FINAL REPORT
SUBMITTED TO
THE U.S. DEPARTMENT OF ENERGY

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TRANSITION METAL ACTIVATION AND FUNCTIONALIZATION OF CARBON-HYDROGEN AND CARBON-CARBON BONDS

William D. Jones, Principal Investigator
Phone: 585-275-5493
Grant No. DE-FG02-86ER13569
Total Project Period: August 15, 2015 – August 14, 2019
(includes 1 year no-cost extension)
Total Award Amount (4 years): $ 440,000
Report Period: August 15, 2015- August 14, 2019
Unexpended Balance from Previous Year: $0

Executive Summary of FY 2015-19 Research in the Chemical Sciences

Title: **Transition Metal Activation and Functionalization of C-H and C-C Bonds**

Grant#: FG02-86ER13569

P.I.: William D. Jones, Department of Chemistry, University of Rochester, Rochester, NY 14627
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Total Grant Period: August 15, 2015 – August 14, 2019, $440,000 for four years (includes 1 year no-cost extension)

Accomplishments (8/15/15 – 8/14/19, 4 years):

1. What are the major goals of the project?

This project has as its overall goal improvement in the intelligent use of our energy resources, specifically petroleum derived products, and is aimed at the development of new routes for the manipulation of C-H and C-C bonds. During this project period, our research is focused on the following general goals: (1) C-H bond activation reactions in functionalized substrates, including alkylnitriles, ketones, esters, ethers, fluoromethanes, alcohols, amines, and alkynes, and fundamental studies of their effects on metal-carbon bond strengths using trispyrazolylborate-rhodium (TpRh) complexes; (2) Hydrogenation reactions using first-row transition metals; and (3) C–CN bond activation in aryl-nitriles and allyl-nitriles.

2. What was accomplished under these goals?

The specific accomplishments of the current grant period include:

(1) We have made a breakthrough in our understanding of rhodium-alkoxide bond strengths by the examination of the kinetics and thermodynamics of O-H bond activation in several alcohols such as methanol, ethanol, isopropanol, and t-butanol. This work demonstrates that there is a tradeoff between the metal-oxygen bond strength and the hydrogen-oxygen bond strength.

(2) We have also investigated the kinetics and thermodynamics of N-H bond activation in several amines. Basic amines coordinate through nitrogen to Tp'Rh(PMe_3), but less basic amines oxidatively add the N-H bond. It was observed that Rh-NHR bonds are stronger than Rh-OR bonds, and that there is a tradeoff between the metal-nitrogen bond strength and the hydrogen-nitrogen bond strength, similar to what was seen with alcohols.

(3) We have published a study of C-C cleavage in acetontrile and benzonitrile using a palladium-dippe precursor.

(4) We have published a book chapter on "The Effects of Ancilliary Ligands on Metal-Carbon Bond Strengths," in *Topics in Organometallic Chemistry: C-H Bond Activation and Catalytic*

Functionalization (vol. 56) 2016, that summarizes about 28 years of DOE supported work with Tp'RhL complexes.

(5) We have investigated the use of a cobalt-PNP catalyst for the hydrogenation of esters

(6) We have investigated the use of Lewis acids to assist in the cleavage of C-C bonds using a nickel(0) complex.

(7) We have assisted in the publication of an important paper "Towards Benchmarking in Catalysis Science: Best Practices, Opportunities and Challenges," Thomas Bligaard, R. Morris Bullock, Charles T. Campbell, Jingguang Chen, Bruce C. Gates, Raymond J. Gorte, Christopher W. Jones, William D. Jones, John R. Kitchin, Susannah L. Scott, *ACS Catalysis* **2016**.

(8) We have established the C-H activation selectivities in a variety of ketones and esters.

(9) We have measured the lifetimes of the transient alkane sigma-complexes that are formed upon irradiation of Tp'Rh(CNneopentyl)(carbodiimide).

3. What opportunities for training and professional development has the project provided?

DOE funds have been used for the support of several graduate students during the grant period. The C-CN work has been done in collaboration with the Center Enabling New Technology for Catalysis (CENTC) which supported a summer REU student.

4. How have the results been disseminated to communities of interest?

In the past 4 years of this grant, we have published 13 manuscripts. The work has been communicated at both national and international meetings. Since 2015, the P.I.has given 64 lectures at many Universities and meetings around the world. He gave a short course at Kyoto University as a visiting professor, and was the Keynote speaker at the Hong Kong Graduate Symposium in Hong Kong in 2019 (includes 6 research universities in Hong Kong).

5. What do you plan to do during the next reporting period to accomplish the goals?

This grant will terminate. A new proposal on the catalytic conversion of ethanol to butanol has been submitted and funded.

Attachments (accomplishments): Doe2019rpt-accomplishments.pdf

Products- DOE Publications Appearing this Grant Period

1. Jones, W. D. The Effects of Ancilliary Ligands on Metal-Carbon Bond Strengths. In *Topics in Organometallic Chemistry: C-H Bond Activation And Catalytic Functionalization (vol. 56);* Doucet, H. and Dixneuf, P., Eds., Springer-Verlag: Berlin, 2016; pp. 67-89. *Top. Organomet. Chem.*, **2016**, *56*, 67-90. doi: 10.1007/3418_2015_138
2. "Towards Benchmarking in Catalysis Science: Best Practices, Opportunities and Challenges," Thomas Bligaard, R. Morris Bullock, Charles T. Campbell, Jingguang Chen, Bruce C. Gates, Raymond J. Gorte, Christopher W. Jones, William D. Jones, John R. Kitchin, Susannah L. Scott, *ACS Catal.* **2016**, *6*, 2590-2602. doi: 10.1021/acscatal.6b00183
3. "Nitrile Coordination to Rhodium Does Not Lead to C-H Activation," Yunzhe Jiao, William W. Brennessel, William D. Jones, *Acta Cryst. C*, **2016**, *72*, 850-852. doi: 10.1107/S2053229616006859
4. "C-CN Cleavage using Palladium Supported by a Dippe Ligand," Lloyd Munjanja, Coralys Torres-López, William W. Brennessel and William D. Jones, *Organometallics* **2016**, *35*, 2010-2013. doi: 10.1021/acs.organomet.6b00304
5. "Determination of Rhodium-Alkoxide Bond Strengths in Tp′Rh(PMe_3)(OR)H," Jing Yuwen, Yunzhe Jiao, William W. Brennessel, and William D. Jones, *Inorg. Chem.* **2016**, *55*, 9482-9491. doi: 10.1021/acs.inorgchem.6b01992
6. "Additive-Free Cobalt-Catalyzed Hydrogenation of Esters to Alcohols," Jing Yuwen, Sumit Chakraborty, William W. Brennessel and William D. Jones, *ACS Catal.* **2017**, *7*, 3735-3740. doi: 10.1021/acscatal.7b00623
7. "Lewis Acid Assisted C-CN Cleavage of Benzonitrile using $[(dippe)NiH]_2$," Brett D. Swartz, William W. Brennessel and William D. Jones, *SYNLETT*, **2018**, *29*, 747-753. Special cluster on C-C bond activation. doi: 10.1055/s-0036-1590801
8. "Probing the Carbon-Hydrogen Activation of Alkanes Following Photolysis of Tp'Rh(CNR)(carbodiimide): A Computational and Time-resolved Infrared Spectroscopic Study," Jia Guan, Alisdair Wriglesworth, Edward N. Brothers, Snežana D. Zarić, Meagan E. Evans, William D. Jones, Michael B. Hall,* and Michael W. George*, *J. Am. Chem. Soc.* **2018**, 140, 1842–1854. doi: 10.1021/jacs.7b12152
9. "Coordination or Oxidative Addition? Activation of N–H with [Tp'Rh(PMe_3)]," Jing Yuwen, William W. Brennessel, and William D. Jones, *Inorg. Chem.*, **2019**, *58*, 557–566. doi: 10.1021/acs.inorgchem.8b02752
10. "Photolysis of Tp'Rh(CNneopentyl)(PhNCNneopentyl) in the presence of ketones and esters: kinetic and thermodynamic selectivity for activation of different aliphatic C-H bonds," Astrid M. Parsons and William D. Jones, *Dalton Trans.* **2019**, *48*, 10945–10952. doi: 10.1039/C9DT03039E

Participants

William D. Jones, PI
Yunzhe Jiao, grad student
Jing Yuwen, grad student
Lloyd Munjanja, grad student
Andy VanderWeide, grad student
Michaela Ritz, grad student
Astrid Olivares, grad student

Collaborators: Prof. Michael George, University of Nottingham, Great Britain. Prof. Michael Hall, Texas A&M, USA.

Impact

1.What is the impact on the development of the principal discipline(s) of the project?

The continued success of this work will lead to the development of new techniques and processes for the manipulation of petroleum-based hydrocarbons. These new processes will be based upon the new methods for making and breaking strong bonds in organic molecules of the type studied here.

2. What is the impact on other disciplines?

The work has the potential to have a significant impact in science and in technologies of interest to DOE as the chemistry relates to the petroleum industry and chemicals derived from petroleum. A more detailed report follows, followed by a listing of the DOE supported publications.

3. What is the impact on the development of human resources?

This work has resulted in the training of 6 professional researchers in organometallic chemistry and catalysis.

4. What is the impact on physical, institutional, and information resources that form infrastructure?

none

5. What is the impact on technology transfer?

none, yet

6. What is the impact on society beyond science and technology?

not apparent at this time.

Changes- Problems

1. Changes in approach and reasons for change - none
2. Actual or anticipated problems or delays and actions or plans to resolve them - none

3. Changes that have a significant impact on expenditures - none

4. Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards – N/A

5. Change of primary performance site location from that originally proposed - none

6. Carryover Amount- $0

Demographic Information

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Attachments Doe2019rpt-accomplishments.pdf

FINAL REPORT

Transition Metal Activation and Functionalization of Carbon-Hydrogen and Carbon-Carbon Bonds

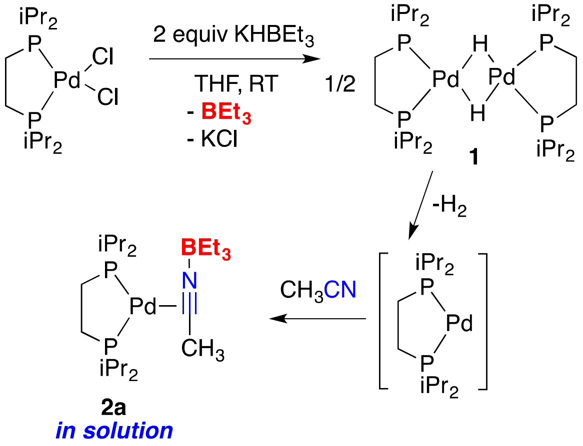
William D. Jones, Principal Investigator
Phone: 585-275-5493
Grant No. DE-FG02-86ER13569
Prepared October 9, 2019

Detailed Final Report for the Project Period August 15, 2015-August 14, 2019.

1. Cleavage of C-C Bonds in Nitriles.

We have investigated C-CN cleavage in acetonitrile and benzonitrile using [Pd(dippe)]. The (dippe)palladium(0) fragment generated from $[(\text{dippe})\text{Pd}(\mu\text{-H})]_2$, has been shown to form an intermediate η^2–nitrile complex with acetonitrile (dippe)Pd(η^2–C,N-CH_3CN-BEt_3) in the presence of BEt_3 [(dippe = bis-diisopropylphosphino)ethane)]. On introducing a solution of this compound to 1 equiv of BPh_3, rapid formation of (dippe)Pd(η^2–C,N-CH_3CNBPh_3) , is observed. Heating this material at 100°C in THF-d_8 results in the C-CN activation product, (dippe)Pd(CH_3)($CNBPh_3$).

Scheme 1:

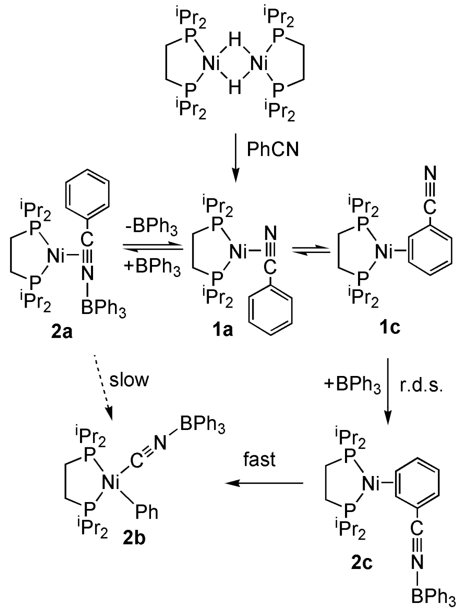


Reaction of the [Pd(dippe)] precursor with benzonitrile in the presence of BEt_3 gives the C-CN activation product, (dippe)Pd(Ph)(CN-BEt_3), exclusively. This work has now appeared in *Organometallics*.

We have also completed studies of C-CN cleavage in benzonitrile by [Ni(dippe)] in the presence of Lewis acids. We have found that BPh_3 dramatically accelerates the reaction if it is present in sub-stoichiometric amounts. However, if a stoichiometric (relative to Ni) amount is used, the reaction is dramatically inhibited. A mechanistic investigation revealed that when the BPh_3 coordinates to the bound nitrogen lone pair, the molecule is to stable to react quickly. The BPh_3 must dissociate and then re-attach once the benzonitrile complex has rearranged to the η^2-arene complex in order for rapid C-CN cleavage to occur (Scheme 2). This result means that one should exercise caution when using Lewis acids as co-catalysts. Too much of a good thing can be bad.

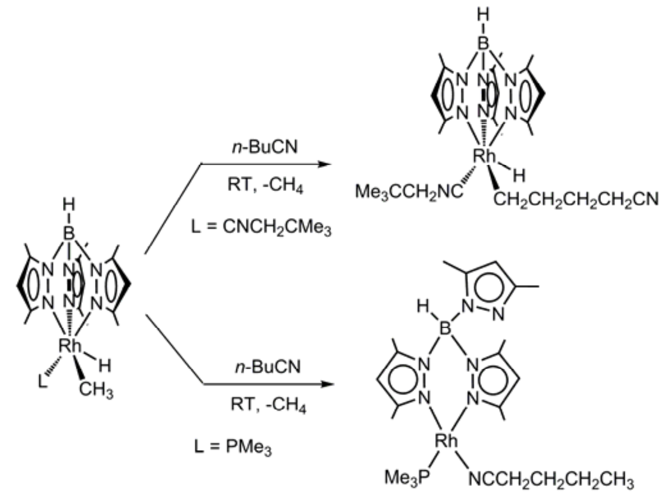
We have also examined the effects of other Lewis acids on this reaction. BF_3 accelerates the cleavage, even if present in excess. This was attributed to the poorer Lewis acidity of BF_3 and the lability of the η^2-C,N adduct. Other Lewis acids such as BEt_3, AlF_3, SnF_4, or $SnPh_4$ had no effect upon the reactivity. This work has been published in *SYNLETT*.

Scheme 2:



We have also examined the reaction of [Tp'Rh(PMe_3)] with valeronitrile. Here, exclusive formation of the N-bound nitrile adduct was observed. In comparison, reaction of [Tp'Rh(CNneopentyl)] with valeronitrile was found to result in exclusive methyl group C-H activation (Scheme 3).

Scheme 3:



2. Cleavage of RO-H Bonds in Alcohols.

One area of research we have just completed is a study of the activation of the O-H bonds of alcohols. The [Tp'Rh(PMe_3)] fragment, generated by methane loss from Tp'Rh(PMe_3)MeH, reacts with many primary and secondary alcohols to give oxidative addition products of the type Tp'Rh(PMe_3)(OR)H. These products are readily isolated and characterized by NMR spectroscopy, and conversion to the bromide derivative permits X-ray structure determination.

Note that these products appear to result from oxidative addition, the detailed mechanism has not been determined. For example, it is possible that the alcohol first protonates the Rh^I intermediate and then coordinates alkoxide. Alternatively, it is possible that the oxygen of the alcohol first binds to the metal, and then a hydrogen migration takes place. We favor the latter, as this type of process has been seen in laser flash photolysis experiments of ROH with $Cr(CO)_6$. Also, it was somewhat surprising not to see C-H activation of the alcohol methyl groups competing with the O-H activation. With [Tp'Rh(CNneopentyl)] and alkyl chlorides and nitriles, C-H activation dominated completely.

Even water undergoes oxidative addition to give Tp'Rh(PMe_3)(OH)H cleanly. Conversion to the bromide Tp'Rh(PMe_3)(OH)Br allows X-ray structure determination. It is worth noting that these ROH studies are only possible with the PMe_3 derivative. Our earlier studies (1990-2010) were exclusively with the neopentylisocyanide derivative as a spectator ligand, but we found that this ligand is susceptible to attack by alcohols to give Fischer carbene adducts (i.e., Rh[=C(NR)(OR)]! The PMe_3 derivative avoids this undesirable side reaction.

With these alkoxide derivatives in hand, we were then able to examine their rate of reductive elimination in C_6D_6. Our first studies were frought with problems of reproducibility, and we discovered that any water present could wreak havoc on the kinetics. With this problem solved, we could obtain reliable rate data that provided the kinetic barrier for RO-H reductive elimination. These barriers are very similar for most alcohols (and water), and are only slightly higher for benzyl alcohol and trifluoroethanol.

Finally, we did kinetic competition studies between each alcohol and benzene. Here, once again, very little variability was seen in the relative rates of activation of the alcohol RO-H bonds. With this $\Delta\Delta G^{\ddagger}$ data in hand, we were able to determine the relative Rh-OR bond strengths for this series of derivatives using equation 1 below. Equation 1 contains a correction for the statistical (entropic) effect of the number of hydrogens available for activation. A plot of the $D_{\text{Rh-OR}}$ vs. the known $D_{\text{RO-H}}$ bond strengths provides a correlation as shown in Figure 1. Here, the slope of the plot is 0.97, which indicates that variations in RO-H bond strengths map exactly onto Rh-OR bond strengths. This conclusion is similar to that made by Bercaw and Bryndza using far less data. These results were published in *Inorg. Chem.*

$$D_{\text{rel}}(\text{Rh-OR}) = [\Delta H(\text{Rh-OR}) - \Delta H(\text{Rh-Ph})] = \Delta G° + RT\ \ln(6/\#H) + [\Delta H(\text{RO-H}) - \Delta H(\text{Ph-H})] \quad (1)$$

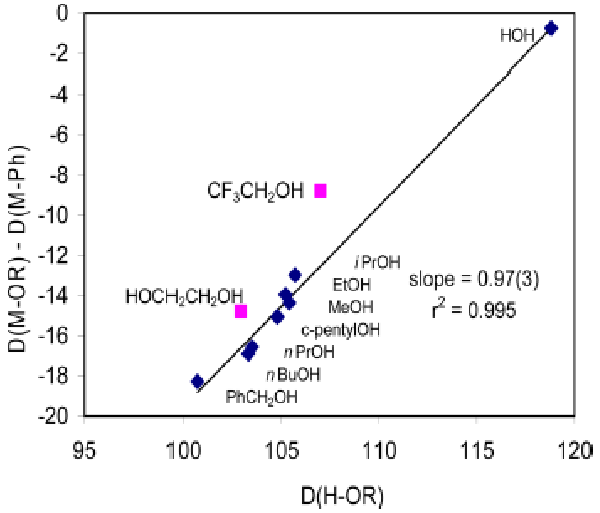
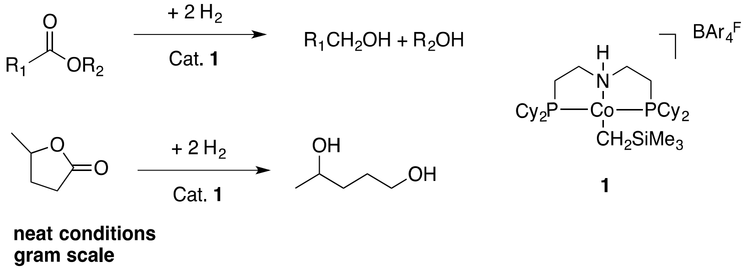


Figure 1. Relative Rh-OR and H-OR bond strengths. The pink data are not included in the fit.

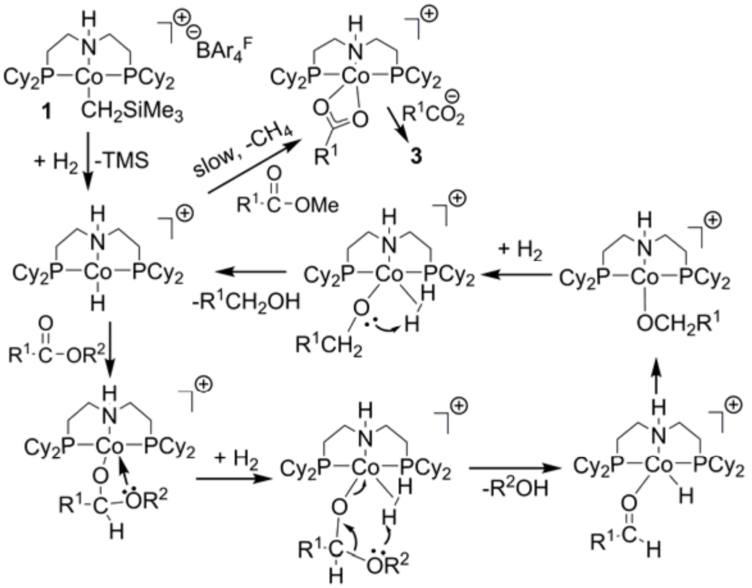
3. Ester Hydrogenation using Cobalt-PNP Complexes.

We have examined the use of the complex $(PNHP)CoCH_2SiMe_3]^+BAr^F{}_4{}^-$, **1**, (where PNHP = $HN(CH_2CH_2P^iPr_2)_2$) for the hydrogenation of esters. The reaction proceeds in good yields under about 55 bar H_2 at 120 °C. The scope of the substrates is good. In addition, lactones such as γ-valerolactone are hydrogenated to the ring-opened diols in good yield on large scale (Scheme 4). The N-methyl derivative hydrogenates these substrates almost as well as catalyst **1**, which means that the mechanism does not necessarily involve the N-H moiety. Methyl esters were noted to be hydrogenated in low yield, due to a competing S_N2 pathway. A mechanism is proposed in Scheme 5.

Scheme 4:



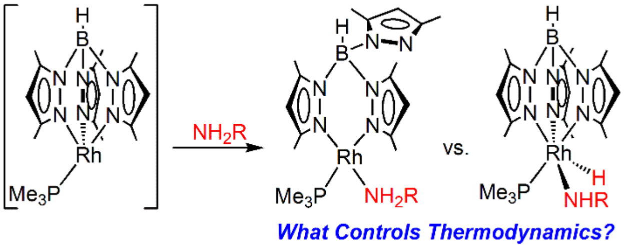
Scheme 5:



4. Cleavage of RHN-H Bonds in Amines.

The thermal reaction of amines, anilines, and amides with $Tp'Rh(PMe_3)(CH_3)H$ was examined (Scheme 6). No N–H bond cleavage was observed for reactions between ammonia or unsubstituted aliphatic amines with the reactive fragment $[Tp'Rh(PMe_3)]$. Instead, amine coordination products $(\kappa^2\text{-}Tp')Rh(PMe_3)(NHR^1R^2)$ (R^1 = H, R^2 = H, ^{n}Pr, ^{i}Pr, octyl; $R^1 = R^2$ = Et; R^1, R^2: pyrrolidine) were observed, and the crystal structure of $(\kappa^2\text{-}Tp')Rh(PMe_3)(NH_2{}^iPr)$ was determined. No coordination products were observed when $Tp'Rh(PMe_3)(CH_3)H$ was reacted with 1,1,1,3,3,3-hexafluoropropan-2-amine, anilines and amides. Instead, the oxidative addition products $(\kappa^3\text{-}Tp')Rh(PMe_3)(NHR)H$ (R = $CH(CF_3)_2$, C_6H_5, 3,5-dimethylbenzyl, C_6F_5, $C(O)CH_3$, C(O)CF$_3$) were observed. Both Rh^{I}–N coordination products (κ^2-Tp')Rh(PMe$_3$)(NH$_2$CH$_2$CF$_3$) and Rh^{III} N–H addition products (κ^3-Tp')Rh(PMe$_3$)(NHCH$_2$CF$_3$)H were generated when Tp'Rh(PMe$_3$)(CH$_3$)H was reacted with 2,2,2-trifluoroethylamine. Coordination products dissociate ammonia and amines in benzene much faster than oxidative addition products eliminate anilines and amides. The relative metal-nitrogen bond energies were studied using established kinetic techniques. Analysis of the relationship between the relative M−N bond strengths and N−H bond strengths showed a linear correlation with $R_{\text{M–N/N–H}}$ of 0.91 (10), indicating that the Rh–N bond strength varies in direct proportion to the N–H bond strength (Figure 2).

Scheme 6:



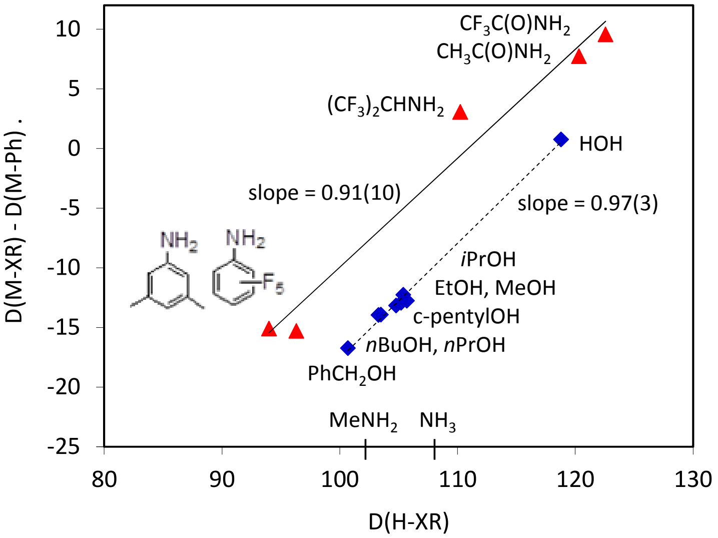
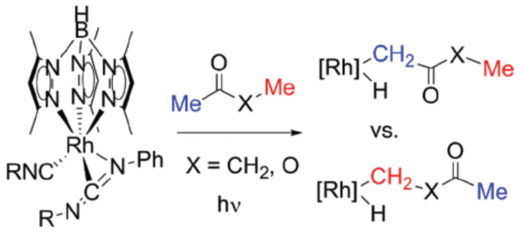


Figure 2. Plot of relative M–N (red) / M–O (blue) bond strengths vs. N–H/O–H bond strengths for Tp′Rh(PMe$_3$)(NHR/OR)H. The solid line is fit to the amines and amides, and the dashed line is fit to the alcohols.

5. Selectivity in the Cleavage of C-H Bonds in Ketones and Esters.

The active fragment [Tp'Rh(CNneopentyl)] underwent oxidative addition of substituted ketones and esters resulting in Tp'Rh(CNneopentyl)(R)(H) complexes (Scheme 7). These C–H activated complexes underwent reductive elimination at varying temperatures (24–70 °C) in C$_6$D$_6$ or C$_6$D$_{12}$. Using previously established kinetic techniques, the relative Rh–C bond strengths were calculated. Analysis of the relative Rh–C bond strengths vs. C–H bond strengths shows a linear correlation with slope $R_{\text{M–C/C–H}}$ = 1.22 (12). In general, α-substituents increase the relative Rh–C bond strengths compared to the C–H bond that is broken (Figure 3).

Scheme 7:



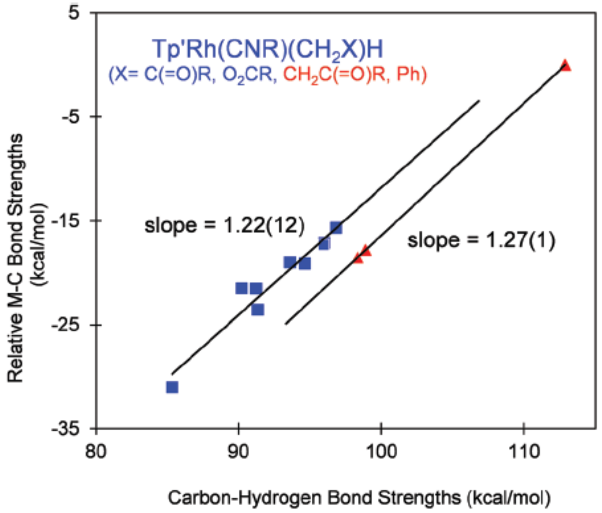


Figure 3. Plot of relative experimental M–C bond strengths vs. C–H bond strengths for Tp'Rh(CNneopentyl)(R)(H). Hydrocarbon C–H bond strengths were calculated using B3LYP/6-311g. Blue squares refer to α-keto or α-O functionalized $Rh–CH_2X$ products. Red triangles refer to β-keto $Rh–CH_2CH_2C(=O)R$ and phenyl products.

6. Ultrafast Investigation of C-H Bonds Oxidative Addition of Hydrocarbons.

In a collaboration with Michael Hall (Texas A&M) and Michael George (Nottingham), we examined the activation of alkanes by irradiation of Tp'Rh(CNR)(carbodiimide) using time-resolved infrared spectroscopy (TRIR) in the ν(CNR) and ν(B-H) spectral regions. The major intermediate species were: κ^3-η^1-alkane complex (**1**), κ^2-η^2-alkane complex (**2**), and κ^3-alkyl hydride (**3**). Calculations predict that the barrier between **1** and **2** arises from a triplet-singlet crossing and intermediate **2** proceeds over the rate-determining C-H activation barrier to give the final product **3**. The activation lifetimes measured for the Tp'Rh(CNR) and Tp'Rh(CO) fragments with n-heptane and four cycloalkanes (C_5H_{10}, C_6H_{12}, C_7H_{14}, and C_8H_{16}) increase with alkanes size and show a dramatic increase between C_6H_{12} and C_7H_{14} (Figure 4) A similar step-like behavior was observed previously with CpRh(CO) and Cp*Rh(CO) fragments and is attributed to the wider difference in C-H bonds that appear at C_7H_{14}. However, Tp'Rh(CNR) and Tp'Rh(CO) fragments have much longer absolute lifetimes compared to those of CpRh(CO) and Cp*Rh(CO) fragments, because the reduced electron density in dechelated κ^2-η^2-alkane Tp' complexes stabilizes the d^8 Rh(I) in a square-planar geometry and weakens the metal's ability for oxidative addition of the C-H bond. Further, the Tp'Rh(CNR) fragment has significantly slower rates of C-H activation in comparison to the Tp'Rh(CO) fragment for the larger cycloalkanes, because the steric bulk of the neopentyl isocyanide ligand hinders the rechelation in κ^2-

Tp'Rh(CNR)(cycloalkane) species and results in the C-H activation without the assistance of the rechelation.

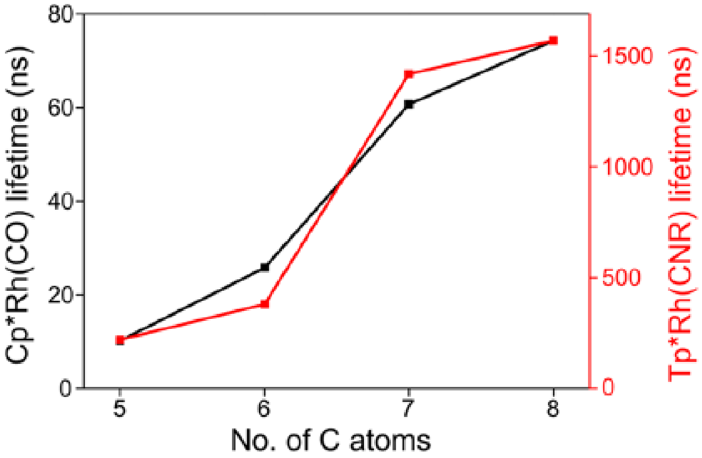


Figure 4. Scaled lifetime trends for the C-H activation of cycloalkanes by Tp'Rh(CNR) (red) and Cp*Rh(CO) (black).