Christopher John Reed
ORCID: 0000-0002-8774-5106

# ACKNOWLEDGEMENTS

I would like to thank Theo for his mentorship over the past five years. I would not be the scientist that I am without your advice, patience, and motivation. I also thank the rest of my PhD committee, Profs. Jonas Peters, Dennis Dougherty, and Harry Gray, who were an excellent source of advice and insight during my studies, and pushed me to think critically of my research. It has been a great opportunity to study chemistry at Caltech.

I would like to thank all the members of the Agapie group, particularly the ones who shared their expertise and resources with me over the years, which was crucial for my development as a chemist; I thank Dr. Graham de Ruiter for training me, and instilling a level-headed approach to working in a synthetic lab.

I want to acknowledge Dr. Kyle Horak for beginning the work on the unsubstituted pyrazolate and hydrogen-bonding pyrazolate clusters in the last year of his PhD. This served as a footing for my later graduate research.

Special thanks to the members of the Peters and Gray groups who had allowed me to use their reagents and instruments, especially the Mössbauer spectrometer, these were invaluable aids in my studies. I would also like to thank the people who ran the facilities in the division, including the NMR (David VanderVelde), Mass spectrometry (Mona Shagoli), X-Ray Crystallography (Mike Takase and Larry Henling), and EPR facilities (Paul Oyala), along with the BILRC (Prof. Harry Gray and Jay Winkler). There were countless times I turned to them for advice on my experiments.

I am grateful for the Resnick Sustainability Institute at Caltech for supporting the last two years of my graduate education, and giving me the opportunity to share my chemistry at the Resnick Fellow Day Seminar.

# ABSTRACT

This dissertation discusses the synthesis, characterization, and reactivity of site-differentiated tetranuclear clusters containing Fe and Mn with NO and $H_2O$-derived ligands. The motivation of this work was to conduct a detailed examination of structure-property relationships in well-defined molecular systems focused on unique features of multinuclear systems, such as bridging ligands, neighboring metal identity, and cluster oxidation state. Reactivity towards NO and $H_2O$-derived ligands was targeted due to their relevance to biological multinuclear transition metal active sites that promote multi-electron small molecule transformations.

Chapter 2 discusses the synthesis of Fe-nitrosyl clusters bearing an interstitial $\mu_4$-F atom. These clusters were prepared to compare their reactivity to previously synthesized [$Fe_3OFeNO$] clusters with an analogous structure. A redox series of the [$Fe_3FFe$] and [$Fe_3FFeNO$] clusters were accessed, with the nitrosyl clusters displaying five cluster oxidation states, from $Fe^{II}_3\{FeNO\}^8$ to $Fe^{III}_3\{FeNO\}^7$. Overall, the weaker bonding of the $F^-$ ligand resulted in attenuation of the activation and reactivity of the $\{FeNO\}^7$, relative to the corresponding $\mu_4$-O clusters. Furthermore, the ability of distal Fe oxidation state changes to influence the activation of NO was decreased, demonstrating lower cooperativity between metals in clusters linked by a weaker $\mu_4$-atom This represents a rare case where the effects of bridging atom ligands could be compared in isostructural multinuclear complexes and decoupled from changes in metal ion coordination number, oxidation states, or geometry.

Chapter 3 describes the synthesis of site-differentiated heterometallic clusters of [$Fe_3OMn$], displaying facile ligand substitution at the five-coordinate Mn. This system was able to coordinate $H_2O$ and thermodynamic parameters of the proton and electron transfer processes from the $Mn^{II}$–$OH_2$ to form a $Mn^{III}$–OH moiety were studied. The oxidation state

distribution of the neighboring Fe centers had a significant influence on these thermodynamic parameters, which was similar to the analogous parameters for mononuclear Mn systems, demonstrating that oxidation state changes in neighboring metals of a cluster can perturb the reactivity of a Mn–$OH_x$ unit nearly as much as an oxidation state change at the Mn–$OH_x$. Subsequent experiments attempted to find spectroscopic or electrochemical evidence for formation of a terminal Mn-oxo in this system; however, that was not obtained, even in relatively extreme conditions. This established a lower limit for the bond dissociation enthalpy of the $Mn^{III}$–OH of ca. 93 kcal/mol, which makes formation of a terminal Mn-oxo cluster unfavorable in most organic solvents, due to expected facile hydrogen atom abstraction of a solvent C–H bond.

The insights obtained on the reactivity of these tetranuclear metal-hydroxide clusters was applied towards stabilizing a terminal metal-oxo in a multinuclear complex, as outlined in Chapter 4. Through the use of pendant hydrogen bond donors with *tert*-butyl-aminopyrazolate ligands, tetranuclear Fe clusters bearing terminal-hydroxide and -oxo ligands could be stabilized and structurally characterized. A similar thermodynamic analysis of the $Fe^{III}$–OH bond dissociation enthalpy was conducted, which demonstrated $Fe^{III}$-oxo clusters could be accessed with a range of reactivity at the terminal-oxo ligand, based on the redox distribution of the neighboring Fe centers. The kinetics of C–H activation for the $[Fe^{II}_2Fe^{III}_2]$-oxo cluster redox state were analyzed, demonstrating a strong dependence of the C–H bond $pK_a$ on the rate of proton coupled electron transfer.

Lastly, Chapter 5 describes the synthesis and reactivity of tetranuclear Fe clusters bearing unsubstituted pyrazolate ligands, focusing on attempts to observe evidence for a terminal Fe-oxo or Fe-imido motif. Clusters bearing a labile trifluoromethanesulfonate ligand at the five-coordinate Fe center could be prepared, and would react with oxygen atom transfer reagents

to produce a terminal Fe-hydroxide cluster, which, upon dehydration, led to isolation of an octanuclear $\mu_2$-O cluster. The pathway for Fe-hydroxide formation was investigated, but could not conclusively determine whether reactivity occurred from a transient terminal Fe-oxo. Similarly, the reduced tetra-iron cluster, in the $[Fe^{II}_3Fe^{III}]$, redox state was prepared, and demonstrated reactivity towards electron deficient aryl azides. Isolation of aryl amide clusters (Fe-NHAr) was observed, suggesting, again, formation of a reactive Fe-imido which decomposes through formal hydrogen atom abstraction. Efforts to stabilize either of these Fe=O/NR multiply-bonded species through a more acidic Fe were investigated by synthesizing the corresponding pyrazolate bridged $\mu_4$-F clusters. The $[Fe^{II}_4]$ cluster also displayed reactivity towards oxygen atom transfer reagents, and produced a similar octanuclear $\mu_2$-O cluster, but the observation of $\mu_4$-F substitution with oxygen to produce $\mu_4$-O clusters with a terminal F ligand likely precluded formation of a reactive terminal-oxo cluster. Instead, thermodynamically favorable cluster rearrangement to the $[Fe_3OFe]$ structure dominates.

# PUBLISHED CONTENT AND CONTRIBUTIONS

Parts of this thesis have been adapted from published articles co-written by the author.

The following articles were reproduced in part with permission from the American Chemical Society:

"Tetranuclear Fe Clusters with a Varied Interstitial Ligand: Effects on the Structure, Redox Properties, and Nitric Oxide Activation" Reed, C. J.; Agapie, T. *Inorganic Chemistry*, **2017**, *56*, 13360-13367.

"Thermodynamics of Proton and Electron Transfer in Tetranuclear Clusters with Mn–$OH_2$/OH Motifs Relevant to $H_2O$ Activation by the Oxygen Evolving Complex in Photosystem II" Reed, C. J.; Agapie, T. *Journal of the American Chemical Society*, **2018**, *140*, 10900-10908.

"A Terminal $Fe^{III}$-Oxo in a Tetranuclear Cluster: Effects of Distal Metal Centers on Structure and Reactivity" Reed, C. J.; Agapie, T. *Journal of the American Chemical Society*, **2019**, *Just Accepted Manuscript*. doi: 10.1021/jacs.9b03157.

# TABLE OF CONTENTS