The Application of Physical Organic Methods to the Investigation of Organometallic Reaction Mechanisms

or

A Nostalgia Trip Through Organometallic Chemistry of the late 20th Century

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G. N. Lewis Lecture
October 23, 2018
Gilbert Newton Lewis’s memorandum of 1902 showing his speculations about the role of electrons in atomic structure. From *Valence and the Structure of Atoms and Molecules* (1923), p. 29
Lewis’s theory of chemical bonding continued to evolve and, in 1916, he published his seminal article suggesting that a chemical bond is a pair of electrons shared by two atoms.... Lewis in 1923 redefined an acid as any atom or molecule with an incomplete octet that was thus capable of accepting electrons from another atom; bases were, of course, electron donors.

Science History Institute; https://www.sciencehistory.org/historical-profile/gilbert-newton-lewis

The 18-electron rule, much beloved of the organometallic chemist, was first formulated by the American chemist, Irving Langmuir in 1921 as part of his program to extend the Lewis static-atom model beyond argon in the periodic table. Langmuir derived an equation relating the number of shared electrons or the covalence (vc) of a given atom in a compound or complex ion to the difference between the number of valence electrons (e) in the isolated atom and the number of electrons (s) required for completion of its valence shell: \( vc = s - e \). In the case of organic chemistry, where the component atoms obeyed the octet rule, this reduced to \( vc = 8 - e \) whereas in the case of the transition-metal carbonyls, it reduced to: \( vc = 18 - e \).

Pinhas, A. in Jensen, W. B. “The Origin of the 18-Electron Rule”;
http://www.che.uc.edu/jensen/w.%20b.%20jensen/reprints/116.%2018e%20rule.pdf
Me – around the time all this started!

Brief professional history:

B.A., Carleton College, 1963

Ph. D., University of Wisconsin, 1966 (Jerome A. Berson)

Postdoctoral Fellow, Columbia University, 1966-67 (Ronald Breslow)

Caltech, 1967-1978

UC Berkeley, 1978 – present (Professor Emeritus since 2016)
Disclaimers!

1. There has been a lot of talk about “self plagiarism” in scientific articles, so….

2. Full disclosure: the chemistry described in this talk has been “self-plagiarized” from earlier talks and papers.


3. Many of the physical organic techniques described in this paper *could* represent the first time they were used to study organometallic reactions. However…

4. **Stigler's law of eponymy**

*(Plagiarized from Wikipedia, the free encyclopedia)*

Stigler's law of eponymy is a process proposed by [University of Chicago](https://www.chicagogrants.org/) [statistics](https://www.stat.uchicago.edu/) professor [Stephen Stigler](https://www.stat.uchicago.edu/~stigler/) in his 1980 publication "Stigler’s law of eponymy." In its simplest and strongest form it says: "No scientific discovery is named after its original discoverer."

Exothermicity of Carbon-Carbon σ – Bond Formation from Alkynes: A Novel Route to 1,4-Dehydrobenzene ("para-Benzyne")

No detection of:

Conclusion: the reactions of the intermediate are consistent with a diradical structure

Only para-dideuteriobenzene (no detectable meta- or ortho-isomers) is formed.

1,4-Dehydrobenzene Chemistry in the 1980’s: Mechanism of Action of Calicheamicin Antibiotic

Presumed DNA-cleaving mechanism of calicheamicin $\gamma_{1\alpha}$ (1).

Calicheamicin-antibody conjugates are now being used as anti-cancer agents: Duebel, S.; Reichert, J. M.; Peipp, M.; Gramatzki, M. Handbook of Therapeutic Antibodies, Wiley-VCH 2014, Ch. 55.

Lemonade from Lemons: Alkyne Trimerization Catalyzed by ($\eta^5$-C$_5$H$_5$)Co(CO)$_2$

Attempts to Make Highly Reduced Cyclopentadienylcobalt Complexes: Early Synthesis of a Binuclear Radical Anion and Binuclear Dialkyl Complexes

\[ \text{CpCoCO}^{2-} \quad \text{[Precedent: Collman's Fe(CO)}_5 \xrightarrow{\text{Na}} \text{Fe(CO)}_4^{2-} \]

1. Na/THF

2. \([\text{Ph}_3\text{P=N=PPh}_3]^+ \text{Cl}^-\]

\[ \text{IR: 1690 cm}^{-1} \]
\[ \mu_{\text{eff}} = 1.69 \text{ B.M.} \]

R = CH₃, CH₂⁻ CF₃

IR: 1790 cm⁻¹

Isolated by air-free chromatography on SiO₂

Radical anion
ESR spectrum
(15 lines due to cobalt spin 7/2; 
g = 3100 G
\(a_{\text{Co}} = 50 \text{ G}\))
and molecular structure

Early use of Crossover Experiments in Organometallic Chemistry: Carbon-carbon Bond-forming Reactions of Binuclear Cobalt Complexes

$RM - M - R + CO \xrightarrow{?} R - C - R + M - M$

Crossover experiment:

$\text{Cp}(CH_3)Co(CO)_{2}Co(CH_3)Cp + CO \rightarrow \text{CH}_3\text{CCH}_3 + 2 \text{Co(CO)CO}$

$\text{Cp}(CD_3)Co(CO)_{2}Co(CD_3)Cp + CO \rightarrow \text{CH}_3\text{CCH}_3 \quad 26\%$

$\quad \text{CH}_3\text{CCH}_3 \quad 26\%$

$\quad \text{CH}_3\text{CDCD}_3 \quad 47\%$

$\quad \text{CD}_3\text{CDCD}_3 \quad 27\%$

White, M. A.; Bergman, R. G. Chem. Commun. 1979, 1056-1058
Spectroscopic Observation of a Metastable Dialkylcarbonyl Species: a Question of Necessary and Sufficient Mechanistic Evidence

Thermolysis of the dinuclear dicarbonyl (no CO added):

\[
\begin{align*}
\text{Cp}_2\text{Co} & \xrightarrow{35 \degree C} \text{R} & \text{R} \\
\text{R} = \text{CH}_3, \text{CH}_2\text{-CH}_3, \text{CH}_2\text{-CF}_3
\end{align*}
\]

R = CH\text{\_}3, CH\text{\_}2\text{\_}CH\text{\_}3, CH\text{\_}2\text{\_}CF\text{\_}3

35 \degree C Monitor by \textsuperscript{1}H NMR

\[
\begin{align*}
\text{R} = \text{CH}_3, \text{CH}_2\text{CH}_3, & \text{ Spectroscopically detectable (NMR, IR)} \\
\text{R} = \text{CH}_2\text{CF}_3 & \text{ isolable}
\end{align*}
\]

Conclusion: ketone formation CAN take place via the mononuclear intermediate. But is that how ketone IS formed from the dinuclear starting material?

This question concerns the kinetic competence of the mononuclear dialkylcarbonyl species.
Variable Temperature NMR Behavior of a Dinuclear Cobalt Complex

Schore, N. E.; Ilenda, C. S.; White, M. A.; Bryndza, H. E.; Matturro, M. G.; Bergman, R. G.

The dialkyl carbonyl reacts with CO too slowly to be an intermediate here. Direct formation of the (alkyl) (acyl) complex bypasses the dialkylcarbonyl complex.

Possible mechanism:

\[
{[\text{CpV(CO)}_3\text{H}]}^- + R\text{X} \rightarrow R\text{H} + {[\text{CpV(CO)}_3\text{X}]}^-
\]

Early Evidence for Radical Intermediates in an Organotransition Metal Hydride/Organic Halide Reduction

\[
\text{Cp(CO)_3VH}^- + R-X \rightarrow R-H + \text{Cp(CO)_3VX}^-
\]

Relative reactivity: \( R-I > R-Br > R-Cl \)

\( R-\text{Hal} \gg R-\text{OSO}_2\text{Ar} \)

1° ~ 2° ~ 3° ~ vinyl ~ cyclopropyl

Stereochemistry:

\[
\text{Br} \quad \text{H} \\
\begin{array}{c}
\text{C}_6\text{H}_5 \\
\text{CH}_3
\end{array}
\]

\( (S) \)

\[
\text{D} \quad \text{H} \\
\begin{array}{c}
\text{C}_6\text{H}_5 \\
\text{CH}_3
\end{array}
\]

racemic

These observations are very similar to those made in the study of the reduction of organic halides by trialkyltin hydrides (\( R_3\text{SnH} \)).
Early Use of a “Radical Clock” in an Organotransition Metal Mechanistic Study

\[
\begin{align*}
\text{Br} & \quad \text{Cp(CO)}_3\text{VH}^- \\
0.02\text{M} & \quad \xrightarrow{>85\%} \quad \text{Cp(CO)}_3\text{VH}^- \\
\text{Br} & \quad \xrightarrow{>85\%} \quad \text{Cp(CO)}_3\text{VH}^- \\
0.02\text{M} & \quad \text{[VH]}^- = 0.08\text{ M} \quad 50 : 50 \\
\text{[VH]}^- = 0.15\text{ M} & \quad 62 : 37
\end{align*}
\]

\[\text{R} - \text{H} \quad \xrightarrow{\text{CpV(CO)}_3^-} \quad \text{R} - \text{Br}\]

\[\text{CpV(CO)}_3\text{H}^- \quad \xrightarrow{\text{R}^\bullet} \quad \text{R}^\bullet \quad \text{CpV(CO)}_3\text{Br}\]

Conclusion: a "super tin hydride" chain mechanism is operating:

\[
\begin{align*}
\text{For Cp(CO)}_3\text{VH}^- \quad + \quad \text{R}^\bullet & \quad \xrightarrow{} \quad \text{CpV(CO)}_3^- \quad + \quad \text{R} - \text{H}
\end{align*}
\]

\[k_H \equiv 10^7 \text{ M}^{-1}\text{s}^{-1}\]
Cycloaddition/reduction reaction could potentially lead to provide a stoichiometric alkene 1,2-diamination reaction.
Scope, Stereochemistry, and Reversibility of Cobalt Nitrosyl/Alkene Addition

Becker, P. N.; Bergman, R. G. Organometallics 1983, 2, 787-796
Application to Stoichiometric Alkene Diamination

**Diastereoselectivity is improved to 80/20 using DIBAL followed by LiAlH₄ at –50 °C**


Becker, P. N.; Bergman, R. G. *Organometallics* 1983, **2**, 787-796
Generation of Spectroscopically Observable CpCo(NO)$_2$ in Solution

![Chemical Structure](image)

$\lambda_{\text{max}} = 650$ nm (THF)

NMR: $\delta$ 4.53 (s) ($C_6D_6$)

$\lambda_{\text{max}} = 375$ nm (THF)

NMR: $\delta$ 4.22 (s) ($C_6D_6$)

[Conversion: 98 ± 2%]

Conclusion: $\text{A}$ is CpCo(NO)$_2$, the active intermediate in the alkene addition reaction

Comparison of the Relative Rates of Organometallic Addition Reactions with Those of Organic 1,3 Dipolar Cycloadditions: An Organometallic “Click” Reaction

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\text{Ph-NN=N}$, $\text{CCl}_4$, 25 °C</th>
<th>$\text{CpCo(NO)}_2$, $\text{C}<em>6\text{H}</em>{12}$, 20 °C</th>
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<tbody>
<tr>
<td>Ph=N=N=N=, CCl$_4$, 25 °C</td>
<td>5700</td>
<td>1960</td>
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<tr>
<td>C$<em>6$H$</em>{12}$, 20 °C</td>
<td>56</td>
<td>59</td>
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<td></td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>7.3</td>
<td>2.3</td>
</tr>
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<td>1</td>
<td>1</td>
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</tbody>
</table>
Proposed "1-3- Dipolar Addition-Like" Transition State for CpCo(NO)$_2$ + Alkene Addition

\[
\text{Cp-Co(NO)}_2 + \text{Alkene} \rightarrow \text{Cp-Co(NO)}_2 + \text{Alkene}
\]

\[
\text{Ph-N=N=N=N}^+ + \text{Alkene} \rightarrow \text{Ph-N=N=N=N}^+ + \text{Alkene}
\]
Holy Grails in Chemistry

Reference works¹ define a Holy Grail ("usually capitalized") as an "eminently desirable and ultimate object of extended effort," a "knightly quest." This issue contains examples in chemistry selected by us and the Editorial Advisory Board from a far longer list of exciting and deserving topics. Holy Grails are also said to be "achievable only by those chaste in thought, word, and deed;" we leave judgment in this regard to our readers.

Linus Pauling's career epitomizes such quests in chemistry. When a student asked if his proposed research could possibly work,² Pauling quoted an old physics text problem: "If you are walking through a forest and come upon a cube of gold that is one foot on each side, should you try and pick it up? Answer: No, you should not, because the cube would weigh about 1200 pounds." Smiling, Pauling said, "But of course you should try and pick it up. Any fool would!" Quite fortunately, Prof. Pauling had replied to our invitation for this issue with the letter shown next, one of the last of his published writings before his death this last August. This issue is dedicated to him because of the breadth, importance, and number of Holy Grails that he identified, provided with form and substance, and even achieved. In his 1964 Priestley Medal address,³ he said, "Every aspect of the world today—even politics and international relations—is affected by chemistry." Reflecting this, his Nobel prizes were in chemistry and in peace.

These articles represent a tiny fraction of the goals in chemistry deserving critical study, chosen to illustrate a variety of viewpoints concerning high professional goals. Although many of these goals may not be achieved, at least in the way set forth, unusual efforts for such goals will almost surely pay unusual rewards in some way. Alchemists sought to turn base metals into gold; crude oil is now black gold, turned into a cornucopia of uniquely useful materials by sophisticated chemistry. We hope that our readership will find these descriptions informative, enjoyable, and even inspiring.

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² Banaszak Holm, M. M. Ph.D. Thesis, Cornell University, 1991. We thank Professor Peter Wolczanski for this reference.
9 April 1994
Dr. Fred W. McLafferty
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Cornell University
Ithaca, NY 14853-1301

Dear Fred:

I am pleased that you should write to me about the series of articles "Holy Grails." I do not have any interest in any of the Holy Grails mentioned in your letter.

[Followed by text of what Linus Pauling WAS interested in at the time]
[Followed by signature]
Selective Intermolecular Carbon–Hydrogen Bond Activation by Synthetic Metal Complexes in Homogeneous Solution

BRUCE A. ARNDTSEN, ROBERT G. BERGMAN,* T. ANDREW MOBLEY, AND THOMAS H. PETERSON

Division of Chemical Sciences, Lawrence Berkeley Laboratory, and Department of Chemistry, University of California, Berkeley, California 94720-1460

Received December 14, 1994

ARTHUR: Yes, we seek the Holy Grail (clears throat very quietly). Our quest is to find the Holy Grail.

KNIGHTS: Yes it is.

ARTHUR: And so we’re looking for it.

KNIGHTS: Yes we are.

BEDEVERE: We have been for some time.

KNIGHTS: Yes.

ROBIN: Months.

ARTHUR: Yes...and any help we get is...is very...helpful.¹

Synthetic methods chemistry has undergone intense development during the past 50 years. As a result, nearly every class of organic compound can now be considered as a source of starting materials for selective conversion to members of other classes, as well as a wide range of more complicated materials, such as polymers, biomolecules, and metal–organic compounds.

An important class of molecules that represents an exception to this generalization is alkanes, or saturated hydrocarbons. Among the thousands of reagents in the modern arsenal of synthetic organic methodology, few have been developed that are capable of carrying out selective chemistry on alkanes. The lack of reactivity of alkane C–H bonds is often attributed to their high bond energies (typically 90–100 kcal/mol) and very low acidity (difficult to measure directly but estimated to have pKₐ = 45–60) and basicity.

The robust nature of alkanes presents both a fundamental and a practical challenge to chemists. At the fundamental level, carbon–hydrogen and carbon–carbon bonds are the most ubiquitous chemical linkages in nature. Elucidating the requirements necessary to effect their cleavage or their transformation into other bonds lies at the heart of chemical reactivity. Or, as alkanes (especially methanethanically inexpensive. Methane is a major source of fuel, but they also share a fraction of the carbon pool that drives chemical synthesis. An abundant resource is presented.

Methane presents a special opportunity in remote places where its use as a fuel is restricted. The danger of liquefying it and discovery to utilization sites.

Despite the fact that C–H bonds are more reactive than other types of linkages to cleave, they are not completely inert. Alkanes have long been known to undergo a number of solution and gas-phase reactions that involve free radicals as intermediates, such as photocatalysis, radical addition, and combustion. More recently very powerful “super acids” have been developed that are capable of adding protons to alkanes; this work was recognized in a Nobel prize to George Olah. A critical feature of nearly all of these processes, however, is that they are relatively unspecific. Two types of selectivity are at issue here. The first involves the capacity of a potential reagent to attack one type of C–H bond in preference to others. For example, free radical reagents exhibit some preference for reaction of tertiary C–H bonds over primary and secondary, but often the degree of selectivity is not high. Reagents that exhibit the reverse preference are extremely rare. A second type of selectivity is defined.

(1) Cleese, J.; Chapman, G.; Gilliam, T.; Idle, E.; Jones, T.; Palin, M.
Intermolecular Alkane C-H Oxidative Addition at Ir(I) Centers

Product identified by NMR; isolated by low-temperature, inert atmosphere chromatography

Selectivity:
primary > secondary >> tertiary; C-H >> O-H, N-H, etc.
Every organic solvent is reactive. Only successful inert solvents: liquid Xe, liquid Kr

Inspired by earlier experiments on Cp₂WH₂ by M.L.H. Green and co-workers

Graham experiment probably carried out several years earlier, but not published due to lack of NMR evidence and difficulty of product isolation

**Kinetic Isotope Effects**

Consider reaction rates:

\[
\begin{align*}
\text{Cp}^* (L) \text{IrH}_2 & \xrightarrow{\text{h}_\nu} \text{C}_6\text{H}_{12} \rightarrow \text{product} \\
\text{Cp}^* (L) \text{IrH}_2 & \xrightarrow{\text{h}_\nu} \text{C}_6\text{D}_{12} \rightarrow \text{Deuterated product}
\end{align*}
\]

Little difference in overall rate of these reactions; determined by photophysics.

But in mixture of deuterated and non-deuterated alkanes:

\[
\begin{align*}
\text{Cp}^* (L) \text{IrH}_2 & \xrightarrow{\text{h}} \left[ \text{Cp}^* \text{IrL} \right] \\
\text{Cp}^* (L) \text{IrH}_2 & \xrightarrow{\text{h}} \left[ \text{Cp}^* \text{IrL} \right] \\
\end{align*}
\]

\[
\begin{align*}
\text{C}_6\text{H}_{12} + \text{C}_6\text{D}_{12} & \xrightarrow{50 : 50} \begin{cases}
\text{Ir} & \text{58%} \\
\text{C}_6\text{H}_{11} \text{D} & \text{42%}
\end{cases}
\end{align*}
\]

\text{Cp}^* \text{IrL} \, \text{intermediate} \, \text{reacts with CH bonds 1.38 times faster than with CD bonds.}

In contrast, thermal reductive elimination from \text{Ir} alkyl hydride and deuteride exhibits an \textit{inverse} KIE.

Explanation: first indication of alkane complex intermediates:

\[
\begin{align*}
\left[ \text{Cp}^* \text{IrL} \right] & \xrightarrow{\text{R-H}} \text{Cp}^* (L) \text{Ir} \\
\text{Overall} & \xrightarrow{k_H/k_D = 1.38} \text{(by competition)} \\
\end{align*}
\]

\[
\begin{align*}
\text{R} & \xrightarrow{\text{H}} \text{H} \\
\end{align*}
\]

\[
\begin{align*}
\text{Cp}^* (L) \text{Ir} & \xrightarrow{k_H/k_D = 0.7} \text{(by direct kinetics)} \\
\end{align*}
\]
Infrared Flash Kinetic Studies in Liquified Noble Gas Solutions: Direct Observation of C-H Activation Intermediates on the Microsecond Timescale

Yeston, J. S.; McNamara, B. K.; Bergman, R. G.; Moore, C. B. *Organometallics* 2000, 19, 3442-3446.

Very similar conclusions have since been drawn for other C–H activating system (e.g., Rh, Pt). Alkane complexes have also been observed directly in ultrafast kinetic studies with Rh and with Re complexes by low T NMR (Graham Ball).
Combined Infrared Picosecond/Nanosecond Flash Kinetic Studies: Direct Observation of Intermediates in C-H Activation Reactions in Solution at Room Temperature

Can C-H Activation Reactions be Carried out in Water Soluble Host-Guest Reaction Media?

Bergman group Ir(III) C-H Activation Chemistry

\[
\begin{align*}
L' &= OTf^- \quad (n = 0) \\
L' &= C_2H_4 \quad (n = +1)
\end{align*}
\]

\[
\begin{align*}
\text{Cp}^*(L)\text{Ir}^+ - H &\quad \text{CH}_3 \\
\text{Cp}^*(L)\text{Ir}^+ - H &\quad \text{CH}_3 \\
\text{Cp}^*(L)\text{Ir}^+ - R &\quad \text{CH}_4 \\
\text{Cp}^*(L)\text{Ir}^+ - R &\quad \text{R} = \text{alkyl}
\end{align*}
\]

Raymond group $M_4L_6^{12-}$ Tetrahedral “Nanovessels”

\[
\begin{align*}
\text{Cp}^*(L)\text{Ir}^+ - \text{H} &\quad \text{CH}_3 \\
\text{Cp}^*(L)\text{Ir}^+ - \text{H} &\quad \text{CH}_3 \\
\text{Cp}^*(L)\text{Ir}^+ - \text{R} &\quad \text{CH}_4 \\
\text{Cp}^*(L)\text{Ir}^+ - \text{R} &\quad \text{R} = \text{alkyl}
\end{align*}
\]

\[
\begin{align*}
\text{Cp}^*(L)\text{Ir}^+ &\quad \text{CO} \\
\text{Cp}^*(L)\text{Ir}^+ &\quad \text{R}
\end{align*}
\]

$\bullet$ = Ga$^{III}$, Fe$^{III}$, Al$^{III}$
Reactivity of Host-Guest Assembly

Selectivity and cavity-blocking studies establish that the C-H activation reaction takes place inside the cluster cavity.

Reactivity of Group 4 Metallocene Imido Complexes

Similar synthetic and reactivity observation have been made with $\text{Cp}^*\text{Zr} = \text{O}$, $\text{Cp}^*\text{Ti} = \text{N-Ph}$, $\text{Cp}^*\text{Ti} = \text{S}$

Walsh, P. J.; Hollander, F. J.; Bergman, R. G. Organometallics 1993, 12, 3705-3723
Zirconium Catalyzed Hydroamination of Alkynes: anti-Markovnikov N-H Addition

Ar = 2,6-dimethylphenyl

What is the cause of this difference? Is it consistent with a similar mechanism for both reactions?
In the stoichiometric reactions, protonation of the azametallacycles is faster than cycloreversion.
Catalytic reaction: cycloreversion is both faster than protonation and reversible (“Curtin-Hammett” situation). Ratio of enamine products is determined only by the relative free energies of the transition states leading to products.
Primary vs. Secondary Kinetic Isotope Effects: Does the Zr = NR Group Activate C-H Bonds Directly, or by Cycloaddition/Rearrangement?

Use of kinetic isotope effects (KIE’s) to address the above question:

\[
\begin{align*}
\text{CpCp}^*\text{Zr} = \text{N} & \rightarrow \text{tBu} & \text{CpCp}^*\text{Zr} = \text{N} & \rightarrow \text{tBu} \\
\text{THF} & \rightarrow \text{THF} & k_H [R-H] & \rightarrow k_H [R-D] \\
(\text{Cp}^* = \text{C}_5\text{Me}_5) & & & \\
\end{align*}
\]

Results:

- H$_6$ vs. D$_6$
- H$_{12}$ vs. D$_{12}$
- H$_{12}$ vs. D$_{12}$
- X = H vs. X = D
- X = H vs. X = D

\[
k_H/k_D = 7.4 \quad 8.9 \quad 6.9 \quad 6.9 \quad 0.8
\]

Dramatically different KIE's for alkynyl C-H activation

Conclusion: $sp^2$ and $sp^3$ Hydrogens are Activated Differently

$[\text{Zr}]_{\text{N}}_{\text{R}_{\text{alkyl}}}_{\text{Bu}}_{\text{Cp}}_{\text{Cp^*Zr=}}_{\text{N-tBu}}_{\text{R}_{\text{alkyl}}}_{\text{NHtBu}}_{\text{Cp}}_{\text{Cp^*Zr}}_{\text{C=C}}_{\text{R}}$

$R_{\text{alkyl}} \cdot H(D)$

R.D.S.

large normal $k_H / k_D$

CpCp*Zr=N-tBu

$R \cdot C=C \cdot H(D)$

R.D.S.

small inverse $k_H / k_D$

CpCp*Zr=H

$\sim H$

cant

fast

CpCp*Zr=C=C

R
The extra-kinetic methods for investigating mechanisms developed in physical organic chemistry provide a powerful way of thinking about how many different kinds of reactions take place, within and beyond classical organic chemistry. They have provided an important supplement to careful kinetic studies, which for many years had been the central method for investigating inorganic reaction mechanisms.

Much early academic work in organotransition metal chemistry focused on stoichiometric transformations, but these studies have provided an important groundwork for later developments in both homogeneous and heterogeneous catalysis.

There are some surprising mechanistic similarities between organometallic reactions (e.g., CpCo(NO)₂/alkene additions, hydride transfer reactions, carbon-hydrogen bond activations) and classical organic reactions (e.g., radical chain reactions, carbene C-H bond insertions, 1,3-dipolar cycloadditions).

Collaboration with colleagues, at both Caltech and Berkeley, has been a crucial aspect of achieving progress in organometallic chemistry, its impact on allied fields, and its practical applications.

Few of the studies in this talk were initiated or first rationalized on the basis of potential practical applications. In fact, if funding had been sought on that basis (e.g., for the enediyne cyclization), it is unlikely that proposal reviewers would have taken the arguments seriously. Fundamental curiosity-driven research has frequently been the source of unpredictable results leading to long range intellectual and practical benefits.
Sources of Support

- National Science Foundation
- National Institutes of Health
- Department of Energy/Lawrence Berkeley National Laboratory
- Camille and Henry Dreyfus Foundation
- Research Corporation
- American Chemical Society (Cope Award Fund, Petroleum Research Fund)
- California Institute of Technology; University of California, Berkeley
Mentors

Prof. Jerome A. Berson
Yale University

Prof. Ronald Breslow
Columbia University
<table>
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<tr>
<th>Name</th>
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<td>Lutz Ackermann</td>
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SOLDIER
STATESMAN
AUTHOR
PATRIOT
BUT STILL
A DISAPPOINTMENT
TO HIS MOTHER

Richter, M., New Yorker, May 7, 1984