Direct Observation of Aryl Gold(I) Carbenes that Undergo Cyclopropanation, C–H Insertion, and Dimerization Reactions

Cristina García-Morales, Xiao-Li Pei, Juan M. Sarria Toro, and Antonio M. Echavarren*

Dedicated to Professor Pablo Espinet on the occasion of his 70th birthday

Abstract: Mesityl gold(I) carbenes lacking heteroatom stabilization or shielding ancillary ligands have been generated and spectroscopically characterized from chloro-(mesityl)methylgold(I) carbenoids bearing JohnPhos-type ligands by chloride abstraction with GaCl\(_2\). The aryl carbenes react with PPh\(_3\) and alkenes to give stable phosphonium ylides and cyclopropanes, respectively. Oxidation with pyridine N-oxide and intermolecular C–H insertion to cyclohexane have also been observed. In the absence of nucleophiles, a bimolecular reaction, similar to that observed for other metal carbenes, leads to a symmetrical alkene.

Gold(I) carbenoids are species in which the metal is bound to an sp\(^3\)-carbon center bearing a good leaving group that can generate a metal carbene upon ionization. This relationship, we have recently developed a method for the preparation of chloromethylgold(I) carbenoids, which, after chloride abstraction, display typical reactivities of gold(I) carbenes in solution. During the course of our investigation, preliminary results suggested that [JohnPhosAuCHPhCl] (1), after chloride abstraction, generates stilbene (2a), which undergoes cyclopropanation by an undetected phenyl gold(I) carbene intermediate (Scheme 1b). The observed cyclopropanation closely resembles the reactivity displayed by aryl gold(I) carbenes (5) generated by a gold(I)-catalyzed retro-Buchner reaction of cycloheptatriene (4; Scheme 1c).

Although these arylidene complexes (5) have never been observed in solution, such species have been detected in the gas phase.

Herein, we report the generation and spectroscopic characterization of mesityl gold(I) carbenes from stable carbenoids (1a–e) bearing JohnPhos-type ligands. These gold(I) carbenes display the same reactivity towards alkenes as the intermediates of the retro-Buchner reaction and many other gold(I)-catalyzed transformations. Importantly, the gold(I) carbenes undergo bimolecular homocoupling to form the corresponding symmetrical alkynes by a process reminiscent to that shown by electrophilic and nucleophilic metal carbenes.

Gold(I) carbenoids (1a–e) were obtained by reaction of the complexes 6a–e with mesityl diazomethane, and their structures were confirmed by X-ray diffraction (Scheme 2). Remarkably, upon addition of GaCl\(_2\) to 1a in CD\(_2\)Cl\(_2\) at...
–90 °C, the solution turned deep red, suggesting the formation of the mesityl gold(I) carbene 5a, which was characterized by NMR techniques (Table 1). Although gold(I) carbeneoids bearing JohnPhos and different substitution patterns in the aryl group were tested under the same reaction conditions, the generation of gold(I) carbenes could not be detected by NMR spectroscopy in those cases. Although 5a partially decomposed at −90 °C, the carbenes 5b–e were stable until −70 °C. These are the first monosubstituted gold(I) carbenes that have been characterized spectroscopically. The complexes 5a–e present a characteristic signal in 1H NMR spectroscopy at δ = 11.74–12.67 ppm corresponding to H1 (Scheme 3, Table 1). The carbenic carbon centers (C1) resonate at δ = 284.6–290.0 ppm as a doublet [1J (13C–31P) = 96.8–99.8 Hz], within the range of previously characterized gold(I) carbenes (δ = 225–321 ppm). In addition, clear correlations between the carbenic carbon (C1) and proton (H1) were observed in the 1H–13C HSQC spectra. DFT calculations for 1b′–c′ and 5b′–e′ complexes at the B3LYP-D3/6-31G(d,p) + SDD(Au) level of theory led to computed 1H and 13C NMR chemical shifts for H1, C1, and 1J(H1–C1) constants consistent with the experimental results (Table 1). Furthermore, 5a–e were detected in the gas phase by ESI-MS from 1a–e.

The calculated structure of 5e′ shows the mesitylidene fragment parallel to the lower ring of the biaryl ligand plane (Figure 1, top). The computed Au–C1 (2.026 Å) and C1–C2 (1.401 Å) bond distances for 5e′ are slightly shorter than those for the precursor 1e, Au–C1 (X-ray: 2.085 Å, computed: 2.095 Å) and C1–C2 (X-ray: 1.498 Å, computed: 1.502 Å).

The reactivity of electrophilic gold(I) carbenes is dominated by the LUMO orbital, which in the case of 5e′ is located over the occupied dπ(Au) orbital at gold and the 2p* system of the carbene ligand (Figure 1, bottom left). An NBO analysis for 5e′ revealed two main electronic contributions involved in the π-orbital stabilization of C1. First, a small π-backdonation from dπ(Au) to 2p*(C1) in a donor–acceptor interaction (24.4 kcal mol⁻¹) and 3.7% contribution of 2p*(C1) in the corresponding NLMO (Figure 1, bottom right), along with a lone pair at C2 [2p*(C2)] highly polarized towards C1 [23.5% on 2p*(C1)].

The calculated energy barrier to Au–C1 (ΔG°* = 1.3 kcal mol⁻¹) and C1–C2 (ΔG°* = 18.6 kcal mol⁻¹) bond rotation supported the low Au–C1 bond π-character and a significant C1–C2 π-bond. Although for these species the benzyl carbocation structure predominates, backdonation from gold is expected to be higher for other alkyl-substituted gold(I) carbenes generated under catalytic conditions.

Gold(I) carbenes (5b–c) were trapped by PPh₃ at −90 °C, affording the phosphonium-ylide complexes 7a,b, whose

### Table 1: Selected measured and calculated NMR data.[a]

<table>
<thead>
<tr>
<th>Complex</th>
<th>Method</th>
<th>H1 (ppm)</th>
<th>C1 (ppm)</th>
<th>J (1H–13C–C1) [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5a</td>
<td>Exp</td>
<td>12.35 (4.92)</td>
<td>290.0 (69.7)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>DFT</td>
<td>12.12 (4.22)</td>
<td>280.8 (72.2)</td>
<td>125.2 (144.2)</td>
</tr>
<tr>
<td>5b</td>
<td>Exp</td>
<td>12.67 (4.28)</td>
<td>287.9 (71.8)</td>
<td>129.8 (143.9)</td>
</tr>
<tr>
<td></td>
<td>DFT</td>
<td>12.17 (4.24)</td>
<td>280.2 (71.2)</td>
<td>124.4 (143.4)</td>
</tr>
<tr>
<td>5c</td>
<td>Exp</td>
<td>12.32 (4.17)</td>
<td>290.0 (71.7)</td>
<td>127.8 (144.3)</td>
</tr>
<tr>
<td></td>
<td>DFT</td>
<td>12.09 (4.30)</td>
<td>278.9 (75.4)</td>
<td>126.1 (144.6)</td>
</tr>
<tr>
<td>5d</td>
<td>Exp</td>
<td>12.57 (4.24)</td>
<td>289.0 (71.4)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>DFT</td>
<td>12.03 (4.69)</td>
<td>274.6 (74.0)</td>
<td>125.6 (144.4)</td>
</tr>
<tr>
<td>5e</td>
<td>Exp</td>
<td>11.74 (3.26)</td>
<td>284.6 (70.7)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>DFT</td>
<td>11.06 (–)</td>
<td>272.4 (–)</td>
<td>125.4 (144.4)</td>
</tr>
</tbody>
</table>


---

**Scheme 2.** Synthesis of the chloro(mesityl)methylgold(I) carbeneoids 1a–e.

**Scheme 3.** Generation of the mesityl gold(I) carbenes 5a–e. 1H NMR spectrum and selected region of 1H–13C HSQC spectra of 5c in CD₂Cl₂ at −90 °C.
structures were confirmed by X-ray diffraction (Scheme 4a). 7a,b resemble the phosphonium-ylide gold adducts previously used to detect aryl gold(I) carbenes in the gas phase.\textsuperscript{[11a–c,f,12]} In our reaction studies, small amounts of 2,4,6-trimethylbenzaldehyde (8) were detected, corresponding to the oxidation of gold(I) carbenes with oxygen.\textsuperscript{[19]} Indeed, we observed instantaneous formation of 8 as the only organic product when oxygen was bubbled through solutions of 5a–d at $-90^\circ\text{C}$.\textsuperscript{[20]} Clean oxygen-atom transfer also took place by treatment of 5a–d with pyridine N-oxide at $-90^\circ\text{C}$ (Scheme 4b). Similar reactivity has been observed for other gold(I) carbenes.\textsuperscript{[3]}

To date, none of the isolated gold(I) carbenes have been shown to undergo C–H insertion into alkanes. In contrast, 5a–e, generated at $-30^\circ\text{C}$ from the corresponding 1a–e in the presence of cyclohexane, undergo clean C–H insertion to give 9 in 39–69\% yield (Scheme 5).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Entry & Complex & $T \, ^\circ\text{C}$ & $E/Z$ & Yield [\%] \\
\hline
1 & 5a & -10 & 25 & 12:1 \% \\
2 & 5b & -20 & 68 & $>60:1$ \% \\
3 & 5c & -10 & 27 & 9:1 \% \\
4 & 5d & -30 & 62 & $>60:1$ \% \\
5 & 5e & 0 & 7 & $>60:1$ \% \\
\hline
\end{tabular}
\caption{Alkene and cyclopropane formation.\textsuperscript{[21]}}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Entry & Precursor & Yield [\%] & 3c & 3d & 3e \\
\hline
1 & 1a & 99 & 80 & 99 & (2.3:1) \% \\
2 & 1b & 87 & 90 & 99 & (3:1) \% \\
3 & 1c & 99 & 99 & 99 & (1:1.2) \% \\
4 & 1d & 99 & 99 & 72 & (2.1:1) \% \\
5 & 1e & 99 & 90 & 99 & (3.5:1) \% \\
6 & 4a & 32 & 38 & 17 & (1.7:5) \% \\
\hline
\end{tabular}
\caption{Cyclopropanation by 5a–e from 1a–e (left) or through decarbonylation of 4a (right).\textsuperscript{[22]}}
\end{table}

In the reactions of 5a–d with pyridine N-oxide or cyclohexane, traces of (E)-1,2-dimethylsilene [(E)-2b] were also detected (Schemes 4b and 5). (E)-2b was cleanly formed, together with the corresponding chloride-bridged digold(I) complexes (10a–e).\textsuperscript{[21]} when solutions of 5a–e in CD$_2$Cl$_2$ were warmed up from $-90^\circ\text{C}$ to either $-30$ or $0^\circ\text{C}$ (Table 2). Significant amounts of the cyclopropane 3b were also obtained in some cases (Table 1, entries 1,3, and 5). Analysis of the reactivity of 5e\textsuperscript{[22a]} shows that (E)-2b was initially formed between $-70$ and $-40^\circ\text{C}$. Then, around $-40^\circ\text{C}$, 3b and small amounts of (Z)-2b were also detected. The formation of (E)-2b follows a second-order dependence on the concentration of 5b.\textsuperscript{[20b]} Related bimolecular couplings to form symmetrical alkenes have been observed as common decomposition pathways for rhenium methylidenes\textsuperscript{[23–24]} and ruthenium carbenes,\textsuperscript{[25,26]} as well as typical Fischer\textsuperscript{[27]} and Schrock carbenes.\textsuperscript{[28]}

As suggested by the competitive cyclopropanation observed in the formal dimerization of the carbene fragments leading to 2b (Table 2), the substituted alkenes 2c–e readily react at $-90^\circ\text{C}$ with 5a–e to form the corresponding cyclopropanes 3c–e (Table 3, entries 1–5).\textsuperscript{[29]} Importantly, the gold(I)-catalyzed retro-Buchner reaction\textsuperscript{[10,30]} of the aryl cycloheptatriene 4a in the presence of 2c,d also leads to cyclopropanes (3c–e; entry 6), and strongly suggests that 5a is also generated under catalytic conditions. The lower yields of 3c–e obtained under catalytic conditions can be explained by the steric hindrance introduced by the mesityl group in the rate-determining cleavage of the cyclopropane bond of the
norcaradiene in tautomeric equilibrium with the cycloheptatriene.

To get a deeper insight into the mechanism of this rate-limiting bimolecular coupling, we performed DFT calculations with 5b′ (Scheme 6). Our calculations suggest that the association complex IntI, which is stabilized by face-to-face π–π interactions between the two mesitylidenes fragments and shows a relatively short C1–C1 distance (3.13 Å), is preferentially formed (ΔG = −3.3 kcal mol⁻¹) and can evolve through TS_int-I-II (ΔG° = 12.1 kcal mol⁻¹) to form a (η²-Z-5a)gold(I) complex (IntIII) in a highly exothermic process (ΔG = −48.2 kcal mol⁻¹). Alternatively, the less stable association complex IntII (ΔG = 1.9 kcal mol⁻¹), with the optimal orientation of the mesitylidenes for trans C1–C1 bond formation, can evolve via TS_int-II-IV (ΔG° = 6.2 kcal mol⁻¹) to form (E)-2b. At −35 °C, the calculated (E/Z)-2b ratio (ΔG° = 0.6 kcal mol⁻¹, 3:1 E/Z) is in close agreement with the experimental results (2:4:1 E/Z). Related mechanisms have been proposed for the formation of alkenes from rhenium²⁵ and ruthenium²⁶ carbenes.

We also examined theoretically the reaction pathways for the cyclopropagation of (Z)-2b and (E)-2b by 5b′.²⁷ As we have found before for intermolecular cyclopropanations of intermediate gold(I) carbenes,²⁸ these reactions proceed by an asynchronous concerted mechanism with an activation barrier for (E)-2b (ΔG° = 12.7 kcal mol⁻¹), 8.5 kcal mol⁻¹ lower than that for (Z)-2b (ΔG° = 21.2 kcal mol⁻¹).²⁹

In summary, we have generated and characterized spectroscopically monosubstituted gold(I) carbenes for the first time in solution, and they undergo representative trans-cyclopropanation, oxidation, and C–H insertion reactions, of intermediate gold(I) carbenes formed under catalytic conditions. These aryl gold(I) carbenes correspond to the intermediates generated in the gold(I)-
catalyzed decarbenation of cycloheptatrienes (retro-Buchner reaction). In the absence of other reagents, we observed dimerization to form preferentially the E-configured alkene by a process similar to that followed by other well-known metal carbenes, and places these highly electrophilic species among the metal carbene family, despite the weak back donation from gold(I) to the carbenic carbon center.

Acknowledgements

We thank the Agencia Estatal de Investigación (AEI)/FEDER, UE (CTQ2016-75960-P and FPI postdoctoral fellowship to C.G.-M.), H2020-Marie Sklodowska-Curie program (postdoctoral fellowship to X.-L.P.), Swiss National Science Foundation (Early Postdoc Mobility fellowship to J.M.S.T.), the AGAUR (2017 SGR 1257), and CERCA Program/Generalitat de Catalunya for financial support. We also thank the ICIQ NMR and X-ray diffraction units for technical support and Ángel L. Mudarra (ICIQ) for helpful discussions.

Conflict of interest

The authors declare no conflict of interest.

Keywords: carbenes · carbenoids · density-functional calculations · gold · structure elucidation

How to cite: Angew. Chem. Int. Ed. 2019, 58, 3957–3961

Angew. Chem. 2019, 131, 3997–4001


Communications
Among all the isolated gold(I) carbenes, three of these species display reactivity related to real intermediates in catalysis. In particular, cyclopropanation of styrenes, oxidation with $\text{H}_2\text{O}_2$, N- pyridine-oxide and B–H and O–H insertion.

Among all the isolated gold(I) carbenes, only three of these species display reactivity related to real intermediates in catalysis. In particular, cyclopropanation of styrenes, oxidation with $\text{H}_2\text{O}_2$, N- pyridine-oxide and B–H and O–H insertion.

Among all the isolated gold(I) carbenes, only three of these species display reactivity related to real intermediates in catalysis. In particular, cyclopropanation of styrenes, oxidation with $\text{H}_2\text{O}_2$, N- pyridine-oxide and B–H and O–H insertion.

Among all the isolated gold(I) carbenes, only three of these species display reactivity related to real intermediates in catalysis. In particular, cyclopropanation of styrenes, oxidation with $\text{H}_2\text{O}_2$, N- pyridine-oxide and B–H and O–H insertion.

Among all the isolated gold(I) carbenes, only three of these species display reactivity related to real intermediates in catalysis. In particular, cyclopropanation of styrenes, oxidation with $\text{H}_2\text{O}_2$, N- pyridine-oxide and B–H and O–H insertion.

Among all the isolated gold(I) carbenes, only three of these species display reactivity related to real intermediates in catalysis. In particular, cyclopropanation of styrenes, oxidation with $\text{H}_2\text{O}_2$, N- pyridine-oxide and B–H and O–H insertion.