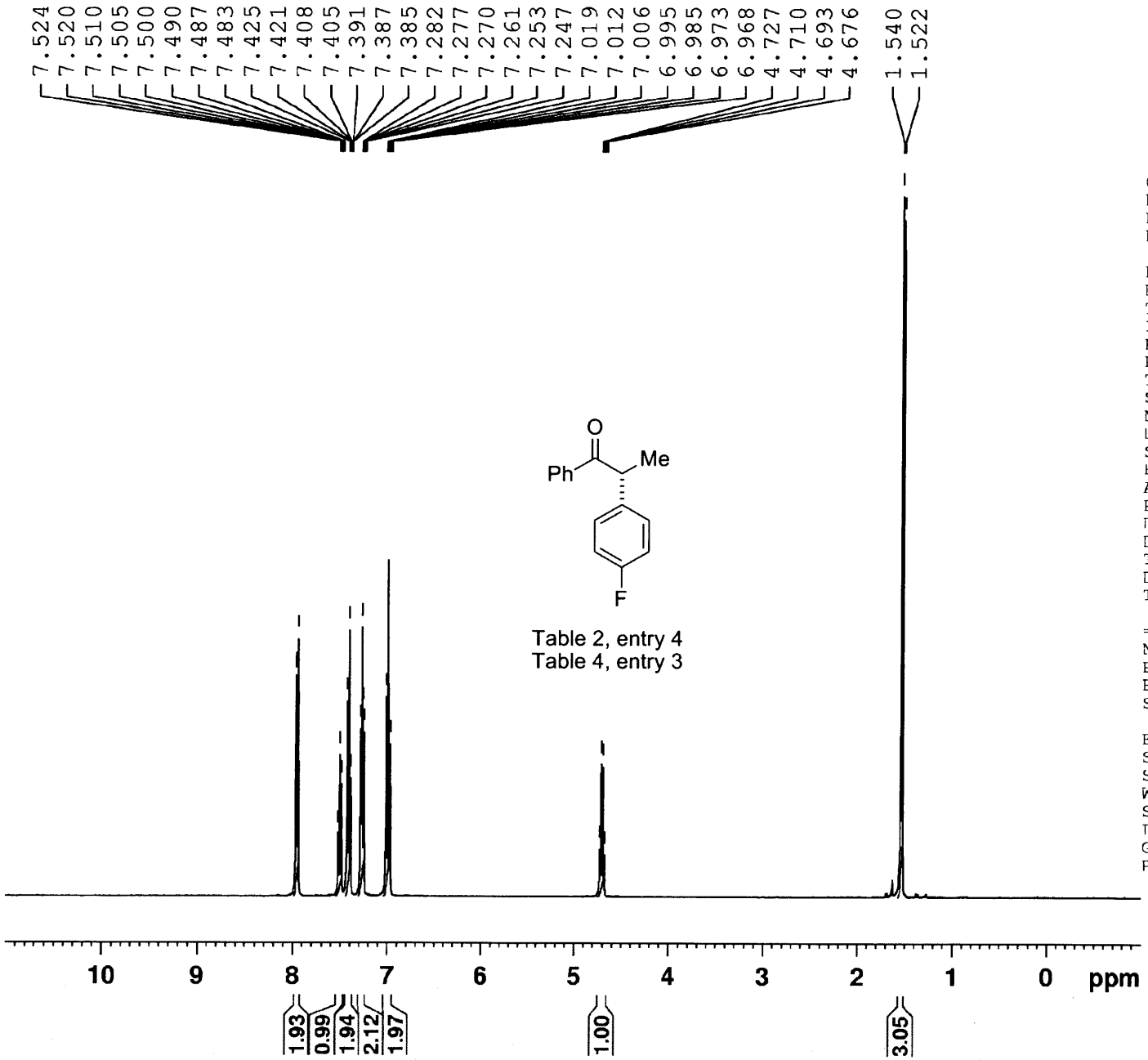
BRUKER

Current Data Parameters
NAME II-284
EXPNO 1
PROCNO 1

F2 - Acquisition Parameters
Date_ 20070614
Time 18.14
INSTRUM spect
PROBHD 5 mm BBO BB-1H
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 128
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 15.07 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300072 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00



BRUKER

Current Data Parameters
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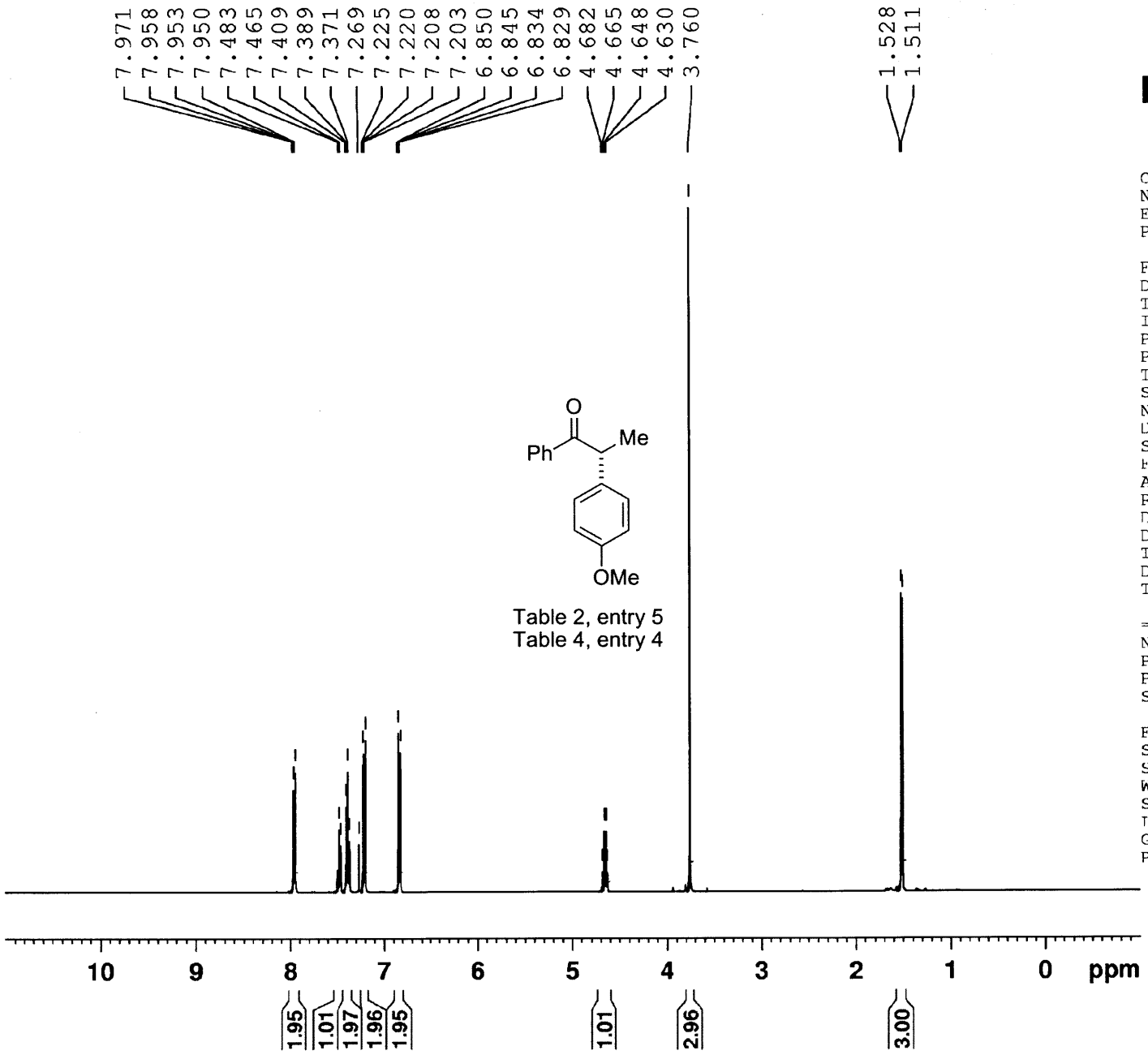
EXPNO 1
PROCNO 1

F2 - Acquisition Parameters
Date_ 20070706
Time 13.34
INSTRUM spect
PROBHD 5 mm QNP 1H/13
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 228.1
DW 60.400 usec
DE 6.00 usec
TE 294.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 14.00 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300057 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00



BRUKER

Current Data Parameters
NAME III-072
EXPNO 1
PROCNO 1

F2 - Acquisition Parameters
Date_ 20070905
Time 9.51
INSTRUM spect
PROBHD 5 mm BBO BB-1H
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 11
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 128
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 15.07 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300059 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00

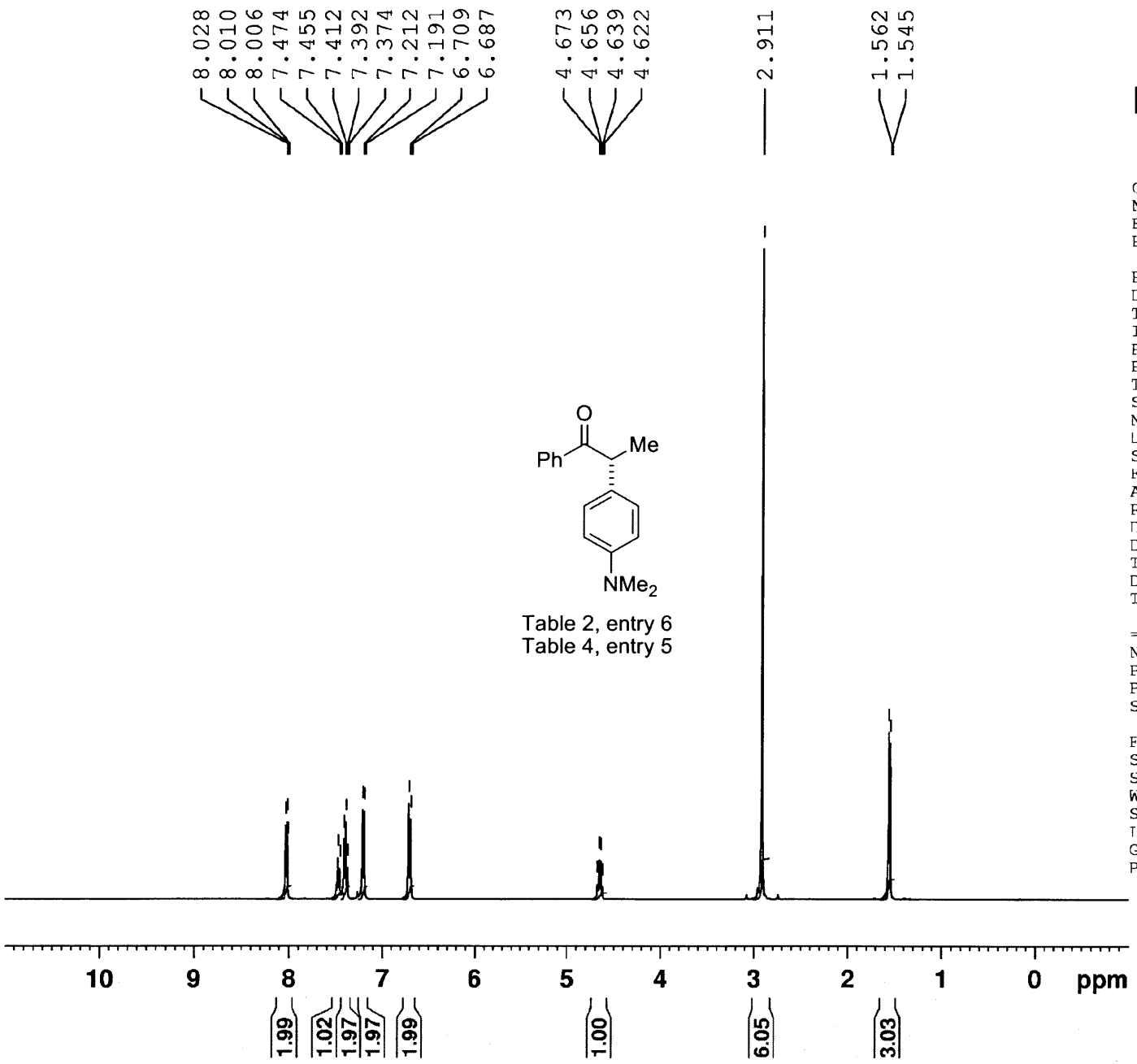


Table 2, entry 6
Table 4, entry 5

Current Data Parameters

NAME	II-276
EXPNO	4
PROCNO	1

F2 - Acquisition Parameters

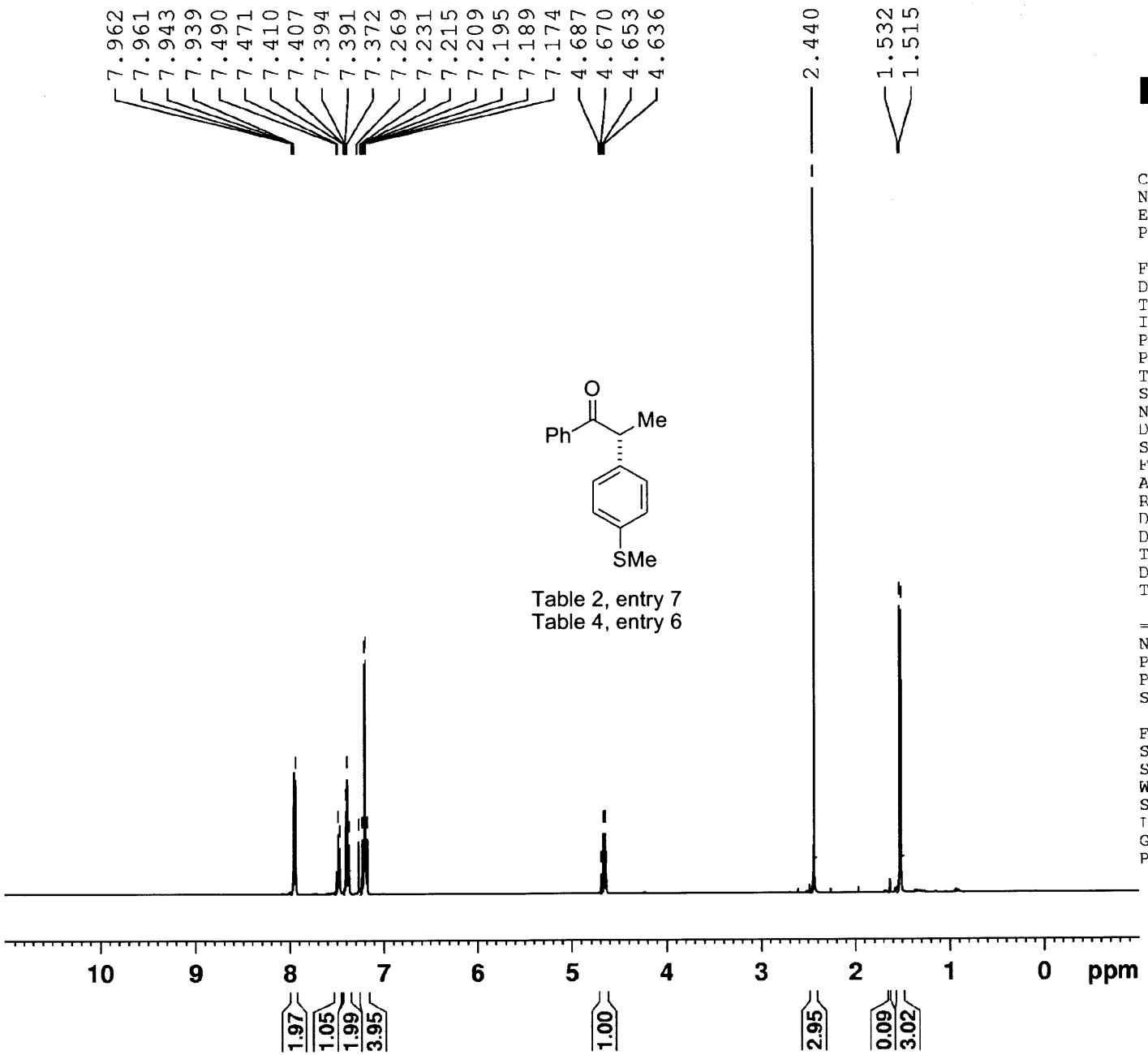
Date_	20070607
Time	16.41
INSTRUM	spect
PROBHD	5 mm BBO BB-1H
PULPROG	zg30
TD	65536
SOLVENT	CDCl3
NS	16
DS	2
SWH	8278.146 Hz
FIDRES	0.126314 Hz
AQ	3.9584243 sec
RG	35.9
DW	60.400 usec
DE	6.00 usec
TE	294.2 K
D1	1.00000000 sec
TD0	1

======== CHANNEL f1 ========

NUC1	1H
P1	15.07 usec
PL1	0.00 dB
SFO1	400.1324710 MHz

F2 - Processing parameters

SI	65536
SF	400.1300065 MHz
WDW	EM
SSB	0
LB	0.30 Hz
GB	0
PC	1.00



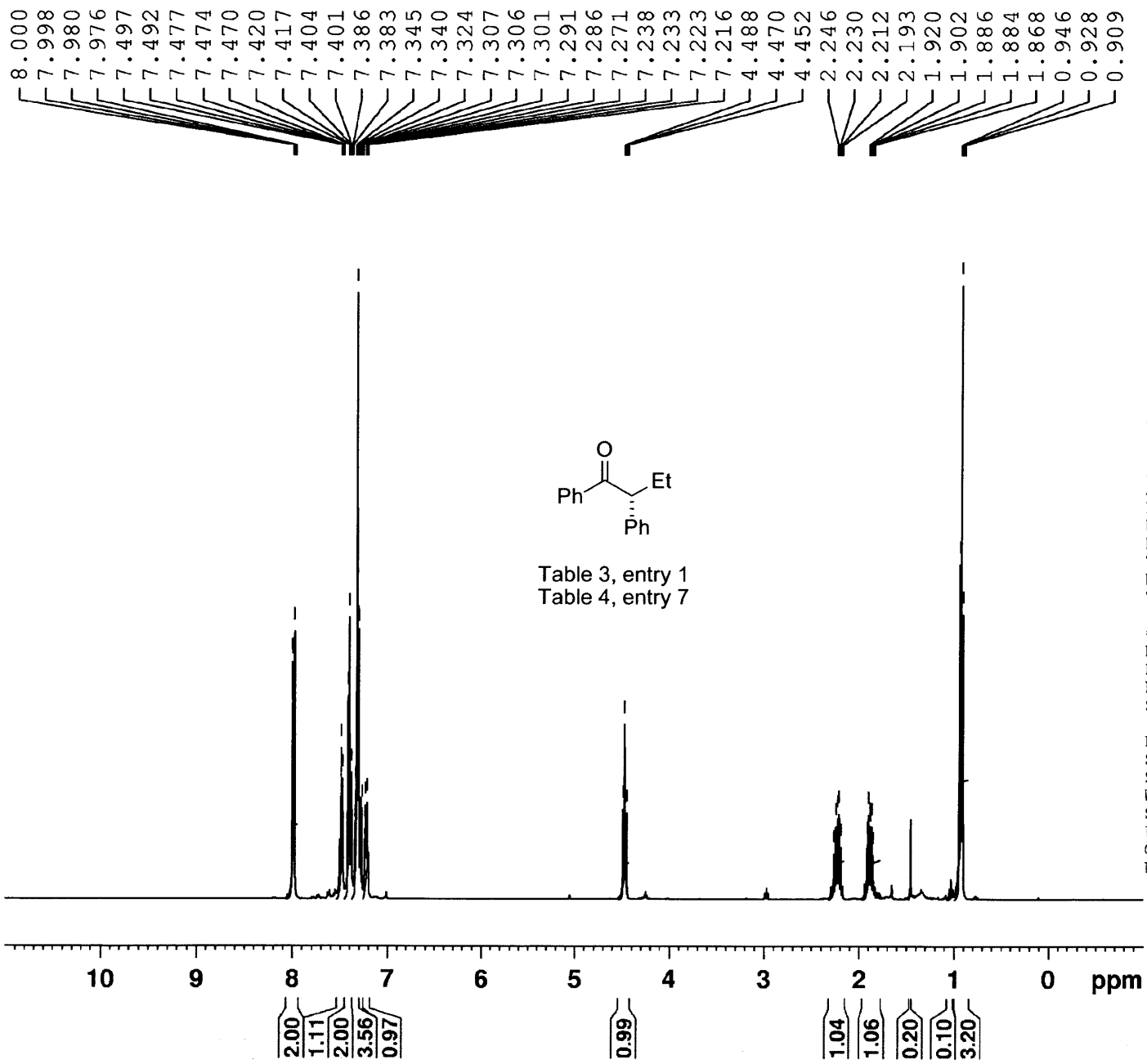
BRUKER

Current Data Parameters
NAME II-280
EXPNO 3
PROCNO 1

F2 - Acquisition Parameters
Date_ 20070606
Time 11.17
INSTRUM spect
PROBHD 5 mm BBO BB-1H
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 128
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 15.07 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300060 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00



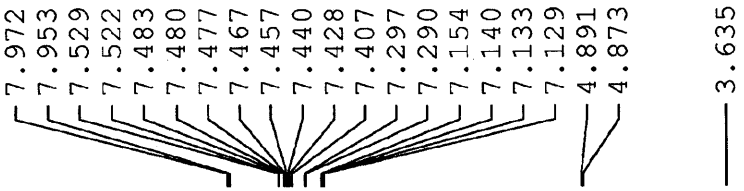
BRUKER

Current Data Parameters
NAME II-287
EXPNO 1
PROCNO 1

F2 - Acquisition Parameters
Date_ 20070617
Time 8.24
INSTRUM spect
PROBHD 5 mm BBO BB-1H
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 80.6
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 15.07 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300053 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00



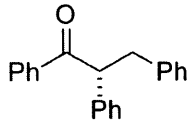
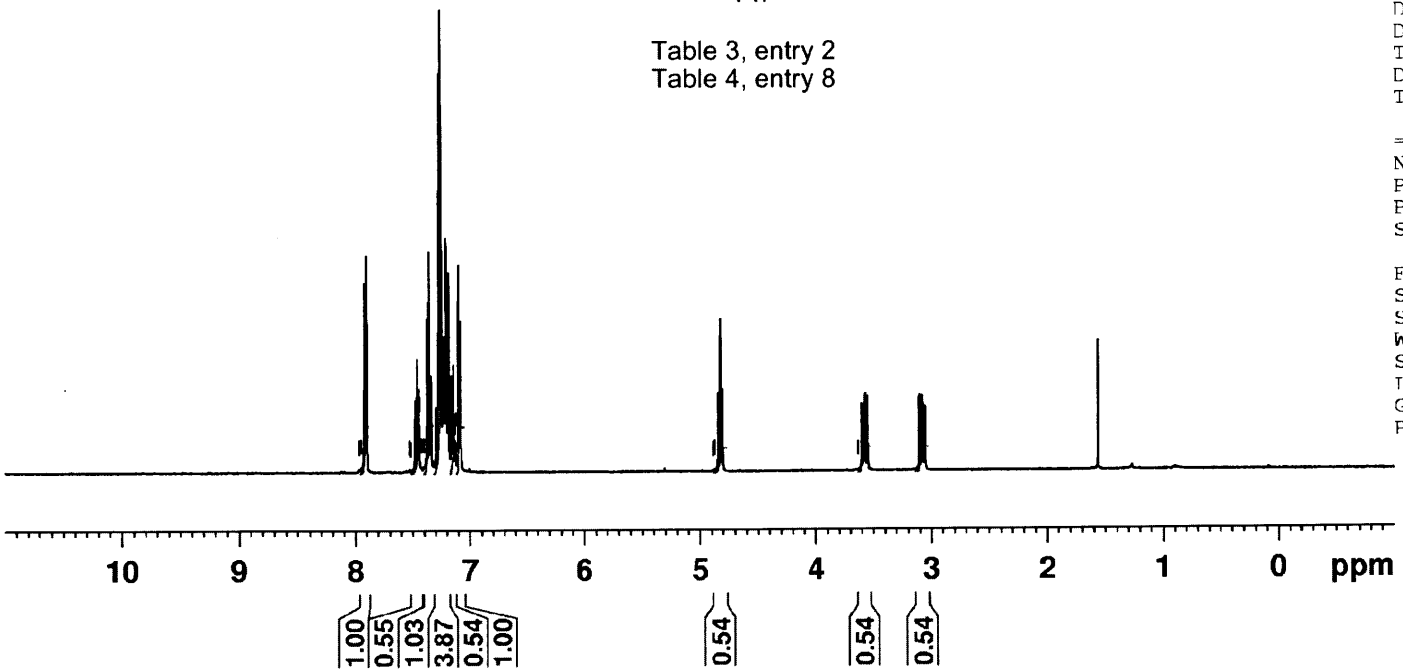


Table 3, entry 2
Table 4, entry 8



BRUKER

```
Current Data Parameters
NAME                  II-299
EXPNO                      1
PROCNO                     1

F2 - Acquisition Parameters
Date_              20070627
Time                  18.26
INSTRUM               spect
PROBHD    5 mm BBO BB-1H
PULPROG                zg30
TD                    65536
SOLVENT               CDCl3
NS                       15
DS                        2
SWH                8278.146 Hz
FIDRES            0.126314 Hz
AQ                3.9584243 sec
RG                      181
DW                 60.400 usec
DE                  6.00 usec
TE                  294.2 K
D1              1.00000000 sec
TD0                        1

======== CHANNEL f1 ========
NUC1                      1H
P1                 15.07 usec
PL1                 0.00 dB
SFO1          400.1324710 MHz

F2 - Processing parameters
SI                    65536
SF            400.1300059 MHz
WDW                      EM
SSB                       0
LB                  0.30 Hz
GB                        0
PC                     1.00
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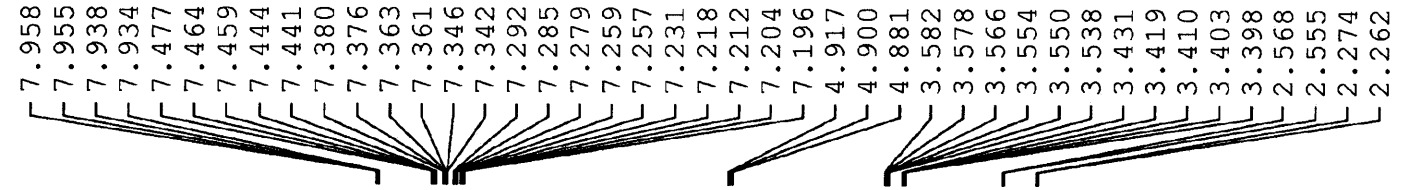

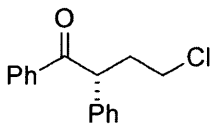

Table 3, entry 3
Table 4, entry 9

Current Data Parameters
NAME II-290
EXPNO 5
PROCNO 1

F2 - Acquisition Parameters
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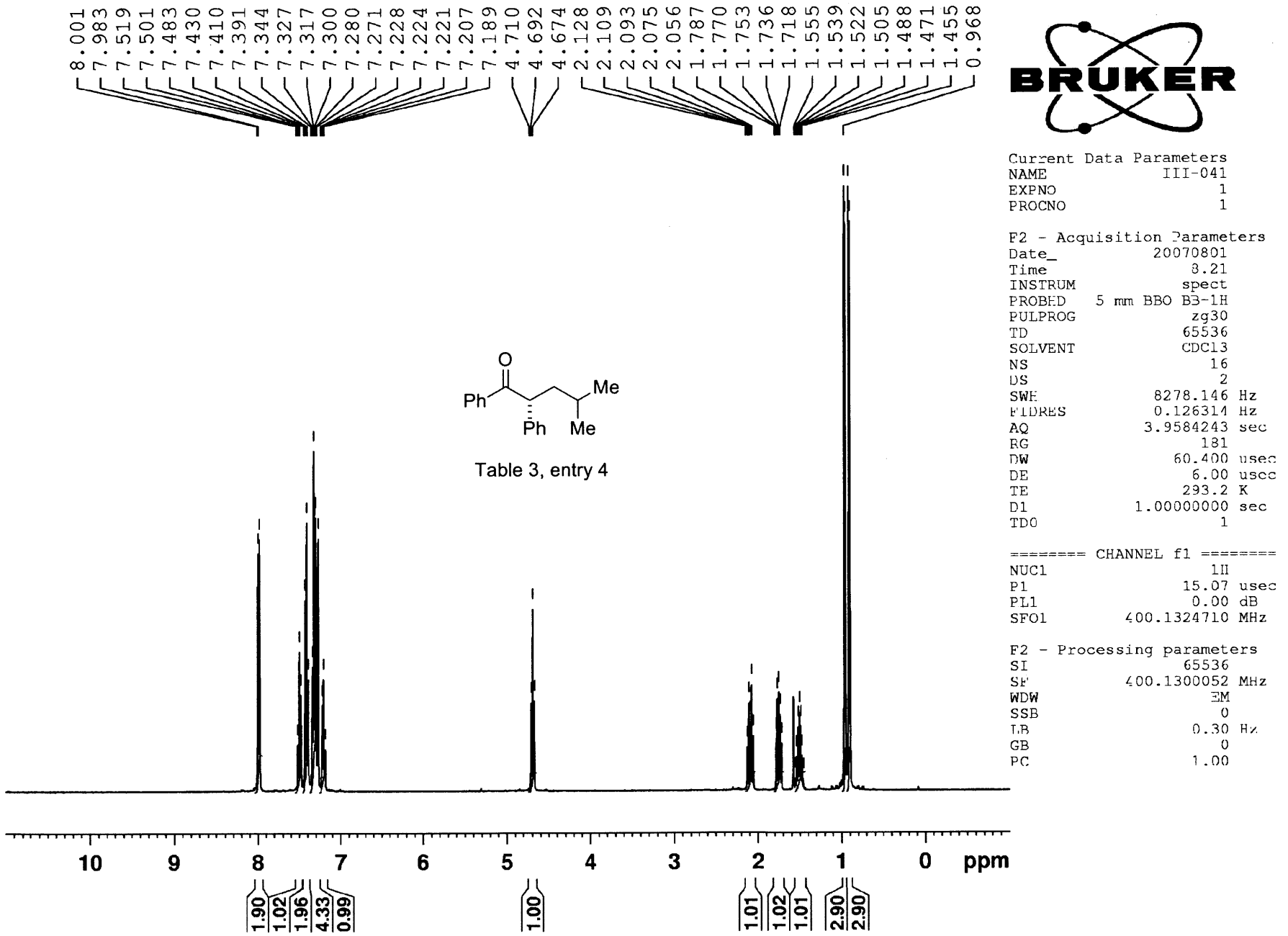
Time 9.18
INSTRUM spect
PROBHD 5 mm BBO BB-1H
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 13
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 128
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 15.07 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300212 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00



BRUKER

Current Data Parameters

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EXPNO	1
PROCNO	1

F2 - Acquisition Parameters

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PULPROG	zg30
TD	65536
SOLVENT	CDCl3
NS	16
DS	2
SWH	8278.146 Hz
FIDRES	0.126314 Hz
AQ	3.9584243 sec
RG	181
DW	60.400 usec
DE	6.00 usec
TE	293.2 K
D1	1.00000000 sec
TD0	1

======== CHANNEL f1 ========

NUC1	1H
P1	15.07 usec
PL1	0.00 dB
SFO1	400.1324710 MHz

F2 - Processing parameters

SI	65536
SF	400.1300052 MHz
WDW	EM
SSB	0
LB	0.30 Hz
GB	0
PC	1.00

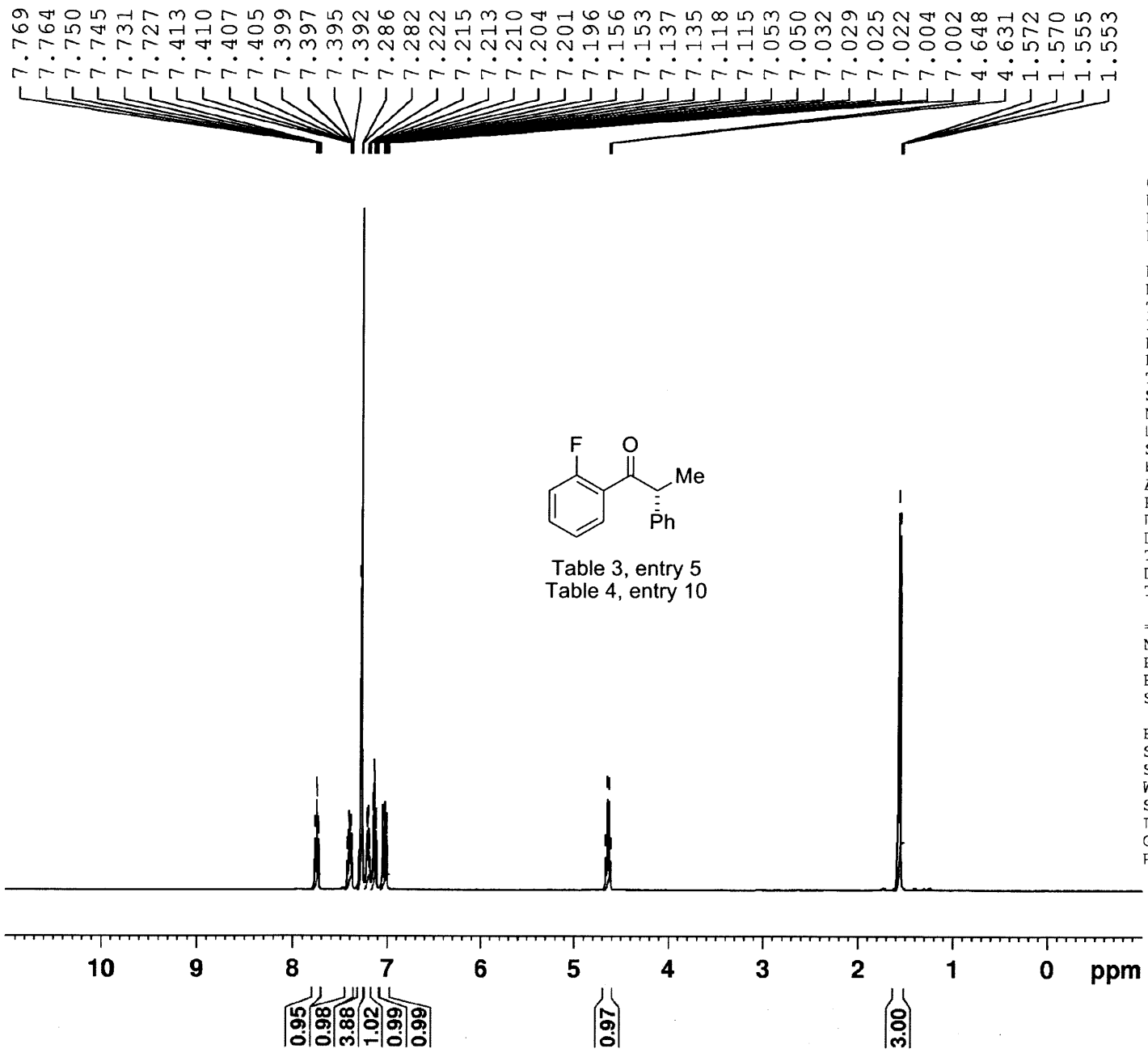

Table 3, entry 5
Table 4, entry 10

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EXPNO	4
PROCNO	1

F2 - Acquisition Parameters

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SOLVENT	CDCl3
NS	16
DS	2
SWH	8278.146 Hz
FIDRES	0.126314 Hz
AQ	3.9584243 sec
RG	57
DW	60.400 usec
DE	6.00 usec
TE	292.2 K
D1	1.00000000 sec
TD0	1

======== CHANNEL f1 ========

NUC1	1H
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PL1	0.00 dB
SFO1	400.1324710 MHz

F2 - Processing parameters

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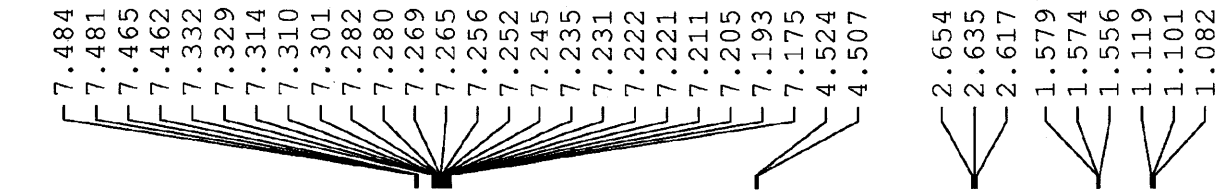

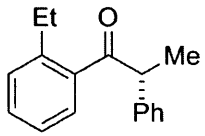

Table 3, entry 6
Table 4, entry 11

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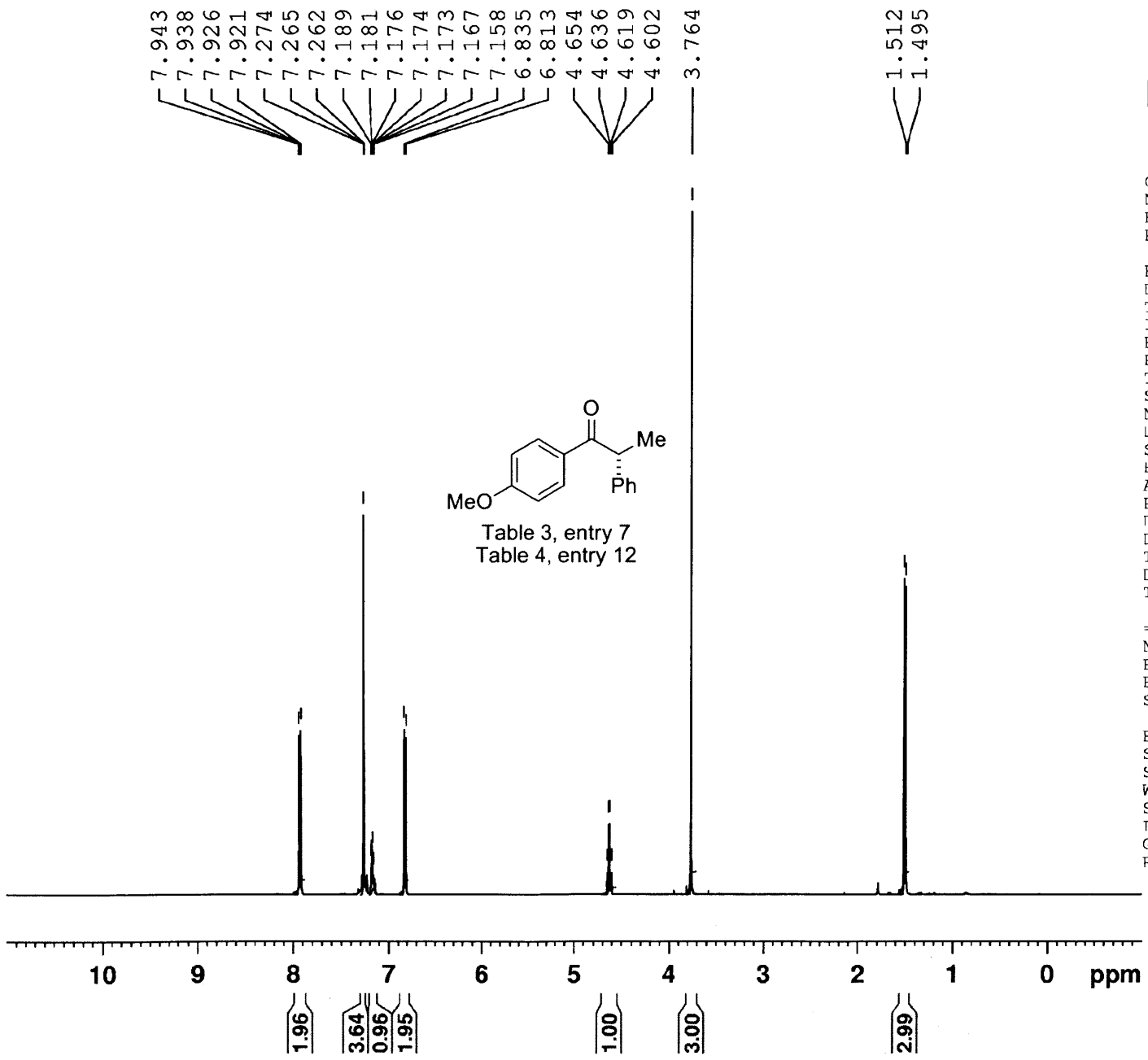
NAME III-011
EXPNO 2
PROCNO 1

F2 - Acquisition Parameters
Date_ 20070702
Time 9.43
INSTRUM spect
PROBHD 5 mm QNP 1H/13
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 322.5
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 14.00 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300061 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00



BRUKER

Current Data Parameters

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EXPNO	1
PROCNO	1

F2 - Acquisition Parameters

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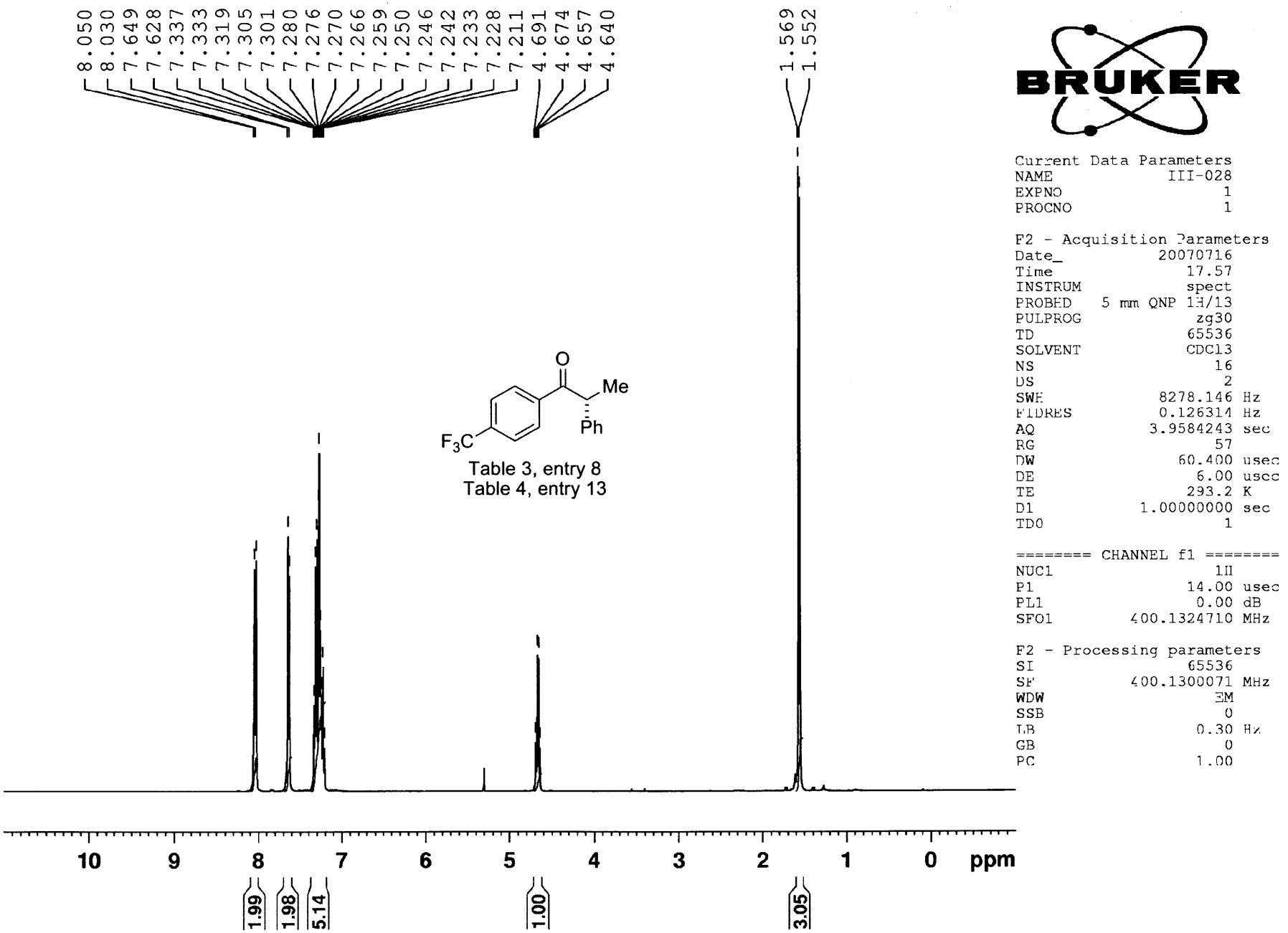
Time	18.19
INSTRUM	spect
PROBHD	5 mm BBO BB-1H
PULPROG	zg30
TD	65536
SOLVENT	CDCl3
NS	12
DS	2
SWH	8278.146 Hz
FIDRES	0.126314 Hz
AQ	3.9584243 sec
RG	45.3
DW	60.400 usec
DE	6.00 usec
TE	293.2 K
D1	1.00000000 sec
TD0	1

======== CHANNEL f1 ========

NUC1	1H
P1	15.07 usec
PL1	0.00 dB
SFO1	400.1324710 MHz

F2 - Processing parameters

SI	65536
SF	400.1300212 MHz
WDW	EM
SSB	0
LB	0.30 Hz
GB	0
PC	1.00



BRUKER

Current Data Parameters
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EXPNO 1
PROCNO 1

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Time 17.57
INSTRUM spect
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PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 57
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 14.00 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300071 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00

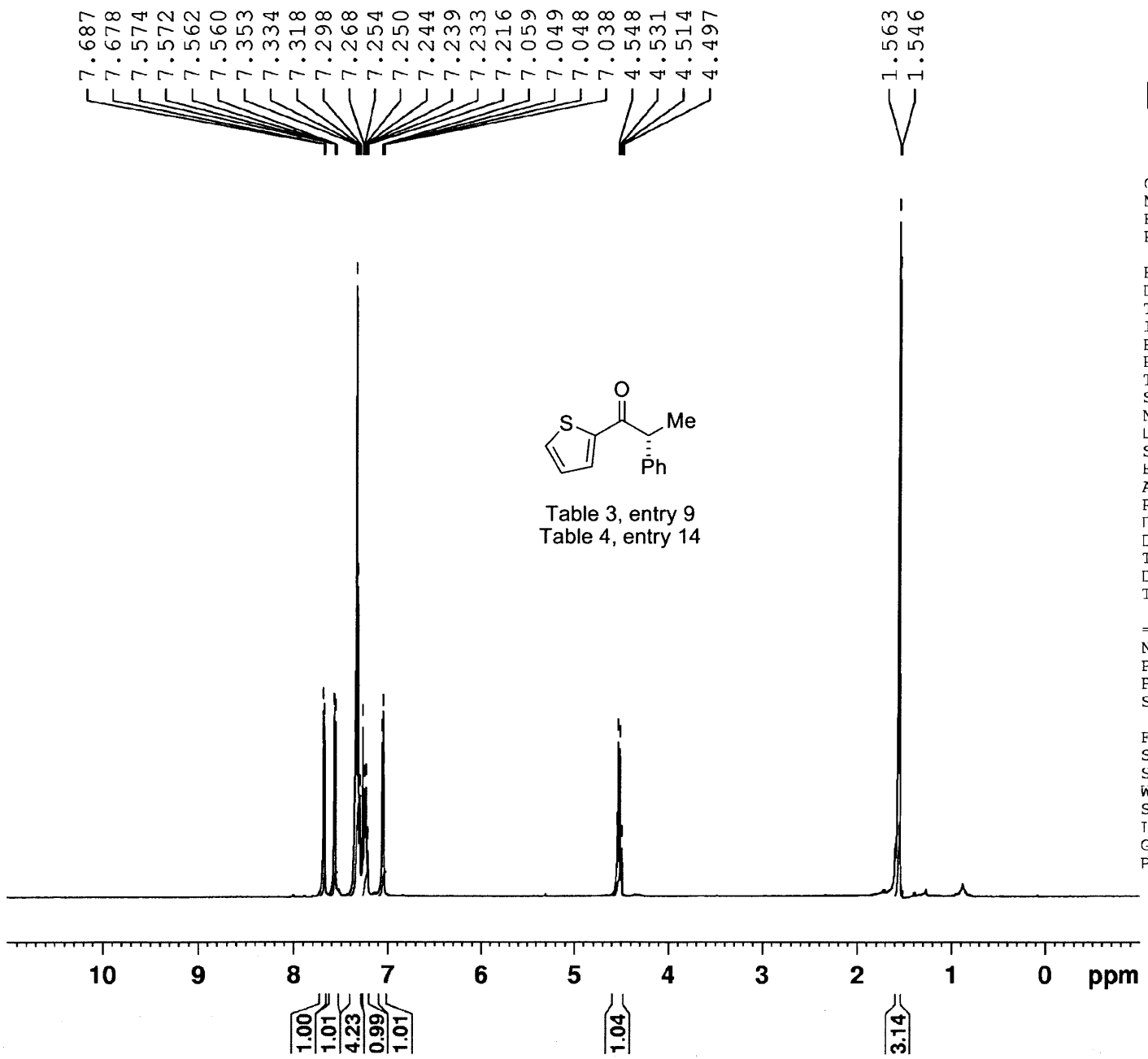


Table 3, entry 9
Table 4, entry 14

BRUKER

Current Data Parameters
NAME III-027
EXPNO 2
PROCNO 1

F2 - Acquisition Parameters
Date_ 20070716
Time 17.50
INSTRUM spect
PROBHD 5 mm QNP 1H/13
PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 14
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 362
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 14.00 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
SI 65536
SF 400.1300067 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00

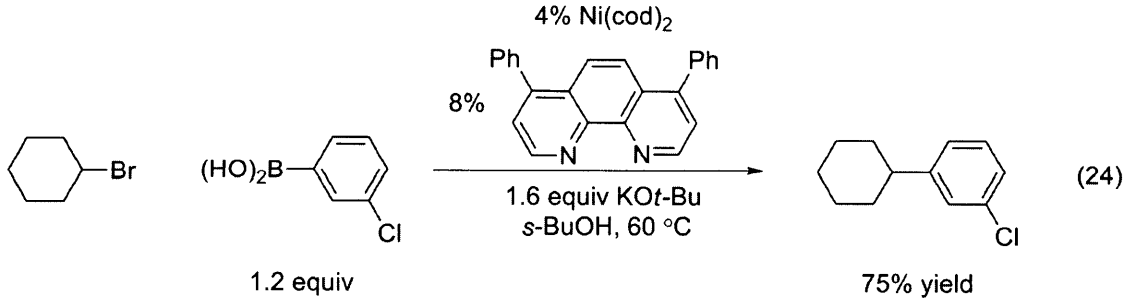
Section 1.3

Asymmetric Suzuki Arylation of α-Haloamides

A: Introduction

The Suzuki cross-coupling is a heavily utilized method for carbon-carbon bond formation due to its functional-group tolerance and the low toxicity of the reaction components.[59] However, the vast majority of these protocols have employed aryl electrophiles. Our group's interest in the development of cross-coupling procedures for secondary alkyl electrophiles plus the attractive qualities of Suzuki cross-couplings have led us to consider Suzuki couplings of secondary alkyl electrophiles as highly desirable goals.[60]

Our first success in this area came in 2004 with Zhou's development of a coupling protocol for arylboronic acids with secondary alkyl bromides and iodides (Equation 24).[61] This nickel-catalyzed process worked with bathophenanthroline as a ligand, and it was applicable to couplings of primary alkyl iodides as well.



(24)

In 2006, González-Bobes reported a more active catalyst system that could couple secondary alkyl chlorides, bromides, and iodides with arylboronic acids, using a

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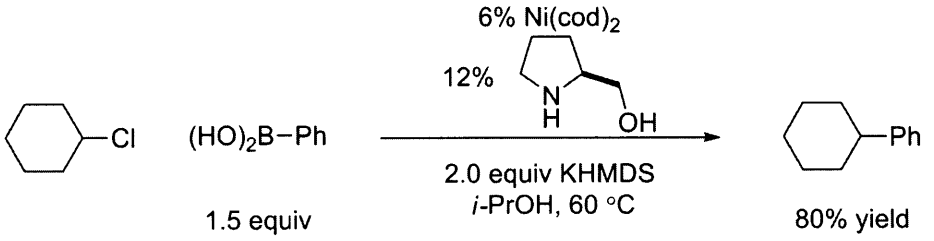
[59] Miyaura, N. In *Metal-Catalyzed Cross-Coupling Reactions*; de Meijere, A., Diederich, F., Eds.; Wiley–VCH: New York, 2004; Chapter 2.

[60] For references regarding Suzuki coupling and other cross-coupling methodologies of *primary* alkyl electrophiles, see: Netherton, M. R.; Fu, G. C. In *Topics in Organometallic Chemistry: Palladium in Organic Synthesis*; Tsuji, J., Ed.; Springer: New York, 2005, p 85–108.

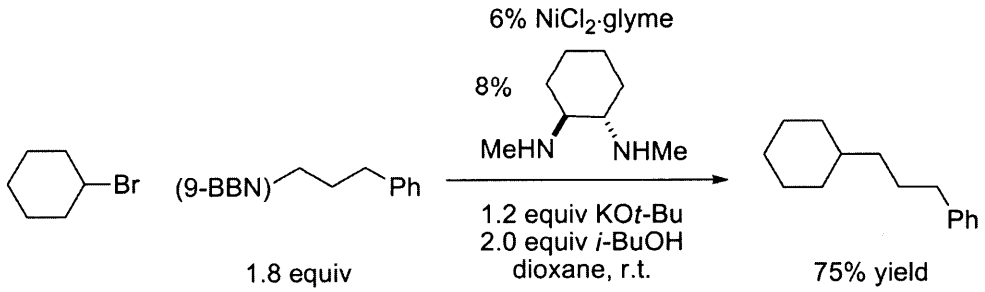
[61] Zhou, J.; Fu, G. C. *J. Am. Chem. Soc.* **2004**, *126*, 1340–1341.

nickel/chiral amino alcohol catalyst (Equation 25).[62] This catalyst system was the first in our group to employ an amino alcohol ligand, and it led to increased interest in the ability of this family of compounds (as well as diamines) to effect other nickel-catalyzed couplings, especially asymmetric transformations.



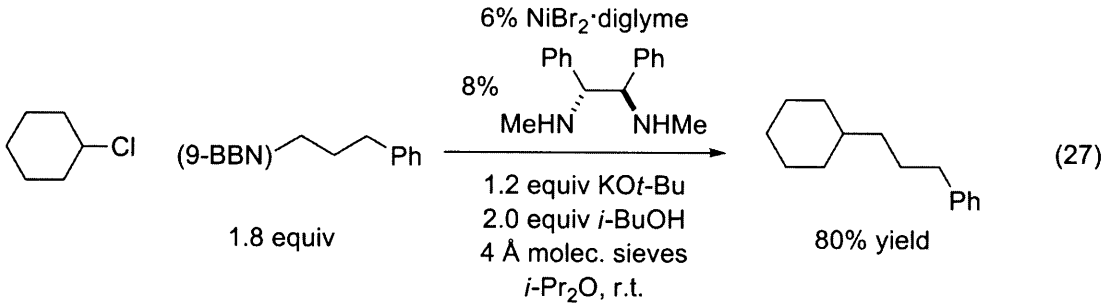
(25)

In addition to these Suzuki arylation protocols, our group has made advances in the nickel-catalyzed Suzuki couplings of *alkyl* nucleophiles with secondary alkyl electrophiles. In 2007, Saito reported that a nickel/diamine catalyst can couple alkyl 9-borabicyclo[3.3.1]nonane (9-BBN) reagents with secondary alkyl bromides under the conditions in Equation 26.[63] Recently, Lu has extended this methodology to include secondary alkyl chlorides (Equation 27).[64]



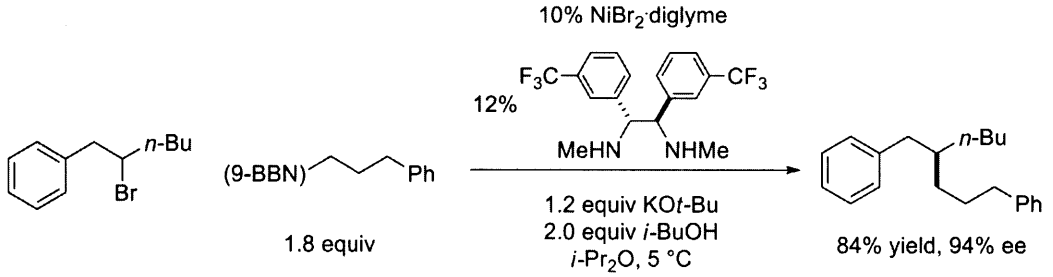
(26)

[62] González-Bobes, F.; Fu, G. C. *J. Am. Chem. Soc.* **2006**, *128*, 5360–5361.
[63] Saito, B.; Fu, G. C. *J. Am. Chem. Soc.* **2007**, *129*, 9602–9603.
[64] Lu, Z.; Fu, G. C. *Angew. Chem., Int. Ed.* **2010**, Early View.



(27)

An asymmetric variant of this chemistry has been developed using *unactivated* homobenzylic electrophiles (Equation 28).[41d] In contrast to previous asymmetric couplings in which the putative radical intermediate is in conjugation with a π-system to facilitate stereoconvergence of the racemic electrophile (for an example, see Scheme 4 in section 1.1C), in this case it is believed that coordination between the phenyl ring and the catalyst produces a more rigid geometry during the stereochemistry-determining step, thus allowing for a high level of enantioselectivity. This class of asymmetric cross-coupling reactions of unactivated secondary alkyl halides has recently been expanded by Owston to include the Suzuki alkylation of acylated halohydrins using alkyl–(9-BBN) reagents and a nickel/diamine catalyst.[41g]



(28)

As was previously mentioned, the chirality of the catalyst system in Equation 25 presented an intriguing opportunity for the development of an asymmetric Suzuki arylation of secondary alkyl electrophiles. Preliminary results conducted by González-

Bobes identified α-bromoamides as good candidates for such a process. Optimization of reaction parameters resulted in the conditions summarized in Figure 3, and these conditions serve as the starting point for the studies of this section of the thesis, which are detailed in section B.

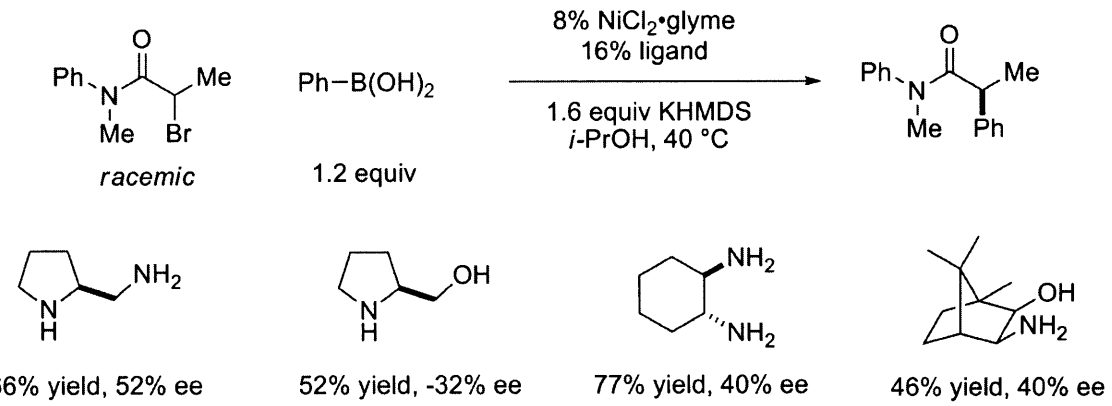


Figure 3: Initial results for the coupling of arylboronic acids with α-bromoamides

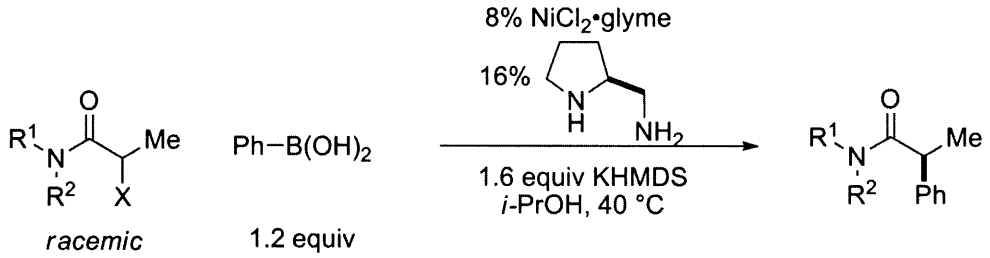
B: Results and Discussion[65]

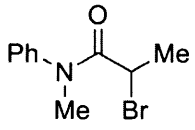
With the results summarized in Figure 3, one strategy for increasing the yield and enantioselectivity was to vary the *N*-substituents of the amide. Therefore, a range of amide electrophiles was synthesized and screened, including *N*-alkyl-*N*-aryl, *N,N*-diaryl, *N,N*-dialkyl, secondary, and Weinreb amide species (Figure 4).[66] However, none of these new electrophiles was able to produce enantioselectivity above 55% (1-indolinyl amide), and of the amides capable of this level of selectivity, the yields, too, remained moderate. Although the screening was focused primarily on α-bromoamides, it is notable that α-*chloro*amides were able to couple with equal or greater efficiency than the α-bromo counterparts (top versus bottom row of Figure 4), despite the lower

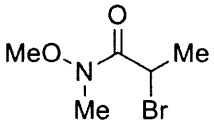
[65] Portions of the work described in this section are published in: Lundin, P. M.; Fu, G. C. *J. Am. Chem. Soc.* **2010**, *132*, 11027–11029.

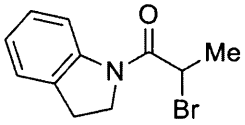
[66] It was found that the identiy of the alkyl α-substituent had a small enough impact on the yield and enantioselectivity. Therefore, in screening N-substituents, an α-methyl group was used as the standard.

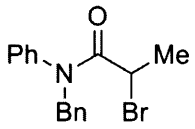
reactivity of alkyl chlorides in oxidative addition reactions with transition metal complexes.[62,63]

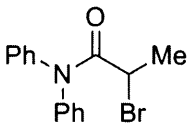


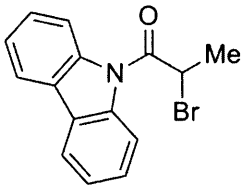

64% yield, 51% ee

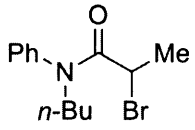

62% yield, 45% ee

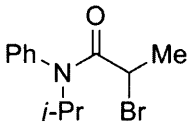

62% yield, 55% ee

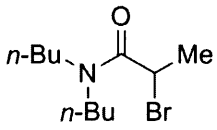

63% yield, 35% ee

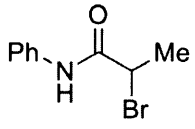

61% yield, 51% ee

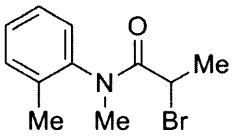

0% yield

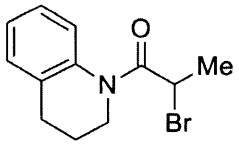

52% yield, 53% ee

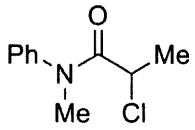

52% yield, 53% ee

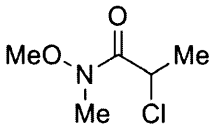

96% yield, 26% ee


68% yield, 4% ee


58% yield, 20% ee


46% yield, 40% ee


68% yield, 46% ee


71% yield, 35% ee

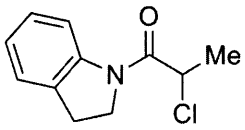

>99% yield, 45% ee

Figure 4: Electrophile screening

A second strategy for improving the reaction yield and ee was to identify a ligand that would allow higher coupling efficiency and selectivity. Previously, extensive screening of commercially available and easily accessible chiral amino alcohols and diamines had been done to reach the conditions in Figure 3. Therefore, effort was directed toward the synthesis of ligands that were variations on the best ligand, the proline diamine (Figure 5). The effects of both larger and smaller ring sizes were investigated, as well as the effects of incorporating substituents at both nitrogen positions. However, these changes only produced inferior results in terms of yield and enantioselectivity. Concurrent with these studies, the family of 1,2-diaryldiamines was gaining prominence in our group due to their success in other coupling systems.[41d, 44] However, they too gave lower yields and enantioselectivities.

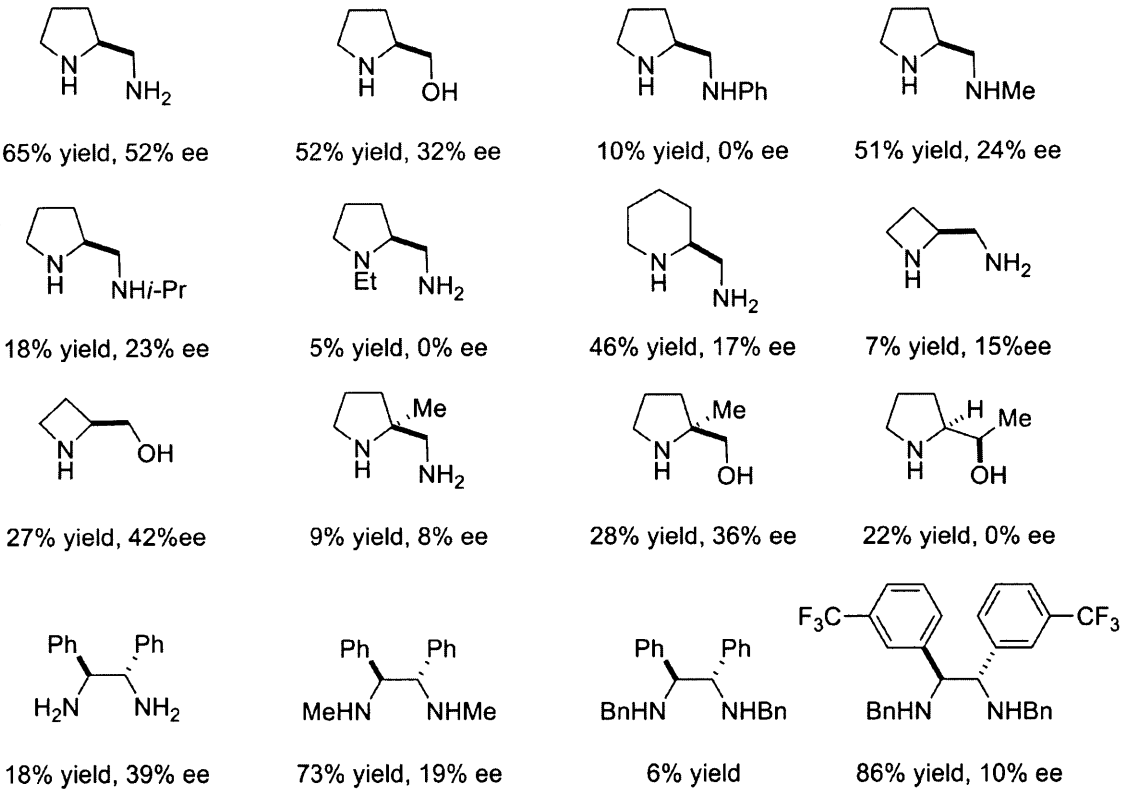


Figure 5: Ligand effects (for conditions, see Figure 4)

As optimization of the electrophile, ligand, and other reaction parameters (solvent, additives, etc.) had not produced fruitful results, we decided to turn to other nucleophile classes with the hope that a suitable reaction partner for this coupling could be found. A variety of *B*-phenyl boronate esters was explored, as well as potassium phenyltrifluoroborate, triphenylboroxin, and Ph-(9-BBN) (Figure 6).[67] Although most species gave inferior results in comparison to those obtained with phenylboronic acid (62% yield, 55% ee, Figure 3), triphenylboroxin did give an ee value of 60%. However, the active nucleophile in this case is thought to be the in situ generated boronic acid which lacks the impurities included in phenylboronic acid powder. It was therefore postulated that the increase in ee was most likely due to this absence of impurities and consequently that further improvement in yield and enantioselectivity would be as difficult as it had been for phenylboronic acid powder.

[67] At this stage, the indolinyl amide was employed, as it was found to be more stable upon storage during long periods of time than the *N*-phenyl-*N*-methyl amide, besides offering a modest increase in enantioselectivity (see Figure 4).

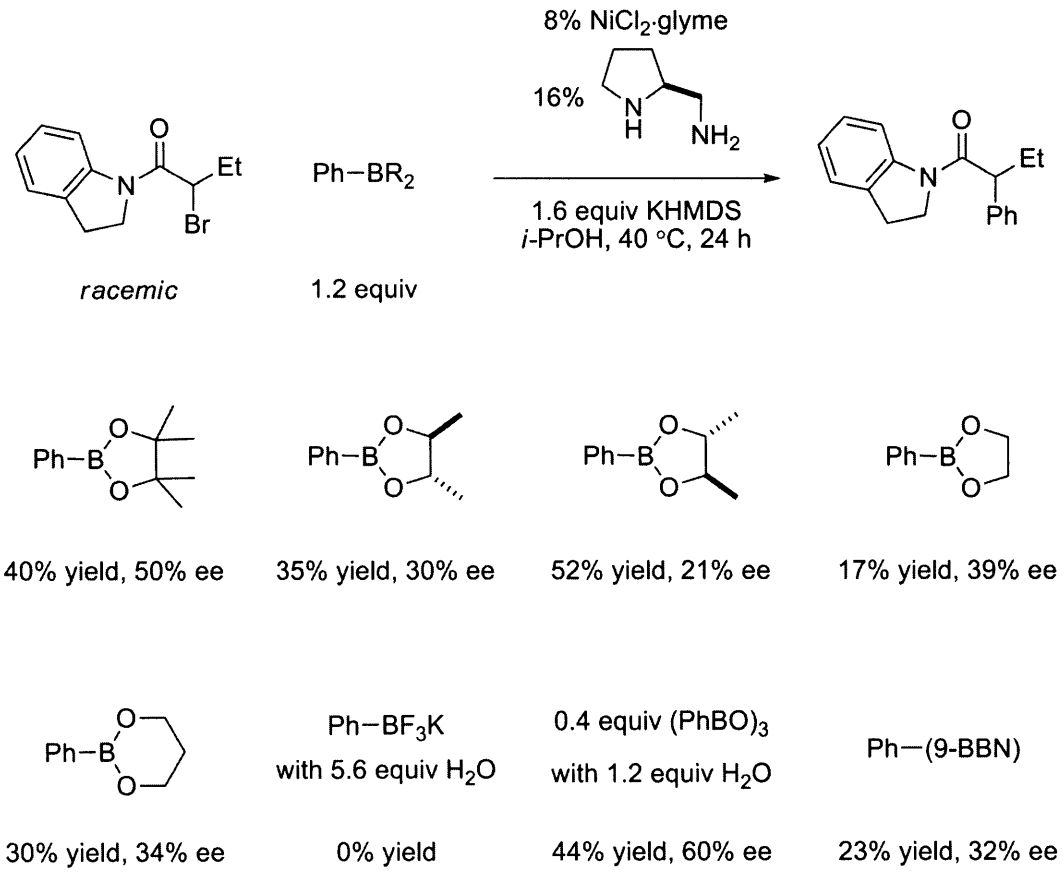
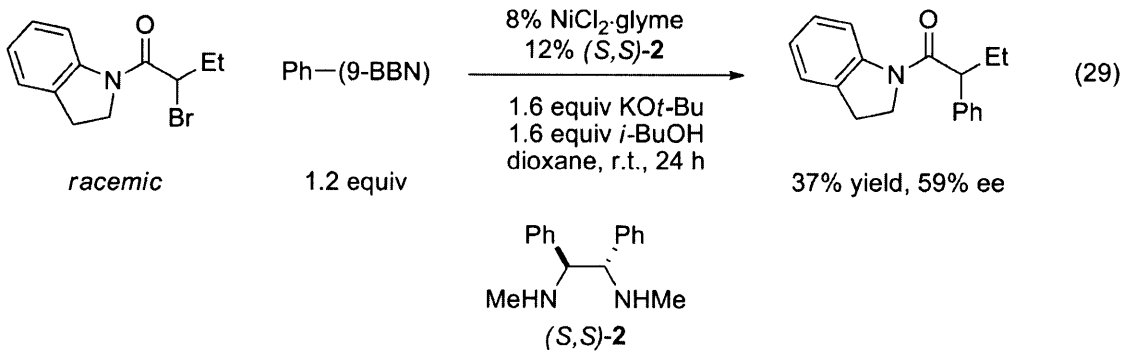


Figure 6: Scope of *B*-phenyl Suzuki nucleophiles

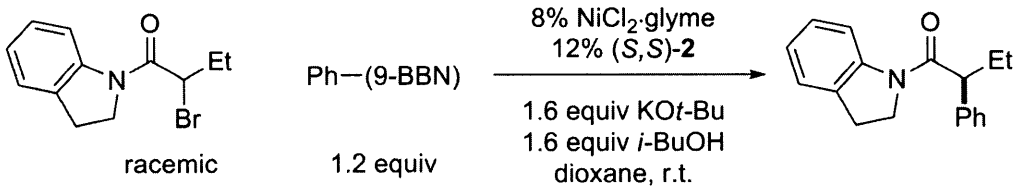
Due to the substantial difference between the standard conditions used up to this point and the best conditions for coupling with alkyl–(9-BBN) reagents, [41d, 63, 64] it was decided to try Ph–(9-BBN) again as a reaction partner under conditions more similar to those employed with alkyl–(9-BBN) nucleophiles. While the yield was lower, the enantioselectivity was among the highest of what had been observed previously (Equation 29).



(29)

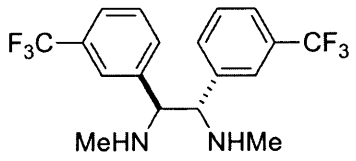
Because these new reaction conditions offered many parameters to be optimized, we decided to pursue coupling with Ph–(9-BBN). Table 5 contains a concise summary of the optimization process. Ethereal solvents were found to be good, but toluene seemed to offer a slight advantage in terms of enantioselectivity of the reaction (entry 3 versus entries 1 and 2). A change of the alcohol additive from *i*-BuOH to MeOH increased the ee (entry 4), whereas increasing the equivalents of nucleophile improved the yield (entry 5). Decreasing the reaction temperature to –10 °C further improved the ee value obtained (entry 6). Variations on the *N,N'*-dimethyl-1,2-diarylethylene-diamine scaffold of **2** led to the identification of **3**, which is commercially available, as the best ligand in this coupling reaction (entry 7). At this juncture, however, reproducibility problems hindered further optimization. Upon switching the alcohol additive back to *i*-BuOH, the reaction mixture was much more homogeneous and the yield dramatically improved (entry 8). Thus, after some additional modifications to the reaction parameters such as slight modifications to the equivalents of base and alcohol additive used, the conditions in Equation 30 were identified as the best for both yield and enantioselectivity.

Table 5: Initial optimization of the coupling conditions employing Ph–(9-BBN)

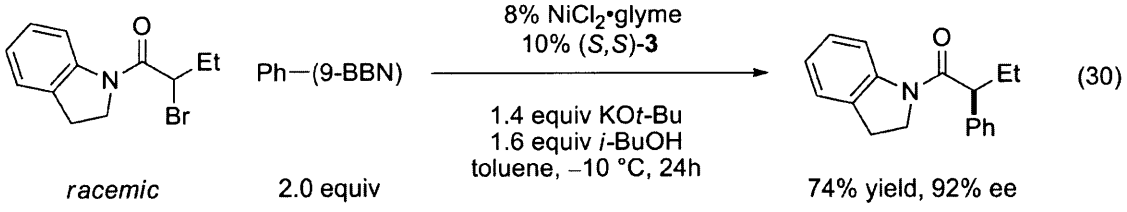


entry	sequential variations from the "standard" conditions	yield (%)[a]	ee (%)
1	none	37	59
2	*i*-Pr_2O instead of dioxane	21	64
3	toluene instead of *i*-Pr_2O	36	70
4	MeOH instead of *i*-BuOH	22	83
5	2.0 equiv instead of 1.2 equiv of Ph–(9-BBN)	72	80
6	–10 °C instead of r.t.	57	84
7	(*S,S*)-**3** instead of (*S,S*)-**2**	44	91
8	*i*-BuOH instead of MeOH	67	92

[a] Yields were determined by GC analysis versus an internal standard.



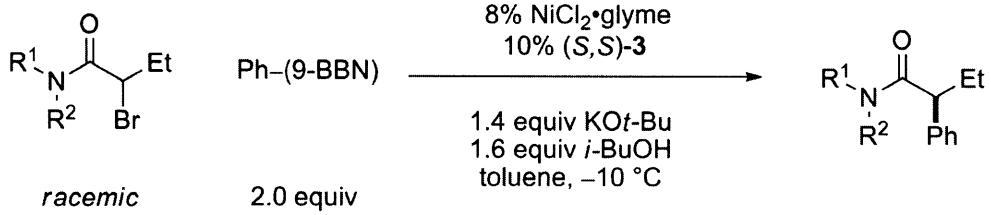
(S,S)-**3**

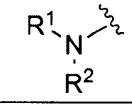
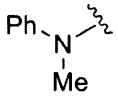
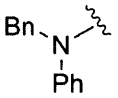
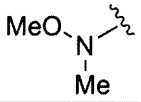


(30)

Under these optimal conditions, the use of other amide electrophiles was tested in the coupling reaction (Table 6). *N*-Methyl-*N*-phenyl-2-bromobutyramide coupled in higher yield but lower enantioselectivity than 1-indolinyl-2-bromobutyramide (entry 1 versus Equation 29). The *N*-benzyl-*N*-phenyl-2-bromobutyramide which was most successful in the Negishi alkylation of α-bromoamides[41a] gave low yield and only moderate ee (entry 2). The Weinreb amide, which would be a very useful synthetic handle for further functionalizations of the product, unfortunately showed very low enantioselectivity in coupling (entry 3).

Table 6: Other α-bromobutyramides in the coupling reaction

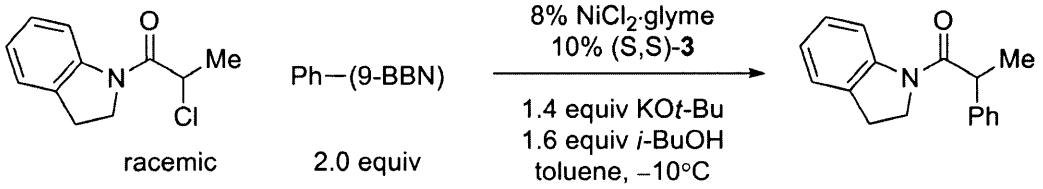


entry		% yield[a]	% ee
1		87	74
2		30	60
3		85	9

[a] Yields were determined by GC versus an *n*-tetradecane internal standard

At this stage, we tested α-chloro-1-indolinylpropionamide in the coupling reaction and found the product was obtained in 75% yield and 92% ee. This result is important as it is the first asymmetric example of the coupling of an α-chlorocarbonyl reagent with high enantioselectivity. The reaction parameters were refined for this new substrate class, as summarized in Table 7. The equivalents of nucleophile, alcohol additive, and base were lowered without diminishing the yield (entry 2). The reaction temperature was slightly raised to –5 °C to avoid reproducibility problems with other, more sluggish coupling substrates; the enantioselectivity appeared unaffected by this change (entry 3). A change of nickel pre-catalyst from $NiCl_2$·glyme to $NiBr_2$·diglyme improved the yield (entry 4).

Table 7: Optimization of reaction parameters for α-chloroamide



entry	variation from the "standard" conditions	yield (%)[a]	ee (%)
1	none	75	92
2	1.5 equiv Ph–(9-BBN), 1.5 equiv *i*-BuOH, 1.3 equiv KO*t*-Bu	74	92
3	–5 °C, instead of –10 °C	75	92
4	8% $NiBr_2$·glyme, instead of 8% $NiCl_2$·glyme	84	85

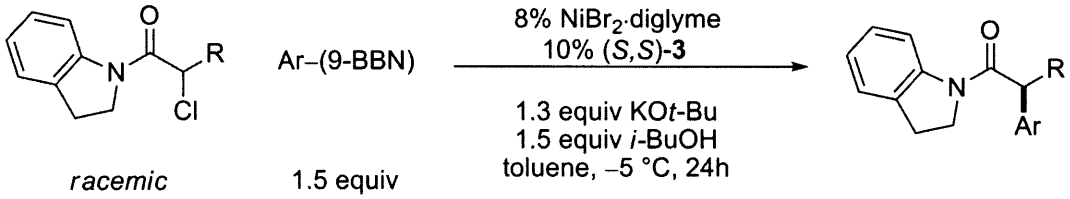
[a] Yields were determined by GC analysis versus *n*-tetradecane as an internal standard.

The $NiBr_2$·diglyme pre-catalyst and both enantiomers of the diamine ligand **3** are all commercially available. The pre-catalyst and ligand components are both necessary for coupling. In the absence of the nickel salt, <2% of the coupling product is obtained; if the ligand is omitted, the coupling proceeds in only 8% yield. Furthermore, if the catalyst loading is lowered, the reaction proceeds in lower yield (78% yield, 92% ee) and is more unreliable.

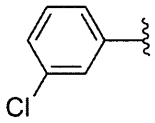
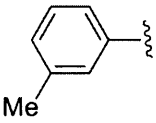
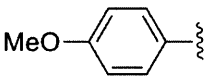
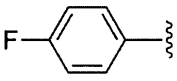
With these conditions in hand, the electrophile and nucleophile scope were examined, and the results are summarized in Table 8. The reaction is tolerant of functional groups such as an olefin or a silyl ether on the alkyl side chain (entries 3 and 4), as well as β-branching (entry 5). The aryl-(9-BBN) nucleophile may bear meta- (entries 6 and 7) or para-substituents (entries 8 and 9). This substituent may be either electron-withdrawing (entry 6) or electron-donating (entries 7 and 8). The reaction can be run on a 5.0 mmol scale, and enantioenrichment to >99% ee of the product is possible through recrystallization (Table 8, entry 2 on a 5.0 mmol scale: 88% yield, 92% ee before recryallization; 70% yield, >99% ee after).[68, 69] These conditions can also be applied to the analogous α-bromoamide with comparable results. For example, starting from the α-bromoamide, the product of Table 8, entry 1 was obtained in 88% yield and 91% ee.

[68] In these studies, the aryl-(9-BBN) reagent was purified by distillation. However, when non-distilled Ph-(9-BBN) was used under the conditions of Table 2 entry 1 (1.8 equiv of nucleophile was used to compensate for impurities), the product was obtained in comparable yield (83%) and the same ee (92%).
[69] The following species were not found to be competent reaction partners: alkyl-(9-BBN) reagents, alkenyl-(9-BBN) reagents, α-isopropyl substituted amide, Ph–$B(OH)_2$, and a pinacol boronate ester.

Table 8: Electrophile and nucleophile scope

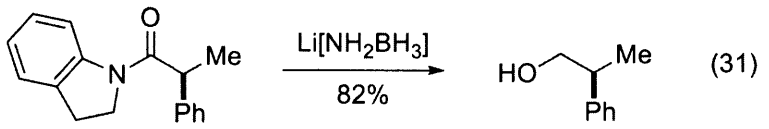


racemic 1.5 equiv

Entry	R	Ar	% yield[a]	ee
1	Et	Ph	79	92
2	Me	Ph	89	87
3	$CH_2CH{=}CH_2$	Ph	83	90
4	CH_2CH_2OTBS	Ph	79	84
5	*i*-Bu	Ph	84	86
6	Et		77	92
7[b]	Et		84	93
8	Et		79	91
9	Et		71	94

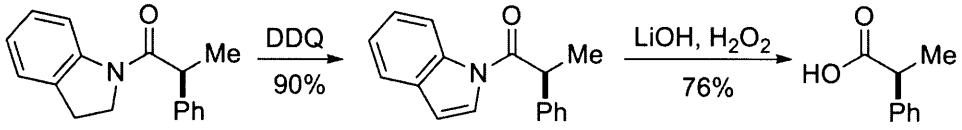
All entries are the average of two runs. [a] Isolated yields. [b] Requires 10% $NiBr_2$·diglyme, 12.5% ligand, and 48 h reaction time.

The amide moiety of these products provides a useful handle for manipulation of the product into other species. For example, the product can be reduced to the primary alcohol (Equation 31) or converted to the free carboxylic acid (Equation 32). Both reactions proceed without racemization.



(31)

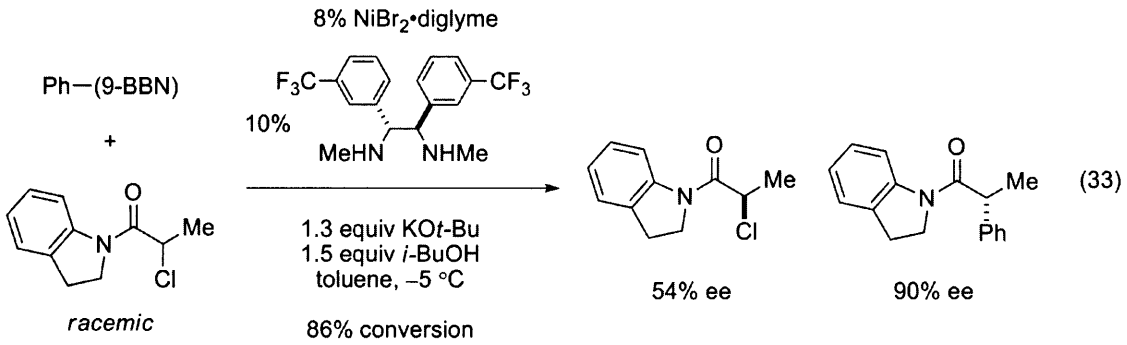
>99% ee >99% ee



(32)

>99% ee >99% ee

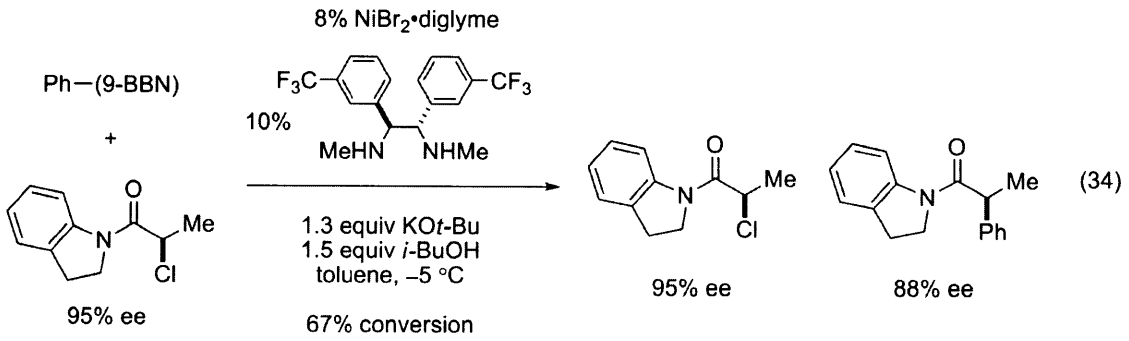
As in other examples of asymmetric nickel-catalyzed cross-coupling reactions of secondary alkyl halides, this reaction is stereoconvergent, in that the racemic starting material is converted preferentially into one enantiomer of product.[41,42,44,45,50] However, in contrast to these earlier reports in which the electrophile remains racemic over the course of the reaction, in this reaction the initially racemic α-chloroamide electrophile undergoes enantioenrichment. For example, at 86% conversion, the ee of the unreacted electrophile is 54% and that of the product is 90% (Equation 33).

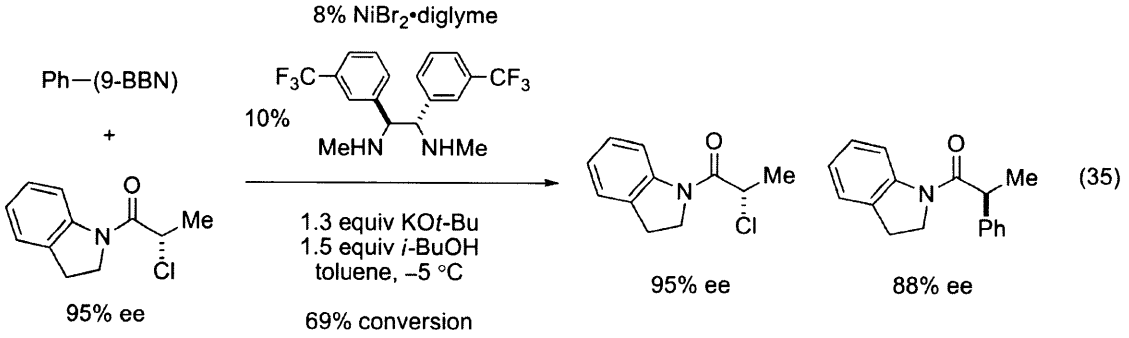


(33)

This enhancement in the enantiomeric ratio of the electrophile must arise from discrimination by the chiral catalyst between the two enantiomers. However, from this data, it is unclear whether the moderate ee value of the electrophile is due to modest enantiomeric discrimination by the chiral catalyst or to a high level of discrimination that is counteracted by a reversible oxidative addition.

To gain insight into this question, enantioenriched electrophiles were subjected to the reaction conditions. It was found that the ee of each electrophile remains essentially unchanged throughout the course of the reaction (Equations 34 and 35), implying that oxidative addition is irreversible, and the enantioenrichment, therefore, must be due to a modest kinetic resolution with a selectivity factor of ~1.8. Furthermore, the reaction operates under complete catalyst control; regardless of the starting enantiomer of electrophile, the obtained coupling product has both the same sense and degree of enantioenrichment with a given enantiomer of catalyst.





C. Conclusions

In conclusion, a nickel-catalyzed α-arylation of α-haloamides has been developed that represents, to the best of our knowledge, the first asymmetric arylation of an α-haloamide, the first enantioselective cross-coupling of an α-chlorocarbonyl, and the first asymmetric cross-coupling of an aryl boron reagent. The catalyst components are both commercially available, and the reaction is applicable to coupling of α-bromoamides as well. This coupling procedure has been performed on scales up to 5.0 mmol. The products can be recrystallized to enhance the enantiomeric ratio and transformed into primary alcohols or carboxylic acids without racemization. Although this process is stereoconvergent like our other asymmetric cross-coupling procedures, it differs in that kinetic resolution is at play during the oxidative addition. Mechanistic studies have been conducted to further elucidate information regarding this kinetic

resolution, which indicate that the resolution occurs through modest differentiation between the two enantiomers of the electrophile in an irreversible oxidative addition step.

D. Experimental Information

1.	**General Information**	91
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1. General Information

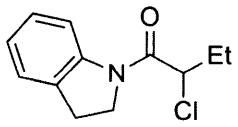
The following reagents were purchased and used without purification: $NiBr_2$·diglyme (Strem), (–)-(*S*,*S*)-**3**, (+)-(*R*,*R*)-**3** (Acros), KO*t*-Bu (Alfa), *i*-BuOH (Aldrich), toluene (Aldrich; anhydrous), and *B*-methoxy-(9-BBN) (Aldrich; 1.0 M solution in hexanes). Indoline (Alfa) was distilled prior to use.

All reactions were carried out in oven-dried glassware under an atmosphere of argon or nitrogen.

HPLC analyses were carried out on an Agilent 1100 series system with Daicel Chiralpak® columns.

2. Preparation of a-Chloroamides

The procedures and yields have not been optimized.



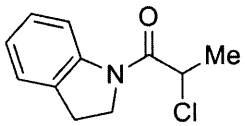
2-Chloro-1-(indolin-1-yl)butan-1-one. 2-Chlorobutyric acid (2.06 mL, 20.0 mmol) and anhydrous CH_2Cl_2 (45 mL) were added to an oven-dried flask under argon. This solution was cooled to 0 °C, and then oxalyl chloride (2.5 mL, 30 mmol, 1.5 equiv) and dimethylformamide (0.15 mL, 1.9 mmol, 0.097 equiv) were added. The reaction mixture was stirred at 0 °C for 1.5 h, and then it was transferred via cannula to an oven-dried flask that contained a solution of indoline (3.4 mL, 30 mmol, 1.5 equiv) and triethylamine (4.18 mL, 30 mmol, 1.5 equiv) in anhydrous CH_2Cl_2 (30 mL) at 0 °C. The reaction mixture was stirred for 1.5 h as it was allowed to warm to room temperature. The reaction was then quenched by the addition of aqueous HCl (1 M; 45 mL), and the resulting mixture was extracted with CH_2Cl_2 (50 mL × 2). The combined organic layers were washed with brine (30 mL), dried over Na_2SO_4, and concentrated. The residue was purified by flash chromatography (5%→10% EtOAc in pentane), which furnished the product as a white crystalline solid (1.5 g, 34%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.26 (d, 1H, J = 8.0 Hz), 7.25-7.19 (m, 2H), 7.09-7.04 (m, 1H), 4.41-4.30 (m, 2H), 4.11 (dt, 1H, J = 7.1, 9.9 Hz), 3.32-3.17 (m, 2H), 2.27-2.16 (m, 1H), 2.10-1.99 (m, 1H), 1.08 (t, 3H, J = 7.3 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 166.5, 142.8, 131.6, 127.9, 124.8, 124.6, 117.8, 58.4, 48.0, 28.3, 27.7, 11.3;

IR (film): 1655, 1598, 1484, 1423, 1342, 1310, 761 cm^{-1};

LRMS (EI) for $C_{12}H_{15}ClNO$ (M+H): calcd 224, found 224.



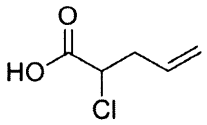
2-Chloro-1-(indolin-1-yl)propan-1-one [107236-27-1]. 2-Chloropropionyl chloride (3.17 g, 25.0 mmol) was added to a flask that contained indoline (3.08 mL, 27.5 mmol, 1.1 equiv), triethylamine (3.83 mL, 27.5 mmol, 1.1 equiv), and THF (30 mL). The solution immediately turned into a thick slurry, which was stirred for 45 min before the reaction was quenched by the addition of HCl (1 M; 30 mL). EtOAc (30 mL) was added, and the phases were separated. The aqueous layer was extracted EtOAc (30 mL × 2), and the combined organic layers, washed with brine (30 mL), dried over Na_2SO_4, and concentrated. The residue was purified by flash chromatography (10% EtOAc in pentane), which furnished the product as a white crystalline solid (2.32 g, 44%).

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.24 (d, 1H, J = 8.0 Hz), 7.25-7.18 (m, 2H), 7.07 (t, 1H, J = 7.4 Hz), 4.59 (q, 1H, J = 6.5 Hz), 4.48-4.36 (m, 1H), 4.14-4.05 (m, 1H), 3.32-3.16 (m, 2H), 1.75 (d, 3H, J = 6.6 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 166.8, 142.8, 131.6, 127.9, 124.8, 124.6, 117.7, 52.2, 47.9 28.3, 20.7;

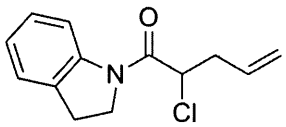
IR (film): 1652, 1595, 1482, 1417, 1060, 1004, 755 cm^{-1};

LRMS (EI) for $C_{11}H_{13}ClNO$ (M+H): calcd 210, found 210.



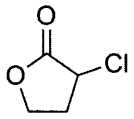
2-Chloropent-4-enoic acid [909778-25-2]. A solution of sodium nitrite (1.30 g, 18.9 mmol, 1.6 equiv) in water (3.5 mL) was added to a solution of D,L-allylglycine (1.36 g, 11.8 mmol, 1.0 equiv) in HCl (5 N; 20 mL) at 0 °C under argon. The reaction mixture was stirred at 0 °C for 5 h, and then it was allowed to warm to room temperature overnight. Sodium carbonate (800 mg) was added, and then the reaction mixture was extracted with Et_2O (10 mL × 4). The organic layers were combined and washed with brine (10 mL). The brine was extracted with Et_2O (10 mL × 3). The organic layers were combined, dried over Na_2SO_4, and concentrated to give a yellow oil (683 mg, 62%), which was used in the next step without further purification.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31 (br s, 1H), 5.81 (tdd, 1H, J = 6.9, 10.2, 17.1 Hz), 5.25-5.18 (m, 2H), 4.39-4.34 (m, 1H), 2.86-2.77 (m, 1H), 2.75-2.66 (m, 1H);
^{13}C NMR (100 MHz, $CDCl_3$): δ 174.6, 131.6, 119.8, 56.0, 38.9;
IR (film): 1734, 1653, 1559, 1507, 1436, 1279, 668 cm^{-1}.



2-Chloro-1-(indolin-1-yl)pent-4-en-1-one. Oxalyl chloride (0.46 mL, 5.42 mmol, 1.1 equiv) and DMF (0.1 mL) were added to a solution of 2-chloropent-4-enoic acid (663 mg, 4.93 mmol) in CH_2Cl_2 (10 mL) at 0 °C. The solution was stirred for 2 h as it warmed to room temperature. Then, it was added via cannula to a solution of indoline (0.61 mL, 5.42 mmol, 1.1 equiv) and triethylamine (0.71 mL, 5.42 mmol, 1.1 equiv) in CH_2Cl_2 (10 mL) at 0 °C. The reaction mixture was stirred for 15 min, and then the reaction was quenched with HCl (1 M; 20 mL) and the phases were separated. The aqueous layer was extracted with CH_2Cl_2 (20 mL × 2). The organic layers were combined, washed with brine (10 mL), dried over Na_2SO_4, and concentrated. The residue was purified by flash chromatography (5% EtOAc in pentane), which furnished 2-chloro-1-(indolin-1-yl)pent-4-en-1-one (360 mg, 31%) as a white solid.

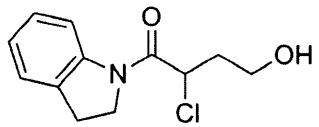
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.25 (d, 1H, J = 8.0 Hz), 7.25-7.19 (m, 2H), 7.10-7.04 (m, 1H), 5.86 (tdd, 1H, J = 6.9, 10.2, 17.1 Hz), 5.25 (dd, 1H, J = 1.4, 17.1 Hz), 5.17 (d, 1H, J = 10.1 Hz), 4.38-4.31 (m, 2H), 4.15-4.06 (m, 1H), 3.31-3.16 (m, 2H), 2.96 (td, 1H, J = 6.8, 13.7 Hz), 2.75 (td, 1H, J = 7.3, 14.5 Hz);
^{13}C NMR (100 MHz, $CDCl_3$): δ 166.0, 142.7, 133.3, 131.7, 127.9, 124.8, 124.7, 119.3, 117.8, 55.7, 48.0, 38.5, 28.3;
IR (film): 1664, 1600, 1483, 1418, 1341, 1318, 924, 756 cm^{-1};
LRMS (EI) for $C_{13}H_{15}ClNO$ (M+H): calcd 236, found 236.



α-Chloro-γ-butyrolactone [31167-90-5]. A cold solution of $NaNO_2$ (3.45 g, 50 mmol, 1.63 equiv) was added by pipette over 5 min to a solution of D,L-homoserine (3.64 g, 30.6 mmol) in HCl (5 N; 50 mL) at 0 °C. The reaction mixture was allowed to warm to room temperature overnight. Next, Na_2CO_3 (1.33 g) was added, and the reaction mixture was extracted with Et_2O (75 mL × 3). The combined organic layers were washed with brine (50 mL), which was then extracted with Et_2O (75 mL × 4). The organic layers were combined, dried over Na_2SO_4, and concentrated. The residue was purified by flash chromatography (30% EtOAc in pentane), which furnished the product (1.82 g, 50%) as a yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 4.53 (td, 1H, J = 6.9, 9.1 Hz), 4.49-4.36 (m, 2H), 2.78 (dt, 1H, J = 7.2, 14.3 Hz), 2.48 (tdd, 1H, J = 5.1, 6.9 Hz, 13.9 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 66.6, 50.4, 33.4;
IR (film): 1785, 1376, 1213, 1168, 1020, 896 cm^{-1}.



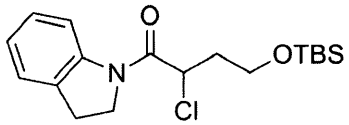
2-Chloro-4-hydroxy-1-(indolin-1-yl)butan-1-one. Indoline (4.1 mL, 36.4 mmol, 2.6 equiv) was added to an oven-dried flask containing $AlCl_3$ (2.43 g, 18.2 mmol, 1.3 equiv) in anhydrous CH_2Cl_2 (15 mL) at 0 °C. The solution was stirred for 5 min at 0 °C, and then α-chloro-γ-butyrolactone (1.68 g, 13.9 mmol, 1.0 equiv) was added. The solution was stirred for 2 h at room temperature, and then the reaction was quenched with water and stirred overnight. The reaction mixture was filtered through celite and concentrated. CH_2Cl_2 and water were added to the residue, and the organic layer was separated and concentrated. The residue was purified by flash chromatography (2:3→2:1 EtOAc:pentane, followed by 1:3→1:1 EtOAc:pentane), which provided the product (750 mg, 20%) as a yellow oil.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.22 (d, 1H, J = 7.9 Hz), 7.25-7.20 (m, 2H), 7.10-7.05 (m, 1H), 4.80-4.74 (m, 1H), 4.39 (dt, 1H, J = 7.3, 9.8 Hz), 4.17 (dt, 1H, J = 7.2, 10.0 Hz), 3.88 (dd, 2H, J = 4.9, 11.0 Hz), 3.32-3.17 (m, 2H), 2.47-2.38 (m, 1H), 2.31-2.22 (m, 1H), 1.80 (t, 1H, J = 4.9 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 166.7, 142.5, 131.7, 127.6, 124.73, 124.66, 117.6, 58.7, 53.8, 47.9, 36.7, 28.0;

IR (film): 1660, 1598, 1483, 1418, 1263, 1054, 756 cm^{-1};

LRMS (EI) for $C_{12}H_{15}ClNO_2$ (M+H): calcd 240, found 240.



4-(*tert*-Butyldimethylsilyloxy)-2-chloro-1-(indolin-1-yl)butan-1-one. TBSCl (0.82 g, 5.33 mmol, 1.25 equiv), imidazole (732 mg, 10.7 mmol, 2.5 equiv), and DMAP (60 mg) were added in turn to a solution of 2-chloro-4-hydroxy-1-(indolin-1-yl)butan-1-one (1.02 g, 4.26 mmol) in DMF (5 mL) at 0 °C. The resulting solution was allowed to warm to room temperature with stirring overnight. Next, the reaction mixture was diluted with EtOAc (15 mL) and poured into saturated $NaHCO_3$ (20 mL). The phases were separated, and the aqueous layer was extracted with EtOAc (15 mL × 2). The organic layers were combined and washed with brine (20 mL), dried over Na_2SO_4, and concentrated. The residue was purified by flash chromatography (7% EtOAc in pentane), followed by recrystallization from EtOAc, which furnished the product as a white solid (720 mg, 43%).

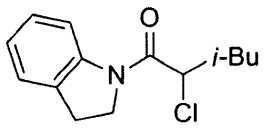
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.26 (d, 1H, J = 8.0 Hz), 7.25-7.19 (m, 2H), 7.09-7.04 (m, 1H), 4.77 (dd, 1H, J = 5.6, 8.2 Hz), 4.36 (dt, 1H, J = 7.2, 9.9 Hz), 4.12 (dt, 1H, J = 7.0, 10.0 Hz), 3.84 (ddd, 1H, J = 3.8, 8.0, 11.7 Hz), 3.76 (ddd, 1H, J = 4.6,

5.3, 10.3 Hz), 3.32-3.17 (m, 2H), 2.34 (dddd, 1H, J = 4.5, 5.5, 8.0, 12.5 Hz), 2.19 (dddd, 1H, J = 3.8, 5.6, 9.3, 11.0 Hz), 0.89 (s, 9H), 0.06 (d, 6H, J = 11.6 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 166.7, 142.8, 131.7, 127.8, 124.8, 124.6, 117.8, 59.2, 53.6, 47.9, 37.3, 28.2, 26.1, 18.4 –5.2 –5.3;

IR (film): 1668, 1600, 1483, 1413, 1257, 1103, 937, 834, 778, 755 cm^{-1};

LRMS (EI) for $C_{18}H_{28}ClNO_2Si$: calcd 353, found 353.



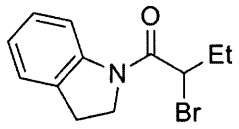
2-Chloro-1-(indolin-1-yl)-4-methylpentan-1-one. Oxalyl chloride (1.18 mL, 13.4 mmol, 1.1 equiv) and DMF (0.1 mL, 1.3 mmol, 0.11 equiv) were added to a 0 °C solution of α-chloroisocaproic acid[70] (1.84 g, 12.2 mmol) in anhydrous CH_2Cl_2 (36 mL) in an oven-dried flask under argon. The reaction mixture was allowed to warm to room temperature with stirring overnight. The solution was then transferred by cannula to a solution of indoline (1.50 mL, 13.4 mmol, 1.1 equiv) and triethylamine (1.87 mL, 13.4 mmol, 1.1 equiv) in anhydrous CH_2Cl_2 (30 mL) at 0 °C under argon. The suspension was stirred for 4 h, and then the reaction was quenched by the addition of HCl (1 M; 20 mL). The reaction mixture was extracted with CH_2Cl_2 (20 mL × 2), and the combined organic layers were washed with brine (20 mL), dried over Na_2SO_4, and concentrated. The residue was purified by flash chromatography (5% EtOAc in hexanes), which furnished the product (2.20 g, 72%) as a white solid.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.25 (d, 1H, J = 8.0 Hz), 7.27-7.19 (m, 2H), 7.06 (t, 1H, J = 7.4 Hz), 4.49 (t, 1H, J = 7.2 Hz), 4.42-4.34 (m, 1H), 4.16-4.07 (m, 1H), 3.32-3.17 (m, 2H), 2.01-1.95 (m, 2H), 1.91-1.80 (m, 1H), 1.00-0.94 (m, 6H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 166.7, 142.9, 131.6, 127.9, 124.8, 124.6, 117.8, 55.2, 48.0, 42.8, 28.3, 25.3, 22.9, 22.1;

IR (film): 1668, 1600, 1482, 1413, 1262, 1107, 755 cm^{-1};

LRMS (EI) for $C_{14}H_{19}ClNO$ (M+H): calcd 252, found 252.



2-Bromo-1-(indolin-1-yl)butan-1-one. Triethylamine (2.77 g, 27.5 mmol, 1.1 equiv) and then 2-bromo-*n*-butyryl bromide were added to an oven-dried flask under argon that contained a solution of indoline (3.28 g, 27.5 mmol, 1.1 equiv) in THF (50 mL) at 0 °C. The reaction mixture was stirred at 0 °C for 1 h, and then the reaction was quenched by the addition of HCl (1 M; 30 mL) and EtOAc (30 mL). The phases were separated, and the aqueous layer was extracted EtOAc (2 × 30 mL). The organic layers were combined, washed with brine (30 mL), and dried over Na_2SO_4. The residue was

[70] Koppenhoefer, B.; Schurig, V. *Org. Syntheses* **1988**, *66*, 151–155.

purified by flash chromatography (10% EtOAc in pentane), which furnished the product (4.22 g, 63%) as a white crystalline solid.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.27 (d, 1H, J = 8.0 Hz), 7.24-7.17 (m, 2H), 7.09-7.03 (m, 1H), 4.37-4.29 (m, 2H), 4.07 (dt, 1H, J = 7.1, 10.0 Hz), 3.30-3.15 (m, 2H), 2.27 (pentet d, 1H, J = 7.2, 14.3 Hz), 2.12 (pentet d, 1H, J = 7.4, 14.7 Hz), 1.06 (t, 3H, J = 7.3 Hz);

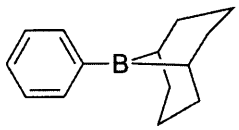
^{13}C NMR (400 MHz, $CDCl_3$): δ 166.6, 142.7, 131.5, 127.7, 124.7, 124.4, 117.6, 48.3, 47.9, 28.1, 27.9, 12.3;

IR (film): 1653, 1576, 1457, 1419, 1161, 755, 668 cm^{-1};

LRMS (EI) for $C_{12}H_{14}BrNO$: calcd 267, found 267 .

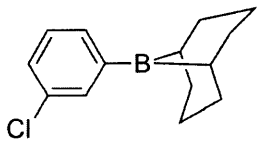
3. Preparation of Aryl-(9-BBN) Reagents

General Procedure. All aryl-(9-BBN) reagents were prepared by following a literature procedure for the synthesis of Ph-(9-BBN) via the reaction of phenylmagnesium chloride with *B*-methoxy-(9-BBN). [71] Although we routinely purified the aryl-(9-BBN) reagents by distillation, we have obtained comparable results when the aryl-(9-BBN) reagent (1.8 equiv) was not distilled prior to use in the asymmetric Suzuki reaction.



9-Phenyl-9-borabicyclo[3.3.1]nonane [23418-91-9]. Prepared from *B*-methoxy-(9-BBN) and phenylmagnesium bromide. Distilled at 95 °C at 240 mTorr.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.98 (d, 2H, J = 7.0 Hz), 7.58-7.53 (m, 1H), 7.50-7.45 (m, 2H), 2.29-2.24 (m, 2H), 2.06-1.96 (m, 6H), 1.87-1.76 (m, 4H), 1.31 (ddd, 2H);



9-(3-Chlorophenyl)-9-borabicyclo[3.3.1]nonane. Prepared from *B*-methoxy-(9-BBN) and 3-chlorophenylmagnesium bromide. Distilled at 150 °C at 400 mTorr.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.91-7.89 (m, 1H), 7.84-7.80 (m, 1H), 7.52 (ddd, 1H, J = 1.2, 2.3, 8.0 Hz), 7.43-7.38 (m, 1H), 2.29-2.22 (m, 2H), 2.06-1.96 (m, 6H), 1.85-1.75 (m, 4H), 1.35-1.25 (m, 2H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 134.7, 134.5, 132.72, 132.67, 129.7, 34.3, 29.8, 23.6;

^{11}B NMR (128 MHz, $CDCl_3$): δ 61.

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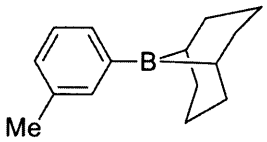
[71] Fang, G. Y.; Wallner, O. A.; Di Blasio, N.; Ginesta, X.; Harvey, J. N.; Aggarwal, V. K. *J. Am. Chem. Soc.* **2007**, *129*, 14632–14639.

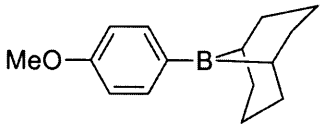


9-(3-Methylphenyl)-9-borabicyclo[3.3.1]nonane. Prepared from *B*-methoxy-(9-BBN) and 3-methylphenylmagnesium bromide. Distilled at 110 °C at 290 mTorr.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.85-7.80 (m, 2H), 7.44-7.40 (m, 2H), 2.46 (s, 3H), 2.35-2.30 (m, 2H), 2.09-2.00 (m, 6H), 1.92-1.81 (m, 4H), 1.40-1.29 (m, 2H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 138.7, 137.5, 135.5, 133.8, 131.9, 128.2, 34.3, 29.3, 23.7, 21.7;

^{11}B NMR (128 MHz, $CDCl_3$): δ 81.

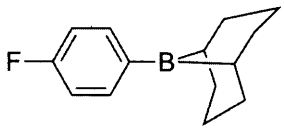


9-(4-Methoxyphenyl)-9-borabicyclo[3.3.1]nonane. Prepared from *B*-methoxy-(9-BBN) and 4-methoxyphenylmagnesium bromide. After filtration and concentration, the aryl-(9-BBN) reagent was used without further purification.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.01-7.96 (m, 2H), 7.03-6.98 (m, 2H), 3.89 (s, 3H), 2.27 (br s, 2H), 2.05-1.95 (m, 6H), 1.86-1.74 (m, 4H), 1.37-1.27 (m, 2H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 163.7, 137.0, 130.9, 113.5, 55.2, 34.1, 28.4, 23.5;

^{11}B NMR (128 MHz, $CDCl_3$): δ 78.



9-(4-Fluorophenyl)-9-borabicyclo[3.3.1]nonane. Prepared from *B*-methoxy-(9-BBN) and 4-fluorophenylmagnesium bromide. Distilled at 76 °C at 200 mTorr.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.01-7.95 (m, 2H), 7.17-7.10 (m, 2H), 2.29-2.22 (m, 2H), 2.05-1.91 (m, 6H), 1.85-1.74 (m, 4H), 1.35-1.25 (m, 2H);

^{13}C NMR (100 MHz, $CDCl_3$): δ 167.7, 165.2, 137.4, 115.3, 34.3, 29.2 23.6;

^{11}B NMR (128 MHz, $CDCl_3$): δ 80.

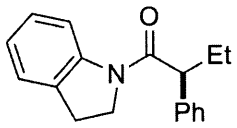
4. Asymmetric Suzuki Arylations of a-Chloroamides

General Procedure. In a nitrogen-filled glovebox, $NiBr_2$·diglyme (14.1 mg, 0.040 mmol, 8.0%), ligand **3** (18.8 mg, 0.050 mmol, 10%; Run 1: (*S,S*)-**3**; Run 2: (*R,R*)-**3**), the electrophile (0.50 mmol), and toluene (2.5 mL) were added to a 10-mL flask. The following materials were added in turn to a 4-mL vial: KO*t*-Bu (73 mg, 0.65 mmol, 1.3 equiv), *i*-BuOH (69 μL, 0.75 mmol, 1.5 equiv), the aryl-(9-BBN) reagent (0.75 mmol, 1.5 equiv), and toluene (2.5 mL). The flask and the vial were each capped with a rubber septum, and the two mixtures were stirred for 10 min. Next, the vessels were removed from the glovebox and placed in a –5 °C bath, and the mixtures were stirred

for 10 min. The solution in the vial was then transferred by syringe to the slurry in the 10-mL flask, which was attached to a nitrogen-filled balloon. The reaction mixture was stirred at –5 °C for 24 h (it turned orange after a few min). Next, the mixture was poured into a separatory funnel and washed with a saturated solution of sodium carbonate (5 mL; if the aqueous layer is very viscous, then distilled water (3 mL) was added). The aqueous phase was extracted with EtOAc (5 mL × 2), and the organic layers were combined and washed with brine (5 mL), dried over Na_2SO_4, and concentrated. The resulting residue was purified by flash chromatography.

Run 1: (*S,S*)-**3**. Run 2: (*R,R*)-**3**.

Practical note: For the cross-couplings illustrated in Table 2, flash chromatography was used to purify the products. However, it was sometimes difficult to remove a 9-BBN-derived impurity by flash chromatography, necessitating the use of more than one chromatography. It is more practical to run a preliminary flash chromatography and then a recrystallization; this effectively removes the impurity and simultaneously enriches the ee of the product.



1-(Indolin-1-yl)-2-phenylbutan-1-one (Table 8, entry 1). 2-Chloro-1-(indolin-1-yl)butan-1-one (112 mg, 0.50 mmol) and 9-phenyl-9-borabicyclo[3.3.1]nonane (149 mg, 0.75 mmol) were used. Solvent system for chromatography: 7.5% EtOAc in pentane, then 1:1 CH_2Cl_2:pentane→CH_2Cl_2. The product was isolated as a white solid.

Run 1: 108 mg (81% yield, 93% ee). Run 2: 101 mg (76% yield, 90% ee).

The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 8.5 (major) and 10.1 (minor) min.

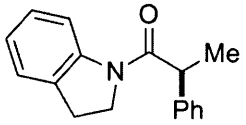
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.33 (d, 1H, J = 8.1 Hz), 7.38-7.29 (m, 4H), 7.26-7.21 (m, 1H), 7.19 (t, 1H, J = 7.8 Hz), 7.12 (d, 1H, J = 7.3 Hz), 6.99 (t, 1H, J = 7.4 Hz), 4.15 (dt, 1H, J = 6.6, 10.3 Hz), 3.84 (dt, 1H, J = 6.6, 10.3 Hz), 3.58 (t, 1H, J = 7.2 Hz), 3.19-3.09 (m, 1H), 3.07-2.96 (m, 1H), 2.28-2.16 (m, 1H), 1.87-1.74 (m, 1H), 0.93 (t, 3H, J = 7.3 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 171.7, 143.5, 139.6, 131.3, 129.0, 128.3, 127.7, 127.3, 124.7, 123.8, 117.4, 54.1, 47.9, 28.22, 28.16, 12.7;

IR (film): 1646, 1559, 1540, 1457, 1406, 757, 668 cm^{-1};

LRMS (EI) for $C_{18}H_{20}NO$ (M+H): calcd 266, found 266;

$[\alpha]^{23}_D$ +123 (*c* 1.20, $CHCl_3$); 93% ee, from (*S,S*)-**3**.



1-(Indolin-1-yl)-2-phenylpropan-1-one (Table 8, entry 2). 2-Chloro-1-(indolin-1-yl)propan-1-one (105 mg, 0.50 mmol) and 9-phenyl-9-borabicyclo[3.3.1]nonane (149 mg, 0.75 mmol) were used. Solvent system for chromatography: (1) 10% EtOAc in pentane; (2) 1:1 CH_2Cl_2:pentane→CH_2Cl_2. The product was isolated as a white solid.

Run 1: 113 mg (90% yield, 88% ee). Run 2: 109 mg (87% yield, 86% ee).

The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 13.0 (major) and 16.9 (minor) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.33 (d, 1H, J = 8.1 Hz), 7.34-7.30 (m, 4H), 7.26-7.22 (m, 1H), 7.20 (t, 1H, J = 7.8 Hz), 7.13 (d, 1H, J = 7.2 Hz), 7.00 (t, 1H, J = 7.4 Hz), 4.10 (dt, 1H, J = 6.6, 10.3 Hz), 3.87 (q, 1H, J = 6.8 Hz), 3.77 (dt, 1H, J = 6.6, 10.3 Hz), 3.17-3.06 (m, 1H), 3.04-2.94 (m, 1H), 1.53 (d, 3H, J = 6.8 Hz);

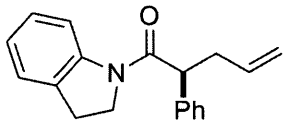
^{13}C NMR (100 MHz, $CDCl_3$): δ 172.2, 143.5, 141.3, 131.3, 129.2, 127.7 (2), 127.2, 124.7, 123.9, 117.4, 47.8, 46.5, 28.2, 20.7;

IR (film): 1653, 1599, 1482, 1403, 1286, 755, 701 cm^{-1};

LRMS (EI) for $C_{17}H_{18}NO$ (M+H): calcd 252, found 252;

$[\alpha]^{23}_D$ –160 (*c* 1.06, $CHCl_3$); 86% ee, from (*R,R*)-**3**.

Reaction on a gram scale (Table 8, entry 2). The reaction was carried out on a 5.0 mmol, rather than a 0.5 mmol, scale. In a nitrogen-filled glovebox, $NiBr_2$·diglyme (141 mg, 0.400 mmol, 8.0%), ligand (*S,S*)-**3** (189 mg, 0.500 mmol, 10%), 1.048 g 2-Chloro-1-(indolin-1-yl)propan-1-one (5.00 mmol), and toluene (25.0 mL) were added to a 100-mL Schlenk flask. The following materials were added in turn to a 50-mL pear-shaped flask: KO*t*-Bu (729 mg, 6.50 mmol, 1.30 equiv), *i*-BuOH (556 mg, 7.50 mmol, 1.5 equiv), Ph–(9-BBN) (1.486 mg, 7.50 mmol, 1.5 equiv), and toluene (25.0 mL). The flasks were capped with rubber septa, and the two mixtures were stirred for 10 min. Next, the vessels were removed from the glovebox and placed in a –5 °C bath, and the mixtures were stirred for 10 min. The nucleophile solution was then transferred by syringe to the slurry in the 10-mL flask, which was attached to a nitrogen-filled balloon. The reaction mixture was stirred at low temperature for 24 h (it turned orange after a few min); the reaction temperature ranged from –20 °C to –5 °C for 20 h, and then it was maintained at –5 °C for the remaining 4 h. After purification by flash chromatography (7.5% EtOAc in pentane), the product was obtained in 88% yield, as determined by ^{1}H NMR spectroscopy (vs. Ph_3CH as a standard), and 92% ee. The internal standard was removed by flash chromatography (1%→15% EtOAc in pentane), and the product was recrystallized from MTBE and hexanes to give the desired compound as white crystals (0.882 g, 70%; >99% ee).



1-(Indolin-1-yl)-2-phenylpent-4-en-1-one (Table 8, entry 3). 2-Chloro-1-(indolin-1-yl)pent-4-en-1-one (118 mg, 0.50 mmol) and 9-phenyl-9-borabicyclo[3.3.1]nonane (149 mg, 0.75 mmol) were used. Solvent system for chromatography: (1) 5% EtOAc in pentane; (2) 3:1 CH_2Cl_2:pentane→CH_2Cl_2. The product was isolated as a white solid.

Run 1: 115 mg (83% yield, 91% ee). Run 2: 105 mg (76% yield, 90% ee).

The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 11.0 (major) and 13.2 (minor) min.

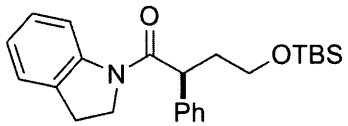
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.33 (d, 1H, J = 8.1 Hz), 7.37-7.29 (m, 4H), 7.27-7.22 (m, 1H), 7.19 (t, 1H, J = 7.8 Hz), 7.13 (d, 1H, J = 7.3 Hz), 6.99 (dt, 1H, J = 0.8, 7.4 Hz), 5.81 (tdd, 1H, J = 6.9, 10.2, 17.1 Hz), 5.07 (ddd, 1H, J = 1.4, 3.1, 17.1 Hz), 5.01-4.97 (m, 1H), 4.14 (dt, 1H, J = 6.5, 10.3 Hz), 3.83 (dt, 1H, J = 6.5, 10.4 Hz), 3.78-3.73 (m, 1H), 3.14 (ddd, 1H, J = 6.5, 10.4, 16.6 Hz), 3.06-2.92 (m, 2H), 2.54-2.45 (td, 1H, J = 6.9, 14.0 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 170.8, 143.3, 138.8, 136.3, 131.1, 128.9, 128.1, 127.5, 127.2, 124.5, 123.7, 117.3, 116.7, 52.1, 47.7, 39.1, 28.0;

IR (film): 1646, 1597, 1479, 1407, 922, 757, 705 cm^{-1};

LRMS (EI) for $C_{19}H_{20}NO$ (M+H): calcd 278, found 278;

$[\alpha]^{23}_D$ –144 (*c* 1.03, $CHCl_3$); 90% ee, from (*R,R*)-**3**.



4-(*tert*-Butyldimethylsilyloxy)-1-(indolin-1-yl)-2-phenylbutan-1-one (Table 8, entry 4). 4-(*tert*-Butyldimethylsilyloxy)-2-chloro-1-(indolin-1-yl)butan-1-one (179 mg, 0.50 mmol) and 9-phenyl-9-borabicyclo[3.3.1]nonane (149 mg, 0.75 mmol) were used. Solvent system for chromatography: (1) 2%→5% EtOAc in pentane; (2) passage through a plug of reverse-phase silica with 8:2 H_2O:MeCN, followed by 2:8 H_2O:MeCN. The product was isolated as a yellow solid.

Run 1: 152 mg (77% yield, 85% ee). Run 2: 162 mg (82% yield, 83% ee).

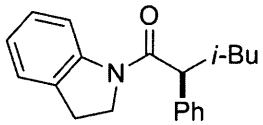
The ee was determined on an IC column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 18.0 (major) and 14.7 (minor) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.32 (d, 1H, J = 8.1 Hz), 7.38-7.28 (m, 4H), 7.26-7.22 (m, 1H), 7.19 (t, 1H, J = 7.8 Hz), 7.13 (d, 1H, J = 7.1 Hz), 6.99 (dt, 1H, J = 0.8, 7.4 Hz), 4.18 (dt, 1H, J = 6.4, 10.4 Hz), 4.08 (t, 1H, J = 7.2 Hz), 3.86 (dt, 1H, J = 6.6, 10.4 Hz), 3.69-3.62 (m, 1H,), 3.58-3.51 (m, 1H), 3.19-3.09 (m, 1H), 3.07-2.97 (m, 1H), 2.45-2.35 (m, 1H), 1.99-1.89 (m, 1H), 0.91 (s, 9H), 0.02 (d, 6H, J = 4.9 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 171.6, 143.5, 139.4, 131.4, 129.0, 128.5, 127.7, 127.3, 124.6, 123.8, 117.4, 60.5, 47.9, 47.6, 37.8, 28.1, 26.1, 18.4, –5.2;

IR (film): 1654, 1482, 1401, 1258, 1101, 834, 754 cm^{-1};

LRMS (EI) for $C_{24}H_{33}NO_2Si$ (M): calcd 395, found 395;
$[\alpha]^{23}_D$ –82 (*c* 1.06, $CHCl_3$); 83% ee, from (*R,R*)-**1**.



1-(Indolin-1-yl)-4-methyl-2-phenylpentan-1-one (Table 8, entry 5). 2-Chloro-1-(indolin-1-yl)-4-methylpentan-1-one (112 mg, 0.50 mmol) and 9-phenyl-9-borabicyclo[3.3.1]nonane (149 mg, 0.75 mmol) were used. Solvent system for chromatography: (1) 5% EtOAc in pentane; (2) 1:1 CH_2Cl_2:pentane→CH_2Cl_2. The product was isolated as a white solid.
Run 1: 128 mg (87% yield, 86% ee). Run 2: 119 mg (81% yield, 84% ee).
The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 8.9 (major) and 11.3 (minor) min.

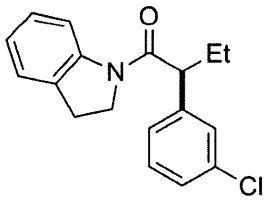
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.32 (d, 1H, *J* = 8.1 Hz), 7.38-7.29 (m, 4H), 7.26-7.22 (m, 1H), 7.19 (t, 1H, *J* = 7.8 Hz), 7.13 (d, 1H, *J* = 7.3 Hz), 6.99 (t, 1H, *J* = 7.4 Hz), 4.17 (dt, 1H, *J* = 6.7, 10.3 Hz), 3.90 (dt, 1H, *J* = 6.5, 10.3 Hz), 3.80 (t, 1H, *J* = 7.2 Hz), 3.21-3.11 (m, 1H), 3.09-2.99 (m, 1H), 2.13 (td, 1H, *J* = 6.7, 13.8 Hz), 1.68-1.51 (m, 2H), 0.94 (dd, 6H, *J* = 6.4, 15.7 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 171.7, 143.5, 139.8, 131.3, 129.0, 128.3, 127.7, 127.2, 124.6, 123.8, 117.5, 49.8, 47.9, 44.2, 28.2, 25.9, 22.9;

IR (film): 2955, 1658, 1600, 1481, 1402, 754, 701 cm^{-1};

LRMS (EI) for $C_{20}H_{24}NO$ (M+H): calcd 294, found 294;

$[\alpha]^{23}_D$ +123 (*c* 1.00, $CHCl_3$); 86% ee, from (*S,S*)-**3**.



2-(3-Chlorophenyl)-1-(indolin-1-yl)butan-1-one (Table 8, entry 6). 2-Chloro-1-(indolin-1-yl)butan-1-one (112 mg, 0.50 mmol) and 9-(3-chlorophenyl)-9-borabicyclo[3.3.1]nonane (149 mg, 0.75 mmol) were used, as well as 10 mol% $NiBr_2$·diglyme (17.6 mg, 0.050 mmol) and 12.5 mol% diamine ligand (23.5 mg, 0.062 mmol). Solvent system for chromatography: (1) 7.5% EtOAc in pentane; (2) 2:1 CH_2Cl_2:pentane to CH_2Cl_2. The product was isolated as a white solid.
Run 1: 118 mg (79% yield, 93% ee). Run 2: 111 mg (74% yield, 91% ee).
The ee was determined on an AD-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 19.8 (major) and 17.3 (minor) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.32 (d, 1H, *J* = 8.1 Hz), 7.36-7.34 (m, 1H), 7.26-7.17 (m, 4H), 7.16-7.12 (d, 1H, *J* = 7.2 Hz), 7.00 (dt, 1H, *J* = 1.0, 7.4 Hz), 4.15 (dt, 1H, *J* = 6.6, 10.3 Hz), 3.86 (dt, 1H, *J* = 6.5, 10.3 Hz), 3.56 (t, 1H, *J* = 7.3 Hz), 3.21-3.11

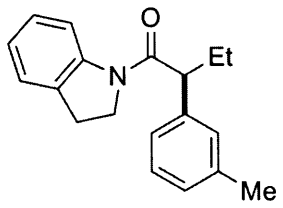
(m, 1H), 3.11-3.01 (m, 1H), 2.26-2.14 (m, 1H), 1.85-1.73 (m, 1H), 0.93 (t, 3H, J = 7.4 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 170.8, 143.2, 141.4, 134.6, 131.1, 130.1, 128.3, 127.6, 127.4, 126.3, 124.5, 123.9, 117.3, 53.5, 47.8, 28.04, 27.98, 12.4;

IR (film): 1646, 1596, 1479, 1407, 1258, 756, 668 cm^{-1};

LRMS (EI) for $C_{18}H_{19}ClNO$ (M+H): calcd 300, found 300;

$[\alpha]^{23}_D$ +136 (c 1.00, $CHCl_3$); 93% ee, from (*S,S*)-**3**.



1-(Indolin-1-yl)-2-m-tolylbutan-1-one (Table 8, entry 7). 2-Chloro-1-(indolin-1-yl)butan-1-one (112 mg, 0.50 mmol) and 9-(3-methylphenyl)-9-borabicyclo[3.3.1]nonane (159 mg, 0.75 mmol) were used. Solvent system for chromatography: (1) 7.5% EtOAc in pentane; (2) 1:1 CH_2Cl_2:pentane to CH_2Cl_2. The product was isolated as a white solid.

Run 1: 112 mg (80% yield, 93% ee). Run 2: 121 mg (87% yield, 92% ee).

The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 9.4 (major) and 10.9 (minor) min.

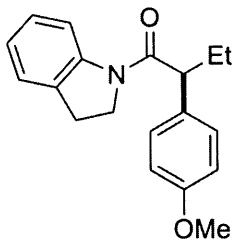
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.34 (d, 1H, J = 8.1 Hz), 7.23-7.17 (m, 2H), 7.17-7.10 (m, 3H), 7.05 (d, 1H, J = 7.4 Hz), 6.99 (t, 1H, J = 7.4 Hz), 4.14 (dt, 1H, J = 6.6, 10.3 Hz), 3.86 (dt, 1H, J = 6.4, 10.4 Hz), 3.54 (t, 1H, J = 7.3 Hz), 3.19-3.09 (m, 1H), 3.07-2.97 (m, 1H), 2.33 (s, 3H), 2.26-2.14 (m, 1H), 1.84-1.72 (m, 1H), 0.93 (t, 3H, J = 7.3 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 171.6, 143.4, 139.3, 138.6, 131.2, 128.59, 128.57, 127.9, 127.5, 125.4, 124.5, 123.6, 117.3, 53.9, 47.7, 28.1, 28.0, 21.5, 12.6;

IR (film): 1653, 1600, 1481, 1401, 1339, 755 cm^{-1};

LRMS (EI) for $C_{19}H_{22}NO$ (M+H): calcd 280, found 280;

$[\alpha]^{23}_D$ –136 (c 1.11, $CHCl_3$); 92% ee, from (*R,R*)-**3**.



1-(Indolin-1-yl)-2-(4-methoxyphenyl)butan-1-one (Table 8, entry 8). 2-Chloro-1-(indolin-1-yl)butan-1-one (112 mg, 0.50 mmol) and 9-(4-methoxyphenyl)-9-borabicyclo[3.3.1]nonane (172 mg, 0.75 mmol) were used. Solvent system for

chromatography: (1) 10% EtOAc in pentane; (2) 1:1 CH_2Cl_2:pentane→CH_2Cl_2 (twice). The product was isolated as a white solid.
Run 1: 116 mg (79% yield, 91% ee). Run 2: 120 mg (81% yield, 90% ee).
The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 18.8 (major) and 21.7 (minor) min.

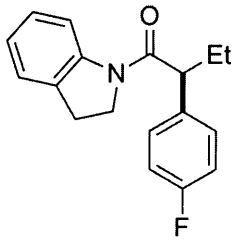
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.32 (m, 1H), 7.27-7.23 (m, 2H), 7.21-7.16 (m, 1H), 7.12 (d, 1H, J = 7.3 Hz), 6.98 (dt, 1H, J = 0.9, 7.4 Hz), 6.87-6.83 (m, 2H), 4.13 (dt, 1H, J = 6.6, 10.3 Hz), 3.90-3.82 (m, 1H), 3.78 (s, 3H), 3.52 (t, 1H, J = 7.3 Hz), 3.19-3.09 (m, 1H), 3.07-2.97 (m, 1H), 2.23-2.12 (m, 1H), 1.82-1.71 (m, 1H), 0.92 (t, 3H, J = 7.3 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 172.0, 158.8, 143.6, 131.6, 131.3, 129.3, 127.7, 124.6, 123.8, 117.4, 114.3, 55.5, 53.1, 47.9, 28.20, 28.16, 12.6;

IR (film): 1653, 1511, 1481, 1401, 1252, 1178, 1033, 756 cm^{-1};

LRMS (EI) for $C_{19}H_{22}NO_2$ (M+H): calcd 296, found 296;

$[\alpha]^{23}_D$ +126 (*c* 1.15, $CHCl_3$); 91% ee, from (*S,S*)-**3**.



2-(4-Fluorophenyl)-1-(indolin-1-yl)butan-1-one (Table 8, entry 9). 2-Chloro-1-(indolin-1-yl)butan-1-one (112 mg, 0.50 mmol) and 9-(4-fluorophenyl)-9-borabicyclo[3.3.1]nonane (166 mg, 0.75 mmol) were used. Solvent system for chromatography: (1) 7.5% EtOAc in pentane; (2) 1:1 CH_2Cl_2:pentane→CH_2Cl_2 (three times). The product was isolated as a white solid.
Run 1: 101 mg (71% yield, 94% ee). Run 2: 99 mg (70% yield, 93% ee).
The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 10.7 (major) and 13.1 (minor) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.31 (d, 1H, J = 8.1 Hz), 7.34-7.28 (m, 2H), 7.23-7.17 (m, 1H), 7.15-7.11 (m, 1H), 7.04-6.97 (m, 3H), 4.15 (dt, 1H, J = 6.6 Hz, J = 10.3 Hz), 3.85 (dt, 1H, J = 6.5 Hz, 10.3 Hz), 3.57 (t, 1H, J = 7.3 Hz), 3.20-3.10 (m, 1H), 3.09-2.99 (m, 1H) 2.24-2.13 (m, 1H), 1.83-1.71 (m, 1H), 0.92 (t, 3H, J = 7.3 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 171.4, 161.9 (d, J = 244 Hz), 143.2, 135.1 (d, J = 3.3 Hz), 131.1, 129.7, 127.6, 124.5, 123.8, 117.3, 115.7 (d, J = 21 Hz), 53.0, 47.7, 28.1, 28.0, 12.4;

IR (film): 1653, 1600, 1501, 1482, 1401, 1223, 756;

LRMS (EI) for $C_{18}H_{19}FNO$ (M+H): calcd 284, found 284;

$[\alpha]^{23}_D$ +131 (*c* 0.99, $CHCl_3$); 94% ee, from (*S,S*)-**3**.

Eq 32. In a nitrogen-filled glovebox, $NiBr_2$• diglyme (7.0 mg, 0.032 mmol, 8.0%), ligand (*R,R*)-**1** (15.1 mg, 0.040 mmol, 10%), 2-chloro-1-(indolin-1-yl)propan-1-

one (83.4 mg, 0.40 mmol), *n*-tetradecane (60.9 mg, 0.31 mmol, 0.77 equiv; internal standard), and toluene (2.0 mL) were added to a 10-mL flask. The following materials were added in turn to a 4-mL vial: KO*t*-Bu (58.3 mg, 0.52 mmol, 1.3 equiv), *i*-BuOH (44.6 mg, 0.60 mmol, 1.5 equiv), Ph-(9-BBN) (119 mg, 0.60 mmol, 1.5 equiv), and toluene (2.0 mL). The flask and the vial were each capped with a rubber septum, and the two mixtures were stirred for 10 min. Next, the vessels were removed from the glovebox and placed in a –5 °C bath, and the mixtures were stirred for 10 min. The solution in the vial was then transferred by syringe to the slurry in the 10-mL flask, which was attached to an argon-filled manifold. The reaction mixture was stirred at –5 °C for 11 h, at which time an aliquot was removed and passed through a plug of silica (washed with Et_2O).

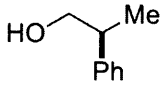
GC analysis showed 86% conversion of the starting material, and HPLC analysis showed a starting-material ee of 54% and a product ee of 90% (AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min); starting material: 21.5 (major) and 30.4 (minor) min; product: 14.1 (minor) and 18.2 (major) min).

Eq 33 and 34. In a nitrogen-filled glovebox, $NiBr_2$·diglyme (8.8 mg, 0.040 mmol, 8.0%), ligand (*S,S*)-**3** (18.8 mg, 0.050 mmol, 10%), 2-chloro-1-(indolin-1-yl)propan-1-one (105 mg; 0.50 mmol; eq 6: *R* enantiomer, 95% ee, eq 7: *S* enantiomer, 95% ee), *n*-tetradecane (99 mg, 0.50 mmol, 1.0 equiv), and toluene (2.5 mL) were added to a 10-mL flask. The following materials were added in turn to a 4-mL vial: KO*t*-Bu (73 mg, 0.65 mmol, 1.3 equiv), *i*-BuOH (55.5 mg, 0.75 mmol, 1.5 equiv), Ph-(9-BBN) (149 mg, 0.75 mmol, 1.5 equiv), and toluene (2.5 mL). The flask and the vial were each capped with a rubber septum, and the two mixtures were stirred for 10 min. Next, the vessels were removed from the glovebox and placed in a –5 °C bath, and the mixtures were stirred for 10 min. The solution in the vial was then transferred by syringe to the slurry in the 10-mL flask, which was attached to an argon-filled manifold. The reaction mixture was stirred at –5 °C for 12 h, at which time an aliquot was removed and passed through a plug of silica (washed with Et_2O).

Eq 33: GC analysis showed 67% conversion of the starting material, and HPLC analysis showed a starting-material ee of 95% and a product ee of 88% (AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min); starting material: 20.7 (major) and 28.3 (minor) min; product: 13.6 (major) and 17.1 (minor) min).

Eq 34: GC analysis showed 67% conversion of the starting material, and HPLC analysis showed a starting-material ee of 95% and a product ee of 88% (AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min); starting material: 20.7 (minor) and 28.3 (major) min; product: 13.6 (major) and 17.1 (minor) min).

5. Functionalization Reactions (eq 30 and eq 31) and Assignment of Absolute Configuration



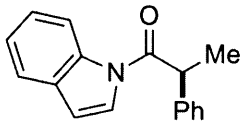
(*S*)-(–)-2-Phenyl-1-propanol [37778-99-7] (eq 30).[72] A solution of *n*-BuLi (1.6 M solution in hexanes; 2.44 mL, 3.9 mmol, 3.9 equiv) was added dropwise to a solution of of diisopropylamine (580 μL, 4.1 mmol, 4.1 equiv) in THF (15 mL) at 0 °C. The mixture was stirred for 15 min, then ammonia·borane (123 mg, 4.0 mmol, 4.0 equiv) was added. The resulting mixture was stirred at 0 °C for 15 min, and then it was warmed to room temperature. A solution of (*S*)-1-(indolin-1-yl)-2-phenylpropan-1-one (recrystallized; >99% ee; 251 mg, 1.0 mmol, 1.0 equiv) in THF (15 mL) was added, and then the reaction mixture was heated to reflux for 24 h. Next, the mixture was cooled to 0 °C, and the reaction was quenched by the addition of aqueous HCl (1 M; 20 mL). The layers were separated, and the aqueous layer was extracted with Et_2O (10 mL × 4). The combined organic layers were washed with HCl (1 M; 5 mL), NaOH (3 M; 5 mL), and brine (10 mL). The organic layer was dried over Na_2SO_4 and concentrated. The residue was purified by flash chromatography (10%→80% Et_2O in hexanes), which furnished the product as a clear, colorless oil.

Run 1: 109 mg (80% yield, >99% ee); Run 2: 116 mg (85% yield, >99% ee).

The ee was determined on an AS-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 17.0 (major) and 18.6 (minor) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36-7.31 (m, 2H), 7.25-7.22 (m, 3H), 3.74-3.69 (m, 2H), 3.01-2.91 (m, 1H), 1.28 (d, 3H, J = 7.0 Hz);

$[\alpha]^{24}_D$ –13.6 (*c* 1.00, $CHCl_3$); >99% ee. Lit.[44] $[\alpha]^{22}_D$ –12 (*c* 1.00, $CHCl_3$), 89% ee (S).



(*S*)-1-(1*H*-Indol-1-yl)-2-phenylpropan-1-one (eq 34). Toluene (7.5 mL) and DDQ (460 mg, 2.03 mmol, 1.30 equiv) were added to a Schlenk flask that contained (*S*)-1-(indolin-1-yl)-2-phenylpropan-1-one (recrystallized; >99% ee; 392 mg, 1.56 mmol) under argon. The resulting solution was heated to reflux overnight. The solution was then diluted with EtOAc (15 mL) and washed with water (10 mL). The aqueous layer was extracted with EtOAc (15 mL), and the combined organic layers were washed with brine (12 mL), dried over $MgSO_4$, and concentrated. The residue was purified by flash chromatography (2%→20% EtOAc in hexanes), which furnished the product as a white solid (351 mg, 90%).

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[72] Myers, A. G.; Yang, B. H.; Chen, H.; McKinstry, L.; Kopecky, D. J.; Gleason, J. L. *J. Am. Chem. Soc.* **1997**, *119*, 6496–6511.

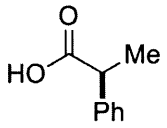
^{1}H NMR (400 MHz, $CDCl_3$): δ 8.53 (d, 1H, J = 8.3 Hz), 7.43 (d, 1H, J = 7.8 Hz), 7.34 (d, 1H, J = 3.8 Hz), 7.32-7.22 (m, 5H), 7.21-7.14 (m, 2H), 6.42 (d, 1H, J = 3.8 Hz), 4.35 (q, 1H, J = 6.9 Hz), 1.57 (d, 3H, J = 6.8 Hz);

^{13}C NMR (100 MHz, $CDCl_3$): δ 172.5, 141.1, 136.1, 130.4, 129.5, 127.6, 127.4, 125.4, 125.1, 124.0, 120.9, 117.1, 109.3, 46.5, 20.5;

IR (film): 1701, 1540, 1451, 1352, 1292, 1208, 910, 750, 700 cm^{-1};

LRMS (EI) for $C_{17}H_{15}NO$ (M): calcd 249, found 249;

$[\alpha]^{18}_D$ +101 (*c* 0.87, $(CH_3)_2CO$); >99% ee, based on the ee of the acid (after hydrolysis).

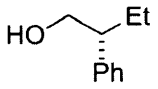


(*S*)-2-Phenylpropionic acid [7782-24-3] (eq 34). A solution of aqueous H_2O_2 (30% w/w; 1 mL) and $LiOH{\cdot}H_2O$ (192 mg, 4.58 mmol, 3.25 equiv) were added to a solution of (*S*)-1-(1*H*-indol-1-yl)-2-phenylpropan-1-one (351 mg, 1.41 mmol) in THF (14 mL) and H_2O (4 mL) at 0 °C. The resulting suspension was allowed to warm to room temperature and stirred overnight. Next, the reaction was quenched by the addition of saturated sodium thiosulfate (8 mL) and saturated sodium bicarbonate (10 mL). The mixture was stirred for 15 min, and then the THF was removed by rotary evaporation, and the aqueous layer was extracted with CH_2Cl_2 (10 mL). Next, the aqueous layer was acidified (pH<5) with HCl (1 M) and extracted with EtOAc (15 mL × 4). The combined organic layers were dried over Na_2SO_4 and concentrated. The residue was purified by flash chromatography (2%→20% EtOAc in hexanes), which furnished the product (161 mg, 76%) as a brown oil.

The ee was determined on an AD-H column (hexanes:isopropanol 97:3, flow 1.0 mL/min), with enantiomers eluting at 29.9 (minor) and 34.2 (major) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 12.01 (br s, 1H), 7.41-7.36 (m, 4H), 7.36-7.29 (m, 1H), 3.74 (q, 1H, J = 7.2 Hz), 1.52 (d, 3H, J = 7.2 Hz);

$[\alpha]^{18}_D$ +59 (*c* 1.01, $CHCl_3$); >99% ee. Lit.[73] $[\alpha]^{20}_D$ +72 (*c* 1.0, $CHCl_3$), 96% ee (S).



(*R*)-(–)-2-Phenyl-1-butanol [16460-75-6].[72] A solution of *n*-BuLi (1.6 M solution in hexanes; 0.83 mL, 1.33 mmol, 3.9 equiv) was added dropwise to a solution of diisopropylamine (200 µL, 1.43 mmol, 4.2 equiv) in THF (5 mL) at 0 °C. The mixture was stirred for 15 min, then ammonia·borane (44 mg, 1.2 mmol, 3.5 equiv) was added. The resulting mixture was stirred at 0 °C for 15 min, and then it was warmed to room temperature. A solution of (*R*)-1-(indolin-1-yl)-2-phenylbutan-1-one (90% ee; 89 mg, 0.34 mmol, 1.0 equiv) in THF (5 mL) was added, and then the reaction mixture was heated to reflux for 22 h. Next, the mixture was cooled to 0 °C, and the reaction was quenched by the addition of aqueous HCl (1 M; 5 mL). The layers were separated,

[73] Coulbeck, E.; Eames, J. *Tetrahedron: Asymmetry* **2008**, *19*, 2223–2233.

and the aqueous layer was extracted with Et_2O (3 mL × 4). The combined organic layers were washed with HCl (1 M; 3 mL), NaOH (2 M; 4 mL), and brine (3 mL). The organic layer was dried over Na_2SO_4 and concentrated. The residue was purified by flash chromatography (8%→60% Et_2O in hexanes), then washed with HCl (1 M; 3 mL; to remove an indoline impurity), thereby producing the alcohol as a yellow oil (25 mg, 49%).

The ee was determined to be 90% on an AD-H column (hexanes:isopropanol 99:1, flow 1.0 mL/min), with enantiomers eluting at 14.3 (major) and 15.7 (minor) min.

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32-7.27 (m, 2H), 7.22-7.16 (m, 3H), 3.75-3.65 (m, 2H), 2.67-2.62 (m, 1H), 1.76-1.68 (m, 1H), 1.62-1.50 (m, 2H), 0.80 (t, 3H, J = 7.4 Hz);

$[\alpha]^{23}_D$ –15.1 (*c* 0.95, $CHCl_3$); 90% ee. Lit. $[\alpha]^{23}_D$ –15.0±2.5 (*c* 1.00, $CHCl_3$), 92% ee (*R*);[74] $[\alpha]^{22}_D$ +18 (*c* 1.50, $CHCl_3$), 99% ee (*S*).[44]

[74] Matsubara, S.; Yamamoto, H.; Oshima, K. *Angew. Chem., Int. Ed.* **2002**, *41*, 2837–2840

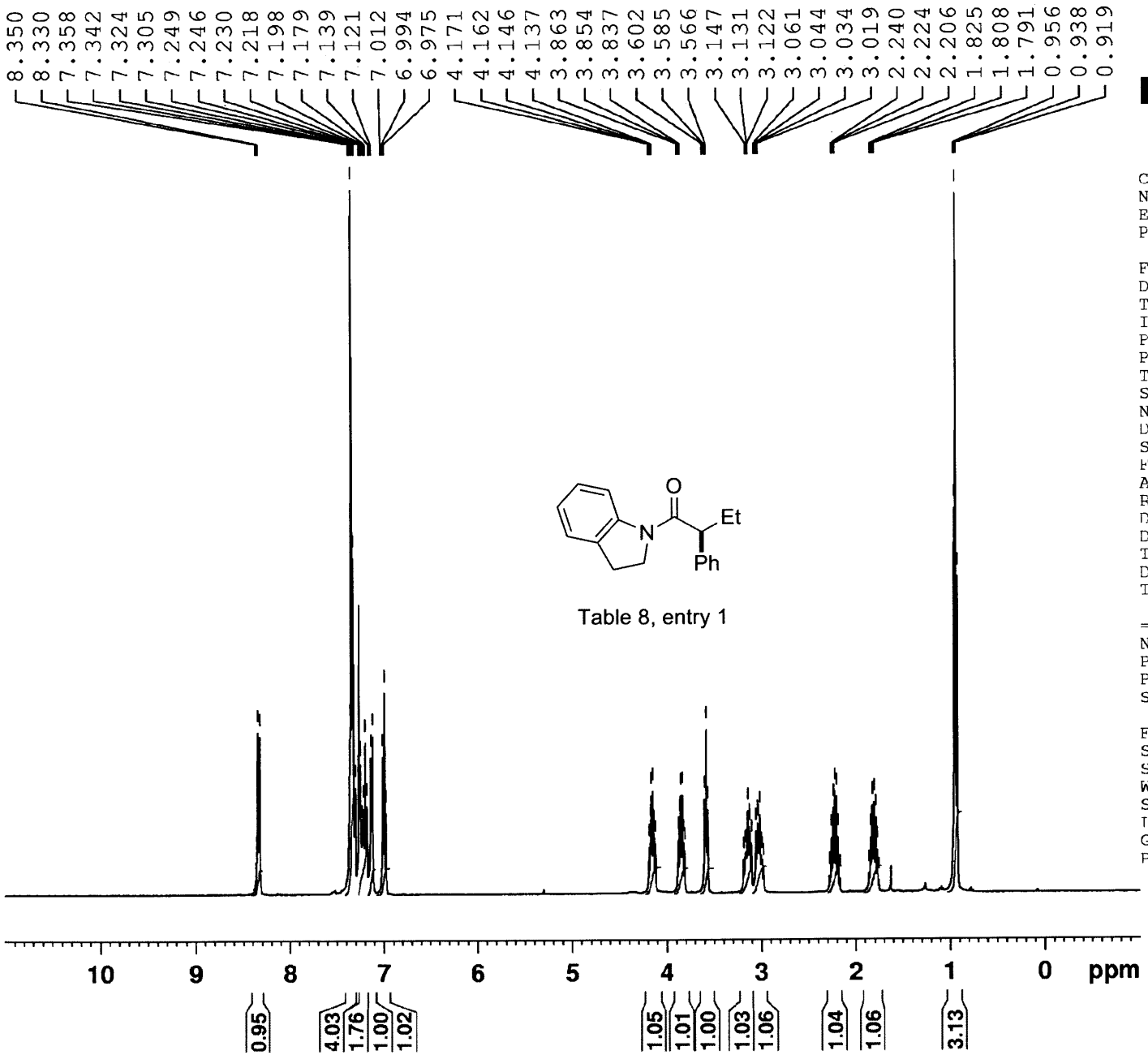


Table 8, entry 1

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PROCNO 1

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NS 16
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FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 362
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TE 292.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
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PL1 0.00 dB
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F2 - Processing parameters
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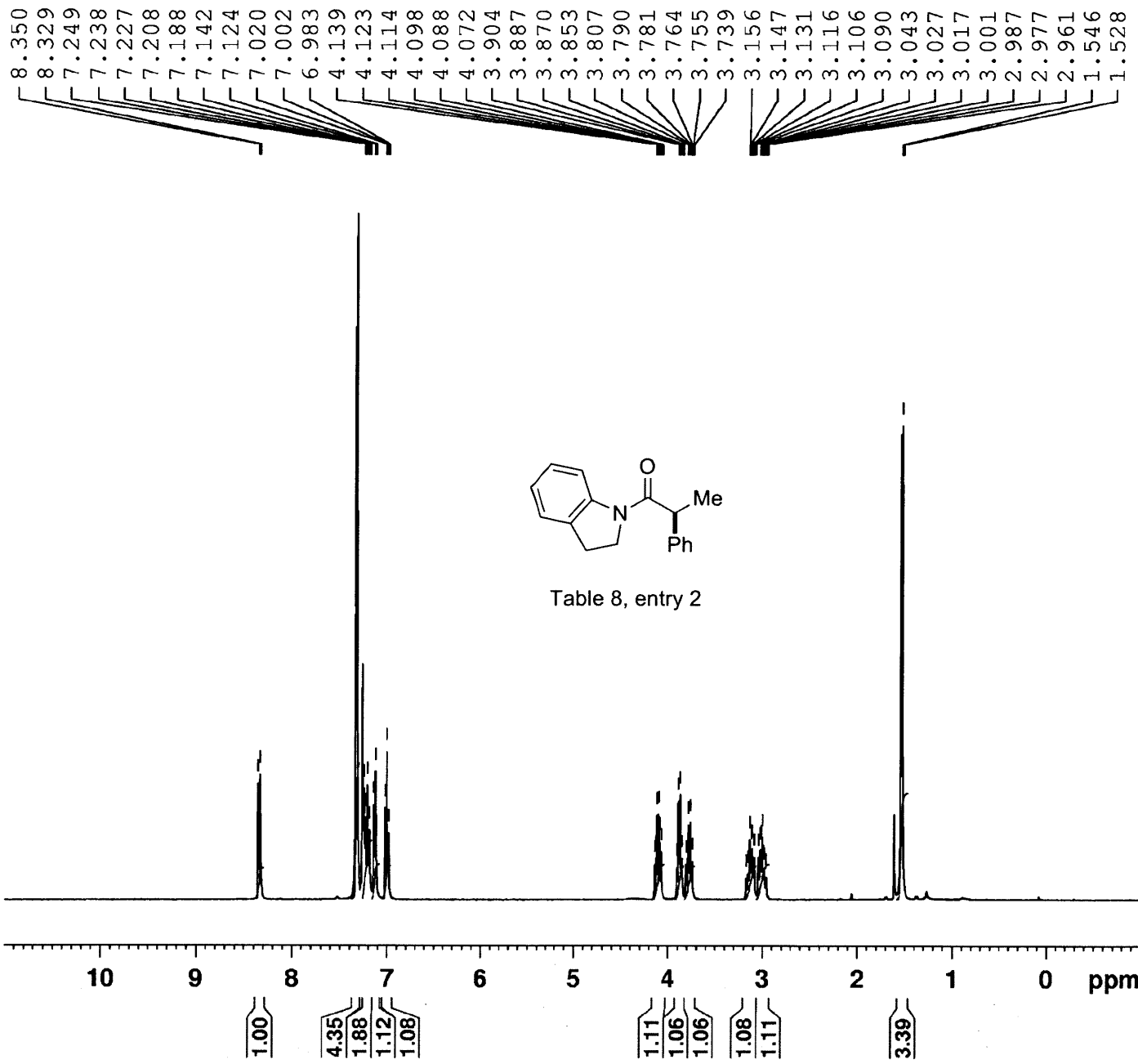

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PROCNO 1

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TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 362
DW 60.400 usec
DE 6.00 usec
TE 291.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
NUC1 1H
P1 14.00 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
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WDW EM
SSB 0
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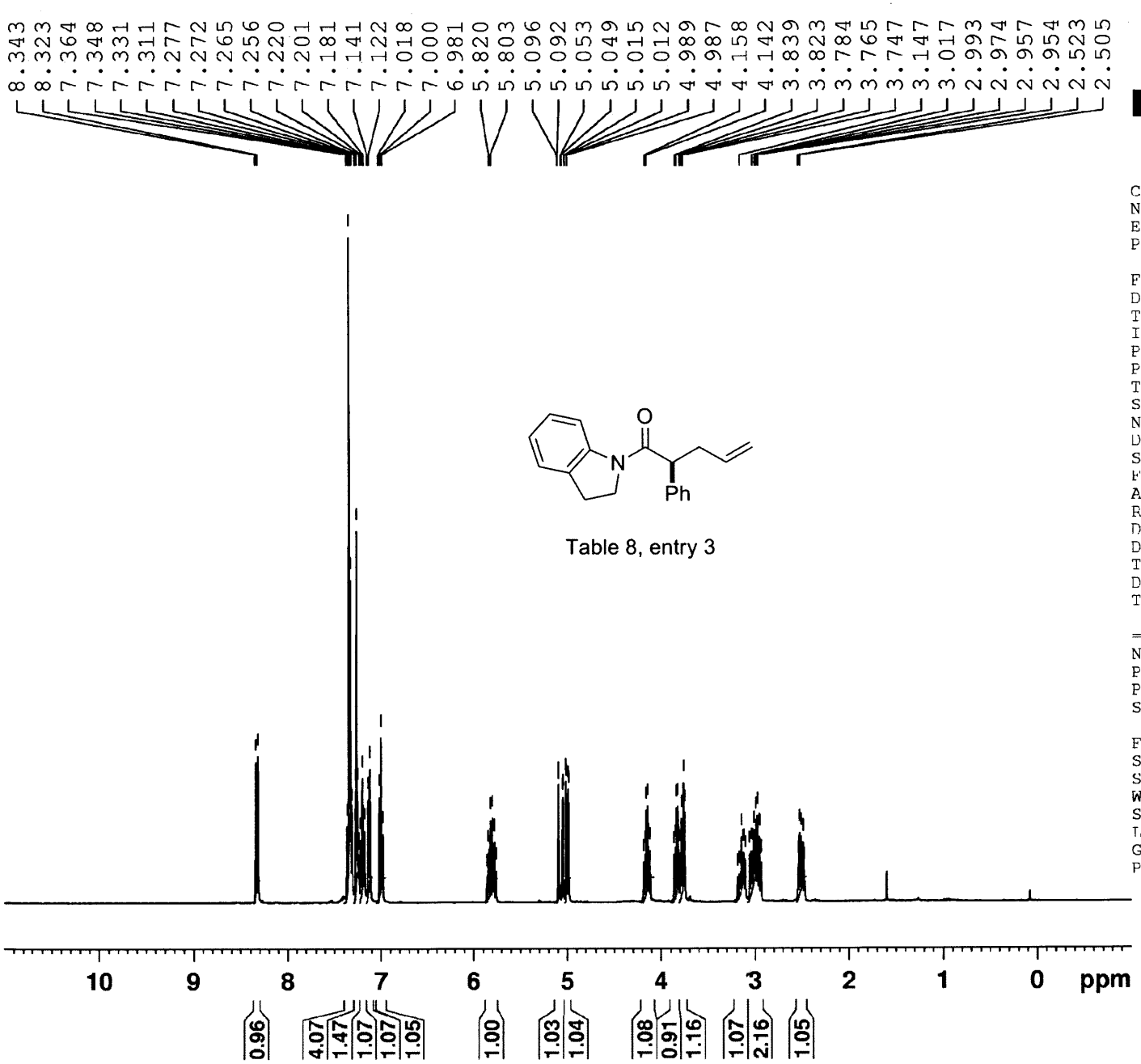
GB 0
PC 1.00



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EXPNO                     5
PROCNO                    1

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Time                  20.24
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PULPROG                zg30
TD                    65536
SOLVENT               CDCl3
NS                       16
DS                        2
SWH                8278.146 Hz
FIDRES             0.126314 Hz
AQ                 3.9584243 sec
RG                      512
DW                   60.400 usec
DE                    6.00 usec
TE                   292.2 K
D1                1.00000000 sec
TD0                       1

======== CHANNEL f1 ========
NUC1                      1H
P1                   14.00 usec
PL1                   0.00 dB
SFO1           400.1324710 MHz

F2 - Processing parameters
SI                    65536
SF             400.1300074 MHz
WDW                      EM
SSB                       0
LB                    0.30 Hz
GB                        0
PC                     1.00
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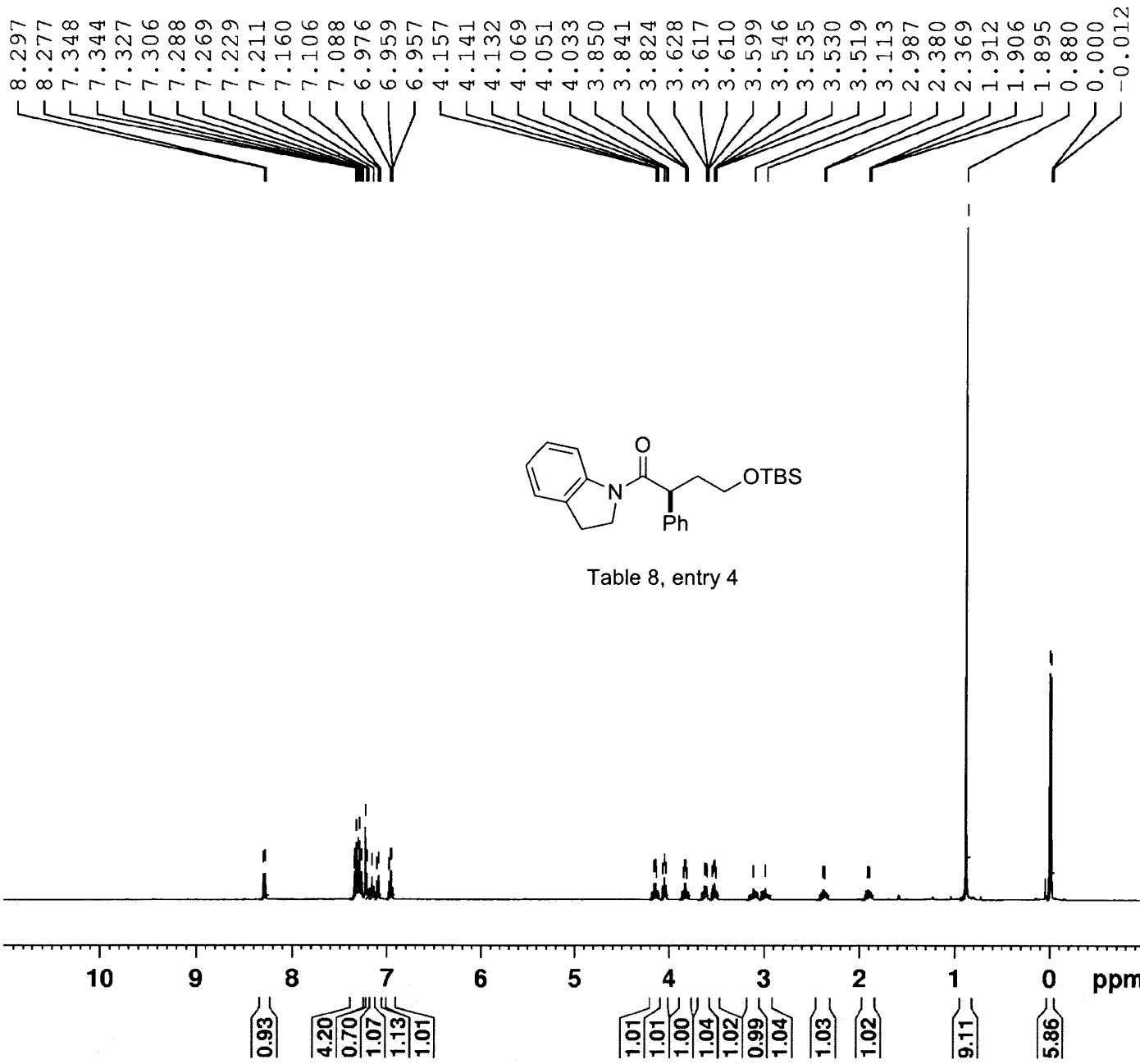

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PROCNO 1

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TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 203.2
DW 60.400 usec
DE 6.00 usec
TE 292.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
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P1 14.00 usec
PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
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WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00

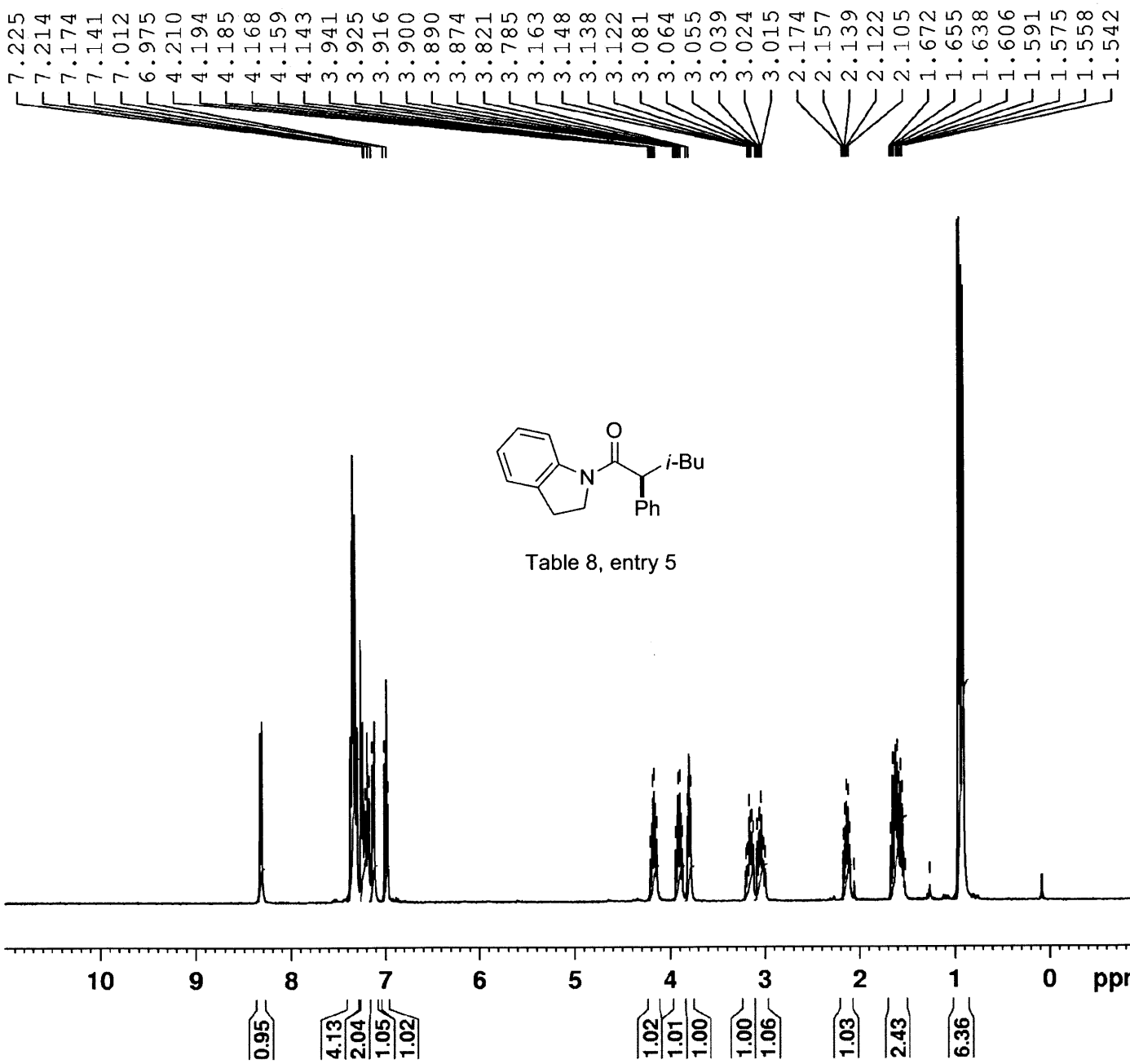

Table 8, entry 5

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PROCNO                    1

F2 - Acquisition Parameters
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Time                  11.07
INSTRUM               spect
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PULPROG                zg30
TD                    65536
SOLVENT               CDCl3
NS                       16
DS                        2
SWH                8278.146 Hz
FIDRES             0.126314 Hz
AQ                 3.9584243 sec
RG                      256
DW                   60.400 usec
DE                    6.00 usec
TE                   292.2 K
D1              1.00000000 sec
TD0                       1

======== CHANNEL f1 ========
NUC1                      1H
P1                   14.00 usec
PL1                   0.00 dB
SFO1          400.1324710 MHz

F2 - Processing parameters
SI                    65536
SF            400.1300074 MHz
WDW                      EM
SSB                       0
LB                    0.30 Hz
GB                        0
PC                    1.00
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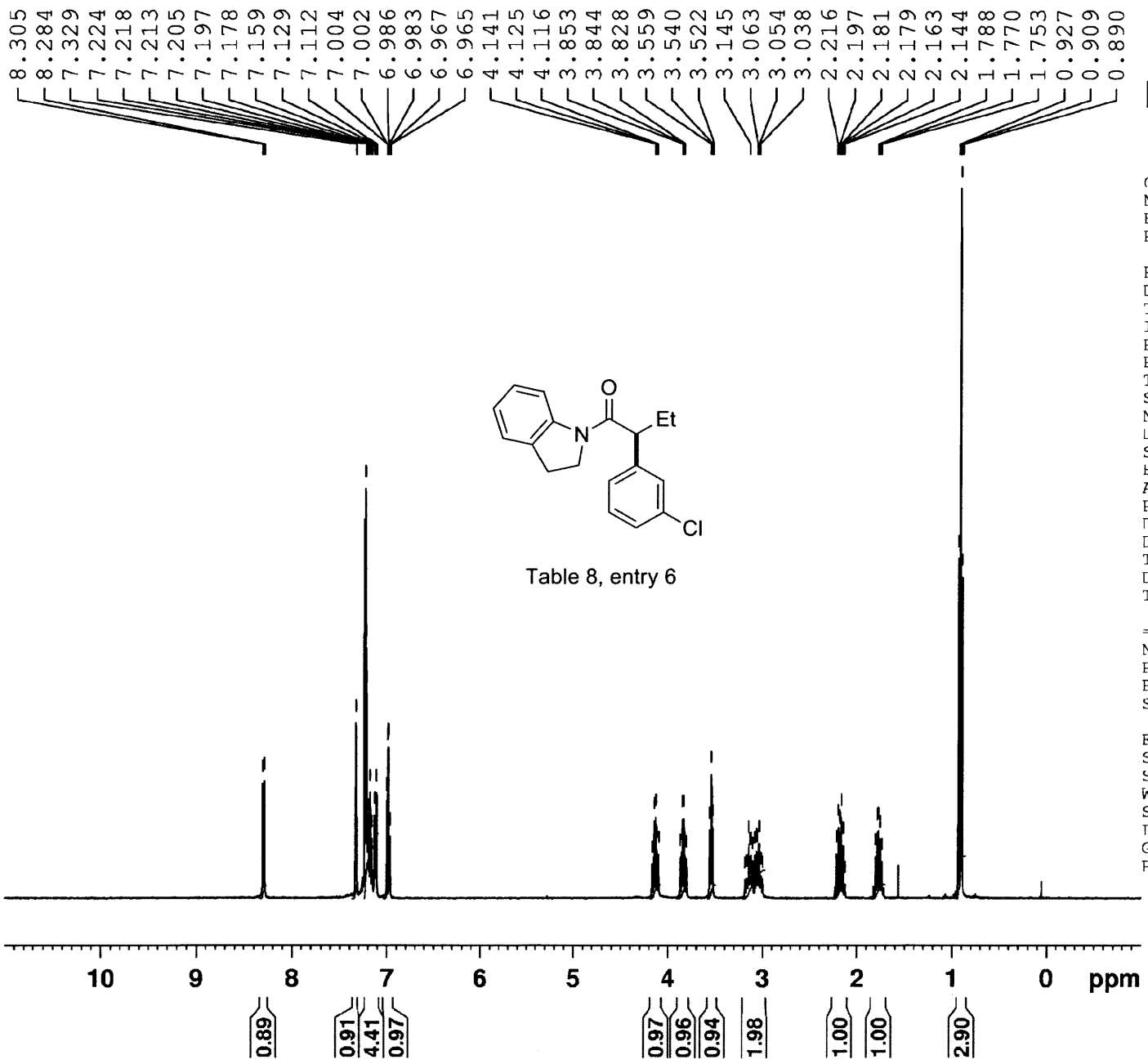

Table 8, entry 6

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EXPNO 7
PROCNO 1

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PULPROG zg30
TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 181
DW 60.400 usec
DE 6.00 usec
TE 293.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
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P1 15.07 usec
PL1 0.00 dB
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F2 - Processing parameters
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SF 400.1300177 MHz
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SSB 0
LB 0.30 Hz
GB 0
PC 1.00

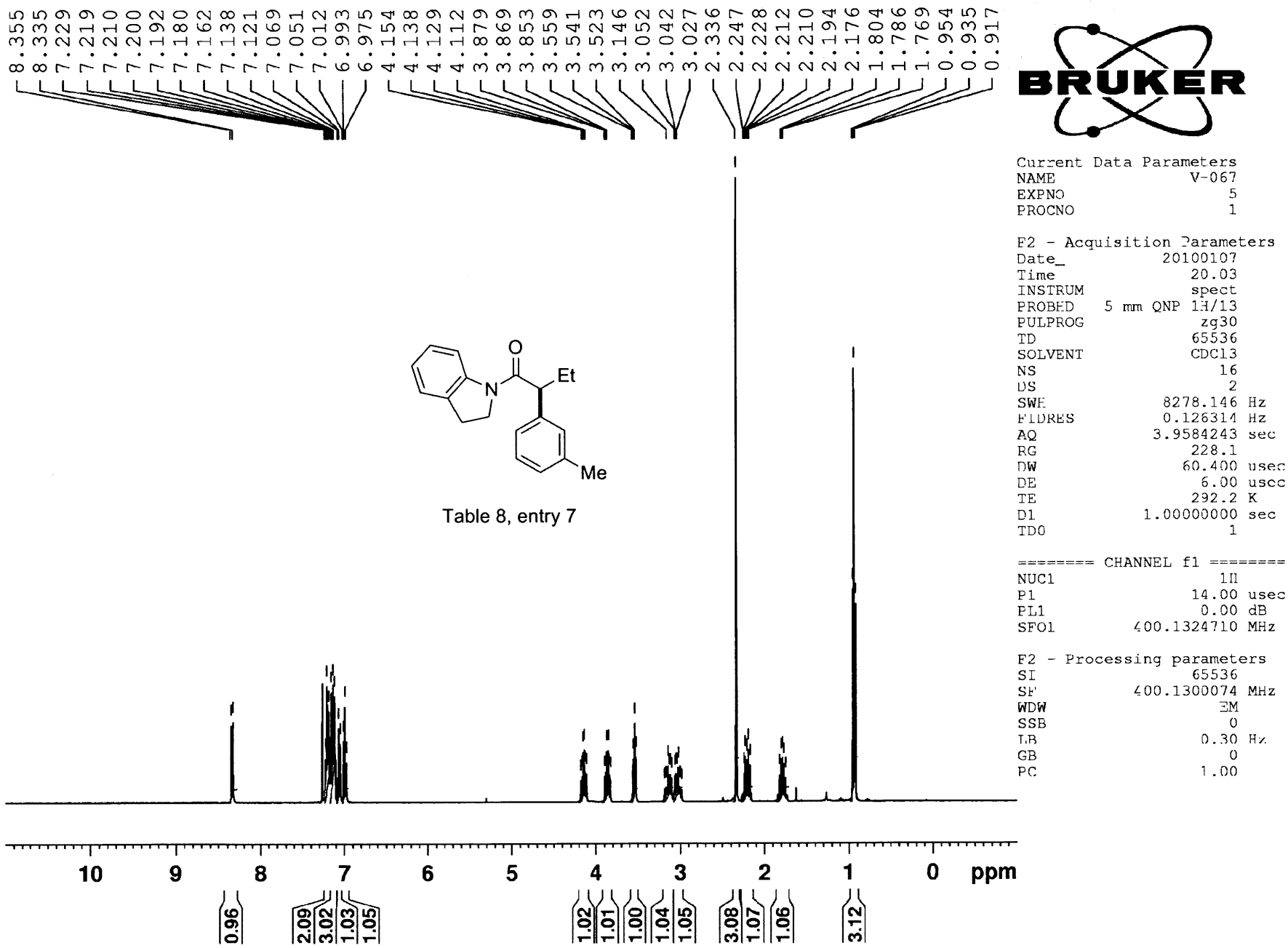

Table 8, entry 7

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EXPNO                     5
PROCNO                    1

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PULPROG                zg30
TD                    65536
SOLVENT               CDCl3
NS                       16
DS                        2
SWH                8278.146 Hz
FIDRES            0.126314 Hz
AQ                3.9584243 sec
RG                    228.1
DW                   60.400 usec
DE                    6.00 usec
TE                   292.2 K
D1              1.00000000 sec
TD0                       1

======== CHANNEL f1 ========
NUC1                      1H
P1                   14.00 usec
PL1                   0.00 dB
SFO1          400.1324710 MHz

F2 - Processing parameters
SI                    65536
SF            400.1300074 MHz
WDW                      EM
SSB                       0
LB                    0.30 Hz
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PC                    1.00
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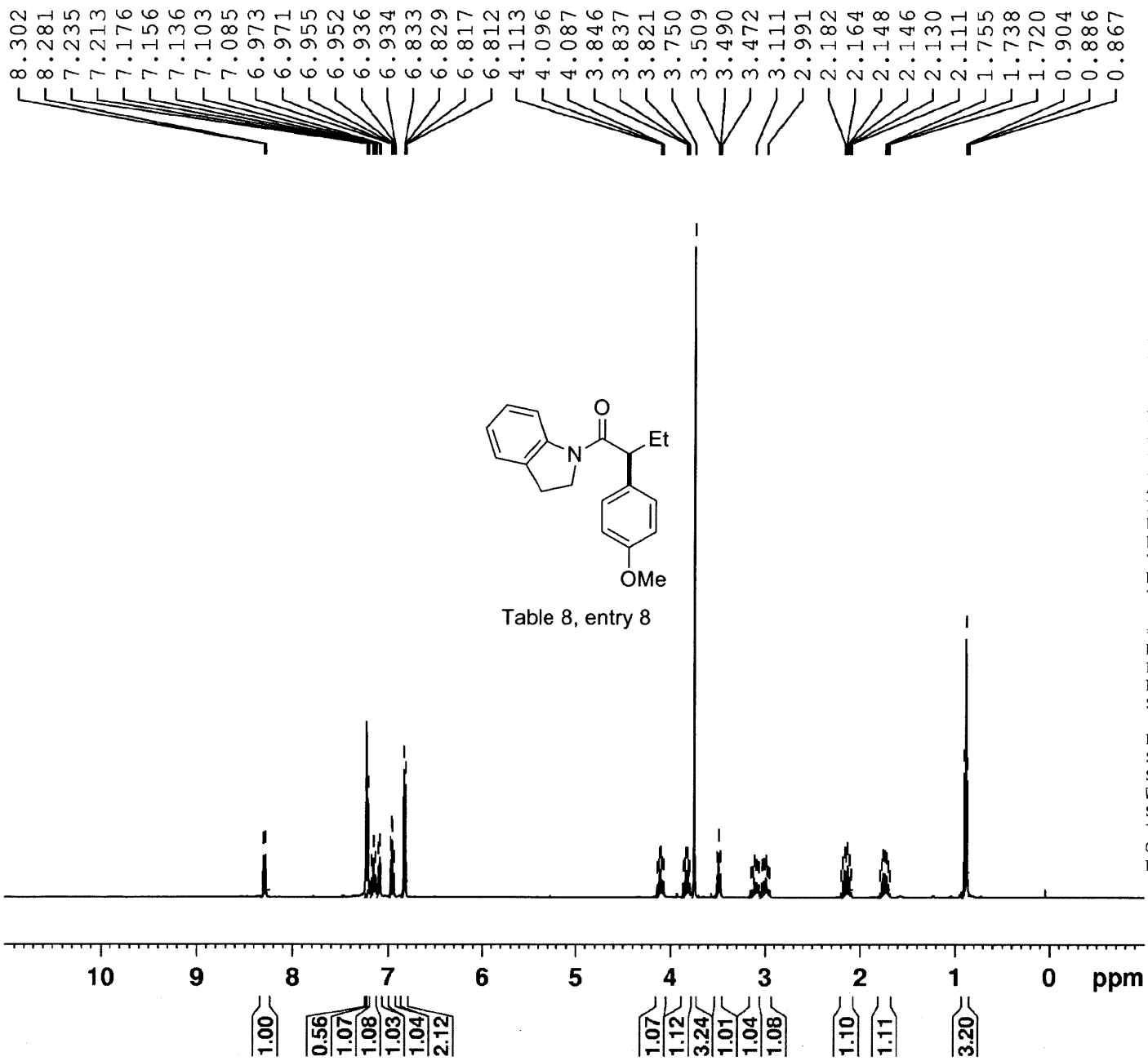

Table 8, entry 8

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EXPNO                     5
PROCNO                    1

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SOLVENT              CDCl3
NS                      16
DS                       2
SWH               8278.146 Hz
FIDRES            0.126314 Hz
AQ                3.9584243 sec
RG                   228.1
DW                  60.400 usec
DE                   6.00 usec
TE                  293.2 K
D1              1.00000000 sec
TD0                      1

======== CHANNEL f1 ========
NUC1                    1H
P1                   15.07 usec
PL1                   0.00 dB
SFO1          400.1324710 MHz

F2 - Processing parameters
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SF            400.1300212 MHz
WDW                     EM
SSB                      0
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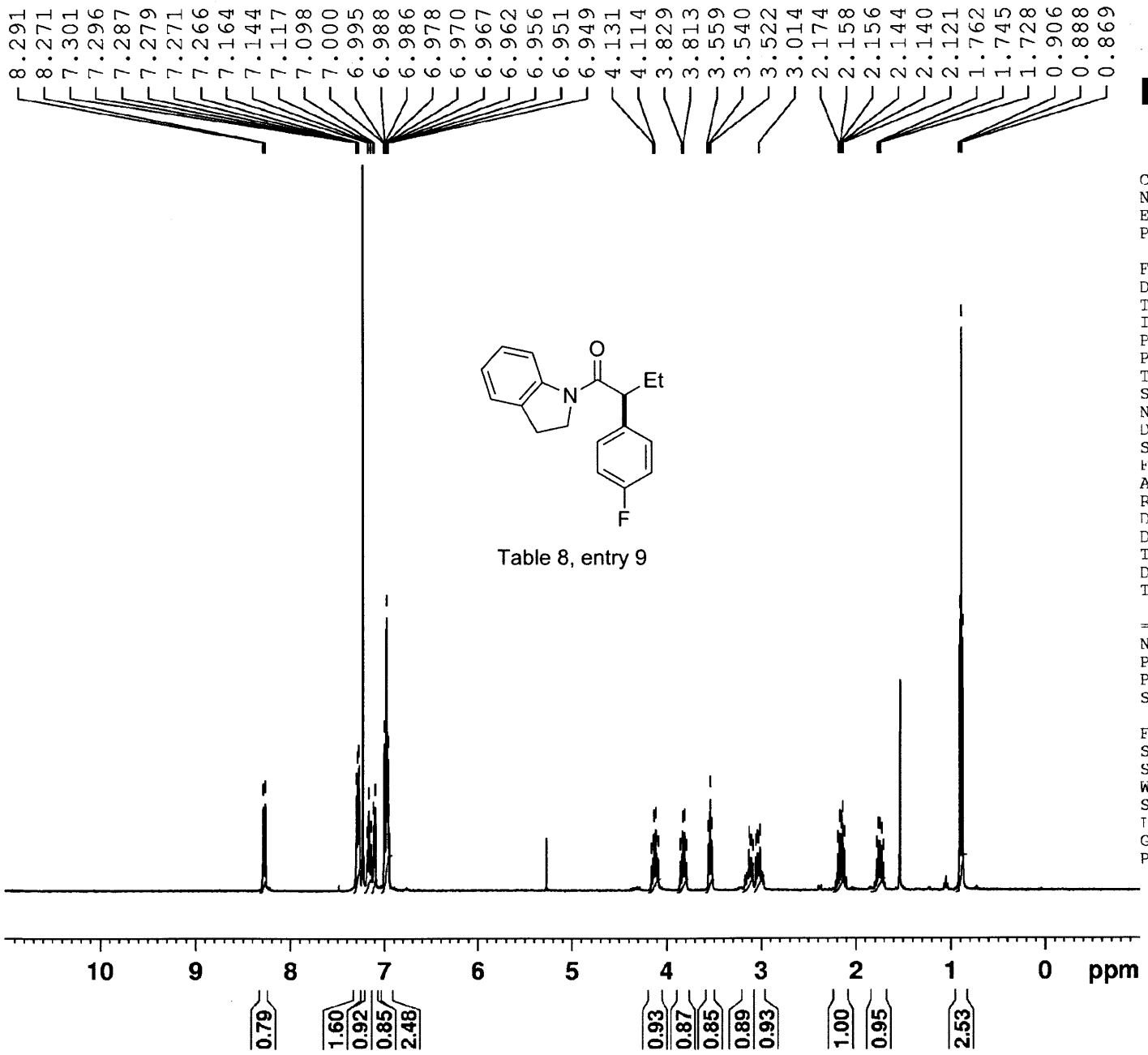

Table 8, entry 9

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Current Data Parameters
NAME V-057
EXPNO 8
PROCNO 1

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Time 8.35
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TD 65536
SOLVENT CDCl3
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 256
DW 60.400 usec
DE 6.00 usec
TE 294.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
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PL1 0.00 dB
SFO1 400.1324710 MHz

F2 - Processing parameters
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SF 400.1300212 MHz
WDW EM
SSB 0
LB 0.30 Hz
GB 0
PC 1.00

Chapter 2

Studies of Boratabenzene-Containing Transition Metal Complexes

A. Introduction

Phosphines are ubiquitous ligands in homogenous catalysis, and the structural diversity of this family of compounds spans a wide spectrum of steric and electronic properties.[75] Various metrics have been established to assess these properties, such as Tolman's definition of the electronic parameter ν as derived from the frequency of a CO stretch in a $[Ni(CO)_3PR_3]$ complex, and the steric parameter θ as determined by a phosphine's cone angle.[76] However understanding the delicate interplay between these two properties in a particular phosphine's success or lack thereof as a ligand is not trivial, as structural modifications often induce both steric and electronic perturbations. Thus, tools to unambiguously separate the effects of these two properties on reactivity are of high utility.

To this end, in 1996 Hoic reported the preparation of potassium diphenylphosphidoboratabenzene (K-DPB, **1**), which is isosteric to triphenylphosphine, yet electronically different as one phenyl ring has been replaced by a negatively charged boratabenzene ring.[77] Once it was established that η^1-phosphorus-bound transition metal complexes could be prepared (as opposed to DPB-complexes bound through the π-system of the negatively charged boratabenzene ring),[78] the CO stretching frequency of $CpFe(CO)_2(DPB)$ (Cp = cyclopentadienyl) was compared to those reported for $[CpFe(CO)_2(PPh_3)]^+$, $Cp^*Fe(CO)_2(PPh_2)$ and $CpFe(CO)_2(SiPh_3)$. DPB was found to be a less electron-releasing ligand than Ph_2P^- and Ph_3Si^-, but, as

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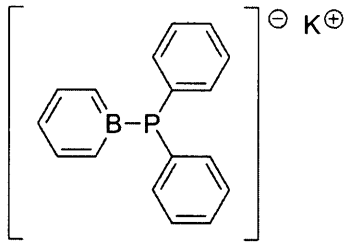
[75] For a review of the properties of phosphine ligands, see: van Leeuwen, P. W. N. M.; Freixa, Z.; Zuidema, E. In *Phosphorus Ligands in Asymmetric Catalysis*; Börner, A., Ed.; Wiley-VCH: Weinheim, 2008, p 1433–1454.

[76] Tolman, C. A. *Chem. Rev.* **1977**, *77*, 313–348.

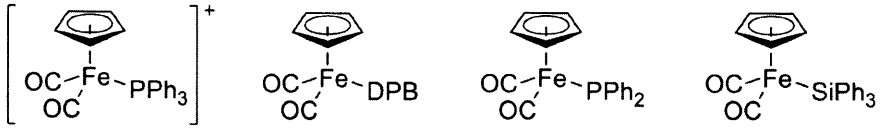
[77] Hoic, D. A.; Davis, W. M.; Fu, G. C. *J. Am. Chem. Soc.* **1996**, *118*, 8176–8177.

[78] $(DPB)_2Sm(THF)$, in which DPB is bound through the boratabenzne ring, has recently been reported: Cui, P.; Chen, Y.; Zeng, X.; Sun, J.; Li, G.; Xia, W. *Organometallics* **2007**, *26*, 6519–6521.

expected, a more electron-donating phosphine than PPh_3 (Figure 1). However, no detailed reactivity studies comparing complexes bearing PPh_3 versus those bearing DPB have been reported.



K-DPB (**1**)



Average ν_{CO} (cm^{-1})	2048	2003	1991	1968

Figure 1: Comparison of ν_{CO} stretches of $CpFe(CO)_2X$ complexes

In a subsequent publication, Hoic noted that the analogous potassium diphenyl*amido*boratabenzene (K-DAB) did not display the same reactivity with transition-metal complexes and attributed this to a difference in the degree of π-character in the phosphorus–boron and nitrogen–boron bonds. This hypothesis was supported by comparison of crystallographic, NMR spectroscopic, and computational data for the two complexes.[79]

In 2009, a collaboration between the Fu and Peters groups began with the aim of examining reactivity patterns of DPB-bearing complexes. The Peters group has long

[79] Hoic, D. A.; DiMare, M.; Fu, G. C. *J. Am. Chem. Soc.* **1997**, *119*, 7155–7156.

had an interest in phosphine ligands bearing a negatively charged borate moiety. Accordingly, they have prepared mono-,[80] bis-,[81] and tris-chelating[82] ligands (Figure 2) and studied the electronic properties of transition metal complexes bearing these ligands. Therefore, the anionic boratabenzene moiety of DPB was a logical continuation of this line of research.

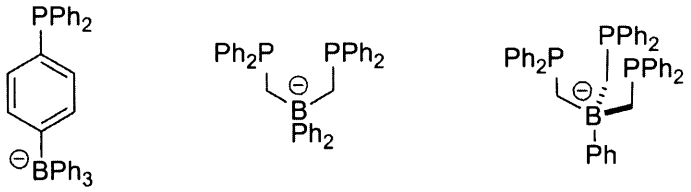


Figure 2: Borate-containing phosphine ligands developed by the Peters group

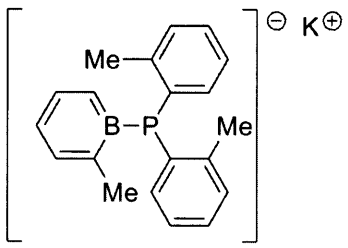
The goals of this collaboration include: 1. to prepare new transition metal complexes bearing DPB-type ligands; 2. to study the reactivity of DPB-bearing transition metal complexes in fundamental reactions such as oxidative additions and reductive eliminations; and 3. to determine whether DPB can be used to modulate reactivity of transition metal complexes for novel transformations. Of these three goals, the work done in this chapter is directed towards the first two. Section B.1 of this chapter contains a summary of our efforts toward developing new routes towards DPB- and boratabenzene containing transition metal complexes, which builds upon the

[80] Thomas, C. M.; Peters, J. C. *Inorg. Chem.* **2004**, *43*, 8–10.

[81] (a) Thomas, J. C.; Peters, J. C. *J. Am. Chem. Soc.* **2001**, *123*, 5100–5101. (b) Lu, C. C.; Peters, J. C. *J. Am. Chem. Soc.* **2002**, *124*, 5272–5273. (c) Thomas, J. C.; Peters, J. C. *Inorg. Chem.* **2003**, *42*, 5055–5073. (d) Betley, T. A.; Peters, J. C. *Angew. Chem., Int. Ed.* **2003**, *42*, 2385–2389. (e)Thomas, J. C.; Peters, J. C. *Polyhedron* **2004**, *23*, 2901–2913. (f) Lu, C. C.; Peters, J. C. *J. Am. Chem. Soc.* **2004**, *126*, 15818–15832.

[82] (a) Shapiro, I. R.; Jenkins, D. M.; Thomas, J. C.; Day, M. C.; Peters, J. C. *Chem. Commun.* **2001**, 2152–2153. (b) Jenkins, D. M.; Di Bilio, A. J.; Allen, M. J.; Betley, T. A.; Peters, J. C. *J. Am. Chem. Soc.* **2002**, *124*, 15336–15350. (c) Betley, T. A.; Peters, J. C. *Inorg. Chem.* **2003**, *42*, 5074–5084. (d) MacBeth, C. E.; Thomas, J. C.; Betley, T. A.; Peters, J. C. *Inorg. Chem.* **2004**, *2004*, 4645–4662.

previously reported work. Section B.2 concerns our studies of di(*ortho*-tolyl)phosphido-2-methylboratabenzene (DPB*o*T, **2**), a DPB derivative bearing ortho-methyl substituents on the boratabenzene and phenyl rings. This section details the preparation of K-DPB*o*T, compares its properties to that of K-DPB, and summarizes our progress towards the synthesis of a DPB*o*T-containing palladium complex in order to compare it to its neutral, isosteric variant tri-*ortho*-tolylphosphine. Tri-*ortho*-tolylphosphine has been used by by Hartwig and co-workers in palladium complexes for their studies on oxidative addition and reductive elimination of aryl halides.[83] If the analogous DPB*o*T-containing complexes can be prepared, similar studies to those of Hartwig will be conducted with the goal of elucidating information regarding the reactive properties of DPB*o*T.



2

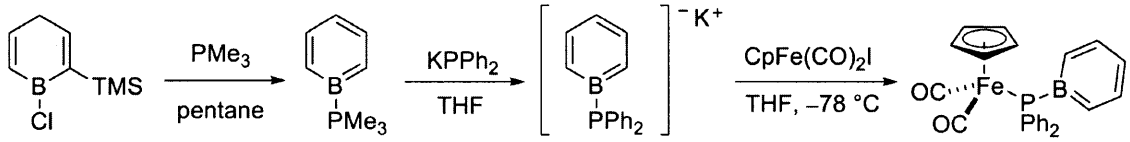
B: Results and Discussion

1. A new route to DPB-containing transition metal complexes

Scheme 1 contains the published synthetic route to the $CpFe(CO)_2DPB$ complex devised by Hoic.[77] Boracycle **3** is prepared by a radical cyclization between Bu_2SnH_2 and 1-trimethylsilyl-1,4-pentadiyne to produce the stannacycle precursor, followed by transmetallation with boron trichloride. The reaction of **3** with trimethylphosphine

[83] (a) Hartwig, J. F.; Paul, F. *J. Am. Chem. Soc.* **1995**, *117*, 5373–5374. (b) Roy, A. H.; Hartwig, J. F. *Organometallics* **2004**, *23*, 1533–1541.

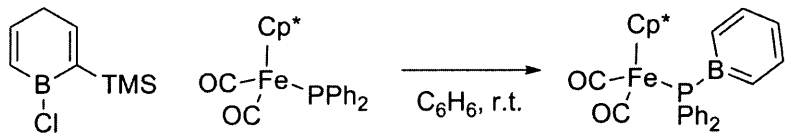
leads to aromatization, resulting in the trimethylphosphine-borabenzene adduct **4**;[84] substitution of trimethylphosphine by the more strongly donating potassium diphenylphosphide forms K-DPB **1**. Halide displacement of $CpFe(CO)_2I$ with K-DPB, to generates $CpFe(CO)_2(DPB)$ **5**.



3 **4** **1** **5**

Scheme 1: Synthesis of $CpFe(CO)_2(DPB)$ (**5**).

A variety of different Lewis bases are able to effect the aromatization of **3** to give the respective borabenzene–Lewis base adduct. We were interested in whether a transition metal–phosphide complex might be capable of performing this transformation as well, which would open a new route to complexes such as **5**. Whereas $CpFe(CO)_2PPh_2$ is rather unstable and difficult to isolate in pure form,[85] $Cp^*Fe(CO)_2PPh_2$ (Cp^* = pentamethylcyclopentadienyl) is a crystalline solid. Upon reaction with 1 equivalent of boracycle **3** at room temperature, the $Cp^*Fe(CO)_2(DPB)$ **6** forms cleanly (Equation 1). The identity of this complex was confirmed through single crystal X-ray diffraction (Figure 3).



4 1 equiv **6** (1)

[84] For mechanistic details, see Hoic, D. A. Synthesis, Structure, and Reactivity of Borabenzene and Boratabenzene Complexes. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1998.
[85] Although some references report the synthesis of $CpFe(CO)_2PPh_2$, others note that it is quite unstable, and, for their purposes, an in situ preparation is preferable. See: Ashby, M. T.; Enemark, J. H. *Organometallics* **1987**, *6*, 1323–1327.

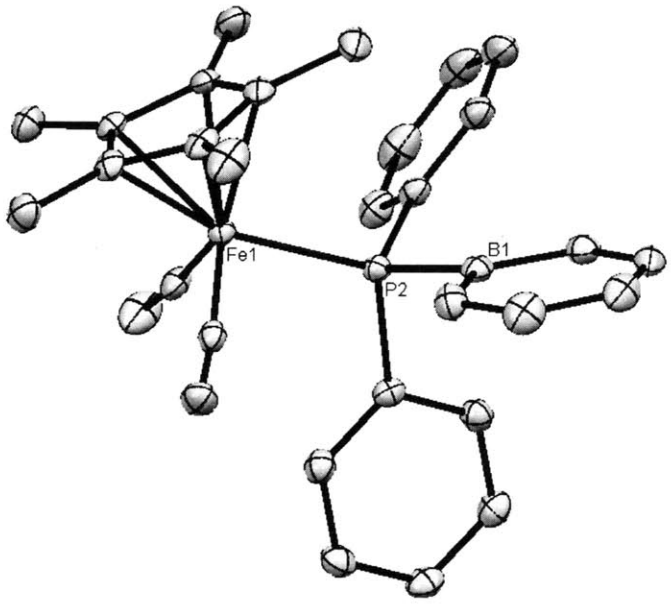
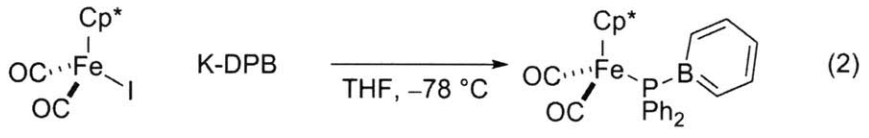


Figure 3: Crystal structure of $Cp^*Fe(CO)_2(DPB)$ (**6**)

As a comparison, **6** was also prepared from $Cp^*Fe(CO)_2I$ and K-DPB (Equation 2). This route required a low reaction temperature, and the product obtained was not as clean by ^{31}P and ^{11}B NMR in this reaction as it was in the reaction in Equation 1. Therefore, this experiment showcases a new, alternate route to transition metal-DPB complexes, which may be preferable in cases where the starting transition metal-diphenylphosphide complex is easily obtained. Furthermore, if a similar transformation with transition metal–amido complexes is possible, the first examples of transition metal–η^1-DAB-type complexes could be prepared.

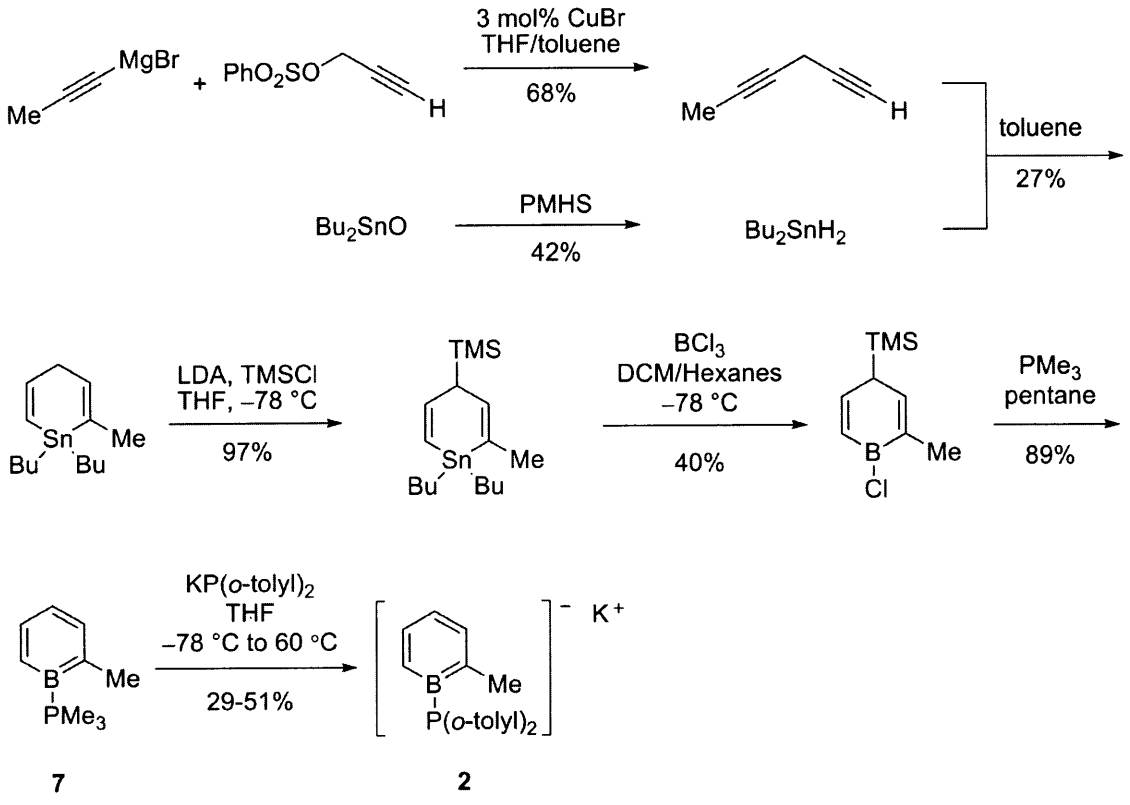


(2)

6

2. The Chemistry of Di(*ortho*-tolyl)phosphido-2-methylboratabenzene

The preparation of potassium di(*ortho*-tolyl)phosphido-2-methyl-boratabenzene (DPB*o*T) is shown in Scheme 2. The synthesis of trimethylphosphine-2-methylborabenzene adduct **7** was carried out following previously established procedures from the Fu group, which are similar to those used to make trimethyphosphine-borabenzene **4**. In the same fashion as the conversion of **4** to K-DPB, K-DPB*o*T was then prepared through reaction of **7** with potassium di(*ortho*-tolyl)phosphide.



Scheme 2: Preparation of K-DPB*o*T

In order to compare the structure of K-DPB, K-DPB*o*T was complexed with 18-crown-6 to generate K-DPB*o*T·18-crown-6 (**8**), which was crystallized to give the

structure in Figure 4. Free K-DPB is known to crystallize as a long polymer chain of potassium ions complexed with the boratabenzene ring, but sequestration of the postassium ion by the crown ether breaks up this chain so as to better approximate the structures of K-DPB and K-DPB*o*T as they exist in transition metal complexes.

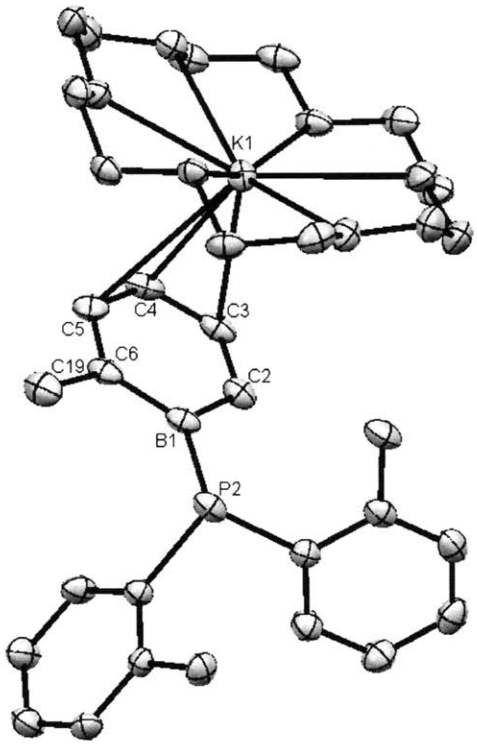


Figure 2: Crystal structure of K-DPB*o*T·18-crown-6 (**8**)

In general, the bond lengths and angles of **8** are similar to those reported for K-DPB·18-crown-6, although there are a few differences (Tables 1 and 2).[79] Although complexed by the crown ether, the potassium ion shows an interaction with the negatively-charged boratabenzene ring in both complexes. However, whereas in K-DPB·18-crown-6 an η^5-interaction with the five carbons of the boratabenzene ring is detected with the crown ether-complexed potassium ion, in complex **8** the potassium interacts in an η^3 fashion with the *meta*- and *para*-carbons on the ring. The para-carbon–potassium bond of **8** is about 0.15 Å shorter, the interatomic distance between

potassium and boron is about 0.61 Å larger, and the interatomic distances between potassium and the ortho carbons are 0.42 Å and 0.48 Å larger than the analogous values for K-DPB·18-crown-6. Moreover, the K-C_{para}-C_{meta} bond angles are slightly larger in **8** than in K-DPB·18-crown-6. This data indicates that the interaction of the potassium ion with the boratabenzene has been compromised so that its position is moved towards the back of the ring away from the ring's center (Figure 5). Presumably this obstruction to binding with the full boratabenzene ring arises from a steric interaction between the methyl substituent and the bulky potassium–crown ether complex.

Table 1: Comparison of interatomic distance data for K-DPB·18-crown-6 and K-DPB*o*T·18-crown-6

Bond	K-DPB*o*T·18-crown-6 (**8**) interatomic distance (Å)	K-DPB·18-crown-6 interatomic distance (Å)[a]
P–B	1.9641(17)	1.968(7)
B–C	1.511(2) (B–C2), 1.513(2) (B–C6)	1.480(8), 1.488(8)
K–B	4.1077(17)	3.498[b]
K–C_{ortho}	3.9085(14) (K–C6), 3.7270(15) (K–C2)	3.491(6), 3.245(5)
K–C_{meta}	3.3708(15) (K–C5), 3.1787(14)(K–C3)	3.341(5), 3.075(5)
K–C_{para}	2.9909(14)	3.143(5)

[a] This data was obtained from reference 79. b This value was obtained by exporting the .cif file of this crystal structure into Mercury 2.3 and measuring the interatomic distance.

Table 2: Comparison of bond angle data for K-DPB*o*T·18-crown-6 (**9**) and K-DPB·18-crown-6

Angle	K-DPB*o*T·18-crown-6 (**8**) (°)	K-DPB·18-crown-6 (°)[a]
P-B-C	119.63(11) (P-B-C6), 123.41(12)(P-B-C2)	117.9(4), 126.7(4)
C-B-C	116.74(13)	115.4(5)
$K\text{-}C_{para}\text{-}C_{meta}$	93.06(9) (K-C4-C5), 84.66(8) (K-C4-C3)	74.4(3), 85.7(3)

[a] This data was obtained from reference 79.

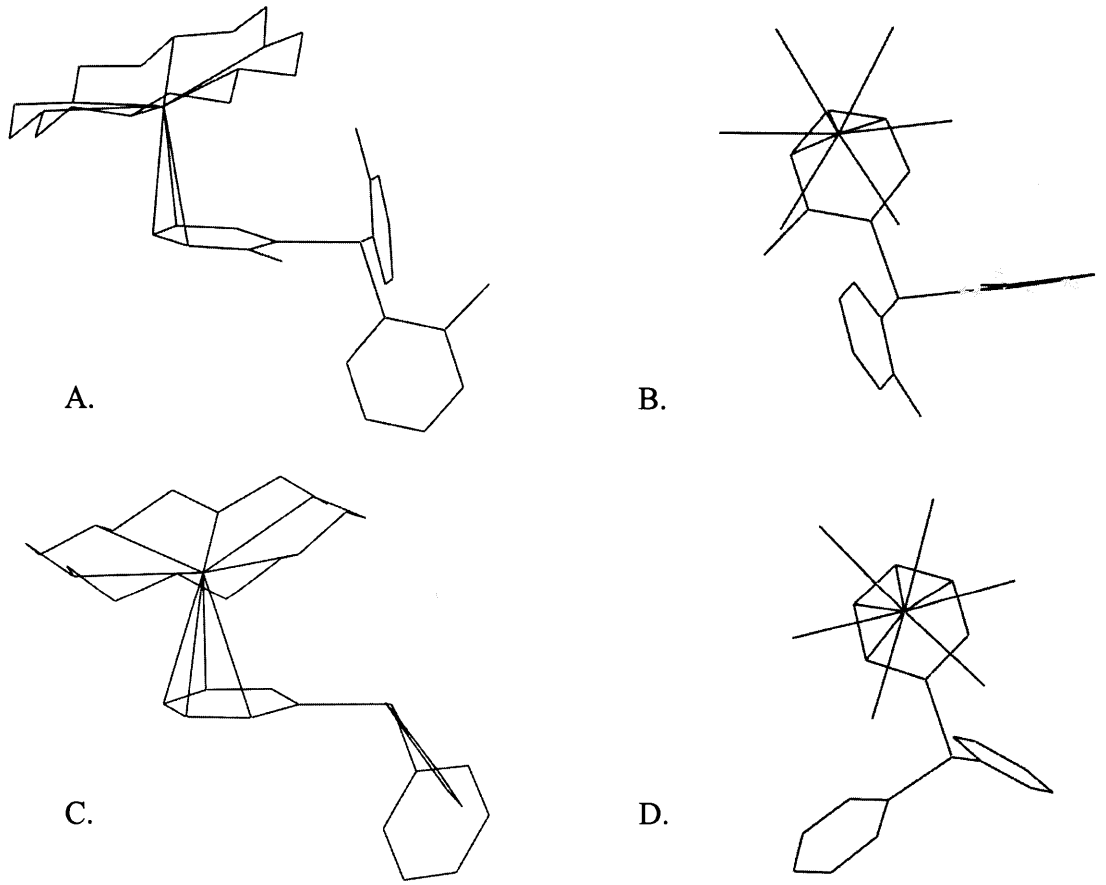


Figure 5: Comparison of the bonding of the crown-ether-complexed potassium ion with DPB*o*T (A. and B.) versus that with DPB (C. and D.).[86] In B. and D. the crown ether-carbons have been deleted for clarity.

[86] In DPB, the distance between the complexed potassium ion and one of the ortho-carbons of the boratabenzene ring is at the threshold be considered a bond. In Mercury, the program used to generate Figures 5, this distance was considered above this bonding threshold, but in the original paper, this interaction was considered below this threshold. Therefore, the potassium–boratabenzene interaction will be considered to be η^5 even though in Figures 5C and 5D it appears as η^4.

To further characterize the structural differences between DPB*o*T and DPB, $CpFe(CO)_2$(DPB*o*T) (**9**) was prepared and the crystal structure in Figure 6 was obtained. The P–B bond length is 0.12 Å shorter in **9** than in **5**, and the B–C bond lengths are 0.07-0.09 Å shorter (Table 3).[77] The bond angles are roughly equivalent for the two species (Table 4).

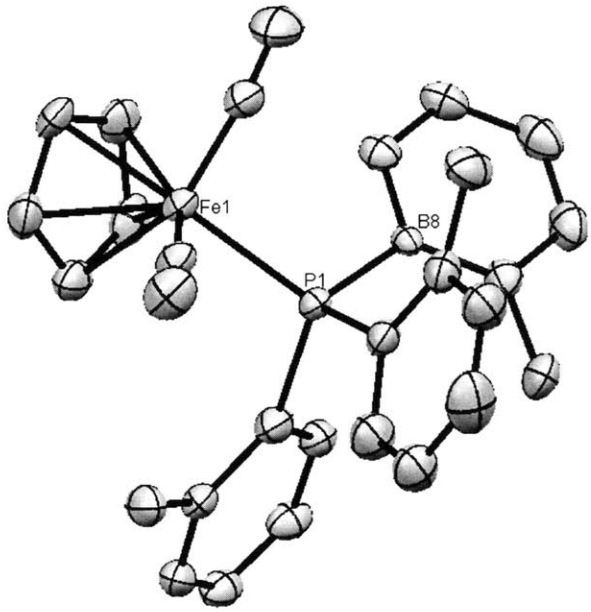


Figure 2: Crystal structure of $CpFe(CO)_2$(DPB*o*T) (**9**)

Table 3: Comparison of bond lengths between $CpFe(CO)_2$(DPB*o*T) (**9**) and $CpFe(CO)_2$(DPB) (**5**)

Bond	$CpFe(CO)_2$(DPB*o*T) (**9**) Bond Length (Å)	$CpFe(CO)_2$(DPB) (**5**) Bond Length (Å) [a]
P–B	1.843(2)	1.967(9)
B–C	1.413(3) (B–CMe), 1.396(3) (B–CH)	1.483(12), 1.489(12)
Fe–P	2.3149(6)	2.276(2)

[a] This data was obtained from reference 77.

Table 4: Comparison of Bond Angle Data for $CpFe(CO)_2$(DPB*o*T) (**9**) and $CpFe(CO)_2$(DPB) (**5**)

Angle	$CpFe(CO)_2$(DPB*o*T) (**9**) (°)	$CpFe(CO)_2$(DPB) (**5**) (°)[a]
Fe-P-B	113.65(7)	115.3(3)
P-B-C	122.48(18) (P-B-CMe), 118.87(17) (P-B-CH)	120.4(6), 121.8(6)
C-B-C	118.6(2)	117.8(7)

[a] This data was obtained from reference 77.

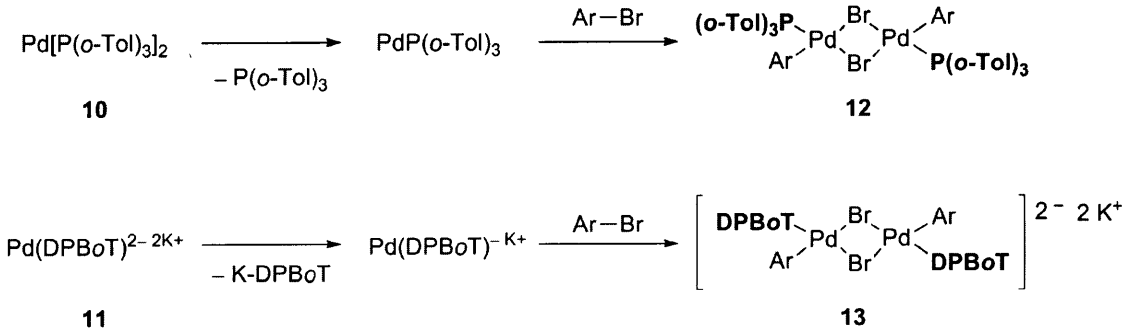
The IR stretching frequency of the CO ligands in **9** further corroborates the near equivalency of electron donation between DPB*o*T and DPB in **9** and **5**, respectively. When measured in a dichloromethane solution, the stretching frequency of **9** is only 1 cm^{-1} less than that of **5**; when measured with a KBr pellet, the difference is 3-5 cm^{-1}. Therefore, any additional electron density conferred to the complex by the presence of the methyl substituents of DPB*o*T is minimal. Unfortunately, a direct comparison of DPB*o*T to other ligand classes is not possible, as complexes such as $CpFe(CO)_2P(o\text{-tolyl})_2$, $CpFe(CO)_2P(o\text{-tolyl})_3$, and $CpFe(CO)_2Si(o\text{-tolyl})_3$ are not known. It is expected, however, that DPB*o*T would be more electron-releasing than tri-*ortho*-tolylphosphine, by analogy to the enhanced electron-releasing character of DPB in comparison with triphenylphosphine.

Table 5: Comparison of IR stretching data for CO of $CpFe(CO)_2$(DPB*o*T) (**9**) and $CpFe(CO)_2$(DPB) (**5**)

IR method	ν (CO) of **9** (cm^{-1})	ν (CO) of **5** (cm^{-1}) (cm^{-1})[a]
CH_2Cl_2 solution	1988, 2034	1989, 2035
KBr pellet	1977, 2027	1982, 2024

[a] This data was obtained from reference 77.

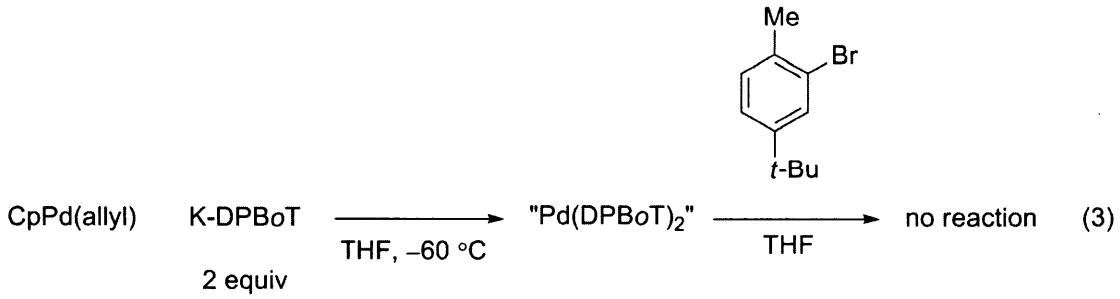
As previously noted, the goal of the development of DPB*o*T is to compare its performance as a ligand against that of tri-*ortho*-tolylphosphine. One example of a system suitable for this assessment is oxidative addition of aryl bromides to bis(tri-*ortho*-tolylphosphine)palladium **10**, which has been studied by Hartwig and co-workers and has been determined to occur through ligand dissociation to form a monoligated complex, followed by oxidative addition of the aryl bromide.[83a] The increased electron-releasing character of DPB*o*T as compared to P(*o*-Tol)$_3$ may impact these two steps differently, but should Coulombic repulsion between the two anionic DPB*o*T ligands of **11** increase the rate of ligand dissociation relative to that of **10**, then the overall rate of conversion of **11** to **13** should be faster than **10** to **12**. In that case, useful conclusions regarding the perturbation in electronic properties in moving from P(*o*-Tol)$_3$ to DPB*o*T could be drawn.



Scheme 3: Comparison of ligand effects of P(*o*-Tol)$_3$ versus DPB*o*T in the oxidative addition of aryl bromides to form dimeric palladium complexes.

To most efficiently prepare **11**, we first needed a better understanding of the reactivity of K-DPB*o*T towards palladium complexes. Therefore, a number of commericially available bisphosphinepalladium(0) complexes and palladium(II) salts were tested in reactions with KDPB*o*T. Of these, most did not proceed to a productive

end. However, the reaction of CpPd(allyl) with 2 equiv of KDPB*o*T at low temperature generated a relatively clean product that resembled a potential bis(DPB*o*T)palladium species by ^{1}H NMR. By ^{31}P NMR, it appeared that kinetic product with a resonance at –16 ppm formed, which gradually converted to a very broad resonance at –29 ppm. However, the ^{1}H NMR spectrum contained a resonance that corresponded to potassium cyclopentadienide, implying that the product generation likely proceeded through a displacement of the organic ligands by DPB*o*T to give $Pd(DPBoT)_2$, rather than reductive elimination of the cyclopentadienyl and allyl ligands followed by K-DPB*o*T ligation to give $[Pd(DPBoT)_2]^{2-}2K^{+}$.[87] Furthermore, this putative $Pd(DPBoT)_2$ species did not appear to undergo oxidative addition of the aryl bromide used by Hartwig with **10**, further supporting the assignment of a +2 oxidation state to the palladium (Equation 3), although other less sterically hindered aryl halides have not been tried.[88]



A different precursor complex, $(COD)Pd(CH_2TMS)_2$, which is also known to react with two equivalents of phosphine to form bisphosphinopalladium(0) complexes,[89] was reacted with 2 equivalents of K-DPB*o*T to generate a very clean product by ^{1}H and ^{31}P NMR (resonance at –17 ppm; Equation 4). The difference in

[87] Tatsuno, Y.; Yoshida, T.; Otsuka, S. *Inorg. Synth.* **1985**, *28*, 342–345.
[88] Roy, A. H.; Hartwig, J. F. *Organometallics* **2004**, *23*, 1533–1541.
[89] Pan, Y.; Young, G. B. *J. Organomet. Chem.* **1999**, *577*, 257–264.

chemical shift between this species and the final product of the reaction of CpPd(allyl) implies that this is a different species, potentially the desired $[Pd(DPBoT)_2]^{2-}2K^+$. Studies regarding the identity of this product and its competency in undergoing oxidative addition of an aryl halide are ongoing.

$$(COD)Pd(CH_2TMS)_2 \quad \underset{2\ equiv}{K\text{-}DPBoT} \xrightarrow[THF,\ r.t.]{} [Pd(DPBoT)_2]^{2-}\,2K^+ \qquad (4)$$

C: Conclusions and Outlook

The chemistry of boratabenzene-containing transition metal complexes has been advanced by some recent findings. A new route has been devised to transition metal complexes bearing a DPB-type ligand through the reaction of chloroboracycle **3** and a transition metal–diphenylphosphide complex. This alternative path to these types of structures reduces the synthetic route by two steps, and may prove to be a useful entryway when the transition metal–phosphide complex is readily obtained. It may also be a means to selectively install a DPB ligand without displacement of a halide, which would expand the scope of DPB-bearing transition metal complexes.

Secondly, a new variant of DPB, DPB*o*T, has been prepared, characterized, and shown to be a competent ligand in transition metal complexes. DPB*o*T contains an ortho-methyl substituent on each aryl ring, thus making it a negatively charged, isosteric variant of triorthotolylphosphine. Through analysis of the IR CO stretch of $CpFe(CO)_2$(DPB*o*T) versus those of $CpFe(CO)_2$(DPB), we have established that the electron-releasing properties of DPB*o*T roughly mimic those of DPB. In order to compare the reactivity of DPB*o*T versus triorthotolylphosphine, preliminary studies

have been conducted on the preparation of a palladium–DPB*o*T complex. Future work will include positive identification of the species generated in these reactions, with the aim of generating the bis(DPB*o*T)palladium (0) complex **11**.

Part D: Experimental Information

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3. **Select ^{1}H NMR Spectra** 139
4. **Crystallographic Characterization Data** 146

1. General Information

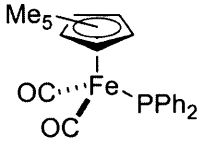
The following reagents were purchased and used without purification: *n*-butyllithium (1.6 M in hexanes, Aldrich), diphenylphosphine (Aldrich), 1-propynyl magnesium bromide (0.5 M solution, Aldrich), copper(I) bromide (Strem), *n*-butyllithium (1.6 M in hexanes, Aldrich), boron trichloride (1.0 M solution in hexanes, Aldrich), trimethylphosphine (Strem), di(*ortho*-tolyl)phosphine (Aldrich), dicarbonylcyclopenta-dienyliron(II) iodide (Aldrich),

Phenyl propargyl sulfonate (Aldrich) was distilled prior to use. Diisopropylamine (Aldrich) and chlorotrimethylsilane (Alfa Aesar) were distilled from calcium hydride prior to use.

The following intermediates were prepared according to literature procedures: dicarbonyliodo(pentamethylcyclopentadienyl)iron(II), [90] (1-chloro-1,4-dihydroborinin-2-yl)trimethylsilane (boracycle),[91] and dibutyltin dihydride.[91]

All reactions were carried out in oven-dried glassware under an atmosphere of argon or nitrogen.

2. Preparation of Compounds



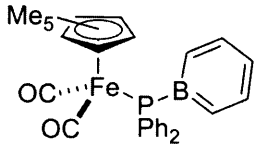
Dicarbonyl(pentamethylcyclopentadienyl)iron(II) diphenylphosphide [96013-18-2]. An oven-dried 20-mL vial with a septum cap under argon was charged with 0.15 mL of a 1.6 M solution of *n*-BuLi in hexanes (0.25 mmol, 1.0 equiv). This was then diluted with 0.5 mL toluene, and then diphenylphosphine was added dropwise at a rate of two drops per second to give a yellow residue that coated the vial. This suspension was cooled to –78 °C and a solution of 94.4 mg of dicarbonyliodo-(pentamethylcyclopentadienyl)iron(II) in 2.0 mL toluene was added. The reaction was stirred overnight as it warmed to room temperature and turned a murky red color. The reaction was brought into a nitrogen-filled glovebox, and the solution was filtered through an acrosdisc to give a dark red solution which was then concentrated. The residue was then taken up in 1.3 mL pentane, filtered through an acrodisc, and placed in a –60 °C freezer for 2.5 h. The supernatant solution was removed and the red crystalline solid product was collected (32.7 mg, 30% yield).

---

[90] Diaz, C.; Cabezas, N.; Mendizabal, F. Boletin de la Sociedad Chilena de Quimica **2002**, *47*, 213–220.
[91] Qiao, S.; Hoic, D. A.; Fu, G. C. *J. Am. Chem. Soc.* **1996**, *1996*, 6329–6330.

^{1}H NMR (400 MHz, C_6D_6): δ 7.91 (ddd, 4H, J = 1.3, 6.2, 8.0 Hz), 7.24-7.18 (m, 4H), 7.12-7.07 (m, 2H), 1.51 (s, 15H);

^{31}P NMR (162 MHz, C_6D_6): δ 41.1.



Dicarbonyl(pentamethylcyclopentadienyl)iron(II) diphenylphosphinoboratabenzene (6). In a nitrogen-filled glovebox, 11.9 mg of dicarbonyl(pentamethylcyclopentadienyl)iron(II) diphenylphosphide (0.0275 mmol, 1.0 equiv) was dissolved in 0.3 mL benzene. A solution of 5.5 mg of (1-chloro-1,4-dihydroborinin-2-yl)trimethylsilane (0.0300 mmol, 1.08 equiv) in 0.3 mL benzene as added dropwise. The resulting solution was shaken, filtered through an acrosdisc, and the product was crystallized by vapor diffusion with pentane with the exclusion of light to give 11.1 mg (0.0218 mmol, 79%) of the product as a orange solid

^{1}H NMR (400 MHz, THF-d_8): δ 7.80-7.74 (m, 4H), 7.51-7.45 (m, 1H), 7.32-7.21 (m, 6H), 7.16-7.04 (m, 1H), 6.79-6.70 (m, 2H), 6.48-6.41 (m, 1H), 1.61 (s, 15H);

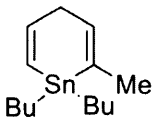
^{13}C NMR (100 MHz, THF-d_8): δ 216.9 (d, J = 19.0 Hz),135.5 (d, J = 9.1 Hz), 133.1 (d, J = 15.1 Hz), 129.7, 129.2, 128.6, 117.3, 99.4, 9.7;

^{11}B NMR (128 MHz, C_6D_6): δ 25.2;

^{31}P NMR (162 MHz, C_6D_6): δ 26.6.

IR (CH_2Cl_2 solution): 3055, 2987, 2013, 1964, 1422, 1263, 896, 765

HRMS (ESI) for $C_{29}H_{31}BFeO_2P$ (M+H): calcd 509.1520, found 509.1504.



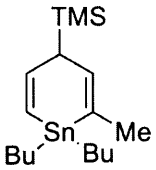
1,1-dibutyl-2-methyl-1,4-dihydrostannine [56578-02-0]. Copper(I) bromide (870 mg, 6.1 mmol, 3.0 mol%) was added to an ovendried, three-neck, 1-L flask equipped with a 50-mL addition funnel, and argon inlet and a septum. The apparatus was evacuated and backfilled with argon three times. Propynyl magnesium bromide (405 mL of 0.5 M solution in THF, 202.5 mmol, 1.01 equiv) was measured out into a flame-dried 500-mL graduated addition funnel, then transferred via canula to the reaction vessel. The resulting solution was concentrated to about half its volume. The solution was cooled to 0 °C, and 32 mL of phenylpropargyl sulfonate (200. mmol, 1.00 equiv) was added dropwise with the addition funnel. The reaction was stirred overnight as it warmed to room temperature, and 72 mL toluene were then added. The solution was stirred for 2 h and cooled to 0 °C, whereupone a solution of 20 g ammonium chloride in 200 mL 1 M HCl was added. The resulting suspension was vacuum filtered and separated in a separatory funnel. The organic layers were washed with 75 mL saturated sodium bicarbonate, which was then extracted with 5 x 75 mL THF. The combined organic layers were dried with sodium sulfate and the resulting solution was weighed. The relative concentration of 1,4-hexadiyne was determined via 1H NMR analysis to be 0.89 M.

A 250-mL oven dried Schlenk flask under argon was charged with 69 mL of the 0.89 M 1,4-hexadiyne solution (61.4 mmol, 1.00 equiv) and 14.43 g dibutyltin dihydride (61.4 mmol, 1.00 equiv). The reaction was heated to 85 °C overnight, and then cooled to room temperature. The solution was concentrated to about half its volume, then transferred to a 100-mL round bottom flask, at which point all the solvent was removed. The stannacycle was then distilled (320 mTorr, 82 °C boiling point) to give 5.69 g (18.2 mmol, 30%) of the product as a yellow oil.

^{1}H NMR (400 MHz, C_6D_6): 6.72-6.65 (m, 1H), 6.35 (dd, J = 6.9, 8.5 Hz, 1H), 6.18-6.14 (m, 1H), 3.03 (ddd, J = 1.9, 3.8, 5.8 Hz, 2H), 2.11-2.08 (m, 3H), 1.69-1.59 (m, 4H), 1.40 (qd, J = 7.2, 14.4Hz, 4H), 1.08-1.02 (m, 4H), 0.98-0.91 (m, 6H);

^{13}C NMR (100 MHz, C_6D_6): 145.4, 137.0, 125.3, 36.5, 29.6, 27.3, 27.2, 13.9, 10.0;

HRMS (EI) for $C_{14}H_{25}Sn$ (M–H): calcd 313.0982, found 313.0969.

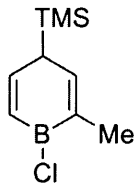


(1,1-dibutyl-2-methyl-1,4-dihydrostannin-4-yl)trimethylsilane. Prepared LDA by addition of 1.94 mL diisopropylamine (14.8 mmol, 1.00 equiv) to an oven dried 100-mL Schlenk flask charged with 9.26 mL 1.6 M *n*-BuLi in hexanes (14.8 mmol, 1.00 equiv) and 15 mL THF at 0 °C. The solution was stirred 30 min at 0 °C, then cooled to –78 °C. The stannacycle was added dropwise over 10 min and the solution turned red. The mixture was stirred at –78 °C for 1.5 h, and 2.06 mL chlorotrimethylsilane (16.3 mmol, 1.10 equiv) was added. The solution was swirled and turned yellow. The reaction was allowed to warm to room temperature overnight. The solution was then cooled to 0 °C, and 25 mL hexanes and 25 mL water was added. The layers were separated and the organic layer was washed with 25 mL saturated sodium bicarbonate solution, 25 mL brine, dried over sodium sulfate, and concentrated to give 5.35 g of the product as a yellow oil (13.9 mmol, 94% yield).

^{1}H NMR (400 MHz, C_6D_6): 6.80 (dd, J = 5.3, 13.7 Hz, 1H), 6.32-6.28 (m, 1H), 6.25 (d, J = 13.8 Hz, 1H), 2.93-2.86 (m, 1H), 2.17 (s, 3H), 1.76-1.64 (m, 4H), 1.55-1.35 (m, 4H), 1.19-1.06 (m, 4H), 0.98 (ddd, J = 5.9, 10.8, 14.2 Hz, 6H), 0.08 (s, 9H);

^{13}C NMR (100 MHz, C_6D_6): 147.0, 138.6, 133.4, 122.3, 43.7, 30.1 (d, J = 24.1 Hz), 28.0 (d, J = 3.0 Hz), 27.9, 14.3 (d, J = 3.0 Hz), 11.7, 10.7, –2.6.

HRMS (EI) for $C_{17}H_{35}SiSn$: calcd 387.1535, found 387.1558.



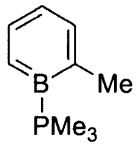
(1-chloro-2-methyl-1,4-dihydroborinin-4-yl)trimethylsilane. An oven-dried 100-mL 2-neck flask was equipped with an oven-dried short path distillation head with a pig and 3 oven-dried receiving flasks; this entire apparatus was vacuum-purged and

placed under argon. Added 5.34 g (1,1-dibutyl-2-methyl-1,4-dihydrostannin-4-yl)trimethylsilane (13.9 mmol, 1.00 equiv) and purged with vacuum and backfilled with argon three times. Added 3.5 mL dichloromethane and cooled to –78 °C. Slowly added 13.9 mL of a 1.0 M boron trichloride solution in hexanes (13.9 mmol, 1.00 equiv) over 15 min, then removed the bath and allowed the solution to warm to room temperature and stir 2 h. Heated under ambient pressure to remove solvent. Then distilled under 300 mTorr-250 mTorr at 57 °C (oil bath 85 °C). Distilled a second time to remove residual stannane impurities at 200 mTorr and 35 °C (oil bath 45 °C) to give the 925 mg of the product as a clear colorless oil (4.66 mmol, 34%).

^{1}H NMR (400 MHz, C_6D_6): δ 7.08 (d, J = 5.8 Hz, 1H), 6.43 (dd, J = 5.4, 8.4 Hz, 1H), 6.27 (dd, J = 6.1, 8.8 Hz, 1H), 3.41 (d, J = 5.2 Hz, 1H), 2.18 (s, 3H), 0.00 (m, 9H);

^{13}C NMR (100 MHz, C_6D_6): δ 147.5, 140.5, 123.3, 53.5, 20.2, –0.9;

^{11}B NMR (128 MHz, C_6D_6): δ 58.8.



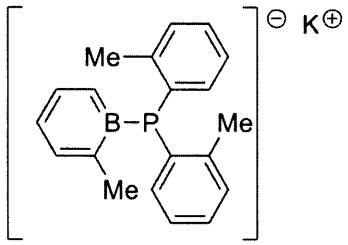
2-Methylborabenzene trimethylphosphine adduct (7). In a nitrogen-filled glovebox, added 0.43 mL trimethylphosphine (4.15 mmol, 1.0 equiv) slowly to 840 mg (1-chloro-2-methyl-1,4-dihydroborinin-4-yl)trimethylsilane (4.23 mmol, 1.02 mmol) in 3.5 mL pentane (*CAUTION:* trimethylphosphine is volatile and an irritant; take care when using this reagent). The solution stirred overnight as the product precipitated out. The product was collected via vacuum filtration and washed with pentane to give 640 mg of a pink solid (3.86 mmol, 93% yield).

^{1}H NMR (400 MHz, C_6D_6): δ 7.90-7.81(m, 1H), 7.71 (t, J = 7.1 Hz, 1H), 7.33-7.28 (m, 1H), 7.07 (dt, J = 1.0, 9.7 Hz, 1H), 2.55 (s, 3H), 0.77 (d, J = 11.1Hz, 9H);

^{13}C NMR (100 MHz, C_6D_6): δ 136.1 (d, J = 15.1 Hz), 131.7 (d, J = 18.1 Hz), 120.7, 24.8 (d, J = 4.0 Hz), 10.8, (d, J = 41.3 Hz);

^{11}B NMR (128 MHz, C_6D_6): δ 18.8 (d, J = 106 Hz);

^{31}P NMR (162 MHz, C_6D_6): δ –22.3 (q, J = 100 Hz).



Potassium di(*ortho*-tolyl)phosphido(2-methylboratabenzene(2). In a nitrogen-filled glovebox, 115 mg of potassium metal (2.94 mmol, 1.3 equiv) was cut into small pieces and added to a 10-mL round bottom flask, and 3 mL THF was added. The flask was equipped with a septum. Diorthotolylphosphine (485 mg, 2.26 mmol, 1.00 equiv) was weighed into a 4-mL vial and 2 mL of THF was added. The vial was capped with a septum cap. The flask and the vial were brought outside the glovebox, attached to an argon line, and cooled to –78 °C. The phosphine solution was added

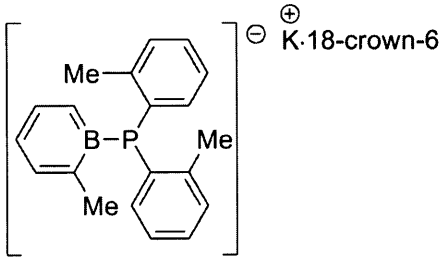
dropwise (1 drop per second) to the potassium suspension. The reaction was stirred at –78 °C overnight, then allowed to warm to room temperature. The supernatant solution was decanted off and added via canula to a solution of 2-methylborabenzene trimethylphosphine adduct (375 mg, 2.26 mmol) in 1.5 mL THF, which had been prepared in the glovebox. The resulting solution was heated to 60 °C, at which point the color turned from red to orange. The flask was cooled to room temperature and brought into the glovebox, and 13 mL of pentane was layer onto the THF solution. The flask was cooled in the –20 °C freezer overnight, and the precipitate was collected. This precipitate was extracted with diethyl ether to furnish 216 mg (28%) of the desired product as a yellow solid.

^{1}H NMR (400 MHz, THF-d_8): δ 7.09 (dd, J = 4.5, 6.4 Hz, 2H), 6.99-6.94 (m, 3H,), 6.94-6.86 (m, 3H), 6.80 (t, J = 7.2 Hz, 2H), 6.15 (t, J = 6.9 Hz, 1H), 5.91 (dd, J = 3.6, 9.3 Hz, 1H), 2.32 (s, 6H) ppm 2.08 (s, 3H);

^{13}C NMR (100 MHz, THF-d_8): δ 143.4 (d, J = 15.1 Hz), 142.7 (d, J = 21.1 Hz), 135.8 (d, J = 3.0 Hz), 134.2 (d, J = 7.0 Hz), 131.32, 131.26, 129.6, 129.5, 126.1, 125.6, 113.2, 24.7 (d, J = 7.0 Hz), 22.6 (d, J = 20.1 Hz);

^{11}B NMR (128 MHz, THF-d_8): δ 31.4;

^{31}P NMR (162 MHz, THF-d_8): δ 55.0.



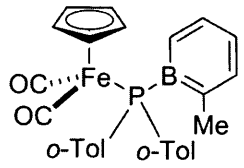
Potassium di(*ortho*-tolyl)phosphido(2-methylboratabenzene) 18-crown-6 adduct (8). In a nitrogen-filled glovebox, a solution of 31.7 mg 18-crown-6 (0.120 mmol, 1.1 equiv) in 1 mL THF was added to 37.5 mg potassium di(*ortho*-tolyl)phosphido(2-methylboratabenzene) powder (0.109 mmol) in a 20-mL vial. The vial was shaken until all solid had dissolved, and the solution was then passed through an acrodisc. Crystallization was induced by vapor diffusion with hexanes.

^{1}H NMR (400 MHz, THF-d_8): δ 7.26-7.19 (m, 2H), 6.94-6.88 (m, 2H), 6.88-6.72 (m, 6H), 6.01 (t, J = 7.0 Hz, 1H), 5.82 (dd, J = 4.5, 9.6 Hz, 1H), 3.47 (s, 24H), 2.30 (s, 6H), 2.05 (s, 3H);

^{13}C NMR (100 MHz, THF-d_8): δ 143.7 (d, J = 17.1 Hz), 143.0 (d, J = 19.1 Hz), 136.1 (d, J = 3.0 Hz), 133.7 (d, J = 8.0 Hz), 130.8, 130.7, 129.23, 129.19, 125.5, 125.2, 112.9, 22.8 (d, J = 18.1 Hz);

^{11}B NMR (128 MHz, THF-d_8): δ +30.0;

^{31}P NMR (162 MHz, THF-d_8): δ –50.3.



Dicarbonyl(cyclopentadienyl)iron(II)di(*ortho*-tolyl)phosphido(2-methyl)-borata-benzene (9). A solution of 15.4 mg dicarbonylcyclopentadienyliron(II) iodide (0.050 mmol, 1.0 mmol) in 0.5 mL THF and a solution of 17.3 mg potassium di(*ortho*-tolyl)phosphido(2-methylboratabenzene) (0.05 mmol) in 1.25 mL THF were both cooled to –78 °C. The K-DPB*o*T solution was added to the Fp-I solution, and the resulting reaction was allowed to warm to room temperature overnight, under the exclusion of light. The solution was brought into the glovebox, filtered through an acrodisc, and the product was crystallized by vapor diffusion with hexanes to give 13.5 mg of the product as an orange crystalline solid (56%).

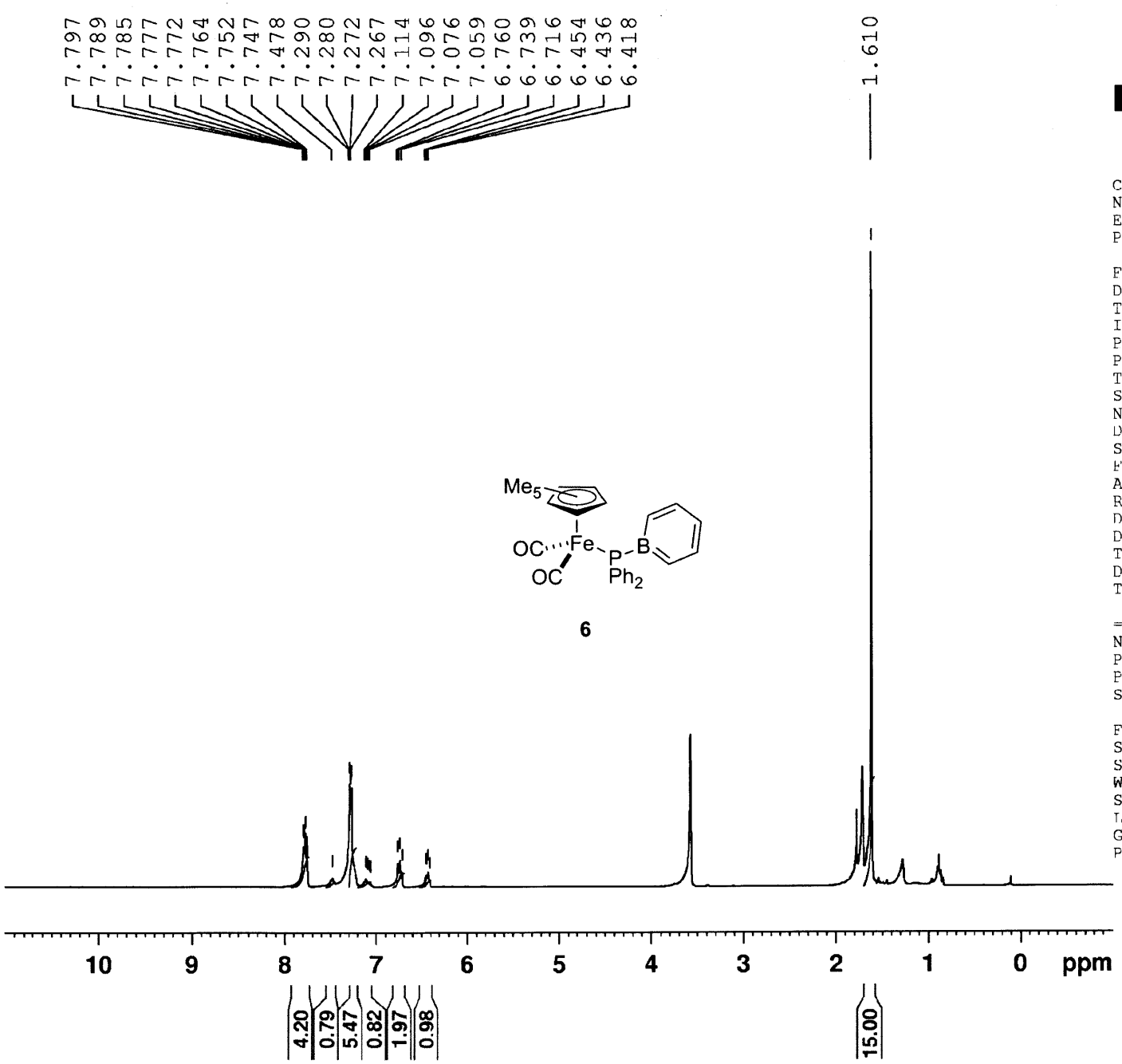
^{1}H NMR (400 MHz, THF-d_8): δ 8.25-8.16 (m, 2H), 8.34-8.23 (m, 4H), 7.14-7.05 (m, 3H), 6.95-6.86 (m, 1H), 6.38-6.31 (m, 1H), 5.93-5.84 (m, 1H), 2.29 (s, 3H), 1.88 (s, 6H);

^{13}C NMR (100 MHz, THF-d_8): δ 221.8, 143.6, 137.4 (d, J = 16.1 Hz), 137.0 (d, J = 14.1 Hz), 135.5, 135.2, 132.6 (d, J = 6.0 Hz), 131.2 (d, J = 16.1 Hz), 130.7 (d, J = 3.0 Hz), 129.1 (d, J = 11.1 Hz), 126.5 (12.1 Hz), 117.7, 91.0, 23.4, 14.7;

^{11}B NMR (128 MHz, THF-d_8): δ 27.8;

^{31}P NMR (162 MHz, THF-d_8): δ 16.9.

IR (CH_2Cl_2 solution): 3052, 2987, 2034, 1988, 1421, 1275, 896, 767, 667, 641.



6

BRUKER

Current Data Parameters
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EXPNO 6
PROCNO 1

F2 - Acquisition Parameters
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Time 15.08
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SOLVENT THF
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DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
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RG 128
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DE 6.00 usec
TE 683.2 K
D1 1.00000000 sec
TD0 1

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PL1 0.00 dB
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F2 - Processing parameters
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WDW EM
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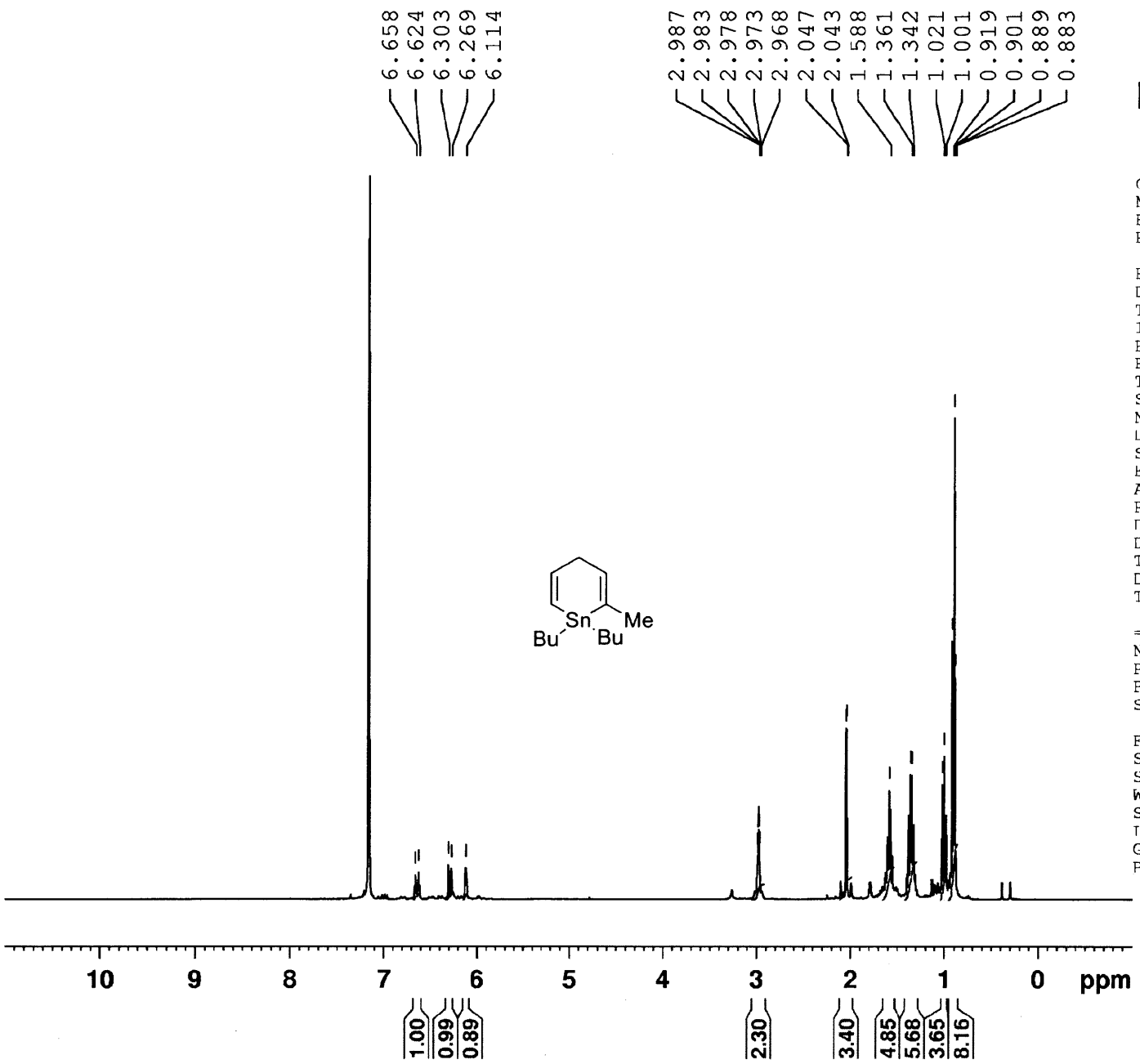
LB 0.30 Hz
GB 0
PC 1.00



BRUKER

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PROCNO 1

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SOLVENT C6D6
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DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 181
DW 60.400 usec
DE 6.00 usec
TE 296.2 K
D1 1.00000000 sec
TD0 1

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PL1 0.00 dB
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F2 - Processing parameters
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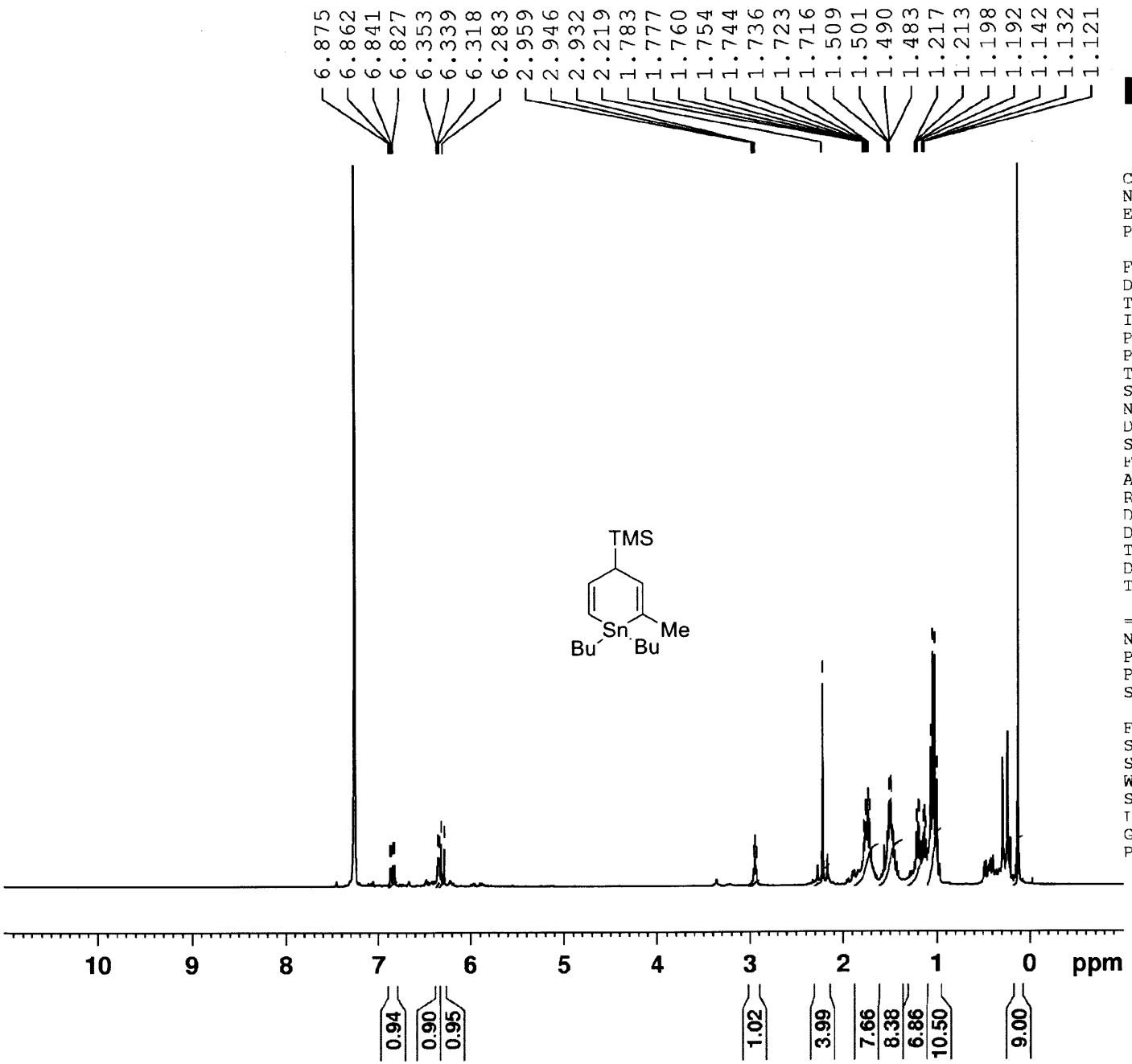
PC 1.00



BRUKER

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EXPNO 3
PROCNO 1

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PULPROG zg30
TD 65536
SOLVENT C6D6
NS 11
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 128
DW 60.400 usec
DE 6.00 usec
TE 294.2 K
D1 1.00000000 sec
TD0 1

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P1 15.07 usec
PL1 0.00 dB
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F2 - Processing parameters
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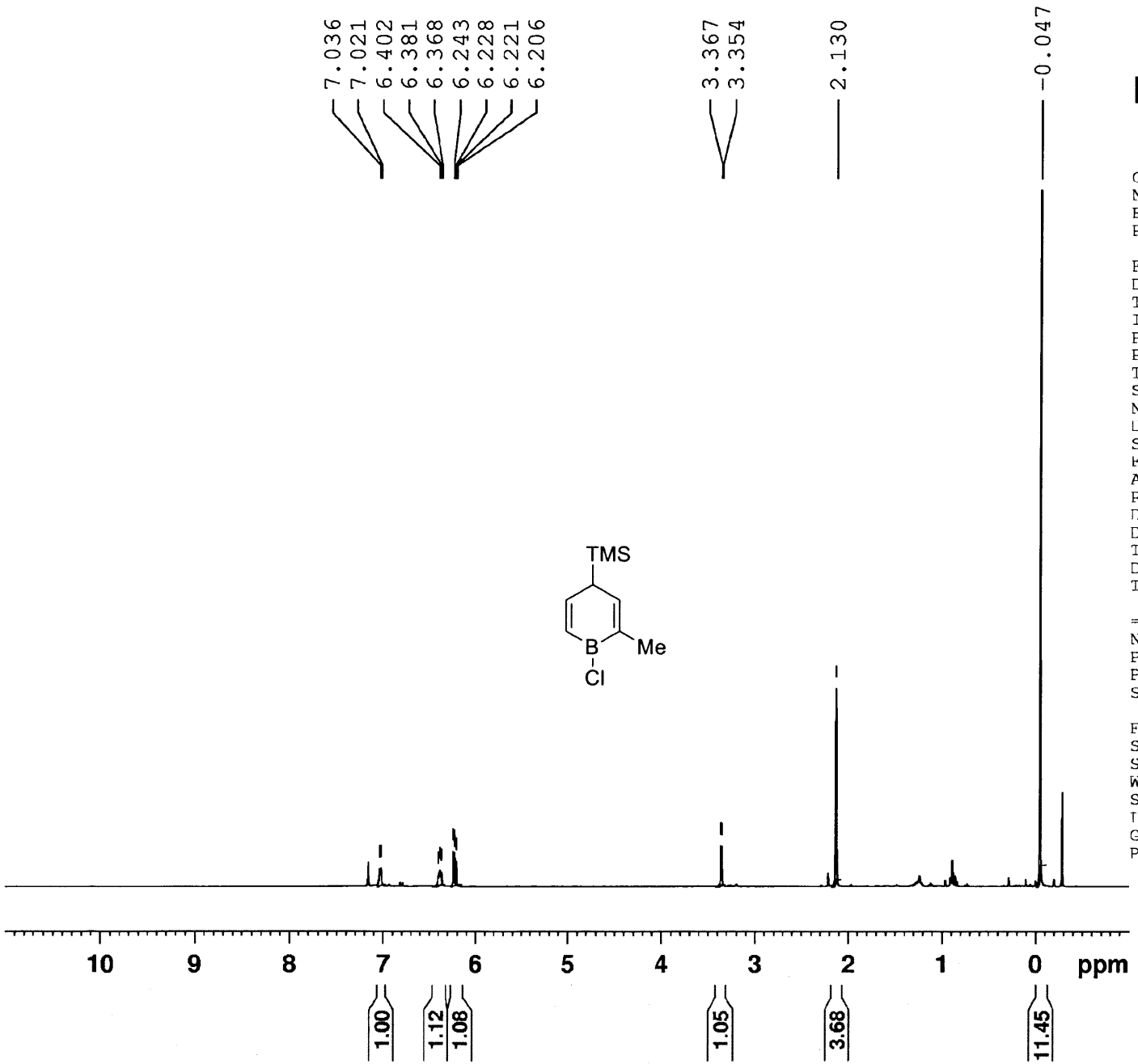

BRUKER

Current Data Parameters

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EXPNO	1
PROCNO	1

F2 - Acquisition Parameters

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PULPROG	zg30
TD	65536
SOLVENT	C6D6
NS	16
DS	2
SWH	8278.146 Hz
FIDRES	0.126314 Hz
AQ	3.9584243 sec
RG	114
DW	60.400 usec
DE	6.00 usec
TE	293.2 K
D1	1.00000000 sec
TD0	1

======== CHANNEL f1 ========

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PL1	0.00 dB
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F2 - Processing parameters

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SSB	0
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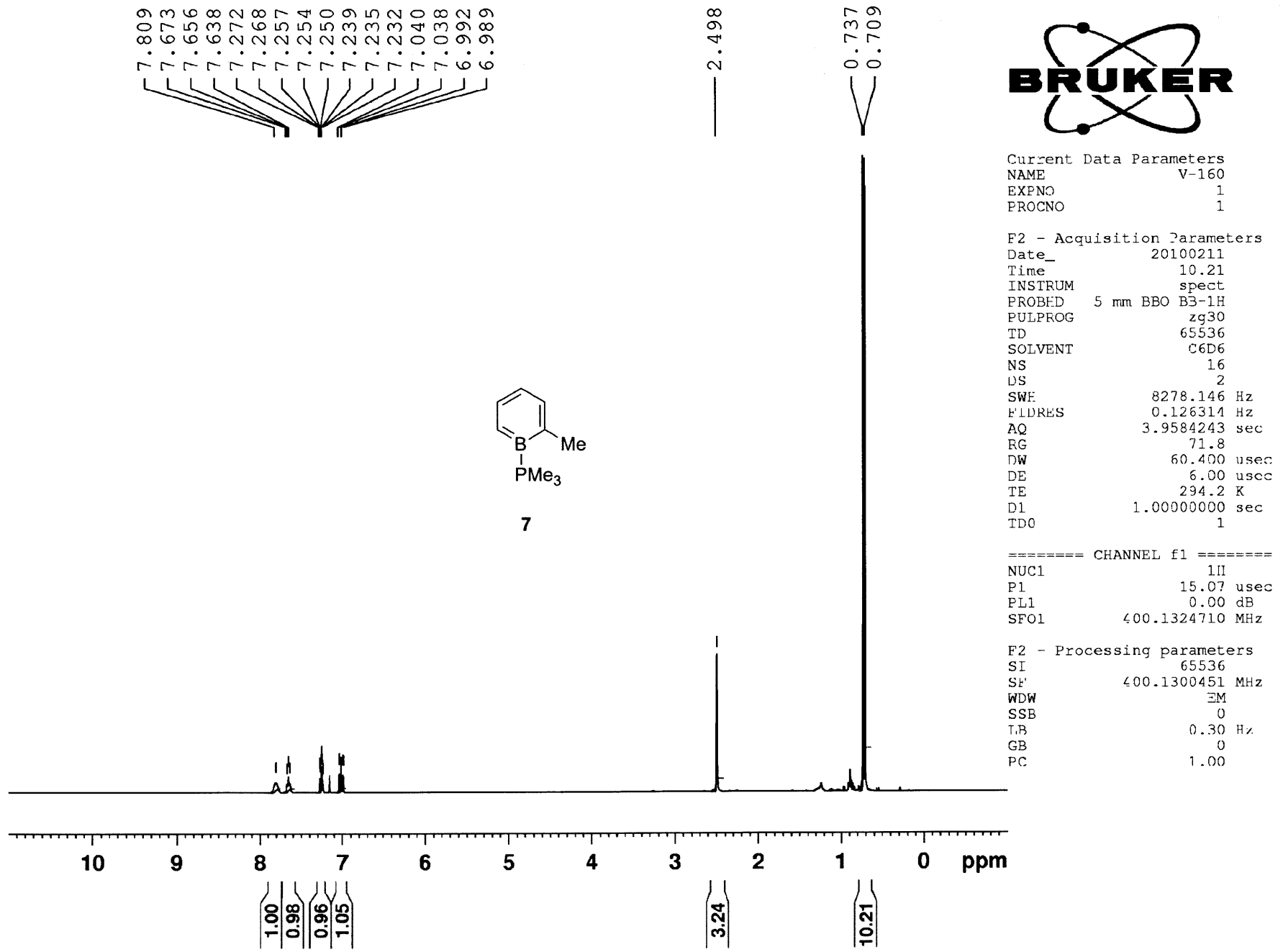

BRUKER

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PROCNO 1

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SOLVENT C6D6
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SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 71.8
DW 60.400 usec
DE 6.00 usec
TE 294.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
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PL1 0.00 dB
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F2 - Processing parameters
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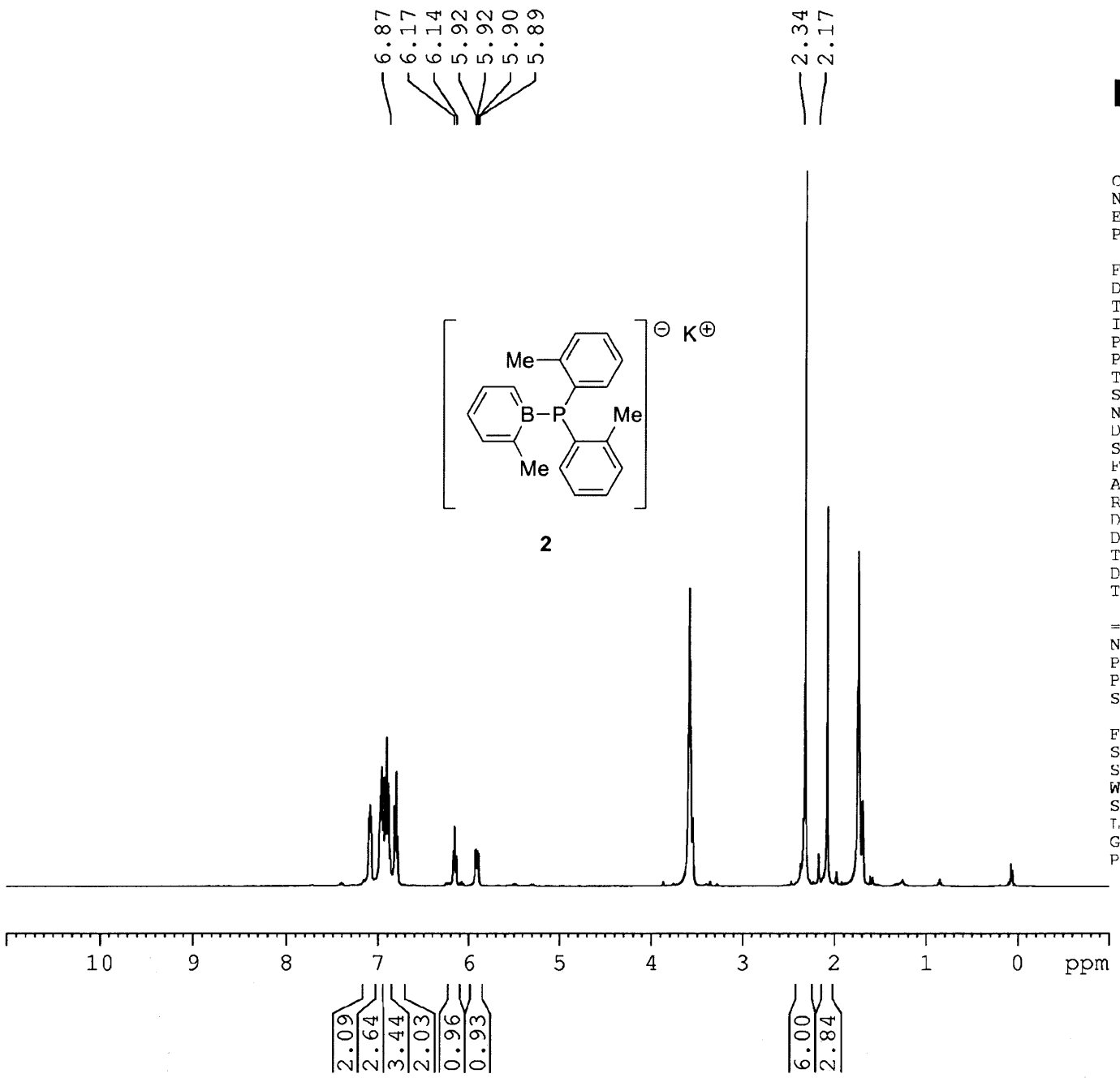

BRUKER

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PROCNO 1

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TD 65536
SOLVENT THF
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 64
DW 60.400 usec
DE 6.00 usec
TE 296.2 K
D1 1.00000000 sec
TD0 1

======== CHANNEL f1 ========
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F2 - Processing parameters
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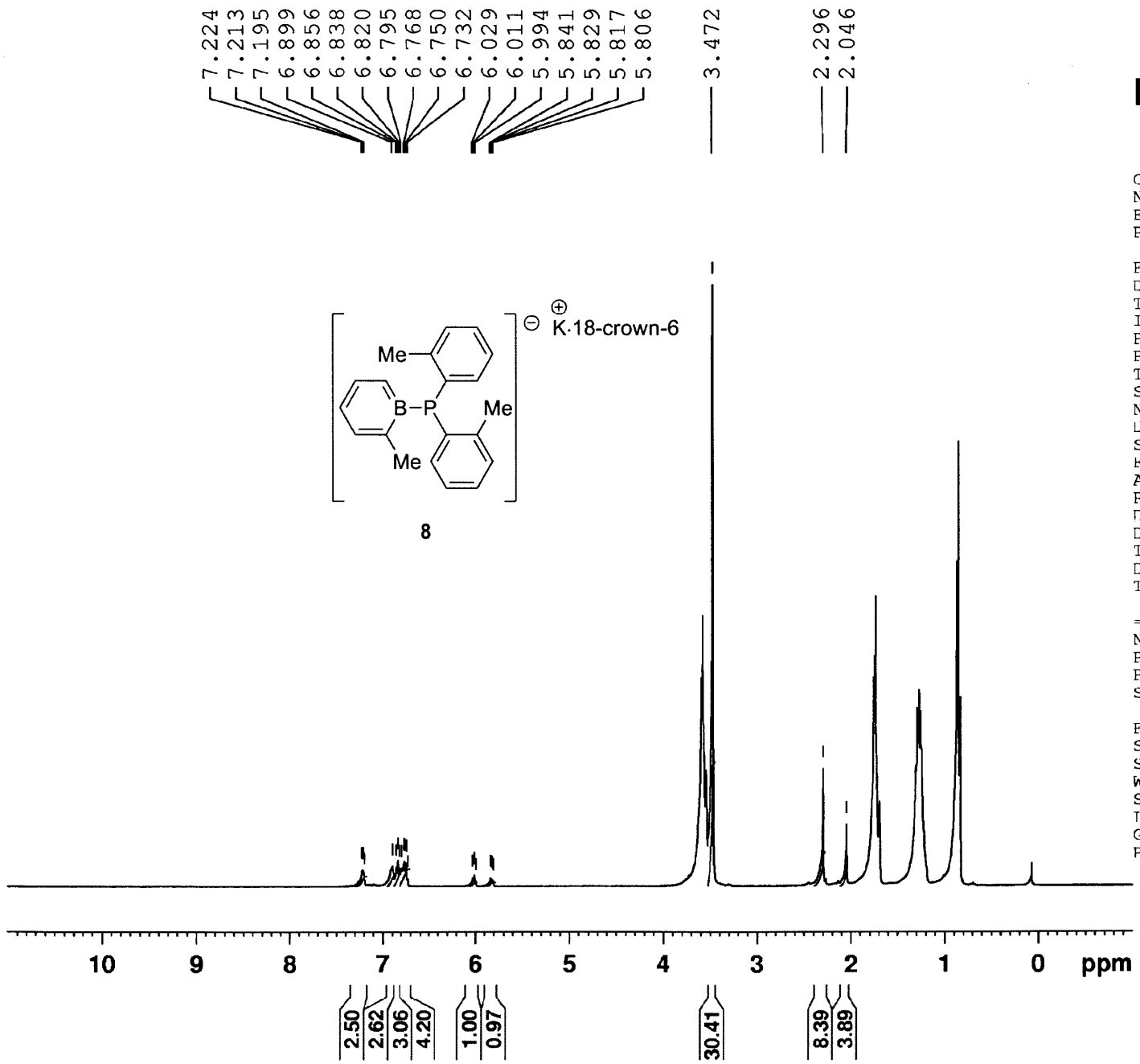
PC 1.40



8

BRUKER

Current Data Parameters
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EXPNO 2
PROCNO 1

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PULPROG zg30
TD 65536
SOLVENT THF
NS 16
DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 128
DW 60.400 usec
DE 6.00 usec
TE 295.2 K
D1 1.00000000 sec
TD0 1

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F2 - Processing parameters
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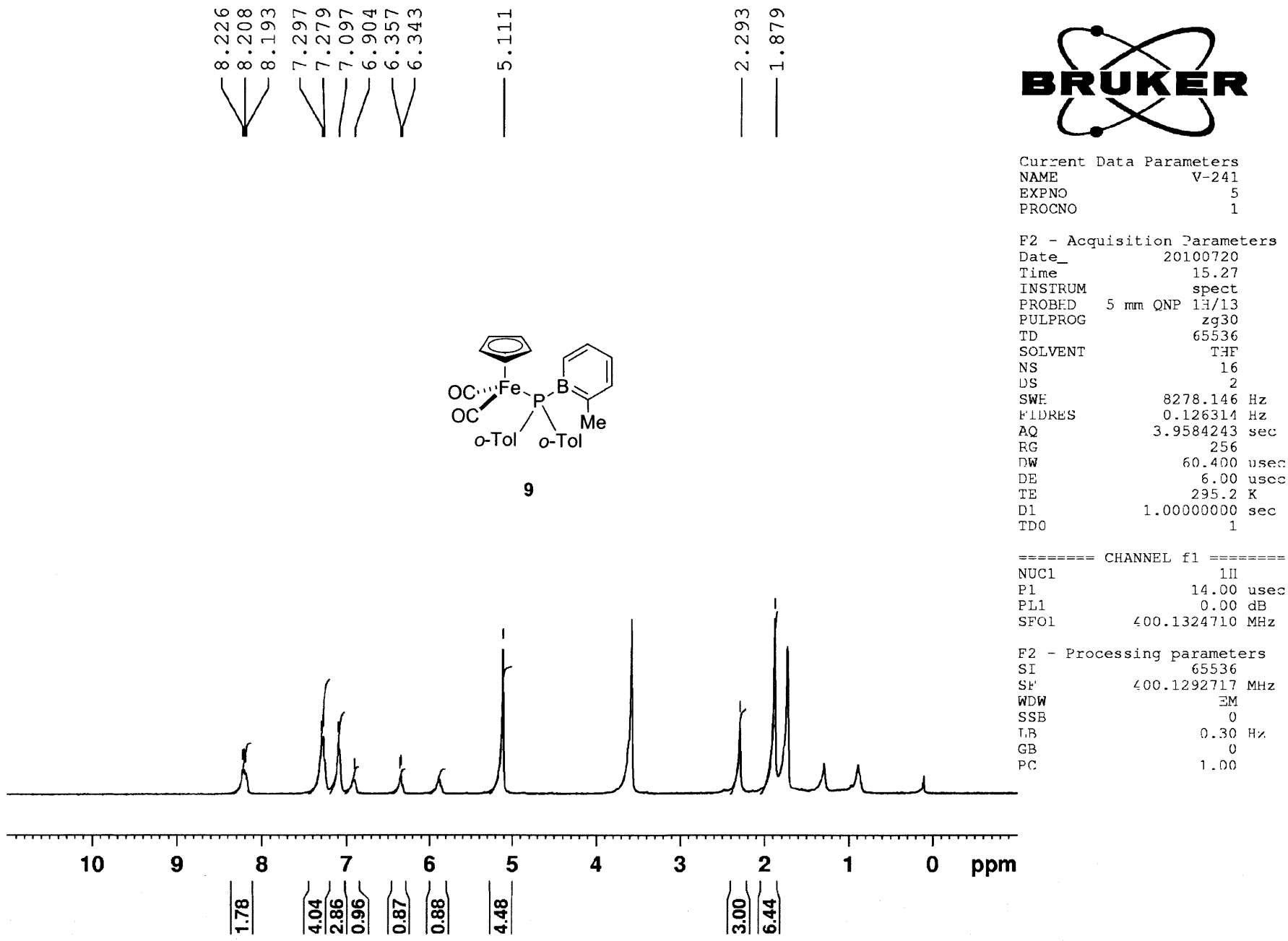
PC 1.00



BRUKER

Current Data Parameters
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PROCNO 1

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SOLVENT THF
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DS 2
SWH 8278.146 Hz
FIDRES 0.126314 Hz
AQ 3.9584243 sec
RG 256
DW 60.400 usec
DE 6.00 usec
TE 295.2 K
D1 1.00000000 sec
TD0 1

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F2 - Processing parameters
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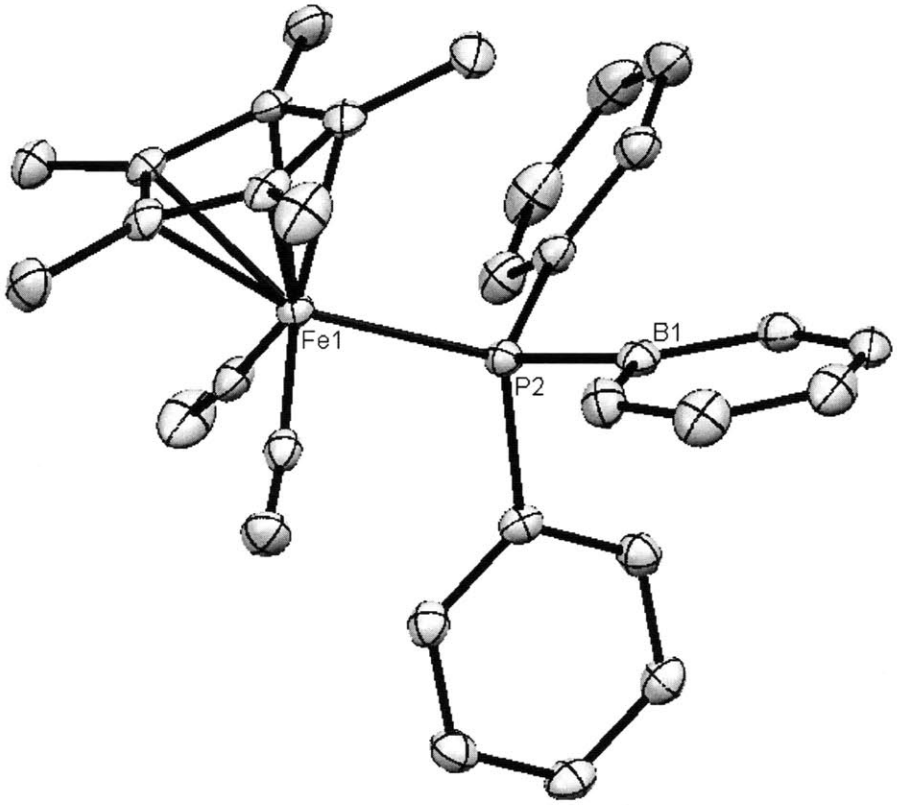
Fe1
P2
B1

Table 1. Crystal data and structure refinement for **6** (D8_10094_0m)

Identification code	d8_10094_0m	
Empirical formula	C29 H30 B Fe O2 P	
Formula weight	508.16	
Temperature	100(2) K	
Wavelength	1.54178 Å	
Crystal system	Orthorhombic	
Space group	Pbca	
Unit cell dimensions	a = 16.5519(2) Å	α= 90°.
	b = 16.8541(2) Å	β= 90°.
	c = 18.1903(2) Å	γ = 90°.
Volume	5074.50(10) $Å^3$	
Z	8	
Density (calculated)	1.330 Mg/m^3	
Absorption coefficient	5.542 mm^{-1}	
F(000)	2128	
Crystal size	0.40 x 0.40 x 0.05 mm^3	
Theta range for data collection	4.46 to 63.69°.	
Index ranges	-19<=h<=19, -19<=k<=19, -21<=l<=16	
Reflections collected	91136	
Independent reflections	4172 [R(int) = 0.0673]	
Completeness to theta = 63.69°	99.9 %	
Absorption correction	None	
Max. and min. transmission	0.7691 and 0.2153	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	4172 / 0 / 312	
Goodness-of-fit on F^2	1.061	
Final R indices [I>2sigma(I)]	R1 = 0.0326, wR2 = 0.0790	
R indices (all data)	R1 = 0.0366, wR2 = 0.0828	
Largest diff. peak and hole	0.497 and -0.366 $e.Å^{-3}$	

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for D8_10094_0m. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
Fe(1)	2175(1)	2321(1)	3791(1)	14(1)
P(2)	3346(1)	2948(1)	4101(1)	15(1)
O(1)	1766(1)	2014(1)	5321(1)	35(1)
C(5)	1671(1)	1188(1)	3605(1)	18(1)
C(7)	1973(1)	2058(1)	2667(1)	21(1)
O(2)	1257(1)	3769(1)	3539(1)	26(1)
C(25)	3234(1)	3644(1)	4884(1)	17(1)
C(1)	1944(1)	2162(1)	4730(1)	22(1)
C(4)	2527(1)	1158(1)	3477(1)	19(1)
C(3)	2702(1)	1688(1)	2883(1)	21(1)
C(26)	3938(1)	3944(1)	5211(1)	21(1)
C(6)	1330(1)	1749(1)	3113(1)	19(1)
C(2)	1645(1)	3226(1)	3664(1)	19(1)
C(10)	1212(1)	671(1)	4124(1)	24(1)
C(18)	3963(1)	1926(1)	5188(1)	26(1)
C(24)	3344(1)	4060(1)	2833(1)	24(1)
B(1)	3863(2)	3611(1)	3359(1)	19(1)
C(27)	3901(1)	4513(1)	5761(1)	23(1)
C(13)	4076(1)	2238(1)	4482(1)	20(1)
C(30)	2491(1)	3935(1)	5128(1)	22(1)
C(20)	4750(1)	3777(1)	3341(1)	23(1)
C(28)	3156(1)	4804(1)	5989(1)	24(1)
C(14)	4727(1)	1967(1)	4066(1)	24(1)
C(22)	4533(2)	4729(1)	2350(1)	29(1)
C(8)	3492(1)	1772(1)	2494(1)	30(1)
C(21)	5041(1)	4320(1)	2829(1)	26(1)
C(23)	3701(2)	4605(1)	2361(1)	30(1)
C(17)	4484(2)	1350(1)	5462(1)	34(1)
C(9)	3095(1)	584(1)	3833(1)	30(1)
C(16)	5118(2)	1076(1)	5034(2)	35(1)
C(12)	1876(2)	2596(2)	2014(1)	33(1)

C(29)	2455(1)	4516(1)	5673(1)	25(1)
C(11)	448(1)	1924(1)	3036(1)	27(1)
C(15)	5243(1)	1385(1)	4340(1)	31(1)

Table 3. Bond lengths [Å] and angles [°] for D8_10094_0m.

Fe(1)-C(1)	1.771(2)
Fe(1)-C(2)	1.775(2)
Fe(1)-C(6)	2.100(2)
Fe(1)-C(5)	2.112(2)
Fe(1)-C(7)	2.119(2)
Fe(1)-C(4)	2.123(2)
Fe(1)-C(3)	2.151(2)
Fe(1)-P(2)	2.2776(6)
P(2)-C(13)	1.835(2)
P(2)-C(25)	1.854(2)
P(2)-B(1)	1.951(2)
O(1)-C(1)	1.142(3)
C(5)-C(6)	1.419(3)
C(5)-C(4)	1.437(3)
C(5)-C(10)	1.492(3)
C(7)-C(3)	1.414(3)
C(7)-C(6)	1.436(3)
C(7)-C(12)	1.504(3)
O(2)-C(2)	1.141(3)
C(25)-C(30)	1.396(3)
C(25)-C(26)	1.403(3)
C(4)-C(3)	1.431(3)
C(4)-C(9)	1.496(3)
C(3)-C(8)	1.494(3)
C(26)-C(27)	1.388(3)
C(6)-C(11)	1.496(3)
C(18)-C(17)	1.390(3)
C(18)-C(13)	1.400(3)
C(24)-C(23)	1.390(3)
C(24)-B(1)	1.492(3)
B(1)-C(20)	1.495(3)
C(27)-C(28)	1.389(3)
C(13)-C(14)	1.394(3)
C(30)-C(29)	1.395(3)

C(20)-C(21)	1.391(3)
C(28)-C(29)	1.383(3)
C(14)-C(15)	1.394(3)
C(22)-C(21)	1.393(3)
C(22)-C(23)	1.394(3)
C(17)-C(16)	1.385(4)
C(16)-C(15)	1.381(4)

C(1)-Fe(1)-C(2)	98.59(10)
C(1)-Fe(1)-C(6)	110.59(9)
C(2)-Fe(1)-C(6)	89.37(9)
C(1)-Fe(1)-C(5)	86.06(9)
C(2)-Fe(1)-C(5)	124.14(9)
C(6)-Fe(1)-C(5)	39.37(8)
C(1)-Fe(1)-C(7)	149.79(9)
C(2)-Fe(1)-C(7)	88.64(9)
C(6)-Fe(1)-C(7)	39.80(8)
C(5)-Fe(1)-C(7)	65.99(8)
C(1)-Fe(1)-C(4)	100.26(9)
C(2)-Fe(1)-C(4)	153.40(9)
C(6)-Fe(1)-C(4)	66.48(8)
C(5)-Fe(1)-C(4)	39.66(8)
C(7)-Fe(1)-C(4)	65.83(8)
C(1)-Fe(1)-C(3)	138.81(9)
C(2)-Fe(1)-C(3)	121.79(9)
C(6)-Fe(1)-C(3)	65.86(8)
C(5)-Fe(1)-C(3)	65.66(8)
C(7)-Fe(1)-C(3)	38.66(8)
C(4)-Fe(1)-C(3)	39.11(8)
C(1)-Fe(1)-P(2)	90.90(7)
C(2)-Fe(1)-P(2)	93.11(7)
C(6)-Fe(1)-P(2)	157.75(6)
C(5)-Fe(1)-P(2)	142.67(6)
C(7)-Fe(1)-P(2)	118.11(6)
C(4)-Fe(1)-P(2)	105.15(6)
C(3)-Fe(1)-P(2)	94.37(6)

C(13)-P(2)-C(25)	100.86(9)
C(13)-P(2)-B(1)	110.24(10)
C(25)-P(2)-B(1)	102.29(9)
C(13)-P(2)-Fe(1)	110.58(7)
C(25)-P(2)-Fe(1)	113.48(7)
B(1)-P(2)-Fe(1)	117.84(7)
C(6)-C(5)-C(4)	108.34(18)
C(6)-C(5)-C(10)	125.77(19)
C(4)-C(5)-C(10)	125.73(19)
C(6)-C(5)-Fe(1)	69.89(11)
C(4)-C(5)-Fe(1)	70.61(11)
C(10)-C(5)-Fe(1)	128.87(15)
C(3)-C(7)-C(6)	108.38(18)
C(3)-C(7)-C(12)	125.3(2)
C(6)-C(7)-C(12)	125.9(2)
C(3)-C(7)-Fe(1)	71.89(12)
C(6)-C(7)-Fe(1)	69.39(11)
C(12)-C(7)-Fe(1)	130.72(15)
C(30)-C(25)-C(26)	118.05(19)
C(30)-C(25)-P(2)	123.70(15)
C(26)-C(25)-P(2)	118.05(15)
O(1)-C(1)-Fe(1)	175.43(19)
C(3)-C(4)-C(5)	107.40(18)
C(3)-C(4)-C(9)	127.1(2)
C(5)-C(4)-C(9)	124.9(2)
C(3)-C(4)-Fe(1)	71.50(11)
C(5)-C(4)-Fe(1)	69.73(11)
C(9)-C(4)-Fe(1)	130.80(15)
C(7)-C(3)-C(4)	108.24(18)
C(7)-C(3)-C(8)	125.0(2)
C(4)-C(3)-C(8)	126.4(2)
C(7)-C(3)-Fe(1)	69.45(11)
C(4)-C(3)-Fe(1)	69.39(11)
C(8)-C(3)-Fe(1)	132.12(15)
C(27)-C(26)-C(25)	121.2(2)
C(5)-C(6)-C(7)	107.60(18)

C(5)-C(6)-C(11)	125.42(19)
C(7)-C(6)-C(11)	126.78(19)
C(5)-C(6)-Fe(1)	70.74(11)
C(7)-C(6)-Fe(1)	70.82(11)
C(11)-C(6)-Fe(1)	127.91(15)
O(2)-C(2)-Fe(1)	173.49(18)
C(17)-C(18)-C(13)	120.6(2)
C(23)-C(24)-B(1)	119.1(2)
C(24)-B(1)-C(20)	117.2(2)
C(24)-B(1)-P(2)	118.79(17)
C(20)-B(1)-P(2)	123.60(17)
C(26)-C(27)-C(28)	119.9(2)
C(14)-C(13)-C(18)	118.5(2)
C(14)-C(13)-P(2)	121.12(17)
C(18)-C(13)-P(2)	120.29(17)
C(29)-C(30)-C(25)	120.7(2)
C(21)-C(20)-B(1)	118.5(2)
C(29)-C(28)-C(27)	119.8(2)
C(15)-C(14)-C(13)	120.7(2)
C(21)-C(22)-C(23)	120.9(2)
C(20)-C(21)-C(22)	122.4(2)
C(24)-C(23)-C(22)	121.9(2)
C(16)-C(17)-C(18)	120.1(2)
C(15)-C(16)-C(17)	120.1(2)
C(28)-C(29)-C(30)	120.4(2)
C(16)-C(15)-C(14)	120.0(2)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for D8_10094_0m. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
Fe(1)	15(1)	16(1)	12(1)	-1(1)	-1(1)	0(1)
P(2)	15(1)	16(1)	14(1)	-1(1)	-1(1)	0(1)
O(1)	52(1)	38(1)	15(1)	-2(1)	6(1)	-15(1)
C(5)	21(1)	15(1)	18(1)	-4(1)	-2(1)	-3(1)
C(7)	28(1)	23(1)	12(1)	-4(1)	-4(1)	-5(1)
O(2)	24(1)	22(1)	31(1)	0(1)	-4(1)	4(1)
C(25)	22(1)	16(1)	13(1)	0(1)	-1(1)	0(1)
C(1)	26(1)	19(1)	21(1)	-4(1)	-2(1)	-6(1)
C(4)	20(1)	14(1)	23(1)	-7(1)	-1(1)	0(1)
C(3)	23(1)	23(1)	17(1)	-10(1)	4(1)	-4(1)
C(26)	20(1)	22(1)	21(1)	-1(1)	-1(1)	2(1)
C(6)	19(1)	22(1)	16(1)	-4(1)	-5(1)	-3(1)
C(2)	18(1)	22(1)	17(1)	-2(1)	0(1)	-4(1)
C(10)	27(1)	22(1)	23(1)	2(1)	0(1)	-6(1)
C(18)	28(1)	25(1)	26(1)	2(1)	-7(1)	-2(1)
C(24)	23(1)	30(1)	20(1)	-2(1)	-1(1)	-3(1)
B(1)	23(1)	18(1)	15(1)	-4(1)	2(1)	-1(1)
C(27)	25(1)	24(1)	21(1)	0(1)	-6(1)	-2(1)
C(13)	20(1)	16(1)	24(1)	-1(1)	-6(1)	-1(1)
C(30)	21(1)	24(1)	19(1)	-2(1)	-2(1)	-3(1)
C(20)	24(1)	21(1)	22(1)	-6(1)	-2(1)	2(1)
C(28)	32(1)	24(1)	18(1)	-6(1)	-1(1)	-2(1)
C(14)	23(1)	21(1)	29(1)	-3(1)	-6(1)	0(1)
C(22)	38(1)	30(1)	18(1)	-1(1)	5(1)	-9(1)
C(8)	26(1)	36(1)	28(1)	-12(1)	8(1)	-8(1)
C(21)	24(1)	29(1)	24(1)	-12(1)	8(1)	-6(1)
C(23)	37(1)	34(1)	18(1)	3(1)	-5(1)	-2(1)
C(17)	40(1)	26(1)	34(1)	9(1)	-18(1)	-5(1)
C(9)	25(1)	19(1)	46(2)	-4(1)	-8(1)	2(1)
C(16)	32(1)	20(1)	52(2)	2(1)	-22(1)	3(1)
C(12)	46(2)	37(1)	16(1)	3(1)	-5(1)	-10(1)

C(29)	23(1)	29(1)	22(1)	-4(1)	4(1)	2(1)
C(11)	21(1)	27(1)	33(1)	-1(1)	-8(1)	-1(1)
C(15)	23(1)	24(1)	46(2)	-6(1)	-9(1)	4(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for D8_10094_0m.

	x	y	z	U(eq)
H(26)	4449	3753	5053	25
H(10A)	752	967	4323	36
H(10B)	1567	507	4527	36
H(10C)	1016	201	3862	36
H(18)	3528	2109	5483	31
H(24)	2776	3974	2821	29
H(27)	4383	4703	5982	28
H(30)	2005	3735	4920	26
H(20)	5107	3518	3671	27
H(28)	3129	5199	6360	29
H(14)	4819	2182	3590	29
H(22)	4757	5098	2012	35
H(8A)	3451	1539	2001	45
H(8B)	3914	1497	2773	45
H(8C)	3630	2336	2452	45
H(21)	5606	4416	2806	31
H(23)	3368	4901	2036	36
H(17)	4404	1143	5942	40
H(9A)	3023	58	3613	45
H(9B)	2980	556	4361	45
H(9C)	3652	762	3758	45
H(16)	5468	676	5219	42
H(12A)	2366	2914	1951	49
H(12B)	1413	2949	2093	49
H(12C)	1784	2277	1571	49
H(29)	1945	4714	5829	30
H(11A)	194	1517	2728	41
H(11B)	377	2446	2807	41
H(11C)	194	1924	3523	41
H(15)	5681	1200	4049	37

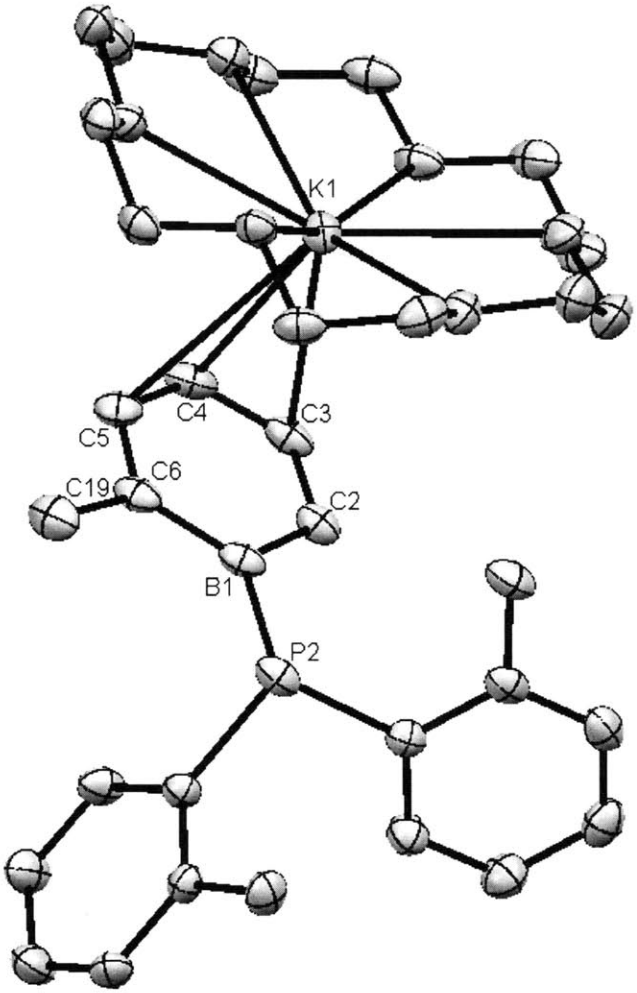
K1
C4
C3
C5
C6
C19
C2
B1
P2

Table 7. Crystal data and structure refinement for **8** (10143_0m).

Identification code	10143_0m	
Empirical formula	C32 H45 B K O6 P	
Formula weight	606.56	
Temperature	100(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	P2(1)/n	
Unit cell dimensions	a = 9.6729(12) Å	α= 90°.
	b = 13.4593(17) Å	β= 98.825(2)°.
	c = 25.290(3) Å	γ = 90°.
Volume	3253.6(7) $Å^3$	
Z	4	
Density (calculated)	1.238 Mg/m^3	
Absorption coefficient	0.253 mm^{-1}	
F(000)	1296	
Crystal size	0.35 x 0.25 x 0.20 mm^3	
Theta range for data collection	1.63 to 29.13°.	
Index ranges	-13<=h<=13, -18<=k<=18, -34<=l<=33	
Reflections collected	49382	
Independent reflections	8766 [R(int) = 0.0411]	
Completeness to theta = 29.13°	99.9 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.9511 and 0.9167	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	8766 / 529 / 403	
Goodness-of-fit on F^2	1.028	
Final R indices [I>2sigma(I)]	R1 = 0.0405, wR2 = 0.0964	
R indices (all data)	R1 = 0.0540, wR2 = 0.1053	
Largest diff. peak and hole	0.733 and -0.651 $e.Å^{-3}$	

Table 8. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for 10143_0m. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
K(1)	4887(1)	8390(1)	1530(1)	24(1)
P(2)	5407(1)	7668(1)	3724(1)	26(1)
B(1)	6027(2)	8486(1)	3162(1)	25(1)
C(2)	5234(2)	9385(1)	2919(1)	26(1)
C(3)	5708(2)	9890(1)	2498(1)	28(1)
C(4)	6895(2)	9583(1)	2295(1)	30(1)
C(5)	7653(2)	8740(1)	2497(1)	29(1)
C(6)	7288(2)	8170(1)	2916(1)	27(1)
C(19)	8177(2)	7270(1)	3100(1)	36(1)
C(7)	6718(1)	7812(1)	4329(1)	22(1)
C(8)	7899(2)	8418(1)	4344(1)	28(1)
C(9)	8902(2)	8489(1)	4800(1)	34(1)
C(10)	8730(2)	7967(1)	5257(1)	34(1)
C(11)	7573(2)	7359(1)	5253(1)	28(1)
C(12)	6573(1)	7259(1)	4795(1)	22(1)
C(20)	5365(2)	6560(1)	4809(1)	30(1)
C(13)	3924(2)	8400(1)	3928(1)	22(1)
C(14)	4066(2)	9023(1)	4376(1)	29(1)
C(15)	2953(2)	9581(1)	4504(1)	33(1)
C(16)	1649(2)	9512(1)	4189(1)	32(1)
C(17)	1473(2)	8879(2)	3750(1)	29(1)
C(18)	2586(2)	8324(1)	3611(1)	26(1)
C(21)	2368(2)	7686(1)	3114(1)	34(1)
C(13A)	3855(11)	8093(9)	3712(5)	22(2)
C(14A)	2757(13)	7730(9)	3327(6)	24(3)
C(15A)	1394(13)	7974(10)	3293(5)	36(3)
C(16A)	1029(16)	8637(11)	3664(6)	29(3)
C(17A)	1962(14)	9069(11)	4029(6)	32(3)
C(18A)	3523(12)	8798(9)	4060(5)	22(2)
C(21A)	4552(15)	9355(11)	4433(6)	34(3)
C(1C)	1194(2)	8533(1)	1756(1)	40(1)

C(2C)	1383(2)	7430(1)	1719(1)	39(1)
O(3C)	2833(1)	7216(1)	1863(1)	30(1)
C(4C)	3104(2)	6176(1)	1930(1)	33(1)
C(5C)	4658(2)	6020(1)	2058(1)	31(1)
O(6C)	5269(1)	6315(1)	1603(1)	26(1)
C(7C)	6727(2)	6068(1)	1663(1)	28(1)
C(8C)	7280(2)	6402(1)	1170(1)	29(1)
O(9C)	7197(1)	7463(1)	1144(1)	27(1)
C(10C)	7655(2)	7858(1)	678(1)	32(1)
C(11C)	7663(2)	8970(1)	720(1)	34(1)
O(12C)	6273(1)	9316(1)	712(1)	26(1)
C(13C)	6230(2)	10376(1)	756(1)	33(1)
C(14C)	4731(2)	10704(1)	678(1)	34(1)
O(15C)	4038(1)	10274(1)	1082(1)	31(1)
C(16C)	2585(2)	10509(1)	992(1)	36(1)
C(17C)	1899(2)	10059(1)	1429(1)	38(1)
O(18C)	1907(1)	9006(1)	1373(1)	33(1)

Table 9. Bond lengths [Å] and angles [°] for 10143_0m.

K(1)-O(3C)	2.7687(11)
K(1)-O(6C)	2.8198(11)
K(1)-O(15C)	2.8461(11)
K(1)-O(9C)	2.8587(11)
K(1)-O(12C)	2.9115(10)
K(1)-O(18C)	2.9669(11)
K(1)-C(4)	2.9909(14)
K(1)-C(3)	3.1787(14)
K(1)-C(5)	3.3708(15)
K(1)-C(5C)	3.4786(16)
P(2)-C(13A)	1.602(11)
P(2)-C(7)	1.8417(14)
P(2)-C(13)	1.8761(19)
P(2)-B(1)	1.9641(17)
B(1)-C(2)	1.511(2)
B(1)-C(6)	1.513(2)
C(2)-C(3)	1.398(2)
C(3)-C(4)	1.391(2)
C(4)-C(5)	1.403(2)
C(5)-C(6)	1.397(2)
C(6)-C(19)	1.516(2)
C(7)-C(8)	1.4002(18)
C(7)-C(12)	1.4168(18)
C(8)-C(9)	1.393(2)
C(9)-C(10)	1.384(2)
C(10)-C(11)	1.385(2)
C(11)-C(12)	1.3976(19)
C(12)-C(20)	1.5057(18)
C(13)-C(14)	1.401(3)
C(13)-C(18)	1.417(2)
C(14)-C(15)	1.391(2)
C(15)-C(16)	1.389(3)
C(16)-C(17)	1.389(3)
C(17)-C(18)	1.400(3)

C(18)-C(21)	1.510(3)
C(13A)-C(18A)	1.367(17)
C(13A)-C(14A)	1.413(19)
C(14A)-C(15A)	1.349(17)
C(15A)-C(16A)	1.380(19)
C(16A)-C(17A)	1.322(19)
C(17A)-C(18A)	1.543(18)
C(18A)-C(21A)	1.468(18)
C(1C)-O(18C)	1.422(2)
C(1C)-C(2C)	1.502(3)
C(2C)-O(3C)	1.4233(18)
O(3C)-C(4C)	1.4285(19)
C(4C)-C(5C)	1.503(2)
C(5C)-O(6C)	1.4286(17)
O(6C)-C(7C)	1.4341(16)
C(7C)-C(8C)	1.500(2)
C(8C)-O(9C)	1.4303(17)
O(9C)-C(10C)	1.4249(18)
C(10C)-C(11C)	1.501(2)
C(11C)-O(12C)	1.4203(18)
O(12C)-C(13C)	1.4325(18)
C(13C)-C(14C)	1.499(2)
C(14C)-O(15C)	1.4281(19)
O(15C)-C(16C)	1.4250(19)
C(16C)-C(17C)	1.501(2)
C(17C)-O(18C)	1.424(2)

O(3C)-K(1)-O(6C)	60.49(3)
O(3C)-K(1)-O(15C)	116.95(3)
O(6C)-K(1)-O(15C)	159.33(3)
O(3C)-K(1)-O(9C)	119.29(3)
O(6C)-K(1)-O(9C)	59.23(3)
O(15C)-K(1)-O(9C)	116.49(3)
O(3C)-K(1)-O(12C)	152.92(3)
O(6C)-K(1)-O(12C)	113.62(3)
O(15C)-K(1)-O(12C)	58.14(3)

O(9C)-K(1)-O(12C)	58.35(3)
O(3C)-K(1)-O(18C)	58.16(3)
O(6C)-K(1)-O(18C)	113.62(3)
O(15C)-K(1)-O(18C)	58.87(3)
O(9C)-K(1)-O(18C)	150.57(3)
O(12C)-K(1)-O(18C)	109.25(3)
O(3C)-K(1)-C(4)	122.32(4)
O(6C)-K(1)-C(4)	115.04(4)
O(15C)-K(1)-C(4)	84.17(4)
O(9C)-K(1)-C(4)	89.49(4)
O(12C)-K(1)-C(4)	84.59(4)
O(18C)-K(1)-C(4)	117.23(4)
O(3C)-K(1)-C(3)	103.55(4)
O(6C)-K(1)-C(3)	124.28(3)
O(15C)-K(1)-C(3)	76.33(3)
O(9C)-K(1)-C(3)	115.09(4)
O(12C)-K(1)-C(3)	100.81(4)
O(18C)-K(1)-C(3)	92.75(4)
C(4)-K(1)-C(3)	25.82(4)
O(3C)-K(1)-C(5)	112.69(4)
O(6C)-K(1)-C(5)	90.52(3)
O(15C)-K(1)-C(5)	108.21(4)
O(9C)-K(1)-C(5)	74.56(3)
O(12C)-K(1)-C(5)	93.14(3)
O(18C)-K(1)-C(5)	134.79(3)
C(4)-K(1)-C(5)	24.56(4)
C(3)-K(1)-C(5)	43.55(4)
O(3C)-K(1)-C(5C)	43.01(3)
O(6C)-K(1)-C(5C)	23.35(3)
O(15C)-K(1)-C(5C)	159.78(4)
O(9C)-K(1)-C(5C)	80.20(3)
O(12C)-K(1)-C(5C)	136.78(3)
O(18C)-K(1)-C(5C)	100.94(4)
C(4)-K(1)-C(5C)	108.45(4)
C(3)-K(1)-C(5C)	108.00(4)
C(5)-K(1)-C(5C)	86.53(4)

C(13A)-P(2)-C(7)	120.1(5)
C(13A)-P(2)-C(13)	20.7(5)
C(7)-P(2)-C(13)	100.05(7)
C(13A)-P(2)-B(1)	100.1(4)
C(7)-P(2)-B(1)	107.16(6)
C(13)-P(2)-B(1)	103.65(7)
C(2)-B(1)-C(6)	116.74(13)
C(2)-B(1)-P(2)	123.41(12)
C(6)-B(1)-P(2)	119.63(11)
C(3)-C(2)-B(1)	119.53(14)
C(4)-C(3)-C(2)	121.49(13)
C(4)-C(3)-K(1)	69.52(8)
C(2)-C(3)-K(1)	101.90(9)
C(3)-C(4)-C(5)	121.38(14)
C(3)-C(4)-K(1)	84.66(8)
C(5)-C(4)-K(1)	93.06(9)
C(6)-C(5)-C(4)	122.81(14)
C(6)-C(5)-K(1)	102.04(9)
C(4)-C(5)-K(1)	62.38(8)
C(5)-C(6)-B(1)	118.01(13)
C(5)-C(6)-C(19)	118.39(14)
B(1)-C(6)-C(19)	123.60(14)
C(8)-C(7)-C(12)	117.93(12)
C(8)-C(7)-P(2)	122.54(10)
C(12)-C(7)-P(2)	119.47(10)
C(9)-C(8)-C(7)	121.55(13)
C(10)-C(9)-C(8)	120.00(13)
C(9)-C(10)-C(11)	119.57(13)
C(10)-C(11)-C(12)	121.28(13)
C(11)-C(12)-C(7)	119.62(12)
C(11)-C(12)-C(20)	118.73(12)
C(7)-C(12)-C(20)	121.64(12)
C(14)-C(13)-C(18)	117.94(16)
C(14)-C(13)-P(2)	123.57(13)
C(18)-C(13)-P(2)	118.49(14)
C(15)-C(14)-C(13)	121.93(17)

C(16)-C(15)-C(14)	119.81(17)
C(15)-C(16)-C(17)	119.33(18)
C(16)-C(17)-C(18)	121.58(19)
C(17)-C(18)-C(13)	119.37(17)
C(17)-C(18)-C(21)	119.85(16)
C(13)-C(18)-C(21)	120.72(16)
C(18A)-C(13A)-C(14A)	117.3(10)
C(18A)-C(13A)-P(2)	123.2(9)
C(14A)-C(13A)-P(2)	119.5(10)
C(15A)-C(14A)-C(13A)	125.7(12)
C(14A)-C(15A)-C(16A)	117.6(13)
C(17A)-C(16A)-C(15A)	122.7(14)
C(16A)-C(17A)-C(18A)	119.3(14)
C(13A)-C(18A)-C(21A)	124.5(11)
C(13A)-C(18A)-C(17A)	117.1(11)
C(21A)-C(18A)-C(17A)	118.3(12)
O(18C)-C(1C)-C(2C)	108.90(13)
O(3C)-C(2C)-C(1C)	107.98(13)
C(2C)-O(3C)-C(4C)	112.57(12)
C(2C)-O(3C)-K(1)	122.12(9)
C(4C)-O(3C)-K(1)	117.94(8)
O(3C)-C(4C)-C(5C)	108.75(12)
O(6C)-C(5C)-C(4C)	108.13(12)
O(6C)-C(5C)-K(1)	51.48(6)
C(4C)-C(5C)-K(1)	84.80(8)
C(5C)-O(6C)-C(7C)	111.86(11)
C(5C)-O(6C)-K(1)	105.17(8)
C(7C)-O(6C)-K(1)	110.74(8)
O(6C)-C(7C)-C(8C)	108.21(11)
O(9C)-C(8C)-C(7C)	108.23(11)
C(10C)-O(9C)-C(8C)	112.81(11)
C(10C)-O(9C)-K(1)	118.55(8)
C(8C)-O(9C)-K(1)	117.49(8)
O(9C)-C(10C)-C(11C)	108.24(13)
O(12C)-C(11C)-C(10C)	109.35(12)
C(11C)-O(12C)-C(13C)	111.38(11)

C(11C)-O(12C)-K(1)	112.86(8)
C(13C)-O(12C)-K(1)	110.42(8)
O(12C)-C(13C)-C(14C)	108.79(12)
O(15C)-C(14C)-C(13C)	109.64(12)
C(16C)-O(15C)-C(14C)	110.87(11)
C(16C)-O(15C)-K(1)	118.54(9)
C(14C)-O(15C)-K(1)	120.50(8)
O(15C)-C(16C)-C(17C)	109.29(12)
O(18C)-C(17C)-C(16C)	108.58(12)
C(1C)-O(18C)-C(17C)	111.57(12)
C(1C)-O(18C)-K(1)	110.28(9)
C(17C)-O(18C)-K(1)	106.54(9)

Symmetry transformations used to generate equivalent atoms:

Table 10. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for 10143_0m. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
K(1)	25(1)	20(1)	28(1)	-2(1)	3(1)	-1(1)
P(2)	30(1)	20(1)	24(1)	4(1)	-4(1)	-4(1)
B(1)	34(1)	20(1)	20(1)	-1(1)	-3(1)	-3(1)
C(2)	30(1)	21(1)	26(1)	0(1)	-3(1)	-2(1)
C(3)	38(1)	19(1)	24(1)	1(1)	-7(1)	-2(1)
C(4)	44(1)	26(1)	18(1)	0(1)	-2(1)	-6(1)
C(5)	37(1)	28(1)	21(1)	-7(1)	2(1)	-2(1)
C(6)	38(1)	21(1)	20(1)	-4(1)	-3(1)	1(1)
C(19)	47(1)	26(1)	33(1)	-3(1)	0(1)	9(1)
C(7)	23(1)	21(1)	22(1)	2(1)	3(1)	-1(1)
C(8)	32(1)	30(1)	23(1)	3(1)	6(1)	-10(1)
C(9)	30(1)	44(1)	29(1)	0(1)	4(1)	-15(1)
C(10)	30(1)	46(1)	24(1)	2(1)	-2(1)	-7(1)
C(11)	30(1)	35(1)	20(1)	5(1)	5(1)	-1(1)
C(12)	20(1)	23(1)	24(1)	2(1)	6(1)	0(1)
C(20)	26(1)	31(1)	32(1)	6(1)	8(1)	-5(1)
C(13)	25(1)	19(1)	22(1)	2(1)	3(1)	-3(1)
C(14)	27(1)	30(1)	28(1)	-3(1)	2(1)	-2(1)
C(15)	35(1)	30(1)	34(1)	-4(1)	8(1)	0(1)
C(16)	30(1)	29(1)	39(1)	6(1)	13(1)	2(1)
C(17)	25(1)	32(1)	30(1)	8(1)	1(1)	-6(1)
C(18)	28(1)	25(1)	23(1)	6(1)	1(1)	-7(1)
C(21)	37(1)	38(1)	24(1)	0(1)	-6(1)	-7(1)
C(1C)	33(1)	55(1)	35(1)	3(1)	14(1)	14(1)
C(2C)	27(1)	53(1)	37(1)	-2(1)	9(1)	-4(1)
O(3C)	27(1)	29(1)	33(1)	-5(1)	7(1)	-3(1)
C(4C)	42(1)	27(1)	32(1)	-3(1)	13(1)	-8(1)
C(5C)	44(1)	26(1)	24(1)	4(1)	7(1)	0(1)
O(6C)	29(1)	26(1)	21(1)	4(1)	2(1)	2(1)
C(7C)	31(1)	24(1)	26(1)	3(1)	-2(1)	6(1)
C(8C)	28(1)	28(1)	29(1)	-1(1)	1(1)	8(1)

O(9C)	30(1)	27(1)	25(1)	3(1)	5(1)	3(1)
C(10C)	26(1)	41(1)	30(1)	6(1)	9(1)	5(1)
C(11C)	25(1)	42(1)	35(1)	9(1)	4(1)	-5(1)
O(12C)	29(1)	24(1)	25(1)	2(1)	2(1)	-3(1)
C(13C)	48(1)	25(1)	24(1)	2(1)	0(1)	-10(1)
C(14C)	56(1)	22(1)	22(1)	3(1)	0(1)	3(1)
O(15C)	45(1)	27(1)	20(1)	2(1)	1(1)	10(1)
C(16C)	50(1)	33(1)	24(1)	-1(1)	3(1)	19(1)
C(17C)	48(1)	41(1)	27(1)	-3(1)	7(1)	22(1)
O(18C)	37(1)	38(1)	27(1)	-3(1)	9(1)	11(1)

Table 11. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for 10143_0m.

	x	y	z	U(eq)
H(2)	4420	9606	3052	32
H(3)	5207	10455	2347	34
H(4)	7200	9951	2014	36
H(5)	8449	8551	2343	35
H(19A)	8796	7120	2839	54
H(19B)	7568	6699	3134	54
H(19C)	8740	7411	3449	54
H(8)	8020	8789	4035	34
H(9)	9704	8895	4798	41
H(10)	9400	8026	5572	41
H(11)	7457	7003	5567	34
H(20A)	5478	6219	5156	44
H(20B)	5343	6068	4522	44
H(20C)	4487	6936	4759	44
H(14)	4948	9066	4600	34
H(15)	3085	10009	4807	39
H(16)	884	9893	4273	38
H(17)	575	8822	3539	35
H(21A)	2849	7986	2840	51
H(21B)	1365	7637	2979	51
H(21C)	2746	7020	3201	51
H(14A)	3001	7275	3069	29
H(15A)	709	7699	3024	43
H(16A)	68	8790	3658	35
H(17A)	1675	9542	4269	38
H(21D)	4859	8950	4751	51
H(21E)	4124	9970	4539	51
H(21F)	5360	9519	4258	51
H(1C1)	186	8701	1685	49
H(1C2)	1577	8767	2121	49

H(2C1)	838	7084	1964	46
H(2C2)	1049	7199	1350	46
H(4C1)	2727	5816	1598	39
H(4C2)	2641	5916	2225	39
H(5C1)	5049	6423	2374	37
H(5C2)	4865	5312	2142	37
H(7C1)	6853	5341	1710	33
H(7C2)	7241	6403	1982	33
H(8C1)	8263	6185	1184	34
H(8C2)	6718	6108	848	34
H(10A)	7016	7645	354	39
H(10B)	8606	7613	651	39
H(11A)	8254	9178	1056	41
H(11B)	8060	9261	416	41
H(13A)	6720	10685	482	40
H(13B)	6705	10587	1114	40
H(14B)	4684	11438	697	40
H(14C)	4260	10494	320	40
H(16B)	2147	10244	641	43
H(16C)	2458	11239	989	43
H(17B)	2414	10252	1783	46
H(17C)	925	10302	1403	46

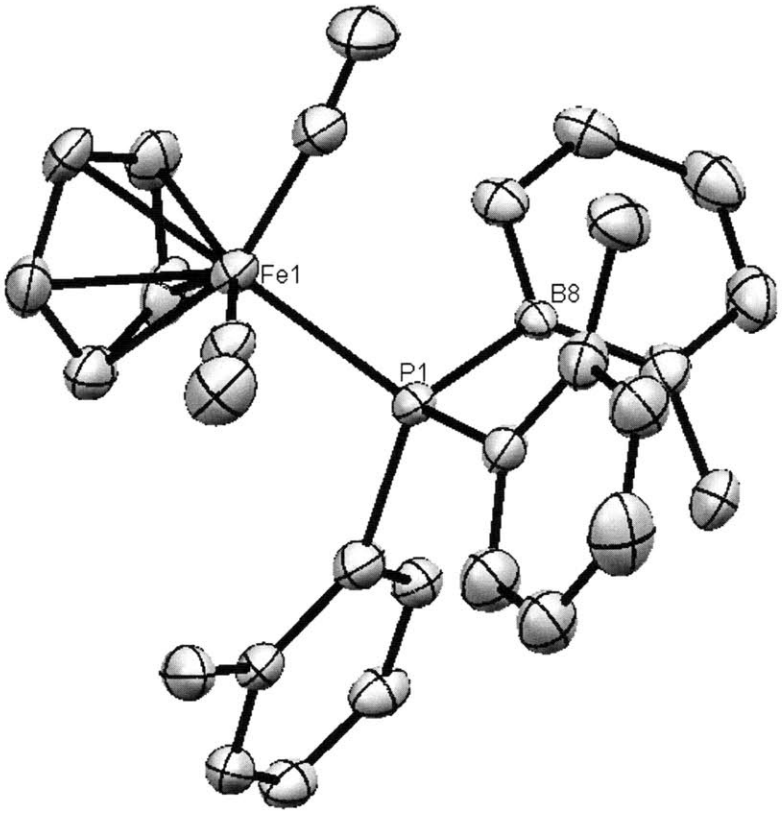
Fe1
B8
P1

Table 1. Crystal data and structure refinement for 10160_0m.

Identification code	10160_0m	
Empirical formula	C30 H32 B Fe O2 P	
Formula weight	522.29	
Temperature	180(2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	P-1	
Unit cell dimensions	a = 8.8096(8) Å	α= 70.9550(10)°.
	b = 11.7362(10) Å	β= 83.4600(10)°.
	c = 13.5372(12) Å	γ = 81.5780(10)°.
Volume	1305.5(2) $Å^3$	
Z	2	
Density (calculated)	1.221 Mg/m^3	
Absorption coefficient	0.659 mm^{-1}	
F(000)	500	
Crystal size	0.50 x 0.15 x 0.10 mm^3	
Theta range for data collection	1.60 to 30.50°.	
Index ranges	-12<=h<=12, -16<=k<=16, -19<=l<=19	
Reflections collected	29041	
Independent reflections	7837 [R(int) = 0.0484]	
Completeness to theta = 30.50°	98.3 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.9371 and 0.7342	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	7837 / 356 / 329	
Goodness-of-fit on F^2	1.082	
Final R indices [I>2sigma(I)]	R1 = 0.0519, wR2 = 0.1504	
R indices (all data)	R1 = 0.0767, wR2 = 0.1703	
Largest diff. peak and hole	0.883 and -0.644 $e.Å^{-3}$	

Table 2. Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for 10160_0m. U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

	x	y	z	U(eq)
Fe(1)	9223(1)	3894(1)	2580(1)	24(1)
P(1)	11631(1)	3373(1)	3236(1)	22(1)
C(1)	12755(3)	2228(2)	2696(2)	27(1)
C(2)	13935(3)	2631(3)	1922(2)	43(1)
C(3)	14781(3)	1869(3)	1424(2)	43(1)
C(4)	14481(4)	675(3)	1688(3)	55(1)
C(5)	13362(3)	261(3)	2460(2)	43(1)
C(6)	12480(3)	1003(2)	2990(2)	34(1)
C(7)	11374(3)	424(3)	3871(3)	47(1)
B(8)	11577(3)	2661(2)	4669(2)	20(1)
C(9)	10185(3)	2756(2)	5259(2)	29(1)
C(10)	10050(3)	2259(2)	6343(2)	35(1)
C(11)	11342(3)	1640(3)	6853(2)	42(1)
C(12)	12746(3)	1539(3)	6285(2)	40(1)
C(13)	12901(3)	2051(2)	5197(2)	31(1)
C(14)	14495(3)	1924(3)	4654(2)	38(1)
C(15)	12747(3)	4813(2)	2921(2)	33(1)
C(16)	13218(3)	5082(2)	3842(2)	28(1)
C(17)	13962(3)	6102(2)	3680(2)	33(1)
C(18)	14249(3)	6889(2)	2691(2)	35(1)
C(19)	13812(3)	6690(2)	1809(2)	34(1)
C(20)	13084(3)	5692(2)	1846(2)	29(1)
C(21)	12747(3)	5624(3)	788(2)	38(1)
C(22)	7983(3)	5486(2)	1657(2)	38(1)
C(23)	6988(3)	4832(2)	2454(2)	37(1)
C(24)	7529(3)	4744(3)	3426(2)	38(1)
C(25)	8855(3)	5328(2)	3224(2)	39(1)
C(26)	9162(3)	5789(2)	2133(2)	38(1)
C(27)	8479(3)	2488(2)	3171(2)	36(1)
O(1)	7870(2)	1638(2)	3508(2)	60(1)
C(28)	9992(3)	3511(2)	1450(2)	32(1)

O(2)	10416(2)	3268(2)	709(2)	46(1)
C(1A)	9290(20)	940(15)	10003(18)	70(5)
C(3A)	11090(30)	-610(20)	10200(30)	91(8)
C(2A)	10040(30)	-600(30)	9430(20)	135(11)
C(4A)	8430(30)	-850(20)	10150(20)	123(9)
C(5A)	8200(20)	279(19)	10429(15)	93(8)
C(6A)	10870(20)	550(20)	10180(30)	70(6)
C(5B)	8840(20)	781(17)	10466(18)	78(5)
C(3B)	11210(30)	-420(30)	10430(30)	110(10)
C(2B)	10240(20)	-1349(13)	10438(12)	79(5)
C(1B)	9070(40)	-450(30)	9570(20)	146(15)
C(6B)	8038(18)	-40(20)	10350(12)	80(6)
C(4B)	10420(30)	647(19)	10080(30)	110(10)

Table 3. Bond lengths [Å] and angles [°] for 10160_0m.

Fe(1)-C(28)	1.767(3)
Fe(1)-C(27)	1.769(3)
Fe(1)-C(26)	2.099(3)
Fe(1)-C(25)	2.105(3)
Fe(1)-C(22)	2.106(3)
Fe(1)-C(23)	2.106(2)
Fe(1)-C(24)	2.110(2)
Fe(1)-P(1)	2.3149(6)
P(1)-B(8)	1.843(2)
P(1)-C(1)	1.846(2)
P(1)-C(15)	1.981(3)
C(1)-C(2)	1.405(4)
C(1)-C(6)	1.411(3)
C(2)-C(3)	1.376(4)
C(3)-C(4)	1.386(4)
C(4)-C(5)	1.370(4)
C(5)-C(6)	1.399(4)
C(6)-C(7)	1.495(4)
B(8)-C(9)	1.396(3)
B(8)-C(13)	1.413(3)
C(9)-C(10)	1.389(3)
C(10)-C(11)	1.381(4)
C(11)-C(12)	1.392(4)
C(12)-C(13)	1.396(4)
C(13)-C(14)	1.520(4)
C(15)-C(16)	1.496(3)
C(15)-C(20)	1.510(4)
C(16)-C(17)	1.392(3)
C(17)-C(18)	1.376(4)
C(18)-C(19)	1.393(4)
C(19)-C(20)	1.400(3)
C(20)-C(21)	1.524(4)
C(22)-C(23)	1.401(4)
C(22)-C(26)	1.424(4)

C(23)-C(24)	1.416(4)
C(24)-C(25)	1.396(4)
C(25)-C(26)	1.407(4)
C(27)-O(1)	1.138(3)
C(28)-O(2)	1.139(3)
C(1A)-C(5A)	1.28(2)
C(1A)-C(6A)	1.42(2)
C(3A)-C(6A)	1.33(2)
C(3A)-C(2A)	1.47(2)
C(2A)-C(4A)	1.64(3)
C(4A)-C(5A)	1.48(2)
C(5B)-C(6B)	1.330(19)
C(5B)-C(4B)	1.43(3)
C(3B)-C(4B)	1.31(2)
C(3B)-C(2B)	1.47(2)
C(2B)-C(1B)	1.65(3)
C(1B)-C(6B)	1.48(3)

C(28)-Fe(1)-C(27)	93.01(12)
C(28)-Fe(1)-C(26)	104.74(12)
C(27)-Fe(1)-C(26)	155.24(11)
C(28)-Fe(1)-C(25)	142.85(12)
C(27)-Fe(1)-C(25)	123.88(12)
C(26)-Fe(1)-C(25)	39.09(11)
C(28)-Fe(1)-C(22)	91.05(11)
C(27)-Fe(1)-C(22)	124.84(11)
C(26)-Fe(1)-C(22)	39.58(10)
C(25)-Fe(1)-C(22)	65.53(11)
C(28)-Fe(1)-C(23)	114.17(11)
C(27)-Fe(1)-C(23)	91.21(11)
C(26)-Fe(1)-C(23)	65.95(10)
C(25)-Fe(1)-C(23)	65.54(10)
C(22)-Fe(1)-C(23)	38.86(10)
C(28)-Fe(1)-C(24)	153.26(11)
C(27)-Fe(1)-C(24)	90.99(12)
C(26)-Fe(1)-C(24)	65.46(11)

C(25)-Fe(1)-C(24)	38.68(11)
C(22)-Fe(1)-C(24)	65.29(11)
C(23)-Fe(1)-C(24)	39.26(11)
C(28)-Fe(1)-P(1)	89.61(8)
C(27)-Fe(1)-P(1)	98.95(9)
C(26)-Fe(1)-P(1)	98.31(7)
C(25)-Fe(1)-P(1)	88.82(7)
C(22)-Fe(1)-P(1)	136.09(8)
C(23)-Fe(1)-P(1)	153.69(8)
C(24)-Fe(1)-P(1)	115.85(8)
B(8)-P(1)-C(1)	105.02(11)
B(8)-P(1)-C(15)	106.09(11)
C(1)-P(1)-C(15)	110.53(10)
B(8)-P(1)-Fe(1)	113.65(7)
C(1)-P(1)-Fe(1)	109.79(7)
C(15)-P(1)-Fe(1)	111.52(8)
C(2)-C(1)-C(6)	118.8(2)
C(2)-C(1)-P(1)	116.66(19)
C(6)-C(1)-P(1)	124.50(18)
C(3)-C(2)-C(1)	121.4(3)
C(2)-C(3)-C(4)	119.9(3)
C(5)-C(4)-C(3)	119.3(3)
C(4)-C(5)-C(6)	122.6(3)
C(5)-C(6)-C(1)	117.9(2)
C(5)-C(6)-C(7)	117.6(2)
C(1)-C(6)-C(7)	124.4(2)
C(9)-B(8)-C(13)	118.6(2)
C(9)-B(8)-P(1)	118.87(17)
C(13)-B(8)-P(1)	122.48(18)
C(10)-C(9)-B(8)	122.5(2)
C(11)-C(10)-C(9)	118.6(2)
C(10)-C(11)-C(12)	120.1(2)
C(11)-C(12)-C(13)	121.8(2)
C(12)-C(13)-B(8)	118.3(2)
C(12)-C(13)-C(14)	117.7(2)
B(8)-C(13)-C(14)	124.0(2)

C(16)-C(15)-C(20)	117.6(2)
C(16)-C(15)-P(1)	116.45(18)
C(20)-C(15)-P(1)	125.88(19)
C(17)-C(16)-C(15)	119.5(2)
C(18)-C(17)-C(16)	121.6(2)
C(17)-C(18)-C(19)	121.1(2)
C(18)-C(19)-C(20)	123.8(2)
C(19)-C(20)-C(15)	116.3(2)
C(19)-C(20)-C(21)	115.5(2)
C(15)-C(20)-C(21)	128.1(2)
C(23)-C(22)-C(26)	108.2(2)
C(23)-C(22)-Fe(1)	70.59(14)
C(26)-C(22)-Fe(1)	69.96(14)
C(22)-C(23)-C(24)	107.6(2)
C(22)-C(23)-Fe(1)	70.55(14)
C(24)-C(23)-Fe(1)	70.50(14)
C(25)-C(24)-C(23)	108.3(2)
C(25)-C(24)-Fe(1)	70.47(14)
C(23)-C(24)-Fe(1)	70.24(14)
C(24)-C(25)-C(26)	108.6(2)
C(24)-C(25)-Fe(1)	70.85(15)
C(26)-C(25)-Fe(1)	70.23(15)
C(25)-C(26)-C(22)	107.3(2)
C(25)-C(26)-Fe(1)	70.68(15)
C(22)-C(26)-Fe(1)	70.46(15)
O(1)-C(27)-Fe(1)	173.3(2)
O(2)-C(28)-Fe(1)	176.7(2)
C(5A)-C(1A)-C(6A)	123.8(17)
C(6A)-C(3A)-C(2A)	101.7(18)
C(3A)-C(2A)-C(4A)	101.9(17)
C(5A)-C(4A)-C(2A)	97.0(13)
C(1A)-C(5A)-C(4A)	111.1(15)
C(3A)-C(6A)-C(1A)	105.7(15)
C(6B)-C(5B)-C(4B)	113.2(17)
C(4B)-C(3B)-C(2B)	108.7(17)
C(3B)-C(2B)-C(1B)	96.6(15)

C(6B)-C(1B)-C(2B)	93.8(16)
C(5B)-C(6B)-C(1B)	99.7(17)
C(3B)-C(4B)-C(5B)	118(2)

Symmetry transformations used to generate equivalent atoms:

Table 4. Anisotropic displacement parameters ($Å^2 x\ 10^3$) for 10160_0m. The anisotropic displacement factor exponent takes the form: $-2\pi^2[\ h^2\ a^{*2}U^{11} + ... + 2\ h\ k\ a^*\ b^*\ U^{12}\ ]$

	U^{11}	U^{22}	U^{33}	U^{23}	U^{13}	U^{12}
Fe(1)	18(1)	29(1)	27(1)	-10(1)	-3(1)	-2(1)
P(1)	18(1)	24(1)	24(1)	-7(1)	-3(1)	-4(1)
C(1)	21(1)	29(1)	30(1)	-9(1)	-4(1)	0(1)
C(2)	42(1)	40(1)	44(1)	-14(1)	2(1)	2(1)
C(3)	42(1)	40(1)	44(1)	-14(1)	2(1)	2(1)
C(4)	62(2)	52(2)	49(2)	-25(2)	1(1)	16(2)
C(5)	42(1)	40(1)	44(1)	-14(1)	2(1)	2(1)
C(6)	31(1)	30(1)	40(1)	-11(1)	-9(1)	1(1)
C(7)	43(2)	28(1)	65(2)	-9(1)	6(1)	-8(1)
B(8)	21(1)	20(1)	19(1)	-4(1)	-4(1)	-7(1)
C(9)	32(1)	29(1)	29(1)	-10(1)	-3(1)	-10(1)
C(10)	42(1)	35(1)	29(1)	-10(1)	4(1)	-14(1)
C(11)	56(2)	43(2)	27(1)	-5(1)	-6(1)	-16(1)
C(12)	44(2)	40(2)	35(1)	-5(1)	-16(1)	-6(1)
C(13)	31(1)	31(1)	33(1)	-8(1)	-9(1)	-6(1)
C(14)	28(1)	43(2)	40(1)	-8(1)	-12(1)	0(1)
C(15)	25(1)	32(1)	41(1)	-10(1)	-3(1)	-4(1)
C(16)	25(1)	29(1)	32(1)	-11(1)	-2(1)	-4(1)
C(17)	27(1)	34(1)	45(1)	-21(1)	-1(1)	-5(1)
C(18)	27(1)	26(1)	55(2)	-15(1)	-1(1)	-5(1)
C(19)	26(1)	28(1)	42(1)	-2(1)	-1(1)	-4(1)
C(20)	20(1)	30(1)	34(1)	-6(1)	-5(1)	-2(1)
C(21)	34(1)	44(2)	32(1)	-2(1)	-6(1)	-10(1)
C(22)	32(1)	39(1)	35(1)	-5(1)	-7(1)	6(1)
C(23)	18(1)	42(1)	48(2)	-12(1)	-7(1)	4(1)
C(24)	31(1)	41(1)	39(1)	-14(1)	2(1)	8(1)
C(25)	37(1)	36(1)	49(2)	-24(1)	-12(1)	8(1)
C(26)	27(1)	28(1)	55(2)	-9(1)	-2(1)	0(1)
C(27)	26(1)	36(1)	45(2)	-10(1)	-3(1)	-4(1)
O(1)	41(1)	43(1)	88(2)	-8(1)	-2(1)	-18(1)
C(28)	25(1)	39(1)	33(1)	-13(1)	-6(1)	-2(1)

O(2)	44(1)	64(1)	37(1)	-27(1)	-2(1)	-2(1)

Table 5. Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$x 10^3) for 10160_0m.

	x	y	z	U(eq)
H(2)	14152	3446	1739	51
H(3)	15571	2161	900	51
H(4)	15045	149	1336	66
H(5)	13177	-562	2644	51
H(7A)	10718	-24	3630	71
H(7B)	10733	1052	4110	71
H(7C)	11946	-138	4452	71
H(9)	9296	3176	4906	35
H(10)	9090	2342	6726	42
H(11)	11272	1284	7593	51
H(12)	13624	1110	6647	48
H(14A)	15272	1740	5165	58
H(14B)	14662	2686	4098	58
H(14C)	14580	1265	4348	58
H(16)	13010	4560	4532	34
H(17)	14280	6259	4266	40
H(18)	14753	7580	2608	42
H(19)	14021	7265	1143	41
H(21A)	12308	6425	357	57
H(21B)	12013	5036	895	57
H(21C)	13704	5368	433	57
H(22)	7888	5693	926	45
H(23)	6109	4506	2360	44
H(24)	7069	4354	4099	46
H(25)	9450	5403	3738	46
H(26)	10000	6221	1778	46
H(1A1)	9033	1691	10199	84
H(1A2)	9209	1181	9236	84
H(3A1)	10805	-1159	10904	110
H(3A2)	12171	-850	9990	110

H(2A1)	10399	-1250	9107	162
H(2A2)	9939	192	8869	162
H(4A1)	7595	-912	9742	148
H(4A2)	8555	-1588	10769	148
H(5A1)	7204	740	10195	112
H(5A2)	8174	77	11200	112
H(6A1)	11531	1043	9602	84
H(6A2)	11114	621	10847	84
H(5B1)	8797	707	11218	94
H(5B2)	8366	1604	10088	94
H(3B1)	11507	-558	11145	132
H(3B2)	12156	-469	9968	132
H(2B1)	9701	-1694	11131	95
H(2B2)	10832	-2010	10200	95
H(1B1)	9575	216	9040	175
H(1B2)	8560	-893	9215	175
H(6B1)	7022	338	10082	96
H(6B2)	7896	-704	11013	96
H(4B1)	10459	880	9311	132
H(4B2)	10956	1237	10257	132

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Developed the asymmetric Negishi arylation of α-bromoketones.
Developed the asymmetric Suzuki arylation of α-haloamides.
Studied boratabenzene-containing transition metal complexes.

June 2004 – August 2004 **Summer Research Associate** Pfizer, Inc.
Developed a library of bioactive compounds for therapeutic use.

August 2003- May 2005 **Researcher with Professor Maurice Brookhart** UNC-Chapel Hill
Synthesized novel iridium pincer ligand complexes

Publications

"Asymmetric Suzuki Cross-Couplings of Activated Secondary Alkyl Electrophiles: Arylations of Racemic α-Chloroamides" Lundin, P. M.; Fu, G. C. *J. Am. Chem. Soc.* **2010**, *132*, 11027–11029.

"Catalytic Asymmetric Cross-Couplings of Racemic α-Bromoketones with Arylzinc Reagents" Lundin, P. M.; Esquivias, J.; Fu, G. C. *Angew. Chem. Int. Ed.* **2009**, *48*, 154-156.

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"Asymmetric Suzuki Arylation of α-Bromoamides" Lundin, P. M.; Fu, G. C. 237th ACS National Meeting in Salt Lake City, UT. March 24, 2009. ORGN-304.

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Awards

2009 Eli Lilly Graduate Fellowship in Organic Chemistry
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