Gold Complexes

Gold(III) Alkyne Complexes: Bonding and Reaction Pathways

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Abstract: The synthesis and characterization of hitherto hypothetical AuIII π-alkyne complexes is reported. Bonding and stability depend strongly on the trans effect and steric factors. Bonding characteristics shed light on the reasons for the very different stabilities between the classical alkyne complexes of PtII and their drastically more reactive AuIII congeners. Lack of back-bonding facilitates alkyne slippage, which is energetically less costly for gold than for platinum and explains the propensity of gold to facilitate C–C bond formation. Cycloaddition followed byaryl migration and reductive deprotonation is presented as a new reaction sequence in gold chemistry.

The reactions of gold complexes with alkynes form the basis of a multitude of organic catalytic transformation involving starting materials with C≡C triple bonds.[1] Invariably these reactions are initiated by coordination of the alkyne to the metal, which induces polarization and susceptibility towards nucleophilic attack. Remarkably, unlike alkyne adducts of gold(I), which have been known since the 1970s,[2–4] alkyne π-complexes of gold(III) have remained unknown.[5] This is in sharp contrast to alkynyl compounds of isoelectronic platinum(II), which were first reported over 50 years ago and provide textbook examples of the Dewar–Chatt–Duncanson π-bonding model.[5,6] Elucidating the reaction chemistry of gold(III) has provided major challenges and has highlighted that drawing mechanistic analogies between gold(III) and the isoelectronic Pt and Pd systems is often not valid.[7–9] We show herein that the hitherto elusive AuIII alkyne complexes can in fact readily be generated and have Au–alkyne bond energies comparable to those of platinum, but are drastically more reactive. The results have enabled the first experiment-based comparison of alkyne bonding in AuIII and PtII systems and shed light on their reactivity differences, which helps explain the superior performance of gold in alkyne catalysis.

The reaction of (C^N^C)AuOAc (1-OAc; OAc^− is tri-fluoroacetate) with B(C6F5)3 in dry dichloromethane generates the ion pair [(C^N^C)Au···Y] [Y = Ac^−OB(C6F5)] (2; Scheme 1). Internal alkynes were added to these solutions at –78°C and the mixture was monitored by 1H NMR spectroscopy at –20°C. The outcome of the reactions proved to be dramatically affected by nature of the substituents at the triple bond (Scheme 1). With sterically less hindered alkynes[2+2] cyclodimination occurs. In the case of 3-hexyne, this leads to the gold-bound cyclobutenyl cation 3, the structure and intermolecular contacts of which were elucidated by 2D NMR methods (see the Supporting Information). By contrast, the interaction of 1-phenyl-1-propyne with 2 leads to a complex NMR spectrum consistent with the formation of the cyclopentenyl complex 4, which is apparently produced by...
a combination of cyclodimerization and 1,3-H shifts. The observed $^{13}$C NMR data are in excellent agreement with the calculated NMR chemical shifts for complexes 3 and 4 (see the Supporting Information). These cyclizations are an expression of the vinyl cation character of Au$^{III}$ alkynes and reflect the tendency toward C–C bond formation that typifies gold-catalyzed alkynyl reactions.

Cycloaddition is suppressed by steric hindrance. For example, mixing 2 with around 2.5 molar equiv of BuC≡CMe or AdC≡CAd resulted in the reaction of only 1 equiv of alkynyl to give the π-complexes 5a and 5b, respectively, without cyclodimerization.[11,12] Complexation was confirmed by $^{13}$C NMR and the selective dipolar interactions of the Me and Bu substituents with the pincer ligand in the $^{1}$H NOESY NMR spectrum. Alkyne coordination induces only modest $^{13}$C NMR shifts [5a: C(Me) $\delta_c = 85.7$ ($\Delta\delta_c = 11.9$ ppm), C-(Bu) $\delta_c = 97.1$ ($\Delta\delta_c = 9.4$); 5b: C-98.3 ($\Delta\delta_c = 10.6$)] very similar to the values observed for [(R,P)Au(alkyne)]BF$_4$.[13] Solutions of 5a show no exchange between free and coordinated alkynyl and are stable for hours at $-30^\circ$C but decompose at 25$^\circ$C within minutes. By contrast, the even more bulky bis(1-adamantyl)acetylene complex 5b is stable for days at room temperature and can be isolated as a yellow microcrystalline solid.[11]

Gold(III) is well known for its ability to catalyze alkyne hydration.[24] This process is modelled by 5, which reacts with water at $-20^\circ$C to give the ketonel complex 6. Evidently the proton released after nucleophilic attack of H$_2$O at the alkynyl cleaves the pincer. The same complex was obtained directly from 1-Cl, AgSbF$_6$/BuC≡CMe, and H$_2$O (D$_2$O), in more than 90% yield. The structure was confirmed by X-ray diffraction (Scheme 1).

A second type of alkyne complex could be generated after Au–C bond cleavage of 1-C$_2$F$_5$ with [H(OEt)$_2$][H$_2$N[1,1,1-(C$_2$F$_3$)$_3$]] in C$_2$D$_2$Cl, followed by removal of associated Et$_2$O.[14] Ether-free 7 reacts with 3-hexyne at $-78^\circ$C in CD$_2$Cl$_2$ to generate 8a (Scheme 2). Alkyne coordination was indicated by a significant shift in the ligand signals. In this type of compound, the π-ligand is trans to an anionic C atom, which, unlike the pyridine donors in 3–5, exerts a strong trans influence, resulting in substantial weakening of the Au–alkynyl bond.

At $-50^\circ$C, 3-hexyne coordination to 8a is strong enough to allow separate observation of the ethyl signals of bound and free alkynyl. The $^{13}$C NMR signal of the coordinated triple bond was located at $\delta_c = 91.7$ ($\Delta\delta_c = 10.7$ ppm). $^{1}$H NOESY NMR experiments revealed the presence of chemical exchange, thus indicating that the complex is still fluxional at $-50^\circ$C. Raising the temperature broadens the resonances, and coalescence between free and bound 3-hexyne occurs at about $-30^\circ$C. The simulation of the VT $^{1}$H NMR spectra of 8a allowed the activation parameters of alkyne exchange to be estimated ($\Delta H^\ddagger = 19.9$ kcal mol$^{-1}$ and a positive $\Delta S^\ddagger = 34$ cal mol$^{-1}K^{-1}$), and the results suggest that the exchange has a dissociative character. For the EtBuC≡CMe complex 8b, well-resolved spectra were obtained at $-60^\circ$C, thereby allowing complete NMR characterization and a direct comparison with complex 5, where the alkyne is trans to a pyridine donor. The alkyne $^{13}$C signals of 8b are very similar to those of 5; there is no detectable trans influence on the $^{13}$C NMR chemical shifts.

While these alkyne complexes have so far resisted all attempts at crystallization, structural confirmation of alkyne bonding was unexpectedly obtained from the reaction of 9[15] with AgC≡CBu, which gives the thermally stable crystalline products 10 and 11. The latter, a product of partial reduction, contains a π-bonded Au(C≡CBu) anion, which, probably due to packing effects, displays two types of Au$^{III}$-alkynyl interactions: one symmetrical Au$^{III}$-alkynyl bond with an elongated C≡C distance of 1.23(3) Å, and one asymmetric alkyne bridge that shows two very different Au$^{III}$–C distances (2.29(2) and 2.52(2) Å) and lacks the C≡C bond elongation (Scheme 3).

The bonding of alkynes to Au$^{III}$ was explored by Density Functional Theory (DFT) calculations (Gaussian 09, TPSSH/cc-pVTZ//B3LYP/SVP), and compared to bonding in structurally related Pt$^{III}$ fragments (Table 1).[16] Surprisingly, the dissociation energies of Au$^{III}$ and Pt$^{III}$ with pyridine ligands in a trans position were remarkably similar, thus suggesting that the observed differences in reactivity are not due to thermodynamic effects. Alkyne bonding to [(C≡N=CH)Au(C$_2$F$_3$)$_2$] was weaker by 30–40 kcal mol$^{-1}$ compared to [(C≡N=CH)Au+] for both electronic and steric reasons: the empty coordination

Scheme 2. Generation of C=N-chelated alkyne complexes.

Scheme 3. Formation of the p-bonded Au$^{III}$ alkyne complex 11. Hydrogen bonds are omitted for clarity; ellipsoids are drawn at 50%.

Selected bond lengths [Å] and angles [°]: Au1–C59 2.33(2), Au1–C60 2.40(2), Au1–C21 1.98(3), Au2–C53 2.29(2), Au2–C54 2.52(2), Au2–C47 2.07(2), C53–C54 1.17(3), C59–C60 1.23(3); C53–Au3–C59 175.6(9), Au1–C60–C59 78(1), Au1–C59–C60 78(1), Au2–C53–C54 87(2), Au2–C54–C53 65(2).
site in \([\{C^N-N\}Au(2-butyne)\}^+\) is trans to a strong Au–C bond, and it is shielded by the dangling aryl arm. General bonding trends are very similar between the two types of complexes, with the more \(\pi\)-donating alkyne binding most strongly.

The \(\text{Au}^{\text{III}}\)-C(alkyne) bond lengths calculated for the model \([\{C^N-N\}Au(2-butyne)\}^+\) correspond remarkably closely to those found for the \(\pi\)-bonded alkylnyl ligand in 11 (Figure 1).

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\begin{array}{|c|c|c|}
\hline
\text{Ligand} & \text{[C^N-N\}Au}\}^+ & \text{[C^N-N\}Pt}\}^+ & \text{[C^N-N\}Au(C_F_3)}^+ \\
\hline
\text{CO} & 46.5 & 55.7 & 8.5 \\
\text{H\equivCH} & 38.9 & 41.7 & 4.3 \\
\text{Me\equivCMe} & 48.7 & 47.6 & 12.3 \\
\text{Et\equivC\equivEt} & 53.0 & 50.8 & 15.0 \\
\text{Me\equivC\equivBu} & 53.1 & 51.0 & 13.4 \\
\text{Me\equivC\equivPh} & 50.6 & 49.7 & 13.8 \\
\hline
\end{array}
\]

(a) \(C^N-N=2,2\text{-bipyridyl}-6-C_7H_4\).

In order to assess the trans influence on back-donation, charge-decomposition analysis was carried out.[17] Back-donation for all gold(III) compounds is very low and is further reduced by strong trans ligands; for example, 5 shows a back-donation/donation (B/D) ratio of 0.43. This drops to B/D = 0.17 for 8a, which is much less than in structurally analogous \([\{C^N-N\}Pt\}^+(3-hexyne)\}^+\) (B/D = 0.77). The stability of alkyne complexes depends almost entirely on \(\pi\)-donation from the alkyne ligand.

The alkyne slippage was probed by using 2-butyne adducts of \(\text{AuCl}_3\) and \(\text{PtCl}_2(\text{H}_2\text{O})\) as models and varying the angle \(\alpha\) in the range 35–120° with steps of 5°, resulting in slippage values of approximately \(-1\) to \(+2\,\text{Å}\) (Figure 2).[18] In the (non-slipped) \(\pi\)-complexes, this angle is close to 75° and 73° for \(\text{Cl}_3\text{Au}(\text{butyne})\) and \(\text{trans-Cl}_2(\text{H}_2\text{O})\text{Pt}(\text{butyne})\), respectively. Back-bonding can be expected to increase the barrier to geometric deformation, and indeed, at a slippage of \(+1\,\text{Å}\), the Au complex has lost only 13% of its acetylene binding energy, while the Pt complex has lost 23% (Figure 2). We believe this easier deformation of Au complexes contributes significantly to the higher reactivity of gold(III) acetylene complexes.

Warming a mixture of 8a and 3-hexyne to room temperature gives the thermally stable product 12 (Scheme 4). Its formation involves [2+2] cycloaddition, followed by \(C_F_3\) migration to the resulting cyclobutenyl cation. The C–C bond is significantly polarized due to a weak interaction with the gold center (\(\delta_C = 138.0\) and 185.1; cf. calculated values (Me model): \(\delta_C = 131.4\) and 189.3).

Alkenes are typically released from metal alkyls by \(\beta\)-H elimination, as recently shown for gold(III) \(\pi\)-alkyls.[19] This process requires a vacant site in a cis position and is suppressed by donor ligands. By contrast, alkenne release from 12 is actually induced by donors (SMe₂ or xylileNC). Monitoring 12/SMe₂ mixtures at \(-30^\circ\text{C}\), where the reaction is quite slow, showed no evidence for the formation of a transient AuV–H species,[20] nor was there evidence for migration to the resulting cyclobutenyl cation. The C–C bond is significantly polarized due to a weak interaction with the gold center (\(\delta_C = 138.0\) and 185.1; cf. calculated values (Me model): \(\delta_C = 131.4\) and 189.3).

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\begin{array}{l}
\text{Scheme 4. Reactivity of the alkyne complexes: C–C coupling and alkenne release.}
\end{array}
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a C(aryl)−H coupling product resulting from such an intermediate. On the other hand, a broad signal at δH = 13.4 appeared, typical of a protonated pyridine. These findings suggest that 12 may follow an alternative path: reductive deprotonation, involving dissociation into a gold(I) aryl and a cyclobutenyl cation (Scheme 4), and likely assisted by stabilizing SMc2 coordination to AuIII, followed by deprotonation of the cyclobutenyl cation by pyridine to give 13 as an E/Z mixture.

The free energy pathway for alkene dimerization and cyclobutenyl–aryl coupling is shown in Scheme 5. Starting with the mono-alkyne π-complex B1, the Au atom moves to one of the two sp-C atoms, creating a gold-bound vinyl cation, which attacks the π-bond of a second alkene. The resulting cyclopolyenymethylene cation B2 is a shallow local minimum. Opening of one of the two ring single bonds leads to the aminated cyclobutenyl cation B3. The rate-limiting step is the initial alkene–alkyne coupling. The transition state for coupling of the C6F5 and cyclobutenyl fragments (B3 to B4/B5) looks somewhat like insertion of cyclobutadiene into the Au-C6F5 bond. The calculated barrier of approximately 20 kcal mol−1 indicates that this reaction should be rather slow at room temperature, as was indeed observed. The product B4 formed immediately from the transition state resembles a combination of neutral (η1-C=N-CH)Au(CH3) (with a long Au−N distance of 3.04 Å) and a cyclobutenyl cation, which would constitute an intramolecular redox reaction. This pair of species easily collapses to rather stable AuIII cyclobutenyl complex B5. We suspect that a direct route from B3 to B5 is avoided because that leads to an unfavorable isomer with the newly formed Au−C bond trans to that of the C=N−CH ligand. With additional stabilization by SMc2, intermediate B4 may also provide a pathway for the release of the organic product through reductive deprotonation (for the possibility of alkene release through β-H elimination, see the Supporting Information).

In conclusion, several distinct types of well-defined gold(III) alkene complexes are now accessible and were characterized by spectroscopic, structural, and computational methods. Their synthesis enabled an outline of their reaction pathways. Alkene bonding is subject to a strong trans influence: ligands trans to pyridine-N are bound significantly more strongly than trans to an anionic Conor. Although AuIII and PtIII alkene adducts show comparable binding energies, the much lower back-bonding in AuIII complexes reduces the energy cost of alkyl slipage and facilitates C=N−C bond polarization. This greatly enhances the susceptibility of gold-bound alkynes towards nucleophilic attack and C=C bond formation, which is in line with the behavior of gold catalysts. Overall, gold(III) alkene complexes display reaction pathways that are unprecedented in gold chemistry and illustrate the drastic reactivity differences between AuIII compounds and their PtIII congeners.

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Conflict of interest
The authors declare no conflict of interest.

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[11] For full experimental details, see the Supporting Information.

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[20] CCDC 1559726 (6) and 1569528 (11) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre.

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