# The Role of Bent Acyclic Allene Gold Complexes in Axis-to-Center Chirality Transfers**

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Dedicated to Professor Jan Reedjik

Electrophilic activation of readily available enantioenriched allenes by transition-metal fragments is a maturing strategy to generate optically active compounds (axis-to-center chirality transfer).[1] The coordination of an allene to a metal may lead to several types of structures that can be divided into two categories (Scheme 1).[2] The η^2 complexes **I** involving one of
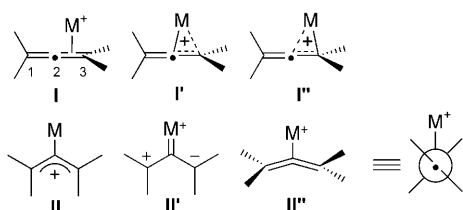
Scheme 1. Various coordination modes of allenes. M = metal–ligand fragment.

the two orthogonal C=C bonds are the most intuitive form. Depending on the substitution pattern of the allene, the contribution of the two carbon atoms to the coordination might not be strictly equivalent, leading to slipped structures of type **I′** or **I″**.[3] This case will manifest itself for instance in the presence of electron-donating groups that will stabilize **I′**, or electron-withdrawing groups that favor **I″**. The second category comprises species in which the metal fragment is coordinated to the central allene carbon only. Along with σ-allylic cations **II**, there are alternatives, such as zwitterionic carbenes **II′** or η^1-coordinated bent allenes **II″**.[4] In this type of complex, the three allene carbons and the metal fragment lie in the same plane, from which the four substituents of the

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allene deviate significantly. Compounds of type **II″** have been recently isolated as tetraaminoallene rhodium[5] or gold complexes[6] and characterized by X-ray diffraction studies.[7] Interestingly, gold is known to activate allenes toward nucleophilic attack.[8] For instance, α- and β-hydroxyallenes or -aminoallenes can be cycloisomerized in the presence of gold(I) or gold(III) catalysts into the corresponding 5- and 6-membered heterocycles.[9] These transformations have also been accomplished with axis-to-center transfer of chirality,[10] even in intermolecular versions.[11] Thus, the question whether the nucleophile attacks a species of type **I–I″** or **II–II″** is of paramount importance in accounting for the chirality transfer. Indeed, although the stereochemical information is maintained in species **I–I″**, the axial chirality of the allene seems to be lost in **II** or **II′**. On the other hand, bent allene complexes should retain the chirality of the starting material. We ran a set of computations[12] on model chiral allene gold complexes to understand which factors govern the ground state of **I–II″**, and how these species interconvert.[13] We then used our findings to predict which structural variations of the allene could favor a successful chirality transfer. Finally, we verified our hypothesis on some gold(I)-catalyzed cycloisomerizations.

We began our study with (R)-1,3-dimethyl allene. Figure 1 shows all the structures that converged as minima in the presence of AuBr₃.[14] We found two diastereomeric complexes of type **I**, and two C2-coordinated complexes of type **II** and **II″**.[15] The type **II** complex is planar, and has C1−C2 and C2−C3 bond lengths of 1.39 Å, and a C1-C2-C3 angle of 116°. The latter has shorter C1−C2 and C2−C3 bond lengths (1.36 Å), and is strongly twisted (Me-C1-C3-Me 65.8°) to minimize the allylic strain. This complex is the less stable form, the ground state being one of the type **I** species ($\Delta H_{298} = 3.5$ kcal mol^{-1}).

We investigated a few other metal fragments (Table 1). With the exception of Au$^+$, no gold(I) complex of type **II″** could be located.[15] Using PtCl₂, the C1−C2 and C2−C3 bond lengths (1.39 Å), the small C1-C2-C3 angle (129.1°), and the moderate Me-C1-C3-Me tilt angle (45.1°) compare quite well with a distorted allylic cation. On the other hand, the allene ligand is less severely bent in AuX₃ complexes (C1-C2-C3 140.1° and 136.6° with X = Br and Cl, respectively), the C=C bonds are much less perturbed (1.36 Å), and the tilt angles are much more pronounced (65.8° and 59.7°). However, in all cases (as for AuBr₃; see Figure 1), the ground states are complexes of type **I**. For instance, with [Au(PMe₃)]$^+$, the allene complexes **1** and **2** were more stable than the allylic cation **3** (Scheme 2). Whereas **3** was the only C2-coordinated
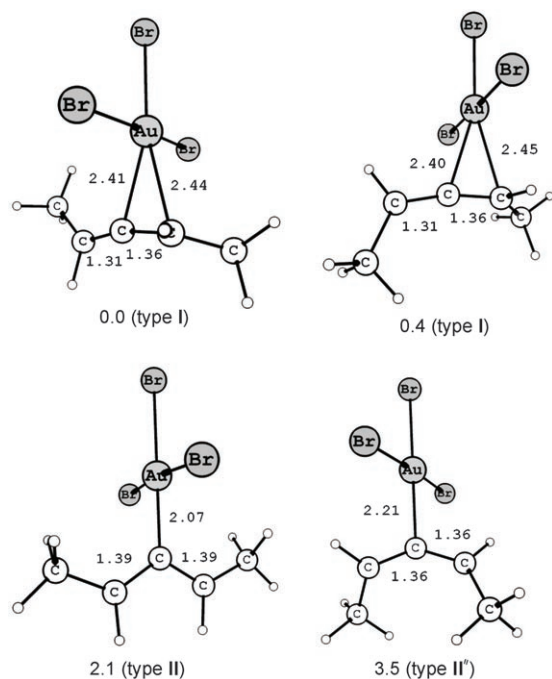
Figure 1. Structures of (R)-1,3-dimethyl allene complexed to AuBr3. Distances in Å, and relative enthalpies in kcal mol^{-1}.

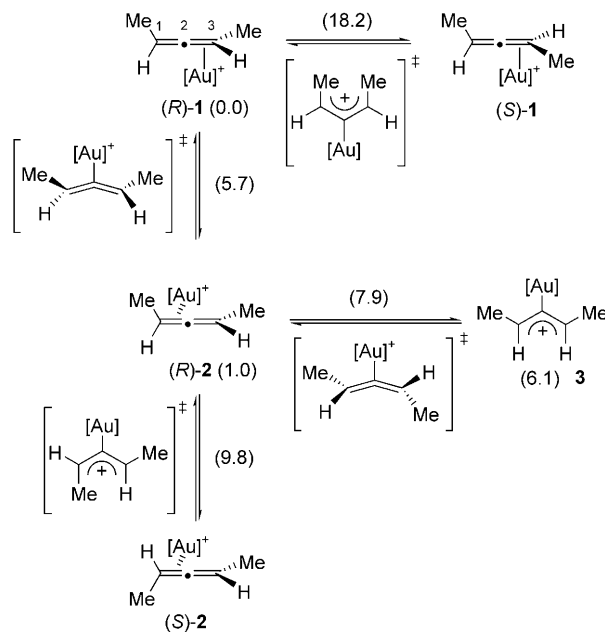**Scheme 2.** Interconversion between gold complexes of 1,3-dimethyl allene. [Au] = {Au(PMe3)}. Relative enthalpies in kcal mol^{-1}. Barrier heights are indicated in parentheses.

Table 1: Structural parameters of some bent allene complexes.

	C1—C2 [Å]	C1-C2-C3 [°]	Me-C1-C3-Me [°]
Au(PR3)$^+$	—[a]	–	–
AuCl	—[a]	–	–
AuBr3	1.36	140.1	65.8
AuCl3	1.36	136.6	59.7
Au$^+$	1.36	130.0	48.7
PtCl2	1.39	129.1	45.1

[a] The corresponding η^2-allene complex was obtained.

structure that could be optimized as a minimum, the other missing geometries were obtained as transition states. The 90° shift of the gold atom on going from (R)-**1** to (R)-**2** is achieved through a bent allene transition state and requires an enthalpy of activation of 5.7 kcal mol^{-1}. The most hindered transition state, TS$_{(R)1-(S)1}$, is planar and allows the inversion of the allene. However, it lies 18.2 kcal mol^{-1} above (R)-**1**. On the other hand, the stereomutation of (R)-**2** occurs at a less hindered planar transition state lying 9.8 kcal mol^{-1} above the complex. Apart from these two racemization processes, the chirality can also be lost when forming the planar intermediate **3**, through a bent allene type transition state lying 7.9 kcal mol^{-1} above **2**.

All these data suggest that there is a continuum between these species which depends on the substituents of the allene and on the metal fragment. A subtle balance between the delocalization of the positive charge and the inherent allylic strain seems to govern the possible geometries. With a simple unfunctionalized allene, coordination to the central carbon atom seems to be disfavored. This could prevent the racemization, and may account for the good chirality transfers

observed with some unfunctionalized disubstituted allenes.[10] However, we reasoned that the presence of an electron-donating group at the allene could modify this trend. The compensation of the electron depletion induced by the metal could balance the steric hindrance at the allylic positions. To this end, we replaced a methyl group by an acetate or a vinyl group. The choice of these substituents was dictated by the numerous applications of gold-catalyzed transformations of allenyl esters[8] or vinyl allenes.[16]

Scheme 3 shows all possible complexes with an acetate at the allene. Eight of the twelve candidates converged as minima.[17] The allylic cation **8** is the ground state of the system. The participation of the oxygen atom in the con-
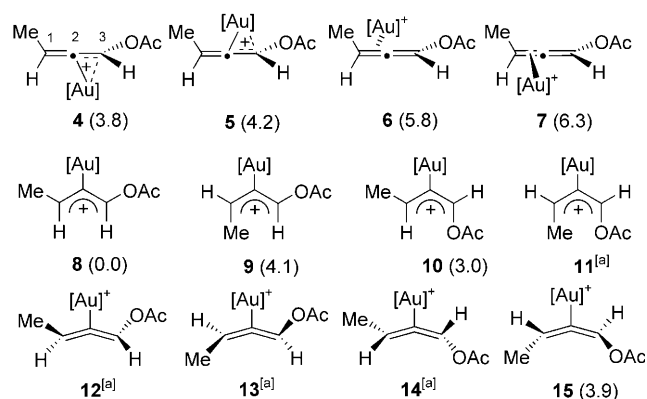
Scheme 3. Various coordination modes of (R)-buta-1,2-dienyl acetate to gold(I). [Au] = {Au(PMe3)}. Relative enthalpies in kcal mol^{-1}.
Selected structural parameters for **15**: C1—C2 1.35, C2—C3 1.38, C3—O 1.33 Å, C1-C2-C3 133°. [a] These species did not converge and collapsed to the corresponding planar or twisted C2-coordinated compound.

jugation is evident from the short C3—O distance of 1.31 Å. All other isomers are at least 3.0 kcal mol^{-1} less stable. It is worthy of note that two other C2-coordinated allenes are more stable (**10**) or of similar energy (**15**) than the most stable η^2-allene complex **4**.

All the species are connected by low-lying transition states; two examples are shown in Scheme 4. The 90° rotation of the CHOAc group to transform **5** into **8** has an enthalpy of
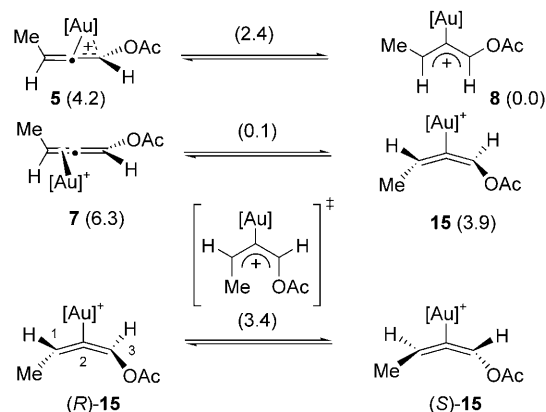
Scheme 4. Interconversion between gold complexes of (*R*)-buta-1,2-dienyl acetate. [Au] = {Au(PMe₃)}. Relative enthalpies in kcal mol^{-1}, barrier heights indicated in parentheses.

activation of 2.4 kcal mol^{-1}. Interestingly, the 45° shift of the metal from the η^2 allene complex **7** to the bent allene complex **15** is straightforward ($\Delta H^{\ddagger}_{298} = 0.1$ kcal mol^{-1}). Importantly, the stereochemistry of the bent allene complex **15** may also invert via a planar transition state.

The same feature was observed with vinyl allenes (Scheme 5). The allylic cation **17** was obtained as the ground state. Again, the conjugation was obvious from the C3—C4 bond length (1.43 Å). In contrast with the 1,3-dimethyl allene system, the bent structures **18** and **19** could be modeled, although they are slightly less stable than the η^2-coordinated allene. The geometrical parameters of these species, and in particular the quite acute C1-C2-C3 angle of 123.5° (**18**) and 126.3° (**19**), suggest that they are close to regular allylic cations, although they are not planar at all. No more planar structures can be modeled in the case of
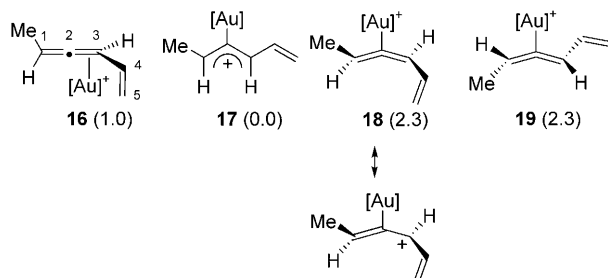
Scheme 5. Selected examples of gold complexes of hexa-1,3,4-triene. [Au] = {Au(PMe₃)}. Relative enthalpies in kcal mol^{-1}. Selected structural parameters for **18**: C1—C2 1.37, C2—C3 1.39, C3—C4 1.44, C4—C5 1.36 Å, C1-C2-C3 123.5, H-C1-C3-C4 48.7°.

trisubstituted allenes (Scheme 6). Nevertheless, the ground state still is a C2-coordinated compound, that is, **21** or **24**.

From this set of results, it seems obvious that the allylic strain can prevent the formation of planar structures, and may
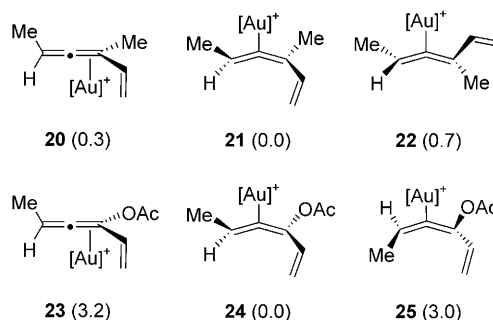
Scheme 6. Selected examples of gold complexes of hexa-1,3,4-triene. [Au] = {Au(PMe₃)}. Relative enthalpies in kcal mol^{-1}.

retard the racemization of allenes (see for instance (*R*)-**1** → (*S*)-**1** in Scheme 2). The formation of C2-coordinated allenes, either as allylic cations, bent allenes, or any other resonance form (such as pentadienyl cations in the case of vinyl allenes), is favored by the presence of electron-donating groups. Although cationic in nature, these species retain the stereochemical information of the substrate. Therefore, a reaction that requires the formation of C2-coordinated allenes may give a better chirality transfer as the substitution of the allene increases. One such reaction could be the gold(I)-catalyzed cycloisomerization of ene–vinyl allenes.[13b] This transformation is known to give polycyclic compounds diastereoselectively (Scheme 7). The mechanism has been previously studied by DFT computations: the first step is a metalla-Nazarov cyclization which gives a cyclopentenylidene intermediate; this gold carbene is then trapped by the pendant C=C bond to furnish the cyclopropyl ring.[13b, 18] Interestingly, the calculations showed that the metalla-Nazarov transition state connects the gold-carbene to a species complexed at C2
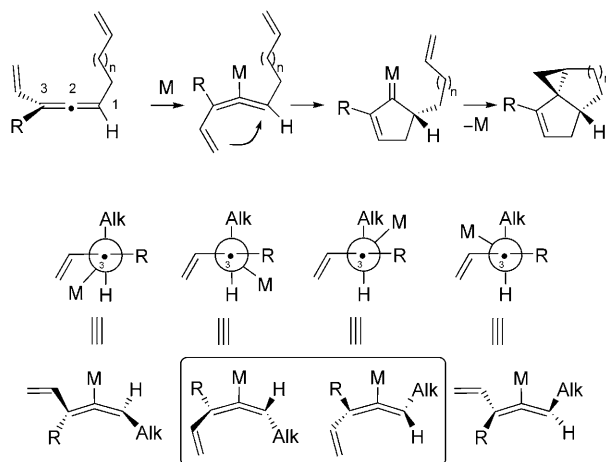
Scheme 7. Cycloisomerization of ene–vinyl allenes. R = H, Me, OAc; Alk = alkenyl group.

of the starting allene framework. That species is not planar and should keep the chiral information.[19]

Of the four possible bent allene structures, only two are reactive with respect to the Nazarov cyclization, that is, those with the vinyl group *anti* to the metal fragment. Interestingly, any of these two diastereomers should lead to the same enantiomer after the cyclization, therefore an efficient transfer of the stereochemical information is expected (see Figure 2 for an example with R = OAc). However, to decrease the rate of racemization of the allene, a third substituent at the allene might be necessary (R ≠ H).
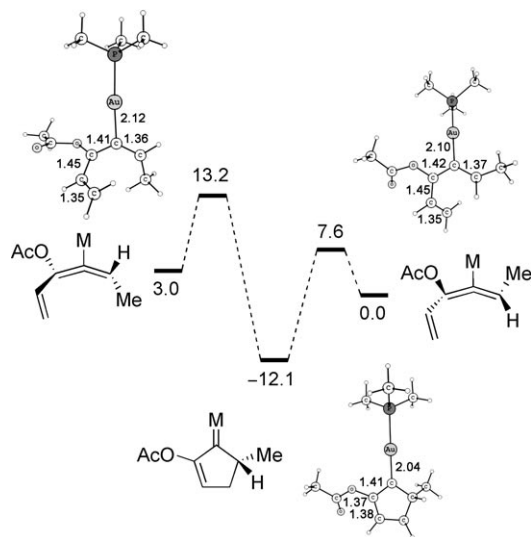

Figure 2. Cycloisomerizations of diastereomeric allene gold complexes leading to the same enantiomer. Distances in Å, relative enthalpies in kcal mol⁻¹. M = [AuPMe₃]⁺.

To verify this hypothesis, we attempted the gold(I)-catalyzed cycloisomerization of enantioenriched ene–vinyl allenes. We synthesized the enantioenriched compounds depicted in Scheme 8. In (*S*)-**26**, the allene moiety is disubstituted. Gold(I)-catalyzed cycloisomerization furnished the tetracyclic compound **27** in 87% yield and 0% enantiomeric excess. Chiral GC analysis after 10 minutes revealed that the starting compound was completely racemized. A similar loss of stereochemical information was made during the gold(I)-catalyzed cycloisomerization of vinyl allenes into cyclopentadienes.[16c] On the other hand, the reaction of the trisubstituted allenes (*R*)-**28** and (*R*)-**30** proceeded with perfect transfer of chirality. Trisubstituted allenes (allenyl acetates) can also be generated in situ by the well-established gold-catalyzed 3,3-rearrangement of propargyl acetates.[20] Under the same experimental conditions, efficient chirality transfers were observed during the cycloisomerization of the esters (*R*)-**32** and (*R*)-**34**.[21]

Thus, with a reaction that transits through central allene carbon complex, the chirality can still be transferred. The reactive species could be described as pentadienyl cations of helical chirality,[22] and argued that the representation as a bent allene complex is convoluted. However, we have shown that the formation of chiral bent allene complexes does not
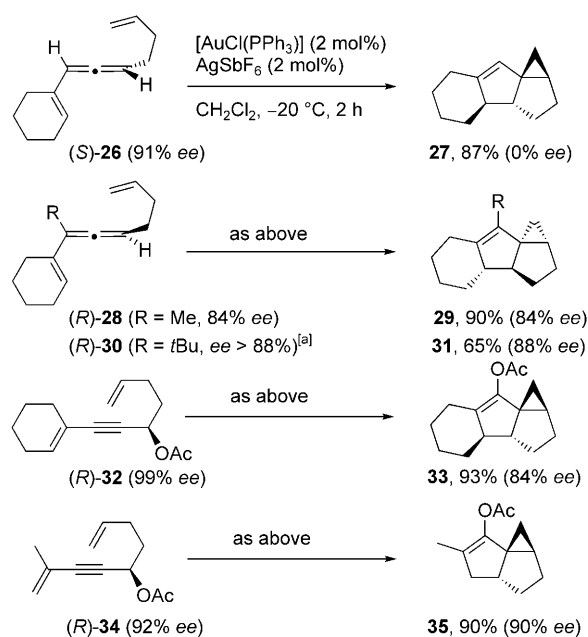
Scheme 8. Gold(I)-catalyzed cycloisomerization of enantioenriched ene-vinyl allenes. [a] The enantiomeric excess could not be determined.

necessitate the presence of a vinyl group. Perhaps the idea of the formation of a chiral η¹-complex as reactive intermediate which is cationic in nature could be extended to other reactions, such as the cycloisomerization of allyl allenes.[23] This reaction has been achieved with very good retention of the stereochemical information. In this case, it is no longer possible to invoke a pentadienyl cation. The cyclization would occur on a chiral type **I-I″** or **II″** intermediate, which will be the object of future study. At this stage, we can say that the formation of C2-coordinated allene complexes is always possible, that these species are not necessarily planar allylic cation but can be twisted and therefore chiral, and that they can be considered as reactive species as good as η²-allene complexes.

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[17] **9** and **10** are not strictly planar, but very close to planarity. Their "racemizations" require an enthalpy of activation of only 0.1 and 0.01 kcal mol^{-1}, respectively.

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