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Reactivity of Alkynyl Metal Carbenoids: DFT Study on the Pt-Catalyzed Cyclopropanation of Propargyl Ester Containing 1,3-Diynes

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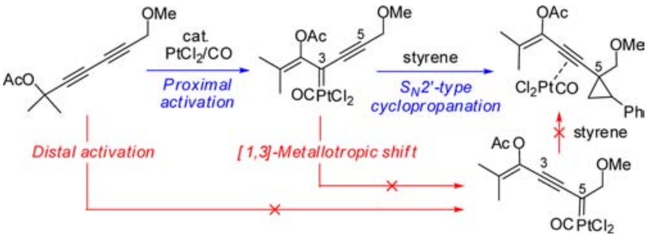
ABSTRACT



DFT/M06 calculations were performed to investigate the mechanism of the Pt-catalyzed intermolecular cyclopropanation of propargyl ester containing diynes with styrene. The results show that the alkynyl Pt-carbenoid formed from proximal activation of the diyne is a more favorable productive intermediate for cyclopropanation, which occurs preferentially at the distal *sp*-hybridized carbon via an S_N2'-type olefin addition. Notably, the widely accepted [1,3]-metallotropic shift of such an alkynyl metal carbenoid is found to be energetically demanding.

The past decade has witnessed rapid developments of alkyne transformations under the catalysis of gold,[1] platinum,[2] and other carbophilic Lewis acids.[3] The metal carbenoids are generally involved as intermediates in these reactions are generated from an intra- or intermolecular addition of nucleophiles to the metal-activated C–C triple bond.[4] The propargyl acetate represents a class of versatile precursors that could be easily converted into compounds of increased molecular complexity in the presence of a catalytic amount of late transition metal complexes.[5] The latent carbene and allene reactivities of these precursors under both gold and platinum catalysis have been well established by recent experimental[6] and theoretical studies.[4d,7]

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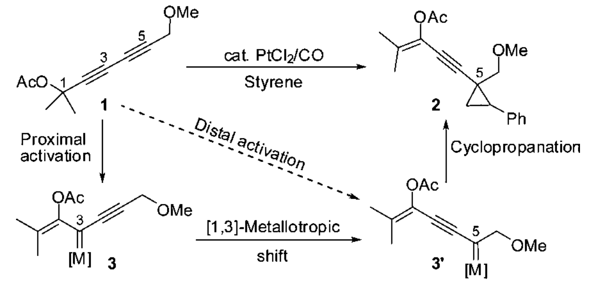
For 1,3-diynes containing propargyl ester, a metal-triggered 1,2-acyl migration would form an alkynyl metal carbenoid as a putative intermediate. Employment of this reactive species had lead to a number of novel tandem reactions, including cyclopropanation.[8] In this regard, the Lee group studied Pt-catalyzed reactions of propargylic acetoxy-1,3-diynes containing a propargylic alkoxyl group. They found diynyl ester **1** exhibited distinct reactivity toward intermolecular cyclopropanation with styrene, which is different from the reaction of monoynyl counterparts (Scheme 1).[8a] The proposed mechanism implies that carbenoid **3** formed from the proximal activation of diyne **1** will rearrange to carbenoid **3′** via a facile [1,3]-metallotropic shift, which in turn undergoes cyclopropanation at the C5 carbon, providing the observed product **2**.[8] Yet, the possibility for direct formation of carbenoid **3′** via the distal activation pathway from **1** could not be excluded.

Scheme 1. Pt-Catalyzed Cyclopropanation of Propargyl Ester Containing 1,3-Diyne and Plausible Mechanism



Although a great deal of effort has been devoted into the synthetic application of 1,3-diyne precursors, and the involvement of [1,3]-metallotropic shift of the putative alkynyl carbenoids is generally accepted,[9,10] considerably less is known about the detailed mechanism of the process. In most cases, the migration of the carbenoids along an extended alkyne system via a metallotropic [1,3]-shift was deduced from the structure of observed products. In the current report, DFT calculations at the M06/6-31+G** (LANL2DZ) level[11] were carried out to study the mechanism of the Pt-catalyzed cyclopropanation of propargylic acetoxy-1,3-diyne systems with styrene, with an emphasis on understanding the generation, property, and reactivity of the putative alkynyl Pt-carbenoid intermediates. This study offers an alternative mechanistic interpretation excluding the [1,3]-metallotropic shift of alkynyl metal carbenoids and thus, it should provide insight to better understand related reactions.[8−10,12]

We assumed that the tetracoordinated $PtCl_2(CO)_2$ would be first formed in the $PtCl_2$/CO catalytic system, and the dissociation of one CO will generate the active $PtCl_2(CO)$ with a vacant site for substrate coordination. The computational results in Figure 1 indicate the CO dissociation from $PtCl_2(CO)_2$ is endergonic by 17.1 kcal/mol. According to the mechanism in Scheme 1, the electrophilic activation of diyne **1** by platinum could be possibly initiated via both the proximal and distal activation pathways, by coordination of the proximal and distal C−C triple bonds to the platinum catalyst, respectively. Figure 1 shows the π-complex **IN1** in the proximal activation is about 14.2 kcal/mol higher in energy than the starting point, and the 5-exo-dig attack of the acetoxy moiety to the C2 position via **TS1** requires a barrier of only 5.3 kcal/mol for converting **IN1** into a more stable cyclic intermediate **IN2**. The subsequent cleavage of the C1−O bond via **TS2** presents a barrier of 6.5 kcal/mol to afford alkynyl Pt-carbenoid **3** slightly exergonically. The Pt-atom in this intermediate is connected to the C3 of the diyne precursor while the C4−C5 triple bond remains intact. Alternatively, the distal activation from **IN1′** could also trigger the stepwise 1,2-acyl migration, but a higher activation barrier of 9.3 kcal/mol is required. The geometries of **TS1′**, **IN2′**, and **TS2′** in this latter process show that the conjugated diyne moiety of the precursor is turned into cumulene structures during the 1,2-acyl migration (Figure 1). In Pt-carbenoid **3′** the C5 is bonded to the Pt-atom and a new triple bond is located between C3 and C4.

The geometric and electronic structures of **3** and **3′** (Figure 1) show that the unsaturated fragments of these carbenoids are highly conjugated to each other with the lengths of C2−C3 (1.406 Å) and C3−C4 (1.384 Å) in **3** and C2−C3 (1.389 Å) and C4−C5 (1.354 Å) in **3′** being shorter than typical C−C single bonds. The distances for the Pt−C3 in **3** and the Pt−C5 in **3′** are slightly longer than 2.0 Å with bond orders around 0.6. NPA charges indicate the carbenoid carbons are almost electrically neutral, and most of the positive charges are populated on C1 and C2

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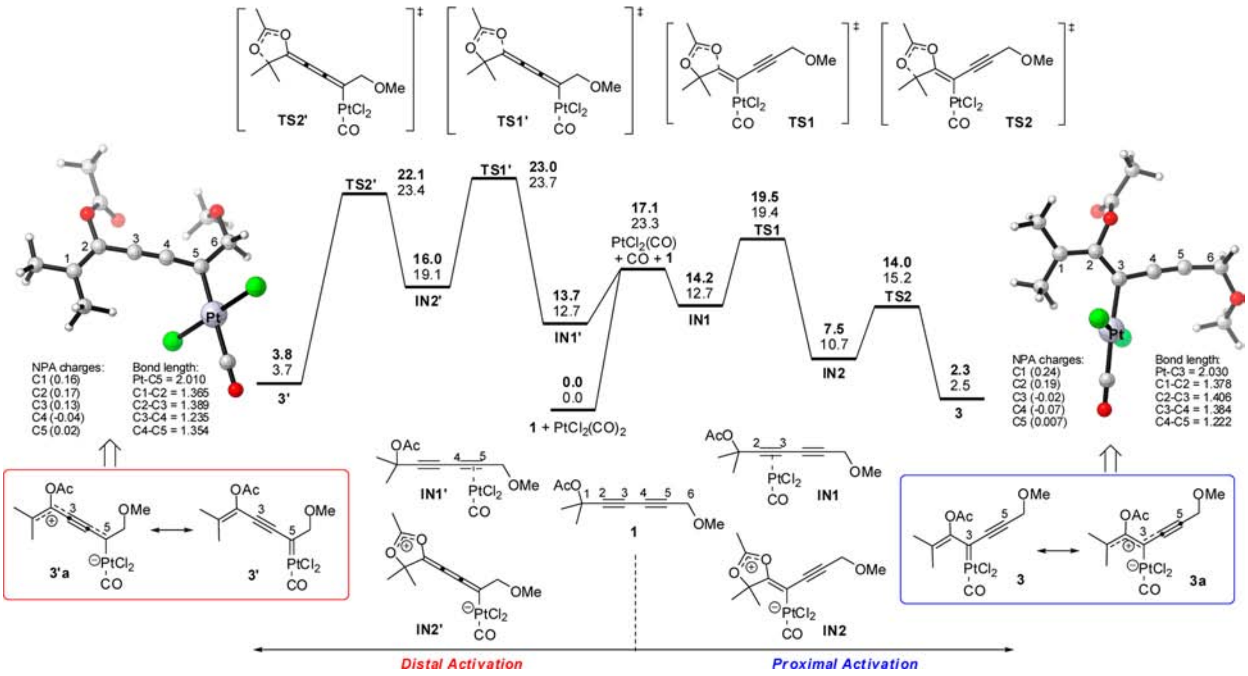
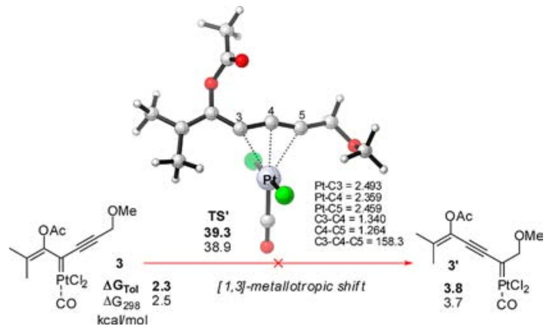


Figure 1. Energy profile for the generations of alkynyl Pt-carbenoids from 1,2-acyl migrations of **1**. Relative free energies in the toluene solution (bold) and in the gas phase (plain) are in kcal/mol. Bond lengths are in Å.

Scheme 2. [1,3]-Metallotropic Shift of **3** and **3′**

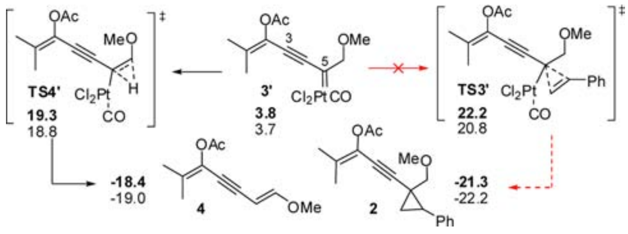


atoms. Thus, the structures of these carbenoids should be depicted more accurately as the zwitterionic mesomeric forms **3a** and **3′a**, in which the carbenoid carbons are singly bonded to the Pt-atoms and the positive charges are delocalized over the conjugative π-systems.

The above results suggest that alkynyl Pt-carbenoid **3** would be both more kinetically and thermodynamically favorable than **3′**. However, both the proximal and distal activation pathways are reversible, since **3** and **3′** are slightly higher in energies than the free reactant and catalyst. Thus, which to become the major reaction channel would depend on the energy barriers of subsequent reaction steps from both **3** and **3′**.

The interconversion between **3** and **3′** via the proposed [1,3]-metallotropic shift was first studied. The results in Scheme 2 show this process requires a very high activation energy of 37.0 kcal/mol. We reasoned that this outcome should be attributed to the strained geometry of **TS′**, in which the shifting Pt-atom interacts almost equally with all C3, C4, and C5 atoms. This leads to a bent allene-like framework with the C3−C4−C5 angle being 158.3°, making the [1,3]-metallotropic shift for generation of carbenoid **3′** from **3** very difficult to occur.[13]

Scheme 3. 1,2-H Shift versus Cyclopropanation of **3′**



To further confirm whether **3′** is a productive intermediate that leads to the C5-cyclopropanated product **2**, the possible 1,2-H shift and intermolecular cyclopropanation toward C5 of **3′** are given in Scheme 3. The results show that the [2 + 1] cycloaddition of **3′** with styrene could be realized via **TS3′**, which has a relative energy of 22.2 kcal/mol and will lead to the experimentally observed product **2**

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(13) Another possibility for this interconversion suggested by a reviewer involves an intermolecular reaction between **3** and another molecule of $PtCl_2CO$.[11] However, this mechanism should be unfavorable due to the low concentrations of both species under the current catalytic conditions with only 5% $PtCl_2$.

irreversibly. However, the calculated energy for the 1,2-H shift via **TS4′** is about 3 kcal/mol lower than that via **TS3′**, predicting the generation of 1,5-diene-3-yne **4** to be more favorable. These results contradict the experimental observations by Lee et al.[8a] and imply the cyclopropanation product could not be formed from intermediate **3′**.

In search of a better mechanism that corroborates the experimental results, the reactivity of carbenoid **3** was next investigated. The results in Figure 2 show the direct cyclopropanation at the carbenoid carbon (C3) via **TS3** demands a relatively high energy of 29.4 kcal/mol. This should be the consequence of the conjugative effect of the alkenyl and alkynyl substituents on C3, which reduces the electrophilicity at this position. Besides, the higher steric effect imposed by these substituents should also disfavor the cyclopropanation via **TS3**. We envisioned that the C5 center of **3**, conjugated with the carbenoid moiety and carrying a net positive charge of 0.007 (Figure 1), should be a possible reactive site.[14] Calculations show that the 1,2-H shift from C6 to C5 via **TS4** is even higher in energy than **TS3**, suggesting that the 1,5-diene-3-yne **4** should not be derived from intermediate **3**. Instead, the intermolecular [2 + 1] addition of olefin to C5 through an S_N2'-type attack would be much more favorable.[15] In this process, the styrene addition is achieved via **TS5** with an activation barrier of 18.6 kcal/mol, leading to product complex **IN3** exergonically. The transition structure **TS5** could be easily reached from **3** and styrene, which has relatively long incipient C7−C5 and C8−C5 bonds with distances of 2.244 and 2.646 Å, respectively, and only a small geometric change of the carbenoid moiety.

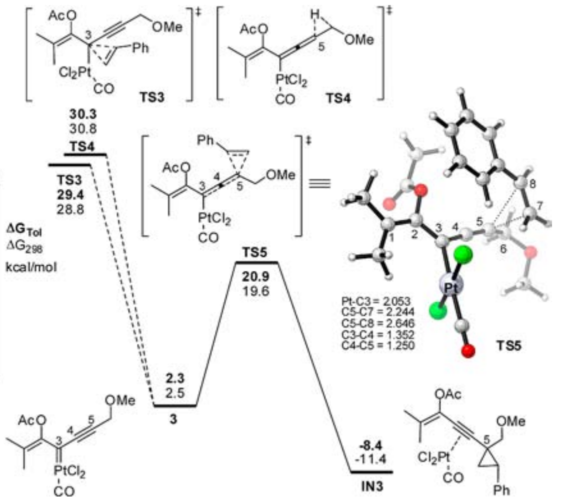

Figure 2. Reaction profile of **3** in cyclopropanation.

The energy of **TS5** is 1.4 kcal/mol higher than that of **TS1** (Figure 1), making the 1,2-acetoxy migration in the proximal activation pathway reversible. However, **TS5** is still 2.1 kcal/mol lower in energy than **TS1′**, which is the rate-determining transition state of the distal activation pathway. This energetic scenario, combined with the results in Scheme 3, can eliminate the involvement of alkynyl Pt-carbenoid **3′** from the reaction.

To further explore the implications of this new mechanism, calculations were carried out for the Au(I)-catalyzed cyclopropanation reaction of 1,3-diynyl ester with styrene by Toste et al.[8b] The calculated energy profile (see Supporting Information) supports the new mechanism described above; the alkynyl metal carbenoid from the proximal activation of the diyne precursor has a lower activation barrier, and the [1,3]-metallotropic shift is highly unfavorable. Instead, the C5 cyclopropanated product could be formed by a facile S_N2'-type olefin addition. Although the isomeric alkynyl metal carbenoid formed from the distal activation could also afford the observed product via direct addition of styrene to the carbenoid carbon of C5, a higher activation barrier rules out this reaction channel. Thus, the S_N2'-type cyclopropanation of the alkynyl metal carbenoid seems to be general for both Au- and Pt-catalyzed reactions.[8]

In summary, DFT calculations on the platinum-catalyzed intermolecular cyclopropanation reactions of proparylic acetoxy-containing 1,3-diynes with styrene revealed that the proximal activation of the 1,3-diyne ester is more favorable than the distal activation. Cyclopropanation occurs preferentially via an S_N2'-type addition of olefin to the distal *sp*-hybridized carbon of the alkynyl metal carbenoid. On the other hand, the carbenoid carbon is less reactive as a result of electronic and steric effects of the alkenyl and alkynyl substituents. This should provide new mechanistic insights into a number of related reactions.[8] Another finding of this study is that the previously proposed [1,3]-metallotropic shift of alkynyl metal carbenoids was found to be energetically demanding, thus posing interesting questions about the actual mechanisms of other systems where a [1,3]-metallotropic shift was suggested.[9,10,12] Ongoing research in our laboratories will explore other mechanism alternatives to the [1,3]-metallotropic shift in transformations of 1,3-diynes.

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Supporting Information Available. Computational details and results. This material is available free of charge via the Internet at http://pubs.acs.org.

The authors declare no competing financial interest.

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(15) Calculations predict carbenoid **3′** could undergo a smilar [2 + 1] cycloaddition at C3, and the energy of this cyclopropanation TS is 0.3 kcal/mol lower than **TS4′**.[11]