Iridium and rhodium analogues of the Shilov cycle catalyst; and the investigation and applications of the Reduction-Coupled Oxo Activation (ROA) mechanistic motif towards alkane upgrading

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To Annie, Bruce, Mom, Dad, and Harold.

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Abstract

This dissertation will cover several disparate topics, with the overarching theme centering on the investigation of organometallic C−H activation and hydrocarbon transformation and upgrading. Chapters 2 and 3 discuss iridium and rhodium analogues of the Shilov cycle catalyst for methane to methanol oxidation, and Chapter 4 on the recently discovered ROA mechanistic motif in catalysts for various alkane partial oxidation reactions. In addition, Chapter 5 discusses the mechanism of nickel pyridine bisoxazoline Negishi catalysts for asymmetric and stereoconvergent C−C coupling, and the appendices discuss smaller projects on rhodium H/D exchange catalysts and DFT method benchmarking.

Chapter 2: The iridium complex (ONO)Ir(PPh_3)$_2$Me, where (ONO) is a bis(phenolate)pyridine pincer ligand, undergoes C−H activation of benzene, related arenes, and acetonitrile. Labeling and kinetic studies indicate a unique and heretofore undescribed mechanism involve intramolecular C−H activation followed by intermolecular C−H activation.

Chapter 3: The Shilov catalytic cycle for methane to methanol oxidation *via* a homogeneous Pt catalyst has long been a target of investigation, with work focusing on improving catalyst stability, yield, and robustness. A Rh analogue to the Shilov cycle was explored due to its increased stability at high oxidation states. A density functional theory-driven virtual screening of ligand frameworks revealed that the fluorine-substituted amidinate (NN^F) ligand provides the lowest transition state energies for methane C−H activation and methyl group functionalization, and stands most promising as a target for experimental investigation.

Chapter 4: The vanadium phosphorus oxide (VPO) catalyst has been used in industry for the remarkably selective conversion of butane to maleic anhydride. Investigation of the reaction mechanism revealed the surprising conclusion that, although redox action occurs in the vanadium centers as expected, initial C−H activation takes place in the phosphorus oxide moieties. Further work has revealed that the same phenomenon can be extended to other transition metal/nonmetal oxo pairs. This phenomenon, which has been named the Reduction-Coupled Oxo Activation (ROA) mechanistic motif, is attributed to the concomitant formation of a strong oxo-hydrogen bond on the nonmetal and a one-electron reduction on the transition

metal. Finally, a homogeneous vanadium phosphorus oxo complex is proposed to incorporate the novel ROA mechanistic pathway as a potential propane oxidation catalyst. Several oxidation pathways are proposed, leading to end products such as propylene, isopropanol, and propylene oxide. These assertions are supported with density functional theory calculations on the potential reaction pathways.

Chapter 5: The *in situ* generated Ni(iPr−pybox) complex catalyzes enantioselectively the cross-coupling of secondary sp^3-C substrates. This system is very notable for its property of stereoconvergence: *both* enantiomers of a racemic substrate may be converted into a single enantiomer of a product. This chapter will computationally explore the mechanism responsible for both the remarkable activity and selectivity of the Ni((S,S)−iPr−pybox system; such a mechanism is believed to deviate substantially from the canonical "textbook" mechanism of Negishi coupling. Furthermore, a generalized calculation scheme is presented that allows for the rapid enantioselectivity prediction of many related pybox ligands as well, in order to help predict the next generation of asymmetric Negishi coupling catalysts.

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Chapter 1

Introduction

1.1 Iridium and Rhodium analogues of the Shilov cycle catalyst

The facile, selective, and direct conversion of methane into methanol has long been a goal of industrial chemists [1]. Methane, the chief component of natural gas, is typically found in abundant quantities wherever petroleum deposits are found. However, due to its difficulty in liquefaction (its boiling point being only 110 K) and its relative paucity of demand as compared to other hydrocarbons, it is often not economical to harvest this gas, which is essentially a byproduct or co-product of petroleum recovery, and to transport it to market. Since methane is also a potent greenhouse gas, with a global warming potential 72 times more powerful than that of carbon dioxide [2], it cannot simply be released either. Hence it is often flared, a process that is both intrinsically wasteful and which results in a large amount of heat pollution.

One potential solution is to convert these vast quantities of methane into methanol. As methanol is liquid at room temperature and pressure, it is much more easily transported and stored. Methanol can be used as a fuel in flex fuel vehicles, blended with gasoline, or converted to gasoline or diesel fuel. In addition, it has many applications as an industrial solvent and chemical feedstock. As methanol is both more easily processed and in greater demand than methane, the efficient conversion from the former to the latter has the potential to be both environmentally friendly and economically favorable.

Although the reaction $CH_4 + \frac{1}{2}O_2 \longrightarrow CH_3OH$ is exoenergetic by 30 kcal/mol, efficient catalysis is hampered by the fact that the C−H bond dissociation energy (BDE) of methane is 104 kcal/mol, whereas the C−H BDE of methanol is only 95 kcal/mol. Hence, overoxidation is a major problem. In fact, potential methods that involve radicals have a theoretical maximum yield of only 5%, even with perfect conversion [3]. Hence, the currently favored industry-scale conversion of methane to methanol involves an indirect pathway *via* syngas [1]:

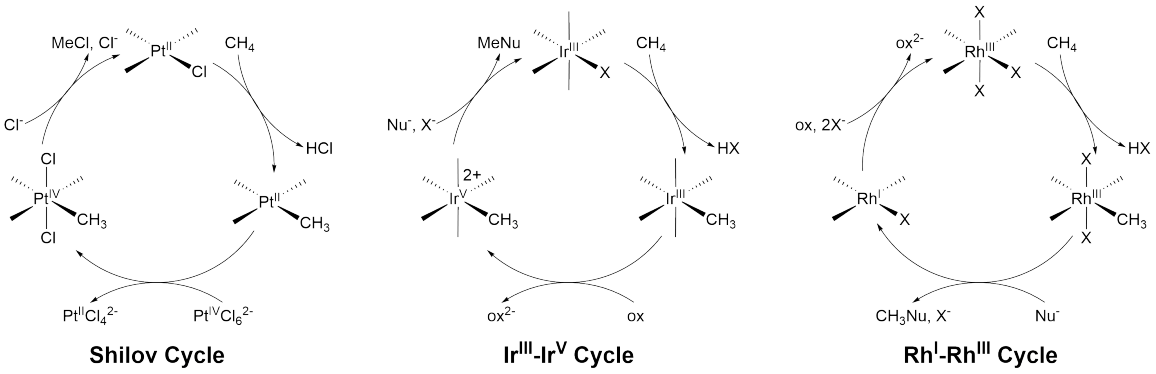
$$CH_4 + H_2O \xrightarrow{Ni} CO + 3\,H_2 \tag{1.1}$$

$$CO + 2\,H_2 \longrightarrow CH_3OH \tag{1.2}$$

However, this pathway suffers from a difficult first step that is highly endergonic, requiring very high temperatures and pressures (700-1100°C, 40 atm). Hence, this state-of-the-art pathway requires large inputs of energy and very expensive production facilities despite the significantly exothermic nature of the overall reaction. An alternative mechanism that does not require such extreme conditions would thus be highly desirable.

Molecular compounds in solution have long been investigated as potential catalysts for this transformation, as they are typically well-defined, easy to characterize and model, and operate under relatively mild conditions. Much of the focus has been on routes involving C−H activation at a transition metal center followed by oxidative cleavage of the resulting C−M bond, which offer greater possibilities for good selectivity by avoiding radical-based pathways. Platinum complexes have received a great deal of attention [4], starting with Shilov's seminal work on the $PtCl_4^{2-}/PtCl_6^{2-}$ system, which can oxidize methane to methanol with some selectivity [5], and including the platinum bipyrimidine system, which has achieved the most impressive performance to date, converting methane to methyl bisulfate in up to 70% yield [6].

However, none of this platinum-based chemistry has yet been shown to lead to a practical process, owing in part to low reactivity, and a good deal of research activity has turned to other metals. Chapters 2 and 3 will address certain Ir and Rh analogues, respectively. The original Pt Shilov cycle, as well as modifications incorporating Ir and Rh, is given in Scheme 1.1.



Scheme 1.1. Left: The original Pt^{II}/Pt^{IV} cycle of the Shilov catalyst. Center: A potential analogous Ir^{III}/Ir^{V} cycle. Right: A potential analogous Rh^{I}/Rh^{III} cycle.

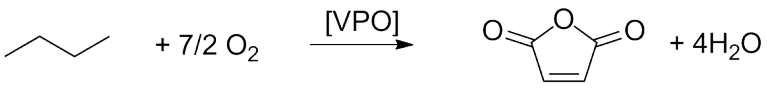
Chapter 2 focuses on bis(phenolate)pyridineiridium(III) ((ONO)Ir) complexes as an Ir analogue to the Shilov catalyst. Iridium as an alkane oxidation catalyst has been a popular choice; many

(primarily low-valent) Ir complexes have been reported to show good activity for C−H activation [7], and examples of oxidative functionalization with Ir systems are known as well [8]. Interconversions between Ir^{III} and Ir^{V} might be important in this chemistry, by analogy to the Shilov system, which involves Pt^{II} and Pt^{IV}. In Chapter 2, the experimental synthesis and characterization of a multitude of ((ONO)Ir) complexes in the +III and +IV oxidation state are described. In particular, the complex (ONO)Ir$(PPh_3)_2$Me has been found to undergo oxidation with iodine to release MeI, analogous to the Shilov system's production of MeCl. Furthermore, (ONO)Ir$(PPh_3)_2$Me has been found to undergo an unusual C−H activation route with benzene that initially proceeds by intramolecular C−H activation, followed by intermolecular C−H activation.

Chapter 3 focuses on rhodium due to its well-documented nature as an effective C−H activating metal [9] and whose lower electronegativity may allow it to avoid poisoning by coordinating media. In this chapter, a computational screening of a variety of ligands was undertaken in order to find a Rh-ligand complex with the predicted optimal combination of low methane activation energy, low methyl group functionalization energy, and overoxidation protection of the MeX product. Our best results were the Rh^{III} bis(*N*-pentafluorophenyl)pentafluorobenzylamidinate ($Rh^{III}(NN^{F})$) complex and the Rh^{III} bis(quinolinyl)benzene (Rh^{III}(bisq)) complex. In addition, we also report a correlation between Rh−Me bond energies and methane activation barriers that would allow us to easily predict the suitability of new complexes for methane activation.

1.2 Investigation and applications of the Reduction-Coupled Oxo Activation (ROA) mechanistic motif towards alkane upgrading.

Vanadium phosphorus oxide (VPO) is an inorganic complex that catalyzes the oxidation of *n*-butane to maleic anhydride with a surprisingly high selectivity of 60-70% [10] (Scheme 1.2). Although the overall yield is only *ca.* 50%, its ease of synthesis, use of common elements, and selectivity have allowed this catalyst to be commercialized, producing *ca.* 500 kilotons of maleic anhydride annually [11].

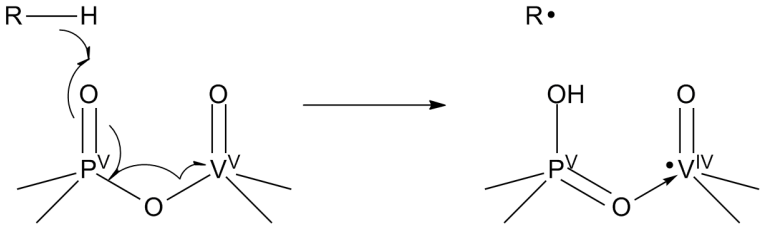


Scheme 1.2. The oxidation of *n*-butane to maleic anhydride using vanadium phosphorus oxide as a catalyst.

Surprisingly, the mechanism has been shown to initiate with C−H activation by a P=O moiety [12]. Whereas the many vanadium oxos and peroxos investigated bound with hydrogen with a

maximum energy of only 70.0 kcal/mol, too low for initial C−H activation of *n*-butane to occur, the phosphorus oxo has a much larger bond strength with hydrogen, at 84.3 kcal/mol. This implies a first step that is endothermic by only 5.0 kcal/mol, with an activation energy later calculated to be 13.6 kcal/mol, which is within the experimental range. The stability of the resulting mono-hydrogenated species was attributed to the fact that spin density appears to be localized on the neighboring vanadium atoms (Figure 1.1).

Figure 1.1. C−H activation by a phosphorus oxo leads to a one electron reduction on the neighboring vanadium. Hence the oxidation state of the phosphorus atom does not change.

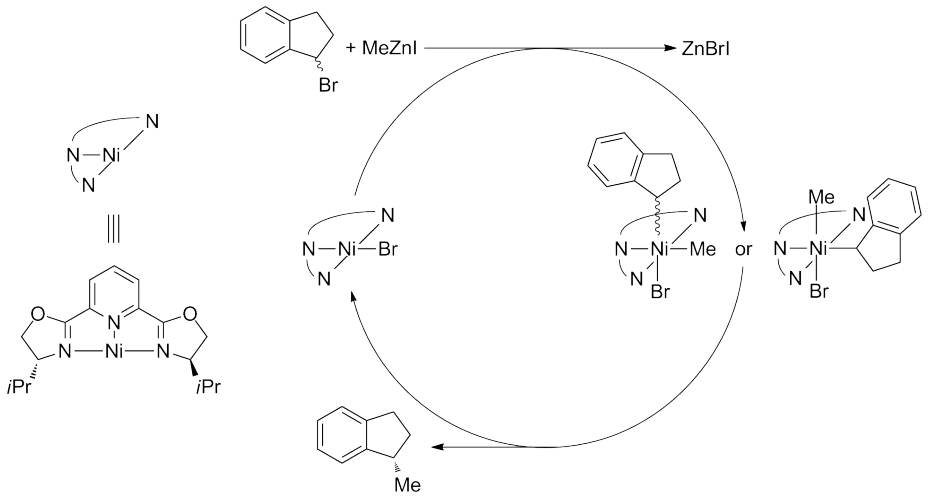


Chapter 4 focuses on deeper investigations into the ROA mechanistic motif. Specifically, questions such as the generalizability of the mechanism to other metal-main group pairs, as well as the applications of the ROA motif to homogeneous catalysts, are addressed. We have designed the homogeneous complex κ-P bis(2-phenoxyl)phosphinite vanadium ((OPO)V) to be a catalyst that may activate propane using the ROA mechanistic motif. We then continued to follow the reaction forward, tracing pathways for the catalytic oxidation of propane in aqueous solution using O_2 as the terminal oxidant. We found that the ((OPO)V) system has the potential to be a viable catalyst in acidic aqueous solution, converting propane to either propylene or isopropanol.

1.3 Other projects

Chapter 5 is a computational mechanistic study of the 2,6-bis(4-isopropyl-2-oxazolin-2-yl)pyridine nickel (Ni((*i*Pr)−pybox)) system, a Negishi C−C coupling catalyst. In our computational work, we investigated the coupling of 1-bromoindane with methylzinc iodide catalyzed by the Ni((*S*,*S*−*i*Pr)-pybox) system to form 1-methylindane. The chiral diastereomers of this catalyst are most notable for their stereoconvergence: Using Ni((*S*,*S*−*i*Pr)−pybox) as a catalyst, both enantiomers of racemic 1-bromoindane will couple with methylzinc iodide to form (*S*)-1-methylindane with 90% enantiomeric excess [**?**]. We confirm that the mechanism proceeds through a Ni^{I}-Ni^{III} couple, in contrast to the classic Ni^{0}-Ni^{II} cycle that Negishi catalysts are typically assumed to undergo [**?**] (Scheme 1.3).

Appendix A is an experimental and computational study of the (L)Rh^{I}(COE)(TFA) complexes in which L is DAB^{F} or BOZO (DAB^{F} = *N*,*N*-bis(pentafluorophenyl)-2,3-dimethyl-1,4-diaza-1,3-butadiene, COE = cyclooctene, TFA = trifluoroacetate, BOZO = bis(2-oxazolin-2-yl)). These com-



Scheme 1.3. The generalized mechanism of the Ni((*i*Pr)−pybox) Negishi coupling catalyst as it proceeds through a Ni^{I}-Ni^{III} cycle. The overall equation is ind−Br + MeZnI ⟶ ind−Me + ZnBrI.

plexes have been shown to catalyze the H/D exchange of benzene in trifluoroacetic acid. Computationally, the mechanism was found to occur by the reversible oxidative addition and reductive elimination of benzene to and from the $(L)Rh^{I}(TFAH)(TFA)$ species.

Appendix B is a comparison of various DFT and electron-correlation methods for calculating the group 10 transition metals Ni, Pd, and Pt. These elements are notable in that, despite being in the same periodic group, they each have a different electronic configuration (d^8s^2, d^{10}, and d^9s^1, respectively). The accuracy of DFT and electron-correlation methods in reproducing the transition energies between the three configurations for the three elements is an important consideration that has deeper implications in the reactivity of more complex systems including these elements.

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