Modeling the Active Sites of Diiiron and Dicopper Metalloproteins with Naphthyridine-, Phthalazine-, and Diethynylbenzene-Based Ligands

by
Jane Kuzelka
B.Sc., Chemistry
University of British Columbia, 1997

SUBMITTED TO THE DEPARTMENT OF CHEMISTRY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY IN INORGANIC CHEMISTRY
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

[September 2003]
August 2003

© Massachusetts Institute of Technology, 2003
All rights reserved

Signature of Author: ____________________________

Department of Chemistry
August 25, 2003

Certified by: ________________________________

Stephen J. Lippard
Arthur Amos Noyes Professor of Chemistry
Thesis Supervisor

Accepted by: ________________________________

Robert W. Field
Chairman, Departmental Committee on Graduate Studies
This doctoral thesis has been examined by a committee of the Department of Chemistry as follows:

Daniel G. Nocera  
W. M. Keck Professor of Energy and Professor of Chemistry  
Committee Chairman

Stephen J. Lippard  
Arthur Amos Noyes Professor of Chemistry  
Thesis Supervisor

Joseph P. Sadighi  
Assistant Professor of Chemistry
Modeling the Active Sites of Diiron and Dicopper Metalloproteins with Naphthyridine-, Phthalazine-, and Diethynylbenzene-Based Ligands

by
JANE KUZELKA

Submitted to the Department of Chemistry on August 25, 2003, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Abstract

Chapter 1. Bio-Inspired Reactions of Diiron Centers with Dioxygen

A variety of biological systems employ carboxylate-bridged diiron centers to achieve substrate oxidation using dioxygen, and numerous small molecule model compounds have been synthesized in order to mimic this chemistry in the absence of a protein scaffold. In this introductory chapter, a brief overview is presented of ligand systems that have been used to prepare diiron complexes, and the subsequent oxidation chemistry of these systems is outlined.

Chapter 2. Carboxylate, Phosphodiester, and Hydroxide-Bridged Diiron(II) Complexes with a Sterically Hindered Phthalazine Ligand

The synthesis and crystallographic characterization of a series of diiron(II) complexes with a sterically hindered bridging phthalazine ligand are presented. The compounds \([\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{CR})_2]^{2+} \ (R = \text{CH}_3 \ (3); \text{C}_2\text{H}_5 \ (4); \text{C}_6\text{H}_5\text{Ph} \ (5); \text{t-C}_4\text{H}_9 \ (6)), \ [\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{P(OPh)}_2)_2]^{2+} \ (7), \text{ and } [\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{OH})(\text{MeCN})_2]^{3+} \ (8)\) were prepared as small molecule models of the catalytic sites in non-heme carboxylate-bridged diiron enzymes. The phenyl rings of Ph_4bdptz form a hydrophobic size-constrained pocket in which additional ligands can be accommodated, and they block the possible formation of tetranuclear species. As the steric bulk of the ancillary ligands is increased, the carboxylates shift from a syn, anti to a syn, syn coordination mode, and
the Mössbauer spectra of the diiron(II) compounds clearly reflect the symmetry of the iron coordination environment. The oxidation chemistry of the diiron(II) compounds is presented.

Chapter 3. Modeling Features of the Non-Heme Diiron Cores in O$_2$-Activating Enzymes through the Synthesis, Characterization, and Oxidation of 1,8-Naphthyridine-Based Complexes

Multidentate naphthyridine-based ligands were used to prepare a series of diiron(II) complexes. The compounds $[\text{Fe}_2(\text{BPMAN})(\mu-\text{O}_2\text{CPh})_2](\text{OTf})_2$ (1), $[\text{Fe}_2(\text{BPMAN})(\mu-\text{OR})(\mu-\text{O}_2\text{Car}^\text{Tr})](\text{OTf})_2$ ($R = \text{H}$ (2); $\text{CH}_3$ (3)), $[\text{Fe}_2(\text{BBAN})(\mu-\text{O}_2\text{Car}^\text{Tr})_2](\text{OTf})_2$ (4), and $[\text{Fe}_2(\text{BEAN})(\mu-\text{O}_2\text{Car}^\text{Tr})_2](\text{OTf})_2$ (5) were prepared as models of the active sites of non-heme diiron enzymes. The rigorously enforced dinuclear core allows the reactivity of the diiron unit to be evaluated. Upon oxidation of these compounds, there is evidence for the formation of a ($\mu$-oxo)diiron(III) unit, a mixed-valent ($\mu$-oxo)Fe(II)Fe(III) species, and oxidative $N$-dealkylation. The electrochemical properties of the compounds were correlated with the observed dioxygen reactivity, and Mössbauer spectroscopic properties of the diiron(II) complexes were also investigated.

Chapter 4. Modeling the Syn Disposition of Nitrogen Donors at the Active Sites of Carboxylate-Bridged Diiron Enzymes. Enforcing Dinuclearity and Kinetic Stability with a 1,2-Diethylbenzene-Based Ligand

The syn coordination of histidine residues at the active sites of several carboxylate-rich non-heme diiron enzymes has not been effectively reproduced with small molecule model compounds. In this study, ligands derived from 1,8-naphthyridine, phthalazine, and 1,2-diethylbenzene were employed to mimic this geometric feature. Simple (N)$_2$-donor ligands afforded either mononuclear compounds or dinuclear complexes that are kinetically labile. This difficulty was circumvented by preparing a family of 1,2-diethylbenzene-based ligands. The ligand 1,2-bis(3-ethynyl-8-carboxylatequinoline)benzene ethyl ester (Et$_2$BCQEB$^{39}$) was used to assemble diiron(II) and dicopper(I) compounds, and provides both structural flexibility and the
desired syn nitrogen donor geometry, thus serving as a good first-generation ligand in this class.

Chapter 5. Synthesis and Characterization of Cu₂(I,II), Cu₃(I,II), and Cu₄(II,II) Compounds Supported by Two Phthalazine-Based Ligands: Dramatic Influence of a Hydrophobic Pocket

Two phthalazine-based ligands of differing steric bulk, bdptz and Ph₅bdptz, were used to study the coordination chemistry of copper. The compounds [Cu₂(bdptz)(MeCN)₂]²⁺ (1) and [Cu₂(Ph₅bdptz)(MeCN)₂]²⁺ (6) served as convenient starting materials for a series of copper(I) and copper(II) complexes. All compounds were characterized structurally by X-ray crystallography, and the electrochemical behavior of several complexes was studied. This work highlights the dramatic influence of a hydrophobic binding pocket upon the stability and reactivity of resulting compounds.

Thesis Supervisor: Stephen J. Lippard
Title: Department Head and Arthur Amos Noyes Professor of Chemistry
To my parents, my sister, and Baback
Acknowledgements

I am delighted to have an opportunity to express my gratitude and appreciation to the many people that have helped me over the course of my graduate work at MIT. I know that I will look back on my time here and think very fondly of the people that I have had the pleasure to know, both professionally and personally, and the experiences that we shared.

First and foremost, I wish to thank my advisor, Steve Lippard. I have learned a great deal about science from Steve, and I appreciate his encouragement and confidence in me. Steve asks insightful questions and uses his creativity and thorough scientific knowledge to guide his research group toward a deeper understanding of chemistry. This approach attracts a wonderful group of scientists to his lab and I am very proud to have been part of this group. I also thank the other Inorganic Chemistry faculty members, especially Professor Dan Nocera, for their support and helpful suggestions.

When I joined the lab in the fall of 1998, Jack Mizoguchi shared his bench with me and helped me with my early synthetic work. I am grateful for his patience and his willingness to answer many questions. I am also indebted to Chuan He for teaching me so much about organic synthesis, as well as for his advice and insights on the naphthyridine project. Dongwhan Lee gave me many useful suggestions and helped with physical measurements, and I enjoyed our conversations while tending to “the mouse”! I appreciate the friendship and guidance offered by Amy Barrios, who was my hynmate for two years. Xiao-Xiang Zhang and Kathy Franz also helped me at the beginning of my graduate studies with practical suggestions and direction.

Much of my research involved solving X-ray crystal structures and I am grateful to the postdocs that I have worked with, Bernhard Spingler, Weiming Bu, and Sumi Mukhopadhyay, for their assistance with difficult structures. On the synthetic front, I have enjoyed discussions with Joshua Farrell, particularly on ligand design strategies. Tom Smith spent a year in the group on sabbatical and I benefited greatly from his time
here. He patiently answered many questions and offered helpful advice on numerous issues. Many computer catastrophes were averted by Jessica Blazyk, and I appreciate Dan Kopp’s talent for fixing broken instruments.

I have had the pleasure of knowing and working with Sungho Yoon, a very friendly, hard-working, and helpful member of the MMO modeling subgroup. Emily Carson’s sense of humor is much appreciated in our subgroup and Rayane Moreira’s background in organic chemistry is a great addition to the project. Rayane is a good friend and I thank her and Katie Barnes for introducing me to birding! Amy Kelly is a recent addition to the modeling effort, and I wish her and the rest of the group continued success in this area. Scott Hilderbrand is my classmate and an honorary member of the modeling subgroup, and I am grateful to have had his company for five years. I also thank Ariel Haskel for his sunny outlook and support, Edna Ambundo for hours of laughter, and Liz Nolan and Chris Chang for their encouragement.

As an undergraduate student, I spent summers in research labs under the supervision of John Schmidt at Papricon, Sep Liang at the Department of National Defense, and Peter Legzdins at UBC. These were extremely valuable experiences and I am especially grateful to Peter for introducing me to research in synthetic chemistry. Peter’s group members, in particular Sean Lumb, Kevin Smith, Jamie Daff, and Elizabeth Tran, were instrumental in my decision to pursue graduate studies.

Lastly, I want to thank my family. I consider myself extremely lucky to have such wonderful parents, whose incredible strength of spirit is a constant inspiration. My sister serves me as an example of what can be accomplished through determination and self-motivation, and I appreciate her confidence in me. Baback Elmieh is a source of strength for me, and I am grateful for his steadfast love and support.
# Table of Contents

Abstract.................................................................................................................. 3

Dedication.................................................................................................................. 6

Acknowledgements .................................................................................................... 7

Table of Contents ..................................................................................................... 9

List of Tables ............................................................................................................ 13

List of Charts ............................................................................................................ 15

List of Schemes ......................................................................................................... 16

List of Figures ............................................................................................................ 17

**Chapter 1. Bio-Inspired Reactions of Diiron Centers with Dioxygen** ................. 21

Dimetallic Units in Nature ....................................................................................... 22

Binding of Dioxygen to Metal Ions .......................................................................... 23

Probing the Reactivity of the Diiron Core with Model Compounds ..................... 23

Pre-Organized Bis(carboxylate) Platforms ............................................................... 24

Sterically Hindered $m$-Terphenyl-Derived Carboxylate Ligands ......................... 25

Tris(pyridylmethyl)amine Ligands ........................................................................... 26

Multidentate Dinucleating Ligand Frameworks ...................................................... 27

  Phthalazine Derivatives .......................................................................................... 27

  Phenoxide- and Alkoxide-Based Ligands ............................................................... 28

  1,8-Naphthyridine as a Bridging Unit .................................................................... 28

  1,2-Diethynylbenzene as a Spacer ....................................................................... 29

Perspectives and Implications for Future Work ...................................................... 30

Acknowledgements .................................................................................................. 31

References and Notes ............................................................................................... 32

**Chapter 2. Carboxylate, Phosphodiester, and Hydroxide-Bridged Diiron(II) Complexes with a Sterically Hindered Phthalazine Ligand** ....................... 51

Introduction .............................................................................................................. 52
Experimental Section ................................................................. 54
  General Procedures .............................................................. 54
  Synthetic Procedures ............................................................ 54
  Physical Measurements .......................................................... 58
  X-ray Crystallography ............................................................ 59
Results and Discussion ............................................................... 60
  Design of a Sterically Hindered Ligand ...................................... 60
  Synthesis and Structural Characterization of Phbdptz..................... 60
  Synthesis of Diiron(II) Compounds ......................................... 61
  Coordination Environment of the Diiron(II) Complexes .................. 62
  Structural Analysis of Dimetallic Compounds .............................. 63
  Mössbauer Spectroscopy .......................................................... 66
  Dioxygen Reactivity ............................................................... 67
Summary and Conclusions .......................................................... 67
Acknowledgements ................................................................. 68
References and Notes ............................................................... 69

Chapter 3.  Modeling Features of the Non-Heme Diiron Cores in O2-Activating Enzymes through the Synthesis, Characterization, and Oxidation of 1,8-Naphthyridine-Based Complexes ............................................. 91
Introduction .................................................................................. 92
Experimental Section ................................................................. 94
  General Procedures ............................................................... 94
  Synthetic Procedures ............................................................. 94
  Physical Measurements .......................................................... 97
  X-ray Crystallography ............................................................. 98
  Electrochemistry ...................................................................... 99
  Mössbauer Spectroscopy .......................................................... 99
Results ................................................................................................................................. 99

Synthesis and Characterization of Dimetallic Complexes .................................................. 99
Mössbauer Spectroscopic Properties of Diiiron(II) Compounds ...................................... 102
Reactions of 1 with Dioxygen and H₂O₂ ............................................................................. 103
Formation of Fe(II)Fe(III) Species from Compounds 2 and 3 .......................................... 104
Oxidative N-Dealkylation Effected by 4 ............................................................................ 105
Comparison of Substrate Oxidation by 4 and 5 ............................................................... 106
Electrochemical Studies .................................................................................................... 107
Discussion .......................................................................................................................... 108
Conclusions ....................................................................................................................... 110
Acknowledgements ........................................................................................................... 111
References and Notes ...................................................................................................... 112

Chapter 4. Modeling the Syn Disposition of Nitrogen Donors at the Active Sites of
Carboxylate-Bridged Diiiron Enzymes. Enforcing Dinuclearity and Kinetic Stability
with a 1,2-Diethylbenzene-Based Ligand .......................................................................... 133
Introduction ....................................................................................................................... 134
Experimental Section ....................................................................................................... 135
General Procedures and Methods .................................................................................... 135
Synthetic Procedures ....................................................................................................... 136
X-ray Crystallographic Studies ......................................................................................... 143
Results .............................................................................................................................. 144
Synthesis and Structural Characterization of Iron(II) Compounds
with Me₂-napy and DMP ligands ....................................................................................... 144
Design and Synthesis of BCQEB Derivatives .................................................................. 147
Synthesis and Structural Characterization of Dimetallic
Complexes of Et₂BCQEB\textsuperscript{Et} .............................................................................. 148
Discussion ......................................................................................................................... 150
Complexes of Me₂-napy and DMP ................................................................. 150
Preparation of BCQEB Ligands and Metal Complexes ....................................... 151
Utilization of BCQEB-Derived Ligands and Relevance to High-Valent Intermediates in Non-Heme Diiron Enzymes .......................................................... 151
Summary and Conclusions ............................................................................... 152
Acknowledgements ......................................................................................... 152
References and Notes ....................................................................................... 153

Chapter 5. Synthesis and Characterization of Cu₂(I,I), Cu₄(I,II), and Cu₃(II,II)
Compounds Supported by Two Phthalazine-Based Ligands: Dramatic Influence of a
Hydrophobic Pocket ......................................................................................... 171
Introduction ..................................................................................................... 172
Experimental Section ....................................................................................... 174
  General Procedures ....................................................................................... 174
  Synthetic Procedures .................................................................................... 174
  Physical Measurements ............................................................................... 178
  X-ray Crystallography .................................................................................. 178
  Electrochemistry .......................................................................................... 179
Results and Discussion ................................................................................... 179
  Synthesis and Characterization of bdptz-derived Complexes ....................... 179
  Preparation and Characterization of Ph₂bdptz-based Compounds ............... 184
  Electrochemical Studies ............................................................................... 185
  Oxidation Chemistry of Dicopper Complexes .............................................. 187
Conclusions .................................................................................................... 189
Acknowledgements ......................................................................................... 190
References and Notes ....................................................................................... 191
Biographical Note ............................................................................................ 211
List of Tables

Chapter 2
Table 2.1. Summary of X-ray crystallographic data for compounds 2-CH₂Cl₂, 3(OTf)₂2.5CH₂Cl₂, and 4(BPh₄)₂2.5MeCN-0.5Et₂O ..................... 74
Table 2.2. Summary of X-ray crystallographic data for compounds 5(OTf)₂2CH₂Cl₂, 7(OTf)₂, 8(OTf)₃·3.5MeCN, and 9(OTf)₂·H₂O .................. 75
Table 2.3. Structural parameters for compounds 3(OTf)₂, 4(BPh₄)₂, and 5(OTf)₂ .................. 76
Table 2.4. Selected bond lengths and angles for 3 and 4 ........................................ 77
Table 2.5. Selected bond lengths and angles for 5 and 7 ........................................ 78
Table 2.6. Selected bond lengths and angles for 8 ........................................ 79
Table 2.7. Summary of Mössbauer parameters for 3(OTf)₂ - 8(OTf)₃ .......................... 80

Chapter 3
Table 3.1. Summary of X-ray crystallographic information ........................................ 119
Table 3.2. Selected bond lengths and angles for 1 and 3 ........................................ 120
Table 3.3. Selected bond lengths and angles for 4 and 5 ........................................ 121
Table 3.4. Summary of Mössbauer parameters for compounds 1 - 4 .......................... 122

Chapter 4
Table 4.1. Summary of X-ray crystallographic data ........................................ 161
Table 4.2. Selected bond lengths and angles for 2, 4, and 5 ........................................ 162
Table 4.3. Selected bond lengths and angles for 6, 7, and 15 ........................................ 163

Chapter 5
Table 5.1. Summary of X-ray crystallographic data ........................................ 197
Table 5.2. Selected bond lengths and angles for 2 and 3 ........................................ 198
Table 5.3. Selected bond lengths and angles for 4 and 5................................. 199
Table 5.4. Selected bond lengths and angles for 6........................................... 200
Table 5.5. Cyclic voltammetry data for 2(OTf)₃, 6(OTf)₂ and related mononuclear and dinuclear models......................................................... 201
List of Charts

Chapter 2
Chart 2.1. The phthalazine-based ligands bdptz and Ph$_4$bdptz .......................... 81
Chart 2.2. Representations of the diiron(II) cations 3 - 8 .................................... 82

Chapter 3
Chart 3.1. Representations of the active sites of Hr, sMMOH, RNR-R2, and Δ9D ... 123
Chart 3.2. The ligands BPMAN, BBAN, BEAN, and Ar$^{Tel}$CO$_2^-$ .......................... 124

Chapter 4
Chart 4.1. Representations of the active sites of sMMOH, RNR-R2, and Δ9D ....... 164
Chart 4.2. Two m-terphenyl-derived carboxylate ligands employed
for the synthesis of diiron(II) compounds ...................................................... 165

Chapter 5
Chart 5.1. The ligands bdptz and Ph$_4$bdptz ...................................................... 202
List of Schemes

Chapter 1
Scheme 1.1. Divergent reactivity of dioxygen with diiron(II) compounds supported by sterically hindered carboxylate ligands ..................37
Scheme 1.2. Oxidation reactions of TPA-derived diiron complexes ..................38

Chapter 2
Scheme 2.1. Synthesis of Ph₂bdptz ..................................................................83

Chapter 3
Scheme 3.1. Oxidative N-dealkylation of internal and external substrates effected by \([\text{Fe}_2(\text{BBAN})(\mu-\text{O}_2\text{C}^{\text{Tol}}\text{Ar})_3](\text{OTf})_2\) (4) .................................................................125

Chapter 4
Scheme 4.1. Reactions of \([\text{Fe}_2(\mu-\text{O}_2\text{CAr}^{\text{Tol}})_2(\text{O}_2\text{CAr}^{\text{Tol}}_2)(\text{THF})_2]\) (1) with nitrogen donor ligands .................................................................166
Scheme 4.2. Synthesis of BCQEB-derived ligands .............................................167

Chapter 5
Scheme 5.1. Reactivity of \([\text{Cu}_2(\text{bdptz})(\text{MeCN})_3]^{2+}\) (1) ...............................................203
List of Figures

Chapter 1

Figure 1.1. Representations of the active sites of the non-heme diiron proteins Hr, sMHOH, RNR-R2, and A9D..........................................................39

Figure 1.2. Some coordination modes of O₂ upon binding to two metal ions........40

Figure 1.3. Examples of polynuclear clusters formed with simple carboxylate ligands..............................................................................41

Figure 1.4. The XDK family of ligands and resulting bis(μ-carboxylato)-diiron(II) complexes........................................................................42

Figure 1.5. The ligand H₂Ph₄DBA and examples of two diiron(II) compounds supported by Ph₄DBA²⁻.........................................................43

Figure 1.6. Examples of sterically hindered carboxylate ligands derived from benzoic acid...........................................................................44

Figure 1.7. The phthalazine-based ligands bdptz and Ph₄bdptz.........................45

Figure 1.8. Examples of phenoxide- and alkoxide-based ligands that afford (μ-peroxo)diiron(III) compounds..................................................46

Figure 1.9. Three alkoxide- and phenoxide-based ligands that promote reversible and stepwise electrochemical reduction...............................47

Figure 1.10. 1,8-Naphthyridine-based ligands used to prepare diiron(II) compounds ....................................................................................48

Figure 1.11. Representation of the cation [Fe₂(Et₂BCQEB⁺)(μ-O₂CAr⁺)₃]⁺ (23) featuring syn disposition of nitrogen donors...........................................49

Chapter 2

Figure 2.1. ORTEP diagram of Ph₂bdptz (2) showing the 50% probability thermal ellipsoids........................................................................84
Figure 2.2. ORTEP diagrams of $[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{CCH}_3)]^2^+ (3)$ and
$[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{CC}_2\text{H}_5)]^2^+ (4)$ showing the 50% probability thermal ellipsoids. 85

Figure 2.3. ORTEP diagrams of $[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{CCH}_2\text{Ph})]^2^+ (5)$
showing the 50% probability thermal ellipsoids. 86

Figure 2.4. ORTEP diagrams of $[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{P(OPh})_2]^2^+ (7)$ and
$[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{OH})(\text{MeCN})]^2^+ (8)$ showing the 50% probability
thermal ellipsoids. 87

Figure 2.5. Mössbauer spectra for solid samples of $3(\text{OTf})_2 - 8(\text{OTf})_3$. 88

Figure 2.6. ORTEP diagram of $[\text{H}_2\text{Ph}_4\text{bdptz}]^2^+ (9)$ showing the
50% probability thermal ellipsoids. 89

Figure 2.7. Mössbauer spectrum of the product formed by reaction of
$[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{C}^\ast\text{C}_2\text{H}_5)](\text{OTf})_2 (6(\text{OTf})_2$ with $\text{O}_2$. 90

Chapter 3

Figure 3.1. ORTEP diagrams of the cations of $[\text{Fe}_2(\text{BPMAN})(\mu-\text{O}_2\text{CPh})_2](\text{OTf})_2 (1),$
$[\text{Fe}_2(\text{BPMAN})(\mu-\text{OMe})(\mu-\text{O}_2\text{Car}^{\text{Toh}})](\text{OTf})_2 (3), [\text{Fe}_2(\text{BBAN})(\mu-\text{O}_2\text{Car}^{\text{Toh}})_3](\text{OTf}) (4)$, and $[\text{Fe}_2(\text{BEAN})(\mu-\text{O}_2\text{Car}^{\text{Toh}})_3](\text{OTf}) (5)$
showing 50% probability thermal ellipsoids. 126

Figure 3.2. Mössbauer spectra for solid samples of $[\text{Fe}_2(\text{BPMAN})(\mu-\text{O}_2\text{CPh})_2](\text{OTf})_2$
(1), $[\text{Fe}_2(\text{BPMAN})(\mu-\text{OH})(\mu-\text{O}_2\text{Car}^{\text{Toh}})](\text{OTf})_2 (2), [\text{Fe}_2(\text{BPMAN})(\mu-\text{OMe})-
(\mu-\text{O}_2\text{Car}^{\text{Toh}})](\text{OTf})_2 (3)$, and $[\text{Fe}_2(\text{BBAN})(\mu-\text{O}_2\text{Car}^{\text{Toh}})_3](\text{OTf}) (4)$ 127

Figure 3.3. UV-vis spectra accompanying the reaction of $[\text{Fe}_2(\text{BPMAN})(\mu-$
$\text{O}_2\text{CPh})_2](\text{OTf})_2 (1)$ with $\text{H}_2\text{O}_2$ in MeCN at $-40 \, ^\circ\text{C}$ and Mössbauer
spectrum for a frozen MeCN solution of 1 treated with $\text{H}_2\text{O}_2$. 128
Figure 3.4. UV-vis spectra accompanying the reaction of [Fe₂(BPMAN)(μ-OH)(μ-O₂CArTol)](OTf)₂ (2) with excess O₂ in CH₂Cl₂ at room temperature and Mössbauer spectrum for the product of 2 exposed to dioxygen in CH₂Cl₂ as a solid sample................................................................. 129

Figure 3.5. X-band EPR spectrum of [Fe₂(BPMAN)(μ-OH)(μ-O₂CArTol)](OTf)₂ (2) exposed to O₂ as a frozen solution at 77 K ............................................. 130

Figure 3.6. Cyclic voltammograms of [Fe₂(BPMAN)(μ-O₂CPh)₂](OTf)₂ (1)............... 131

Figure 3.7. Cyclic voltammograms of [Fe₂(BPMAN)(μ-OH)(μ-O₂CArTol)](OTf)₂ (2).... 132

Chapter 4

Figure 4.1. ORTEP diagrams of [Fe(O₂CArTol)₂(Me₂-napy)] (2), [Fe(O₂CArTol)(vpy)₂] (4), [Fe₂(μ-O₂CArTol)₂(O₂CArTol)(vpy)₂] (5), [Fe(O₂CAr₄BuPh)₂(THF)₂] (6), and [Fe(O₂CAr₄BuPh)₂(DMP)₂] (7) showing 50% probability thermal ellipsoids .................................................. 168

Figure 4.2. Representation of [Fe₂(BQEB)(μ-OH)(μ-O₂CArTol)(O₂CArTol)₂-(THF)(H₂O)] displaying syn nitrogen donors ................................................. 169

Figure 4.3. ORTEP diagram of the cation of [Fe₂(Et₂BCQEB)(μ-O₂CArTol)₂](OTf) (15) showing 50% probability thermal ellipsoids and ball and stick diagram showing the connectivity of [Cu₂(Et₂BCQEB)(μ-I)₂] (16)........... 170

Chapter 5

Figure 5.1. Examples of [Cu₂O₂] adducts supported by multidentate dinucleating ligands ................................................................................. 204

Figure 5.2. ORTEP diagrams of [Cu₂(bdptz)₂]³⁺ (2), [Cu₂(bdptz)(μ-OH)(MeCN)₂]³⁺ (3), [Cu₂(bdptz)(μ-OH)₃]²⁺ (4), and [Cu₂(bdptz)(μ-vpy)]²⁺ (5) showing 50% probability thermal ellipsoids.................................................. 205
Figure 5.3. X-band EPR spectrum of [Cu$_5$(bdptz)$_2$](OTf)$_3$ (2(OTf)$_3$) as a frozen solution at 77 K

Figure 5.4. ORTEP diagram of [Cu$_3$(Ph$_3$bdptz)(MeCN)$_2$]$_2^+$ (6) showing 50% probability thermal ellipsoids and ball and stick representation of [Cu$_2$(Ph$_4$bdptz)(µ-O$_2$CCH$_3$)]$^+$ (7)

Figure 5.5. Cyclic voltammograms of [Cu$_5$(bdptz)$_2$](OTf)$_3$ (2(OTf)$_3$)

Figure 5.6. Cyclic voltammogram of [Cu$_5$(Ph$_3$bdptz)(MeCN)$_2$](OTf)$_2$ (6(OTf)$_2$)

Figure 5.7. Experimental and theoretical ESI-MS spectra of an oxygenated solution of 6(OTf)$_2$ in CH$_2$Cl$_2$ and a possible aromatic hydroxylation product
Chapter 1
Bio-Inspired Reactions of Diiron Centers with Dioxygen
Dimetallic Units in Nature

Dimetallic cores are ubiquitous in nature, occurring at the active sites of numerous proteins. The Lewis acidity of transition metal ions such as Zn\(^{2+}\), Co\(^{2+}\), Ni\(^{2+}\), and Mn\(^{2+}\) is harnessed by a variety of metallohydrolases to effect hydrolytic reaction chemistry,\(^1\) whereas other metalloproteins utilize the redox activity of certain metals, notably iron and copper, to bind and/or activate dioxygen. The latter chemistry occurs at non-heme diiron centers in hemerythrin (Hr),\(^2\) the hydroxylase component of soluble methane monooxygenase (sMMOH),\(^3\) the R2 subunit of ribonucleotide reductase (RNR-R2),\(^4,5\) \(\Delta 9\) desaturase (\(\Delta 9D\)),\(^6\) toluene monooxygenase (TMO),\(^7\) alkene monooxygenase,\(^8\) and phenol hydroxylase.\(^9\) The crystal structures of Hr, sMMOH, RNR-R2, and \(\Delta 9D\) have been solved and representations of their active sites are provided in Figure 1.1. Among these four metalloproteins, the active site of Hr is unique, featuring a \((\mu\text{-hydroxo})\text{bis(\mu-carboxylato)}\)diiron(II) core that is supported by five histidine residues. The dimetallic centers of sMMOH, RNR-R2, and \(\Delta 9D\), on the other hand, consist of four carboxylates from aspartate and glutamate amino acids and two histidine residues. Structural characterization of TMO, alkene monooxygenase, and phenol hydroxylase is not yet available, but other data support the presence of diiron units at their active sites. The scope of the reactions performed by non-heme diiron centers is remarkable and includes reversible binding of dioxygen (Hr), oxidation of \(\text{CH}_4\) to \(\text{CH}_3\text{OH}\) (sMMOH), generation of an essential tyrosine radical (RNR-R2), desaturation of fatty acids (\(\Delta 9D\)), oxidation of toluene to cresol (TMO), epoxidation of alkenes (alkene monooxygenase), and oxidation of phenol to catechol (phenol hydroxylase). This chemistry is mirrored in related proteins with active sites featuring two coupled copper(I) ions. Hemecyanin,\(^10\) like Hr, binds \(\text{O}_2\) reversibly, whereas activation of the O-O bond by tyrosinase\(^11,12\) and catechol oxidase\(^13\) facilitates oxidation of both mono- and di-phenols.
Binding of Dioxygen to Metal Ions

The requirement of a metal co-factor by biological systems to achieve substrate oxidation using dioxygen stems from the chemical properties of the O₂ molecule. Dioxygen is a paramagnetic species with a \((1s\sigma)^2(1s\sigma^*)^2(2s\sigma)^2(2s\sigma^*)^2(2p\pi)^4(2p\pi^*)^2\) electronic configuration. Because of its triplet ground state, the reaction of dioxygen with organic molecules, usually having paired electrons and singlet ground states, is spin forbidden. Upon formation of a metal-O₂ adduct, however, the two unpaired electrons of dioxygen interact with the d electrons of the metal ion, and a low-energy pathway permitting spin-allowed oxidation reactions is made available.

Coordination of dioxygen to two metal ions can occur by a variety of different binding modes, some of which are shown in Figure 1.2. The \(\mu-1,2\) coordination mode is proposed for the peroxy intermediates in sMMOH,\(^3\) RNR-R2,\(^4\) and \(\Delta 9\)D,\(^1\) \(2\) and further activation of the peroxide unit to afford a di(\(\mu\)-oxo)diiron(IV) species (Q) in sMMOH\(^3\) or a (\(\mu\)-oxo)diiron(III,IV) species (X) in RNR-R2\(^4\) has been observed. The terminal peroxide coordination mode was identified in Hr,\(^2\) whereas the \(\mu-\eta^2:\eta^2\) geometry has been characterized with several dicopper proteins.\(^1\)\(^0\)\(^,\)\(^1\)\(^2\)\(^,\)\(^1\)\(^3\)

Probing the Reactivity of the Diiron Core with Small Molecule Model Compounds

The important chemical transformations that occur at carboxylate-bridged diiron centers in nature have prompted the synthesis of small molecule model compounds in order to achieve this chemistry in the absence of a protein scaffold.\(^2\)\(^1\)\(^-\)\(^2\)\(^3\) Early work using facially capping tris(pyrrozolyl)borate or triazaacyclononane ligands to model Hr provided a detailed characterization of the diiron core by a variety of spectroscopic methods.\(^2\)\(^4\)\(^-\)\(^2\)\(^7\) Biomimetic activation of dioxygen by model compounds, however, requires the diiron core to be housed within a carboxylate-rich coordination sphere. Simple ligands such as acetate or benzoate frequently afford polynuclear clusters\(^2\)\(^8\) rather than discrete dinuclear units, several examples of which are represented in
Figure 1.3. This tendency has prompted the design and synthesis of more sophisticated molecules that feature a pre-organized binding unit to promote the formation of dimetallic compounds. In this introductory section, several of these ligand systems are presented and the oxidation chemistry of the resulting diiron complexes is outlined. Examination of the model compounds provides insight into strategies for future ligand design in order to prepare dimetallic cores capable of carrying out the bio-inspired chemistry.

**Pre-Organized Bis(carboxylate) Platforms**

The methyl, propyl, and benzyl derivatives of XDK, where XDK is m-xylylenediamine bis(Kemp's triacid imide), facilitate the preparation of carboxylate-bridged diiron(II) complexes (Figure 1.4). Incorporation of two additional carboxylate ligands affords compounds having the same combination of carboxylate and N-donor groups as found at the active sites of sMMOH, RNR-R2, and Δ9D. Regardless of the ancillary ligands used in the assembly of the dimetallic cores, the Fe···Fe separation is roughly constant (~3.5 Å) in this series of compounds, attesting to the rigidity conferred by the XDK platform to the diiron centers. Upon reaction with dioxygen at −78 °C, (μ-peroxo)diiron(III) intermediates are generated. The rate of formation of these species is inversely proportional to the steric demands imposed by the ancillary carboxylate ligands, suggesting that a carboxylate shift occurs at the rate-determining step, whereas the stability of the O₂-adducts is heavily dependent upon the bulk provided by the supporting XDK units. Although the peroxo species are good compositional models for the (peroxo)diiron(III) intermediates that form in the related non-heme diiron enzymes, their reactivity towards substrates differs substantially from that of the natural systems. In particular, hydrocarbon oxidation by [Fe₃(μ-O₂)(μ-PXDK)(μ-O₂CPhCy)(O₂CPhCy)(Bu-Im)] (1) appears to proceed through a radical
autoxidation pathway, in marked contrast to the selective hydroxylation chemistry that is effected by sMOMOH.\textsuperscript{34,35}

Despite extensive efforts, the ($\mu$-hydroxo)diiron(II) core of Hr could not be accessed by using the XDK ligand systems. Instead, the core features of Hr, including the hydroxide-bridge and the nearly orthogonal orientation of the carboxylate groups, were reproduced with the introduction of a bis(carboxylate) ligand derived from a dibenzofuran spacer, dibenzofuran-4,6-bis(diphenylacetic acid) (H$_2$Ph$_4$DBA).\textsuperscript{36,37} In particular, the complexes [Fe$_2$(\textit{\mu}-OH)(Ph$_4$DBA)(L)$_2$(OTf)] (Figure 1.5), where L is TMEDA (2) or dipyrrolidinoethane (3), were prepared and, in the presence of a small N-donor base, they react with dioxygen at −78 °C to generate ($\mu$-oxo)diiron(III) species bearing a terminally bound hydroperoxide unit.\textsuperscript{36,37} These intermediates thus serve as good models of oxyHr, but irreversible oxidation of the diiron core at higher temperatures thwarted attempts to generate a truly functional mimic of the protein.

**Sterically Hindered $m$-Terphenyl-Derived Carboxylate Ligands**

The steric bulk provided by the $m$-terphenyl-based carboxylate ligands Ar$^x$CO$_2^-$ ($x =$ toiyl, 4-fluorophenyl, mesityl) shown in Figure 1.6 facilitated the synthesis of carboxylate-bridged diiron(II) compounds which, like the compounds supported by the XDK family of ligands, feature the correct combination of carboxylate and N-donor groups for modeling sMOMOH, RNR-R2, and A9D.\textsuperscript{38-40} In contrast to the XDK ligands, however, the disubstituted benzoate units form flexible diiron complexes, as evidenced by the occurrence of carboxylate shifts and a wide range of inter-metal distances (≈2.7–4.4 Å). The tetra(carboxylato)diiron(II) complexes are reactive toward dioxygen, and the nature of the [Fe$_2$(O)$_2$] adduct depends upon the substituents of both the carboxylate and N-donor ligands (Scheme 1.1). The compound [Fe$_2$(\textit{\mu}-O$_2$CAr$_{10}$)$_6$(4-$^\text{Bu}$C$_6$H$_4$N)$_2$] (4) reacts with dioxygen at −78 °C to afford an approximately equimolar mixture of diiron(II,III) and diiron(III,IV) species, presumably via an unobserved peroxo
These intermediates were not seen when \([\text{Fe}_2(\mu-O_2\text{Car}^\text{Tol})_2(O_2\text{Car}^\text{Tol})_2(N,N-\text{Bn}_2\text{en})_2]\) (5) was exposed to dioxygen.\(^{39,46}\) Rather, oxidative \(N\)-dealkylation of the benzyl substituents occurred to yield \(\text{PhCHO}\) and \([\text{Fe}_2(\mu-\text{OH})_2(\mu-O_2\text{Car}^\text{Tol})(O_2\text{Car}^\text{Tol})_2(N,N-\text{Bn}_2\text{en})(N-\text{Bn}en)]\) (6), the \(\mu\)-hydroxo)(\(\mu\)-carboxylato)diiron(III) core of which was the first structural mimic of the active site of \(\text{sMMOH}_{\text{ox}}\). In contrast, reaction of dioxygen with \([\text{Fe}_2(\mu-O_2\text{Car}^{\text{Mes}})_2(O_2\text{Car}^{\text{Mes}})_2(\text{MeCN})_2]\) (7) at \(-50^\circ\text{C}\) permitted the spectroscopic detection of a symmetric \(\mu\)-peroxo)diiron(III) species.\(^{40}\) The related ligand system, \(\text{dxlCO}_2\), in which the flanking phenyl substituents are separated from the benzoate unit by methylene groups, yielded a diiron(II) compound, \([\text{Fe}_2(\mu-O_2\text{Cdxl})_4(\text{C}_x\text{H}_5\text{N})_2]\) (8), however, which reacted with dioxygen to generate an unsymmetrical peroxy species.\(^{34,47}\)

**Tris(pyridylmethyl)amine Ligands**

The preceding sections illustrate the use of specially designed, complex carboxylate ligands for modeling the aspartate and glutamate amino acid residues present at the active sites of non-heme diiron proteins. Alternatively, ligands promoting the formation of relevant \([\text{Fe}_2(\text{O})_2]\) adducts can be employed that lack chemical units found in nature and are used in conjunction with oxidants other than molecular oxygen. This approach allows the reactivity of the diiron cores to be explored, without delineating the factors necessary to access the peroxy or high-valent species in the related biological systems. In this category are ligands derived from tris(pyridylmethyl)amine (TPA), a family of tetradentate N-donors that facilitate the formation of diiron species, the dinuclear cores and reactivity of which are relevant to the metalloenzymes of interest.

The \(\mu\)-hydroxo)diiron(II) core in \([\text{Fe}_2(\mu-\text{OH})_2(6-\text{Me}_3-\text{TPA})_2]\)(\text{ClO}_4)_2 (9) reacts with dioxygen at \(-40^\circ\text{C}\) to afford a diiron(III) peroxy intermediate which, in the presence of \(\text{HClO}_4\), slowly decays to a diiron(III,IV) species that oxidizes 2,4,5-tri-tert-
butylphenol to the phenoxy radical (Scheme 1.2).\textsuperscript{48} Compound 9 thus mimics the dioxygen activation and tyrosine radical generation steps proposed for RNR-R2. Similarly, addition of \( \text{H}_2\text{O}_2 \) at \(-40\) °C to \([\text{Fe}_2(\mu-\text{O})_2(6-\text{Me}_3\text{-TPA})_2]\text{[ClO}_4\text{]}_2 \) (10) affords a metastable diiron(III,IV) species by decomposition of a peroxo intermediate.\textsuperscript{49} This mixed-valent intermediate was also generated by one-electron oxidation of 10 with \((\text{Bu}_4\text{N})_2\text{Ce(NO}_3\text{)}_6\).\textsuperscript{50} Sufficient stability was imparted to the di(\(\mu\)-oxo)diiron(III,IV) intermediate with the 5-\text{Et}_3\text{-TPA analogue to permit crystallographic characterization, providing important metrical parameters for the high-valent \{\text{Fe}_2(\mu-\text{O})_2\}_3^{3+} \) core.\textsuperscript{51} Reactivity studies using the unsubstituted TPA derivative revealed that, in addition to \( \text{O}-\text{H} \) activation, the diiron(III,IV) species also oxidizes cumene and ethylbenzene, effecting both hydroxylation and desaturation chemistry.\textsuperscript{52} Oxidation of substrates with stronger C–H bonds was not observed, probably a consequence of having the \( \text{Fe}_2(\text{III,IV}) \) rather than the \( \text{Fe}_2(\text{IV,IV}) \) oxidation state.

**Multidentate Dinucleating Ligand Frameworks**

In the absence of a strongly dinucleating ligand, the species responsible for the observed chemistry can be difficult to identify unambiguously. For example, isolation of a diiron complex, the nuclearity of which is determined by X-ray crystallographic methods, could result from the concentrated conditions necessary for crystallization and not reflect the true nature of the compound in dilute solution. Furthermore, oxidation of a dinuclear compound may result in dissociation of the core to afford highly reactive monomers as the active oxidants. Multidentate ligand frameworks have, therefore, been developed both to stabilize and to maintain the nuclearity of dioxygen adducts. Presented in this section are several ligand systems that have been employed to enforce diiron cores in this manner.

**Phthalazine Derivatives.** Multidentate ligands derived from phthalazine have been successfully used to prepare diiron(II) compounds. The ligands bdptz\textsuperscript{34,53} and its
sterically hindered derivative, Ph₄bdptz, provide nitrogen-rich frameworks for the assembly of carboxylate-bridged diiron cores (Figure 1.7). Depending upon the steric bulk of the ancillary carboxylate ligands, oxidation of the bdptz derivatives afforded either oxo-bridged diiron(III) or (µ-oxo),Fe₄(III) species, whereas the steric bulk provided by the phenyl substituents of Ph₄bdptz was sufficient to prevent the formation of such high-nuclearity oxidation products. Although the dimetallic core was stabilized with Ph₄bdptz, no peroxo or high-valent intermediates were detected, suggesting that the phthalazine fragment does not offer sufficient flexibility to accommodate relevant [Fe₂(O₂)]⁴⁺ species.

**Phenoxide- and Alkoxide-Based Ligands.** Adequate structural flexibility of diiron cores is provided by phenoxo- and alkoxo-based ligands, and the facile synthesis of these molecules makes them an accessible and readily tuned scaffold. Two of the three crystallographically characterized (µ-peroxo)diiron(III) compounds, [Fe₂(Ph-bimp)(µ-O₂CPh)(µ-O₂)](BF₄)₂ (11) and [Fe₂(N-Et-hptb)(µ-O₂)(OPPh₃)₂](BF₄)₃ (12), are supported by multidentate ligands based on phenoxide or alkoxide spacers (Figure 1.8). The formation of 11 is reversible, as evidenced by loss of the peroxo moiety upon boiling in MeCN solution under a N₂ atmosphere and subsequent regeneration of the O₂-adduct following exposure to dioxygen. Other phenoxide- and alkoxide-based ligands stabilize diiron cores in a variety of oxidation states, an important feature for modeling non-heme diiron proteins. The diiron(III) compounds [Fe₂L₁²] (13), [Fe₂L₃²] (14), and [Fe₂(salmp)₂] (15), shown in Figure 1.9, display cyclic voltammograms attributed to reversible, stepwise reduction to Fe³⁺Fe²⁺ and Fe³⁺Fe²⁺ species, and compounds with all three oxidation states were crystallographically characterized using the salmp ligand.

**1,8-Naphthyridine as a Bridging Unit.** In contrast to the single atom bridge provided by phenoxide- and alkoxide-derived ligands, the µ-1,3 coordination to two metal ions by the 1,8-naphthyridine unit is analogous to the bidentate mode of bridging
carboxylate groups. The naphthyridine moiety is, therefore, considered to be a “masked carboxylate.” Multidentate ligands derived from this spacer have been used to model the active sites of carboxylate-bridged metalloproteins. In particular, the ligands shown in Figure 1.10 were employed to assemble and study the oxidation of diiron(II) compounds. The complexes [Fe₂(BPMAN)(µ-O₂CPhC₅H₄)]₂(OTf)₂ (16) and [Fe₂(BPMAN)(µ-O₂CPhC₅H₄)](OTf)₂ (17) exhibit reversible cyclic voltammograms, in which both the Fe³⁺Fe II/Fe²⁺Fe II and Fe³⁺Fe III/Fe²⁺Fe II redox couples are evident. A single atom bridging ligand is therefore not necessary to facilitate this electrochemistry. In contrast, a diiron(II) compound supported by the hexadentate ligand BBBAN displayed irreversible electrochemical oxidation, indicating that the higher denticity provided by BPMAN is better able to stabilize diiron cores in multiple oxidation states.

The ancillary ligands of the complexes also play an important role in the observed oxidation chemistry. For example, 17 reacts with dioxygen or H₂O₂ to form a (µ-oxo)diiron(III) compound without the detection of any intermediate species, whereas reaction of [Fe₂(BPMAN)(µ-OH)(µ-O₂CAr Tol)](OTf)₂ (18) with dioxygen affords a mixed-valent (µ-oxo)diiron(II,III) intermediate that decomposes to a (µ-oxo)diiron(III) product. Good spectroscopic models of Hr were generated by reaction of [Fe₂(BPEAN)(µ-OH)(OTf)](OTf)₂ (19) and [Fe₂(BEPEAN)(µ-OH)](OTf)₃ (20) with H₂O₂ at low temperature, both forming oxo-bridged diiron(III) intermediates with a terminally bound hydroperoxide unit. On the other hand, [Fe₂(BBAN)(µ-O₂CAr Tol)](OTf) (21) effected oxidative N-dealkylation of a pendant benzyl substituent, similar to the reactivity of 6. These findings indicate that C–H bond activation can be achieved by positioning substrates suitably close to the diiron core, and suggest a strategy for promoting this chemistry. As expected for the stronger C–H bonds of ethyl groups, no oxidation of the ligand fragment occurred with [Fe₂(BEAN)(µ-O₂CAr Tol)](OTf) (22).

**1,2-Diethylnylbenzene as a Spacer.** In addition to stabilizing dimetallic centers, multidentate ligand platforms also facilitate the incorporation of geometric features that
are difficult to enforce by using self-assembly methods. For example, the two histidine residues at the active sites of sMMOH, RNR-R2, and Δ9β are bound in a syn fashion, on the same side of the Fe···Fe vector. In contrast, the [Fe₂(O₂CR)₄(N)₂] cores afforded by spontaneous self-assembly of the XDK or sterically hindered terphenyl-derived carboxylate ligands invariably feature anti coordination of the N-donors. The ligand Et₂BCQEB³⁻ was designed to model the correct orientation of the nitrogen groups in a dinucleating platform and facilitates the synthesis of [Fe₂(Et₂BCQEB³⁻)(µ-O₂CAr²d)₃](OTf) (23) (Figure 1.11). In addition to enforcing the desired N-donor geometry, the BCQEB framework is structurally flexible, as evidenced by the range of M···M and N···N distances (~1 and 0.6 Å, respectively) accommodated in complexes derived from Et₂BCQEB³⁻. Both of these features are emerging as key requirements for preparing functional model compounds of non-heme diiron enzymes.

Perspectives and Implications for Future Work

The ligand systems outlined here highlight both the advances and challenges of modeling carboxylate-bridged non-heme diiron proteins with small molecule synthetic compounds. Adequate flexibility of the dimetallic fragment is of central importance to ensure the success of this endeavor, whether provided by a carboxylate group or other dinucleating unit. Sufficient steric hindrance afforded by the ligand sphere is necessary to prevent undesired bimolecular reactions, but this bulk cannot restrict the approach of dioxygen or substrates to the diiron core. The dimetallic center must support multiple oxidation states in order to mimic the chemistry of the metalloproteins, and the ligand environment should promote relatively low redox potentials to permit facile reaction with dioxygen. Ligand scaffolds that promote some, but not all, of these properties may be better suited to modeling the chemistry of metallohydrodrolases.

Relatively minor ligand perturbations dramatically influence the reactivity of diiron compounds, implying that a modular ligand design is well suited to delineating
the effects of electronic and steric factors upon the resulting chemistry. Metalloproteins display extensive hydrogen-bonding networks, a feature that has been reproduced in mononuclear\textsuperscript{67,68} and porphyrin-based iron(II) model systems.\textsuperscript{69,70} Incorporation of either hydrogen donors or acceptors into a dinucleating platform could offer significant insight into the role of the secondary coordination sphere in the binding and activation of dioxygen, as well as in the positioning of substrates. Because addition of steric hindrance to a ligand system is often at the expense of accessibility to the diiron core by oxidants and/or substrates, a balance might be achieved by encapsulation of the complexes in a solid support, similar to the site isolation of diiron units using dendrimers that was reported recently.\textsuperscript{71} To achieve C–H bond activation, oxidation of appended substrates or relatively compact organic molecules highlights the importance of ensuring that the diiron cores are accessible to external substrates. The design of a binding pocket or substrate access channel into the ligand framework may be an effective strategy for achieving this goal efficiently and, ultimately, in a catalytic fashion.

Acknowledgements. Work in our laboratory presented here has been supported over the years by grants from the National Science Foundation and the National Institutes of Health.
References


(34) Abbreviations used: PhCyCO$_2^-$ = 1-phenylcyclohexanecarboxylate; dxlCO$_2^-$ = 2,6-bis[(2,6-dimethylphenyl)methyl]-4-tert-butylbenzoic acid; bdptz = 1,4-bis(2,2'-...
dipyridylmethyl)phthalazine; Ph$_2$bdptz = 1,4-bis[bis(6-phenyl-2-pyridyl)methyl]-phthalazine; Ph-bimp = 2,6-bis[bis[2-(1-methyl-4,5-diphenylimidazolyl)methyl]aminomethyl]-4-methylphenolate; N-Et-hptb = N,N,N,'N'-tetrakis[2'-(1'-ethylbenzimidazolyl)]-1,3-diamino-2-hydroxypropane; L$_1$ = 1,3-bis(salicylideneamino)propan-2-ol; L$_3$ = 4-methyl-2,6-bis(salicylideneaminomethyl)phenol; salmp = 2-bis(salicylideneamino)phenymethylphenolate; BPMAN = 2,7-bis[bis(2-pyridylmethyl)aminomethyl]-1,8-naphthyridine; BBNAN = 2,7-bis[2-[2-(1-methyl)benzimidazolylethyl]-N-benzylaminomethyl]-1,8-naphthyridine; BPEAN = 2,7-bis[bis[2-(2-pyridyl)ethyl]aminomethyl]-1,8-naphthyridine; BEPEAN = 2,7-bis[bis[2-(2-(5-ethyl)pyridyl)ethyl]aminomethyl]-1,8-naphthyridine; BBAN = 2,7-bis(N,N-diubenzyl-aminomethyl)-1,8-naphthyridine; BEAN = 2,7-bis(N,N-diethylaminomethyl)-1,8-naphthyridine; Et$_3$BCQEB$_{Et}^+$ = 1,2-bis(3-ethynyl-8-carboxylatequinolino)benzene ethyl ester.


(64) Carson, E. H.; Lippard, S. J. Unpublished results.


Scheme 1.1.
Scheme 1.2.
Figure 1.1. Representations of the active sites of the non-heme diiron proteins Hr, sMMOH, RNR-R2, and Δ9D.
Figure 1.2. Some coordination modes of O$_2$ upon binding to two metal ions.
Figure 1.3. Examples of polynuclear clusters formed with simple carboxylate ligands.
Figure 1.4. The XDK family of ligands and resulting bis(μ-carboxylato)diiron(II) complexes.
Figure 1.5. The ligand $\text{H}_2\text{Ph}_4\text{DBA}$ and examples of two diiron(II) compounds supported by $\text{Ph}_4\text{DBA}^2$. 
Figure 1.6. Examples of sterically hindered carboxylate ligands derived from benzoic acid.
Figure 1.7. The phthalazine-based ligands bdptz and Ph₄bdptz.
Figure 1.8. Examples of phenoxide- and alkoxide-based ligands that afford crystallographically-characterized (μ-peroxo)diiron(III) compounds.
Figure 1.9. Three alkoxide- and phenoxide-based ligands that support diiron(III) compounds exhibiting reversible, stepwise electrochemical reduction to Fe^{III}Fe^{II} and Fe^{II}Fe^{II} species.
Figure 1.10. 1,8-Naphthyridine-based ligands used to prepare diiron(II) compounds.
Figure 1.11. Representation of the cation $[\text{Fe}_2(\text{Et}_2\text{BCQEB}^3)(\mu-\text{O}_2\text{C}_{\text{Tol}})_3]^+$ (23) featuring syn disposition of nitrogen donors.
Chapter 2

Carboxylate, Phosphodiester, and Hydroxide-Bridged Diiiron(II)
Complexes with a Sterically Hindered Phthalazine Ligand*
Introduction

Carboxylate-bridged diiron centers occur at the active sites of a variety of non-heme proteins and enzymes that interact with dioxygen.\textsuperscript{1-4} Important members of this class of proteins include hemerytin (Hr), the R2 subunit of ribonucleotide reductase (RNR-R2), \( \Delta-9 \) desaturase (\( \Delta 9D \)), and the hydroxylase component of soluble methane monooxygenase (sMMOH). Although these metalloproteins share common structural features, the chemistry that occurs at their active sites varies significantly. Whereas Hr is a dioxygen transport protein that reversibly binds molecular oxygen,\textsuperscript{5} the other members of this family of proteins activate dioxygen. The diiron center in RNR-R2, responsible for the first committed step in DNA biosynthesis, forms an essential tyrosine radical.\textsuperscript{6,7} \( \Delta 9D \) introduces a double bond into a saturated fatty acid,\textsuperscript{8,9} and sMMOH places an oxygen atom into the C–H bond of a variety of exogenous substrates, the most biologically relevant of which is methane.\textsuperscript{10,11}

The desire to understand the factors that relate structure and function of these metalloenzymes has inspired and motivated the synthesis of small molecule models containing the (\( \mu \)-carboxylato)diiron(II) structural motif.\textsuperscript{1} Numerous coordination compounds have been prepared using carboxylate ligands to bridge two iron centers. The synthesis of such compounds, however, often relies upon self-assembly and can lead to unpredictable and undesired product formation, such as mononuclear species\textsuperscript{12-14} and oligomers.\textsuperscript{15-19}

In an effort to control more effectively the composition of dinuclear compounds, the bridging carboxylate unit can be replaced by other chemical groups capable of coordinating two metal ions. Ligands derived from the derivatization of phenol,\textsuperscript{20-32} pyrazole,\textsuperscript{33-37} naphthyridine,\textsuperscript{26,38-40} pyridazine,\textsuperscript{41-47} and phthalazine\textsuperscript{45,48-52} have been utilized to prepare discrete dinuclear species with biologically-relevant transition metals. In general, these ligands consist of an O- or N-derived spacer to which various pendant arms are attached. This approach allows two metal ions to be brought into
close proximity by the dinucleating spacer, and the donor arms of the ligand coordinate to the metal centers to produce predictable and well-defined structures. In addition, the ligands often leave several coordination sites on the metal ions available for coordination by ancillary ligands, solvent molecules, and substrates.

Previously, our laboratory successfully exploited the dinucleating ability of phthalazine through the preparation of the hexadentate ligand bdptz, where \( \text{bdptz} = 1,4\text{-bis}(2,2'\text{-dipyridylmethyl})\text{phthalazine} \) (Chart 2.1).\(^{48}\) This ligand readily forms dinuclear compounds with nickel, zinc, manganese, copper and iron.\(^{48,53-55}\) Diiron(II) complexes with bridging carboxylate units typically react with dioxygen to yield iron(III) species, the nuclearity of which depends upon the steric bulk of the carboxylate. When a sufficiently large carboxylate such as 2,6-di(p-tolyl)benzoate \( (\text{Ar}^\text{TolCO}_2^-) \) is employed, a \((\mu\text{-oxo})\text{diiron(III)}\) compound results.\(^{53}\) On the other hand, the use of sterically undemanding ligands such as acetate leads to the formation of tetranuclear iron(III) complexes, in which two \((\mu\text{-oxo})\text{diiron(III)}\) units are bridged by additional oxo ligands.\(^{56}\) A possible mechanism of formation of the Fe\(_4\) complex could involve a transient diiron(III) peroxy intermediate which, upon dimerization, collapses to the isolated tetranuclear compound.\(^{57}\) It occurred to us that the incorporation of steric bulk at the pyridine rings of bdptz might prevent the formation of such higher-nuclearity species, and possibly allow for the detection of the postulated diiron(III) peroxy or high-valent intermediates.

In this report, the synthesis of the ligand \( \text{Ph}_4\text{bdptz} \), where \( \text{Ph}_4\text{bdptz} = 1,4\text{-bis[bis(6-phenyl-2-pyridyl)methyl]phthalazine} \), is presented (Chart 2.1). This ligand was used to prepare a series of \((\mu\text{-carboxylato})\text{diiron(II)}\) complexes. The synthesis and structural characterization of the compounds \([\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu\text{-O}_2\text{CR})_2]^{2+} \) \((\text{R} = \text{CH}_3 \text{ (3); C}_2\text{H}_5 \text{ (4); CH}_2\text{Ph} \text{ (5); t-C}_4\text{H}_9 \text{ (6)})\) is discussed. The preparation and crystallographic characterization of the bis\((\mu\text{-phosphato})\) complex \([\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu\text{-O}_2\text{P(OPh)}_3)_2]^{2+} \) (7) and the hydroxide-bridged compound \([\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu\text{-OH})(\text{MeCN})_2]^{3+} \) (8) is also
described. Mössbauer spectra of the diiron(II) compounds are presented and a trend, related to the symmetry of the carboxylate coordination mode, is evident in the derived parameters. The dioxygen reactivity of these complexes is discussed.

Experimental

**General Procedures.** Dichloromethane and acetonitrile were distilled over CaH₂ under nitrogen. Diethyl ether and tetrahydrofuran were saturated with nitrogen and purified by passing over a column of activated Al₂O₃ under nitrogen. The compounds Fe(OTf)₂2MeCN, 2-amino-6-phenylpyridine, 2-bromo-6-phenylpyridine, and 2-methyl-6-phenylpyridine were prepared according to published literature procedures. All other reagents were purchased from commercial sources and used as received. All manipulations of the air-sensitive iron(II) compounds were performed by using standard Schlenk techniques or under nitrogen in a Vacuum Atmospheres or MBraun glovebox. Crystalline samples of the diiron(II) compounds were pulverized and heated in vacuo prior to elemental analysis, and the validity of solvent inclusion in samples of 4 – 6 was verified by the detection of CH₂Cl₂ in the ¹H NMR spectra of these compounds.

**Bis(6-phenyl-2-pyridyl)methane (I).** To a solution of 2-methyl-6-phenylpyridine (6.5 g, 39 mmol) in dry Et₂O (20 mL), cooled to 0 °C in an ice-water bath, was added a solution of 1.6 M n-BuLi (25 mL, 40 mmol), and the resulting dark deep red solution was stirred for 5 – 10 min. Separately, 2-bromo-6-phenylpyridine (4.5 g, 19 mmol) was dissolved in dry Et₂O (50 mL) and slowly added to the lithiated solution via cannula, after which time the dark red suspension was refluxed overnight. The solution was then cooled to room temperature and poured onto ice (50 mL). The yellow solution was extracted with Et₂O (3 x 25 mL) and the combined organic layers were dried over MgSO₄, filtered, and the solvent was removed by rotary evaporation. Fractional vacuum distillation of the resulting material yielded a viscous orange-yellow oil with a
boiling point of 210 – 240 °C (0.1 Torr). To this oil was added hexanes (20 mL) and the mixture was brought to a boil. Upon cooling in a −20 °C freezer, 1 precipitated and was isolated as a pale cream-colored solid (3.3 g, 53%). $^1$H NMR (300 MHz, CDCl₃) δ: 8.05 (m, 4H), 7.70 – 7.35 (m, 10H), 7.28 (m, 2H), 4.50 (s, 2H). M.p., 86 – 88 °C.

1,4-Bis[bis(6-phenyl-2-pyridyl)methyl]phthalazine (Ph₄bdptz, 2). A dry flask, charged with 1 (4.2 g, 13 mmol) and freshly distilled THF (50 mL), was cooled to 0 °C and a 2.5 M solution of n-BuLi (5.7 mL, 14 mmol) was added dropwise. The resulting deep red solution was stirred at 0 °C for 15 min. Separately, 1,4-dichlorophthalazine (1.3 g, 6.5 mmol) was dissolved in freshly distilled THF (20 mL) and slowly added to the lithiated solution via cannula. The reaction mixture was stirred at room temperature for 1 h, followed by the careful addition of H₂O (~5 mL) to quench the reaction. The resulting orange-yellow solution was extracted with CH₂Cl₂ (3 x 50 mL) and the combined organic layers were dried over MgSO₄, filtered, and the solvent removed under vacuum to yield an oily orange solid. Recrystallization twice from CH₂Cl₂/Et₂O yielded Ph₄bdptz as a pale yellow solid (2.9 g, 58%). X-ray quality crystals of 2·CH₂Cl₂ were obtained by following the same procedure. $^1$H NMR (300 MHz, CDCl₃) δ: 8.40 (m, 2H), 7.90 (m, 8H), 7.65 (m, 10H), 7.38 (m, 16H), 7.0 (s, 2H). $^{13}$C NMR (100 MHz, CDCl₃) δ: 160.31, 159.54, 156.58, 139.57, 137.19, 131.71, 128.87, 128.72, 127.11, 126.96, 125.88, 123.52, 118.55, 60.58. IR (cm⁻¹, KBr pellet): 1589 (m), 1564 (s), 1497 (w), 1446 (s), 1358 (w), 1180 (w), 1156 (w), 1095 (w), 1026 (w), 989 (w), 821 (w), 806 (w), 758 (s), 694 (m), 624 (w), 582 (w). M.p., 137 – 143 °C (dec).

$[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{CCH}_3)_2](\text{OTf})_2$ (3(OTf)_2). To a colorless solution of Fe(OTf)_2·2MeCN (170 mg, 0.39 mmol) in MeCN (6 mL) was added solid Ph₄bdptz (150 mg, 0.195 mmol). Vigorous stirring effected dissolution within several min to yield a pale orange solution. Solid NaO₂CCH₃ (32 mg, 0.39 mmol) was added and the resulting red-orange solution was stirred for 2 h, followed by removal of the solvent under reduced pressure. The orange residue was dissolved in CH₂Cl₂ and filtered through a
plug of Celite. Exposure of this solution to Et₂O vapor diffusion yielded orange-red X-ray quality crystals 3(OTf)₂·2.5CH₂Cl₂ (193 mg, 76%). IR (cm⁻¹, KBr pellet): 1581 (s), 1563 (s), 1453 (s), 1359 (w), 1282 (s), 1256 (s), 1224 (m), 1154 (m), 1030 (s), 765 (m), 702 (m), 638 (s), 573 (w), 517 (w). Anal. Calcd for C₅₀H₄₄N₆O₁₆F₁₆S₂Fe₂: C, 55.48; H, 3.41; N, 6.47. Found: C, 55.26; H, 3.31; N, 6.43.

[Fe₂(Ph₄bdptz)(μ-O₂CC₂H₅)₂](OTf)₂ (4(OTf)₂). To a solution of Fe(OTf)₂·2MeCN (113 mg, 0.26 mmol) in MeCN (4 mL) was added solid Ph₄bdptz (100 mg, 0.13 mmol). Solid NaO₂CC₂H₅ (25 mg, 0.26 mmol) was added to the resulting pale orange solution and the mixture was stirred vigorously for 2 h to generate a red-orange solution. The solvent was removed under reduced pressure, and the residue was dissolved in CH₂Cl₂ and filtered through a plug of Celite. Exposure of this solution to Et₂O vapor diffusion yielded an orange microcrystalline solid (112 mg, 65%). X-ray quality crystals of the BPh₄ salt, 4(BPh₄)₂·2.5MeCN·0.5Et₂O, were obtained from the reaction of 4(OTf)₂ with 2.2 equiv of NaBPh₄ in MeCN, followed by exposure of the solution to Et₂O vapor diffusion. IR (cm⁻¹, KBr pellet): 1606 (m), 1562 (s), 1453 (s), 1367 (w), 1283, (s) 1257 (s), 1224 (m), 1149 (m), 1031 (s), 825 (w), 814 (m), 785 (w), 767 (s), 732 (m), 702 (s), 638 (s), 572 (w), 516 (m). Anal. Calcd for C₆₂H₄₃N₆O₁₅F₁₆S₂Cl₀.₅Fe₂ (4(OTf)₂·0.25CH₂Cl₂): C, 55.46; H, 3.63, N, 6.23. Found: C, 55.17; H, 3.76, N, 6.40.

[Fe₂(Ph₄bdptz)(μ-O₂CC₂Ph₂)₂](OTf)₂ (5(OTf)₂). To a solution of Fe(OTf)₂·2MeCN (68 mg, 0.16 mmol) in MeCN (4 mL) was added solid Ph₄bdptz (60 mg, 0.078 mmol) and the mixture was stirred to produce a pale orange solution. Separately, HO₂CC₂Ph (21 mg, 0.16 mmol) and NEt₃ (22 µL, 0.16 mmol) were dissolved in THF (2 mL) and dropwise added to the MeCN solution. After 2 h of vigorous stirring, the solvent was removed from the red-orange solution under reduced pressure. The solid residue was dissolved in CH₂Cl₂ and filtered through a small plug of Celite. Orange-red X-ray quality crystals of 5(OTf)₂·2CH₂Cl₂ were grown by Et₂O vapor diffusion into this solution (79 mg, 70%). IR (cm⁻¹, KBr pellet): 1593 (s), 1561 (s), 1458 (s), 1407 (m), 1364
(w), 1256 (s), 1224 (m), 1148 (m), 1030 (s), 813 (w), 768 (m), 731 (m), 700 (m), 637 (s), 516 (m). Anal. Calcd for C_{72.75}H_{53.5}N_{6}O_{10}F_{6}S_{2}Cl_{2.5}Fe_{2} (5(OTf)_{2}·0.75CH_{2}Cl_{2}): C, 57.69; H, 3.56; N, 5.55. Found: C, 57.87; H, 3.79; N, 5.63.

[Fe₂(Ph₄bdptz)(μ-O₂C'C₄H₉)₂](OTf)₂ (6(OTf)₂). To a stirred solution of Fe(OTf)₂·2MeCN (340 mg, 0.78 mmol) in MeCN (6 mL) was added solid Ph₄bdptz (300 mg, 0.39 mmol). Separately, HO₂C'C₄H₉ (80 mg, 0.78 mmol) and NEt₃ (112 µL, 0.78 mmol) were combined in MeCN (4 mL) and added dropwise to the orange solution. An orange precipitate formed several min after addition of the pivalate solution. Following 2 h of stirring, the solvent was removed under reduced pressure. The residue was dissolved in CH₂Cl₂, filtered through a plug of Celite, and exposed to Et₂O vapor diffusion to yield 6(OTf)₂ as an orange-red microcrystalline solid (424 mg, 79%). IR (cm⁻¹, KBr pellet): 1561 (s), 1483 (w), 1458 (m), 1421 (w), 1364 (w), 1277 (s), 1224 (m), 1155 (m), 1030 (s), 814 (w), 766 (m), 700 (m), 638 (s), 573 (w), 517 (w). Anal. Calcd for C_{67.5}H_{59}N_{6}O_{10}F_{6}S_{2}Cl_{3}Fe₂ (6(OTf)₂·1.5CH₂Cl₂): C, 53.68; H, 3.94; 5.56. Found: C, 53.69; H, 3.94; N, 5.81.

[Fe₂(Ph₄bdptz)(μ-O₂P(OPh)₃)₂](OTf)₂ (7(OTf)₂). The same procedure was followed as described for the synthesis of 6(OTf)₂ except that HO₂P(OPh)₃ was used in place of HO₂C'C₄H₉. Orange-red X-ray quality crystals of 7(OTf)₂ were grown from a solution of CH₂Cl₂ and Et₂O. IR (cm⁻¹, KBr pellet): 1595 (m), 1562 (m), 1451 (s), 1438 (m), 1360 (w), 1275 (s), 1257 (s), 1222 (m), 1164 (s), 1138 (s), 1030 (s), 764 (s), 728 (m), 701 (m), 637 (s), 558 (s), 515 (m). Anal. Calcd for C_{80}H_{60}N_{6}O_{14}F_{6}P₃S₂Fe₂: C, 57.23; H, 3.48; N, 5.00. Found: C, 57.13; H, 3.72; N, 5.12.

[Fe₂(Ph₄bdptz)(μ-OH)(MeCN)₂](OTf)₃ (8(OTf)₃). To a colorless solution of Fe(OTf)₂·2MeCN (121 mg, 0.28 mmol) in MeCN (6 mL) was added solid Ph₄bdptz (107 mg, 0.14 mmol), and the light orange solution was stirred for 20 min. Portions of NEt₃ (19.5 µL, 0.14 mmol) and H₂O (2.5 µL, 0.14 mmol) were added to yield a dark orange solution. The solvent volume was reduced under vacuum, and exposure of the resulting
solution to Et₂O vapor diffusion yielded X-ray quality crystals of 8(OTf)₃·3.5MeCN. IR (cm⁻¹, KBr pellet): 3430 (w, br), 3085 (w), 2932 (w), 1607 (m), 1597 (m), 1581 (w), 1563 (m), 1500 (w), 1455 (m), 1373 (m), 1263 (s), 1223 (m), 1151 (m), 1030 (s), 819 (m), 765 (m), 704 (m), 681 (w), 637 (s), 572 (m), 516 (m). Anal. Calcd for C₆₁H₄₅N₈O₁₀F₂S₂Fe₂: C, 51.27; H, 3.17; N, 7.84. Found: C, 51.13; H, 3.33; N, 7.67.

**Reaction of 3(OTf)₂ with Dioxygen to Yield [H₂Ph₂bdptzl(OTf)₂] (9(OTf)₂).** A solution of 3(OTf)₂ (40 mg, 0.031 mmol) in CH₂Cl₂ (5 mL) was stirred overnight under an O₂ atmosphere. A brown precipitate was removed by filtration through a plug of Celite. X-ray quality crystals of 9(OTf)₂·H₂O (16 mg, 49%) were obtained from vapor diffusion of Et₂O into the resulting pale green filtrate. IR (cm⁻¹, KBr pellet): 3062 (w), 1626 (m), 1564 (w), 1448 (w), 1270 (s), 1261 (s), 1159 (m), 1042 (m), 1030 (m), 760 (m), 695 (w), 637 (m), 573 (w), 516 (w). ESI-MS (+m/z): Calcd for (M – H – 2OTf)⁺, 771.32; Found 771.32.

**Physical Measurements.** ¹H NMR spectra were obtained on a 300 MHz Varian Unity or Mercury spectrometer, and ¹³C NMR spectra were recorded with a Bruker Avance (DPX) 400 spectrometer. FT-IR spectra were measured on a Bio-Rad FTS 135 instrument running Win-IR software. Melting points were determined by using a Thomas Hoover capillary melting point apparatus. Mössbauer spectra were recorded at 4.2 K in the MIT Department of Chemistry Instrumentation Facility on an MS1 spectrometer (WEB Research Co.) with a ⁵⁷Co source in a Rh matrix at room temperature, and fit to Lorentzian line shapes by using the WMOSS plot and fit program. Isomer shifts were referenced to natural abundance Fe at room temperature. Samples of the triflate salts of 3 – 8 were prepared by suspending powdered material (~0.04 mmol) in Apiezon N grease and placing the mixture in a nylon sample holder. A sample of the oxidation product of 6(OTf)₂ was prepared by gently purging a slurry of the diiron(II) compound and BN in CH₂Cl₂ with dioxygen, followed by removal of the
solvent under reduced pressure. The residue was then transferred to the nylon sample holder.

**X-ray Crystallography.** Crystals were mounted in Paratone N oil on the ends of glass capillaries and frozen into place under a low-temperature nitrogen cold stream. Data were collected on a Bruker (formerly Siemens) SMART (2 − 7, 9) or APEX (8) CCD X-ray diffractometer running the SMART software package, with Mo Kα radiation (λ = 0.71073 Å). Details of the data collection and reduction protocols are described elsewhere. The structures were solved by direct methods and refined on \( F^2 \) by using the SHELXTL program package. Empirical absorption corrections were applied by using the SADABS program, and the possibility of higher symmetry was checked by the program PLATON. All non-hydrogen atoms were located and their positions refined by least-squares cycles and Fourier syntheses. Hydrogen atoms were assigned idealized positions and given a thermal parameter 1.2 times the thermal parameter of the carbon atom to which each was attached.

In the structure of 2, one chlorine atom of the dichloromethane solvent molecule was disordered over two positions and refined to occupancies of 75% and 25%. The structure of 3 contains two fully occupied and one half-occupied (isotropic refinement) dichloromethane solvent molecules in the lattice. Three acetonitrile solvent molecules were found in the lattice of structure 4. Two of the molecules were refined with full occupancy and one with 50% occupancy (isotropic refinement). A partially occupied molecule of diethyl ether was also refined isotropically with 50% occupancy. Two oxygen atoms in one of the phenylacetate ligands in structure 5 were disordered over two positions, and refined with occupancies of 75% and 25%. Five acetonitrile solvent molecules were found in structure 8, two of which were refined with full occupancy and three with 50% occupancy. The \(-SO_3^-\) unit of one triflate counterion was disordered over two positions and refined with occupancies of 65 and 35%. Two of the fluorine atoms of this triflate were also disordered over two positions and each was refined with
50% occupancy. The structure of 9 contained two half-occupied water molecules. Crystallographic information is provided in Tables 2.1 and 2.2.

**Results and Discussion**

**Design of a Sterically Hindered Ligand.** Our approach to increasing the steric bulk of the bdptz ligand was to functionalize the pyridine rings. With the goal of maximizing steric hindrance in order to prevent the formation of tetrinuclear species, it was clear that the placement of the bulk would be most effective in positions ortho to the nitrogen atoms of the pyridine rings. By examination of CPK models, it was uncertain whether the incorporation of simple alkyl substituents such as methyl or ethyl would suffice. The introduction of either isopropyl groups or phenyl rings, however, appeared promising. For ease of synthesis, we chose to prepare and evaluate the phenyl derivative. The rigidity of the aromatic rings, coupled with their significant bulk, minimized the likelihood of dimerization. In addition, the CPK model indicated that the phenyl rings would form a pocket around the coordinated metal ions, a feature that could facilitate substrate activation. Furthermore, the presence of a large number of aromatic rings was expected to increase the solubility of compounds containing this ligand in a variety of organic solvents, as well as to improve their crystallinity.

**Synthesis and Structural Characterization of the Ligand Ph,bdptz.** The ligand Ph,bdptz was synthesized in five steps, as shown in Scheme 2.1, starting from commercially available 2-phenylpyridine. Following published procedures, reaction of 2-phenylpyridine with NaNH₂ yielded 2-amino-6-phenylpyridine, which was converted to 2-bromo-6-phenylpyridine by treatment with Br₂ and NaNO₂ in HBr. Suzuki coupling of phenylboronic acid and 2-chloro-6-phenylpyridine afforded 2-methyl-6-phenylpyridine, as described in the literature. n-Butyllithium was sufficient to deprotonate the methyl group of 2-methyl-6-phenylpyridine and the addition of 2-bromo-6-phenylpyridine, followed by overnight reflux, generated bis(6-phenyl-2-
pyridyl)methane (1) in ~ 50% yield. Treatment of 2 equiv of 1 with n-BuLi and 1,4-dichlorophthalazine at 0 °C produced the desired ligand Ph₄bdptz (2) in ~ 50% yield.⁴⁸

Single crystals of Ph₄bdptz were grown from CH₂Cl₂ and Et₂O. An X-ray crystallographic analysis confirms the structure that was proposed on the basis of NMR spectroscopic measurements, showing the connectivity to be as planned (Figure 2.1). Although no pre-organization of the ligand to form a hydrophobic pocket is apparent, the addition of metal ions causes the requisite conformational changes, as described below.

**Synthesis of Diiron(II) Compounds.** The ligand Ph₄bdptz promotes the formation of dinuclear iron(II) compounds containing additional bridging ligands. The reaction of 2 equiv of Fe(OTf)₂·2MeCN with Ph₄bdptz in dry MeCN, followed by addition of various carboxylate salts, yielded the orange-red compounds [Fe₂(Ph₄bdptz)(μ-O₂CCH₃)₂](OTf)₂, [Fe₂(Ph₄bdptz)(μ-O₂CC₆H₄)(μ-O₂CCH₂Ph)₂](OTf)₂, [Fe₂(Ph₄bdptz)(μ-O₂CCH₂Ph)₂](OTf)₂, and [Fe₂(Ph₄bdptz)(μ-O₂CC₆H₄)(μ-O₂CCH₂Ph)₂](OTf)₂ containing cations 2–6, shown in Chart 2.2, in good yields (~ 70%). All compounds gave satisfactory elemental analyses when residual solvent of crystallization was included, and their structures were determined by X-ray diffraction studies. The addition of bulkier carboxylates such as PhCO₂⁻, Ph₃CCO₂⁻, and PhCyCO₂⁻ did not lead to isolable solids. This result is attributed to unfavorable steric hindrance that prevents the accommodation of these ligands in the binding cavity that forms upon coordination of Ph₄bdptz to a pair of iron(II) atoms.

A phosphodiester-bridged complex, [Fe₂(Ph₄bdptz)(μ-O₂P(OPh)₂)](OTf)₂ (7(OTf)₂), was synthesized as a possible model compound for the active site of the enzyme purple acid phosphatase (PAP). PAP also belongs to the emerging class of carboxylate-bridged diiron proteins, although it performs a hydrolytic function, rather than activating dioxygen.⁶⁹ Compound 7 was prepared in a similar manner to the carboxylate-bridged complexes, except that diphenylphosphate was added to the
reaction mixture in place of a carboxylate salt. Although diphenylphosphate is a sterically hindered ancillary ligand, the bulk evolves from a site four bonds away from the iron(II) centers, well removed from the size-constrained cavity of the coordinated Ph₄bdptz ligand.

The hydroxide-bridged compound [Fe₂(Ph₄bdptz)(μ-OH)(MeCN)]₂(OTf)₃ (8(OTf)₃) was prepared in good yield (75%) by reaction of Fe(OTf)₂·2MeCN with Ph₄bdptz, H₂O, and NEt₃ in a ratio 2:1:1:1 in MeCN. Although complex 8(OTf)₃ is synthesized by using H₂O, this compound decomposes in the presence of large quantities of this solvent (>100 equiv). Attempts to replace the coordinated acetonitrile molecules with higher homologues such as EtCN or PhCN afforded oily materials from which crystalline solids could not be obtained.

**Coordination Environment of the Diiron(II) Complexes.** The coordination geometry in cations 3 - 7 is similar. Each square pyramidal iron(II) center is ligated by one phthalazine and two pyridine nitrogen atoms. Both metal ions are further coordinated by two oxygen atoms derived from either carboxylate ligands (3 - 6) or a phosphodiester moiety (7), and charge is neutralized by the presence of two counterions. In contrast, the iron centers in the structure of 8 adopt distorted trigonal bipyramidal geometry in which the two pyridine nitrogen atoms and the bridging hydroxide ligand form the equatorial plane. The coordinated MeCN solvent molecules are in axial sites and three triflate counterions are present to maintain charge neutrality. As predicted by the CPK models, the phenyl substituents on the pyridine rings of Ph₄bdptz form a pocket in which the metal ions and ancillary ligands are encapsulated. Examination of the solid-state structures of these compounds reveals that the presence of the additional phenyl substituents on the dinucleating ligand prevents formation of the tetranuclear compounds that were isolated with the parent ligand bdptz. The phenyl groups extend sufficiently below the line that contains the two iron centers,
making it virtually impossible for additional ligands to bring two units containing the Ph₄bdptz ligand into close proximity.

**Structural Analysis of 3–8.** In order to study systematically the geometry of carboxylate ligands bridging two metal ions, a series of structural parameters were defined (Table 2.3). The parameters for cations 3–5 are an extension of those defined for monodentate carboxylate-bridged polymetallic centers. The solid-state molecular structure of the acetate derivative (3) is shown in Figure 2.2, and selected bond lengths and angles are provided in Table 2.4. In this structure, the two metal centers, separated by 3.479(1) Å, are bridged by two acetate ligands coordinated in a syn, anti fashion. Both syn, anti and anti, anti coordination modes are much less frequently encountered than the syn, syn coordination geometry. The value of D is less than that of A, although the opposite occurs more frequently. The different bond lengths may be due to differences in basicity of the syn and anti lone pairs. For 3, however, other effects may also be important, because the longer A bonds are trans to pyridine. A similar feature was noted for [Fe₂(μ-Ο₂CCH₃)₂(TPA)₂](BPh⁴)₂. The oxygen atoms of 3 that are coordinated through their anti lone pairs, O(2) and O(3), appear to interact with both metal centers, albeit weakly, as indicated by additional B distances of 2.506(4) Å and 2.731(4) Å. Because the syn, anti coordination mode usually results in large M···M distances (>4 Å), an additional B interaction is not common. The polymeric complex catena-μ-(N-salicylidene-L-tyrosinato-O,O’)copper(II), with an M···M separation of 4.358(2) Å, has a B value of ~2.487 Å. This long M···M distance results in a large θ value of 163.1(4)°, which is in contrast to the nearly orthogonal θ angles in 3.

With triflate as counterion, the propionate cation 4 could only be obtained as a microcrystalline orange solid. X-ray quality crystals, however, were obtained of the BPh⁴⁺ salt. The structure of 4 is shown in Figure 2.2 and Table 2.4 lists selected bond lengths and angles. In contrast to the acetate derivative, complex 4 has one carboxylate that is bound in a syn, anti fashion with a longer D bond. Based on the observations for
3, this result is somewhat unexpected because 4 also has the A bond located trans to a pyridine. Clearly, a combination of factors affects the difference in bond lengths. The second carboxylate ligand is bound in a syn, syn fashion with significantly longer D bond lengths of 2.053(2) and 2.076(2) Å. As in 3, 4 displays a weak interaction of the anti oxygen atom of the propionate ligand with both iron centers (B = 2.820(3) Å).

In the phenylacetate derivative, both carboxylate oxygen atoms are bound to the iron(II) centers in a syn, syn fashion with Fe–O bond distances ranging from 1.952(3) to 2.072(2) Å (Figure 2.3, Table 2.5). The three longer D bonds are located trans to a pyridine, whereas the shortest bond is not. The γ values vary by more than 20°, showing that the carboxylate groups are not bound symmetrically. Examination of the solid-state structure of 5 reveals that both phenylacetate ligands are on the same face of the complex, leaving the opposite face largely exposed (Figure 2.3, right). This unsymmetrical orientation may be a solid state phenomenon and, in solution, the two phenylacetate groups are likely to adopt a geometry that minimizes steric interactions. The M···M separation in 5 of 3.698(1) Å is appreciably longer than that observed in the acetate and propionate derivatives. Most carboxylate-bridged dimetallic species that have been structurally characterized show the opposite trend, in which the M···M distance greatly increases as the coordination mode of the carboxylate ligand changes from syn, syn to syn, anti.72-75 In the series of compounds presented here, the presence of an additional bridging moiety, phthalazine, adds significant rigidity to the dimetallic core. Although it has been suggested that a syn, anti carboxylate would not be a likely intermediate between monodentate and syn, syn bridging modes in metalloproteins due to the large M···M changes that are accompanied by such a transition,71 the presence of a second bridging unit, such as another carboxylate or a carbamylated lysine residue, could restrict structural changes sufficiently to allow such an intermediate to form during the carboxylate shift.
The pivalate complex $6$(OTf)$_2$ was isolated as a microcrystalline solid and, despite numerous attempts, X-ray quality crystals could not be grown. A metathesis reaction with NaBPh$_4$ resulted in single crystals that were subjected to X-ray diffraction. The exchange of triflate for BPh$_4$ was not complete, however, and the crystal structure revealed the presence of both counterions. The disorder and overlap of the two types of counterions was severe and prevented satisfactory structural refinement. Nevertheless, the geometry of this compound was clearly discernable and displayed the expected core structure. The M···M separation is $\sim$3.660 Å and both carboxylate oxygen atoms are bound to the iron centers in a syn, syn fashion.

The phosphodiester-bridged compound $7$(OTf)$_2$ has an Fe···Fe distance of 4.045(1) Å, the largest metal-metal separation observed thus far in this series of diiron(II) compounds (Figure 2.4, Table 2.5). This result most likely reflects the larger bite angle of the coordinated diphenylphosphate as compared to the carboxylates of $3$-$6$, which stems from longer P–O ($\sim$1.48 Å) compared to C–O ($\sim$1.25 Å) bonds. The Fe–N bond lengths, ranging from 2.152(2) to 2.266(2) Å, are typical, as are the Fe–O bond lengths (Fe–O$_{av}$ = 1.980(10) Å). The phosphodiester coordination mode is syn, syn. The restrictive cavity that is formed by the Ph$_4$bdptz ligand probably prevents the larger ligands of $5$–$7$ from adopting the syn, anti conformation, which would create unfavorable steric hindrance by forcing the bulk of the ancillary ligands deeper into the cavity.

The structure of $8$ differs from that of $3$–$7$ because it features a single hydroxide unit as a bridging group in place of a $\mu$-1,3-ligand (Figure 2.4, Table 2.6). The resulting Fe···Fe separation of 3.536(1) Å matches closely that of $4$ ($\Delta_{Fe-Fe} \sim$0.03 Å) but is somewhat elongated compared to that in $3$ ($\Delta_{Fe-Fe} \sim$0.06 Å). Although the presence of a single atom bridge typically results in a shorter metal separation, oxygen atoms of the two acetate ligands in $3$ interact with both metal centers and serve as two single atom bridging units. Because only one carboxylate ligand in $4$ interacts with both metal centers, the
Fe–Fe distance in this compound more closely resembles that of 8. The hydroxide ligand coordinates to the iron centers in 8 with bond distances of 1.960(3) and 1.964(3) Å, and an Fe–O(H)–Fe bond angle of 128.61(15)°. This value is significantly larger than in compounds 3 and 4, where θ ranges from 90.09(12) – 94.68(10)°. The difference in nitrogen atom hybridization of the acetonitrile ligands in 8 is reflected in shorter Fe–N(MeCN)\textsubscript{av} bonds lengths of 2.120(3) Å, relative to the Fe–N(Ph\textsubscript{4}bdptz)\textsubscript{av} bond distances of 2.179(1) Å.

**Mössbauer Spectroscopy.** The Mössbauer spectra of compounds containing the cations 3 – 8 were obtained at 4.2 K in the absence of an external applied magnetic field. These spectra are portrayed in Figure 2.5, and extracted parameters are provided in Table 2.7. The isomer shifts and quadrupole splittings are similar for the compounds in this series (δ\textsubscript{av} = 1.15 mm s\textsuperscript{-1} and ΔE\textsubscript{Qav} = 2.59 mm s\textsuperscript{-1}), and compare well with those of other high-spin iron(II) complexes in N/O-coordination environments.\textsuperscript{78-80}

The cluster of phenyl rings that forms upon metallation of Ph\textsubscript{4}bdptz results in fairly symmetric coordination of the larger μ-1,3-ancillary ligands. The smaller acetate and propionate groups have more flexibility within the binding pocket, leading to substantially more asymmetric coordination. The degree of symmetry of carboxylate/phosphate coordination is reflected in the shapes of the Mössbauer spectra. Compound 3(OTf)\textsubscript{2} displays a broad and asymmetric signal that was fit as two overlapping quadrupole doublets. The presence of two distinct iron sites is consistent with the crystallographic data, which reveal small differences in the coordination geometry of the two iron atoms. The spectra of 4(OTf)\textsubscript{2} and 5(OTf)\textsubscript{2} were also fit with overlapping quadrupole doublets, although the shape of these signals appears more symmetrical than that of 3(OTf)\textsubscript{2}. The two iron sites of cations 6 - 8 are equivalent on the Mössbauer time scale, as evidenced by sharp quadrupole doublets. The iron centers of compound 7(OTf)\textsubscript{2} are crystallographically equivalent, resulting in a Mössbauer
spectrum that is significantly sharper than that of the carboxylate-bridged compounds ($\Gamma = 0.24$ mm s$^{-1}$).

**Dioxygen Reactivity.** Solutions of complexes $3(\text{OTf})_2 - 7(\text{OTf})_2$ in CH$_2$Cl$_2$ react slowly with dioxygen at room temperature. Upon oxidation of the compounds with small ancillary ligands, $3(\text{OTf})_2 - 5(\text{OTf})_2$, a brown precipitate formed and crystallization of the material that remained in solution yielded [H$_2$Ph$_4$bdptz](OTf)$_2$ (9(OTf)$_2$), the structure of which is shown in Figure 2.6. Although 9 lacks a diiron center, its conformation is similar to that of Ph$_4$bdptz in the structures of 3 - 8 and different from that of the free ligand. Protonation of two pyridine nitrogen atoms and the resulting hydrogen bonds between N(1)–N(3) and N(5)–N(6) are responsible for maintaining this pre-organized structure. Evidently, the small carboxylate ligands are not able to support diiron(III) structures of Ph$_4$bdptz. In contrast, oxidation of 6(OTf)$_2$ and 7(OTf)$_2$ did not decompose to form 9. Because the resulting products could not be obtained in a crystalline form, Mössbauer spectroscopy was employed to probe the nature of the oxidation products. The Mössbauer spectrum of oxidized 6(OTf)$_2$ is displayed in Figure 2.7. The quadrupole doublet has parameters of $\delta \sim 0.51$ mm s$^{-1}$ and $\Delta E_Q \sim 1.19$ mm s$^{-1}$, and the isomer shift is typical of high-spin iron(III).$^{78-80}$ The larger ancillary ligands, therefore, appear to support an iron(III) species.

**Summary and Conclusions**

A series of diiron(II) compounds was prepared with the sterically hindered ligand Ph$_4$bdptz as small molecule models of the active sites of non-heme carboxylate-bridged metalloproteins. The phthalazine moiety is an effective dinucleating agent that can accommodate a range of metal····metal distances and ancillary bridging ligands. The pendant pyridine arms coordinate to the metal centers to provide additional stability to the coordinatively unsaturated diiron(II) unit, and functionalization of these rings with aromatic groups was designed to prevent the formation of tetranuclear iron(III) species.
from forming upon oxidation. The Mössbauer spectra of the diiron(II) compounds effectively demonstrate the relationship between the symmetry of the iron coordination environment and the observed Mössbauer signal. The low reactivity of the diiron compounds towards dioxygen suggests that the observed flexibility of the Ph₄bdptz ligand framework may not be sufficient to permit access to reactive \([\text{Fe}_2(\text{O})_2]\) species.

**Acknowledgements.** This work was supported by a grant from the National Science Foundation. I thank NSERC for a graduate student fellowship, Dr. Bernhard Spingler for assistance with the X-ray crystallographic refinements, and Dr. Dongwhan Lee for help in the acquisition of the Mössbauer spectra.
References


(40) Evens, G.; Caluwe, P. Macromolecules 1979, 12, 803-808.
(63) SMART v4.0: Software for the CCD Detector System; Siemens Industrial Automation Inc.: Madison, WI, 1995.
(65) SHELXTL v5.0: Structure Analysis Program; Siemens Industrial Automation Inc.: Madison, WI, 1995.
(66) Sheldrick, G. M. SADABS: Area-Detector Absorption Correction; University of Göttingen: Göttingen, Germany, 1996.

(68) Osuch, C.; Levine, R. J. Am. Chem. Soc. 1956, 1723-1725.


Table 2.1. Summary of X-ray crystallographic data for compounds 2·CH₂Cl₂, 3(OTf)₂·2.5CH₂Cl₂, and 4(BPh₄)₂·2.5MeCN·0.5Et₂O

<table>
<thead>
<tr>
<th></th>
<th>2·CH₂Cl₂</th>
<th>3(OTf)₂·2.5CH₂Cl₂</th>
<th>4(BPh₄)₂·2.5MeCN·0.5Et₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td>formula</td>
<td>C₅₅H₃₈N₆Cl₂</td>
<td>C₆₂.₅H₄₅N₆O₁₀Cl₅F₆Fe₂S₂</td>
<td>C₁₁₅H₈₈N₈₅O₄₅B₂Fe₂</td>
</tr>
<tr>
<td>fw</td>
<td>853.81</td>
<td>1507.11</td>
<td>1794.26</td>
</tr>
<tr>
<td>space group</td>
<td>P2₁ / n</td>
<td>P̅T</td>
<td>P̅T</td>
</tr>
<tr>
<td>a, Å</td>
<td>13.1916(3)</td>
<td>12.6549(1)</td>
<td>14.106(5)</td>
</tr>
<tr>
<td>b, Å</td>
<td>10.6109(2)</td>
<td>15.5715(4)</td>
<td>17.320(5)</td>
</tr>
<tr>
<td>c, Å</td>
<td>31.3786(5)</td>
<td>17.3374(4)</td>
<td>21.521(5)</td>
</tr>
<tr>
<td>α, deg</td>
<td>99.947(1)</td>
<td>105.984(2)</td>
<td>73.085(5)</td>
</tr>
<tr>
<td>β, deg</td>
<td>93.730(1)</td>
<td>74.859(5)</td>
<td></td>
</tr>
<tr>
<td>γ, deg</td>
<td>91.434(1)</td>
<td>84.342(5)</td>
<td></td>
</tr>
<tr>
<td>V, Å³</td>
<td>4326.19(15)</td>
<td>3274.11(12)</td>
<td>4854(2)</td>
</tr>
<tr>
<td>Z</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>T, °C</td>
<td>-85</td>
<td>-85</td>
<td>-85</td>
</tr>
<tr>
<td>ρcalcd, g cm⁻³</td>
<td>1.311</td>
<td>1.529</td>
<td>1.228</td>
</tr>
<tr>
<td>μ(M₀ Kα), mm⁻¹</td>
<td>0.197</td>
<td>0.790</td>
<td>0.358</td>
</tr>
<tr>
<td>θ range, deg</td>
<td>1.32-28.28</td>
<td>1.31-28.35</td>
<td>1.22-28.28</td>
</tr>
<tr>
<td>total no. of data</td>
<td>37488</td>
<td>20717</td>
<td>43559</td>
</tr>
<tr>
<td>no. of unique data</td>
<td>10169</td>
<td>14413</td>
<td>21781</td>
</tr>
<tr>
<td>observed data</td>
<td>6413</td>
<td>10490</td>
<td>14219</td>
</tr>
<tr>
<td>no. of parameters</td>
<td>579</td>
<td>856</td>
<td>1188</td>
</tr>
<tr>
<td>R a,b</td>
<td>0.0679</td>
<td>0.0709</td>
<td>0.0625</td>
</tr>
<tr>
<td>wR² a,c</td>
<td>0.1386</td>
<td>0.1912</td>
<td>0.1686</td>
</tr>
<tr>
<td>max, min peaks, e Å⁻³</td>
<td>0.589, -0.572</td>
<td>1.278, -0.943</td>
<td>1.162, -0.449</td>
</tr>
</tbody>
</table>

*a Observation criterion: I > 2σ(I). \( bR = \frac{\sum |F_o| - |F_C|}{\sum |F_o|} \), \( cR^2 = \frac{\sum [w(F_o^2 - F_c^2)]^2}{\sum [w(F_o^2)]^2}]^{1/2}. \)
<table>
<thead>
<tr>
<th></th>
<th>5(OTf)$_2$·2CH$_2$Cl$_2$</th>
<th>7(OTf)$_2$</th>
<th>8(OTf)$_3$·3.5MeCN</th>
<th>9(OTf)$_2$·H$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>formula</strong></td>
<td>C$<em>{74}$H$</em>{56}$N$<em>6$O$</em>{10}$Cl$_4$F$_6$Fe$_2$S$_2$</td>
<td>C$<em>{80}$H$</em>{58}$N$<em>6$O$</em>{14}$P$_2$F$_6$Fe$_2$S$_2$</td>
<td>C$<em>{68}$H$</em>{38}$N$<em>{11.5}$O$</em>{10}$F$_9$Fe$_2$S$_3$</td>
<td>C$<em>{56}$H$</em>{40}$N$_6$O$_7$F$_6$S$_2$</td>
</tr>
<tr>
<td><strong>fw</strong></td>
<td>1620.87</td>
<td>1679.08</td>
<td>1554.98</td>
<td>1087.06</td>
</tr>
<tr>
<td><strong>space group</strong></td>
<td>P$_2_1$/c</td>
<td>C2/c</td>
<td>Pbca</td>
<td>C2/c</td>
</tr>
<tr>
<td><strong>a, Å</strong></td>
<td>14.1628(2)</td>
<td>14.873(5)</td>
<td>23.536(5)</td>
<td>17.7052(4)</td>
</tr>
<tr>
<td><strong>b, Å</strong></td>
<td>21.8567(3)</td>
<td>20.350(5)</td>
<td>21.075(5)</td>
<td>26.3716(9)</td>
</tr>
<tr>
<td><strong>c, Å</strong></td>
<td>22.9624(1)</td>
<td>23.332(5)</td>
<td>29.781(5)</td>
<td>22.3645(7)</td>
</tr>
<tr>
<td><strong>α, deg</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>β, deg</strong></td>
<td>95.064(1)</td>
<td>92.918(5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>γ, deg</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>V, Å$^3$</strong></td>
<td>7080.31(14)</td>
<td>7053(3)</td>
<td>14772(5)</td>
<td>10379.9(5)</td>
</tr>
<tr>
<td><strong>Z</strong></td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td><strong>T, °C</strong></td>
<td>-85</td>
<td>-85</td>
<td>-100</td>
<td>-85</td>
</tr>
<tr>
<td><strong>ρcalcd, g cm$^{-3}$</strong></td>
<td>1.521</td>
<td>1.581</td>
<td>1.398</td>
<td>1.391</td>
</tr>
<tr>
<td><strong>μ(Mo Kα), mm$^{-1}$</strong></td>
<td>0.700</td>
<td>0.607</td>
<td>0.563</td>
<td>0.184</td>
</tr>
<tr>
<td><strong>θ range, deg</strong></td>
<td>1.44-28.30</td>
<td>1.70-28.35</td>
<td>1.37-25.00</td>
<td>1.39-25.00</td>
</tr>
<tr>
<td><strong>total no. of data</strong></td>
<td>43522</td>
<td>31288</td>
<td>73688</td>
<td>30363</td>
</tr>
<tr>
<td><strong>no. of unique data</strong></td>
<td>16205</td>
<td>8333</td>
<td>13005</td>
<td>9134</td>
</tr>
<tr>
<td><strong>observed data$^a$</strong></td>
<td>13598</td>
<td>6758</td>
<td>9751</td>
<td>4870</td>
</tr>
<tr>
<td><strong>no. of parameters</strong></td>
<td>956</td>
<td>506</td>
<td>1029</td>
<td>711</td>
</tr>
<tr>
<td><strong>R$^a,b$</strong></td>
<td>0.0463</td>
<td>0.0434</td>
<td>0.0788</td>
<td>0.0831</td>
</tr>
<tr>
<td><strong>wR$^2$ $^a,c$</strong></td>
<td>0.1175</td>
<td>0.1070</td>
<td>0.2086</td>
<td>0.2197</td>
</tr>
<tr>
<td><strong>max, min peaks, e Å$^{-3}$</strong></td>
<td>0.955, -0.829</td>
<td>0.493, -0.541</td>
<td>1.003, -0.659</td>
<td>0.551, -0.347</td>
</tr>
</tbody>
</table>

$^a$ Observation criterion: I > 2σ(I). $^b$R = ∑|Fo| - |Fc| / ∑|Fo|. $^c$wR$^2$ = [∑w(Fo$^2$ - Fc$^2$)$^2$] / [∑w(Fo$^2$)$^2$]$^{1/2}$. 
Table 2.3. Structural parameters for compounds $3$(OTf)$_2$, $4$(BPh)$_4$, and $5$(OTf)$_2$

![Diagram of molecular structure](image)

<table>
<thead>
<tr>
<th>Complex</th>
<th>$M\cdots M$ (Å)</th>
<th>$D$ (Å)</th>
<th>$A$ (Å)</th>
<th>$B$ (Å)</th>
<th>$\gamma$ (°)</th>
<th>$\alpha$ (°)</th>
<th>$\theta$ (°)</th>
<th>$\beta$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3$(OTf)$_2$</td>
<td>3.4794(8)</td>
<td>1.983(3)</td>
<td>2.151(3)</td>
<td>2.506(4)</td>
<td>111.3(3)</td>
<td>127.6(3)</td>
<td>90.09(12)</td>
<td>76.1(3)</td>
</tr>
<tr>
<td></td>
<td>2.021(3)</td>
<td>2.180(3)</td>
<td>2.731(4)</td>
<td></td>
<td>103.0(3)</td>
<td>127.8(3)</td>
<td>95.64(12)</td>
<td>80.9(3)</td>
</tr>
<tr>
<td>$4$(BPh)$_4$</td>
<td>3.5689(10)</td>
<td>2.006(2)</td>
<td>1.969(3)</td>
<td>2.820(3)</td>
<td>113.9(2)</td>
<td>125.0(2)</td>
<td>94.68(10)</td>
<td>74.2(2)</td>
</tr>
<tr>
<td></td>
<td>2.053(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.076(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$5$(OTf)$_2$</td>
<td>3.6978(4)</td>
<td>1.952(3)</td>
<td></td>
<td></td>
<td></td>
<td>123.3(2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0719(19)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>143.7(3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0267(18)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>138.97(16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.983(3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>129.81(16)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2.4. Selected bond lengths (Å) and angles (deg) for 3 and 4

<table>
<thead>
<tr>
<th></th>
<th>Bond Lengths</th>
<th></th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Fe(1)⋯Fe(2)</td>
<td>3.4794(8)</td>
<td>C(55)⋯O(1)–Fe(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–N(1)</td>
<td>2.145(3)</td>
<td>C(55)⋯O(2)–Fe(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–N(3)</td>
<td>2.126(4)</td>
<td>C(57)⋯O(3)–Fe(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–N(4)</td>
<td>2.290(4)</td>
<td>C(57)⋯O(4)–Fe(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(1)</td>
<td>1.983(3)</td>
<td>O(1)⋯Fe(1)–O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(3)</td>
<td>2.180(3)</td>
<td>O(2)⋯Fe(2)–O(4)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(2)</td>
<td>2.731(4)</td>
<td>N(3)⋯Fe(1)–O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–N(2)</td>
<td>2.160(3)</td>
<td>N(4)⋯Fe(1)–O(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–N(5)</td>
<td>2.154(4)</td>
<td>N(5)⋯Fe(2)–O(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–N(6)</td>
<td>2.259(4)</td>
<td>N(6)⋯Fe(2)–O(4)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(2)</td>
<td>2.151(3)</td>
<td>Fe(1)⋯O(2)–Fe(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(4)</td>
<td>2.021(3)</td>
<td>Fe(1)⋯O(3)–Fe(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(3)</td>
<td>2.506(4)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Fe(1)⋯Fe(2)</td>
<td>3.5689(10)</td>
<td>C(55)⋯O(1)–Fe(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–N(1)</td>
<td>2.144(3)</td>
<td>C(55)⋯O(2)–Fe(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–N(3)</td>
<td>2.147(3)</td>
<td>C(58)⋯O(3)–Fe(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–N(4)</td>
<td>2.256(3)</td>
<td>C(58)⋯O(4)–Fe(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(1)</td>
<td>1.969(3)</td>
<td>O(1)⋯Fe(1)–O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(3)</td>
<td>2.053(2)</td>
<td>O(2)⋯Fe(2)–O(4)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–N(2)</td>
<td>2.188(2)</td>
<td>N(3)⋯Fe(1)–O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–N(5)</td>
<td>2.203(2)</td>
<td>N(4)⋯Fe(1)–O(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–N(6)</td>
<td>2.165(2)</td>
<td>N(5)⋯Fe(2)–O(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(2)</td>
<td>2.006(2)</td>
<td>N(6)⋯Fe(2)–O(4)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(4)</td>
<td>2.076(2)</td>
<td>Fe(1)⋯O(1)⋯Fe(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(1)</td>
<td>2.820(3)</td>
<td></td>
</tr>
</tbody>
</table>

\*Number in parentheses are estimated standard deviations of the last significant figure. Atoms are labeled as indicated in Figure 2.2.
Table 2.5. Selected bond lengths (Å) and angles (deg) for 5 and 7

<table>
<thead>
<tr>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>5</strong></td>
<td></td>
</tr>
<tr>
<td>Fe(1)--Fe(2)</td>
<td>3.6978(4)</td>
</tr>
<tr>
<td>Fe(1)--N(1)</td>
<td>2.1688(18)</td>
</tr>
<tr>
<td>Fe(1)--N(3)</td>
<td>2.230(2)</td>
</tr>
<tr>
<td>Fe(1)--N(4)</td>
<td>2.1410(19)</td>
</tr>
<tr>
<td>Fe(1)--O(1)</td>
<td>1.952(3)</td>
</tr>
<tr>
<td>Fe(1)--O(3)</td>
<td>2.0719(19)</td>
</tr>
<tr>
<td>Fe(2)--N(2)</td>
<td>2.1829(18)</td>
</tr>
<tr>
<td>Fe(2)--N(5)</td>
<td>2.1685(18)</td>
</tr>
<tr>
<td>Fe(2)--N(6)</td>
<td>2.2375(19)</td>
</tr>
<tr>
<td>Fe(2)--O(2)</td>
<td>1.983(3)</td>
</tr>
<tr>
<td>Fe(2)--O(4)</td>
<td>2.0267(18)</td>
</tr>
<tr>
<td><strong>7</strong></td>
<td></td>
</tr>
<tr>
<td>Fe(1)--Fe(1A)</td>
<td>4.0447(11)</td>
</tr>
<tr>
<td>Fe(1)--N(1)</td>
<td>2.2658(18)</td>
</tr>
<tr>
<td>Fe(1)--N(2)</td>
<td>2.1963(18)</td>
</tr>
<tr>
<td>Fe(1)--N(3)</td>
<td>2.1515(19)</td>
</tr>
<tr>
<td>Fe(1)--O(1)</td>
<td>1.9904(17)</td>
</tr>
<tr>
<td>Fe(1)--O(2A)</td>
<td>1.9754(17)</td>
</tr>
<tr>
<td>P(1)--O(1)</td>
<td>1.4837(17)</td>
</tr>
<tr>
<td>P(1)--O(2)</td>
<td>1.4873(17)</td>
</tr>
</tbody>
</table>

*a Number in parentheses are estimated standard deviations of the last significant figure. Atoms are labeled as indicated in Figures 2.3 and 2.4.*
Table 2.6. Selected bond lengths (Å) and angles (deg) for 8<sup>a</sup>

<table>
<thead>
<tr>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8</strong></td>
<td><strong>Bond Angles</strong></td>
</tr>
<tr>
<td>Fe(1)···Fe(2)</td>
<td>3.536(1)</td>
</tr>
<tr>
<td>Fe(1)–N(1)</td>
<td>2.147(3)</td>
</tr>
<tr>
<td>Fe(1)–N(3)</td>
<td>2.205(3)</td>
</tr>
<tr>
<td>Fe(1)–N(4)</td>
<td>2.188(3)</td>
</tr>
<tr>
<td>Fe(1)–N(7)</td>
<td>2.114(4)</td>
</tr>
<tr>
<td>Fe(1)–O(1)</td>
<td>1.960(3)</td>
</tr>
<tr>
<td>Fe(2)–N(2)</td>
<td>2.148(3)</td>
</tr>
<tr>
<td>Fe(2)–N(5)</td>
<td>2.204(3)</td>
</tr>
<tr>
<td>Fe(2)–N(6)</td>
<td>2.184(3)</td>
</tr>
<tr>
<td>Fe(2)–N(8)</td>
<td>2.126(4)</td>
</tr>
<tr>
<td>Fe(2)–O(1)</td>
<td>1.964(3)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Number in parentheses are estimated standard deviations of the last significant figure.

Atoms are labeled as indicated in Figure 2.4.
Table 2.7. Summary of Mössbauer parameters (mm s$^{-1}$) for 3(OTf)$_2$ - 8(OTf)$_3$ recorded at 4.2 K

<table>
<thead>
<tr>
<th>Complex</th>
<th>$\delta$</th>
<th>$\Delta E_Q$</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3(OTf)$_2$</td>
<td>1.17(2)</td>
<td>2.25(2)</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>1.14(2)</td>
<td>2.78(2)</td>
<td>0.33</td>
</tr>
<tr>
<td>4(OTf)$_2$</td>
<td>1.14(2)</td>
<td>2.14(2)</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>1.15(2)</td>
<td>2.64(2)</td>
<td>0.39</td>
</tr>
<tr>
<td>5(OTf)$_2$</td>
<td>1.14(2)</td>
<td>2.49(2)</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>1.17(2)</td>
<td>2.85(2)</td>
<td>0.26</td>
</tr>
<tr>
<td>6(OTf)$_2$</td>
<td>1.16(2)</td>
<td>2.66(2)</td>
<td>0.33</td>
</tr>
<tr>
<td>7(OTf)$_2$</td>
<td>1.18(2)</td>
<td>2.79(2)</td>
<td>0.24</td>
</tr>
<tr>
<td>8(OTf)$_3$</td>
<td>1.12(2)</td>
<td>2.67(2)</td>
<td>0.26</td>
</tr>
</tbody>
</table>
Chart 2.1.
Chart 2.2.
Scheme 2.1.
Figure 2.1. ORTEP diagram of Ph₄bdptz (2) showing the 50% probability thermal ellipsoids for all non-hydrogen atoms.
Figure 2.2. ORTEP diagrams of $[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{CCH}_3)]^{2+}$ (3) and $[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{CC}_2\text{H}_5)]^{2+}$ (4) showing the 50% probability thermal ellipsoids for all non-hydrogen atoms (left to right).
Figure 2.3. ORTEP diagrams of $[\text{Fe}_3(\text{Ph}_3\text{bdptz})](\mu-\text{O}_2\text{CCH}_2\text{Ph})_2]^{2-}$ (5) with the 50% probability thermal ellipsoids for all non-hydrogen atoms shown full (left) and truncated (right, side-on view).
Figure 2.4. ORTEP diagrams of \([\text{Fe}_2(\text{Ph}_2\text{bdptz})(\mu-\text{O}_2\text{P(OPh)}_2)\text{]}^{2+} (7)\) and \([\text{Fe}_2(\text{Ph}_2\text{bdptz})(\mu-\text{OH})(\text{MeCN})_2]^{32} (8)\) showing the 50% probability thermal ellipsoids for all non-hydrogen atoms. The phenyl rings of the symmetry generated diphenylphosphate group of 7 are omitted for clarity.
Figure 2.5. Mössbauer spectra (experimental data (1), calculated fit(−)) recorded at 4.2 K for a solid sample of [Fe₂(Ph₄bdptz)(μ-O₂CCH₃)₂][OTf]₂ (3(OTf)₂) (A); [Fe₂(Ph₄bdptz)(μ-O₂CC₆H₄)₂][OTf]₂ (4(OTf)₂) (B); [Fe₂(Ph₄bdptz)(μ-O₂CCH₃Ph)₂][OTf]₂ (5(OTf)₂) (C); [Fe₂(Ph₄bdptz)(μ-O₂C'C₆H₄)₂][OTf]₂ (6(OTf)₂) (D); [Fe₂(Ph₄bdptz)(μ-O₂P(OPh)₃)₂][OTf]₂ (7(OTf)₂) (E); [Fe₂(Ph₄bdptz)(μ-OH)(MeCN)₂][OTf]₃ (8(OTf)₃) (F). The upper curves of A – C show two subsets for the calculated spectra.
Figure 2.6 ORTEP diagram of \([\text{H}_2\text{Ph}_{bdptz}]^2^-\) (9) showing the 50% probability thermal ellipsoids for all non-hydrogen atoms.
Figure 2.7. Mössbauer spectrum (experimental data (1), calculated fit(-)) recorded at 4.2 K of the product formed by reaction of $[\text{Fe}_2(\text{Ph}_4\text{bdptz})(\mu-O_2\text{C}^\text{t}C_4\text{H}_6)_2](\text{OTf})_2$ (6(OTf)$_2$) with $\text{O}_2$. 
Chapter 3
Modeling Features of the Non-Heme Diiron Cores in O$_2$-Activating Enzymes through the Synthesis, Characterization, and Oxidation of 1,8-Naphthyridine-Based Complexes*
Introduction

Carboxylate-bridged non-heme diiron centers occur in an important class of metalloproteins that react with dioxygen to effect a variety of essential chemical transformations.\textsuperscript{1-4} Well-studied members of this family of proteins include hemerythrin (Hr), the hydroxylase component of soluble methane monooxygenase (sMMOH), the R2 subunit of ribonucleotide reductase (RNR-R2), and Δ-9 desaturase (Δ9D). The diiron core structures of these proteins in their reduced states are illustrated in Chart 3.1. Although these biological units all contain a carboxylate-bridged dimetallic motif, their functions vary dramatically. The protein Hr, found in certain marine invertebrates, reversibly binds dioxygen,\textsuperscript{5} whereas some methanotrophs utilize the enzyme sMMOH to oxidize CH\textsubscript{4} to CH\textsubscript{3}OH in the first step of the carbon metabolic pathway.\textsuperscript{6} DNA biosynthesis is initiated by RNR-R2 through the generation of a tyrosyl radical,\textsuperscript{7,8} and Δ9D produces a double bond in a saturated fatty acid.\textsuperscript{9,10} Diiron components have also been identified at the active sites of toluene monooxygenase,\textsuperscript{3,11} alkene monooxygenase,\textsuperscript{12} and phenol hydroxylase.\textsuperscript{13} These enzymes effect the oxidation of toluene to cresol, the epoxidation of alkenes, and the conversion of phenol to catechol, respectively.

The remarkable diversity of functions exhibited by these metalloproteins has inspired the synthesis of small molecule model compounds that not only reproduce structural and geometric features of the active sites, but also display similar reactivities toward exogenous substrates. A critical incentive for mimicking the chemistry of the enzymes is to understand how modifications in the ligand can affect the steric, electronic, and ultimately, oxidation properties of complexes in which two iron(II) ions are held in close proximity within a restricted coordination environment. By confining metal centers in a ligand framework that rigorously enforces dinuclearity, the properties of ancillary ligands can be modulated, and these variations can be correlated with the reactivity of the metal compounds.
Diiron complexes have been prepared with bridging carboxylate ligands as well as with a variety of other dinucleating units. The motivation for using non-carboxylate bridging ligands stems from the often unpredictable and undesired formation of high-nuclearity clusters or simple monomeric species that can occur by self-assembly when only carboxylate ligands are employed. One dinucleating spacer that has been employed successfully in our laboratory is 1,8-naphthyridine. The similarity in coordination mode of carboxylate and 1,8-naphthyridine for bridging two metal ions suggested to us that it might be considered as a “masked carboxylate.” A family of nitrogen-rich, 1,8-naphthyridine-based ligands of varying denticity have been reported and utilized in the synthesis of diiron(II) compounds. In general, these compounds are less reactive toward dioxygen than their carboxylate counterparts, although they have allowed the synthesis of spectroscopic models for oxyHr using H₂O₂.

Presented here is a family of naphthyridine-based diiron(II) compounds in which the nature of both the multidentate naphthyridine framework and the ancillary bridging ligands are systematically modified. Through these structural variations (Chart 3.2), the reactivity of the complexes toward dioxygen was altered dramatically. The syntheses of the compounds [Fe₂(BPMAN)(μ-O₂CPh)₂](OTf)₂ (1), [Fe₂(BPMAN)(μ-OH)(μ-O₂CArTol)](OTf)₂ (2), [Fe₂(BPMAN)(μ-OMe)(μ-O₂CArTol)](OTf)₂ (3), [Fe₂(BBAN)(μ-O₂CArTol)₂](OTf) (4), and [Fe₂(BEAN)(μ-O₂CArTol)₃](OTf) (5) are reported. Complexes 1, 3, 4, and 5 were characterized by X-ray crystallography. Cyclic voltammograms of 1, 2, and 4 were recorded and the redox potentials were correlated with their observed reactivity towards dioxygen. In addition, the Mössbauer properties of 1 - 4 were investigated. Comparison with related naphthyridine-based diiron systems facilitated a deeper understanding of the influence of the ligand properties on the electrochemical and oxidation chemistry of the complexes.
Experimental

**General Procedures.** Dichloromethane, acetonitrile, diethyl ether, and tetrahydrofuran were saturated with argon and purified by passing over a column of activated Al₂O₃ under argon.³¹ Methanol was distilled from Mg and I₂ under nitrogen. Triethylamine was distilled from CaH₂ under nitrogen. The compounds Fe(OTf)₂·2MeCN,³² BPMAN,²⁹ BBAN,²⁹ BEAN,²⁹ and NaO₂CArTol³³-³⁵ were prepared according to published literature procedures. All other reagents were purchased from commercial sources and used as received. Air sensitive manipulations, including the synthesis of 1 – 5, were performed by using standard Schlenk techniques or under nitrogen in an MBraun glovebox. Crystalline samples of the diiron(II) complexes were pulverized and heated in vacuo prior to elemental analysis. Removal of the CH₂Cl₂ solvent from solid samples of 1, 2, and 4 was incomplete, however, as judged from the analyses.

**[Fe₅(BPMAN)(μ-O₂CPh)₂](OTf)₂ (1).** To a solution of Fe(OTf)₂·2MeCN (158 mg, 0.36 mmol) in MeCN (4 mL) was added solid BPMAN (100 mg, 0.18 mmol). The resulting red-orange solution was treated with PhCO₂H (44 mg, 0.36 mmol) and NEt₃ (50 µL, 0.36 mmol) in MeCN (1 mL) to generate a dark red solution that was stirred for 1 h. The solvent was removed under reduced pressure and the residue was dissolved in CH₂Cl₂ and filtered through a plug of Celite. Blue crystals of 1·CH₂Cl₂, suitable for X-ray diffraction study, were obtained following Et₂O vapor diffusion into this solution (163 mg, 79%). FT-IR (cm⁻¹, KBr): 3431 (w), 3065 (w), 2932 (w), 1608 (s), 1568 (m), 1514 (w), 1480 (w), 1406 (s), 1275 (s), 1262 (s), 1222 (m), 1150(m), 1098 (w), 1070 (w), 1053 (w), 1030 (s), 978 (w), 905 (w), 888 (w), 862 (w), 839 (w), 791 (w), 763 (m), 725 (m), 672 (m), 636 (s), 571 (m), 516 (m). UV-vis (CH₂Cl₂, λₘₐₓ nm (ε, M⁻¹ cm⁻¹)) 380 (5800), 500 (1800). Anal. Calcd for 1·0.25CH₂Cl₂·Fe₂Cl₆·S₂F₆O₆·N₈·C₅₀₂₅·H₄₂₅: C, 49.23; H, 3.49; N, 9.14. Found: C, 49.00; H, 3.21; N, 9.46.
[Fe₄(BPMAN)(μ-OH)(μ-O₂CAR°)](OTf)₂ (2). To a red-orange solution of Fe(OTf)₂·2MeCN (158 mg, 0.36 mmol) and BPMAN (100 g, 0.18 mmol) in MeCN (4 mL) was added solid NaO₂CAR° (58 mg, 0.18 mmol) to form a brown-green solution. The addition of NEt₃ (25 µL, 0.18 mmol) and argon-saturated H₂O (3.3 µL, 0.18 mmol) resulted in a bright green solution that was stirred for 1 h. Evaporation of the solvent was followed by dissolution of the residue in CH₂Cl₂ and filtration through Celite. Diffusion of Et₂O into this solution yielded 2 as a green flocculent solid (200 mg, 87%). FT-IR (KBr, cm⁻¹): 3509 (w), 3061 (w), 2918 (w), 1603 (m), 1559 (m), 1515 (w), 1480 (w), 1445 (m), 1408 (w), 1382 (w), 1269 (s), 1224 (m), 1155 (m), 1099 (w), 1030 (s), 817 (w), 798 (w), 765 (m), 735 (w), 704 (w), 637 (s), 573 (w), 542 (w), 518 (m). UV-vis (CH₂Cl₂, λmax nm (ε, M⁻¹ cm⁻¹)) 325 (11 000), 400 (3000), 650 (250). ESI-MS (+m/z): Calcd for (M − OTf)^−1, 1131.22; Found 1131.33; Calcd for [(M − OTf) + H₂O]^+1, 1149.23; Found 1149.31; Calcd for (M − 2OTf)^−2 491.14; Found 491.13; Calcd for [(M − 2OTf) + H₂O]^+2 500.14; Found 500.11. Anal. Calcd for 2·0.25CH₂Cl₂, Fe₂Cl₂S₂F₆O₅N₅C₅₇₂₅₅H₃₀₅: C, 52.81; H, 3.91; N, 8.61. Found: C, 52.59; H, 3.75; N, 8.79.

[Fe₄(BPMAN)(μ-OMe)(μ-O₂CAR°)](OTf)₂ (3). Vapor diffusion of Et₂O into a solution of 2 (216 mg, 0.17 mmol) in MeOH yielded green blocks of 3·0.3Et₂O, suitable for X-ray crystallographic analysis (170 mg, 78%). FT-IR (cm⁻¹, KBr): 3503 (w), 3070 (w), 2924 (w), 1605 (m), 1562 (m), 1516 (w), 1480 (w), 1445 (m), 1410 (w), 1384 (w), 1274 (s), 1222 (m), 1153 (m), 1098 (m), 1030 (s), 980 (w), 906 (w), 890 (w), 840 (w), 793 (m), 767 (m), 737 (w), 703 (w), 637 (s), 583 (w), 572 (w), 516 (m). ESI MS (+m/z): Calcd for (M − OTf)^+1, 1145.24; Found 1145.26; Calcd for (M − 2OTf)^+2, 498.14; Found 498.15. Anal. Calcd for 3, Fe₂S₂F₆O₅N₅C₅₈H₅₂: C, 53.80; H, 4.05; N, 8.65. Found: C, 53.90; H, 3.95; N, 8.48.

[Fe₄(BBAN)(μ-O₂CAR°)]₃(OTf) (4). Treatment of Fe(OTf)₂·2MeCN (159 mg, 0.36 mmol) with BBAN (100 mg, 0.18 mmol) in MeCN (10 mL) afforded a pale yellow-brown solution. Solid NaO₂CAR° (175 mg, 0.54 mmol) was added and the reaction mixture
was stirred vigorously for 1 h to generate a pale orange solution. The solvent was evaporated under reduced pressure and the residue was dissolved in CH$_2$Cl$_2$ and filtered through Celite. Exposure of this solution to Et$_2$O vapor diffusion gave tan X-ray quality crystals of 4·2CH$_2$Cl$_2$ (225 mg, 73%). FT-IR (cm$^{-1}$, KBr): 3057 (m), 3027 (m), 2944 (w), 2920 (m), 2865 (w), 1606 (s), 1587 (s), 1560 (m), 1514 (m), 1496 (w), 1443 (s), 1406 (s), 1386 (s), 1307 (w), 1267 (s), 1222 (m), 1149 (s), 1110 (s), 1071 (w), 1031 (s), 979 (w), 942 (w), 914 (w), 885 (w), 823 (m), 805 (s), 788 (m), 743 (m), 729 (m), 703 (s), 636 (s), 584 (m), 533 (m). Anal. Calcd for 4·0.5CH$_2$Cl$_2$: Fe$_2$ClSF$_5$O$_9$N$_4$C$_{102.5}$H$_{95.5}$: C, 70.11; H, 5.05; N, 3.19. Found: C, 70.09; H, 5.17; N, 3.33.

[Fe$_x$(BEAN)(μ-O$_2$CAr$_{Tol}$)$_2$](OTf)$_3$ (5). A mixture of Fe(OTf)$_2$·2MeCN (145 mg, 0.33 mmol), BEAN (50 mg, 0.17 mmol), and NaO$_2$CAr$_{Tol}$ (162 mg, 0.50 mmol) in MeCN (20 mL) was vigorously stirred for 5 h. The suspension was filtered through a medium-porosity frit and a pale pink solid was collected. The filtrate was evaporated to dryness under reduced pressure, and the resulting solid was dissolved in CH$_2$Cl$_2$, filtered through Celite, and exposed to Et$_2$O vapor diffusion to give tan crystals of 5·CH$_2$Cl$_2$ that were suitable for X-ray diffraction study (44 mg, 18%). The pink solid that was initially collected on the frit was dissolved in MeOH, followed by evaporation of the solvent under reduced pressure. The residue was then dissolved in CH$_2$Cl$_2$ and exposed to Et$_2$O vapor diffusion to give additional 5 (112 mg, 45%). FT-IR (cm$^{-1}$, KBr): 3054 (w), 3025 (w), 2974 (w), 2936 (w), 2922 (w), 2887 (w), 1609 (m), 1586 (m), 1562 (m), 1514 (m), 1447 (m), 1408 (m), 1385 (s), 1306 (w), 1279 (s), 1261 (s), 1223 (m), 1112 (w), 1084 (w), 1031 (s), 974 (w), 945 (w), 870 (w), 834 (m), 780 (s), 765 (w), 733 (m), 704 (m), 637 (s), 612 (w), 581 (w), 533 (s). Anal. Calcd for 5, Fe$_2$SF$_5$O$_9$N$_4$C$_{92}$H$_{89}$: C, 67.22; H, 5.43; N, 3.82. Found: C, 67.13; H, 5.22; N, 3.98.

Bis(4-methylbenzyl)amine (6). This compound was prepared by an alternative route to published procedures and its properties matched well those reported in the literature. 36-38 A 500 mL round bottom flask was charged with 4-methylbenzylamine (5
mL, 0.039 moles), tolualdehyde (4.6 mL 0.039 moles), and NaBH(OAc)₃ (10.8 g, 0.051 moles) in dichloroethane (200 mL). The reaction mixture was stirred under Ar for 5 h, followed by addition of aqueous NaOH (1 M, 150 mL). The crude product was extracted with CH₂Cl₂ (~150 mL), dried over MgSO₄, and the solvent was removed by rotary evaporation to yield a pale yellow oil. Vacuum distillation afforded a colorless oil with a boiling point of 110 – 118 °C (0.15 Torr) that was placed under dynamic vacuum overnight to give 6 as a white solid (3.4 g, 39%). ¹H NMR (300 MHz, CDCl₃): δ 7.26 m (4H), 7.14 d (J = 26 Hz, 4H), 3.77 s (4H), 2.35 s (6H). FT-IR (cm⁻¹, thin film): 3047 (m), 3019 (m), 2920 (m), 2862 (m), 2819 (m), 1891 (w), 1514 (s), 1450 (m), 1378 (w), 1359 (w), 1303 (w), 1198 (w), 1177 (w), 1101 (m), 1040 (w), 1021 (w), 845 (w), 806 (s), 772 (m), 719 (w), 695 (w), 584 (m), 486 (m).

Procedures for Amine N-Dealkylation Studies. Samples were prepared and analyzed following a procedure described elsewhere. For the oxidation of bis(4-methylbenzyl)amine, 2 equiv (with respect to the diiron(II) compound) were added to a solution of 4 or 5 prior to addition of the oxidant.

Physical Measurements. ¹H NMR spectra were obtained on a 300 MHz Varian Unity spectrometer. FT-IR spectra were measured on a Thermo Nicolet Avatar 360 spectrometer. Optical spectra were collected on a Hewlett-Packard 8453 diode-array spectrophotometer; experiments were performed by using a custom-made quartz cuvette fused onto a vacuum-jacketed Dewar. EPR spectra of reaction mixtures of 2 with dioxygen were recorded as frozen solutions on a Bruker Model 300 ESP X-Band spectrometer (9.37 GHz) running WinEPR software. A specially designed cold finger with liquid N₂ was used to maintain the temperature at 77 K. ESI-MS spectra of 2 and 3 were obtained as solutions in MeCN on a Bruker Daltonics APEXII 3 Tesla Fourier Transform Mass Spectrometer in the MIT Department of Chemistry Instrumentation Facility.
**X-ray Crystallography.** Crystals were mounted in Paratone-N oil on the ends of glass capillaries and frozen into place under a low-temperature nitrogen cold stream. Data were collected on a Bruker (formerly Siemens) SMART (1, 4, 5) or APEX (3) CCD X-ray diffractometer running the SMART software package,\(^4^0\) with Mo Kα radiation (\(\lambda = 0.71073 \ \text{Å}\)), and refined using SAINT software.\(^4^1\) Details of the data collection and reduction protocols are described elsewhere.\(^4^2\) The structures were solved by direct methods using SHELXS-97 software\(^4^3\) and refined on \(F^2\) by using the SHELXL-97 program\(^4^4\) incorporated in the SHELXTL software package.\(^4^5\) Empirical absorption corrections were applied with SADABAS,\(^4^6\) and the possibility of higher symmetry was checked by the program PLATON.\(^4^7\) All non-hydrogen atoms were located and their positions refined with anisotropic thermal parameters by least-squares cycles and Fourier syntheses. Hydrogen atoms were assigned idealized positions and given a thermal parameter 1.2 times that of the carbon atom to which each was attached.

The structure of 3 contains one ordered and one disordered triflate counterion. The three positions of the disordered triflate moiety are located on an inversion center, a three-fold axis, and an inversion center combined with a three-fold axis, respectively. They are all fully occupied, but due to the symmetry, only contribute 50, 33, and 17% to the content of the asymmetric unit. Two of the partially occupied triflate units contained positionally disordered SO\(_3\) and CF\(_3\) moieties. A diethyl ether solvent molecule was refined with 33% occupancy. Additional high residual electron density (1.27 e Å\(^3\)) located on a special position near a triflate counterion was not modeled. The structure of 4 contains a CH\(_2\)Cl\(_2\) solvent molecule, the carbon and one chlorine atom of which were disordered and modeled over two positions, each with 50% occupancy. The carbon atom of the CH\(_2\)Cl\(_2\) solvent molecule in structure 5 was disordered over two positions, each refined with occupancies of 50%. In addition, two half-occupied triflate counterions were present in the lattice, the SO\(_3\) and CF\(_3\) components of which were
positionally disordered. Crystallographic information for compounds 1, 3, 4, and 5 is provided in Table 3.1.

**Electrochemistry.** Cyclic voltammograms were recorded in an MBraun glovebox under a nitrogen atmosphere using an EG&G Model 263 potentiostat. The cell contained a platinum working electrode, a Ag/AgNO₃ (0.1 M in MeCN) reference electrode, and a platinum wire auxiliary electrode. A 0.5 M Bu₄N(PF₆) solution was used as the supporting electrolyte. All measurements were externally referenced to ferrocene.

**Mössbauer Spectroscopy.** Mössbauer spectra (4.2 K) were recorded in the MIT Department of Chemistry Instrumentation Facility on an MS1 spectrometer (WEB Research Co.) with a ⁵⁷Co source in a Rh matrix kept at room temperature. Spectra were fit to Lorentzian line shapes by using the WMOSS plot and fit program⁴⁸ and isomer shifts were referenced to natural abundance Fe at room temperature. Solid samples were prepared by suspending powdered material (~0.04 mmol) in Apiezon N grease and placing the mixture in a nylon sample holder. Frozen solutions (~50 mM) were prepared by transferring ~800 µL of a solution generated in a septum-sealed vial to a nylon sample holder via a gastight syringe. The solutions were then flash-frozen in liquid N₂.

**Results**

**Synthesis and Structural Characterization of the Bis(carboxylato)diiron(II) Complex** [Fe₂(BPMAN)(μ-O₂CPh)₃J(OTf)₂ (1). The reaction of Fe(OTf)₂·2MeCN with BPMAN, PhCO₂H, and NEt₃ in a 2:1:2:2 ratio afforded compound 1 as a blue solid in good yield (79%). Figure 3.1 shows the structure of 1 and Table 3.2 lists selected bond lengths and angles. The crystallographically equivalent iron centers have distorted octahedral stereochemistry and are bridged by the naphthyridine moiety of BPMAN, as well as by the two benzoate ligands (Fe···Fe = 3.790(2) Å). The Fe–N(naphthyridine) bond length of 2.334(4) Å is substantially longer than the corresponding pyridine and
amine distances, which average to 2.208(2) Å. The carboxylate groups are coordinated
to the iron(II) centers with Fe–O distances of 2.088(3) and 1.994(3) Å, with the shorter
bond disposed trans to the amine nitrogen atom of BPMAN. The geometric parameters
of 1 are similar to that of the related complex [Fe₂(BPMAN)(μ-O₂CPhCy)₂](OTf)₂
prepared previously in our laboratory.²³

Synthesis and Characterization of the Hydroxide- and Methoxide-Bridged
Compounds [Fe₂(BPMAN)(μ-OH)(μ-O₂CAt₂)](OTf)₂ (2) and [Fe₂(BPMAN)(μ-
OMe)(μ-O₂CAt₂)](OTf)₂ (3). Compound 2 was prepared as a green flocculent solid in
high yield (87%) by allowing 2 equiv of Fe(OTf)₂·2MeCN to react with 1 equiv each of
BPMAN, NaO₂CAt₂, H₂O, and NEt₃. X-ray quality crystals of 2 could not be obtained
despite numerous attempts, but ESI-MS confirmed its identity. Two sets of signals that
correspond to monocations were detected. These were identified as the parent
compound, minus a triflate anion, in the presence (m/z = 1149.31) or absence (m/z =
1131.33) of a molecule of water. Signals belonging to dications were also identified and
assigned to the parent compound following loss of both triflate counterions ((M –
2OTf)²⁺, 491.13; [(M – 2OTf) + H₂O]²⁺, 500.11). The water was most likely introduced
from the MeCN solvent in which this measurement was performed. All four
experimental values match well with the calculated masses.

Recrystallization of 2 from a solution of MeOH and Et₂O afforded the methoxide
derivative, compound 3, in 78% yield. As with the hydroxide derivative, 3 was analyzed
by ESI-MS and signals corresponding to both the monocation (m/z = 1145.26) and
dication (m/z = 498.15) were observed. Fortunately, X-ray quality crystals of 3 were
obtained, permitting a full structural analysis. Figure 3.1 shows the structure and Table
3.2 lists selected bond lengths and angles. The two iron centers are triply-bridged by the
naphthylidyne unit of BPMAN and the carboxylate and methoxide ligands. The
metal–metal separation of 3.237(1) Å is contracted relative to that of 1 (ΔFe–Fe = 0.553(2)
Å), reflecting the presence of the single atom bridge in 3. The methoxide unit is
coordinated to the distorted octahedral iron(II) centers with Fe–O bond lengths of 1.959(2) and 2.030(3) Å, and the Fe–O–Fe bond angle is 108.48(12)°. The Fe–O distances of the bound ArTolCO₂⁻ ligand are 2.123(3) and 2.083(3) Å, and the Fe–N bonds average to 2.252(1) Å. The significant steric bulk of the carboxylate moiety forces the terphenyl group to lie approximately perpendicular to the Fe···Fe vector in order to avoid interaction with the pyridine groups of the BPMAN ligand. Attempts to prepare the bis(μ-carboxylato) complex were unsuccessful, but an examination of the structure of 3 reveals that such a compound is unlikely to form because of the resulting steric interactions. The position of the carboxylate ligand leaves the opposite face on which the methoxide unit is located largely exposed. The structural features of 3 closely resemble those of [Fe₂(BPMAN)(μ-OH)(μ-O₂CPhCy)](OTf)₂ 23 and a similar coordination environment is expected for the hydroxide-bridged complex 2.

Whereas numerous methoxide-bridged diiron(III) compounds are known, 49,54 a survey of the Cambridge Structural Database revealed that no dinuclear iron(II) complexes with bridging methoxide ligands have been crystallographically characterized. The (μ₅-OMe)triiron unit is frequently encountered, however, as a component of iron(II) alkoxide cubes 55,56 and in mixed-valent dodecairon oxo compounds. 57-59 The octadentate BPMAN ligand and the sterically hindered ArTolCO₂⁻ moieties of 3 stabilize the coordination of methoxide as a ligand bridge between only two metal ions, preventing the formation of higher nuclearity species.

**Preparation and Crystallographic Analysis of the Paddle-Wheel Compounds**

[Fe₂(BBAN)(μ-O₂CArTol)₂](OTf) (4) and [Fe₂(BEAN)(μ-O₂CArTol)₂](OTf) (5). The synthesis of complex 4 was achieved by allowing 2 equiv of Fe(OTf)₂·2MeCN to react with BBAN and Na₂O₂Ar₂Tol in a 1:3 ratio. Tan crystals of 4 were obtained in good yield (73%) upon recrystallization from CH₂Cl₂/Et₂O. The structure of 4 is shown in Figure 3.1 and selected bond lengths and angles are provided in Table 3.3. In addition to the naphthyridine unit of BBAN, the pseudo square pyramidal iron centers are bridged by
three carboxylate ligands. The quadruply-bridged core results in a short Fe···Fe separation of 2.854(2) Å, similar to the inter-metal distances of tetrakis(μ-carboxylato)diiron(II) complexes.\textsuperscript{60-62} The Fe–N bond lengths in 4 are demonstrably shorter (Fe–N, = 2.181(2) Å) than the corresponding bonds in 1 and 3 (Δ_{Fe–N} = 0.102(4) and 0.0980(3) Å, respectively), reflecting the lower coordination number of the iron centers in 4. The Fe–O bond lengths range from 2.035(3) to 2.110(3) Å with one metal site, Fe(2), having a particularly long Fe–O bond (Fe(2)–O(4) = 2.110(3) Å) and an unusually short Fe–N bond length (Fe(2)–N(2) = 2.138(4) Å). Since the 1,8-naphthyridine moiety can be thought of as a masked carboxylate, the structure of 4 is best described as a paddle-wheel, with four approximately orthogonal adjacent "carboxylate" groups.

Complex 5 was prepared by following a similar procedure, except that the ligand BEAN bearing dangling ethyl groups was used in place of the benzyl derivative BBAN. The resulting tan crystalline solid was initially isolated in low yield (18%) due to the precipitation of a pink material over the course of the reaction. Although not soluble in MeCN, CH\textsubscript{2}Cl\textsubscript{2}, or THF, this solid could be dissolved in MeOH and single crystals were grown from a solution of MeOH and Et\textsubscript{2}O. An X-ray diffraction study of these crystals revealed the structure of 5. Presumably, the pink solid that initially forms is a polymeric material that converts into discrete dinuclear units in MeOH. Therefore, recrystallization of this solid increases the isolated yield of 5 to 63%.

Figure 3.1 shows the structure of 5 and pertinent bond lengths and angles are listed in Table 3.3. The square pyramidal iron(II) centers are separated by 2.890(1) Å, and the average Fe–N and Fe–O bond lengths of this paddle-wheel complex are 2.189(2) and 2.061(1) Å, respectively. The structural parameters of 4 and 5 are similar, and match well with those of the related compound [Fe\textsubscript{2}(BEAN)(μ-O\textsubscript{2}CPhCy)_\textsubscript{2}](OTf).\textsuperscript{23}

\textbf{Mössbauer Spectroscopic Properties of Diiron(II) Compounds.} Zero-field Mössbauer spectra of powdered samples of 1 - 4 were recorded at 4.2 K. Spectra are
displayed in Figure 3.2, and extracted parameters are provided in Table 3.4. The isomer shifts and quadrupole splittings are typical of high-spin iron(II) compounds in an N/O coordination environment. The extracted Mössbauer parameters of the four compounds closely resemble those of related complexes. Noteworthy is the spectrum of 4, in which the two quadrupole doublets are well resolved. The doublets were fit with identical isomer shifts and significantly different quadrupole splitting values, \( \Delta(\Delta E_Q) = 0.9 \text{ mm s}^{-1} \). This model was chosen over one in which the two doublets have similar quadrupole splitting parameters \( (\delta_1 = 1.29(2), \Delta E_{Q1} = 2.45(2), \delta_2 = 0.84(2), \Delta E_{Q2} = 2.44(2) \text{ mm s}^{-1} ) \) because of the unusually low value of \( \delta_2 \) required to fit the data. Two well-defined doublets were similarly observed in the Mössbauer spectrum of [Fe₂(BEAN)(μ-O₂CPhCy)₃](OTf). Both 4 and [Fe₂(BEAN)(μ-O₂CPhCy)₃](OTf) contain one iron site, Fe(2) in 4, that is in a more asymmetric environment than the other. As suggested for [Fe₂(BEAN)(μ-O₂CPhCy)₃](OTf), the crystallographically observed asymmetry of the iron centers in 4 may give rise to the large difference in quadrupole splitting parameters.

**Reactions of 1 with Dioxygen and H₂O₂.** The reaction between 1 and dioxygen was monitored by UV-visible spectroscopy. A solution of 1 in CH₂Cl₂ is blue, and we assign the optical band \( (\lambda_{\text{max}} = 600 \text{ nm}; \varepsilon = 1800 \text{ M}^{-1} \text{ cm}^{-1}) \) as a metal-to-ligand charge transfer (MLCT) transition. Compound 1 is unreactive towards dioxygen at -78 °C, but at room temperature two new features appear at 450 nm \( (\varepsilon = 1700 \text{ M}^{-1} \text{ cm}^{-1}) \) and 500 nm \( (\varepsilon = 1500 \text{ M}^{-1} \text{ cm}^{-1}) \) over a period of 2 h. Similar behavior was observed when the oxygenation was carried out in MeCN. As shown in Figure 3.3A, treatment of 1 with H₂O₂ in MeCN at -40 °C resulted in clean conversion to a similar species with shoulders at 450 nm \( (\varepsilon = 1900 \text{ M}^{-1} \text{ cm}^{-1}) \) and 500 nm \( (\varepsilon = 1500 \text{ M}^{-1} \text{ cm}^{-1}) \). These spectral features are consistent with the formation of a (μ-oxo)diiron(III) complex. The frozen solution Mössbauer spectrum of 1 following treatment with H₂O₂ in MeCN revealed a new species that was fit as a quadrupole doublet with \( \delta = 0.47(2) \) and \( \Delta E_Q = 1.59(2) \text{ mm s}^{-1} \).
(Figure 3.3B). These parameters are typical for high-spin iron(III) centers and resemble those of (μ-oxo)(μ-carboxylato)n diiron(III) (n = 1 or 2) cores supported in nitrogen-rich ligand frameworks.\textsuperscript{67,71,72} Because both iron centers of 1 are six-coordinate, the introduction of a bridging oxo ligand would probably be accompanied by a carboxylate shift\textsuperscript{73} to make available the requisite O-binding sites, as has been suggested for both diiron model compounds and protein cores.\textsuperscript{68,74-76}

**Formation of Fe(II)Fe(III) Species from Compounds 2 and 3.** Upon exposure to dioxygen, a green solution of 2 in CH\textsubscript{2}Cl\textsubscript{2} gradually turns brown. Within ~20 min, a new band, shown in Figure 3.4A, at 430 nm (ε = 6000 M\textsuperscript{-1} cm\textsuperscript{-1}) forms, and decay of this same band begins within 1 h. The final product has shoulders at 450 and 500 nm (ε ~ 2000 and 1500 M\textsuperscript{-1} cm\textsuperscript{-1}, respectively). Similar behavior was observed with the methoxide derivative 3. The spectral features of the oxidation product of 2 resemble those resulting from the oxidation of 1, and suggest that the final species is a (μ-oxo)diiron(III) complex. The Mössbauer spectrum of this compound (δ = 0.46(2) and ΔE\textsubscript{Q} = 1.71(2) mm s\textsuperscript{-1}, Figure 3.4B) is consistent with high-spin Fe(III) centers and the large quadrupole splitting value is characteristic of a bridging oxo ligand.

In order to investigate the nature of the intermediate (λ\textsubscript{max} = 430 nm), EPR spectroscopy was employed. At 77 K, the diiron(II) compound is EPR silent. A signal was observed, however, one minute after oxygenation of the solution. Figure 3.5 displays the resulting rhombic spectrum with g\textsubscript{x} = 1.98, g\textsubscript{y} = 1.94, and g\textsubscript{z} = 1.78, typical of antiferromagnetically coupled high-spin Fe(II)Fe(III) ions having an S = 1/2 ground state.\textsuperscript{77} The S = 1/2 signal accounts for up to 20 % of the total iron content in the sample, consistent with UV-visible spectroscopic studies that reveal the intermediate to decompose more rapidly at the concentrations used for the EPR measurements (1 - 5 mM), and with the Mössbauer spectrum of the final oxidized product showing ~ 50% of unreacted 2. A much weaker signal at g ~ 4 (not shown) may arise from a mononuclear impurity. Spectra recorded at later time points (5 - 195 min after oxygenation) are more
isotropic and less intense. The EPR spectrum of the intermediate matches well those of
(μ-oxo)diiron(II,III) centers prepared by chemical,\textsuperscript{78} electrochemical,\textsuperscript{79} and radiolytic
methods,\textsuperscript{80-82} and is distinct from those of (μ-hydroxo)diiron(II,III) systems.\textsuperscript{81-83}

We interpret these spectroscopic features to arise from the formation of a mixed-
valent, oxo-bridged Fe(II)Fe(III) intermediate that decomposes to a (μ-oxo)diiron(III)
species. A similar reaction was observed in the oxidation of a series of (μ-
hydroxo)diiron(II) complexes supported by Me\textsubscript{3}tacn ligands in MeCN and was
attributed to outer-sphere electron transfer.\textsuperscript{78} In contrast, the mixed-valent intermediate
is not observed when the oxidation of 2 is performed in MeCN, possibly because the
reaction of 2 with dioxygen occurs by an inner-sphere mechanism, in which a
carboxylate shift is necessary to open a site for dioxygen coordination. Use of a
coordinating solvent such as MeCN may prevent direct interaction between the iron(II)
center and dioxygen. Mixed-valent diiron(II,III) species also result from the reaction
between dioxygen and the carboxylate-rich compounds [Fe\textsubscript{2}(μ-O\textsubscript{2}C\textsubscript{6}H\textsubscript{5}Ar\textsuperscript{Tol})\textsubscript{2}(O\textsubscript{2}C\textsubscript{6}H\textsubscript{5}Ar\textsuperscript{Tol})\textsubscript{2}-(C\textsubscript{5}H\textsubscript{5}N)\textsubscript{2}] and [Fe\textsubscript{2}(μ-O\textsubscript{2}C\textsubscript{6}H\textsubscript{5}Ar\textsuperscript{Tol})\textsubscript{4}(4-ButC\textsubscript{6}H\textsubscript{4}N)\textsubscript{2}]\textsuperscript{84-86} The reaction chemistry of these two
compounds, however, differs significantly from that of the (μ-hydroxo)diiron
complexes discussed above. The postulated mechanism\textsuperscript{84} involves oxidation of the
diiron(II) compound by dioxygen to generate a putative peroxo [Fe\textsuperscript{II}(O\textsubscript{2}\textsuperscript{2+})]\textsuperscript{4+} or bis(μ-
oxo) [Fe\textsuperscript{IV}(O\textsuperscript{2+})]\textsuperscript{4+} intermediate which reacts rapidly with a second equivalent of the
initial diiron(II) complex to afford equimolar mixtures of valence-delocalized Fe\textsuperscript{II}Fe\textsuperscript{III}
and valence-trapped Fe\textsuperscript{III}Fe\textsuperscript{IV} species.

**Oxidative N-Dealkylation Effected by 4.** Compound 4 rapidly reacts with
dioxygen in CH\textsubscript{2}Cl\textsubscript{2} to yield a brown solution that exhibits a broad feature extending
across the entire visible region. Similar spectra were observed over a wide temperature
range (-78 to 23 °C) and also by addition of H\textsubscript{2}O\textsubscript{2} to a solution of 4 in MeCN (-40 to 23
°C). The recent observation of oxidative N-dealkylation of activated benzyl groups in
the complex [Fe\textsubscript{2}(μ-O\textsubscript{2}C\textsubscript{6}H\textsubscript{5}Ar\textsuperscript{Tol})\textsubscript{4}(N,N-Bn\textsubscript{2}en)\textsubscript{2}] following exposure to dioxygen\textsuperscript{39,87} led us to
analyze solutions of 4 + O₂ for ligand oxidation. GC-MS analysis revealed that benzaldehyde was indeed generated by oxidation of 4. With O₂ in CH₂Cl₂, PhCHO formed in 30% yield relative to 4, and a 51% yield was obtained when H₂O₂ in MeCN was employed.

The ability of 4 to promote the oxidation of external substrates was also examined. Gentle purging by dioxygen of a CH₂Cl₂ solution of 4 and bis(4-methylbenzyl)amine yielded both PhCHO and tolualdehyde in a ratio of ~1:1 (Scheme 3.1). When the reaction was performed using H₂O₂ in MeCN, a copious amount of precipitate formed; analysis of the reaction mixture by GC and GC-MS was precluded by similar retention times of tolualdehyde and the other products that formed. Other substrates were screened; PPh₃ did not convert to Ph₃PO nor did oxidation of 9,10-dihydroanthracene afford anthracene. Use of 2,4-di-tert-butylphenol did not generate the corresponding biphenol, although the solution dramatically changed color to dark blue, most likely the result of a phenoxide-to-iron(III) charge transfer band. The coordination of the phenol to the iron center was accompanied by a substantial decrease in PhCHO production (O₂, 7%; H₂O₂, 39%). Taken together, these results suggest that the oxidation chemistry does not proceed by a simple hydrogen atom abstraction mechanism and that the amine oxidation is not due to an organic radical.

**Comparison of Substrate Oxidation by 4 and 5.** The relatively inefficient yield of tolualdehyde by 4 led us to study the oxidation chemistry of compound 5. Replacement of the pendant benzyl groups of the BBAN ligand of 4 with the ethyl groups of BEAN was expected to eliminate oxidative N-dealkylation of the ligand framework due to the significantly stronger (12 kcal/mol) C–H bonds of the ethyl substituents. We hypothesized that elimination of ligand oxidation might lead to higher yields for the oxidation of external substrates, owing to diminished competition from an internal ligand fragment.
Reaction of 5 with dioxygen in CH₂Cl₂ afforded a brown solution with a broad feature in the optical spectrum, similar to that observed for 4. Analysis of the reaction mixture by GC revealed no acetaldehyde, a product that would form following N-dealkylation. This conclusion was confirmed by a colorimetric test for CH₃CHO,⁹⁰ which similarly gave a negative result. Acid decomposition of the oxidized species, followed by analysis using ¹H NMR spectroscopy, showed the BEAN ligand to be intact, with no indication that hydroxylation of the ethyl groups had occurred. Exposure of a solution of 5 and bis(4-methylbenzyl)amine to dioxygen afforded tolualdehyde in only ~0.8%. A possible explanation for this low yield is that a carboxylate shift is required in order to allow approach of the amine to the iron centers. In the absence of such a structural change, the amine cannot easily access the iron sites of 5 and formation of aldehyde is negligible.

**Electrochemical Studies.** Cyclic voltammograms (CVs) of compounds 1, 2, and 4 in CH₂Cl₂ were recorded to study their relative ease of oxidation. The CV of the bis(μ-carboxylato) complex 1, shown in Figure 3.6, reveals two reversible redox waves with \( E_{1/2} \) values of +310 mV (\( \Delta E_p = 80 \) mV) and +733 mV (\( \Delta E_p = 94 \) mV) vs Cp₂Fe⁺/Cp₂Fe, corresponding to the \( \text{Fe}^{III}\text{Fe}^{II}/\text{Fe}^{II}\text{Fe}^{II} \) and \( \text{Fe}^{III}\text{Fe}^{II}/\text{Fe}^{III}\text{Fe}^{II} \) couples, respectively. These redox waves are reversible only when each is studied in isolation; irreversible behavior occurs on the return reduction scan when the two oxidation sweeps are carried out consecutively. The unusually sharp peak on the return scan probably indicates compound decomposition. The related compound \([\text{Fe}_2(\text{BPMAN})(\mu-\text{O}_2\text{CPhCy})_2]\)OTf, which has \( E_{1/2} \) values of +296 mV (\( \Delta E_p = 80 \) mV) and +781 mV (\( \Delta E_p = 74 \) mV), was the first carboxylate-bridged diiron(II) complex without an additional single atom bridge to exhibit two, rather than just one, reversible redox waves.²³ Probably, the larger PhCyCO₂⁻ ligands are better able to stabilize the \( \text{Fe}^{III}\text{Fe}^{II}/\text{Fe}^{II}\text{Fe}^{II} \) and \( \text{Fe}^{III}\text{Fe}^{II}/\text{Fe}^{III}\text{Fe}^{II} \) couples than the benzoate groups of 1.
The CV of the ($\mu$-hydroxo)($\mu$-carboxylato) compound 2, presented in Figure 3.7, shows a reversible redox wave with an $E_{1/2}$ value of $+11$ (AE_p = 82 mV) vs Cp_2Fe'/Cp_2Fe when potentials less than 400 mV are applied. As observed with [Fe_2(BPMAN)($\mu$-OH)($\mu$-O_2CPPhCy)](OTf)_2,^{23} higher potentials caused the reduction wave to split into three components. The redox potential of 2 is 33 mV above that of the PhCyCO_2 derivative, consistent with aromatic ligands being less donating than alkyl groups, and 299 mV below that of 1, reflecting the more donating nature of the hydroxide unit.

The CV of the paddle-wheel compound 4 displays irreversible oxidation at potentials above +1000 mV vs Cp_2Fe*/Cp_2Fe. This result can be compared to the irreversible electrochemistry exhibited by [Fe_2(BEAN)($\mu$-O_2CPPhCy)_3](OTf) at potentials above +400 mV^{23} and the reversible behavior of [Fe_2($\mu$-O_2CAr^tλ3)(4'-BuC_6H_4N)_2] (E_{1/2} = -216 mV).^{91} The studies with [Fe_2(BEAN)($\mu$-O_2CPPhCy)_3](OTf) made clear the need for a fourth carboxylate ligand to stabilize a diiron(II,III) species in compounds with these paddle-wheel motifs. The significant difference in oxidation potential between 4 and [Fe_2(BEAN)($\mu$-O_2CPPhCy)_3](OTf) ($\Delta E_{1/2} = 600$ mV) is consistent with the more electron-withdrawing ligand environment of 4, but since the processes are irreversible, a more quantitative explanation cannot be offered. Unlike 4, [Fe_2(BEAN)($\mu$-O_2CPPhCy)_3](OTf) is not sensitive to dioxygen, but this property is not probably due to electronic differences since the opposite behavior would be expected based on $E_{1/2}$ values.

**Discussion**

The naphthyridine moiety of the ligands BPMAN, BBAN, and BEAN can be viewed as a "masked carboxylate," because the two units bridge metal ions in an analogous manner. In particular, both moieties facilitate the synthesis of dimetallic compounds that feature the $\mu$-1,3-coordination mode found at the active sites of carboxylate-bridged dinuclear metalloproteins. The multidentate nature of the naphthyridine ligands, afforded by appendages that are readily installed and
positioned to coordinate to the bridged dimetallic center, ensure that a dinuclear core is maintained not only in the diiron(II) starting compounds, but also in their subsequent oxidation products. This property is much more difficult to achieve with substituted carboxylate ligands. By varying both the naphthyridine fragment and the ancillary ligands, a variety of diiron(II) compounds was prepared. Use of the relatively compact benzoate unit in conjunction with the octadentate BPMAN ligand afforded the bis(μ-carboxylato)diiron(II) core of complex 1. Such a species cannot be accommodated with the sterically-demanding Ar^TolCO_2 ligand, and when this ligand is employed, only one bridging carboxylate group is encountered. The resulting complexes 2 and 3 incorporate as their third bridging ligand the less sterically demanding, single-atom hydroxide and methoxide groups, respectively. When the tetradentate ligands BBAN and BEAN were employed, the paddle-wheel compounds 4 and 5 were readily assembled. In addition to promoting the quadruply bridged core of these complexes, BBAN and BEAN also serve to bring potential substrates, benzyl and ethyl substituents, respectively, into close proximity to the diiron core.

The electrochemical properties of the naphthyridine-based diiron(II) complexes reflect the expected trend of ligands bearing electron-donating substituents, which convey lower redox potentials. A comparison of the cyclic voltammograms of 1 and the related compound [Fe_2(BPMAN)(μ-O_2CPhCy)_2](OTf)_2 reveals the latter to have a more reversible second oxidation wave, which may imply that the higher oxidation state is better stabilized by bulkier ligands. If so, it suggests a design strategy for future synthetic work aimed at accessing higher oxidation level diiron complexes. In general, the compounds exhibiting low redox potentials react with dioxygen or H_2O_2 more readily than those with higher oxidation values. Complex 4, however, is more reactive toward O_2 despite its high redox potential, which we attribute to the need for a carboxylate shift.
The dinucleating nature of the 1,8-naphthyridine-based ligands allowed the reactivity of compounds 1 - 5 to be probed within an environment constrained to enforce dimetallic character. This feature is important because the related non-heme diiron enzymes rigorously maintain dinuclear cores. In contrast, the nuclearity or ligand composition of active oxidants in model systems that display substrate oxidation is often uncertain.\textsuperscript{92-94} The oxidation of compounds 1 - 3 to afford (\(\mu\)-oxo)diiron(III) and (\(\mu\)-oxo)Fe(II)Fe(III) species mirrors well-documented reactivity between Fe(II) compounds and dioxygen. Although oxidation of mononuclear iron(II) compounds to afford oxo-bridged diiron(III) units can occur,\textsuperscript{95-97} in the present case we can rule out such a pathway owing to the dinucleating nature of the ligands.

Oxidative N-dealkylation of the benzyl groups of the BBAN ligand or of added bis(4-methylbenzyl)amine to form PhCHO and tolualdehyde, respectively, was observed in the reaction of 4 with dioxygen or \(\text{H}_2\text{O}_2\). Such reactivity is common with iron porphyrins,\textsuperscript{98} but in non-heme diiron systems it is limited to the reaction of [Fe\(_2\)(\(\mu\)-O\(_2\)CAR\(\text{Tol}\))\(_4\)(N\(_2\)-Bn\(_2\)en)] with dioxygen.\textsuperscript{39,87} Oxidative N-dealkylation of 4 is thus a worthy addition to the emerging class of diiron compounds displaying this chemistry. Consistent with the stronger C-H bonds of the ethyl substituents of BEAN in 5, N-dealkylation with this compound was not observed.

**Conclusions**

A major aim of this work was to delineate the requirements for accessing \(\text{O}_2\)-activating non-heme diiron(II) compounds of controlled nuclearity. Although the 1,8-naphthyridine-based ligands employed in this study did not allow the detection of [Fe\(_2\)(O\(_2\))]\(_2\) adducts, the dinuclear structures of both the starting diiron(II) compounds and the oxidized products were kinetically controlled by the multidentate ligand scaffolds. Enhanced dioxygen reactivity was achieved by introduction of electron-donating or coordinately flexible ligands. Inner-sphere reactions between the diiron core and
dioxygen are implied, and carboxylate ligands are good candidates to promote this reaction because of their ability to adopt different coordinate modes in order to allow access to the iron centers.

The activation of C–H bonds, the ultimate goal in modeling non-heme diiron enzymes, requires the substrate to be in close proximity to the active \( \text{Fe}_2(\text{O})_2 \) oxidant. The studies with compound 4 show that an intermediate can be intercepted by appending the substrate to the supporting ligand scaffold, thus promoting accessibility to the diiron core. This strategy, therefore, suggests a viable route for achieving efficient activation of C–H bonds by diiron compounds. In the related non-heme diiron enzymes, the dinuclear core is proximal to a substrate-binding cavity. The design and construction of such a feature into future ligand frameworks remains an important future objective for the preparation of fully functional model compounds.

Acknowledgements. This work was supported by grants from the National Science Foundation and National Institute of General Medical Sciences. I thank NSERC for a graduate student fellowship, Drs. Bernhard Spingler and Sumitra Mukhopadhyay for assistance with the crystallographic analyses, Mr. Sungho Yoon for help in acquiring the Mössbauer spectra, and Ms. Li Li of the MIT Department of Chemistry Instrumentation Facility for performing the ESI-MS measurements of compounds 2 and 3.
References


(30) Abbreviations used: OTf = triflate; Ar\textsuperscript{Roe}CO\textsuperscript{2} = 2,6-di(p-tolyl)benzoate; BPMAN = 2,7-bis[bis(2-pyridylmethyl)aminomethyl]-1,8-naphthyridine; BBAN = 2,7-bis(N,N-dibenzylaminomethyl)-1,8-naphthyridine; BEAN = 2,7-bis(N,N-diethylaminomethyl)-1,8-naphthyridine; PhCyCO\textsuperscript{2} = 1-phenylcyclohexanecarboxylate; Me\textsubscript{3}tacn = 1,4,7-trimethyl-1,4,7-triazacyclononane.


(41) SAINT v5.01: Software for the CCD Detector System; Bruker AXS: Madison, WI, 1998.
(46) Sheldrick, G. M. SADABS: Area-Detector Absorption Correction; University of Göttingen: Göttingen, Germany, 1996.


(66) Baik, M.; Kuzelka, J.; Lippard, S. J.; Friesner, R. A. Unpublished results. Transition dipole moment calculations on 2 indicate that the HOMO-LUMO electronic transition probability, $|\mu|^2$, is 0.056 Debye$^2$. This corresponds to a metal-to-ligand charge transfer excitation.


<table>
<thead>
<tr>
<th>Formula</th>
<th>1·CH₂Cl₂</th>
<th>3·0.3Et₂O</th>
<th>4·2CH₂Cl₂</th>
<th>5·CH₂Cl₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₆₁H₄₂N₆Fe₂O₁₆S₂FeCl₂</td>
<td>C₅₉H₅₃N₆Fe₂O₂S₃S₂F₂</td>
<td>C₁₀₆H₈₇N₆Fe₂O₅SF₃Cl₄</td>
<td>C₈₅H₇₉N₆Fe₂O₅SF₃Cl₂</td>
<td></td>
</tr>
<tr>
<td><strong>Formula</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>fw</strong></td>
<td>1287.65</td>
<td>1316.24</td>
<td>1879.34</td>
<td>1548.16</td>
</tr>
<tr>
<td><strong>Space Group</strong></td>
<td>Pccn</td>
<td>R3</td>
<td>Pt</td>
<td>C2/c</td>
</tr>
<tr>
<td><strong>a, Å</strong></td>
<td>22.383(3)</td>
<td>29.007(3)</td>
<td>13.525(5)</td>
<td>20.150(3)</td>
</tr>
<tr>
<td><strong>b, Å</strong></td>
<td>13.4299(15)</td>
<td>15.559(5)</td>
<td>20.181(3)</td>
<td></td>
</tr>
<tr>
<td><strong>c, Å</strong></td>
<td>18.332(2)</td>
<td>37.806(5)</td>
<td>23.417(5)</td>
<td>19.832(3)</td>
</tr>
<tr>
<td><strong>α, deg</strong></td>
<td>84.290(5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>β, deg</strong></td>
<td>89.860(5)</td>
<td>114.242(2)</td>
<td>68.820(5)</td>
<td></td>
</tr>
<tr>
<td><strong>γ, deg</strong></td>
<td></td>
<td></td>
<td></td>
<td>68.820(5)</td>
</tr>
<tr>
<td><strong>V, Å³</strong></td>
<td>5510.6(11)</td>
<td>27549(5)</td>
<td>4569(2)</td>
<td>7353.4(18)</td>
</tr>
<tr>
<td><strong>Z</strong></td>
<td>4</td>
<td>18</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td><strong>T, °C</strong></td>
<td>-85</td>
<td>-100</td>
<td>-80</td>
<td>-80</td>
</tr>
<tr>
<td><strong>ρ Calcd. g cm⁻³</strong></td>
<td>1.552</td>
<td>1.428</td>
<td>1.366</td>
<td>1.398</td>
</tr>
<tr>
<td><strong>μ (Mo Kα), mm⁻¹</strong></td>
<td>0.784</td>
<td>0.623</td>
<td>0.525</td>
<td>0.566</td>
</tr>
<tr>
<td><strong>θ Range, deg</strong></td>
<td>1.77-25.00</td>
<td>1.35-25.00</td>
<td>1.41-25.00</td>
<td>2.02-28.28</td>
</tr>
<tr>
<td><strong>Total No. of Data</strong></td>
<td>26661</td>
<td>67805</td>
<td>24043</td>
<td>22797</td>
</tr>
<tr>
<td><strong>No. of Unique Data</strong></td>
<td>4848</td>
<td>10788</td>
<td>15910</td>
<td>8431</td>
</tr>
<tr>
<td><strong>Observed Data</strong></td>
<td>3320</td>
<td>8273</td>
<td>10503</td>
<td>6809</td>
</tr>
<tr>
<td><strong>No. of Parameters</strong></td>
<td>368</td>
<td>782</td>
<td>1164</td>
<td>512</td>
</tr>
<tr>
<td><strong>R</strong></td>
<td>0.0627</td>
<td>0.0627</td>
<td>0.0759</td>
<td>0.0632</td>
</tr>
<tr>
<td><strong>wR²</strong></td>
<td>0.1488</td>
<td>0.1639</td>
<td>0.1964</td>
<td>0.1644</td>
</tr>
<tr>
<td><strong>Max. Min. Peaks, e Å⁻³</strong></td>
<td>1.178, -0.587</td>
<td>1.271, -0.310</td>
<td>1.064, -1.184</td>
<td>0.613, -0.960</td>
</tr>
</tbody>
</table>

a Observation criterion: I > 2σ(I). b R = Σ ||Fo| - |Fc|| / Σ |Fo|. c wR² = [Σ[w(Fo²-FC²)²] / Σ[w(Fo²)]]¹/².
Table 3.2. Selected bond lengths (Å) and angles (deg) for 1 and 3

<table>
<thead>
<tr>
<th></th>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fe(1)--Fe(1A)</td>
<td>N(4)--Fe(1)--O(1)</td>
</tr>
<tr>
<td>1</td>
<td>Fe(1)--N(1)</td>
<td>N(3)--Fe(1)--N(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--N(2)</td>
<td>N(3)--Fe(1)--O(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--N(3)</td>
<td>N(2)--Fe(1)--N(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--N(4)</td>
<td>N(2)--Fe(1)--O(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--O(1)</td>
<td>N(1)--Fe(1)--O(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--O(2)</td>
<td>N(2)--Fe(1)--O(1)</td>
</tr>
<tr>
<td>3</td>
<td>Fe(1)--Fe(2)</td>
<td>Fe(1)--O(3)--Fe(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--N(1)</td>
<td>O(1)--Fe(1)--O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--N(3)</td>
<td>O(2)--Fe(2)--O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--N(4)</td>
<td>N(3)--Fe(1)--O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--N(5)</td>
<td>N(4)--Fe(1)--O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--O(1)</td>
<td>N(5)--Fe(1)--O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)--O(3)</td>
<td>N(1)--Fe(1)--O(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)--N(2)</td>
<td>N(4)--Fe(1)--O(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)--N(6)</td>
<td>N(6)--Fe(2)--O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)--N(7)</td>
<td>N(7)--Fe(2)--O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)--N(8)</td>
<td>N(8)--Fe(2)--O(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)--O(2)</td>
<td>N(2)--Fe(2)--O(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)--O(3)</td>
<td>N(6)--Fe(2)--O(2)</td>
</tr>
</tbody>
</table>

\(^a\) Number in parentheses are estimated standard deviations of the last significant figure. Atoms are labeled as indicated in Figure 3.1.
Table 3.3. Selected bond lengths (Å) and angles (deg) for 4 and 5

<table>
<thead>
<tr>
<th></th>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe(1)···Fe(2)</td>
<td>2.854(2)</td>
<td>N(1)–Fe(1)–O(1)</td>
</tr>
<tr>
<td>Fe(1)–N(1)</td>
<td>2.205(4)</td>
<td>N(1)–Fe(1)–O(3)</td>
</tr>
<tr>
<td>Fe(1)–N(3)</td>
<td>2.197(4)</td>
<td>O(1)–Fe(1)–O(5)</td>
</tr>
<tr>
<td>Fe(1)–O(1)</td>
<td>2.072(3)</td>
<td>N(3)–Fe(1)–O(1)</td>
</tr>
<tr>
<td>Fe(1)–O(3)</td>
<td>2.035(3)</td>
<td>N(3)–Fe(1)–O(5)</td>
</tr>
<tr>
<td>Fe(1)–O(5)</td>
<td>2.066(3)</td>
<td>N(3)–Fe(1)–O(3)</td>
</tr>
<tr>
<td>Fe(2)–N(2)</td>
<td>2.138(4)</td>
<td>N(2)–Fe(2)–O(2)</td>
</tr>
<tr>
<td>Fe(2)–N(4)</td>
<td>2.182(4)</td>
<td>N(2)–Fe(2)–O(4)</td>
</tr>
<tr>
<td>Fe(2)–O(2)</td>
<td>2.068(3)</td>
<td>O(2)–Fe(2)–O(6)</td>
</tr>
<tr>
<td>Fe(2)–O(4)</td>
<td>2.110(3)</td>
<td>O(4)–Fe(2)–O(6)</td>
</tr>
<tr>
<td>Fe(2)–O(6)</td>
<td>2.038(3)</td>
<td>N(4)–Fe(2)–O(4)</td>
</tr>
<tr>
<td><strong>5</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe(1)···Fe(1A)</td>
<td>2.890(1)</td>
<td>N(1)–Fe(1)–O(1)</td>
</tr>
<tr>
<td>Fe(1)–N(1)</td>
<td>2.207(3)</td>
<td>N(1)–Fe(1)–O(2)</td>
</tr>
<tr>
<td>Fe(1)–N(2)</td>
<td>2.170(3)</td>
<td>O(1)–Fe(1)–O(3)</td>
</tr>
<tr>
<td>Fe(1)–O(1)</td>
<td>2.045(2)</td>
<td>O(2)–Fe(1)–O(3)</td>
</tr>
<tr>
<td>Fe(1)–O(2)</td>
<td>2.089(2)</td>
<td>N(2)–Fe(1)–O(1)</td>
</tr>
<tr>
<td>Fe(1)–O(3)</td>
<td>2.048(2)</td>
<td>N(2)–Fe(1)–O(3)</td>
</tr>
</tbody>
</table>

\(^a\) Number in parentheses are estimated standard deviations of the last significant figure. Atoms are labeled as indicated in Figure 3.1.
Table 3.4. Summary of Mössbauer parameters for compounds 1 - 4 recorded at 4.2 K (mm s\(^{-1}\))

<table>
<thead>
<tr>
<th>Complex</th>
<th>(\delta)</th>
<th>(\Delta E_Q)</th>
<th>(\Gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.16(2)</td>
<td>3.03(2)</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>1.13(2)</td>
<td>2.66(2)</td>
<td>0.28</td>
</tr>
<tr>
<td>3</td>
<td>1.14(2)</td>
<td>2.62(2)</td>
<td>0.27 ((\Gamma_1))</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.29 ((\Gamma_2))</td>
</tr>
<tr>
<td>4</td>
<td>1.06(2)</td>
<td>1.99(2)</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>1.06(2)</td>
<td>2.89(2)</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Chart 3.1.
Chart 3.2.
Scheme 3.1.
Figure 3.1. ORTEP diagrams of the cations of \([\text{Fe}_2(\text{BPMAN})(\mu-\text{O}_2\text{CPh})_2](\text{OTf})_2\) (1), \([\text{Fe}_2(\text{BPMAN})(\mu-\text{OMe})(\mu-\text{O}_2\text{C}^\text{Ar}^{\text{To}})](\text{OTf})_2\) (3), \([\text{Fe}_2(\text{BBAN})(\mu-\text{O}_2\text{C}^\text{Ar}^{\text{To}})](\text{OTf})\) (4), and \([\text{Fe}_2(\text{BEAN})(\mu-\text{O}_2\text{C}^\text{Ar}^{\text{To}})](\text{OTf})\) (5) showing 50% probability thermal ellipsoids for all non-hydrogen atoms (left to right, top to bottom).
Figure 3.2. Mössbauer spectra (experimental data (−)), calculated fit (−−)) recorded at 4.2 K for a solid sample of [Fe₂(BPMAN)(μ-O₂CPh)₂](OTf)₂ (1) (A); [Fe₂(BPMAN)(μ-OH)(μ-O₂CAr₉tów)](OTf)₂ (2) (B); [Fe₂(BPMAN)(μ-OMe)(μ-O₂CAr₉tów)](OTf)₂ (3) (C); [Fe₂(BBAN)(μ-O₂CAr₉tów)](OTf) (4) (D). The upper curves of D shows two subsets for the calculated spectrum.
Figure 3.3. UV-vis spectra accompanying the reaction of \([\text{Fe}_2(\text{BPMAN})(\mu-\text{O}_2\text{CPh})_2](\text{OTf})_2\) (1) with 5 equiv of 30% aqueous \(\text{H}_2\text{O}_2\), 0.4 mM in MeCN at \(-40^\circ\text{C}\) (A) and Mössbauer spectrum (experimental (|), calculated fit (–)) recorded at 4.2 K for a frozen MeCN solution of 1 treated with 5 equiv \(\text{H}_2\text{O}_2\) (B). The upper curve shows two subsets for the calculated spectrum (unreacted diiron(II) complex (—), oxidized product (–––)).
Figure 3.4. UV-vis spectra accompanying the reaction of [Fe₂(BPMAN)(μ-OH)(μ-O₂CAr₈β)][OTf]₂ (2) with excess O₂, 0.1 mM in CH₂Cl₂ at room temperature (A) and Mössbauer spectrum (experimental (-), calculated fit (--)) recorded at 4.2 K for the product of 2 exposed to dioxygen in CH₂Cl₂ as a solid sample following removal of solvent under reduced pressure (B). The upper curve shows two subsets for the calculated spectrum (unreacted diiron(II) complex (--), oxidized product (---)).
Figure 3.5. X-band EPR spectrum of [Fe$_2$(BPMAN)(μ-OH)(μ-O$_2$CAr$^{Tol}$)](OTf)$_2$ (2) exposed to O$_2$ as a frozen solution (5 mM in CH$_2$Cl$_2$) at 77 K.
Figure 3.6. Cyclic voltammograms of 2 mM [Fe₂(BPMAN)(μ-O₂CPh)₂](OTf)₂ (1) in CH₂Cl₂ with 0.5 M [Bu₄N](PF₆) as supporting electrolyte with applied potentials of +1.2 to -0.4 V (scan rate = 100 mV/s) (A); +0.5 to 0 V (scan rate = 200 mV/s) (B); +1 to +0.4 V (scan rate = 200 mV/s) (C) vs Cp₂Fe⁺/Cp₂Fe.
Figure 3.7. Cyclic voltammograms of 2 mM [Fe$_3$(BPMAN)(μ-OH)(μ-O$_2$CAr$^\text{Tol}$)](OTf)$_2$ (2) in CH$_2$Cl$_2$ with 0.5 M [Bu$_4$N](PF$_6$) as supporting electrolyte and a scan rate of 100 mV/s and the insert shows the CV recorded when potentials greater than +0.4 V vs Cp$_2$Fe$^+/$/Cp$_2$Fe were applied.
Chapter 4

Modeling the Syn Disposition of Nitrogen Donors at the Active Sites of Carboxylate-Bridged Diiron Enzymes. Enforcing Dinuclearity and Kinetic Stability with a 1,2-Diethynylbenzene-Based Ligand*
Introduction

Dioxygen-activating metalloenzymes containing carboxylate-bridged diiron centers perform a variety of remarkable chemical reactions. Well-studied members of this class of proteins include the hydroxylase component of soluble methane monooxygenase (sMMOH), an enzyme that converts CH₄ into CH₃OH,¹⁵ the R2 subunit of ribonucleotide reductase (RNR-R2), responsible for the first step of DNA biosynthesis through the generation of a tyrosine radical,⁶,⁷ and Δ-9 desaturase (Δ9D), the diiron core of which effects the desaturation of fatty acids.⁸⁻¹¹ These functions differ dramatically, yet X-ray crystallographic studies reveal strikingly similar active sites.¹²⁻¹⁵ As shown in Chart 4.1, the primary coordination spheres of the carboxylate-bridged diiron centers in sMMOH, RNR-R2, and Δ9D comprise of four glutamate or aspartate side chains and two histidine residues. Whereas the coordination modes of the carboxylate groups vary among the enzymes, the two nitrogen donors are consistently bound in a syn fashion, on the same side of the Fe····Fe vector. This geometric feature is important both in the activation of dioxygen and subsequent substrate oxidation. For the oxidation of CH₄ by sMMOH, which is effected by a di(μ-oxo)diiron(IV) species Q,¹⁶⁻¹⁸ preliminary DFT calculations reveal the conversion to be energetically unfavorable for histidine residues disposed in the anti geometry.¹⁹

The ability of carboxylate-bridged diiron units in nature to promote such important chemical transformations has prompted the synthesis of small molecule analogues. The propensity of carboxylate complexes to form oligomers²⁰⁻²⁹ rather than discrete diiron compounds can be overcome with the use of multidentate nitrogen-rich ligands³⁰ or sterically-hindered carboxylate groups.³¹,³² The resulting complexes often reproduce features of non-heme metalloproteins including dinuclearity, structural flexibility, and dioxygen-reactivity. All three properties are modeled especially well with the use of bulky m-terphenyl-derived carboxylate ligands displayed in Chart 4.2. The occurrence of carboxylate shifts in [Fe₂(O₂CAr')₄(N)₂] compounds attests to the
flexibility of the building blocks,\textsuperscript{31,32} and formation of \textit{(peroxo)}diiron(III) or di(\textit{\mu}-
oxo)diiron(III,IV) species mimics the reactive intermediates that form in the catalytic 
cycles of the related biological systems.\textsuperscript{33-37} The activation of strong C–H bonds by these 
diiron compounds has not yet been achieved, however, possibly because of the 
invariable anti disposition of the N-donor ligands.

The theoretical prediction that the relative orientation of nitrogen donors may 
dramatically influence the reactivity of intermediate Q inspired us to investigate its 
validity with small molecule complexes having this property. Self-assembly methods 
have thus far failed to produce such complexes, as manifest by the many compounds 
with N-donors bound in an anti fashion.\textsuperscript{31,32} Our strategy, therefore, was to employ 
ligands in which the connectivity would enforce the desired coordination mode. 
Presented here are the results of our first efforts in this area, in which dimetallic 
complexes were assembled with several (N)\textsubscript{2}-ligands employed in conjunction with 
sterically demanding carboxylate groups. Ligands derived from a 1,2-diethynylbenzene 
backbone and their use in the synthesis of diiron(II) and dicopper(I) compounds are 
described. Comparison of the structural features of the resulting complexes reveals that 
the ligand framework is sufficiently flexible to support features relevant to the 
formation of intermediate Q of sMMOH.

\textbf{Experimental}

\textbf{General Procedures and Methods.} Solvents were saturated with nitrogen and 
purified by passing over a column of activated Al\textsubscript{2}O\textsubscript{3} under nitrogen.\textsuperscript{38} The compounds 
[Fe\textsubscript{2}(\textit{\mu}-O\textsubscript{2}CAr\textsuperscript{Tol})\textsubscript{2}(O\textsubscript{2}CAr\textsuperscript{Tol})(THF)\textsubscript{2}] (1),\textsuperscript{31} Me\textsubscript{2}-napy,\textsuperscript{39,40} DMP,\textsuperscript{41,42} Fe(OTf)\textsubscript{2}2MeCN,\textsuperscript{43} 
NaO\textsubscript{2}CAr\textsubscript{4-\textit{Bu}Ph},\textsuperscript{44-47} 8-quinolinecarboxylic acid,\textsuperscript{48} 8-quinolinecarboxylate ethyl ester,\textsuperscript{48} 3-
hydroxy-8-carboxylatequinoline ethyl ester,\textsuperscript{49} and 1,2-diiodo-4,5-diethylbenzene,\textsuperscript{50} were 
prepared according to published literature procedures. Prior to use, vpy was freshly 
distilled. All other reagents were purchased from commercial sources and used as
received. Air sensitive manipulations were performed by using standard Schlenk techniques or under nitrogen in an MBraun glovebox. NMR spectra were obtained on a 300 MHz Varian Unity or Mercury spectrometer. FT-IR spectra were measured on a Thermo Nicolet Avatar 360 spectrometer and melting points were determined with a Thomas Hoover capillary melting point apparatus. ESI-MS spectra were recorded on a Bruker Daltonics APEXII 3 Tesla Fourier Transform Mass Spectrometer in the MIT Department of Chemistry Instrumentation Facility.

\[[\text{Fe(O}_2\text{CAr}^{\text{tol}})_2(\text{Me}_2\text{-napy})]\] (2). Treatment of 1 (60 mg, 0.041 mmol) in CH\textsubscript{2}Cl\textsubscript{2} (2 mL) with Me\textsubscript{2}-napy (14.3 mg, 0.090 mmol) in CH\textsubscript{2}Cl\textsubscript{2} (1 mL) afforded a pink-red solution that was stirred for 15 min. The solution was filtered through Celite and to the filtrate was added THF (1 mL). Vapor diffusion of Et\textsubscript{2}O into this solution yielded 2 as pink prisms that were suitable for X-ray diffraction study (54 mg, 81%). FT-IR (cm\textsuperscript{-1}, KBr): 3059 (m), 3029 (m), 3009 (m), 2912 (m), 1607 (m), 1539 (w), 1510 (m), 1464 (w), 1454 (m), 1413 (w), 1376 (m), 1310 (w), 1213 (w), 1190 (w), 1110 (w), 1036 (m), 1020 (m), 863 (m), 820 (m), 799 (s), 784 (m), 764 (m), 737 (w), 714 (m), 642 (w), 585 (m), 541 (m), 517 (m). Anal. Calcd for C\textsubscript{52}H\textsubscript{44}N\textsubscript{2}O\textsubscript{4}Fe: C, 76.47; H, 5.43; N, 3.43. Found: C, 76.65; H, 5.70; N, 3.70.

\[[\text{Fe}_2(\mu\text{-DMP})(\mu\text{-O}_2\text{CAr}^{\text{tol}})(\text{O}_2\text{CAr}^{\text{tol}})_2(\text{THF})]\] (3). To a clear solution of 1 (200 mg, 0.14 mmol) in CH\textsubscript{2}Cl\textsubscript{2} (2 mL) was added DMP (24 mg, 0.15 mmol) in CH\textsubscript{2}Cl\textsubscript{2} (1 mL) and the color turned orange. The reaction mixture was stirred for 15 min and filtered through Celite. Addition of THF (1 mL) and exposure to pentane vapor diffusion yielded yellow-orange needles of 3 (204 mg, 94%). FT-IR (cm\textsuperscript{-1}, KBr): 3019 (w), 2918 (w), 2863 (w), 1626 (m), 1549 (s), 1514 (s), 1454 (s), 1411 (s), 1400 (s), 1384 (s), 1336 (s), 1271 (w), 1183 (w), 1146 (w), 1109 (w), 1069 (w), 1038 (w), 1019 (w), 856 (m), 831 (m), 819 (s), 801 (s), 788 (m), 765 (s), 735 (s), 702 (s), 584 (m), 546 (m), 533 (m), 522 (s). Anal. Calcd for C\textsubscript{59}H\textsubscript{66}N\textsubscript{2}O\textsubscript{8}Fe\textsubscript{2}: C, 76.07; H, 5.60; N, 1.81. Found: C, 76.03; H, 5.51; N, 1.93.
[Fe(O$_2$CAr$^{30+}$)$_2$(vpy)$_2$] (4). Treatment of 3 (61 mg, 0.039 mmol) in CH$_2$Cl$_2$ (2 mL) with vpy (84 µL, 0.78 mmol) afforded an orange solution that was stirred for 30 min. Volatile components were evaporated under reduced pressure and the residue was redissolved in CH$_2$Cl$_2$. Exposure of this solution to Et$_2$O vapor diffusion yielded orange crystals of 4 that were suitable for X-ray diffraction (53 mg, 78%). FT-IR (cm$^{-1}$, KBr): 3045 (w), 3016 (w), 2918 (w), 2860 (w), 1555 (s), 1514 (s), 1455 (s), 1398 (s), 1383 (s), 1182 (w), 1153 (w), 1146 (w), 1110 (w), 1068 (w), 1031 (w), 1021 (w), 853 (m), 840 (m), 834 (w), 818 (m), 803 (s), 784 (s), 763 (s), 735 (w), 704 (m), 585 (m), 557 (w), 538 (s), 521 (m). Anal. Calcd for C$_{56}$H$_{48}$N$_2$O$_4$Fe: C, 77.41; H, 5.57; N, 3.22. Found: C, 77.22; H, 5.60; N, 3.12.

[Fe$_2$µ-O$_2$CAr$^{30+}$]$_2$(O$_2$CAr$^{30+}$)$_2$(vpy)$_2$ (5). To 1 (100 mg, 0.068 mmol) in CH$_2$Cl$_2$ (2 mL) was added vpy (14.8 µL, 0.14 mmol) and the resulting bright yellow solution was stirred for 15 min. The solvent was removed under reduced pressure, and recrystallization of the residue from CH$_2$Cl$_2$ by Et$_2$O vapor diffusion yielded 5·2CH$_2$Cl$_2$·MeOH as yellow crystals of X-ray diffraction quality (88 mg, 85%). FT-IR (cm$^{-1}$, KBr): 3052 (w), 3024 (w), 2918 (w), 2859 (w), 1607 (s), 1563 (s), 1515 (m), 1477 (m), 1453 (m), 1441 (m), 1413 (m), 1368 (m), 1311 (w), 1187 (w), 1145 (w), 1107 (w), 1029 (w), 1015 (w), 970 (w), 920 (w), 852 (m), 814 (m), 799 (s), 785 (m), 767 (m), 735 (m), 711 (m), 699 (w), 644 (w), 584 (w), 543 (m), 523 (m), 516 (m). Anal. Calcd for C$_{98}$H$_{82}$N$_2$O$_6$Fe$_2$: C, 77.06; H, 5.41; N, 1.83. Found: C, 76.59; H, 5.83; N, 1.54.

[Fe(O$_2$CAr$^{4-tBu}$)$_2$(THF)$_2$] (6). To Fe(OTf)$_2$·2MeCN (214 mg, 0.49 mmol) in THF (8 mL) was added solid NaO$_2$CAr$^{4-tBu}$ (400 mg, 0.98 mmol) and the pale yellow solution was stirred for 30 min. The solvent was evaporated under reduced pressure, and to the residue was added CH$_2$Cl$_2$. The resulting suspension was filtered through a medium-porosity frit and the filtrate was evaporated to dryness under reduced pressure. The off-white solid was recrystallized from THF by pentane vapor diffusion to yield colorless crystals of 6 that were suitable for X-ray diffraction study (309 mg, 65%). FT-IR (cm$^{-1}$, KBr): 3062 (m), 3027 (m), 2960 (s), 2902 (s), 2865 (s), 1586 (m), 1541 (m), 1512 (m), 1458
(m), 1409 (m), 1383 (s), 1362 (m), 1268 (m), 1201 (m), 1149 (w), 1120 (m), 1099 (w), 1075 (w), 1040 (s), 1015 (m), 888 (m), 856 (s), 830 (m), 803 (s), 781 (s), 752 (s), 735 (m), 695 (m), 685 (m), 648 (w), 613 (m), 592 (m), 573 (s), 554 (m), 487 (m). Anal. Calcd for C_{82}H_{74}O_{6}Fe: C, 76.68; H, 7.68. Found: C, 76.38; H, 7.65.

[Fe(O_2C^+(Bu^+))_2(DMP)_2] (7). Treatment of 6 (100 mg, 0.10 mmol) in CH_2Cl_2 (3 mL) with DMP (33 mg, 0.21 mmol) in CH_2Cl_2 (1 mL) rapidly generated an orange solution that was stirred for 30 min. The reaction mixture was filtered through Celite and THF (1 mL) was added. Exposure of this solution to Et_2O vapor diffusion afforded orange X-ray quality crystals of 7-2THF (80 mg, 68%). FT-IR (cm⁻¹, KBr): 3060 (w), 3026 (w), 2960 (s), 2902 (m), 2864 (s), 1583 (m), 1557 (s), 1512 (w), 1454 (m), 1397 (s), 1381 (s), 1269 (m), 1201 (w), 1148 (w), 1122 (w), 1099 (w), 1065 (s), 1017 (m), 908 (w), 853 (s), 835 (m), 806 (s), 785 (m), 774 (s), 751 (s), 733 (m), 696 (m), 686 (m), 613 (w), 586 (m), 575 (s), 556 (m). Anal. Calcd for C_{74}H_{76}N_{4}O_{4}Fe: C, 77.74; H, 6.88; N, 4.90. Found: C, 77.81; H, 6.73; N, 4.79.

3-Trifluoromethanesulfonate-8-carboxylatequinoline Ethyl Ester (8). An oven-dried 200 mL 3-neck round-bottom flask was cooled to room temperature under N_2 and charged with 3-hydroxy-8-quinolinecarboxylate ethyl ester (4.42 g, 20.36 mmol), freshly-distilled CH_2Cl_2 (80 mL), and dry pyridine (15 mL). The resulting pale orange solution was further cooled to 0 °C in an ice-water bath and triflic anhydride (3.43 mL, 20.36 mmol) was slowly added via syringe. The orange solution was warmed to room temperature over ~5 h, washed with saturated aqueous NaHCO₃ (100 mL), and the product was extracted with CH_2Cl_2 (3 x 50 mL). The organic layer was dried over MgSO₄, filtered, and the solvent removed by rotary evaporation. The resulting pink-orange solid 8 (6.73 g, 95%) was used in subsequent reactions with no additional purification. FT-IR (cm⁻¹, thin film): 3440 (w), 3085 (w), 3058 (m), 2987 (m), 2914 (w), 1729 (s), 1604 (m), 1576 (w), 1496 (m), 1468 (m), 1428 (s), 1409 (m), 1326 (m), 1280 (m), 1249 (m), 1217 (m), 1140 (m), 1036 (m), 961 (m), 900 (m), 877 (m), 861 (m), 838 (m), 773
(m), 741 (s), 705 (m), 659 (w), 636 (s), 607 (s), 574 (w), 503 (m). ESI-MS (+m/z): Calcd for (M + Na)^+, 372.0130; Found 372.0113. ^1H NMR (300 MHz, CDCl₃): δ 8.957 d (J = 9 Hz, 1H), 8.131 – 8.094 m (2H), 8.005 dd (1H), 7.724 – 7.673 m (1H), 4.539 q (J = 24 Hz, 2H), 1.465 t (J = 23 Hz, 3H). ^13C NMR (75 MHz, CDCl₃): δ 166.92, 144.61, 144.26, 143.45, 132.36, 131.34, 131.22, 128.01, 127.69, 127.16, 118.79 q, 62.02, 14.59. ^19F NMR (282 MHz, CDCl₃): δ 103.41. M.p.: 87 – 90 °C.

3-Trimethylsilanyleneethyl-8-carboxylatequinoline Ethyl Ester (9). A 20 mL scintillation vial was charged with 8 (1 g, 2.87 mmol) and THF (15 mL) under an N₂ atmosphere. To the resulting mixture was added [PdCl₂(PPh₃)₂] (98 mg, 0.14 mmol), PPh₃ (19 mg, 0.072 mmol), NEt₃ (599.3 μL, 4.3 mmol), and HCCSiMe₃ (606.3 μL, 4.3 mmol). The dark red suspension was stirred for 15 min, after which time CuI (6.5 mg, 0.034 mmol) was added and the mixture was stirred vigorously overnight. Rotary evaporation of the volatile components afforded a dark red oil that was dissolved in CH₂Cl₂ and purified by column chromatography on silica gel (3:1 hexanes/EtOAc). The resulting pale yellow oil was triturated to yield 9 as a light yellow solid (0.7 g, 82%). FT-IR (cm⁻¹, thin film): 2960 (w), 2898 (w), 2155 (w), 1732 (m), 1575 (w), 1478 (w), 1372 (w), 1284 (m), 1251 (m), 1204 (m), 1032 (m), 968 (w), 904 (w), 845 (s), 771 (m), 760 (m), 658 (m). ESI-MS (+m/z): Calcd for (M + Na)^+, 320.1083; Found 320.1066. ^1H NMR (300 MHz, CDCl₃): δ 9.034 d (J = 7 Hz, 1H), 8.280 d (J = 7 Hz, 1H), 8.027 dd (1H), 7.893 dd (1H), 7.587 m (1H), 4.543 q (J = 23 Hz, 2H), 1.457 t (J = 23 Hz, 3H), 0.310 s (9H). ^13C NMR (75 MHz, CDCl₃): δ 167.306, 153.151, 144.038, 138.898, 131.855, 130.878, 130.770, 127.252, 126.326, 117.931, 101.672, 99.050, 61.730, 14.599, 0.147. M.p.: 54 - 57 °C.

3-Ethynyl-8-carboxylatequinoline Ethyl Ester (10). To a solution of 9 (1.02 g, 3.43 mmol) in THF (80 mL) was added a 1 M solution of Bu₄NF in THF (3.43 mL, 3.43 mmol), and the resulting dark red solution was stirred for 2 h under N₂. The solvent was removed under reduced pressure and the resulting dark red oil was dissolved in CH₂Cl₂ and purified by column chromatography on silica gel (1:1 EtOAc/hexanes).
Compound 10 was isolated as a cream-colored solid (0.39 g, 51%). FT-IR (cm⁻¹, thin film): 3178 (w), 2984 (w), 2095 (w), 1727 (s), 1577 (w), 1478 (w), 1373 (w), 1331 (w), 1281 (m), 1201 (m), 1189 (m), 1141 (m), 1113 (w), 1062 (w), 1048 (w), 1026 (m), 922 (w), 906 (m), 853 (w), 767 (m), 744 (m), 689 (m), 644 (w), 519 (w). ESI-MS (+m/z): Calcd for (M + Na)⁺, 248.0688; Found 248.0680. ¹H NMR (300 MHz, CDCl₃): δ 9.017 d (J = 7 Hz, 1H), 8.321 d (J = 6 Hz, 1H), 8.054 dd (1H), 7.922 dd (1H), 7.614 m (1H), 4.556 q (J = 24 Hz, 2H), 3.330 s (1H), 1.478 t (J = 24 Hz, 3H). ¹³C NMR (75 MHz, CDCl₃): δ 167.274, 153.172, 144.289, 139.337, 131.946, 131.024, 130.919, 127.191, 126.491, 116.915, 81.354, 80.650, 61.815, 14.627. M.p.: 90 – 93 °C.

1,2-Bis(3-ethyl-8-carboxylatequinoline)benzene Ethyl Ester (Et₂BCQEB, 11). A thick-walled reaction tube was charged with 1,2-diiodobenzene (79.3 μL, 0.606 mmol), 10 (0.3 g, 1.33 mmol), [PdCl₂(PPh₃)₂] (43 mg, 0.0613 mmol), PPh₃ (7.8 mg, 0.0298 mmol), CuI (2.7 mg, 0.0142 mmol), and Et₂NH (10 mL). The reaction vessel was sealed under N₂ with a screw-top lid and the mixture was heated at 70 °C overnight behind a blast shield. Rotary evaporation of the solvent yielded a dark red oil that was dissolved in CH₂Cl₂ and purified by column chromatography on silica gel (1:1 EtOAc/hexanes). The resulting oily orange residue was dissolved in hot MeOH and placed in a −20 °C freezer overnight. Compound 11 was collected as an off-white solid (211 mg, 66%) and washed with cold MeOH. FT-IR (cm⁻¹, thin film): 2980 (w), 2206 (w), 1729 (s), 1573 (w), 1485 (m), 1444 (w), 1373 (w), 1297 (m), 1275 (s), 1204 (s), 1183 (m), 1151 (m), 1122 (m), 1066 (w), 1030 (m), 901 (w), 856 (w), 771 (m), 662 (w). ESI-MS (+m/z): Calcd for (M + Na)⁺, 547.1634; Found 547.1608. ¹H NMR (300 MHz, CDCl₃): δ 9.13 d (J = 7 Hz, 2H), 8.31 d (J = 7 Hz, 2H), 8.00 dd (2H), 7.83 dd (2H), 7.63 m (2H), 7.54 m (2H), 7.37 m (2H), 4.52 q (J = 23 Hz, 4H), 1.44 t (J = 23 Hz, 6 H). ¹³C NMR (75 MHz, CDCl₃): δ 167.432, 152.870, 144.221, 138.477, 132.337, 132.058, 131.045, 130.910, 128.892, 127.465, 126.552, 125.203, 117.945, 91.872, 90.733, 61.860, 14.679. M.p.: 91 – 93 °C.
1,2-Bis(3-ethynyl-8-carboxylatequinoline)benzene, Potassium Salt ($K_2$BCQEB 12). To 11 (100 mg, 0.19 mmol) in THF (6 mL) was added KOSiMe$_3$ (54 mg, 0.42 mmol) in THF (5 mL) under N$_2$, and the resulting suspension was stirred overnight. The off-white solid 12 was collected and washed with Et$_2$O (100 mg, 97%). FT-IR (cm$^{-1}$, KBr): 3049 (w), 2204 (w), 1725 (w), 1619 (s), 1584 (s), 1482 (m), 1440 (w), 1388 (s), 1361 (s), 1287 (w), 1183 (w), 1151 (w), 1124 (w), 1017 (w), 966 (w), 898 (m), 850 (m), 833 (w), 789 (m), 756 (s), 665 (m), 636 (w), 546 (w), 509 (w). ESI-MS (-m/z): Calcd for (M - K)$^+$, 505.0591; Found 505.0575. $^1$H NMR (300 MHz, CD$_3$OD): δ 9.02 d ($J = 7$ Hz, 2H), 8.49 d ($J = 7$ Hz, 2H), 7.79 m (4H), 7.69 m (2H), 7.58 m (2H), 7.46 m (2H). M.p.: > 300 °C.

1,2-Bis(3-ethynyl-8-carboxylatequinoline)-4,5-diethylbenzene Ethyl Ester ($Et_2$BCQEB$_E$, 13). This compound was prepared in a procedure analogous to that used for the synthesis of 11 by substituting 1,2-diodo-4,5-diethylbenzene for 1,2-diodobenzene. Purification was achieved by column chromatography on silica gel (1:1 EtOAc/hexanes) followed by recrystallization from EtOH to yield 13 as an off-white solid (45%). FT-IR (cm$^{-1}$, thin film): 2968 (m), 2934 (w), 2873 (w), 2208 (w), 1730 (s), 1573 (w), 1494 (w), 1479 (w), 1467 (w), 1372 (w), 1277 (s), 1181 (m), 1152 (w), 1139 (w), 1127 (m), 1065 (w), 1031 (m), 899 (m), 772 (m), 746 (w), 664 (w), 550 (w). ESI-MS (+m/z): Calcd for (M + Na)$^+$, 603.2260; Found 603.2255. $^1$H NMR (300 MHz, CDCl$_3$): δ 9.192 d ($J = 8$ Hz, 2H), 8.361 d ($J = 7$ Hz 2H), 8.045 dd (2H), 7.897 dd (2H), 7.598 m (2H), 7.491 s (2H), 4.563 q ($J = 24$ Hz, 4H), 2.736 q ($J = 26$ Hz, 4H), 1.481 t ($J = 24$ Hz, 6H), 1.318 t ($J = 26$ Hz, 6H). $^{13}$C NMR (75 MHz, CDCl$_3$): δ 167.461, 152.970, 144.056, 143.379, 138.383, 132.109, 131.994, 131.059, 130.848, 127.586, 126.536, 122.618, 118.327, 92.449, 89.694, 61.881, 25.666, 15.150, 14.704. M.p.: 125 – 127 °C.

1,2-Bis(3-ethynyl-8-carboxylatequinoline)-4,5-diethylbenzene, Sodium Salt ($Na_2$BCQEB$_E$ 14). A suspension of 13 (85 mg, 0.15 mmol) in MeOH (15 mL) was refluxed for 1 h, at which time the resulting pale yellow solution was treated with an aqueous solution of NaOH (1M, 0.31 μL, 0.31 mmol). The mixture was refluxed
overnight, and the solvent was removed under reduced pressure to afford 14 as a tan powder in quantitative yield. FT-IR (cm⁻¹, KBr): 2961 (m), 2931 (w), 2873 (w), 2205 (w), 1613 (s), 1581 (s), 1567 (s), 1492 (w), 1466 (w), 1396 (m), 1363 (m), 1259 (w), 1239 (w), 1230 (w), 1131 (w), 1054 (w), 1018 (w), 964 (w), 894 (m), 849 (m), 832 (w), 794 (w), 757 (s), 671 (m), 658 (m), 549 (w), 516 (w). ESI-MS (-m/z): Calcd for (M - 2Na + H⁺): 523.1658; Found 523.1651. ¹H NMR (300 MHz, CD3OD): δ 9.02 m (2H), 8.46 m (2H), 7.80 m (4H), 7.58 m (2H), 7.50 s (2H), 2.75 q (J = 20 Hz, 4H), 1.30 t (J = 26 Hz, 6H). M.p.: > 300 °C.

[Fe₂(Et₂BCQEB²⁺)(μ-O₂CAtol)₃]OTf (15). A mixture of Fe(OTf)₂2MeCN (60 mg, 0.14 mmol) in THF (3 mL) was treated with a solution of 13 (40 mg, 0.069 mmol) in THF (2 mL). To the resulting bright orange solution was added solid Na₂O₂CAtol (67 mg, 0.21 mmol) and the suspension was stirred for 2 h. The solvent was evaporated under reduced pressure and the residue was dissolved in CH₂Cl₂ and filtered through a plug of Celite. Pink-red crystals of 15-3.25CH₂Cl₂-Et₂O, suitable for X-ray crystallographic study, were obtained from a saturated solution of CH₂Cl₂ and Et₂O at room temperature (50 mg, 42%). FT-IR (cm⁻¹, KBr): 3046 (w), 3021 (w), 2966 (m), 2920 (m), 2870 (m), 2209 (w), 1674 (m), 1598 (s), 1573 (s), 1513 (m), 1496 (m), 1451 (m), 1405 (m), 1384 (s), 1297 (s), 1264 (s), 1222 (s), 1147 (m), 1029 (s), 907 (w), 834 (w), 814 (m), 799 (m), 771 (m), 702 (m), 636 (s), 581 (w), 530 (m), 517 (m). Anal. Calcd for C₄₃₀₂H₈₃N₂O₁₅F₃SFe₂: C, 70.19; H, 4.79; N, 1.60. Found: C, 69.98; H, 4.88; 1.61.

[Cu₂(Et₂BCQEB²⁺)(μ-I)₂] (16). To 13 (50 mg, 0.086 mmol) in CH₂Cl₂ (2 mL) was added CuI (33 mg, 0.17 mmol) in Et₃NH (2 mL) and the pale yellow solution was stirred for 30 min. The solvent was evaporated under reduced pressure and the residue was dissolved in CH₂Cl₂ to afford an orange solution. Exposure of this solution to Et₂O vapor diffusion afforded 16 as a flocculent orange solid (57 mg, 69%), and single crystals of 16·CH₂Cl₂, suitable for X-ray diffraction study, were obtained by slow Et₂O vapor diffusion. FT-IR (cm⁻¹, KBr): 3032 (w), 2963 (w), 2209 (w), 1684 (s), 1596 (w), 1569 (w), 1484 (w), 1406 (w), 1366 (w), 1276 (m), 1240 (w), 1209 (m), 1157 (w), 1138 (m), 1036
(m), 905 (m), 771 (m), 748 (w), 730 (m), 555 (m). Anal. Calcd for C<sub>38</sub>H<sub>38</sub>N<sub>2</sub>O<sub>4</sub>I<sub>2</sub>Cu<sub>2</sub>: C, 47.47; H, 3.35; N, 2.91. Found: C, 47.25; H, 3.31; N, 2.89.

X-ray Crystallographic Studies. Crystals were mounted in Paratone N oil on the ends of glass capillaries and frozen into place under a low-temperature nitrogen cold stream. Data were collected on a Bruker (formerly Siemens) APEX CCD X-ray diffractometer running the SMART software package<sup>51</sup> with Mo Kα radiation (λ = 0.71073 Å), and refined using SAINT software<sup>52</sup>. Details of the data collection and reduction protocols are discussed in detail elsewhere<sup>53</sup>. The structures were solved by direct methods using SHELXS-97 software<sup>54</sup> and refined on F<sup>2</sup> by using the SHELXL-97 program<sup>55</sup> incorporated in the SHELXTL software package<sup>56</sup>. The program SADABS was used to apply empirical absorption corrections<sup>57</sup> and PLATON was used to check the possibility of higher symmetry<sup>58</sup>. All non-hydrogen atoms were located and their positions refined with anisotropic thermal parameters by least-squares cycles and Fourier syntheses. Hydrogen atoms were assigned idealized positions and given a thermal parameter 1.2 times that of the carbon atom to which each was attached.

In the structure of 6, the methyl groups of one tert-butyl substituent of the crystallographically equivalent Ar<sup>4</sup>-<sup>18</sup>CH<sub>3</sub>CO<sub>2</sub>⁻ ligands were disordered over two positions and refined with occupancies of 81 and 19%. The crystallographically equivalent dichloromethane solvent molecules in the structure of 5 have one chlorine atom that was disordered over two positions and refined with occupancies of 50%. In addition, there are two half-occupied methanol solvent molecules. In the structure of 15, one ethyl group of the Et<sub>2</sub>BCQEB<sup>61</sup> backbone is disordered over two positions and was refined with occupancies of 75 and 25%, and the sulfur atom of the triflate counterion was modeled over two positions with occupancies of 82 and 18%. Five dichloromethane solvent molecules were found in the structure of 15. One chlorine atom in two molecules was disordered over two positions and modeled with occupancies of 50/50 and 75/25%, respectively. Two additional molecules were refined with 50% occupancy,
and one chlorine molecule of each was shared by another dichloromethane molecule, the occupancy of which was refined as 25%. Crystallographic data are summarized in Table 4.1.

Results

Synthesis and Structural Characterization of [Fe(O₂CAr⁴Ts)₂(Me₂-napy)] (2). Multidentate 1,8-naphthyridine-based ligands have previously been used to prepare of a variety of diiron(II) compounds.⁵⁹−⁶¹ In search for a unit that would provide two nitrogen donors for coordination to the diiron core in a syn fashion, we reasoned that a simple naphthyridine derivative might, by virtue of its connectivity, be a suitable candidate. The complex [Fe₂(μ-O₂CAr⁴Ts)₂(O₂CAr⁴Ts)₂(THF)₂] (1), having a pre-assembled, carboxylate-rich diiron(II) core and two readily displaceable THF molecules, served as a convenient starting material (Scheme 4.1).⁶¹ Reaction of 1 with Me₂-napy in a ratio of 1:1 afforded the mononuclear complex 2, the yield of which was subsequently optimized (> 80%) by use of two equivalents of Me₂-napy. Disruption of the dinuclear cores of 1 and the related compound [Fe₂(μ-O₂CAr⁴Mes)₂(O₂CAr⁴Mes)₂(MeCN)₂] has similarly been observed by addition of basic N-donor ligands.⁶²,⁶³

The structure of 2 reveals that the two nitrogen atoms of Me₂-napy chelate a single highly distorted octahedral metal ion (Figure 4.1, Table 4.2). The N–Fe–N bite angle of 60.93(9)° is within the range reported for other transition-metal complexes coordinated by bidentate 1,8-naphthyridine fragments,⁶⁴−⁶⁸ and this small angle is responsible for the pronounced distortion at the metal center. The two Ar⁴TsCO₂⁻ ligands are bound quite symmetrically to the iron(II) ion in an η²-fashion, with Fe–O bond lengths of 2.137(2) and 2.180(2) Å. Similar structures result with other N-donors and sterically demanding m-terphenyl-derived ligands,⁶²,⁶³ but not with simpler carboxylates such as acetate or benzoate, attesting to the ability of the flanking phenyl groups to prevent undesired oligomerization reactions. In the absence of additional
donor atoms, the 1,8-naphthyridine unit frequently adopts the chelating coordination mode evident in \(2^{64-68}\) whereas the bridging mode is more common when a metal–metal interaction is present to stabilize the dinuclear core\(^{69,75}\), a feature lacking in our system.

**Synthesis and Reactivity of** \([\text{Fe}_2(\mu-\text{DMP})(\mu-\text{O}_2\text{CAr}^{\text{Tol}})_2(\text{O}_2\text{CAr}^{\text{Tol}})_2(\text{THF})]\) (3). **Preparation and Crystallographic Analysis of** \([\text{Fe}(\text{O}_2\text{CAr}^{\text{Tol}})_2(\text{ppy})_2]\) (4) and \([\text{Fe}_2(\mu-\text{O}_2\text{CAr}^{\text{Tol}})_2(\text{O}_2\text{CAr}^{\text{Tol}})_2(\text{ppy})_2]\) (5). Whereas the flexible orientation of the nitrogen lone pairs of the 1,8-naphthyridine unit permits the formation of both mononuclear and dinuclear species, the phthalazine moiety should promote dinuclearity because the lone pairs point away from one another. In support of this expectation, we note that no mononuclear compounds with \(\eta^2\)-bound phthalazine have been crystallographically characterized. Upon treatment of 1 with DMP, the dinuclear core remained intact and complex 3 was isolated in excellent yield (94%). The data quality of repeated X-ray crystallographic analyses was sufficient to ascertain the gross structure of the compound, but was unsatisfactory for full complete refinement. The coordination environment of 3, shown in Scheme 4.1, features two asymmetric iron sites, separated by \(\sim 3.4\ \text{Å}\), that are bridged by DMP and two \(\text{Ar}^{\text{Tol}}\text{CO}_2^-\) ligands. One iron is additionally coordinated by a bidentate carboxylate ligand, and a monodentate carboxylate and an additional solvent molecule complete the coordination sphere of the remaining iron center. Dinuclear compounds generally form with multidentate ligands derived from phthalazine,\(^{76-85}\) but such structures are rare with phthalazine units lacking additional donor groups.\(^{72,87-89}\)

Compound 3 is significant because it reproduces the syn coordination geometry of the two nitrogen donors present at the active sites of sMMOH, RNR-R2, and \(\Delta 9\)D. To our knowledge, the only other diiron(II) compound that displays this feature in a carboxylate-rich environment is \(\text{Et}_4\text{N}[\text{Fe}_2(\mu-\text{H}_2\text{O})(\mu-\text{O}_2\text{CCH}_3)_2(\text{O}_2\text{CCH}_3)_2(\text{C}_5\text{H}_5\text{N})_2]\).\(^{90,91}\) Although this complex was formed by self-assembly, kinetic lability of the core was
evident in the subsequent reaction with dioxygen to afford a (μ₃-oxo)triiron(III) basic acetate complex.⁹⁰ Not surprisingly, the dinuclear core in 3 also does not remain intact upon oxidation, and preliminary reactivity studies indicate that a hexanuclear iron(III) complex forms upon exposure to dioxygen.⁹²

The lability of the dinuclear core in 3 is further manifest by reaction with vpy to generate mononuclear 4 (Figure 4.1, Table 4.2). The pseudooctahedral iron(II) center in this compound is ligated by two bidentate Ar₅TolCO₂⁻ ligands and two vpy groups. The coordination of the carboxylate ligands is asymmetric, with Fe–O bond lengths ranging from 2.065(2) to 2.303(2) Å. The N–Fe–N bond angle of 97.84(9)° is substantially larger than that in 2, resulting in a less distorted octahedral geometry at the iron center.

A combination of Ar₅TolCO₂⁻ and vpy ligands can also support a diiron(II) core, as seen by the synthesis of 5 when 1 reacts with vpy in a ratio of 1:2 (Figure 4.1, Table 4.2). A survey of the Cambridge Structural Database revealed that 4 and 5 are the only crystallographically characterized iron compounds ligated by vpy ligands. Not surprisingly, the vpy groups in 5 are bound in an anti fashion with Fe–N bond lengths of 2.154(2) Å, and the alkene units are directed away from the metal centers. The arrangement of the four carboxylate ligands in a windmill rather than paddlewheel fashion results in a Fe⋯Fe separation of 4.343(1) Å that is slightly elongated relative to the inter-metal distances found in related diiron compounds.³¹,³³,³⁷,⁹³ The Fe–O bond lengths of the monodentate Ar₅TolCO₂⁻ ligands of 2.030(2) Å are shorter than those of the chelating carboxylates in 2 and 4, although a weak Fe⋯Oダンギング interaction is suggested by the ~2.48 Å separation between Fe(1) and O(4).

**A More Sterically Demanding Carboxylate Ligand. Synthesis and Crystal Structures of [Fe(O₂Ar₅Tol)(THF)]_2 (6) and [Fe(O₂Ar₅-tBuPh)(DMP)]_2 (7).** The propensity of the [Fe₂(O₂C₅Ar₅Tol)]₄ core to be disrupted prompted us to modify the substituents of the m-terphenyl carboxylate ligands in an effort to stabilize the dimetallic unit. In order to restrict access to bimolecular reaction pathways that lead to
high-nuclearity species upon oxidation, we employed the sterically demanding 4-tert-butyl derivative. Reaction of Fe(OTf)$_2$2MeCN with NaO$_2$CAr$^{4\text{-Bu}}$ in a ratio of 1:2 in THF generated mononuclear 6, and prolonged reaction times (>12 h) did not afford a dinuclear compound. This result differs from the chemistry of diiron analogues supported by Ar$^{\text{Tol}}$CO$_2$,$^{31}$ Ar$^{4\text{FFP}}$CO$_2$,$^{31}$ and Ar$^{\text{Mes}}$CO$_2$ ligands.$^{37}$ The stereochemistry at the iron(II) center in 6 is similar to that of 4, with two bidentate carboxylate ligands and two THF molecules coordinating to the metal ion (Figure 4.1, Table 4.3). The Fe–O bonds located trans to the coordinated THF molecules are elongated relative to the other bonds ($\Delta_{\text{Fe–O}} = 0.132(1)$ Å), and the O$_{\text{THF–Fe–O}_{\text{THF}}}$ bond angle of 95.93(8)$^\circ$ is close to the N–Fe–N angle in 4.

Addition of either one or two equivalents of DMP to 6 affords mononuclear 7 by exchange of the THF ligands, and the stereochemistry at the iron center of this compound is similar to that of 4 and 6 (Figure 4.1, Table 4.3). One nitrogen atom of each DMP ligand remains unmetallated. Such $\eta^1$-coordination of the phthalazine unit has been observed in other compounds.$^{72,94-97}$ The tert-butyl substituents of the carboxylate ligands presumably confer too much steric bulk to permit the formation of a carboxylate-rich diiron core similar to that of 3.

**Design and Synthesis of BCQEB Derivatives.** Studies with the ligands Me$_2$-napy and DMP illustrate the difficulty of controlling nuclearity and kinetic lability with simple units. We therefore reasoned that a ligand in which the connectivity enforces the relative disposition of the N-donors and additional donor groups promote dinuclearity should address these shortcomings. Exploratory work in our laboratory with 1,2-diethylbenzene as a spacer between two pyridine or quinoline groups proved to be an effective strategy to enforce the desired syn coordination of two nitrogen donors, as demonstrated by the synthesis and characterization of [Fe$_2$(BQEB)(μ-OH)(μ-O$_2$CAr$^{\text{Tol}}$)-(O$_2$CAr$^{\text{Tol}}$)$_2$(THF)(H$_2$O)],$^{98}$ where BQEB is 1,2-bis(3-ethylquinoline)benzene.$^{99}$ This complex, depicted in Figure 4.2, displays the desired geometry and reveals that the 1,2-
diethylbenzene spacer can support a dimetallic unit with a single atom bridge, a feature important for modeling high-valent intermediates formed in the related diiron metalloenzymes. The hydroxide-bridged diiron compound, however, could be isolated only in low yield by a synthetic route that was difficult to reproduce. Moreover, reactions with dioxygen afforded mainly oligomeric species.  

We hypothesized that additional chelating groups should enhance the stability of the resulting diiron complex, and that incorporation of carboxylate groups into the quinoline unit would be a good strategy for producing the desired biomimetic compounds.

Scheme 4.2 outlines the synthesis of 1,2-bis(3-ethynyl-8-carboxylatequinoline)-benzene (BCQEB) derivatives. Multigram quantities of the 3-hydroxy-8-carboxylate-quinoline ethyl ester were synthesized following literature procedures, and treatment with triflic anhydride in CH$_2$Cl$_2$ and pyridine yielded 8 in nearly quantitative yield. Efficient Sonogashira coupling between 8 and HCCSiMe$_3$ in THF afforded 9, the trimethylsilyl group of which was subsequently deprotected with $\text{sBu}_4\text{NF}$ in THF to yield 10. Compound 11 was synthesized in > 65% yield by a second Sonogashira reaction and the ethyl ester was removed by treatment with KO$\text{SiMe}_3$ in THF to yield the potassium salt 12, K$_2$BCQEB. In an analogous procedure, Et$_2$BCQEB$_{\text{Et}}$ (13) was prepared by using 1,2-diido-4,5-diethylbenzene, and ester deprotection was achieved with NaOH in MeOH affording Na$_2$BCQEB$_{\text{Et}}$ (14).

**Synthesis and Structural Characterization of [Fe$_2$(Et$_2$BCQEB$_{\text{Et}}$)($\mu$-O$_2$CaT$_{6\text{th}}$)$_2$](OTf) (15).** Metallation of K$_2$BCQEB or Na$_2$BCQEB$_{\text{Et}}$ with iron(II) proved to be difficult because reaction with 1 or iron(II) salts and a variety of different carboxylate ligands invariably led to materials with poor solubility in common organic solvents, suggesting the formation of an oligomeric product. Extended structures might arise from interaction of the dangling carbonyl oxygen atom of the BCQEB scaffold and other metal ions such as Fe(II) or K$^+$/Na$^+$. We therefore employed as ligand Et$_2$BCQEB$_{\text{Et}}$, the
ethyl ester of which protects one oxygen atom and precludes the formation of higher nucularity species.

Reaction of \( \text{Fe(OtF)}_2 \cdot 2\text{MeCN} \) with \( \text{Et}_2\text{BCQEB}^{\text{Et}} \) and \( \text{NaO}_2\text{CAR}^{\text{Tol}} \) in a ratio of 2:1:3 in THF affords compound 15 in moderate yield. The two iron centers adopt square pyramidal geometry and are separated by 3.576(1) Å (Figure 4.3, Table 4.3). The diiron core is spanned by three bridging \( \text{Ar}^{\text{Tol}}\text{CO}_2^− \) groups, two of which are bound in a \textit{syn}, \textit{syn} fashion, whereas the third carboxylate adopts the less common \textit{syn}, \textit{anti} coordination mode.\(^{104}\) The \( \text{Et}_2\text{BCQEB}^{\text{Et}} \) ligand coordinates each metal ion through the nitrogen and carbonyl oxygen atoms of the quinolinic acid unit, forming six-membered chelate rings with O–Fe–N bite angles of 82.17(12) and 82.22(13)°. The dinuclear core is thus stabilized, permitting a reliable synthesis of 15. Significantly, the N-donors are bound to the iron centers in a \textit{syn} fashion with Fe–N bond lengths of 2.164(3) and 2.193(3) Å. The N···N separation of 6.077(5) Å is comparable to that of the donor nitrogen atoms of the two histidine residues at the diiron(II) active sites of sMHOH (−5 Å),\(^{12}\) RNR−R2 (−5.4 Å),\(^{14}\) and Δ9D (−6 Å).\(^{15}\) The Fe–O bond lengths of the carboxylate ligands range from 1.974(3) to 2.084(3) Å, with the longer bonds located trans to the quinoline nitrogen atoms. The ester unit has Fe–O bond distances of 2.081(3) Å, which fall in the upper range of other crystallographically characterized Fe–O(C)OR units.\(^{105−118}\)

**Preparation and Crystallographic Characterization of \([\text{Cu}_2(\text{Et}_2\text{BCQEB}^{\text{Et}})(\mu-\text{I})_2] \) (16).** To probe the ability of \( \text{Et}_2\text{BCQEB}^{\text{Et}} \) to support dinuclear cores displaying a range of geometries and metal···metal distances, a dicopper(I) complex was prepared. Reaction of \( \text{Et}_2\text{BCQEB}^{\text{Et}} \) with two equivalents of CuI in a mixture of \( \text{CH}_2\text{Cl}_2 \) and \( \text{Et}_2\text{NH} \) afforded 16. The amine solvent was necessary to dissolve CuI and no reaction occurs in pure \( \text{CH}_2\text{Cl}_2 \). Although a full refinement of the crystal structure of 16 was not possible because of poor data, the geometry at the copper centers could be unambiguously established. In 16 there are two pseudotetrahedral copper(I) centers bound to bidentate
units of Et₂BCQEB⁺⁺ and two iodide ligands (Figure 4.3). The Cu–N bond lengths, ~2.08 Å, are shorter than the Fe–N bond distances in 15 (Δ_{M-N} ~0.1 Å), as expected for a complex with lower coordination number. The M–O bond lengths in 16 are longer by ~0.05 Å relative to those in 15, however, reflecting the soft character of Cu(I) compared to Fe(II). The iodide ligands form two single atom bridges between the copper sites with Cu–I bond lengths of ~2.59 Å. The Cu–I–Cu and I–Cu–I bond angles of ~120 and 59°, respectively, give rise to a short Cu···Cu separation (~2.54 Å). This distance is slightly less than the inter-metal separation in metallic copper (2.56 Å), suggesting that there may be a weak copper–copper interaction. The two nitrogen atoms of Et₂BCQEB⁺⁺ are ~5.41 Å apart in 16, a substantial reduction compared to that in 15 (Δ_{N-N} > 0.6 Å). Di(μ-iodo)dicopper(I) compounds supported by alkyl esters of quinoidal acid have similar geometric parameters.¹¹⁹

Discussion

Complexes of Me₂-napy and DMP. Use of sterically-hindered m-terphenyl-derived carboxylate ligands with the 1,8-naphthyridine and phthalazine units Me₂-napy and DMP afforded both mononuclear and dinuclear compounds. Complexes 2, 4, and 7 all feature a pseudo-octahedral iron(II) center coordinated by two carboxylates and two nitrogen donor ligands (Figure 4.1). Relatively long Fe–N bonds (2.163(2) – 2.214(2) Å) promote bidentate, rather than monodentate, coordination of the Ar^{Tol}CO₂⁻ and Ar^{4-ButPh}CO₂⁻ groups.⁶²,⁶³ The carboxylate ligands in 4 and 7 are bound asymmetrically, with the Fe–O bonds located trans to the N-donors being substantially elongated (~0.2 Å). Because of the highly distorted stereochemistry at the iron(II) center in 2, neither of the Ar^{Tol}CO₂⁻ ligands is bound directly opposite the Me₂-napy unit and the coordination of the carboxylates is symmetric (Δ_{Fe-O} ~0.04 Å). The coordination mode of the phthalazine moiety appears to be dictated by the nature of the ancillary ligands, binding in an η¹ fashion in 7 and in an η² manner in 3. Unfavorable steric interactions
arising from the large tert-butyl groups of \( \text{Ar}^{4-\text{BuPh}}\text{CO}_2^- \) would appear to preclude the formation of a dinuclear compound, whereas the smaller methyl substituents of \( \text{Ar}^{\text{Tol}}\text{CO}_2^- \) readily support a carboxylate-rich dimetallic unit.

**Preparation of BCQEB Ligands and Metal Complexes.** The BCQEB ligands were designed and synthesized to enforce dinuclearity and kinetic stability on the diiron(II) unit, features that were difficult to maintain with Me_2-napy and DMP. Compound 8 serves as a convenient starting material, and a series of Sonogashira coupling reactions afforded the BCQEB derivatives in three to four synthetic steps (Scheme 4.2). The connectivity of the molecular scaffold ensures that the separation of nitrogen atoms remains close to that observed for the N-donors of the histidine residues in sMMOH, RNR-R2, and \( \Delta 9\text{D} (\sim 5 - 6 \text{ Å}) \), and incorporation of a chelating moiety, ester or carboxylate, is an effective strategy for promoting dinuclearity upon metallation. The syntheses of compounds with well-defined dimetallic cores were effected with the ligand \( \text{Et}_2\text{BCQEB}^{\text{Et}} \), affording \( [\text{Fe}_2(\text{Et}_2\text{BCQEB}^{\text{Et}})(\mu-\text{O}_2\text{CAr}^{\text{Tol}})_2](\text{OTf}) \) (15) and \( [\text{Cu}_2(\text{Et}_2\text{BCQEB}^{\text{Et}})(\mu-\text{I})_2] \) (16), illustrated in Figure 4.3.

**Utilization of BCQEB-Derived Ligands and Relevance to High-Valent Intermediates in Non-Heme Diiron Enzymes.** A comparison of structures 15 and 16 allows the efficacy of the BCQEB framework to facilitate modeling non-heme diiron enzymes to be evaluated. The ligand \( \text{Et}_2\text{BCQEB}^{\text{Et}} \) supports both four- and five-coordinate complexes, and accommodates either three \( \mu-1,3\)-carboxylate ligands (15) or two single-atom bridging groups (16). The structural flexibility of the ligand scaffold is manifest in the range of metal···metal and N···N distances, \( \sim 1 \) and 0.6 Å, respectively, supported by \( \text{Et}_2\text{BCQEB}^{\text{Et}} \). Significantly, the syn disposition of the nitrogen donors is enforced with this ligand, which thus mimics histidine residues supplied by the four-helix bundle surrounding the diiron active sites of sMMOH, RNR-R2, and \( \Delta 9\text{D} \). The geometry of catalytically active species in these non-heme diiron enzymes differs substantially from their reduced and oxidized forms, and the ability of a ligand to
support such variety of the dinuclear core structure is crucial for the preparation of functional model analogues. The flexibility of Et₂BCQEBᵦᵥ satisfies this requirement, thus representing a significant achievement towards the goal. Moreover, compound 16 accommodates the short metal···metal separation in the \( \{M₂O₂\} \) core of intermediate Q in MMOH. The ability of the BCQEB framework to support such a structure indicates its suitability for modeling biologically-relevant dimetallic species.

Summary and Conclusions

The ligands Me₂-napy and DMP were introduced in an attempt to model the syn coordination of the two histidine residues at the diiron cores of sMMOH, RNR-R2, and A9D. In the absence of additional donor groups, the 1,8-naphthyridine and phthalazine fragments yielded iron(II) compounds, the nuclearity and kinetic stability of which were difficult to control. To address these challenges, the BCQEB-derived ligands were prepared and employed in the synthesis of \([\text{Fe₄(Et₂BCQEB}ᵦᵥ)(\mu-\text{O₂CAr}^\text{tol})₂] \text{(OTf)} \) \( (15) \) and \([\text{Cu₃(Et₂BCQEB}ᵦᵥ)(\mu-I)₂] \) \( (16) \). Both 15 and 16 feature dinuclear cores in which the desired syn disposition of nitrogen donors is enforced, and the range of M···M and N···N distances observed in these compounds attest to the structural flexibility of the BCQEB framework.

Acknowledgements. This work was funded by grants from the National Science Foundation and National Institute of General Medical Sciences. I thank NSERC for a graduate student fellowship, Dr. Joshua R. Farrell and Mr. Dylan Stiles for preparing the first diethynylbenzene ligands and complexes investigated in our laboratory, and Ms. Li Li of the MIT Department of Chemistry Instrumentation Facility for collecting the ESI-MS spectra.
References


(52) SAINT v5.01: Software for the CCD Detector System; Bruker AXS: Madison, WI, 1998.


(57) Sheldrick, G. M. SADABS: Area-Detector Absorption Correction; University of Göttingen: Göttingen, Germany, 1996.


(92) Kuzelka, J.; Lippard, S. J. Unpublished results. Pentane vapor diffusion into an O$_2$-saturated THF solution of 3 afforded red-brown crystals of [Fe$_6$(μ$_5$-O)$_2$(μ-OH)$_6$(μ-O$_2$CR)$_8$(THF)$_2$].


Table 4.1. Summary of X-ray crystallographic data

<table>
<thead>
<tr>
<th></th>
<th>2</th>
<th>4</th>
<th>5-2CH\textsubscript{2}Cl\textsubscript{2}MeOH</th>
<th>6</th>
<th>7-2THF</th>
<th>15-3.25CH\textsubscript{2}Cl\textsubscript{2}Et\textsubscript{2}O</th>
</tr>
</thead>
<tbody>
<tr>
<td>formula</td>
<td>C\textsubscript{32}H\textsubscript{44}N\textsubscript{2}FeO\textsubscript{4}</td>
<td>C\textsubscript{36}H\textsubscript{48}N\textsubscript{2}FeO\textsubscript{4}</td>
<td>C\textsubscript{101}H\textsubscript{82}N\textsubscript{2}Fe\textsubscript{2}O\textsubscript{5}Cl\textsubscript{4}</td>
<td>C\textsubscript{62}H\textsubscript{56}FeO\textsubscript{6}</td>
<td>C\textsubscript{82}H\textsubscript{54}N\textsubscript{4}FeO\textsubscript{6}</td>
<td>C\textsubscript{109.25}H\textsubscript{93}N\textsubscript{2}Fe\textsubscript{2}SO\textsubscript{4}F\textsubscript{3}Cl\textsubscript{5.5}</td>
</tr>
<tr>
<td>fw</td>
<td>816.74</td>
<td>868.81</td>
<td>1721.19</td>
<td>952.92</td>
<td>1287.46</td>
<td>2089.04</td>
</tr>
<tr>
<td>space group</td>
<td>C 2/c</td>
<td>P 2\textsubscript{1}c</td>
<td>P 2\textsubscript{1}n</td>
<td>C 2/c</td>
<td>C 2/c</td>
<td>P 2\textsubscript{1}c</td>
</tr>
<tr>
<td>a, Å</td>
<td>21.272(5)</td>
<td>14.543(5)</td>
<td>15.161(2)</td>
<td>35.297(6)</td>
<td>14.8112(10)</td>
<td>27.237(7)</td>
</tr>
<tr>
<td>b, Å</td>
<td>16.099(5)</td>
<td>11.941(5)</td>
<td>10.8129(16)</td>
<td>11.092(2)</td>
<td>31.795(2)</td>
<td>14.188(4)</td>
</tr>
<tr>
<td>α, deg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>β, deg</td>
<td>114.962(5)</td>
<td>103.030(5)</td>
<td>93.126(3)</td>
<td>114.840(3)</td>
<td>104.9430(10)</td>
<td>113.644(4)</td>
</tr>
<tr>
<td>γ, deg</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V, Å\textsuperscript{3}</td>
<td>4239(2)</td>
<td>4566(3)</td>
<td>4299.7(11)</td>
<td>5409.4(17)</td>
<td>7652.0(9)</td>
<td>10381(5)</td>
</tr>
<tr>
<td>Z</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>T, °C</td>
<td>-100</td>
<td>-70</td>
<td>-70</td>
<td>-70</td>
<td>-70</td>
<td>-100</td>
</tr>
<tr>
<td>ρ calcld. g cm\textsuperscript{-3}</td>
<td>1.280</td>
<td>1.264</td>
<td>1.329</td>
<td>1.170</td>
<td>1.118</td>
<td>1.337</td>
</tr>
<tr>
<td>μ(M\textsubscript{0} Kα), mm\textsuperscript{-1}</td>
<td>0.404</td>
<td>0.380</td>
<td>0.523</td>
<td>0.328</td>
<td>0.249</td>
<td>0.535</td>
</tr>
<tr>
<td>total no. of data</td>
<td>13206</td>
<td>27049</td>
<td>25519</td>
<td>15913</td>
<td>19849</td>
<td>75408</td>
</tr>
<tr>
<td>no. of unique data</td>
<td>4885</td>
<td>10101</td>
<td>9737</td>
<td>6117</td>
<td>6730</td>
<td>18275</td>
</tr>
<tr>
<td>observed data\textsuperscript{a}</td>
<td>3598</td>
<td>8261</td>
<td>7379</td>
<td>4836</td>
<td>5466</td>
<td>14971</td>
</tr>
<tr>
<td>no. of parameters</td>
<td>269</td>
<td>569</td>
<td>550</td>
<td>420</td>
<td>420</td>
<td>1306</td>
</tr>
<tr>
<td>R\textsuperscript{b}</td>
<td>0.0447</td>
<td>0.0625</td>
<td>0.0609</td>
<td>0.0477</td>
<td>0.0791</td>
<td>0.0805</td>
</tr>
<tr>
<td>wR\textsuperscript{2c}</td>
<td>0.0708</td>
<td>0.1281</td>
<td>0.1454</td>
<td>0.1344</td>
<td>0.2487</td>
<td>0.2048</td>
</tr>
<tr>
<td>max, min peaks, e Å\textsuperscript{-3}</td>
<td>0.339, -0.234</td>
<td>0.344, -0.346</td>
<td>0.713, -0.535</td>
<td>0.431, -0.317</td>
<td>1.032, -0.542</td>
<td>1.320, -1.002</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Observation criterion: I > 2σ(I). \textsuperscript{b} R = \sum|Fo-Fc|/\sum|Fo|. \textsuperscript{c} wR\textsuperscript{2} = \{\sum[w(Fo\textsuperscript{2}-Fc\textsuperscript{2})\textsuperscript{2}]/\sum[w(Fo\textsuperscript{2})\textsuperscript{2}]\}\textsuperscript{1/2}. 
<table>
<thead>
<tr>
<th></th>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Fe(1)–N(1)</td>
<td>N(1)–Fe(1)–N(1A)</td>
</tr>
<tr>
<td></td>
<td>2.214(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(1)</td>
<td>N(1)–Fe(1)–O(1)</td>
</tr>
<tr>
<td></td>
<td>2.137(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(2)</td>
<td>N(1)–Fe(1)–O(2)</td>
</tr>
<tr>
<td></td>
<td>2.180(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>O(1)–Fe(1)–O(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>O(1)–Fe(1)–O(1A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>O(1)–Fe(1)–O(2A)</td>
</tr>
<tr>
<td>4</td>
<td>Fe(1)–N(1)</td>
<td>N(1)–Fe(1)–N(2)</td>
</tr>
<tr>
<td></td>
<td>2.163(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–N(2)</td>
<td>N(1)–Fe(1)–O(1)</td>
</tr>
<tr>
<td></td>
<td>2.194(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(1)</td>
<td>N(1)–Fe(1)–O(2)</td>
</tr>
<tr>
<td></td>
<td>2.303(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(2)</td>
<td>N(1)–Fe(1)–O(3)</td>
</tr>
<tr>
<td></td>
<td>2.065(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(3)</td>
<td>N(1)–Fe(1)–O(4)</td>
</tr>
<tr>
<td></td>
<td>2.102(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(4)</td>
<td>N(2)–Fe(1)–O(1)</td>
</tr>
<tr>
<td></td>
<td>2.265(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N(2)–Fe(1)–O(2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N(2)–Fe(1)–O(3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N(2)–Fe(1)–O(4)</td>
</tr>
<tr>
<td>5</td>
<td>Fe(1)–Fe(1A)</td>
<td>O(1)–Fe(1)–O(2)</td>
</tr>
<tr>
<td></td>
<td>4.3429(8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(1)</td>
<td>O(1)–Fe(1)–O(3)</td>
</tr>
<tr>
<td></td>
<td>2.013(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(2)</td>
<td>O(1)–Fe(1)–N(1)</td>
</tr>
<tr>
<td></td>
<td>1.958(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(3)</td>
<td>O(2)–Fe(1)–O(3)</td>
</tr>
<tr>
<td></td>
<td>2.030(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fe(1)–N(1)</td>
<td>O(2)–Fe(1)–N(1)</td>
</tr>
<tr>
<td></td>
<td>2.154(2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>O(3)–Fe(1)–N(1)</td>
</tr>
</tbody>
</table>

*a Number in parentheses are estimated standard deviations of the last significant figure. Atoms are labeled as indicated in Figure 4.1.
Table 4.3. Selected bond lengths (Å) and angles (deg) for 6, 7, and 15<sup>a</sup>

<table>
<thead>
<tr>
<th></th>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Fe(1)–O(1)</td>
<td>2.250(1)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(2)</td>
<td>2.118(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(3)</td>
<td>2.099(2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Fe(1)–N(1)</td>
<td>2.163(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(1)</td>
<td>2.059(2)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(2)</td>
<td>2.384(3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Fe(1)···Fe(2)</td>
<td>3.576(1)</td>
</tr>
<tr>
<td></td>
<td>N(1)···N(2)</td>
<td>6.077(5)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–N(1)</td>
<td>2.164(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(1)</td>
<td>2.054(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(3)</td>
<td>2.017(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(5)</td>
<td>2.048(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(1)–O(7)</td>
<td>2.081(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–N(2)</td>
<td>2.193(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(2)</td>
<td>2.084(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(4)</td>
<td>2.034(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(6)</td>
<td>1.974(3)</td>
</tr>
<tr>
<td></td>
<td>Fe(2)–O(9)</td>
<td>2.081(3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Number in parentheses are estimated standard deviations of the last significant figure. Atoms are labeled as indicated in Figures 4.1 and 4.3.
Chart 4.1.
Chart 4.2.
Scheme 4.1.
(a) Tf₂O/CH₂Cl₂/pyridine, 95%; (b) Me₃SiCH/NEt₃/THF, (PPh₃)₂PdCl₂/Cul (cat), 80%; (c) Bu₄NF/THF, 50%;
(d) R = H: 1,2-dilodobenzene/Et₂NH, (PPh₃)₂PdCl₂/Cul (cat), Δ, 66%; (e) R = Et: 1,2-dilodo-4,5-diethylbenzene/Et₂NH,
(PPh₃)₂PdCl₂/Cul (cat), Δ, 45%; (f) R = H: KOSiMe₃/THF; (g) R = Et: NaOH/MeOH

Scheme 4.2.
Figure 4.1. ORTEP diagrams of \([\text{Fe(O}_2\text{CAr}^{\text{Tol}})]_2(\text{Me}_2\text{-napy})\) (2), \([\text{Fe(O}_2\text{CAr}^{\text{Tol}})]_2(\text{vpy})_2\) (4), \([\text{Fe}_2(\mu-\text{O}_2\text{CAr}^{\text{Tol}})]_2(\text{O}_2\text{CAr}^{\text{Tol}})]_2(\text{vpy})_2\) (5), \([\text{Fe(O}_2\text{CAr}^{\text{t-BuPh}})]_2(\text{THF})_2\) (6), and \([\text{Fe(O}_2\text{CAr}^{\text{t-BuPh}})]_2(\text{DMP})_2\) (7) showing 50% probability thermal ellipsoids for all non-hydrogen atoms (left to right, top to bottom). The phenyl rings of the bridging \(\text{Ar}^{\text{Tol}}\text{CO}_2^-\) ligands are omitted for clarity.
Figure 4.2. Representation of \([\text{Fe}_2(\text{BQFB})(\mu-\text{OH})(\mu-\text{O}_2\text{CAr}^{\text{Tol}})(\text{O}_2\text{CAr}^{\text{Tol}})_2(\text{THF})(\text{H}_2\text{O})]\) displaying syn nitrogen donor ligands.
Figure 4.3. ORTEP diagram of the cation of $[\text{Fe}_2(\text{Et}_2\text{BCQEB}^\text{En})(\mu-\text{O}_2\text{CAR}^\text{Tol})_2]\text{(OTf)}$ (15) showing 50% probability thermal ellipsoids for all non-hydrogen atoms and ball and stick diagram showing the connectivity of $[\text{Cu}($Et$_2\text{BCQEB}^\text{En}$)$($\mu-\text{I}$)$_2$] (16) (top to bottom). The phenyl rings of the bridging Ar$^{\text{Tol}}$CO$_2$ ligands in 15 are omitted for clarity.
Chapter 5
Synthesis and Characterization of $\text{Cu}_2(\text{I,I})$, $\text{Cu}_2(\text{I,II})$, and $\text{Cu}_2(\text{II,II})$
Compounds Supported by Two Phthalazine-Based Ligands:
Dramatic Influence of a Hydrophobic Pocket*
Introduction

The reductive activation of dioxygen by low valent copper ions is accomplished in a variety of biological contexts. Many enzymes use copper to oxidize organic substrates and the scope of this reactivity is remarkable. For example, dopamine β-monooxygenase (DβM) regulates the levels of neurotransmitters by converting dopamine to norepinephrine,\(^1\) peptidylglycine α-hydroxylating monoxygenase (PHM) hydroxylates peptidylglycine units,\(^1\) galactose oxidase (GAO) transforms primary alcohols to aldehydes,\(^1,2\) tyrosinase oxidizes monophenols to o-diphenols and o-diphenols to o-quinones,\(^3\) the latter reaction also being performed by catechol oxidase,\(^4\) and particulate methane monoxygenase (pMMO) converts a C–H bond of methane to produce methanol.\(^5\) In addition to substrate oxidation, hemocyanin (Hc) uses copper to bind dioxygen reversibly, thus serving as a dioxygen transport protein in arthropods and mollusks.\(^3,6\) The primary function of several other copper metalloproteins is to mediate electron transfer. Both mononuclear blue copper proteins\(^7\) and multicopper oxidases\(^3,8\) belong to this class, as do the fully-delocalized Cu(I)Cu(II) centers found at the Cu\(_A\) sites in cytochrome c oxidase and nitrous oxide reductase.\(^9,10\)

The reduced forms of several of these metalloenzymes, notably Hc, tyrosinase, and catechol oxidase, feature active sites with coupled dicopper(I) units in a histidine-rich coordination environment. These copper centers interact with dioxygen to afford dicopper(II) peroxy species in which the O\(_2\)\(^2\) moiety is bound in a μ-η\(^2\):η\(^2\) fashion.\(^3\) Inspired by the natural systems, significant effort has been devoted to the synthesis of small molecule model compounds that mimic both the active site geometry and dioxygen reactivity of these copper proteins.\(^11-16\) A common approach to modeling the chemistry of the metalloenzymes is to prepare mononuclear copper(I) complexes using bidentate, tridentate, or tetradequate N-donor ligands. Depending upon the ligand system, reaction with dioxygen can afford either dicopper(II) intermediates with μ-η\(^2\):η\(^2\)-side-on or μ-1,2-end-on peroxy coordination, or bis(μ-oxo)dicopper(III) species.\(^17\)
Dinucleating ligands designed to hold two copper(I) ions in close proximity have also been employed to model the dinuclear core of copper proteins. Typically, such ligands feature two clusters of pyridine and/or amine moieties linked by a hydrocarbon spacer.\textsuperscript{11,14,16} Compared to their mononuclear counterparts, the reaction of dioxygen with dicopper(I) complexes supported by dinucleating ligands is more entropically favorable but generates less enthalpically stable peroxo species.\textsuperscript{18} Force field calculations highlight the effect of the linker unit on the stability of the resulting peroxo species.\textsuperscript{19}

Fewer investigations have focused on the utility of dinucleating ligands in which the linker moiety directly coordinates to and bridges two copper centers for the reductive activation of dioxygen. Several noteworthy examples are depicted in Figure 5.1. Phenoxide units afford O\textsubscript{2}-sensitive dicopper(I) compounds, including a complex that reacts with dioxygen to afford a terminally-bound peroxo species.\textsuperscript{20,21} When a relatively rigid 1,8-naphthyridine-based ligand was employed, a (μ-1,2-peroxo)dicopper(II) intermediate with a short copper···copper separation of ~2.84 Å resulted, indicating that such a short metal–metal distance can be accommodated in the absence of a single-atom bridge.\textsuperscript{22} As a final example, use of a multidentate functionalized pyrazolate ligand allowed for the crystallographic characterization of an unusual tetranuclear (μ\textsubscript{4}-peroxo)Cu\textsubscript{4}(II) complex.\textsuperscript{23} Clearly, dinucleating ligands enable the preparation of unique [Cu\textsubscript{4}O\textsubscript{2}] species, distinct from those generated by the reaction of dioxygen with mononuclear copper(I) complexes.

The nitrogen-rich hexadentate ligands bdptz and Ph\textsubscript{4}bdptz (Chart 5.1), where bdptz is 1,4-bis(2,2′-dipyridylmethyl)phthalazine and Ph\textsubscript{4}bdptz is 1,4-bis[bis(6-phenyl-2-pyridyl)methyl]phthalazine, have previously been used to prepare dinuclear compounds of several divalent first-row transition metal ions.\textsuperscript{24,28} These two dinucleating ligands feature a phthalazine bridge linking two clusters of pyridine groups and support dimetallic structures with a variety of ancillary ligands. The
copper(I) and copper(II) chemistry of these two phthalazine-based ligands is now presented. The readily assembled complex \( [\text{Cu}_2(\text{bdptz})(\text{MeCN})_2](\text{OTf})_2 \) serves as a convenient starting material for preparing the compounds \( [\text{Cu}_2(\text{bdptz})_2](\text{OTf})_2 \), \( [\text{Cu}_2(\text{bdptz})(\mu-\text{OH})(\text{MeCN})_2](\text{OTf})_2 \), \( [\text{Cu}_2(\text{bdptz})(\mu-\text{OH})_2](\text{OTs})_2 \), \( [\text{Cu}_2(\text{bdptz})(\mu-vpy)](\text{OTf})_2 \), and \( [\text{Cu}_2(\text{bdptz})(\mu-\text{O}_2\text{CCH}_3)](\text{OTf})_2 \). The use of Ph\(_4\)bdptz permitted the isolation of \( [\text{Cu}_2(\text{Ph}_4\text{bdptz})(\text{MeCN})_2](\text{OTf})_2 \), \( [\text{Cu}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{CCH}_3)](\text{OTf})_2 \), 7(OTf). All compounds were studied by X-ray crystallography, and the electrochemical behavior of triflate salts of 1, 2, and 6 was investigated. Pronounced differences in reactivity and stability between the two series of complexes derived from bdptz and Ph\(_4\)bdptz were encountered. This work shows that the incorporation of a hydrophobic binding pocket, highly desirable for facilitating the activation of small molecule substrates, dramatically influences the properties of the resulting coordination compounds relative to complexes lacking such a binding cavity.

**Experimental**

**General Procedures.** Dichloromethane, acetonitrile, and diethylether were saturated with argon and purified by passage over a column of activated alumina under argon.\(^{30}\) Methanol was distilled from Mg and I\(_2\) under nitrogen. The compounds \( [\text{Cu}(\text{MeCN})_4]X \ (X = \text{OTf}^{21} \text{ or BF}_4^{32}) \), bdptz,\(^{28}\) and Ph\(_4\)bdptz\(^{24}\) were prepared according to published literature procedures. Prior to use, vpy was freshly distilled. All other reagents were purchased from commercial sources and used as received. Air-sensitive manipulations were performed under nitrogen in an MBraun glovebox or by using standard Schlenk techniques.

\( [\text{Cu}_2(\text{bdptz})(\text{MeCN})_2](\text{OTf})_2 \), 1(OTf). To a colorless solution of \( [\text{Cu}(\text{MeCN})_4](\text{OTf}) \) (404 mg, 1.07 mmol) in MeCN (5 mL) was added solid bdptz (253 mg, 0.543 mmol) to generate an orange suspension. After further addition of MeCN (4 mL) the solution became homogenous and was stirred for 30 min. The orange solution
was saturated with Et₂O and left at r.t. overnight to give 1(OTf)₂ as an orange microcrystalline solid (436 mg, 83%). FT-IR (cm⁻¹, KBr): 3126 (w), 3097 (w), 3073 (w), 3051 (w), 3000 (w), 2932 (w), 1596 (s), 1569 (m), 1536 (w), 1473 (m), 1441 (s), 1414 (w), 1364 (m), 1328 (w), 1300 (s), 1284 (s), 1261 (s), 1238 (s), 1165 (m), 1147 (m), 1029 (s), 861 (w), 822 (w), 771 (s), 759 (s), 683 (w), 637 (s), 573 (s), 517 (m). ¹H NMR (300 MHz, CD₂Cl₂): δ 9.16 m (2H), 8.69 d (J = 13 Hz, 4H), 8.27 m (2H), 8.11 d (J = 26 Hz, 4H), 7.81 m (4H), 7.36 m (4H), 7.08 s (2H), 2.47 s (6H). Anal. Calcd for C₃₆H₂₈N₈O₆F₆S₂Cu₂: C, 44.40; H, 2.90; N, 11.51. Found: C, 44.16; H, 2.86; N, 11.38.

[Cu₂(bdptz)₂](OTf)₃, 2(OTf)₃. To an orange solution of 1(OTf)₂ (50 mg, 0.051 mmol) in MeOH (2 mL) was added dropwise a solution of NaO₂CCH₃ (8.4 mg, 0.10 mmol) in MeOH (2 mL). A red-brown mixture was generated and stirred for 2 h. Filtration through a plug of Celite followed by exposure to Et₂O vapor diffusion yielded 2(OTf)₃ as a red crystalline solid (20 mg, 53%). Single crystals of 2(OTf)₃·2MeCN·0.5Et₂O suitable for X-ray diffraction study were grown from MeCN by Et₂O vapor diffusion. FT-IR (cm⁻¹, KBr): 3062 (w), 3022 (w), 2929 (w), 1596 (m), 1596 (m), 1570 (m), 1546 (w), 1472 (m), 1442 (m), 1405 (m), 1364 (m), 1276 (s), 1223 (m), 1150 (m), 1054 (w), 1030 (s), 854 (w), 832 (w), 817 (w), 759 (m), 685 (w), 680 (w), 655 (w), 636 (s), 585 (m), 572 (m), 517 (m). Anal. Calcd for C₆₅H₄₄N₁₂O₄F₄S₂Cu₂: C, 50.20; H, 2.94; N, 11.15. Found: C, 49.91; H, 2.77; N, 11.19.

[Cu₅(bdptz)(μ-OH)(MeCN)₂](OTf)₃, 3(OTf)₃. To an orange solution of 1(OTf)₂ (100 mg, 0.103 mmol) in MeOH (4 mL) was added AgOTf (53 mg, 0.206 mmol) in MeOH (2 mL) and a cloudy, yellow-green mixture formed. The suspension was stirred for 30 min, followed by filtration through Celite and evaporation of the solvent under reduced pressure. Blue X-ray quality crystals of 3(OTf)₃·2.25MeCN were obtained by vapor diffusion of Et₂O into a solution of MeCN and CH₂Cl₂ (47 mg, 40%). FT-IR (cm⁻¹, KBr): 3219 (br, m), 1670 (w), 1611 (m), 1575 (w), 1479 (w), 1450 (m), 1373 (w), 1289 (s), 1237 (s), 1165 (s), 1029 (s), 823 (w), 772 (m), 685 (w), 637 (s), 578 (m), 517 (m). Difficulty
in separating 3(OTf)₃ from an oil that formed upon crystallization prevented satisfactory elemental combustion analysis.

\[ \text{[Cu_2(bdptz)(μ-OH)_2]_2(OTs)_4, 4(OTs)_4. Method A. A solution of [Cu(H₂O)_6](OTs)_2} \]

(110 mg, 0.215 mmol) in MeCN/H₂O (10:1, 4 mL) was treated with solid bdptz (50 mg, 0.107 mmol) to generate a dark blue solution to which an aqueous solution of NaOH (1M, 215 µL, 0.215 mmol) was added. The resulting blue-green mixture was stirred for 30 min, filtered through Celite, and Et₂O vapor was allowed to diffuse into the solution. Green crystals of 4(OTs)_4·MeCN·12H₂O, suitable for X-ray diffraction study, were isolated (30 mg, 29%). FT-IR (cm⁻¹, KBr): 3447 (br, m), 3076 (w), 3048 (w), 3008 (w), 2919 (w), 2868 (w), 1607 (m), 1592 (m), 1570 (w), 1473 (w), 1444 (m), 1364 (w), 1233 (m), 1212 (s), 1191 (s), 1165 (s), 1118 (s), 1031 (s), 1008 (s), 918 (w), 875 (w), 819 (m), 769 (m), 680 (s), 650 (w), 636 (w), 625 (w), 581 (w), 563 (s), 549 (m), 526 (w). Anal. Calcd for C₉₈H₇₈N₁₂O₁₇S₄Cu₄, 4(OTs)_4·H₂O: C, 53.98; H, 4.02; N, 8.58. Found: C, 53.76; H, 3.81; N, 8.61.

\[ \text{Method B. An orange solution of 1(OTf)_2 (65 mg, 0.067 mmol) in MeCN (4 mL) was gently} \]

was gently purged with O₂ for 45 min to yield a green solution. An aqueous solution of NaOTs (2.7 M, 0.5 mL, 1.34 mmol) was added dropwise to afford a green precipitate that was collected on filter paper and washed with H₂O. Slow evaporation of the filtrate gave green crystals of 4(OTf)_4 (30 mg, 46%).

\[ \text{[Cu_2(bdptz)(μ-vpy)](OTf)_2, 5(OTf)_2. Treatment of 1(OTf)_2 (150 mg, 0.15 mmol) with vpy (18.3 µL, 0.17 mmol) in CH₂Cl₂ (6 mL) afforded a yellow mixture that was} \]

was stirred for 30 min. Filtration through Celite was followed by evaporation of the solvent under reduced pressure. The resulting residue was dissolved in MeOH and Et₂O vapor was allowed to diffuse into the solution. Orange crystals of 5(OTf)_2·Et₂O, suitable for X-ray crystallography, were obtained by this procedure (128 mg, 86%). FT-IR (cm⁻¹, KBr): 3131 (w), 3073 (w), 2976 (w), 2933 (w), 2855 (w), 1598 (s), 1570 (m), 1549 (w), 1531 (w), 1473 (m), 1442 (m), 1419 (w), 1365 (w), 1351 (w), 1260 (s), 1223 (m), 1161 (m), 1115 (w),
1029 (s), 937 (w), 861 (w), 774 (m), 756 (m), 679 (w), 637 (s), 585 (m), 572 (m), 517 (m). $^1$H NMR (300 MHz, CD$_2$Cl$_2$): δ 9.39 m (1H), 9.27 m (1H), 8.89 d (J = 18 Hz, 1H), 8.72 dd (J = 14 Hz, 2H), 8.56 d (J = 14 Hz, 1H), 8.37 d (J = 18 Hz, 2H), 8.29 – 8.10 m (7H), 7.92 – 7.82 m (3H), 7.71 m (1H), 7.57 m (1H), 7.48 – 7.34 m (5H), 7.24 – 7.13 m (2H), 5.60 d (J = 53 Hz, 1H), 4.85 d (J = 31 Hz, 1H). Anal. Calcd for C$_{39}$H$_{23}$N$_7$O$_6$S$_2$Cu$_2$: C, 46.99; H, 2.93; N, 9.84. Found: C, 47.19; H, 3.17; N, 9.99.

$[\text{Cu}_2(\text{Ph}_4\text{bdptz})(\text{MeCN})_3](\text{OTf})_2$, 6(OTf)$_2$. To a solution of [Cu(MeCN)$_4$](OTf) (67 mg, 0.18 mmol) in MeCN (10 mL) was added solid Ph$_4$bdptz (69 mg, 0.090 mmol) and the resulting orange mixture was stirred for 30 min. The slightly cloudy solution was filtered through Celite and evaporated to dryness. The residue was dissolved in CH$_2$Cl$_2$ and Et$_2$O vapor diffusion into this solution afforded 6(OTf)$_2$ as a yellow flocculent solid (83 mg, 73%). X-ray quality crystals of the BF$_4^-$ salt, 6(BF$_4$)$_2$, were obtained from the corresponding reaction using [Cu(MeCN)$_4$](BF$_4$)$_2$, followed by recrystallization from MeCN with Et$_2$O vapor diffusion. FT-IR (cm$^{-1}$, KBr): 3062 (w), 3033 (w), 2993 (w), 2932 (w), 1591 (s), 1579 (m), 1561 (s), 1542 (m), 1497 (w), 1448 (s), 1421 (m), 1357 (m), 1263 (s), 1223 (s), 1148 (s), 1030 (s), 919 (w), 813 (m), 764 (s), 699 (s), 676 (m), 572 (m), 516 (m). $^1$H NMR (300 MHz, CH$_2$Cl$_2$): δ 9.36 m (2H), 8.37 m (2H), 8.20 d (J = 25 Hz, 4H), 7.92 t (J = 25 Hz, 4H), 7.55 – 7.45 m (16H), 7.40 – 7.32 m (10H), 1.21 s (6H). Anal. Calcd for C$_{60}$H$_{40}$N$_8$O$_6$S$_2$Cu$_2$: C, 56.38; H, 3.47; N, 8.77. Found: C, 56.09; H, 3.38; N, 8.67.

$[\text{Cu}_2(\text{Ph}_4\text{bdptz})(\mu-\text{O}_2\text{CCH}_3)](\text{OTf})$, 7(OTf). To a mixture of 6(OTf)$_2$ (52 mg, 0.041 mmol) in CH$_2$Cl$_2$ (4 mL) was added dropwise a solution of NaO$_2$CCH$_3$ (6.7 mg, 0.081 mmol) in MeOH (1 mL). The resulting dark red solution was stirred for 30 min and evaporated to dryness under reduced pressure. The residue was dissolved in CH$_2$Cl$_2$, filtered through Celite, and diffusion of Et$_2$O vapor into this solution afforded a mixture of 6(OTf)$_2$ and 7(OTf)$_2$, as revealed by an X-ray diffraction study. FT-IR (cm$^{-1}$, KBr): 3062 (w), 3032 (w), 2923 (w), 1589 (s), 1579 (s), 1559 (s), 1448 (s), 1420 (m), 1358 (w), 1280 (s),
1255 (s), 1223 (w), 1156 (m), 1029 (s), 821 (w), 808 (m), 782 (w), 760 (s), 742 (w), 697 (s), 693 (s), 653 (w), 638 (s), 573 (w), 517 (w).

**Physical Measurements.** $^1$H NMR spectra were obtained on a 300 MHz Varian Mercury spectrometer. FT-IR spectra were recorded on a Thermo Nicolet Avatar 360 spectrometer. Optical spectra were measured on a Hewlett-Packard 8453 diode-array spectrophotometer and low-temperature experiments were carried out by using a custom-made quartz cuvette fused onto a vacuum-jacketed Dewar. Frozen solution EPR spectra of $2$(OTf)$_3$ were recorded on a Bruker Model 300 ESP X-band spectrometer operating at 9.37 GHz and running WinEPR software. A temperature of 77 K was maintained by using a specially designed cold finger filled with liquid N$_2$. ESI-MS spectra of oxidized solutions of $6$(OTf)$_2$ were obtained on a Bruker Daltons APEXII Tesla Fourier Transform Mass Spectrometer in the MIT Department of Chemistry Instrumentation Facility.

**X-ray Crystallography.** Crystals were mounted in Paratone N oil on the ends of glass capillaries and rapidly cooled under a low-temperature nitrogen cold stream. Crystals of $6$(BF$_3$)$_2$ were found to be thermally sensitive and room temperature data for this structure were subsequently acquired. Data were collected on a Bruker (formerly Siemens) SMART (1 - 3) or APEX (4 - 7) CCD X-ray diffractometer running the SMART software package,$^{33}$ with Mo Kα radiation ($\lambda = 0.71073$ Å), and refined using SAINT software.$^{34}$ Details of the data collection and reduction protocols are described elsewhere.$^{35}$ The structures were solved by direct methods using SHELXS-97 software$^{36}$ and refined on $F^2$ by using the SHELXL-97 program$^{37}$ incorporated in the SHELXTL software package.$^{38}$ Empirical absorption corrections were applied by using the SADABS program,$^{39}$ and PLATON software$^{40}$ was used to check the possibility of higher symmetry. All non-hydrogen atoms were located and their positions refined with anisotropic thermal parameters by least-squares cycles and Fourier syntheses.
Hydrogen atoms were assigned idealized positions and given a thermal parameter 1.2 times the thermal parameter of the carbon atom to which each was attached.

The Et₂O molecule in the structure of 2 is located on a special position and has disordered methylene carbon atoms, each of which was modeled at 50% occupancy. In the structure of 3, one triflate is disordered over two positions and was refined with occupancies of 58 and 42%. Four acetonitrile solvent molecules are present in the lattice. One of these molecules is located on a special position and was refined with full occupancy, a second molecule was modeled with 50% occupancy, and the remaining two solvent molecules share a common methyl group and were refined with occupancies of 50 and 25%, with the occupancy of the shared carbon atom fixed at 75%. The structure of 4 includes two acetonitrile solvent molecules that were refined with 50% occupancy and eighteen water molecules, eight of which were modeled with full occupancy, six with 50% occupancy, and four with 25% occupancy. In the structure of 5, the oxygen atom of the Et₂O solvent molecule was refined over two positions with occupancies of 75 and 25%. One fluorine atom of a tetrafluoroborate counterion in the structure of 6(BF₄)₂ is disordered over two positions and was modeled with occupancies of 50%. Crystallographic data for compounds 2 – 6 are listed in Table 5.1.

**Electrochemistry.** Cyclic voltammograms were recorded in an MBraun glovebox under a nitrogen atmosphere using an EG&G Model 263 potentiostat. The three-component cell consisted of a platinum working electrode, a Ag/AgNO₃ (0.1 M in MeCN) reference electrode, and a platinum wire auxiliary electrode. The supporting electrolyte was a 0.5 M Bu₄N(PF₆) solution. All measurements were referenced externally to Cp₂Fe.

**Results and Discussion**

**Synthesis of a Dicopper(I) Starting Material.** Compound 1(OTf)₂ was obtained in good yield (>80%) by reaction of [Cu(MeCN)]₄(OTf) and bdptz in a 2:1 ratio.
Although the ability of bdptz to promote the formation of dinuclear complexes is well established,\textsuperscript{25-28} 1 is the first example of a dicopper(I) compound with this ligand. X-ray crystallographic analysis was sufficient to ascertain the structure of 1, but poor data quality precluded a satisfactory refinement, and substitution of the triflate counterions for other units did not afford better crystals. The cationic moiety contains two Cu(I) centers, \( \sim 3.74 \) Å apart, bridged by the phthalazine unit and further ligated by the pyridine rings of bdptz and two MeCN solvent molecules. NMR spectroscopy and elemental analysis support the formulation of compound 1(OTf). Coordination of acetonitrile rather than the triflate counterions to the metal centers reflects its good solvation properties, and the ability to substitute these coordinated solvent molecules for other ligands renders 1 a convenient starting material for preparing a variety of compounds, as shown in Scheme 5.1.

**Preparation and Characterization of a Mixed-Valent Cu(I)Cu(II) Compound.** Treatment of 1(OTf) with NaO\(_2\)CCH\(_3\) in MeOH did not yield the anticipated acetate-bridged complex. Rather, the mixed-valent Cu(I)Cu(II) compound 2(OTf)\(_3\) was isolated. The concomitant precipitation of Cu metal over the course of the reaction suggests that disproportionation of Cu(I) is responsible for the generation of the divalent metal component.\textsuperscript{41} Initial coordination of the acetate to copper(I) probably occurs, followed by disproportionation and rearrangement to afford compound 2. It is well established that copper(I) carboxylate species readily undergo disproportionation, particularly in protic solvents,\textsuperscript{42,43} although 2 forms from 1 and NaO\(_2\)CCH\(_3\) even in MeCN or CH\(_2\)Cl\(_2\).

The structure of 2, shown in Figure 5.2 with pertinent bond lengths and angles listed in Table 5.2, features two copper centers that are asymmetrically coordinated by two bdptz ligands and closely resembles that of the related mixed-valent complex, [Cu\(_2\)(bdpdz)\(_2\)](ClO\(_4\))\(_3\), formed by reduction of a Cu(II) salt, where bdpdz is the pyridazine analogue of bdptz.\textsuperscript{29,44} The distorted tetrahedral Cu(I) site is ligated by a pair of pyridine groups from each bdptz ligand, whereas the axially elongated pseudo
octahedral environment of the Cu(II) center utilizes the remaining pyridine rings and one phthalazine N-donor of each ligand. As a result, one phthalazine nitrogen atoms of each bdptz ligand remains unmetallated. A Jahn-Teller distortion accounts for the axial bonds of the Cu(II) site being significantly longer (Cu(1)–N_{axav} = 2.293(2) Å) than the equatorial ones (Cu(1)–N_{eqav} = 2.042(1) Å). Surprisingly, the latter are virtually identical to the bond distances of the Cu(I) center (Cu(2)–N_{av} = 2.055(1) Å); the anticipated elongation of metal–ligand bonds upon moving from a coordination number of four to six is offset by the increase in oxidation state of the copper center, which causes bond contraction. The long Cu⋯Cu separation of 5.204(2) Å suggests that the unpaired electron is probably not delocalized between the two metal centers.

Examination of 2(OTf)$_3$ by EPR spectroscopy confirms that the valencies are localized, as suggested by X-ray crystallography. A frozen solution of 2(OTf)$_3$ in MeOH or MeCN gave a four-line EPR spectrum with $g_{||} = 2.25$ ($A_{||} = 169$ G) and $g_{\perp} = 2.06$ at 77 K. This spectrum, shown in Figure 5.3, is typical of an isolated Cu(II) ion, confirming that 2 is a class I mixed-valent compound, with the unpaired electron localized on the Cu(II) site. A similar spectrum was reported for the closely related pyridazine derivative [Cu$_2$(bdpz)$_2$](ClO$_4$)$_3$. Complex 2 is an example of a synthetic model in which the stereochemistry at the metal centers dictates the location of the unpaired electron. In contrast, the Cu$_A$ centers of cytochrome c oxidase and nitrous oxide reductase contain fully-delocalized mixed-valent centers in close proximity to each other and display a 7-line EPR spectrum typical for class III mixed-valent dicopper units.

Synthesis and Crystallographic Analysis of Hydroxide-Bridged Dicopper(II) Complexes. Compound 1(OTf)$_2$ was treated with one equivalent of AgOTf to determine whether a mixed-valent complex could also be accessed through chemical oxidation. The dicopper(II) complex 3(OTf)$_3$ was formed, however, indicating that Ag$^+$ is too strong an oxidant to achieve this goal. As expected, the structure of 3, shown in Figure
5.2 with selected bond lengths and angles provided in Table 5.2, is similar to that of the cation in \([\text{Cu}_2(\text{bdptz})(\mu-\text{OH})(\text{H}_2\text{O})_3](\text{OTs})_4\), a complex that was prepared directly from \([\text{Cu}(\text{H}_2\text{O})_6](\text{OTs})_2\). Three coordination sites of each pseudo-square-pyramidal copper(II) ion are occupied by the nitrogen donors of bdptz. In addition to the phthalazine unit, the two Cu(II) centers are also bridged by a single oxygen atom. The Cu–O bond distances of 1.909(5) and 1.904(5) Å unequivocally show that this ligand is a hydroxide ion, which was probably introduced as an adventitious solvent component. The Cu–O(H)–Cu bond angle is 112.9(3)°, and the presence of the single atom bridge significantly diminishes the Cu···Cu separation in 3 to 3.178(2) Å, a reduction of > 0.5 Å relative to that in 1. The Cu–N bond lengths of the pyridine groups bound trans to the hydroxide are substantially shorter (Cu–N\(_{av}\) = 2.003(4) Å) than those of the other pyridine ligands (Cu–N\(_{av}\) = 2.282(4) Å). Coordination of an acetonitrile solvent molecule to each metal center completes their coordination spheres.

Reaction of 1(OTf)\(_2\) with dioxygen, or treatment of \([\text{Cu}(\text{H}_2\text{O})_6](\text{OTs})_2\) with bdptz and NaOH in a ratio of 2:1:2, yielded the tetracopper compound 4(OTs)\(_4\). The structure of cation 4 is composed of two crystallographically equivalent (μ-hydroxo)dicopper(II) units that are joined by two additional hydroxide groups (Figure 5.2, Table 5.3). The \([\text{Cu}_2(\text{bdptz})(\mu-\text{OH})]^{3+}\) moieties of 4 have bond lengths and angles similar to those in 3, including the contraction of the Cu–N bond located trans to the bridging hydroxide ligands. The phthalazine-bridged metal ions are separated by 3.169(1) Å with a Cu–O(H)–Cu angle of 112.47(10)°, essentially identical to that found in the structure of 3. In contrast, the Cu···Cu separation between the two dinuclear units is significantly greater, Cu(1)···Cu(2A) = 3.560(1) Å, presumably resulting from the presence of one, rather than two, bridging groups and the larger Cu–O(H)–Cu bond angle of 135.19(12)°.

Tetracopper(II) compounds with four hydroxide ligands are known to adopt cubane\(^{47,48}\) or "stepped-cubane"\(^{49-51}\) type structures. Prior to this work, the \([\text{M}_4(\mu-\text{OH})_4]^{4+}\) structural motif of 4 was not observed with copper(II), although it was
characterized with nickel(II),\textsuperscript{28} and similar structures of iron(III) with oxo, rather than hydroxo, ligands have also been encountered.\textsuperscript{52} The formation of tetr nuclar 4(OTs)\textsubscript{4} rather than a bis(\(\mu\)-hydroxo)dicopper(II) compound probably results because the geometric restrictions imposed by the bridging phthalazine unit disfavor the \(\{\text{Cu}_2(\mu\text{-OH})_4\}^{3+}\) core found in other complexes.\textsuperscript{53-56}

**Preparation and Crystal Structure of a Bridging Vinylpyridine Dicopper(I) Derivative.** Complex 5(OTf)\textsubscript{2} was synthesized in high yield (86\%) by reaction of 1(OTf)\textsubscript{2} with vpy. Both the pyridine N-atom and the alkene moiety of vpy bind to the dimetallic core. The only other structurally characterized compounds in which vpy coordinates to two metal centers in this fashion are \([\text{Cu}_2(\mu\text{-vpy})\text{(vpy)}_2]\text{(ClO}_4\text{)}_2\text{)}\text{57} and the linear polymers [(vpy)CuCl]\text{\_n} and [(vpy)CuBr]\text{\_n}.\textsuperscript{58} The \(\eta^2\)-interaction of an alkene\textsuperscript{59-67} or aromatic group\textsuperscript{68} with copper(I) centers supported by three nitrogen donors is well-documented. It is also noteworthy that copper(I) is the only metal known to bind olefins in nature.\textsuperscript{41} In particular, plants utilize a copper(I) center to bind ethylene, a hormone that is involved in many aspects of plant development, including fruit ripening.\textsuperscript{69,70}

The structure of cation 5 (Figure 5.2, Table 5.3) reveals that each distorted tetrahedral Cu(I) center is ligated by bdptz in the usual manner, with Cu–N\textsubscript{av} bond distances of 2.081(1) Å. The pyridine N-atom of the vpy ligand coordinates to Cu(1) with a bond length of 1.951(2) Å, which is somewhat shorter than the corresponding bonds in the complex \([\text{Cu}_2(\mu\text{-vpy})\text{(vpy)}_2]\text{(ClO}_4\text{)}_2\text{)}\text{,} 1.981(9)\text{ and } 2.008(10) \text{ Å}.\textsuperscript{57} Coordination of the alkene moiety to Cu(2) is asymmetric, as was observed in \([\text{Cu}_2(\mu\text{-vpy})\text{(vpy)}_2]\text{(ClO}_4\text{)}_2\text{), with longer bond lengths for the inner (2.050(3) Å) than the outer (2.008(3) Å) olefinic carbon atoms. The olefinic C=C bond length in 5 of 1.368(4) Å matches well with those of the coordinated vpy ligands in \([\text{Cu}_2(\mu\text{-vpy})\text{(vpy)}_2]\text{(ClO}_4\text{)}_2\text{,} 1.358(16)\text{ and } 1.368(17) \text{ Å, and is slightly longer than those of the non-coordinated vpy C=C groups, 1.319(23) and 1.307(23) Å, in the latter complex.}
Synthesis and Structural Characterization of a Bis(acetonitrile) Complex with Ph₄bdptz. Tetranuclear compounds such as 4(OTs)₄ form through undesired bimolecular interactions, frequently resulting from oxidation reactions. Because bdptz supports such structures with several first row transition metal ions, we introduced the sterically hindered derivative Ph₄bdptz in an effort to prevent the formation of high-nuclearity species. Treatment of [Cu(MeCN)₄]OTf with Ph₄bdptz in a 2:1 ratio afforded 6(OTf)₂ in > 70% yield. As an analogue of 1, compound 6 also serves as a useful starting material. Although the triflate salt is a flocculent solid, single crystals suitable for X-ray crystallographic study were obtained when BF₄⁻ was used as the counterion.

The geometry around the copper centers in cation 6, shown in Figure 5.4 with selected bond lengths and angles listed in Table 5.4, is similar to that in 1. The copper(I) ions are separated by 3.792(1) Å, ~0.05 Å longer than the Cu⋯Cu distance in 1. The average Cu–N(Ph₄bdptz) bond length of 2.115(2) Å is substantially longer than the Cu–N(MeCN) bond distances of 1.893(4) and 1.879(5) Å. This difference in bond lengths is evident in related compounds containing [N₃(aromatic)Cu¹(MeCN)]fragments, and is a result of the different nitrogen atom orbital hybridizations and lesser steric demands of the linear CH₃CN ligand. The Cu–N bond lengths in 6 are slightly longer than the corresponding distances in 1 (ΔCu–N(bdptz) ~0.05, ΔCu–N(MeCN) ~0.02 Å). The increased metal–ligand and metal–metal distances in 6 relative to the bdptz analogue result from a combination of electronic and steric factors; the electron-withdrawing phenyl rings of Ph₄bdptz weaken the Cu–N bonds, and the steric repulsion created by the proximity of these bulky groups is minimized when the ligand components are farther from the metal centers. The N(Ph₄bdptz)–Cu–N(Ph₄bdptz) bond angles average to ~90° and the N(Ph₄bdptz)–Cu–N(MeCN) bond angles range from 113.63(16) to 140.39(17)°, similar to the angles found in C₁₂ and C₃₃-symmetric mononuclear copper(I) compounds with facial-capping N-donor ligands. These bond angles are essentially unchanged relative to those in 1.
Preparation of Carboxylate-Bridged Dicopper(I) Complex. In contrast to the mixed-valent compound \([\text{Cu}_2(bdptz)_2](\text{OTf})_2\), that was isolated using the bdptz analogue, reaction of \(6(\text{OTf})_2\) with \(\text{NaO}_2\text{CCH}_3\) yields the acetate-bridged dicopper(I) complex \(7(\text{OTf})\). The steric bulk provided by the phenyl substituents of \(\text{Ph}_4\text{bdptz}\) precludes the formation of a compound with a structure similar to that of \(2\), and the high redox potentials of \(6\) (\textit{vide infra}) stabilize the +1 oxidation state and disfavor disproportionation. The synthesis of \(7(\text{OTf})\) proceeds in a mixture of \(\text{CH}_2\text{Cl}_2\) and \(\text{MeOH}\). The latter solvent is necessary to dissolve \(\text{NaO}_2\text{CCH}_3\) and no reaction occurs in its absence. Use of prolonged reaction times (> 12 h) did not improve matters. Furthermore, the reaction does not go to completion even in the presence of a large excess of \(\text{NaO}_2\text{CCH}_3\) (> 20 equivalents), as evidenced by isolation of a mixture of \(6(\text{OTf})_2\) and \(7(\text{OTf})\). This result is probably due to \(\text{MeCN}\) being a better ligand than acetate for copper(I) and is supported by complete regeneration of \(6(\text{OTf})_2\) from the mixture upon addition of \(\text{MeCN}\).

A full crystallographic refinement of \(7(\text{OTf})\) was hampered by severe disorder of the triflate counterion, and substitution of triflate by \(\text{BF}_4^-, \text{PF}_6^-, \text{ClO}_4^-, \text{or BPh}_4^-\) did not afford single crystals of suitable quality to permit analysis by X-ray diffraction. The structure of the cation \(7\) is shown in Figure 5.4. Briefly, \(\text{Ph}_4\text{bdptz}\) coordinates two copper(I) ions in the usual manner, and the acetate ligand bridges the metal centers in a \textit{syn, syn} fashion\textsuperscript{76} with Cu–O bond distances of \(~1.93\) Å. The Cu–Cu separation of \(~3.53\) Å is shorter than that in \(1\) and \(6\), which lack a second bridging ligand, but longer than in the single-atom bridged cations \(3\) and \(4\). Whereas \(\mu\text{-carboxylato} \text{dicopper(II)}\) compounds are common, the analogous dicopper(I) complexes are rare, typically requiring \(\pi\)-acceptor ancillary ligands,\textsuperscript{77,80} sterically demanding and preorganized bis(carboxylate) platforms,\textsuperscript{81,82} or a copper–copper interaction.\textsuperscript{83}

**Electrochemical Studies of Compounds** \([\text{Cu}_2(bdptz)(\text{MeCN})_2](\text{OTf})_2\), \(1(\text{OTf})_2\), and \([\text{Cu}_2(bdptz)_2](\text{OTf})_2\), \(2(\text{OTf})_3\). Cyclic voltammograms (CVs) of compounds \(1(\text{OTf})_2\),
2(OTf)_2 and 6(OTf)_2 were recorded in MeCN and the E_{1/2} values of 2(OTf)_2, 6(OTf)_2, and selected mononuclear and dinuclear compounds are compiled in Table 5.5. Compound 1 showed highly irreversible electrochemical behavior, indicating that the dinuclear core is not stable under these conditions. Compound 2, on the other hand, displayed a reversible wave with an E_{1/2} value of -452 mV (ΔE_p = 74 mV) vs Cp_2Fe^+/Cp_2Fe when potentials lower than -100 mV were applied. Application of higher potentials resulted in irreversible redox waves, as shown in Figure 5.5. When converted to the same scale, the Cu^{II}/Cu^{II}/Cu^{II}/Cu^{I} couple of 2 is more than 150 mV below that of [Cu_2(bdpdz)_2](ClO_4)_2.²⁹,⁴⁴ Although the two compounds are structurally very similar, phthalazine (pK_a = 3.47)⁸⁴ is a stronger base than pyridazine (pK_a = 2.24),⁸⁴ which may explain why the copper(I) center in 2(OTf)_2 is easier to oxidize. The redox potential of 2 is comparable to that of the copper(I) complexes [Cu(TMPA)(MeCN)](ClO_4),²⁹,⁸⁵ [Cu(H-MePY2)](C_6H_5)_4,²⁹,⁸⁶ and [Cu_2(bTMPA)](ClO_4)_2,²⁹,⁸⁷ all of which bear ligands featuring a combination of pyridine and amine substituents. In contrast, the E_{1/2} value of 2 is significantly more negative than that of [Cu(L^0)(MeCN)](OTf), the +1 oxidation state of which is stabilized by the facially-capping tris(pyridyl) moiety.²⁹,⁷¹

**Electrochemistry of [Cu_2(Ph_bdpdz)(MeCN)](OTf)_2, 6(OTf)_2.** Irreversible electrochemical behavior was observed with 6 in CH_2Cl_2. In contrast, two well-separated reversible waves with E_{1/2} potentials of +41 mV (ΔE_p = 122 mV) and +516 mV (ΔE_p = 124 mV) vs Cp_2Fe^+/Cp_2Fe corresponding to the Cu^{III}/Cu^{II}/Cu^{I} and Cu^{III}/Cu^{II}/Cu^{I} couples, respectively, were observed when MeCN was employed as the solvent (Figure 5.6). Evidently, the species generated electrochemically from 6 are stabilized in the coordinating solvent. Addition of MeCN often improves the reversibility of CV traces of copper(I) compounds, possibly by providing an additional ligand to stabilize copper(II) species.⁷¹,⁸⁸ The relatively high redox potentials displayed by 6 relative to the majority of the compounds listed in Table 5.5 are probably largely due to the electron-withdrawing phenyl substituents of Ph_bdpdz, which make
oxidation to Cu(II) more difficult. Electrochemical studies on a series of dicopper(I) complexes supported by macrocyclic ligands, including the compound 
\[ \text{[Cu}_2(L^2)(\text{MeCN})_2]\text{(ClO}_4\text{)}_2 \], also showed well-resolved sequential one-electron redox waves at comparably high potentials.\(^{29,89}\) By using the \(E_{1/2}\) values for the two redox couples, a comproportionation constant, \(K_{\text{com}}\), of \(1 \times 10^8\) was calculated for \(6(\text{OTf})_2\) according to the equilibrium in equation 1:\(^{90}\)

\[
[Cu^I Cu^I (\text{Ph}_4\text{bdptz})]^{2+} + [Cu^{II} Cu^{II} (\text{Ph}_4\text{bdptz})]^{4+} \overset{K_{\text{com}}}{\longrightarrow} 2[Cu^I Cu^{II} (\text{Ph}_4\text{bdptz})]^{3+}
\] (1)

The large value of \(K_{\text{com}}\), comparable to that determined for \([\text{Cu}_2(L^2)(\text{MeCN})_2]\text{(ClO}_4\text{)}_2\) \((K_{\text{com}} = 2 \times 10^7)\),\(^{29,89}\) suggests that the mixed-valent species should have significant thermodynamic stability, although attempts to generate it from \(6(\text{OTf})_2\) have thus far been unsuccessful. In contrast to the two redox waves seen with \(6\), only one apparent wave, corresponding to a two electron oxidation process, is displayed by \([\text{Cu}_2(\text{bTMPA})]\text{(ClO}_4\text{)}_2\) and \([\text{Cu}_2(D^3)(\text{MeCN})_2]\text{(ClO}_4\text{)}_2\), indicating that the two non-interacting metal centers of each of these compounds are oxidized at approximately the same potential.\(^{18,29,87}\) The bridging phthalazine unit in \(6\), therefore, confers greater communication between the copper ions.

**Dioxygen Reactivity Studies of Dicopper Complexes Derived from bdptz.** The addition of dioxygen to an orange solution of \(1(\text{OTf})_2\) in MeOH at \(-78^\circ\text{C}\) caused an immediate color change to pale green. Similar behavior was observed when low temperature oxygenations were performed in \(\text{CH}_2\text{Cl}_2\) or MeCN. The optical spectrum of the reaction products does not indicate the formation of a copper-dioxygen adduct, such as a peroxy, bis(\(\mu\)-oxo), or superoxo intermediate, all of which have distinctive electronic transitions in the visible region.\(^{17}\) Oxygenation of \(1\) afforded the tetranuclear compound \(4\). A possible mechanism for the formation of \(4\) is by dimerization of a (peroxy)dicopper(II) species followed by rearrangement, as has been proposed for
related diiron(II) chemistry. If a \([\text{Cu}_2\text{O}_2]^{2+}\) adduct is generated in the initial stages of the reaction, the species may form and decay too rapidly to allow observation by either conventional UV-visible spectroscopy or stopped-flow methods at -60 °C.

Reaction of dioxygen with a solution of mixed-valent 2 in CH₂Cl₂ proceeded more slowly, turning green only after several hours at room temperature. This decreased reactivity is inconsistent with the low redox potential of the compound and may result from restricted access of dioxygen to the copper(I) site. Although the final product has not been characterized, oxidation of the pyridazine analogue afforded a mixture of \([\text{Cu}_2(bdpdz)_2]\text{(ClO}_4\text{)}_4\) and a compound formulated as \([\text{Cu}_2(bdpdz)_2(\text{OH})_2]\text{(ClO}_4\text{)}_2\).²⁹,⁴⁴

Oxygenation of 5 in CH₂Cl₂, MeOH, or MeCN proceeded as for 1 and also afforded the tetranuclear species. The slight increase in the C–C bond distance the bound alkene unit of vpy in the structure of 5 relative to an uncoordinated one suggested to us that this bond might be activated. Analysis of oxygenated solutions of 5 by GC-MS, however, revealed no conversion of vpy to its epoxide. Similarly, no activation of the vinyl substituent occurred when the reaction with dioxygen was carried out in the presence of the proton source \([\text{H}(\text{OEt})_2]\text{(BAR')}_4\)²⁹,⁹² or when H₂O₂ was used as oxidant. A related dicopper(I) compound supported by a ligand with a pendant alkene moiety also failed to show oxidation of the C=C bond,⁶² and a mononuclear β-diketiminate-based Cu(I) complex with coordinated ethylene similarly oxidized to Cu(II) without involvement of the alkene.⁶⁷

**Oxidation of Ph₄bdptz-Based Dicopper Compounds.** The sterically hindered Ph₄bdptz ligand was expected to prevent formation of tetranuclear species because of the presence of the phenyl rings on the pyridine groups that extend well below the line joining the two copper centers. We thought it possible, therefore, to trap a putative \([\text{Cu}_2(\text{O})_2]^{2+}\) intermediate by employing this bulky ligand, since the reaction pathway to generate tetranuclear species should not be accessible. An attractive feature of Ph₄bdptz
is that the phenyl groups form a hydrophobic cavity in which the two copper centers are positioned such as to provide a binding pocket for the activation of small molecule substrates. The steric bulk provided by the pocket, however, appears to affect the access of O₂ to the dimetallic core and significantly diminishes the reactivity of compounds supported by this ligand. The decreased reactivity towards dioxygen is consistent with the rather high redox potentials of 6 observed by CV. Compound 6 is inert to dioxygen in MeCN, but turns brown over several minutes upon exposure to dioxygen in CH₂Cl₂. Similarly, addition of H₂O₂ to a solution of 6 in MeCN afforded a brown solution at room temperature, but no reaction occurred at -40 °C. The decreased dioxygen reactivity for Ph₄bdptz relative to bdptz complexes is also shared by compound 7, which is an air-stable solid that turns green in solution only after several weeks at room temperature.

Attempts to crystallize the product of the reaction between 6 and dioxygen have thus far been unsuccessful. Analysis of the reaction mixture by ESI-MS, however, shows peaks corresponding to a number of different compounds including unreacted 6 (m/z = 449, [Cu₂(Ph₄bdptz)]²⁺; m/z = 1047, [Cu₂(Ph₄bdptz)][OTf]+) and mononuclear copper(I) compounds (m/z = 833, [Cu(Ph₄bdptz)]⁺; m/z = 874, [Cu(Ph₄bdptz)(MeCN)]⁺). A peak at m/z = 1062, however, exhibits the correct mass and isotope pattern for [[Cu₂(Ph₄bdptz)][OTf]+ after loss of a proton and incorporation of an oxygen atom, possibly corresponding to hydroxylation of a phenyl ring of the Ph₄bdptz ligand (Figure 5.7). Aromatic hydroxylation by copper(I) complexes upon reaction with dioxygen is well preceded,¹¹¹,¹³,¹⁶ and charge balance could be attained by a mixed-valent Cu(I)Cu(II) species, a possibility for which is shown in Figure 5.7.

Conclusions

A family of dicopper compounds were prepared and characterized with the ligands bdptz and Ph₄bdptz. The phthalazine bridge supports a range of metal···metal
distances and a variety of ancillary ligands, but does not permit the detection of dioxygen adducts. The incorporation of the phenyl substituents in Ph₄bdptz prevents the formation of undesired high-nuclearity species, however, and allows the observation of two reversible redox waves by CV.

A difficult feature of metalloenzymes to model effectively is the composition and chemistry of their secondary coordination sphere features. Many proteins have a hydrophobic channel that facilitates access of small molecules to the active site, which is buried in the protein matrix. The phenyl rings of Ph₄bdptz form a binding pocket that mirrors this property and suggests a general strategy for the introduction of secondary sphere components into a dinucleating scaffold.

Acknowledgements. This work was supported by grants from the National Science Foundation and National Institute of General Medical Sciences. I thank NSERC for a graduate student fellowship, Drs. Bernhard Spingler and Sumitra Mukhopadhyay for assistance with the X-ray crystallographic refinements, Ms. Li Li of the MIT Department of Chemistry Instrumentation Facility for performing the ESI-MS measurements, and Professor Thomas J. Smith for valuable discussions.
References

* Reproduced in part with permission from Kuzelka, J.; Mukhopadhyay, S.;


Rosenzweig, A. C. PNAS 2003, 100, 3820-3825.


(8) Messerschmidt, A. In Multi-Copper Oxidases; Messerschmidt, A., Ed.; World

(9) Farrar, J. A.; Neese, F.; Lappalainen, P.; Kroneck, P. M. H.; Saraste, M.; Zumft, W.

1996, 118, 8692-8699.

(11) Zhang, C. X.; Liang, H.-C.; Humphreys, K. J.; Karlin, K. D. In Catalysis by Metal
Complexes; James, B. R., van Leeuwen, P. W. N. M., Eds.; Kluwer Academic


(17) Blackman, A. G.; Tolman, W. B. Struct. Bond. 2000, 97, 179-211.


(29) Abbreviations used: OTf = triflate; OTs = tosylate; vpy = 2-vinylpyridine; bdpdz = 3,6-bis(di-2-pyridylmethyl)pyridazine; TMPA = tris(2-pyridylmethyl)amine; H-MePY2 = bis[2-(2-pyridyl)ethyl]methylamine; bTMPA = 6,6′-bis[bis(2-pyridylmethyl)amino]methyl]-2,2′-bipyridine; L⁰ = tris(2-pyridyl)methoxymethane; L² = 5,5,16,16-tetramethyl-23,24-dioxo-3,7,14,18-tetraazatricyclo[18.2.1.1³¹²]tetracosa-1(22),2,7,9,11,13,18,20-octaene; D₁ = [5-(2-(6-[(bis(2-pyridyl)methylamino))-methyl]-3-pyridyl)ethyl)-(2-pyridylmethyl)]bis(2-pyridylmethyl)amine; BBAN = 2,7-bis(N,N-dibenzylaminomethyl)-1,8-naphthyridine; [BAR₄]⁺ = [(3,5-(CF₃)₂C₆H₃)₄B].


(39) Sheldrick, G. M. *SADABS: Area-Detector Absorption Correction*; University of Göttingen: Göttingen, Germany, 1996.


Table 5.1. Summary of X-ray crystallographic data

<table>
<thead>
<tr>
<th></th>
<th>2(OTf)$_3$·2MeCN-0.5Et$_2$O</th>
<th>3(OTf)$_3$·2.25MeCN</th>
<th>4(OTf)$_3$·MeCN·12H$_2$O</th>
<th>5(OTf)$_2$·Et$_2$O</th>
<th>6(BF$_4$)$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>formula</td>
<td>C$<em>{69}$H$</em>{48}$N$_{12}$Cu$<em>2$O$</em>{38}$S$_3$F$_9$</td>
<td>C$<em>{41}$H$</em>{32}$N$_{12}$Cu$<em>2$O$</em>{10}$S$_3$F$_9$</td>
<td>C$<em>{90}$H$</em>{78}$N$_{13}$Cu$<em>4$O$</em>{28}$S$_4$</td>
<td>C$<em>{43}$H$</em>{52}$N$_{13}$Cu$_2$O$_2$S$_2$F$_6$</td>
<td>C$<em>{58}$H$</em>{58}$N$_{8}$Cu$_2$B$_2$F$_8$</td>
</tr>
<tr>
<td>fw</td>
<td>1615.44</td>
<td>1213.46</td>
<td>2173.06</td>
<td>1060.93</td>
<td>1147.66</td>
</tr>
<tr>
<td>space group</td>
<td>P1</td>
<td>C2/c</td>
<td>P 21/c</td>
<td>P 21/n</td>
<td>P1</td>
</tr>
<tr>
<td>a, Å</td>
<td>15.408(5)</td>
<td>21.197(4)</td>
<td>14.128(2)</td>
<td>15.005(8)</td>
<td>11.355(2)</td>
</tr>
<tr>
<td>b, Å</td>
<td>15.733(5)</td>
<td>23.198(4)</td>
<td>25.037(4)</td>
<td>18.358(10)</td>
<td>14.373(3)</td>
</tr>
<tr>
<td>c, Å</td>
<td>15.804(5)</td>
<td>22.497(4)</td>
<td>14.146(2)</td>
<td>16.459(9)</td>
<td>17.592(3)</td>
</tr>
<tr>
<td>α, deg</td>
<td>67.990(5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>β, deg</td>
<td>77.430(5)</td>
<td>111.357(3)</td>
<td>95.695(3)</td>
<td>91.162(8)</td>
<td>80.904(3)</td>
</tr>
<tr>
<td>γ, deg</td>
<td>83.600(5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V, Å$^3$</td>
<td>3464.9(19)</td>
<td>10303(3)</td>
<td>4979.3(13)</td>
<td>4533(4)</td>
<td>2604.4(9)</td>
</tr>
<tr>
<td>Z</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T, °C</td>
<td>-85</td>
<td>-85</td>
<td>-70</td>
<td>-100</td>
<td>-22</td>
</tr>
<tr>
<td>ρ calcld. g cm$^{-3}$</td>
<td>1.548</td>
<td>1.565</td>
<td>1.449</td>
<td>1.555</td>
<td>1.463</td>
</tr>
<tr>
<td>μ(Mo Kα), mm$^{-1}$</td>
<td>0.798</td>
<td>1.043</td>
<td>1.008</td>
<td>1.113</td>
<td>0.893</td>
</tr>
<tr>
<td>θ range, deg</td>
<td>1.42-25.00</td>
<td>1.35-25.00</td>
<td>1.63-28.26</td>
<td>1.66-28.29</td>
<td>1.17-25.00</td>
</tr>
<tr>
<td>total no. of data</td>
<td>18335</td>
<td>26967</td>
<td>30356</td>
<td>27923</td>
<td>13599</td>
</tr>
<tr>
<td>no. of unique data</td>
<td>12069</td>
<td>9099</td>
<td>11380</td>
<td>10330</td>
<td>8491</td>
</tr>
<tr>
<td>observed data$^a$</td>
<td>9471</td>
<td>5664</td>
<td>8774</td>
<td>8497</td>
<td>7127</td>
</tr>
<tr>
<td>no. of parameters</td>
<td>970</td>
<td>683</td>
<td>658</td>
<td>613</td>
<td>712</td>
</tr>
<tr>
<td>R$^b$</td>
<td>0.0413</td>
<td>0.0769</td>
<td>0.0492</td>
<td>0.0500</td>
<td>0.0602</td>
</tr>
<tr>
<td>wR$^{2c}$</td>
<td>0.1011</td>
<td>0.2202</td>
<td>0.1281</td>
<td>0.1226</td>
<td>0.1594</td>
</tr>
<tr>
<td>max, min peaks, e Å$^{-3}$</td>
<td>0.653, -0.457</td>
<td>1.063, -0.856</td>
<td>0.788, -0.410</td>
<td>0.749, -0.337</td>
<td>1.187, -0.407</td>
</tr>
</tbody>
</table>

$^a$ Observation criterion: I > 2σ(I). $^b$R = Σ||Fo|| - ||Fc|| / Σ||Fo||. $^c$wR$^2$ = Σ[w(Fo$^2$ - Fc$^2$)] / Σ[w(Fo$^2$)]$^{1/2}$.
<table>
<thead>
<tr>
<th></th>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu(1)···Cu(2)</td>
<td>5.2037(15)</td>
<td>N(1)–Cu(1)–N(4)</td>
</tr>
<tr>
<td>Cu(1)–N(1)</td>
<td>2.036(3)</td>
<td>N(1)–Cu(1)–N(7)</td>
</tr>
<tr>
<td>Cu(1)–N(3)</td>
<td>2.035(3)</td>
<td>N(4)–Cu(1)–N(10)</td>
</tr>
<tr>
<td>Cu(1)–N(4)</td>
<td>2.287(3)</td>
<td>N(7)–Cu(1)–N(10)</td>
</tr>
<tr>
<td>Cu(1)–N(7)</td>
<td>2.030(2)</td>
<td>N(3)–Cu(1)–N(9)</td>
</tr>
<tr>
<td>Cu(1)–N(9)</td>
<td>2.065(3)</td>
<td>N(5)–Cu(2)–N(6)</td>
</tr>
<tr>
<td>Cu(1)–N(10)</td>
<td>2.299(3)</td>
<td>N(5)–Cu(2)–N(11)</td>
</tr>
<tr>
<td>Cu(2)–N(5)</td>
<td>2.076(3)</td>
<td>N(5)–Cu(2)–N(12)</td>
</tr>
<tr>
<td>Cu(2)–N(6)</td>
<td>2.035(3)</td>
<td>N(6)–Cu(2)–N(12)</td>
</tr>
<tr>
<td>Cu(2)–N(11)</td>
<td>2.090(3)</td>
<td></td>
</tr>
<tr>
<td>Cu(2)–N(12)</td>
<td>2.020(2)</td>
<td></td>
</tr>
<tr>
<td><strong>3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu(1)···Cu(2)</td>
<td>3.1775(12)</td>
<td>Cu(1)–O(1)–Cu(2)</td>
</tr>
<tr>
<td>Cu(1)–N(1)</td>
<td>2.045(6)</td>
<td>N(1)–Cu(1)–N(3)</td>
</tr>
<tr>
<td>Cu(1)–N(3)</td>
<td>2.299(6)</td>
<td>N(1)–Cu(1)–N(4)</td>
</tr>
<tr>
<td>Cu(1)–N(4)</td>
<td>2.005(6)</td>
<td>N(3)–Cu(1)–N(4)</td>
</tr>
<tr>
<td>Cu(1)–N(7)</td>
<td>1.991(8)</td>
<td>O(1)–Cu(1)–N(3)</td>
</tr>
<tr>
<td>Cu(1)–O(1)</td>
<td>1.909(5)</td>
<td>O(1)–Cu(1)–N(4)</td>
</tr>
<tr>
<td>Cu(2)–N(2)</td>
<td>2.045(6)</td>
<td>N(2)–Cu(2)–N(5)</td>
</tr>
<tr>
<td>Cu(2)–N(5)</td>
<td>2.264(6)</td>
<td>N(2)–Cu(2)–N(6)</td>
</tr>
<tr>
<td>Cu(2)–N(6)</td>
<td>2.001(6)</td>
<td>N(5)–Cu(2)–N(6)</td>
</tr>
<tr>
<td>Cu(2)–N(8)</td>
<td>2.008(8)</td>
<td>O(1)–Cu(2)–N(5)</td>
</tr>
<tr>
<td>Cu(2)–O(1)</td>
<td>1.904(5)</td>
<td>O(1)–Cu(2)–N(6)</td>
</tr>
</tbody>
</table>

\(^a\) Number in parentheses are estimated standard deviations of the last significant figure. Atoms are labeled as indicated in Figure 5.2.
<table>
<thead>
<tr>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu(1)--Cu(2)</td>
<td>3.1690(7)</td>
</tr>
<tr>
<td>Cu(1)--Cu(2A)</td>
<td>3.5603(7)</td>
</tr>
<tr>
<td>Cu(1)--N(1)</td>
<td>2.053(2)</td>
</tr>
<tr>
<td>Cu(1)--N(3)</td>
<td>2.275(3)</td>
</tr>
<tr>
<td>Cu(1)--N(4)</td>
<td>2.021(2)</td>
</tr>
<tr>
<td>Cu(1)--O(1)</td>
<td>1.905(2)</td>
</tr>
<tr>
<td>Cu(1)--O(2A)</td>
<td>1.926(2)</td>
</tr>
<tr>
<td>Cu(2)--N(2)</td>
<td>2.066(2)</td>
</tr>
<tr>
<td>Cu(2)--N(5)</td>
<td>2.327(3)</td>
</tr>
<tr>
<td>Cu(2)--N(6)</td>
<td>2.016(3)</td>
</tr>
<tr>
<td>Cu(2)--O(1)</td>
<td>1.907(2)</td>
</tr>
<tr>
<td>Cu(2)--O(2)</td>
<td>1.925(2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu(1)--Cu(2)</td>
<td>3.7024(13)</td>
</tr>
<tr>
<td>Cu(1)--N(1)</td>
<td>2.144(2)</td>
</tr>
<tr>
<td>Cu(1)--N(3)</td>
<td>2.144(2)</td>
</tr>
<tr>
<td>Cu(1)--N(4)</td>
<td>2.015(2)</td>
</tr>
<tr>
<td>Cu(1)--N(7)</td>
<td>1.951(2)</td>
</tr>
<tr>
<td>Cu(2)--N(2)</td>
<td>2.018(2)</td>
</tr>
<tr>
<td>Cu(2)--N(5)</td>
<td>2.103(3)</td>
</tr>
<tr>
<td>Cu(2)--N(6)</td>
<td>2.060(2)</td>
</tr>
<tr>
<td>Cu(2)--C(36)</td>
<td>2.050(3)</td>
</tr>
<tr>
<td>Cu(2)--C(37)</td>
<td>2.008(3)</td>
</tr>
<tr>
<td>C(36)--C(37)</td>
<td>1.368(4)</td>
</tr>
</tbody>
</table>

*a* Number in parentheses are estimated standard deviations of the last significant figure. Atoms are labeled as indicated in Figure 5.2.
<table>
<thead>
<tr>
<th></th>
<th>Bond Lengths</th>
<th>Bond Angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Cu(1)--Cu(2)</td>
<td>N(1)--Cu(1)--N(3)</td>
</tr>
<tr>
<td></td>
<td>3.7923(9)</td>
<td>91.64(15)</td>
</tr>
<tr>
<td></td>
<td>Cu(1)--N(1)</td>
<td>N(1)--Cu(1)--N(4)</td>
</tr>
<tr>
<td></td>
<td>2.141(4)</td>
<td>88.23(14)</td>
</tr>
<tr>
<td></td>
<td>Cu(1)--N(3)</td>
<td>N(1)--Cu(1)--N(7)</td>
</tr>
<tr>
<td></td>
<td>2.132(4)</td>
<td>120.23(15)</td>
</tr>
<tr>
<td></td>
<td>Cu(1)--N(4)</td>
<td>N(3)--Cu(1)--N(4)</td>
</tr>
<tr>
<td></td>
<td>2.069(4)</td>
<td>90.36(15)</td>
</tr>
<tr>
<td></td>
<td>Cu(1)--N(7)</td>
<td>N(2)--Cu(2)--N(5)</td>
</tr>
<tr>
<td></td>
<td>1.893(4)</td>
<td>90.32(15)</td>
</tr>
<tr>
<td></td>
<td>Cu(2)--N(2)</td>
<td>N(2)--Cu(2)--N(6)</td>
</tr>
<tr>
<td></td>
<td>2.099(4)</td>
<td>89.54(14)</td>
</tr>
<tr>
<td></td>
<td>Cu(2)--N(5)</td>
<td>N(2)--Cu(2)--N(8)</td>
</tr>
<tr>
<td></td>
<td>2.103(4)</td>
<td>129.58(16)</td>
</tr>
<tr>
<td></td>
<td>Cu(2)--N(6)</td>
<td>N(5)--Cu(2)--N(6)</td>
</tr>
<tr>
<td></td>
<td>2.145(4)</td>
<td>87.10(15)</td>
</tr>
<tr>
<td></td>
<td>Cu(2)--N(8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.879(5)</td>
<td></td>
</tr>
</tbody>
</table>

* Number in parentheses are estimated standard deviations of the last significant figure.

Atoms are labeled as indicated in Figure 5.4.
Table 5.5. Cyclic voltammetry data for compounds 2(OTf)$_3$, 6(OTf)$_2$, and related mononuclear and dinuclear models

<table>
<thead>
<tr>
<th>Compound</th>
<th>$E_{1/2}$, mV (vs Cp$_2$Fe$^+$/Cp$_2$Fe)</th>
<th>Solvent</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td><a href="ClO$_4$">Cu(TMPA)(MeCN)</a></td>
<td>-400</td>
<td>MeCN</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>-628$^a$</td>
<td>DMF</td>
<td>18</td>
</tr>
<tr>
<td><a href="B(C$_6$F$_5$)$_4$">Cu(H-MePY2)</a></td>
<td>-310</td>
<td>DMF</td>
<td>86</td>
</tr>
<tr>
<td><a href="OTf">Cu(L$^0$)(MeCN)</a></td>
<td>+60$^p$</td>
<td>MeCN/CH$_2$Cl$_2$</td>
<td>71</td>
</tr>
<tr>
<td><a href="ClO$_4$">Cu$_2$(bdpdz)$_2$</a>$_3$</td>
<td>-290$^c$</td>
<td>MeCN/H$_2$O</td>
<td>44</td>
</tr>
<tr>
<td><a href="OTf">Cu$_2$(BBAN)(μ-O$_2$CCPh$_2$)</a></td>
<td>-25</td>
<td>THF</td>
<td>83</td>
</tr>
<tr>
<td><a href="ClO$_4$">Cu$_2$(bdTMPA)</a>$_2$</td>
<td>-346$^d$</td>
<td>DMF</td>
<td>87</td>
</tr>
<tr>
<td><a href="ClO$_4$">Cu$_2$(D$^1$)(MeCN)$_2$</a>$_2$</td>
<td>-639$^e$</td>
<td>DMF</td>
<td>18</td>
</tr>
<tr>
<td><a href="ClO$_4$">Cu$_2$(L$^2$)(MeCN)$_2$</a>$_2$</td>
<td>+140$^e$</td>
<td>MeCN</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>+568$^e$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2(OTf)$_3$</td>
<td>-452</td>
<td>MeCN</td>
<td>this work</td>
</tr>
<tr>
<td>6(OTf)$_2$</td>
<td>+41</td>
<td>MeCN</td>
<td>this work</td>
</tr>
</tbody>
</table>

$^a$ Cp$_2$Fe$^+$/Cp$_2$Fe = +20 mV vs Ag/AgNO$_3$; $^b$ Cp$_2$Fe$^+$/Cp$_2$Fe = +450 mV vs SCE. $^c$ Cp$_2$Fe$^+$/Cp$_2$Fe = +380 mV vs SCE in MeCN with (Bu$_4$N)ClO$_4$ as supporting electrolyte (see: Connelly, N. G. and Geiger, W. E. Chem. Rev. 1996, 96, 877-910). $^d$ Cp$_2$Fe$^+$/Cp$_2$Fe = +545 mV vs Ag/AgCl. $^e$ Cp$_2$Fe$^+$/Cp$_2$Fe = +401 mV vs Ag/AgCl.
Chart 5.1.
Scheme 5.1.
Figure 5.1. Examples of $[\text{Cu}_2\text{O}_2]$ adducts supported by multidentate dinucleating ligands.
Figure 5.2. ORTEP diagrams of $[\text{Cu}_2(\text{bdptz})_2]^{3+}$ (2), $[\text{Cu}_2(\text{bdptz})(\mu-\text{OH})(\text{MeCN})_2]^{2+}$ (3), $[\text{Cu}_2(\text{bdptz})(\mu-\text{OH})_2]^{2+}$ (4), and $[\text{Cu}_2(\text{bdptz})(\mu-\text{vpy})]^{2+}$ (5) showing 50% probability thermal ellipsoids for all non-hydrogen atoms (left to right, top to bottom).
Figure 5.3. X-band EPR spectrum of [Cu₂(bdptz)₂](OTf)₃ (2(OTf)₃) as a frozen solution (4.8 mM in MeOH) at 77 K.
Figure 5.4. ORTEP diagram of [Cu₂(Ph₄bdptz)(MeCN)]₂⁺ (6) showing 50% probability thermal ellipsoids for all non-hydrogen atoms and ball and stick representation of [Cu₂(Ph₄bdptz)₂(μ-O₂CCH₃)]⁺ (7) (top to bottom).
Figure 5.5. Cyclic voltammograms of 2 mM [Cu₂(bdptz)₂](OTf)₃ (2(OTf)₃) in MeCN with 0.5 M Bu₄N(PF₆) as supporting electrolyte. The full CV was recorded with a scan rate of 200 mV/s, and the insert shows the CV recorded with a scan rate of 100 mV/s when potentials below -0.1 V vs Cp₂Fe⁺/Cp₂Fe were applied.
Figure 5.6. Cyclic voltammogram of 2 mM $[\text{Cu}_2(\text{Ph}_3\text{bdptz})(\text{MeCN})_2](\text{OTf})_2$ ($6(\text{OTf})_2$) in MeCN with 0.5 M $\text{Bu}_4\text{N}(\text{PF}_6)$ as supporting electrolyte and a scan rate of 100 mV/s.
Figure 5.7. ESI-MS spectra of an oxygenated solution of $6(\text{OTf})_2$ in CH$_2$Cl$_2$ showing m/z = 1062, possible aromatic hydroxylation product (A) and corresponding theoretical spectrum for m/z = 1062, Cu$_2$C$_{58}$H$_{77}$N$_6$SF$_3$O$_4$ (B). The insert shows a possible structure for the aromatic hydroxylation product.
Biographical Note

The author was born on June 12, 1975 in Malmö, Sweden. She received her B.Sc. in Chemistry from the University of British Columbia in 1997. As a graduate student in the laboratory of Professor Stephen J. Lippard at the Massachusetts Institute of Technology, she was a recipient of an NSERC pre-doctoral fellowship. Upon completion of her graduate work, she will pursue postdoctoral research with Professor M. G. Finn at The Scripps Research Institute.
Education

Ph.D Chemistry 1998-2003
Massachusetts Institute of Technology
Advisor: Professor Stephen J. Lippard

B.Sc. Chemistry 1993-1997
University of British Columbia
Advisor: Professor Peter Legzdins

Publications


Presentations

J. Kuzelka, S. J. Lippard. Modeling the Syn Disposition of Nitrogen Donors at the Active Site of Methane Monoxygenase. Santa María del Mar Workshop II (Havana, Cuba: July 2003).


J. Kuzelka, S. J. Lippard. Dicopper Complexes Supported by Phthalazine-Based Ligands. 7th Annual Bruker/MIT Crystallographic Symposium (Cambridge, MA: May 2002).