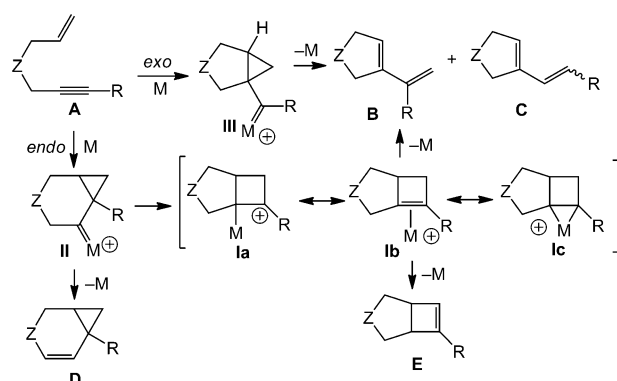


Cycloaddition

Direct Observation of a Cationic Gold(I)–Bicyclo[3.2.0]hept-1(7)-ene Complex Generated in the Cycloisomerization of a 7-Phenyl-1,6-enyne**

Rachel E. M. Brooner, Timothy J. Brown, and Ross A. Widenhoefer*

The cycloisomerization of enynes catalyzed by electrophilic noble-metal complexes,^[1] in particular Au and Pt,^[2] has attracted considerable attention owing to the formation of skeletal rearrangement products, including vinylcyclopentenes (**B** and **C**), bicyclo[4.1.0]heptenes (**D**), and bicyclo[3.2.0]hept-6-enes (**E**) from 1,6-enynes (**A**; Scheme 1).^[3,4]



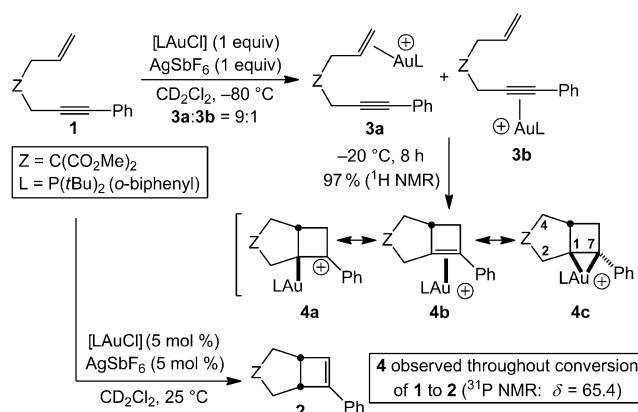
Scheme 1. Ligand- and substrate-dependent pathways for enyne cycloaddition catalyzed by electrophilic noble-metal complexes.

Fürstner first posited that these outcomes were consistent with the intermediacy of metal-stabilized nonclassical cyclopropylmethyl-, cyclobutyl-, and homoallylic carbocations/carbenes accessed through attack of the C=C moiety on a metal-complexed C≡C bond (Scheme 1),^[5] and mechanistic thought in this area has evolved largely within this conceptual framework. The involvement of nonclassical carbocations/carbenes is supported by a wealth of indirect experimental evidence, including trapping experiments, isotopic labeling studies, and stereochemical analyses, and through numerous computational studies.^[1,2] Absent, however, is direct experimental evidence regarding the structure and reactivity of

these cationic complexes, as no organometallic intermediate has been observed spectroscopically in any of these transformations.^[6–10]

Platinum(II),^[11] gold(I),^[12,13] and rhodium(II)^[14] complexes catalyze the cycloisomerization of 7-aryl-1,6-enynes (**A**, R = Ar) to form vinylcyclopentenes **C** and/or bicyclo[3.2.0]hept-6-enes **E** (Scheme 1). Directly implicated in these and related^[15,16] transformations is the strained bicyclo[3.2.0]hept-1(7)-ene species **I**, presumably generated through 6-endo-cyclization followed by 1,2-alkyl migration from cyclopropyl carbene **II** and consumed either by ring opening to form **B** and/or 1,3-hydrogen migration to form **E** (Scheme 1).^[11–14] Possible contributors to **I** include the metalated cyclobutyl carbenium ion **Ia**, the π -alkene complex **Ib**, and the metallacyclopropane complex **Ic**. In this context, it appeared likely that contribution of the latter forms would engender stability to **I** not realized in the corresponding cyclopropyl carbene intermediates **II** or **III**, such that **I** might represent a local minimum on the reaction coordinate. Indeed, here we report the selective generation, spectroscopic characterization, and reactivity analysis of a gold–bicyclo[3.2.0]hept-1(7)-ene complex formed in the gold-catalyzed cycloisomerization of a 7-phenyl-1,6-enyne.

Toward detection of a reactive bicyclo[3.2.0]hept-1(7)-ene complex, we investigated the gold(I)-catalyzed conversion of the 7-phenyl-1,6-enyne **1** into the 6-phenylbicyclo[3.2.0]hept-6-ene **2** reported by Echavarren (Scheme 2).^[12] In an initial experiment, a 1:1:1 mixture of **1**, [LAuCl] (L = P(*t*Bu)₂(*o*-biphenyl)), and AgSbF₆ in CD₂Cl₂ was mixed thoroughly at –78 °C. ³¹P and ¹H NMR analysis at –80 °C showed formation of an approximately 9:1 mixture of π -alkene and π -alkyne



Scheme 2. Gold-mediated conversion of **1** into **4**.

[*] R. E. M. Brooner, T. J. Brown, Prof. R. A. Widenhoefer
French Family Science Center, Duke University
Durham, NC 27708–0346 (USA)
E-mail: rwidenho@chem.duke.edu

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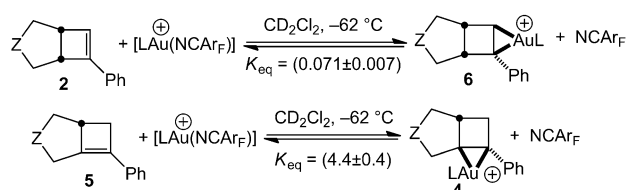
complexes **3a** and **3b** that together constituted around 90 % of the reaction mixture (Scheme 2).^[17–19] When this solution was warmed at -20°C for 8 h, **3a** and **3b** were consumed to form the gold–7-phenylbicyclo[3.2.0]hept-1(7)-ene complex **4** in 97 % yield (^1H NMR spectroscopy).^[17] Complex **4** was likewise the only phosphine-containing species observed by ^{31}P NMR spectroscopy ($\delta = 65.4$) during the catalytic conversion of **1** into **2** (Scheme 2).

Complex **4** was thermally unstable and was characterized in solution at or below -20°C by NMR spectroscopy and by comparison with free 7-phenylbicyclo[3.2.0]hept-1(7)-ene **5** (see below).^[20] Coordination of gold to the C1–C7 bond of the bicyclo[3.2.0]heptene ligand was established by the large upfield shift ($\Delta\delta = -20$) of the C1 carbon atom of **4** relative to **5** and by the presence of phosphorous coupling to both the C1 ($\delta = 126.9$; $J_{\text{CP}} = 13.8$ Hz) and C7 carbon atom ($\delta = 141.2$; $J_{\text{CP}} = 7.5$ Hz) of the bicycloheptene ligand of **4** in the ^{13}C NMR spectrum. ^1H – ^1H NOESY analysis established binding of the $[\text{LAu}]^+$ fragment to the convex face of the bicycloheptene ligand. Regarding the electronic structure of **4**, the C7 ($\delta = 141.2$) and C7-phenyl resonances ($\delta = 131.8$, 129.1, 127.2) of **4** were shifted downfield only slightly relative to those of free **5** ($\delta = 137.59$ (C7), 128.6, 127.7, 125.0 (Ph)) in the ^{13}C NMR spectrum;^[21] this observation points to modest accumulation of positive charge at the C7 carbon atom of **4** and hence nominal contribution of the cyclobutyl cation structure **4a**. Rather, the $^1J_{\text{C1C7}}$ coupling constant of **4** ($^1J_{\text{C1C7}} = 33$ Hz) was diminished significantly relative to that of **5** ($^1J_{\text{C1C7}} = 61$ Hz),^[21] consistent with sp^3 hybridization of the C1 and C7 carbon atoms of the bicycloheptene ligand of **4**. This observation points to significant $d \rightarrow \pi^*$ back-bonding and the predominant contribution of the metallacyclopropane structure **4c** (Scheme 2).^[22] The metallacyclopropane character of **4** stands in sharp contrast to the predominant σ -bonding character of extant gold– π -alkene complexes,^[18] a discrepancy attributed to the strain associated with free **5**.^[23]

Treatment of **4** with pyridine or $n\text{Bu}_4\text{N}^+ \text{Br}^-$ (1 equiv) at -20°C led to quantitative formation of free **5** and $[\text{LAu}(\text{py})]^+$ SbF_6^- or $[\text{LAuBr}]$, respectively (Scheme 3); warming the latter solution at 25°C led to the slow ($t_{1/2} \approx 9$ h) decomposition of **5** without detectable formation of **2** or vinylcyclopentene. Conversely, warming a solution of **4** at 25°C led to rapid ($t_{1/2} \approx 16$ min) 1,3-hydrogen migration to form the thermally sensitive gold–6-phenylbicyclo[3.2.0]hept-6-ene complex **6** in 82 % yield at 85 % conversion (96 % selectivity)

without detectable formation of vinylcyclopentene (Scheme 3).^[24]

As was the case with **4**, the $^1J_{\text{C6C7}}$ coupling constant of **6** ($^1J_{\text{C6C7}} = 35$ Hz) was diminished significantly relative to that of free **2** ($^1J_{\text{C6C7}} = 63$ Hz).^[25] The strain of **2**, although attenuated relative to **5**,^[23] is apparently sufficient to significantly bias the gold–alkene bond of **6** toward the metallacyclopropane structure. However, the lower strain of **2** relative to **5** was evidenced by the about 60-fold lower binding affinity of **2** to the $[\text{LAu}]^+$ fragment relative to that of **5**, determined by displacement of the weak σ -donor ligand NCAr_F ($\text{NCAr}_F = \text{NC-3,5-C}_6\text{H}_3(\text{CF}_3)_2$) from $[\text{LAu}(\text{NCAr}_F)]^+ \text{SbF}_6^-$ (Scheme 4).^[26] The higher binding affinity of **5** relative to **2** is significant, considering that the binding affinity of the trisubstituted alkene 2-methyl-2-butene to $[\text{LAu}]^+$ is approximately 350 times greater than is that of the tetrasubstituted alkene 2,3-dimethyl-2-butene.^[18]



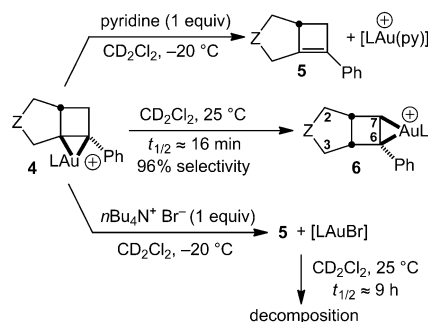
Scheme 4. Equilibrium binding affinities of **2** and **5** to $[\text{LAu}]^+$ relative to NCAr_F ($\text{NCAr}_F = \text{NC-3,5-C}_6\text{H}_3(\text{CF}_3)_2$).

In summary, the stoichiometric reaction of 1,6-enyne **1** with $[\text{LAuCl}]/\text{AgSbF}_6$ at -20°C led to selective (97 %) formation of the gold–bicyclo[3.2.0]hept-1(7)-ene complex **4**, which is the only phosphine-containing species observed in the gold-catalyzed conversion of **1** into **2**. Complex **4** undergoes rapid 1,3-hydrogen migration at room temperature ($t_{1/2} \approx 16$ min) to form the gold–bicyclo[3.2.0]hept-1(7)-ene complex **6** with more than 90 % selectivity. ^{13}C NMR analysis of both **4** and **6** established the dominant metallacyclopropane character of these complexes, which differs markedly from the predominant σ -donating character of known cationic, two-coordinate gold– π -alkene complexes.^[18]

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