Non-Classical Carbocations

Nate Dow
Group Meeting Literature Talk
June 30th, 2021
Outline

- Fundamentals of non-classical carbocations: bonding, reactivity and common examples
- How it all began: the 2-norbornyl cation debate
- Non-classical reactivity in action: biosynthesis and reactions of complex molecules
- Modern developments in non-classical carbocation chemistry
  - enantioselective transformations (List/Schreiner)
  - intermolecular non-classical interactions in C–H activation (Nelson)
Non-classical carbocations: the basics

non-classical carbocation: cations that receive stabilization via charge delocalization into adjacent C–H or C–C σ-bonds
Non-classical carbocations: the basics

commonly encountered forms of carbocation stabilization

lone pair stabilization

π-bond stabilization

σ-bond stabilization

traditional resonance

anchimeric assistance

allylic + benzylic resonance

C–H + C–C hyperconjugation

non-classical stabilization

Non-classical carbocations: the basics

- applies specifically to C–C and C–H σ-bond donation
- full charge delocalization across participating filled/empty orbitals; all atoms involved bear charge and electrophilic character

anchimeric assistance

C–H + C–C
hyperconjugation

single sites of reactivity

non-classical stabilization

multiple reactive sites

The 3-center, 2-electron bond

diborane: prototypical example of 3-center, 2-electron bonding

The 3-center, 2-electron bond

The 3-center, 2-electron bond

The 3-center, 2-electron bond

- best described as 3-center, 2-electron bonding in all resonance forms
- all participating C atoms are pentavalent AND electron-deficient

Carbenium vs. carbonium ions for simple systems

3-center, 2-electron bonding description applies to numerous cases that appear to be carbenium ions

carbenium: trivalent C-centered cation  vs.  carbonium: pentavalent C-centered cation

case study: ethyl cation

expectation: hyperconjugation moderately stabilizes carbenium ion
Carbenium vs. carbonium ions for simple systems

3-center, 2-electron bonding description applies to numerous cases that appear to be carbenium ions

carbenium: trivalent C-centered cation  vs.  carbonium: pentavalent C-centered cation

\[
\begin{align*}
C_2H_3D_2^+ & \quad + \quad \text{Alk–D} \quad \rightarrow \quad C_2H_3D_3 \\
C_2H_2D_3^+ & \quad \quad \text{Alk–H} \quad \quad \text{various isomers}
\end{align*}
\]

ethyl cation precursor  \quad \quad H^+/D^- donor

<table>
<thead>
<tr>
<th>CD_3CH_2I</th>
<th>\quad i-C_4H_{10}</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH_3CD_2I</td>
<td>\quad i-C_4D_{10}</td>
</tr>
<tr>
<td>CD_3CH_2Br</td>
<td>\quad c-C_5H_{10}</td>
</tr>
</tbody>
</table>

if carbenium predominates, direct \(H^+/D^-\) transfer should provide one isomer

Carbenium vs. carbonium ions for simple systems

3-center, 2-electron bonding description applies to numerous cases that appear to be carbenium ions

carbenium: trivalent C-centered cation vs. carbonium: pentavalent C-centered cation

\[
\begin{array}{ccc}
\text{C}_2\text{H}_3\text{D}_2^+ & + & \text{Alk–D} \\
\text{C}_2\text{H}_2\text{D}_3^+ & + & \text{Alk–H}
\end{array}
\]

\[
\text{C}_2\text{H}_3\text{D}_3 \\
\text{various isomers}
\]

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<th>ethyl cation precursor</th>
<th>(H^+/D^-) donor</th>
<th>% CD_2HCDH_2</th>
<th>% CD_3CH_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD_3CH_2I</td>
<td>(i)-C_4H_{10}</td>
<td>89%</td>
<td>11%</td>
</tr>
<tr>
<td>CH_3CD_2I</td>
<td>(i)-C_4D_{10}</td>
<td>90%</td>
<td>10%</td>
</tr>
<tr>
<td>CD_3CH_2Br</td>
<td>c-C_5H_{10}</td>
<td>90%</td>
<td>10%</td>
</tr>
<tr>
<td>CD_3CH_2CD_3 (via electron-beam radiolysis)</td>
<td>c-C_4H_8</td>
<td>90%</td>
<td>10%</td>
</tr>
</tbody>
</table>

Carbenium vs. carbonium ions for simple systems

3-center, 2-electron bonding description applies to numerous cases that appear to be carbenium ions

isotopic scrambling consistent with hypervalence, delocalized intermediate

low barrier carbenium/carbonium interconversion

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Carbenium vs. carbonium ions for simple systems

3-center, 2-electron bonding description applies to numerous cases that appear to be carbenium ions

isotopic scrambling consistent with hypervalence, delocalized intermediate

low barrier carbenium/carbonium interconversion

greater degree of substitution: higher interconversion barrier, carbenium favored

Carbenium vs. carbonium ions for simple systems

3-center, 2-electron bonding description applies to numerous cases that appear to be carbenium ions

isotopic scrambling consistent with hypervalence, delocalized intermediate

low barrier carbenium/carbonium interconversion

consistent with carbonium behavior observed in rearrangements and hydride shifts

2°, carbenium less stable

3°, thermodynamically favored

Carbenium vs. carbonium ions for simple systems

3-center, 2-electron bonding description applies to numerous cases that appear to be carbenium ions

isotopic scrambling consistent with hypervalence, delocalized intermediate

low barrier carbenium/carbonium interconversion

consistent with carbonium behavior observed in rearrangements and hydride shifts

3°, carbenium already stable

2°, uphill rearrangement

Carbonium ions via alkane protonation

Olah, Conroy, Lewis, Symons:

\[ \text{H}^+ + \text{Me} \xrightarrow{\text{superacid}} \text{Me} \xrightarrow{\text{protonation}} \text{Me} \xrightarrow{\text{dissociation}} \text{Me} + \text{H}_2 \]

Hogeveen, Gaasbeek, Bickel:

\[ \text{H}^+ + \text{Me} \xrightarrow{\text{linear}} \text{Me} \xrightarrow{\text{trajectory}} \text{Me}^+ \]

- no possibility to form methine-deuterated isobutane when using D-labeled acid (H–D gas in low [ ])
- should not be capable of C–C bond protonation

Carbonium ions via alkane protonation

Olah (1971):

\[
\text{H}^+ + \text{Me}_3\text{C} = \text{Me} \xrightarrow{\text{superacid}} \text{Me}_3\text{C}^+ \xrightarrow{\text{protonation}} \text{Me} + \text{Me} + \text{Me} \xrightarrow{\text{dissociation}} \text{Me} + \text{Me} + \text{Me} + \text{H}_2
\]

\[
\text{DSO}_3\text{F-SbF}_5 \quad \text{or} \quad \text{DF-SbF}_5 + \text{Me}_3\text{C} \xrightarrow{\text{superacid}} \text{Me}_3\text{C}^+ \xrightarrow{\text{deuteration}} \text{Me} + \text{Me} + \text{Me} + \text{D/H}
\]

- D-incorporation only at methine of recovered isobutane, Me groups unlabeled
- tert-butyl carbocation stable under conditions, no evidence of olefin formation

Carbonium ions via alkane protonation

Olah (1971):

\[ \text{H}^+ + \text{Me}_3\text{CH} \rightarrow \text{Me}_3\text{C}^+ + \text{H}_2 \]

Path 1: \( \text{H}_2 \) dissociation

\[ \text{DSO}_3\text{F} - \text{SbF}_5 \text{ or } \text{DF} - \text{SbF}_5 + \text{Me}_3\text{CH} \rightarrow \text{Me}_3\text{C}^+ + \text{Me} \]

vs.

Carbonium ions via alkane protonation

Olah (1971):

\[
\begin{align*}
\text{H}^+ & \quad + \quad \text{Me}_3\text{C} - \text{Me} \quad \xrightarrow{\text{superacid}} \quad \text{Me}_3\text{C} + \text{Me} \quad \xrightarrow{\text{protonation}} \quad \text{Me}_3\text{C}^+ \quad \xrightarrow{\text{Path 1: } \text{H}_2}\quad \text{Me} - \text{C} - \text{Me} + \text{Me} \quad \xrightarrow{\text{Path 1: } \text{dissociation}} \quad \text{Me} - \text{C}^+ - \text{Me} + \text{Me} + \text{H}_2 \\
\text{C} - \text{C} & \quad \xrightarrow{\text{protonation}} \quad \text{Me}_3\text{C} - \text{Me} - \text{D} \quad \xrightarrow{\text{Path 2: } \text{methane}} \quad \text{Me} - \text{C} - \text{Me} + \text{Me} \quad \xrightarrow{\text{Path 2: } \text{dissociation}} \quad \text{Me} - \text{C}^+ - \text{Me} + \text{Me} + \text{CH}_4 \\
\end{align*}
\]

Superacid protonation of C–H and C–C σ-bonds showcases non-classical behavior in cations derived from “simple” alkanes.

Typical examples of non-classical carbocations

\[
\begin{array}{c}
\text{methonium} \\
\text{parent non-classical cation} \\
\text{computed } C_s \\
\text{symmetry} \\
\text{rapid exchange of protons, highly delocalized}
\end{array}
\]

Typical examples of non-classical carbocations

numerous variations have been proposed

methonium  cyclopropyl carbinyl

cyclopropyl carbinyl  bicyclobutonium  tricyclobutonium
Typical examples of non-classical carbocations

Typical examples of non-classical carbocations

Roberts, 1951:

\[
\begin{align*}
\text{NH}_2 & \quad \xrightarrow{\text{NaNO}_2} \quad \text{OH} \\
\text{H}_3\text{C} & \quad \xrightarrow{\text{HClO}_4 \text{ (dil. aq.)}} \quad \text{OH} \\
\end{align*}
\]

48% 47% 5%

most consistent with:

cyclopropyl carbinyl bicyclobutonium

(ignore homoallyl contribution)

Typical examples of non-classical carbocations

\[
\begin{align*}
\text{methonium} & \quad \text{cyclopropyl carbinyl} \\
\end{align*}
\]

Schleyer, 1966:

relative solvolysis rates in aq. acetone

\[
\begin{align*}
\text{ODNB} & \quad \text{ODNB} & \quad \text{ODNB} \\
\text{Me} & \quad \text{Me} \\
k_{\text{rel}} = 1 & \quad k_{\text{rel}} = 11 & \quad k_{\text{rel}} = 124 \\
\end{align*}
\]

most consistent with:

increased participation from distal ring \( C \) atoms than previous structures

Typical examples of non-classical carbocations

- Methonium
- Cyclopropyl carbinyl

p-rich nature of cyclopropane C–C bonds leads to donation more similar to olefin π-systems

Typical examples of non-classical carbocations

Tsuji, 1967:

relative solvolysis rates in aq. acetone

$cyclopropane delocalization more effective than norbornene stabilization!$

requires proper geometry for orbital overlap

Typical examples of non-classical carbocations

Winstein, 1956:

relative solvolysis rates in HOAc

\[ k_{rel} = 1 \]

\[ k_{rel} = 10^{11} \]

via:

\[ \text{\(\pi\)-donation not formally “non-classical” but often included based on degree of rate enhancement} \]

Typical examples of non-classical carbocations

methonium  cyclopropyl carbinyl  7-norbornenyl  phenonium

similar case to π-donation of olefins, not formally “non-classical” but uncommon homobenzylic delocalization

optically pure SM leads to two possible product enantiomers

**Typical examples of non-classical carbocations**

- methonium
- cyclopropyl carbinyl
- 7-norbornenyl
- phenonium

**most iconic non-classical cation: the 2-norbornyl system**
Outline

- Fundamentals of non-classical carbocations: bonding, reactivity and common examples

- How it all began: the 2-norbornyl cation debate

- Non-classical reactivity in action: biosynthesis and reactions of complex molecules

- Modern developments in non-classical carbocation chemistry
  - enantioselective transformations (List/Schreiner)
  - intermolecular non-classical interactions in C–H activation (Nelson)
Initial investigations of the 2-norbornyl cation

Wagner, turn of the 20th century:

Meerwein, 1922:

2-norbornyl rearrangements were well-established but treated as classical Wagner-Meerwein processes

Initial investigations of the 2-norbornyl cation

Winstein, 1949:

\[
\begin{align*}
\text{OBs} \\
\text{H}
\end{align*}
\]

rates and selectivity of 2-norbornyl substitution reactions
Initial investigations of the 2-norbornyl cation

Winstein, 1949:

\[
\begin{align*}
\text{KOAc} & \quad \text{HOAc} \\
\text{KOAc} & \quad \text{HOAc}
\end{align*}
\]

exclusive isomer
\(<0.02\% \text{ endo–OAc via GC}\)

\[k_{rel} = 350\]

\[k_{rel} = 1\]

enantiopure

1:1 ratio

enantiopure

Initial investigations of the 2-norbornyl cation

Winstein, 1949:

\[ \text{<exclusive isomer (}<0.02\% \text{ endo–OAc via GC)} \]

\[ k_{rel} = 350 \]

\[ k_{rel} = 1 \]

Proposal: delocalized ("bridged") carbonium intermediate;
anchimeric assistance leading to faster generation from exo-brosylate

Classical vs. non-classical: the debate begins

H. C. Brown, 1960’s:

However, Brown was also heavily invested in showcasing the role of sterics in substitution reactions:

As $X$ becomes larger, more steric strain is relieved when rehybridizing from $sp^3$ to $sp^2$

faster solvolysis and nucleophile trapping

most recognized for developments in boron-mediated transformations

Classical vs. non-classical: the debate begins

H. C. Brown, 1960’s:

most recognized for developments in boron-mediated transformations

Winstein’s report upends classical steric arguments for carbocation reactions

cations subsequently described via non-classical delocalization

reports retracted soon after

Classical vs. non-classical: the debate begins

H. C. Brown, 1960’s:

Brown enters debate to protect classical perspective as well as intellectual rigor of field

most recognized for developments in boron-mediated transformations

**Classical rationales: sterics and thermochemistry**

*H. C. Brown, 1960’s:*

Comparing exo/endo rates for acetate solvolysis:

\[
\frac{k_{\text{exo}}}{k_{\text{endo}}} = 350 \quad \frac{k_{\text{exo}}}{k_{\text{endo}}} = 140 \quad \frac{k_{\text{exo}}}{k_{\text{endo}}} = 1230
\]

3° cation better described as carbenium than carbonium;

similar magnitudes of \( \frac{k_{\text{exo}}}{k_{\text{endo}}} \) rule out dominant non-classical effect

Classical rationales: sterics and thermochemistry

H. C. Brown, 1960’s:

comparing exo/endo rates for acetate solvolysis:

\[ \frac{k_{\text{exo}}}{k_{\text{endo}}} = 350 \]

\[ \frac{k_{\text{exo}}}{k_{\text{endo}}} = 140 \]

\[ \frac{k_{\text{exo}}}{k_{\text{endo}}} = 1230 \]

rationalized exo/endo ratios purely through steric effects and strain relief

exo: relief of diaxial strain in cation enhances rate

endo: leaving group trajectory obstructed by axial substituent

**Classical rationales: steric and thermochemistry**

**H. C. Brown, 1960’s:**

Comparing exo/endo rates for acetate solvolysis:

\[
\frac{k_{\text{exo}}}{k_{\text{endo}}} = 350
\]

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\]

The 2-norbornyl cation: common ground and key energetic differences

H. C. Brown, 1960’s:

comparing exo/endo rates for acetate solvolysis:

\[
\frac{k_{\text{exo}}}{k_{\text{endo}}} = 350 \quad \frac{k_{\text{exo}}}{k_{\text{endo}}} = 140 \quad \frac{k_{\text{exo}}}{k_{\text{endo}}} = 1230
\]

beyond relative rate data, Winstein’s “enantiopure to racemic” experiment indicates cation must be migrating

enantiopure \quad \text{1:1 ratio} \quad \text{enantiopure}

How would Brown interpret this result?
The 2-norbornyl cation: common ground and key energetic differences

Brown: non-classical cation is transition state between rapidly equilibrating classical intermediates

Winstein: non-classical cation is intermediate and local energetic minimum
Characterizing a non-classical intermediate

Olah, 1960’s–1980’s:

first expert in obtaining/characterizing stable carbocations

Sb-based superacids (e.g. “magic acid” - FSO₃H•SbF₅) can reach pKa ~ –28 (10¹⁶ times more acidic than anhydrous H₂SO₄)

originally designed to prevent elimination of carbocations to olefins

Olah embraced early NMR techniques for probing reactive intermediates

Characterizing a non-classical intermediate

Olah, 1960’s–1980’s:
Saunders, Schleyer

convergence to singlet in $^1H$ NMR

rapid Wagner-Meerwein and hydride shifts

Characterizing a non-classical intermediate

Olah, 1960’s–1980’s:
Saunders, Schleyer

consistent with Wagner-Meerwein equilibration of classical cations

Characterizing a non-classical intermediate

Olah, 1960’s–1980’s:

X-ray photoelectron spectroscopy: photo-emitted electrons can be trapped by cations as core electrons

highly localized charge leads to large increases (3–5 eV) in electron binding energy ($\Delta E_b$) relative to standard tetravalent carbon

$\Delta E_b = 3.9 \text{ eV}$


Characterizing a non-classical intermediate

Olah, 1960's–1980's:

consistent with high degree of charge delocalization in 2-norbornyl cation

\[ \Delta E_b = 3.9 \text{ eV} \]

\[ \Delta E_b = 3.7 \text{ eV} \]

\[ \Delta E_b = 1.7 \text{ eV} \]


Characterizing a non-classical intermediate


Verification that delocalized 2-norbornyl cation can be long-lived and stable, suggests intermediacy

Characterizing a non-classical intermediate

even at 5 K, $^{13}$C NMR shows deshielding across multiple C atoms in 2-norbornyl cation

for classical ions related by Wagner-Meerwein shifts:

calculated Wagner-Meerwein barrier to observe process at 5 K < 0.2 kcal/mol - unreasonable!

Unambiguous proof from a crystal structure

although numerous derivatives were crystallized over decades, the 2-norbornyl structure was only solved in 2013

stable below 213 K, but solid state too disordered above 86 K for XRD
(undesired rotations and 6,1,2-hydride shifts)

BUT

rapid cooling initiates phase transition, lattice change, cracks crystal

~10 careful annealing/cooling cycles, helium-cooled diffractometer required (final temp <50 K)

Karsten Meyer: “The crystallography was a tour de force… the procedure is insane – it put us through torture”

Although numerous derivatives were crystallized over decades, the 2-norbornyl structure was only solved in 2013.

Unambiguous proof from a crystal structure

Highly symmetric, with two C–C bond orders <1 and one C–C bond with double-bond character.

Unambiguous confirmation of the non-classical nature of the 2-norbornyl cation.

Looking back: who came out on top?

**winners:** Weinstein, Olah, Schleyer, Saunders, Roberts, etc.  
**losers:** primarily Brown

although these debates resulted in numerous experimental advances, the discourse was notoriously hostile


“It was hoped that [the non-classical evidence] would put an end to the prolonged ‘nonclassical ion controversy’. The controversy, however, was kept alive by Brown… any further continuation of the classical-nonclassical ion controversy seems to be a futile exercise of semantics and not of relevant experimental facts.”

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“Invariably, the arguments and evidence [for non-classical behavior] have crumpled after careful study…[the 2-norbornyl cation] clearly does not have the non-classical stabilization energy that has been postulated for so long… it ill befits serious scientific workers in this area to ignore [our] data and results.”

Looking back: who came out on top?

**winners:** Winstein, Olah, Schleyer, Saunders, Roberts, etc.

**losers:** primarily Brown

John D. Roberts, who coined the term “non-classical ion”

when asked at age 95 whether the 2013 crystal structure would have caused Brown to reconsider his position:

“Herb would be Herb no matter what happened.”
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Non-classical biosynthetic pathways

Computational modeling identified competent non-classical transition states/intermediates that lead to additional products.

Non-classical biosynthetic pathways

\[ \text{double Prins} \rightarrow \text{tandem hydride shift} \rightarrow \text{ring-expanding Wagner-Meerwein} \rightarrow \Delta^6\text{-protoilludene} \]

Non-classical biosynthetic pathways

computational modeling identified competent non-classical transition states/intermediates that lead to additional products

Non-classical approaches in total synthesis

Johnson, 1975:

Uncommon rearrangements on complex substrates

macrolide ring contractions via deoxygenative fluorination

DAST, CH₂Cl₂
73% yield

cyclopropyl carbinyl-type cation

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Enantiocontrol in non-classical carbocation reactions

List and Schreiner, 2020:

numerous modern methods for enantiocontrol

no known strategies for enantioinduction with σ-delocalized cations

- H-bond donor catalysis (i.e. squaramides)
- host-guest catalysis (supramolecular)
- Brønsted acid catalysis

Enantiocontrol in non-classical carbocation reactions

List and Schreiner, 2020:

- H-bond donor catalysis (i.e. squaramides)
- Host-guest catalysis (supramolecular)
- Brønsted acid catalysis

strategy: entrap intermediate in chiral ion pair “binding pocket”

"The reverse Winstein"

Winstein, 1949:

\[ \text{enantiopure} \quad \xrightarrow{\text{KOAc}} \quad \text{enantiopure} \]

1:1 ratio


"The reverse Winstein"
"The reverse Winstein"

80% yield

97:3 er in both cases

84% yield

using racemic substrate, same conditions: 86% yield, 97:3 er

catalyst and leaving group optimization critical

other Brønsted acids produced conjugate bases capable of adding directly to 2-norbornyl cation

Enantiocontrol in non-classical carbocation reactions

norbornene protonation:
81% yield, 92:8 er

Prins cyclization/EAS:
77% yield, 87:13 er

C–C activation:
92% yield, 92:8 er

$Si^+$ fluoride abstraction: 89% yield, 92:8 er

Imidodiphosphorimidate catalyst

Enantiocontrol in non-classical carbocation reactions

isotopic labeling studies uninformative

Recall - Olah, 1964:

similar scrambling consistent with non-classical intermediate

Enantiocontrol in non-classical carbocation reactions

DFT suggestive of anionic stabilization of three electrophilic positions in non-classical cation

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C–H insertion by aryl cations

Nelson, 2017:

C–H insertion by aryl cations

Nelson, 2017:

$\text{[Ph}_3\text{C}^+\text{[WCA}^-\)] (5 \text{ mol}%)$
$(\text{-Pr})_3\text{SiH (10 mol%)}$

$\text{[WCA}^-\] = [\text{HCB}_{11}\text{Cl}_{11}]^-$

arylation  alklylation  methylation  cyclization

C–H insertion by aryl cations

_Nelson, 2017:_

\[
[\text{Ph}_3\text{C}^+][\text{WCA}^-] \text{ (5 mol\%)} \\
(i-\text{Pr})_3\text{SiH} \text{ (10 mol\%)}
\]

\[
[WCA^-] = [\text{HCB}_{11}\text{Cl}_{11}]^-
\]

_notable observations_

C–H insertion by aryl cations

Nelson, 2017:

\[
[\text{Ph}_3\text{C}^+][\text{WCA}^-] \text{ (5 mol\%)} \quad \text{and} \quad (i-\text{Pr})_3\text{SiH (10 mol\%)}
\]

\[
[WCA^-] = [\text{HCB}_{11}\text{Cl}_{11}]^-
\]

notable observations

alkane = cyclohexane-\text{d}_{12}

C–H insertion by aryl cations

**Nelson, 2017:**

\[
\begin{align*}
&\text{[Ph}_3\text{C}^+\text{[WCA}^-] \text{ (5 mol\%)} \quad \text{([i-Pr]}_3\text{SiH (10 mol\%)} \\
&\quad \text{[WCA}^-] = [\text{HCB}_{11}\text{Cl}_{11}]^-
\end{align*}
\]

**notable observations**

\[
\text{alkane} = \text{cyclohexane-d}_{12} \\
+ \text{cyclohexane (1:1)}
\]

\[
k_H/k_D = 1.08
\]

**non-rate-limiting C–H insertion?**

C–H insertion by vinyl cations: evidence of a non-classical mechanism

Nelson, 2018:

\[
[\text{Ph}_3\text{C}]^+[\text{WCA}^-] \text{ (2 mol\%)} \quad \text{Et}_3\text{SiH (1.5 equiv.)}
\]

\[
\text{H} \quad 87\% \text{ yield}
\]

initial mechanistic proposal

C–H insertion by vinyl cations: evidence of a non-classical mechanism

DFT (w/ Ken Houk):

\[
\begin{align*}
\text{cis-cyclooctene} & \rightarrow \text{cis-1,2-dihydroy)cyclooctene}^+ \xrightarrow{H^- \text{transfer}} \text{trans-1,2-dihyrdroy)cyclooctene}^+ \xrightarrow{\text{H}^+} \text{trans-2,2-dihyrdroy)cyclooctene}^+ \\
\end{align*}
\]

unexpected finding that reaction depends on non-classical intermediates and favors geminal (1,1) insertion

hydride shifts still possible prior to reduction, resulting in scrambling of (1,1) arrangement

C–H insertion by vinyl cations: evidence of a non-classical mechanism

Nelson, 2018:

\[
\text{[Ph}_3\text{C}^+\text{[WCA}^-\text{]} (2 \text{ mol\%}) \rightarrow \text{Et}_2\text{Si–D} (1.5 \text{ equiv.})}
\]

\[\text{only product}\]

\[\text{[WCA}^-\text{]} = [\text{HCB}_{11}\text{Cl}_{11}]^-\]

(1,1) intermediate

C–H insertion by vinyl cations: evidence of a non-classical mechanism

Nelson, 2018:

\[
[\text{Ph}_{3}C]^+ [\text{WCA}^-] \text{ (2 mol\%)} \quad \text{Et}_3\text{SiH (1.5 equiv.)}
\]

[\text{WCA}^-] = [\text{HCB}_{11}\text{Cl}_{11}]^-

67% D/H
65% D/H
35% D/H

will not shift (3° to 2°)
either H or D could shift (2° to 3° or benzylic)

expect 100% D-incorporation
expect H/D mixture

1,2-insertion
1,1-insertion

favored

C–H insertion by vinyl cations: evidence of a non-classical mechanism

*Nelson, 2018:*

\[
[\text{Ph}_3\text{C}]^+\text{[WCA}^-] (2 \text{ mol%}) \quad \text{Et}_3\text{SiH (1.5 equiv.)}
\]

\[
\text{Ph} \quad \text{D}
\]

\[
\text{H} \quad \text{H}
\]

\[
\text{H} \quad \text{D}
\]

\[
\text{Ph} \quad \text{D}_x
\]

\[
88\% \quad 12\%
\]

\[
\text{D}/\text{H} \quad \text{D}/\text{H}
\]

\[
\text{[WCA}^-] = \text{[HCB}^{11}\text{Cl}_{11}]^-
\]

*intermediate must be highly stabilized (i.e. non-classical) if formation of benzylic cation is slow*

C–H insertion by vinyl cations: evidence of a non-classical mechanism

Nelson, 2018:

\[ [\text{Ph}_3\text{C}]^+[\text{WCA}^-] (2 \text{ mol\%}) \]
\[ \text{Et}_3\text{SiH} (1.5 \text{ equiv.}) \]

\[ \text{[WCA}^-] = [\text{HCB}_{11}\text{Cl}_{11}]^- \]

Trends hold for additional cases (i.e. intramolecular, transannular)

C–H insertion by vinyl cations: evidence of a non-classical mechanism

New intermolecular reactivity can be obtained via non-classical interactions of “naked” carbocations