The Design and Synthesis of Transition Metal Complexes Supported by Non-innocent Ligand Scaffolds for Small Molecule Activation

Thesis by
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To Mom and Dad,
and my younger brother Erik

"All's well that ends better."

-J.R.R. Tolkien, *The Lord of the Rings*

"Ah yes… I was wondering what would break first… your spirit, or your body?"

-Bane*, The Dark Knight Rises*

ACKNOWLEDGMENTS

Much like the concluding remarks of a presentation, it appears that all that remains for me to do is acknowledge the numerous people that have mentored, supported, and inspired me to arrive at where I am today. Looking back at the past six years, I feel that I have come a long way as a scientist and I believe this to be largely attributable to the invaluable interactions and experiences that I have accumulated over my time here. My time in graduate school has certainly had its ups and downs as projects started and ended (sometimes crashing and burning in a spectacular fashion), and as friends were found and then would graduate. However, if you were to add up all those moments and interactions, both good and bad, the result would be a net positive and rewarding experience. I am grateful for the opportunity to study at the truly unique scientific environment that is the California Institute of Technology.

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I have also worked with a number of postdocs throughout my time here. Prof. Dave Herbert, thanks for being a source of great insight into my projects while I was on team phosphine. You always had references handy regardless of what my question was. Prof. Po-heng Lin, thanks for good times and laughs we had together, and that super helpful crash course in SQUID. To the more recent post-docs, Graham de Ruiter, Zhiji Han, Siti Riduan, Aimee Bryan, Gyeongshin Choi, and Alejo Lifshitz, I wish you the best of luck in your continued research, future jobs, and job searches.

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Thanks again to everyone who has helped me complete the body of work contained within my thesis. I am glad to have been part of the Caltech community. And with that, on to the science.

Published Content

Parts of this thesis have been adapted from published articles co-written by the author and articles that are currently in preparation.

The following article was reproduced in part with permission from the Royal Society of Chemistry:

"Arene non-innocence in dinuclear complexes of Fe, Co, and Ni supported by a *para*-terphenyl diphosphine" Horak, K. T.; Velian, A.; Day, M. W.; Agapie, T. *Chem. Commun.*, **2014**, *50*, 4427-4429. URL: http://pubs.rsc.org/en/Content /ArticleLanding/2014/CC/c4cc00838c#!divAbstract

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"Trinuclear Nickel Complexes with Metal–Arene Interactions Supported by Tris- and Bis(phosphinoaryl)benzene Frameworks" Suseno, S.; Horak, K. T.; Day, M. W.; Agapie, T. *Organometallics*, **2013**, *32*, 6883-6886. URL: http://pubs.acs.org/doi/abs/10.1021 /om400976x

"Heterometallic Effects in Trinuclear Complexes Supported by *p*-Terphenyl Diphosphine Ligands" Horak, K. T.; Lin, S.; Rittle, J.; Agapie, T. *Organometallics*, **2015**, *34*, 4429-4432. URL: http://pubs.acs.org/doi/abs/10.1021/acs.organomet.5b00579

"Tuning of Metal Complex Electronics and Reactivity by Remote Lewis Acid Binding to π-Coordinated Pyridine Diphosphine Ligands" Horak, K. T.; VanderVelde, D. G.; Agapie, T. *Organometallics*, **2015**, *34*, 4753-4765. URL: http://pubs.acs.org/doi/abs/10.1021/acs.organomet.5b00562

RESPECTIVE CONTRIBUTIONS

Parts of the work described in this thesis are the result of collaborative efforts, without which these studies would not have been possible. Specific notes are included for compounds synthesized by other researchers and spectroscopic characterization carried out by our collaborators.

In Chapter 2, the initial synthesis and characterization of complex **11** was carried out by Dr. Alexandra Velian. The late Dr. Michael W. Day was responsible for refining the solid-state structure of complex **11**. Density functional theory calculations were run by Dr. Sibo Lin. Mössbauer data were collected and simulated in collaboration with Dr. Jonathan Rittle from the Peters group.

In Chapter 4, the 2D NMR assignments for complex **6Ni**, **7Ni**, and **8Ni** were completed with the assistance of Dr. David VanderVelde.

In Chapter 5, Mössbauer data were collected and simulated in collaboration with Matthew Chalkley from the Peters group with additional help provided by Niklas Thompson (Peters Group) and Chris Reed (Agapie Group).

ABSTRACT

This dissertation focuses on the incorporation of non-innocent or multifunctional moieties into different ligand scaffolds to support one or multiple metal centers in close proximity. Chapter 2 focuses on the initial efforts to synthesize hetero- or homometallic tri- or dinuclear metal carbonyl complexes supported by *para*-terphenyl diphosphine ligands. A series of $[M_2M'(CO)_4]$-type clusters (M = Ni, Pd; M' = Fe, Co) could be accessed and used to relate the metal composition to the properties of the complexes. During these studies it was also found that non-innocent behavior was observed in dinuclear Fe complexes that result from changes in oxidation state of the cluster. These studies led to efforts to rationally incorporate central arene moieties capable managing both protons and electrons during small molecule activation.

Chapter 3 discusses the synthesis of metal complexes supported by a novel *para*-terphenyl diphosphine ligand containing a non-innocent 1,4-hydroquinone moiety as the central arene. A Pd^0-hydroquinone complex was found to mediate the activation of a variety of small molecules to form the corresponding Pd^0-quinone complexes in a formal two proton / two electron transformation. Mechanistic investigations of dioxygen activation revealed a metal-first activation process followed by subsequent proton and electron transfer from the ligand. These studies revealed the capacity of the central arene substituent to serve as a reservoir for a formal equivalent of dihydrogen, although the stability of the M-quinone compounds prevented access to the Pd^{II}-quinone oxidation state, thus hindering of small molecule transformations requiring more than two electrons per equivalent of metal complex.

Chapter 4 discusses the synthesis of metal complexes supported by a ligand containing a 3,5-substituted pyridine moiety as the linker separating the phenylene

phosphine donors. Nickel and palladium complexes supported by this ligand were found to tolerate a wide variety of pyridine nitrogen-coordinated electrophiles which were found to alter central pyridine electronics, and therefore metal-pyridine π-system interactions, substantially. Furthermore, nickel complexes supported by this ligand were found to activate H–B and H–Si bonds and formally hydroborate and hydrosilylate the central pyridine ring. These systems highlight the potential use of pyridine π-system-coordinated metal complexes to reversibly store reducing equivalents within the ligand framework in a manner akin to the previously discussed 1,4-hydroquinone diphosphine ligand scaffold.

Chapter 5 departs from the phosphine-based chemistry and instead focuses on the incorporation of hydrogen bonding networks into the secondary coordination sphere of $[Fe_4(\mu_4\text{-}O)]$-type clusters supported by various pyrazolate ligands. The aim of this project is to stabilize reactive oxygenic species, such as oxos, to study their spectroscopy and reactivity in the context of complicated multimetallic clusters. Herein is reported this synthesis and electrochemical and Mössbauer characterization of a series of chloride clusters have been synthesized using parent pyrazolate and a 3-aminophenyl substituted pyrazolate ligand. Efforts to rationally access hydroxo and oxo clusters from these chloride precursors represents ongoing work that will continue in the group.

Appendix A discusses attempts to access $[Fe_3Ni]$-type clusters as models of the enzymatic active site of [NiFe] carbon monoxide dehydrogenase. Efforts to construct tetranuclear clusters with an interstitial sulfide proved unsuccessful, although a $(\mu_3\text{-}S)$ ligand could be installed through non-oxidative routes into triiron clusters. While $[Fe_3Ni(\mu_4\text{-}O)]$-type clusters could be assembled, accessing an open heterobimetallic edge site proved challenging, thus prohibiting efforts to study chemical transformations, such as hydroxide attack onto carbon monoxide or carbon dioxide coordination, relevant to the native enzyme. Appendix B discusses the attempts to synthesize models of the full H-cluster of [FeFe]-hydrogenase using a bioinorganic approach. A synthetic peptide containing three cysteine donors was successfully synthesized and found to chelate a preformed synthetic [Fe_4S_4] cluster. However, efforts to incorporate the diiron subsite model complex proved challenging as the planned thioester exchange reaction was found to non-selectively acetylate the peptide backbone, thus preventing the construction of the full six-iron cluster.

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