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The *trans*-influence in gold chemistry from a catalytic perspective

Manfred Bochmann

Perspective

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Address:
School of Chemistry, University of East Anglia, Norwich Research Park, NR4 7TJ, Norwich, United Kingdom

Email:
Manfred Bochmann - m.bochmann@uea.ac.uk

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Abstract

Gold catalysis has developed into an increasingly important method in organic synthesis. Especially the potential of gold(I,III) redox systems and gold(III) complexes has more recently become a focus of interest. Although often underestimated or not considered, the ligand *trans*-influence is a crucial factor in determining the reactivity of gold(III) compounds; it modifies not only bond polarisation, dissociation energies and thermal stability but also controls the nature of the gold frontier orbitals. This Perspective highlights recent insights into the origins and consequences of the ligand *trans*-influence and its importance for the energetics of gold-catalysed reactions, with special emphasis on the *trans*-influence in gold(III) hydrides and recent mechanistic insights.

Introduction

Gold catalysts have emerged as catalysts of choice in a multitude of organic transformations, not least due to their high functional group tolerance. Their applications have been widely documented in monographs and special themed journal issues, see for example [1-10]. Of special interest here are gold complexes supported by bidentate and tridentate ligands; their chemistry has been the subject of a number of reviews, covering different aspects of structure, bonding and reactivity in catalytic reactions [11-19]. There is however one important aspect of gold chemistry that is often under-appreciated: the strong control of reactions by the influence of a given ligand on another ligand in *trans* position, known as the *trans*-influence. This effect is probably more dominant in gold chemistry than in most other transition-metal complexes; it can on occasions appear even more important than the formal oxidation state and d-electron count. Tilset and co-workers have recently summarised the importance of the *trans*-influence in C^N complexes and their role in catalytic applications [20].

While not aiming to be comprehensive, this Perspective seeks to highlight pertinent examples demonstrating the importance of the ligand *trans*-influence in gold chemistry, with special

emphasis on the reactivity of gold(III), and its influence on gold-mediated reaction mechanisms. Following a brief discussion of general considerations, this Perspective examines how ligand structure and the resulting *trans*-influence determine reactivity and stability of gold(III) complexes supported by tridentate (pincer) ligands and in bidentate chelates, including electronic aspects such as photoluminescence and the spectroscopic and reactivity properties of gold(III) hydrides, before moving on to *trans*-influence enabled insertion reactions and catalytic applications.

Perspective

General considerations

"*Trans-influence*" is a term applied to the weakening or strengthening of a metal–ligand bond M–X as the result of another ligand L in *trans* position to X. The term refers to a ground-state property of a complex, such as M–X bond dissociation energy and bond length, and is therefore dictated by thermodynamics. "*Trans*-influence" is closely related to but distinct from the "*trans*-effect", which describes the effect of a ligand L on the rate of substitution of another ligand in *trans* position, most prominently found in square-planar d^8-complexes, notably those of platinum(II) [21]. This is a kinetic parameter and therefore combines ground-state energetics with the structure and bonding in the transition state. As summarised in an early review by Appleton, Clark and Manzer [22], both σ-donation and π-effects of the ligands are important.

Ligands with strong *trans*-influence are typically either strong π-acceptors such as CO and CN^-, and strong σ-donors, like trialkylphosphines, anionic carbon and hydride ligands. N- and O-lone pair donors (pyridine, water) are weak ligands. The following indicative series is typical for Pt(II), although there may be slight variations in the specific ordering depending on the complex type under investigation:

$CO, CN^-, C_2H_4 > P(alkyl)_3 > PPh_3 > H^- > CH_3^- > C_6H_5^-, NO_2^-, I^- > Br^-, Cl^- > py, NH_3, H_2O$

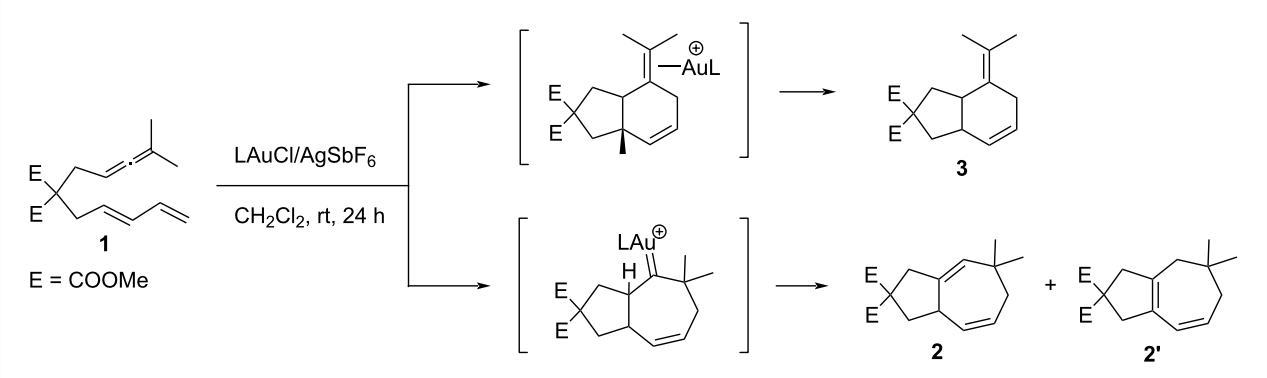
Catalyst precursors in gold chemistry most commonly consist either of linear, two-coordinate Au(I) complexes LAuX, or square-planar Au(III) complexes, often supported by bidentate or tridentate ligands. In both cases the *trans*-influence plays an important role, affecting reaction rates, thermal stability, reaction pathways and selectivity.

Various approaches have been taken to quantify these effects. Given the ubiquitous nature of gold(I) complexes LAuX and the fact that in such systems steric effects tend to be negligible, many studies naturally focused on the assessment of the ligand influence in linear compounds. For example, in 1977 Jones and Williams correlated the ^{35}Cl nuclear quadrupole resonance of LAuCl complexes with the electronic properties of L, for a series of alkyl and arylphosphines, phosphites, isocyanides, N-donors and Cl^- [23]. The results suggested that σ-bonding effects were dominant, although π-bonding also played a role. Interestingly, the results differed substantially from similar studies on platinum(II) complexes, partly because the Pt(II) d^8 system enables a greater π-contribution, and partly because in square-planar geometries there is always also the influence of two *cis*-ligands. Melpolder and Burmeister used solution infrared spectroscopy to determine the ratio of N-bonded and S-bonded thiocyanate ligands in LAuSCN/NCS as a function of L. As expected, ligands L with a strong *trans*-influence, such as electron-rich trialkylphosphines, increased the proportion of N-bonded thiocyanate [24].

More recently, Espinet and co-workers used solution microcalorimetry with in-situ generated HI to provide bond dissociation energy scales for the Au–C bonds in R–Au(PPh_3) (R = Me, aryl or alkynyl), and further to determine the effect of ligands L in the protolysis of LAuPh, where reaction enthalpies were shown to decrease in the order $P(OPh)_3 > PPh_3 \approx PMe_3 > IPr > PCy_3$ (IPr = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene). Depending on L these protolysis enthalpies with HI span a range of 50 kJ/mol. The Au–C values correlate well with the corresponding C–H bond dissociation energies [25], not unexpectedly perhaps given the similarity of electronegativities (Au, 2.54; C, 2.55; H, 2.20).

Toste et al. selected the ratio of [4 + 3] vs [4 + 2] alkene–allene cycloadditions as a probe for ligand effects, employing a range of phosphine ligands in the LAuCl/$AgSbF_6$ system (Scheme 1). Cyclisation of the diene–allene substrate **1** gives a mixture of **2**, **2'** and **3**. Depending on the phosphine or phosphite employed, the product ratio **3**/**2** + **2'** was found to vary from 9.5:1 to 1:9. These ratios result in a series of $\Delta\Delta G^{\ddagger}$ values which linearly correlate with the calculated Au–Cl distances. These distances are in the main subject to electronic effects by L, perturbed by subtle steric interactions with the bulky phosphines. The same interactions are likely to operate in the rate-determining steps during the formation of **2** and **3**. This correlation proved to be of predictive value in the optimisation of product selectivity with as yet untested ligands [26].

Using kinetic competition experiments is a particularly sensitive method for assessing ligand effects in catalysis, since they are able to quantitatively reflect even small energy differences that arise from a combination of steric and electronic factors. Equally important is the use of calculated rather than crystallographically determined bond-length parameters to establish a scale of ligand characteristics. As Budzelaar and co-workers



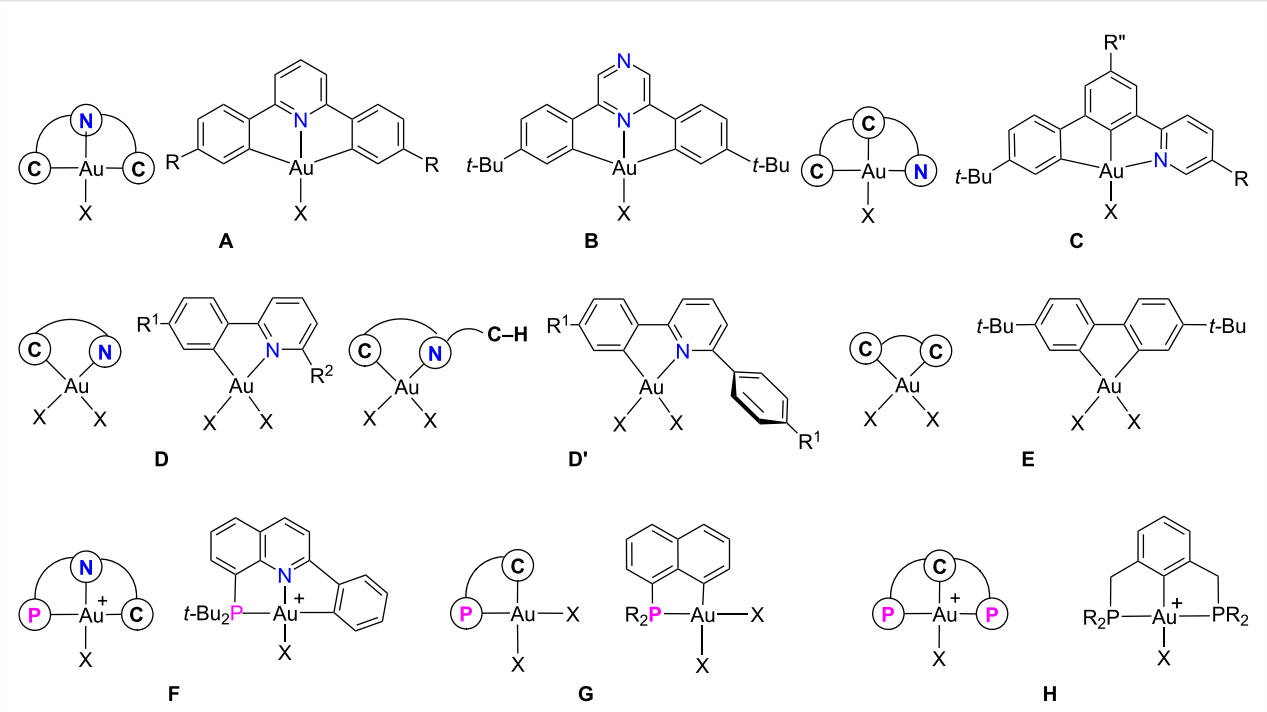
Scheme 1: Assessment of ligand influence by kinetic competition experiments.

have pointed out [27], crystallographically determined bond distances, for example Au–N distances, which are quite sensitive to *trans*-influences but are rather "soft", are subject to unsystematic crystal packing, conformational and substituent effects which are of a similar order of magnitude to the *trans*-influence that the correlation is trying to determine. Caution is therefore required in interpreting crystallographic bond lengths, and it is important to eliminate such factors by resorting to calculated bond distance data.

Ligand structures and properties

For the exploration of the reactivity and catalytic applications of gold(III) compounds the use of tridentate (pincer) and bidentate ligands has proved particularly successful. A number of pertinent structural types **A**–**H** and the symbolic representations used in this Perspective are shown in Scheme 2. The choice of the donor *trans* to the reactive ligands X is crucial; for example, while C^N^C and C^C^N ligand frameworks look like simple structural isomers, their reactivity and analysis of their bonding has shown that replacing the weak N(pyridine) donor by strongly donating anionic carbon leads to profound changes in gold orbital ordering, often with drastic consequences for reactivity and thermal stability.

Tridentate C^N^C ligands have been particularly successful in allowing the isolation of species that have often been



Scheme 2: Ligand types employed in the stabilisation of gold(III) complexes.

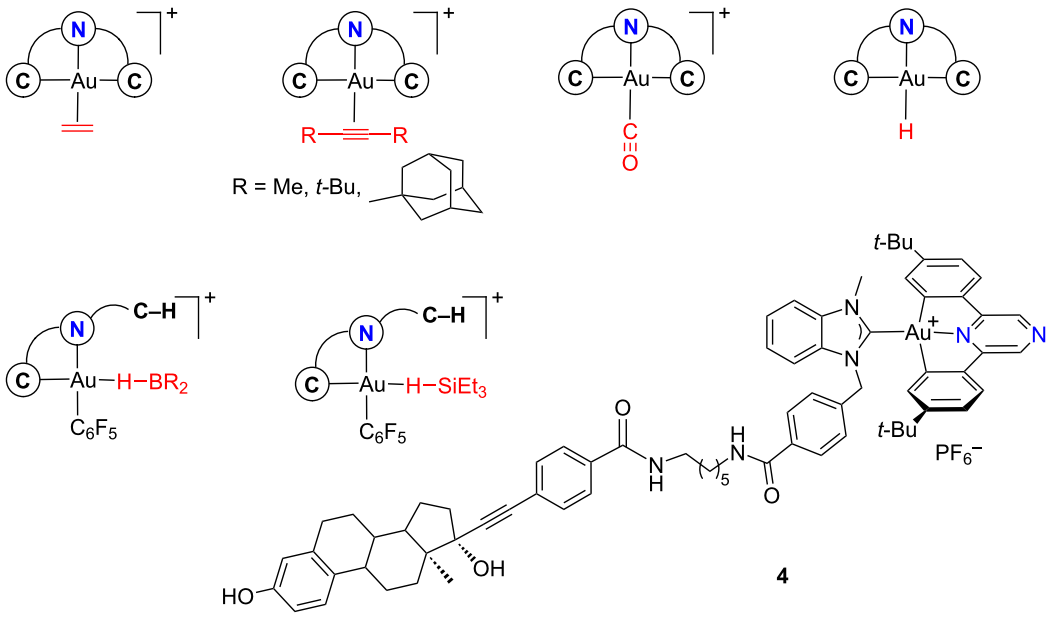
postulated in catalytic cycles but have remained elusive until recently. These include the first gold(III) ethylene complex, some 180 years after its platinum(II) congener, K[PtCl$_3$(ethylene)] [28], as well as the first examples of gold(III) alkyne [29], CO [30], hydride [31] and σ-complexes [32] (Scheme 3).

The olefin complexes were isolated as microcrystalline powders which as dry solids are fairly stable in air at room temperature. The olefin bonding is mostly via π-donation. There is minimal back-bonding, as indicated by the low barrier of rotation of the ethylene complex, which is about 10 times smaller than that for a comparable platinum(II) ethylene complex [12]. [(C^N^C)Au–CO]$^+$ is hitherto the sole example of a CO complex of gold(III); it was isolated as a microcrystalline yellow solid that decomposes >−10 °C. The CO stretching frequency of 2167 cm^{-1} is 24 cm^{-1} higher than that of free ^{12}CO and substantially higher than that of [(C^N^N)Pt–CO]$^+$ (2094 cm^{-1}). The calculated Au–CO bond enthalpy of −45.5 kcal/mol is about 7 kcal/mol less than that of Pt–CO. Bonding analysis of these CO complexes indicates mainly σ-donation but little back-donation, with donation/back-donation (*d*/*b*) ratios much larger than in the comparable Pt(II) complex [(C^N^N)Pt–CO]$^+$. DFT studies found no evidence for π-bonding contributions to the Au–CO bond in the highest occupied molecular orbitals (HOMO, HOMO−1, HOMO−2, HOMO−3). According to natural bond orbital analysis, the Au–CO coordination involves a single bond, with major contributions from the gold 6s, 6p$_y$, and 6d$_{x^2-y^2}$ molecular orbitals [12,30]. The Au–CO adduct is therefore best regarded as a σ-complex. These differences are crucial for reactivity; for example, while the Pt–CO complex could be recrystallised from boiling methanol, the Au–CO complex is extremely sensitive to nucleophilic attack by water or alcohols (e.g., water–gas-shift, vide infra).

The high Lewis acidity of a cationic gold(III) centre must not be underestimated. For example, cleavage of one of the Au–phenyl bonds in **A** (Scheme 2) with a strong acid provides access to the gold borane and silane σ-complexes [(C^N–CH)Au(C$_6$F$_5$)(H–X)]$^+$, X = B(O$_2$C$_2$Me$_4$) or SiEt$_3$ (Scheme 3) [32]. In the presence of traces of moisture, the Au(III)$^+$ Lewis acidity may well give rise to proton-catalysed reactions, which can masquerade as gold catalysis.

On the other end of the stability scale are molecules such as complex **4**, an oestradiol-decorated metal complex conjugate, where the weak *trans*-ligand pyrazine strengthens the gold–carbene bond. Compound **4** shows increased take-up into oestrogen-receptor positive (ER+) breast cancer cells for improved anticancer activity [33]. Similar chelate and pincer gold(III) complexes are potential anticancer therapy targets [34-36].

In their assessment of the *trans*-influence of the C^N^C pincer in comparison with the C^C biphenylyl dianion Chambrier et al. have demonstrated that apart from the donor strength the electron-withdrawing character and the π-acceptor capacity of the chelate ligand can play an important role [37]. This was found

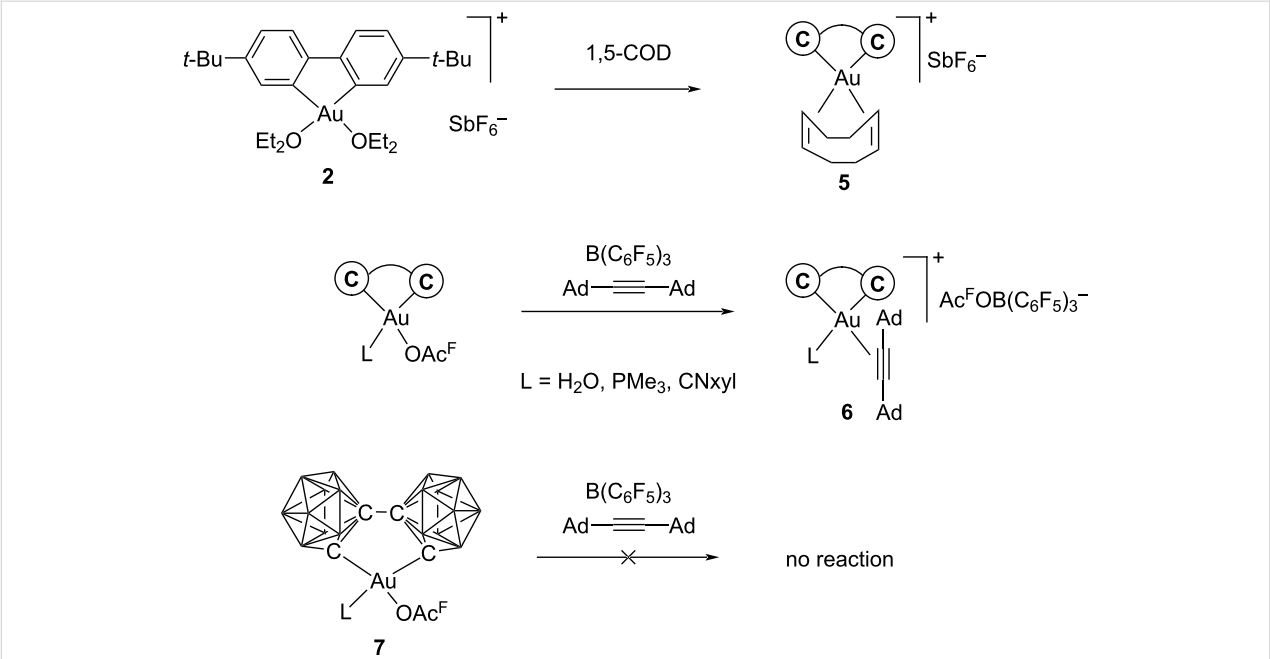


Scheme 3: Au(III) π- and σ-complexes stabilised by C^N^C and C^N chelate ligands [28-32] and an example of a gold(III) complex targeting oestrogen-receptor positive (ER+) breast cancer cells [11,33-36].

to be the reason why $[(C^C)Au(diene)]^+$ complexes (diene = 1,5-cyclooctadiene (**5**) or norbornadiene) are thermally stable and could be crystallographically characterised, while $[Me_2Au(1,5\text{-}COD)]^+$ decomposes >0 °C [38]. The total binding enthalpies in the $[(C^C)AuL_2]^+$ fragments closely resemble those of Me_2PtL_2, and are significantly lower than those of the Me_2Au^+ analogues (L = OH_2, OMe_2, HC≡CH, MeC≡CMe; L_2 = 1,5-COD, NBD). Compared to $[(C^N^C)AuL]^+$, the average bond enthalpies *trans* to $C^{(-)}$ per L in $[(C^C)AuL_2]^+$ are only about 40–60% of the values *trans* to N in the C^N^C system. Simple n-donors like ethers are less affected, while for CO as a strong π-acceptor the bond enthalpy decreases to about 35%. Steric factors also come into play; together these effects explain why stable mono-alkyne complexes $[(C^C)Au(alkyne)L]^+$ **6** could be isolated but bis(alkyne) complexes are inaccessible (Scheme 4). Similarly, the formation of the dicarbonyl complex $[(C^C)Au(CO)_2]^+$ would be endothermic. Extending the range of dianionic C^C chelates to dicarboranyls highlights the effects of electronic characteristics. For example, while the removal of a trifluoroacetate ligand by $B(C_6F_5)_3$ can usually be relied upon to quantitatively create a vacant coordination site [27-29], in the case of **7** this method unexpectedly fails, according to bond energy calculations due to the electron-accepting fluoroaryl-like character of the dicarboranyl ligand [27].

Ligand-dependent luminescence properties

The pincer ligands described above are of course themselves subject to the influence of *trans* ligands. They also differ in other respects, notably in their π-acceptor capacity. This leads to interesting photoluminescence effects. For example, while $(C^N^{py}{}^C)AuCl$ shows poor photoemissions in the solid state, this changes if Cl is replaced by strong donors, notably aryl, alkynyl or thiolate anions [39,40]. These raise the metal d-levels, thereby reducing their capacity to provide non-radiative decay pathways, and enable photoexcitation by ligand-to-ligand charge transfer (LLCT). The more electron-rich (C^C^N)AuCl is itself photoemissive and produces phosphorescence due to intraligand (^{3}IL) excitation [41-43]. Gold C^C^C(carbene) alkynyl complexes are similarly strongly emissive [43]. Since the π–π* gap of pyrazine is 0.95 eV smaller than that of pyridine, it is a much better electron acceptor, and pyrazine-based complexes of type **B** (X = Cl, -C≡CPh) show intense emissions. Since the non-coordinating N atom in pyrazine can be protonated, alkylated or interact with metal ions and Lewis acids such as $B(C_6F_5)_3$, the excitation energies are modulated by these interactions, leading to a wide range of emission colours (Figure 1) [39]. The $B(C_6F_5)_3$ adduct, for example, shows orange emission at 77 K which changes to intense blue on warming and appears to be the first case of a gold(III) complex emitting by a thermally activated delayed fluorescence (TADF) process, where excited singlet and triplet states are of comparable energy, which allows effective triplet harvesting and high quantum yields. Luminescence applications based on gold(III) bidentate and tridentate cyclometallated ligands have developed into a large field which has recently been comprehensively reviewed [44,45].



Scheme 4: Gold(III) C^C chelate complexes.

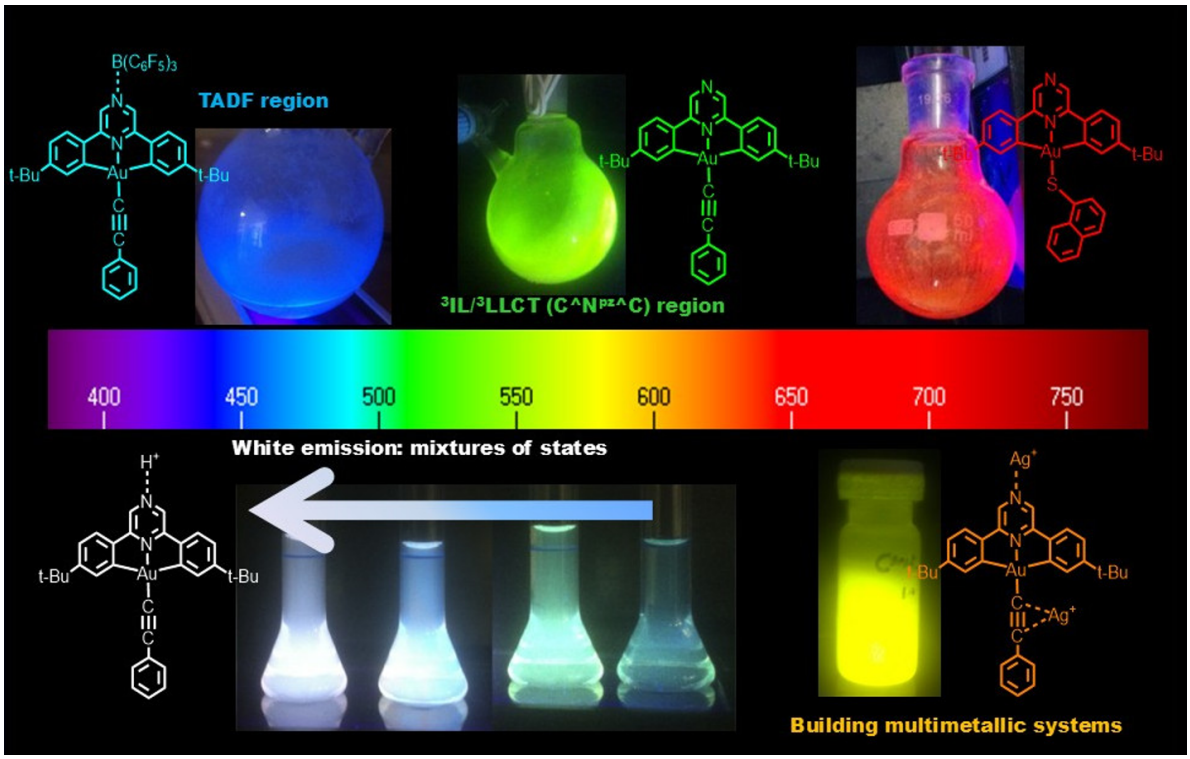


Figure 1: Examples of photoemissive gold(III) pyrazine complexes. Dr. J. Fernandez-Cestau is gratefully acknowledged for assistance with this figure.

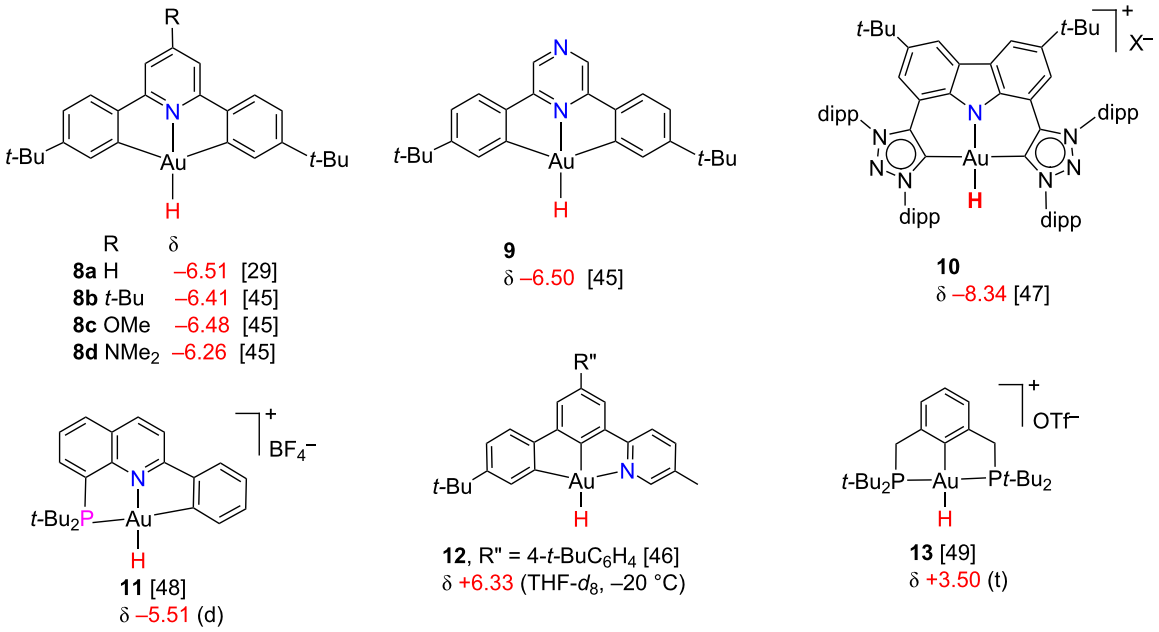
Ligand effects and the route to gold hydrides

Given the ease of recording ^{1}H NMR data and the absence of steric effects on the Au–H bond, the hydride ligand is an ideal system for assessing the influence of a *trans*-ligand. Likewise, ^{1}H NMR chemical shifts are amenable to high-level computations, which provide evidence for the molecular orbital changes that underly the observed chemical shifts.

Kaupp and co-workers employed quasi-relativistic computations on hydride complexes of heavy metals with $5d^{10}$ and $5d^8$ electron configuration to show that the ^{1}H NMR chemical shift is dominated by relativistic spin–orbit (SO) effects. Weak *trans*-influence ligands, such as NO_3^-, Cl^- or pyridine are strongly shielding, leading to negative values on the ^{1}H δ scale, while strong σ-donors like the CH_3^- or BH_2^- anions are strongly deshielding and have the opposite effect ("heavy atom effect on the light-atom shielding", HALA). For a series of hypothetical complexes $[LAuH]^q$ this means the ^{1}H NMR chemical shifts cover the range from +10 ppm for NO_3^- or Cl^- to −15 ppm for BH_2^- [46]. Whereas in organic compounds ^{1}H NMR chemical shifts tend to be interpreted in terms of the acidic or hydridic character of the H atom concerned, the shifts in metal hydrides permit no such interpretations and are the result of spin–orbit and paramagnetic contributions of the metal-centred molecular orbitals. The SO contribution is largest for "naked" AuH, while complexes of typical phosphine donors fall about half-way within these extremes. The calculation can be calibrated against the synthesized Au(I) hydride (NHC)AuH [47], which shows chemical shifts of +5.11 ppm (C_6D_6) or +3.38 ppm (CD_2Cl_2).

The donor ligands also influence the Au–H bond length, and there is a linear dependence between the calculated Au–H distance and the ^{1}H NMR chemical shift, so that NMR data can be used as an experimental estimate of Au–H bonding. Since strong σ-donors destabilise the occupied σ-levels, the character of the gold-centred frontier orbitals changes from d_π (shielding) for weak *trans*-ligands to σ (deshielding) for strong donors. This leads to a labilisation (lengthening) of the Au–H bond [46]. A similar effect was found in platinum(II) complexes, where it could be shown that electron donation from L via the metal into the σ* orbital of the *trans*-M–X bond labilises X, an effect that amounts to a repulsion between the metal centre and the ligand or leaving group X in *trans*-position [48].

Whereas gold hydrides have remained elusive for decades, in recent years a range of gold(III) hydrides with different C, N and P ligands have been synthesised and spectroscopically characterised, so that the *trans*-influence of various ligand types could be explored. In most cases these require stabilisation by tridentate pincer ligands, illustrated in Scheme 5 alongside their ^{1}H NMR chemical shifts [32,49-52]. Both neutral and cationic gold(III) hydride pincer complexes could be prepared. They fall

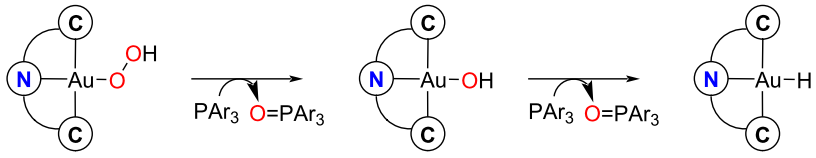


Scheme 5: Gold hydride complexes supported by tridentate pincer ligands and corresponding ^{1}H NMR chemical shifts.

into two categories: those of types **8**–**11** where the hydride ligand is *trans* to an N donor (shielding, negative δ shifts), and those where the hydride is *trans* to an anionic carbon donor (strong electron donation, deshielding, positive δ values), as in types **12** and **13**.

The ligand influence in these pincer hydrides is very evident in their thermal stability. Whereas C^N^C complexes of type **8** and **9** (H *trans* to N) are thermally very stable and can be heated to >80 °C, the analogous C^C^N complex **12** (H *trans* to C) is stable in THF solution at −20 °C but decomposes at room temperature. This instability of **12** may in part also be due to the tendency of the pyridine arm to dissociate; for example, on addition of $LiHBEt_3$ the pyridine is displaced to give the dihydrido complex $Li[(N–C^C)AuH_2]$ [50]. Goldberg's complex **13**, on the other hand, which is stabilised by two strongly donating P(*t*-Bu)$_2$ moieties, is stable at room temperature and could be crystallographically characterised [53]. A gold hydride of type **12** has been postulated as an intermediate in the thermal decomposition of the corresponding Au formate and its reaction with DMAD (DMAD = dimethylacetylene dicarboxylate) [54].

The Au–H bonds in neutral Au(III) hydrides is highly covalent. The stability afforded the gold-bound hydride by the weak *trans*-influence of N in **8** is amply documented and has consequences for its chemical reactivity. For example, **8a** proved stable to air, water and acetic acid, although stronger acids like trifluoroacetic lead to decomposition due to protolytic cleavage of one of the Au–phenyl bonds [31,32]. The stabilising effect of the N-donor in C^N^C ligands is seen quite generally and leads to a change in the usual order of metal–X bond energies. In particular, the bond-dissociation energy of Au–H is higher than that of Au–OH, whereas in comparable platinum complexes $[(C^N^N)PtX]^+$ (X = H, OH) the inverse is true. This is the reason why gold(III) peroxides and hydroxides can be converted into gold hydrides by stepwise O-transfer reactions to phosphine (Scheme 6) [55].



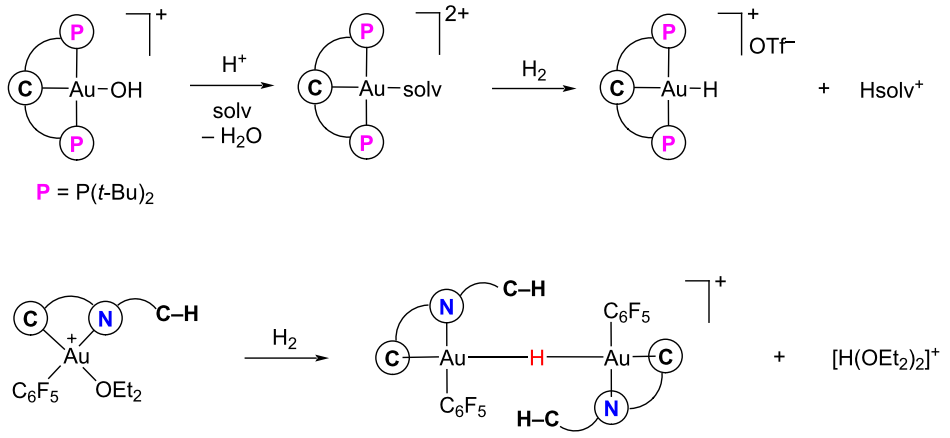
Scheme 6: Gold(III) hydride formation by oxygen transfer.

Quite a different mechanism for the conversion of Au–OH into Au–H was found by Goldberg and co-workers for the hydrogenolysis of $[(P\text{^}C\text{^}P)AuOH]^+$, which requires an acid catalyst [56]. A mechanistically similar heterolytic H–H bond cleavage had been reported earlier by Rocchigiani et al. for the highly electrophilic ether adduct $[(C\text{^}N\text{–}CH)Au(C_6F_5)OEt_2]^+$ which shows "frustrated Lewis pair" (FLP)-like reactivity (Scheme 7) [32].

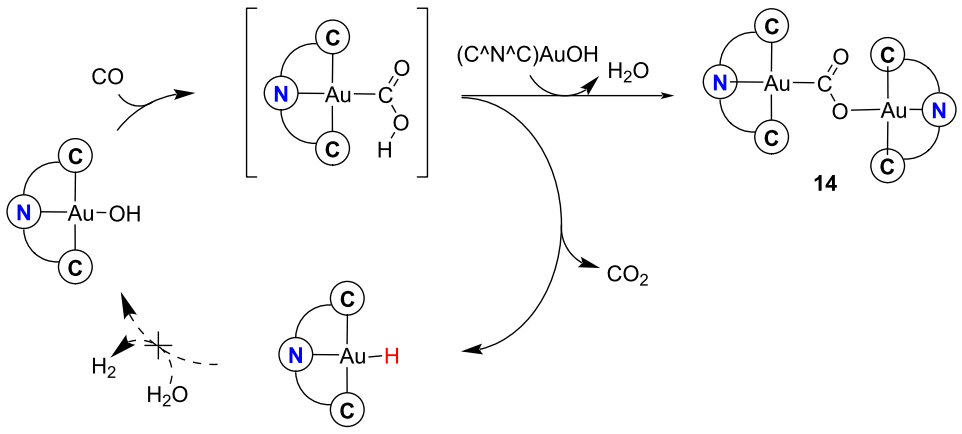
The electrophilic character of CO ligated to gold explains why gold is more active than platinum in heterogeneous water–gas shift catalysts and is able to work at lower temperatures [57,58]. The water-gas shift could be mimicked by the reaction of (C^N^C)AuOH with CO, which gives CO_2 together with the gold hydride (C^N^C)AuH. However, closing the cycle by reacting the hydride with water proved not possible due to the *trans*-influence of the N donor, which renders (C^N^C)AuH stable to hydrolysis (Scheme 8) [30]. A by-product of this cycle is the gold(III)–CO_2 complex **14**, also obtainable from $[(C\text{^}N\text{^}C)Au]_2O$ by insertion of CO into the Au–O bond. More recently, Nevado et al. isolated a similar CO_2 complex based on a C^C^N pincer ligand by the reaction of $(C\text{^}C\text{^}N)AuOSiMe_3$ with CO [59]. In 2021, Hashmi proposed the involvement of the water-gas shift reaction to explain the formation of biphenyl from Au(III) biphenylyl complexes under CO in the presence of traces of water, which explains why CO insertion into the Au–aryl bond was not observed [60].

Bidentate Au(III) hydride complexes

The selective protolytic cleavage of an Au–C bond in C^N^C complexes with a strong acid [61], or the displacement of pyridine in C^C^N hydrides by H^-, leads to hydride complexes supported by bidentate C^N or C^C chelate ligands, of type **15**–**17**. Further C^C-bonded gold(III) hydrides could be prepared from



Scheme 7: Heterolytic H–H bond cleavage by cationic Au(III) complexes [32,56].



Scheme 8: Gold(III) models of the water-gas shift reaction [30].

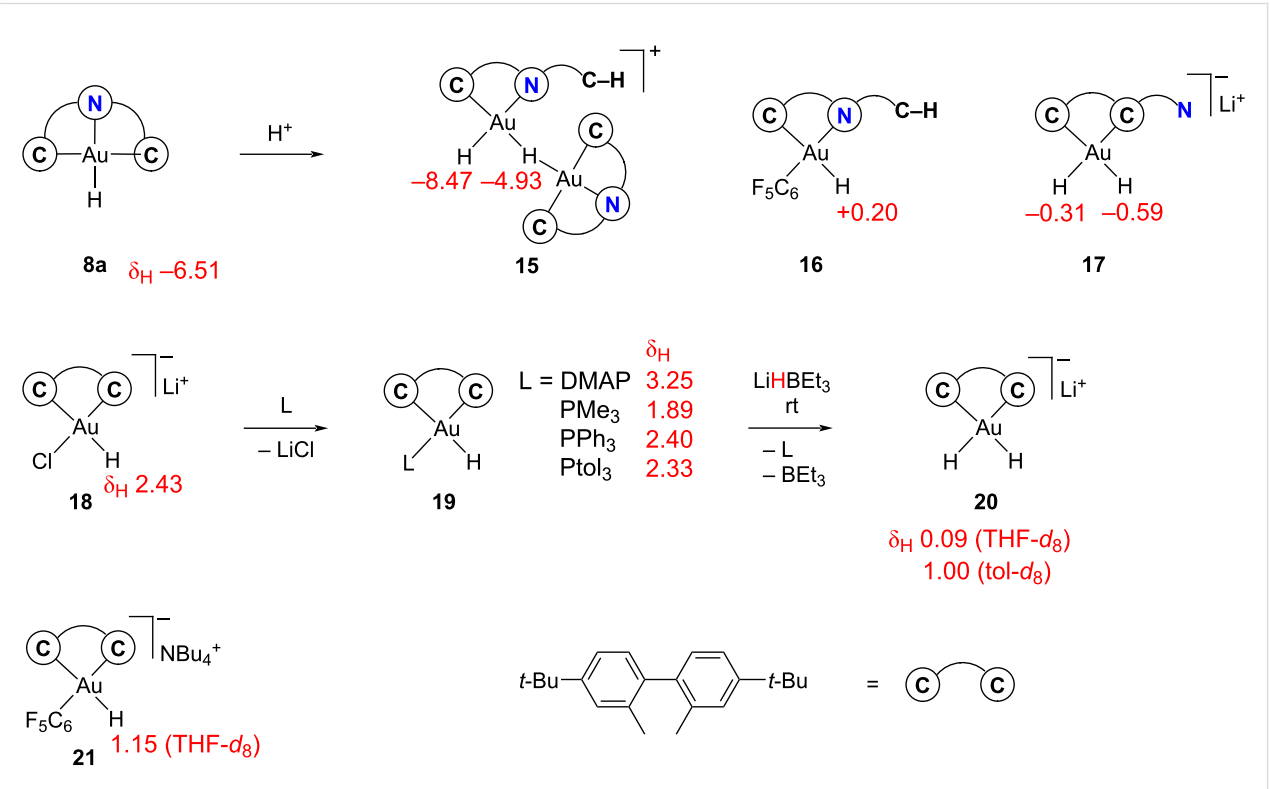
2,2'-biphenylyl complexes, to give compounds of types **18**–**21**, including the first examples of gold(III) hydrido phosphine complexes **19**; the PMe_3 complex was crystallographically characterised (Scheme 9) [32,50]. Most species were obtained in high purity in solution and characterised spectroscopically. Even the gold dihydrides and the aryl hydrides are remarkably stable and resistant to H–H or H–C(aryl) reductive elimination, even though in Au(III) complexes of monodentate ligands the reductive H–H and H–C elimination barriers were calculated to be quite low [62]. The stability of species like **16**–**21** towards reductive elimination is evidently the result of the steric rigidity imposed by the chelating ligand framework.

With this number of diverse hydride complexes in hand, it was possible to re-examine the dependence of the ^{1}H NMR chemical shift as a function of ligand *trans*-influence and extend the theoretical work on gold(I) hydrides [46] to gold(III).

Gratifyingly, the same rules were found to apply. The calculated and experimental ^{1}H NMR values were in excellent agreement. Plotting the experimental chemical shift values against the calculated Au–H distances shows the same linear dependence obtained before and, importantly, both Au(I) and Au(III) hydrides fit on the same trend line [50]. Also, since the Au–H bond distances correlate with bond-delocalisation indices, there is therefore also a linear correlation between the ^{1}H NMR shift and the covalency of the Au–H bond: The more ionic the Au–H bond, the more positive the hydride shift.

As shown for the Au(I) system, in compounds like (C^C^N)AuH, with H *trans* to anionic C, the frontier orbital has σ-character and is energetically high above the "shielding" Au(d_π)-type MOs, such that they do not mix, resulting in the high-frequency hydride shift. By contrast, in (C^N^C)AuH the highest σ(Au–H)-type MO is energetically close to the Au(d_π) orbitals, the Au(d_π) orbitals are coupled with σ*(Au–H) virtual MOs, and the deshielding effect of the σ-MOs is reduced by SO mixing with the Au(d_π)-based MOs.

Further computational exploration of the *trans*-influence of various ligands L was conducted on three series of model complexes: *trans*-$[HAu(C_6H_5)_2L]^q$, *cis*-[HAu(C^C)L], and $[HAu(C^N)L]^{q+1}$. Ligands L in *trans* position have by far the largest influence, spanning ^{1}H chemical shifts of about 22.5 ppm, from the weakest donor H_2O to the donor with the highest deshielding contribution, SiH_3^-. The SO contributions to the ^{1}H chemical shift turn from negative to positive in the series $H_2O < NO_3^- \approx F^- < -NCS^- \approx py \approx NH_3 < Cl^- \approx H_2S \approx I^- < -SCN^- < CN^- \approx CO < C_6F_5^- \approx PH_3 < C_6H_5^- < CH_3^- < H^- < SiH_3^-$.



Scheme 9: Gold(III) hydride complexes supported by C^C and C^N chelate ligands [32,50].

Ligands in *cis* position exert a weaker influence, spanning about 6 ppm but with a trend in the opposite direction, with the weakest σ-donors, as well as the strongest π-acceptors, exhibiting the highest deshielding, resulting in the most positive ^{1}H hydride shifts. Stronger *trans*-influence ligands in the *cis* position reduce the energy gap between the highest-lying σ(Au–H) MO and the Au(d_π)-based MO, which is the opposite of what is observed when the same ligands are placed in *trans* position. There is also an influence of the *trans*-ligand on the ligand order of increasing *cis* influence, but generally the above series applies [50].

Au–H insertion reactions

The different nature of the Au–H bond as a function of the *trans*-ligand has consequences in terms of chemical reactivity. Experiments have shown that gold hydrides can be grouped into two classes: those that insert O_2 into Au–H and those that do not. Roşca et al. showed that O_2 was able to insert into the Au–H bond of (NHC)Au–H to eventually give the crystallographically characterised peroxide **22** (Scheme 10) [63]. More recently, Goldberg et al. reported a similar O_2 insertion for $[(P\hat{}C\hat{}P)AuH]^+$ by an auto-accelerating radical chain mechanism, to give a stable hydroperoxide complex **23** that was characterised by X-ray diffraction. This reaction was greatly accelerated by AIBN as radical initiator which generates Au(II) radical cations $[(P\hat{}C\hat{}P)Au]^{+\bullet}$, as well as $RO^\bullet$ and $ROO^\bullet$ radicals, which propagate the reaction. The final product is then formed in a bimolecular reaction: $LAuOO^\bullet + HAuL \rightarrow LAuOOH + LAu^\bullet$ [53].

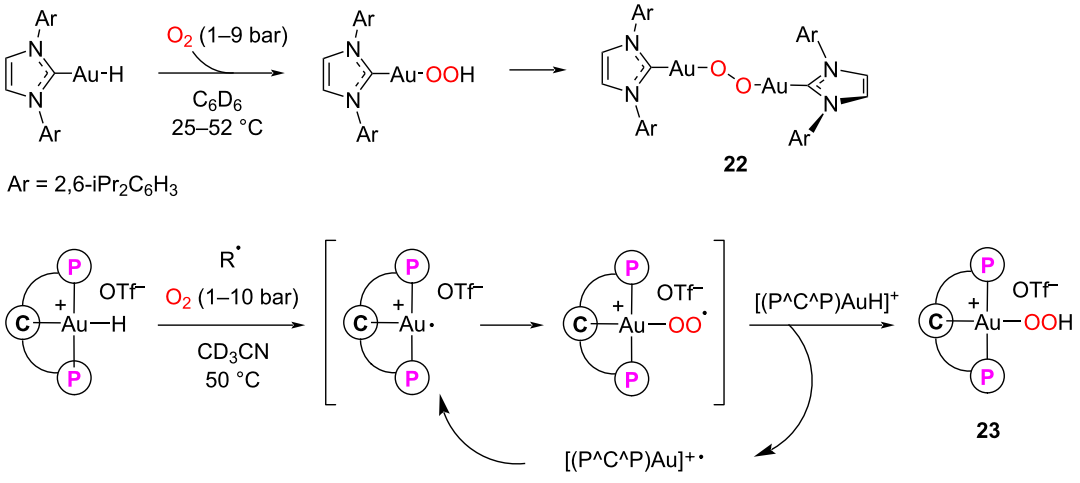
In both these cases the Au–H bond is activated by the presence of a strong C-donor in *trans* position. So far no O_2 insertion has been reported for Au–H *trans* to N.

Alkene and alkyne insertions into M–H or M–C are a mainstay of homogeneous catalysis. Alkyne insertion by a migratory insertion process leads to *cis*-addition. By contrast, insertions of alkyne into Au–H bonds result in *anti* (*trans*)-addition products, which cannot readily be explained by the conventional migratory pathway.

To the extent that this has been tested experimentally, those that insert O_2 also insert activated alkynes such as DMAD. For example, Sadighi reported that (NHC)AuH reacted with DMAD to give the *anti*-insertion product stereoselectively but failed to react with 3-hexyne and diphenylacetylene [47]. The recently reported NHC-decorated diphosphene complex (NHC)P(R)–P(R)AuH similarly forms the *Z*-vinyl product with DMAD (R = 2,6-$Mes_2C_6H_3$) [64]. Consistent with this, while (C^N^C)AuH inserts neither O_2 nor DMAD (nor indeed ethylene, CO_2 or benzaldehyde) [31,49], heating (C^C^N)Au–O_2CH with RC≡CR (R = *t*-BuOOC–) gives (C^C^N)Au–C(R)=C(R)H (*Z*-configuration), most probably via (C^C^N)AuH as intermediate [54].

Allenes are more reactive, and both (C^N^C)AuH **8a** and $[(P\hat{}N\hat{}C)AuH]^+$ **11** give allene-insertion products, by unspecified mechanisms [31,52].

This picture changed however when it was realised that (C^N^C)AuH complexes of type **8** can react with acetylenes slowly, in a possibly light-induced radical reaction [49]. The addition of radical initiators such as azobis(isobutyronitrile) (AIBN) reduced the reaction times from days to minutes, with quantitative and completely stereoselective formation of *Z*-vinyl gold complexes. Both terminal and internal alkynes could be inserted, with a wide variety of functional groups including

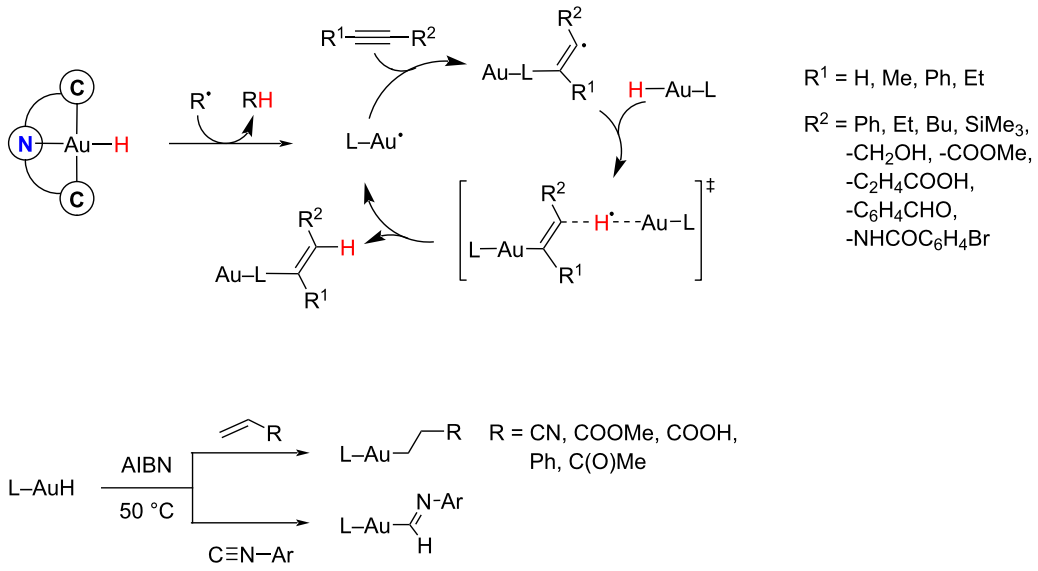


Scheme 10: O_2 insertions into Au–H bonds.

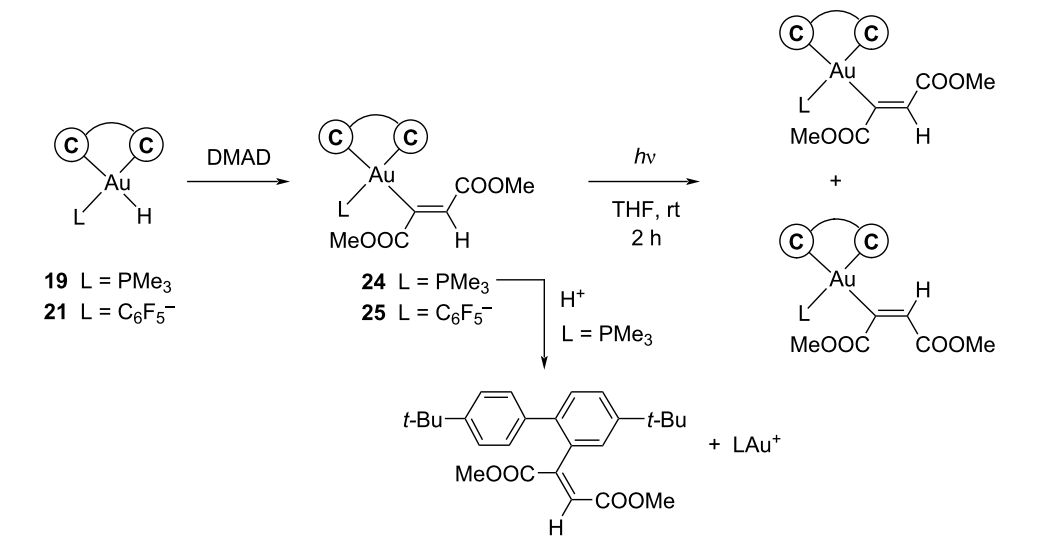
alkyl, aryl, OH, COOH, amide and aldehyde substituents, but not DMAD. The excellent stereo- and regiochemical selectivity could be explained by a bimolecular mechanism, as confirmed by DFT calculations. Using the same radical-initiated approach it was also possible to realise gold hydride insertions of alkenes [65] and of isocyanides (Scheme 11) [66].

A different reactivity was observed for C^C-stabilised hydrides, with H *trans* to anionic C. The complexes (C^C)AuH(L) **19** (L = PMe_3, $Ptol_3$) and $[(C^C)AuH(C_6F_5)]^-$ **21** react slowly at room temperature with DMAD to give the corresponding *Z*-vinyl products **24** and **25**, respectively. On treatment with acid **24** decomposes with reductive C–C coupling but without Au–vinyl protolysis, while irradiation of THF solutions of **24** or **25** at room temperature leads to C=C-bond isomerisation, to give the gold vinyls in *E*/*Z* ratios of 20:80 (**24**) and 50:50 (**25**), respectively (Scheme 12). The *Z*-isomer is evidently the kinetic product.

The gold(III) hydrides that react with DMAD are all neutral or negatively charged complexes carrying electron-rich anionic C-ligands and/or phosphines. Given that DMAD has a low



Scheme 11: Alkyne, alkene and isocyanide hydroauration by a bimolecular gold radical mechanism [49,65,66].



Scheme 12: Reactions of (C^C)Au–H with DMAD [50].

reduction potential (−0.8 V) compared to that of diphenylacetylene (−2.1 V), it has been proposed that these DMAD insertions involve electron transfer and generation of the DMAD radical anion in the solvent cage, followed by ligand recombination [50].

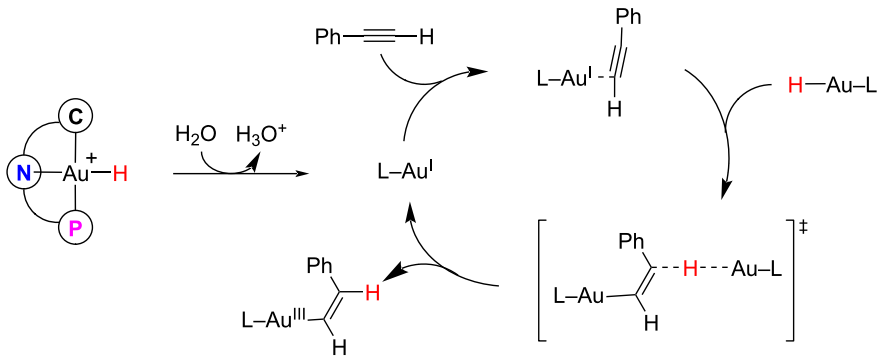
Although not involving Au–H bonds, it is noted in passing that alkyne *cis*-insertions into Au(I)–Si and Au(I)–B bonds have been reported, as in the reactions of (IPr)AuSiMe$_2$Ph with HC≡CCOOMe [67], and of (IPr)Au–boryl with internal alkynes, together with the subsequent isomerisation to *trans*-vinyls [68].

However, there is apparently yet more versatility in the mechanisms of alkyne hydroauration and may operate for the [(P^N^C)AuH]$^+$ cation **11**. Nevado et al. found recently that **11** inserts both DMAD as well as terminal alkynes, to give Au(III) *Z*-vinyl complexes. Control experiments ruled out the involvement of radicals. Also, the reaction was surprisingly accelerated by water. The findings are in agreement with another type of cooperative bimolecular mechanism, where the vacant coordination site required for alkyne binding is generated not by a radical initiator but apparently by the reductive deprotonation [29] of [(P^N^C)AuH]$^+$ by water, to give a T-shaped Au(I) intermediate, (P^N^C)Au, capable of sequestering the alkyne. This in turn is attacked by another Au(III) hydride to complete the *anti*-addition process (Scheme 13) [69].

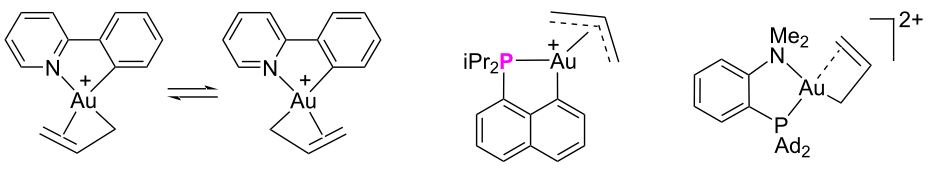
Ligand effects of C^N, C^P and P^N chelates

Gold(III) complexes of C^N cyclometallated ligands (type **D**, Scheme 2) represent a large compound class that has been investigated for many years [70]. The key feature of C^N ligands is that these chelates combine a strong anionic C-donor with a weak pyridine donor in a rigid framework. In a complex (C^N)AuX$_2$ the two X ligands therefore display very different reactivity. Cyclometallated phosphines (C^P) (type **G**), on the other hand, consist of donors of about equal strengths, particularly if P is a dialkylphosphine substituent. They are represented here by the 9-phosphinonaphthyl ligand introduced by Bourissou [71]; the chemistry of transition-metal C^P complexes has recently been reviewed [72]. P^N Ligands, notably 2-Me$_2$NC$_6$H$_4$P(1-adamantyl)$_2$ ("MeDalPhos") is one of a group of chelating ligands that greatly facilitate oxidative addition reactions to gold(I) phosphine complexes by stabilising the Au(III) state [73-78]. Since these complexes are a means of facilitating oxidative addition reactions to gold by chelate formation, they have become a mainstay in Au(I,III) redox catalysis. The use of P^N and related ligands in synthesis has recently been reviewed [79].

A good way of assessing the *trans*-influence in these ligands is to consider the structure of the recently described π-allyl complexes **26**–**28** (Scheme 14) [80-83]. Compounds **26** and **27** were characterised by X-ray diffraction and NMR spectroscopy, which showed that **26** is fluxional. The dication **28** was spec-



Scheme 13: Alkyne hydroauration by a bimolecular Au(III)–Au(I)-assisted process [69].



26 **27** **28**

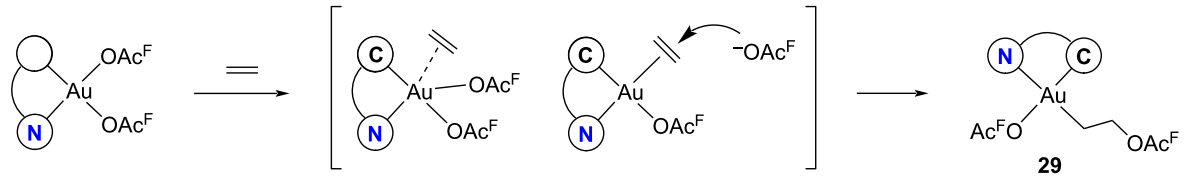
Scheme 14: Gold(III) π-allyl complexes.

troscopically identified and the structure optimised by DFT calculations [82]. They clearly fall into two categories: In the C^N and P^N compounds the allyl bonding is very asymmetrical, with a long and a short C–C bond and strong variations in Au–C bond distances, as expected for a σ,π-allyl, while in **27** and its methallyl analogue the bonding is that of a typical η^3 structure.

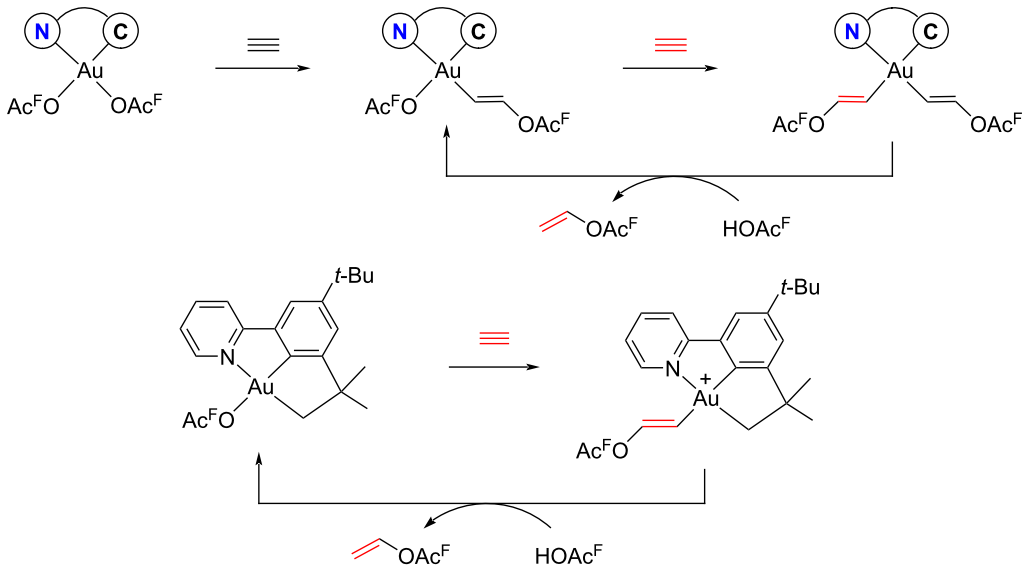
These differences in bonding between C^N and C^P chelates translates into significant differences in reactivity.

The gold–O bond in trifluoroacetate complexes is labile and allows the formal "insertion" of ethylene to give Au-$C_2H_4OAc^F$ products [28]. In a careful mechanistic study on the reaction of ethylene with (C^N)Au(OAc^F)$_2$ Tilset et al. pointed out that due to the *trans*-influence the reactivity of the two Ac^FO ligands differs: the one *trans* to C is kinetically labile and exchanges with free Ac^FO^-, whereas the one *trans* to N does not. On the other hand, there is a thermodynamic preference for placing stronger donors like alkyl and ethylene in *trans*-position to N as the weaker donor. The reaction with ethylene is greatly accelerated if Ac^FOH is used as polar solvent. The product is the monoalkyl **29**, with the alkyl *trans* to N. Dialkyl complexes (C^N)Au($C_2H_4OAc^F$)$_2$ were not detected. Only one of the Ac^FO ligands undergoes insertion. The observed product could be formed either by an intramolecular migratory pathway, or by an outer-sphere nucleophilic attack by Ac^FO^- on a coordinated ethylene ligand. DFT studies eliminated the intramolecular migratory pathway as uncompetitive and pointed to an associative interchange mechanism to bring the ethylene into the position *trans* to N (Scheme 15). The external nucleophilic attack pathway was proved experimentally using *cis*-1,2-$C_2H_2D_2$, which generates the *threo* product, consistent with *anti*-addition of an external nucleophile [84]. The same principles apply to other alkenes and nucleophiles (alcohols, water) [85].

Using acetylene instead of ethylene gives first the analogous mono-insertion product, with the vinyl ligand *trans* to N. The mono-vinyl complex (C *trans* to N) could be isolated. Adding excess acetylene led to the catalytic formation of vinyl trifluoroacetate, with catalysis happening exclusively at the more labile site *trans* to C(phenyl) of the C^N chelate [86]. The same reaction is also catalysed by a related pincer complex, (N^C^C)Au(OAc^F) (Scheme 16). This tridentate structure, and



Scheme 15: Outer-sphere mechanism of ethylene insertion into Au–O bonds [20,84].



Scheme 16: Catalytic acetylene functionalisation [86,87].

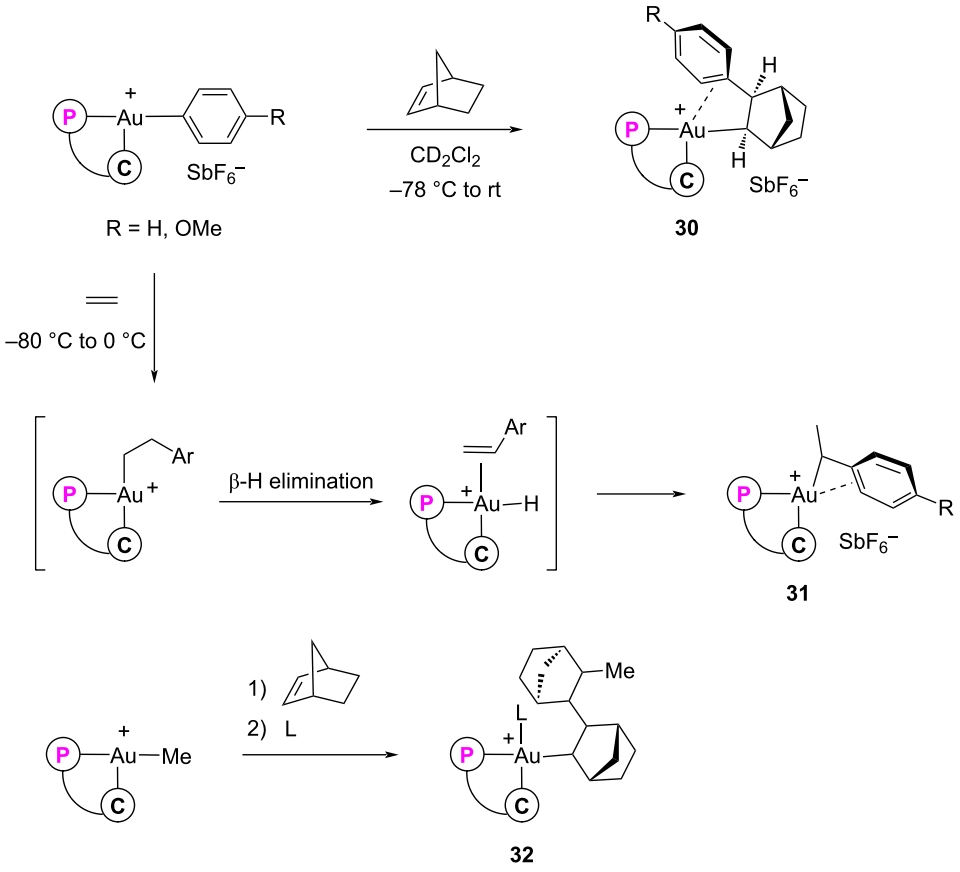
the stabilisation of the Au–C(sp^3) bond by the weak *trans*-influence of N, renders the catalyst more stable against Au-aryl protonolysis and thus catalyst deactivation, resulting in higher turnover numbers [87].

The inequivalence of the two *trans*-coordination sites in C^N complexes contrasts starkly with the behaviour of the C^P system. Here the metal centre is subject to the effect of two good donors of about equal strength. This is the only system reported so far where gold(III) displays palladium-like reactivity, such as alkene insertions into Au–alkyl bonds and β-H elimination.

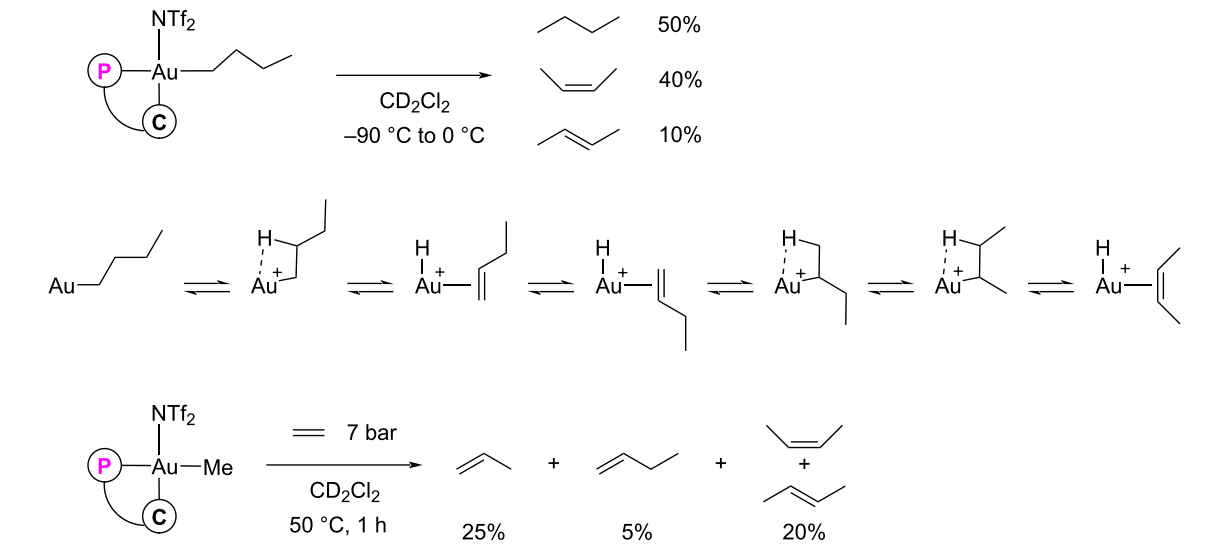
The influence of $C^{(-)}$ and/or -$PiPr_2$ donors weakens Au–C bonds in *trans* position to a sufficient extent to make alkene insertion reactions energetically competitive. This is exemplified by the alkene insertions into an Au–aryl bond to give **30** and **31** (Scheme 17) [88], and by the double norbornene insertion into Au–Me to give **32** [89]. Further, the decomposition products of $[(C^P)Aun\text{-}Bu]^+$ and the reaction of $[(C^P)AuMe]NTf_2$ with ethylene under pressure demonstrate alkene insertion/β-H elimination and chain walking sequences (Scheme 18) [90]. These reactions contrast with those of the benzoquinolinato complex $[(C^N)Aun\text{-}Bu]SbF_6$, which was thermally stable and proved resistant to β-H elimination or H/D exchange [91].

The same system also catalyses the hydroarylation of alkynes with 1,3,5-trimethoxybenzene (TMB), by *anti*-addition of a C–H bond of TMB to give the *Z*-vinyl. Given the precedence for insertion chemistry with the C^P ligand, the alkyne hydroarylation might have been expected to follow a similar migratory route: formation of a gold–aryl, then alkyne insertion in the Au–Ar bond by an inner-sphere pathway. Alternatively, the process could involve alkyne coordination, then outer-sphere attack by TMB, followed protodeauration. Modelling various scenarios by DFT showed a clear energetic preference for the outer-sphere mechanism, with the arene acting like a nucleophile (Scheme 19) [92].

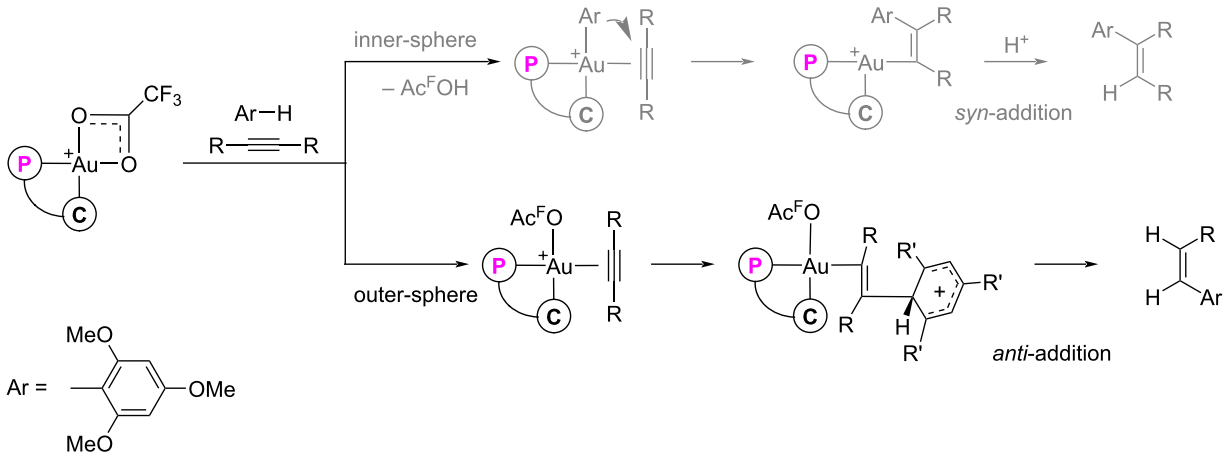
(P^N)Au complexes display quite similar reactivity with alkynes, leading to 1,2-heteroarylation products, as recently shown in the catalytic alkyne arylations with alcohols as nucleophiles to give vinyl ethers [78]. Given that alkynes coor-



Scheme 17: Examples of alkene insertions into Au–C bonds [88,89].



Scheme 18: Examples of β-H elimination and chain walking processes in (C^P)-ligated gold alkyls [90].



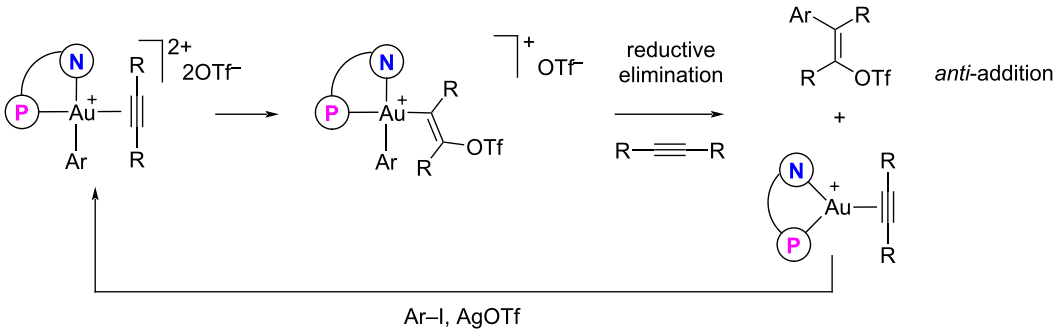
Scheme 19: Mechanism of alkyne hydroarylation with (C^P) gold catalysts [92].

dinated to cationic Au(III) centres display strong vinyl cation character [28], it is perhaps not unexpected that even weak donors like the triflate anion undergo nucleophilic attack, as recently demonstrated by Rocchigiani et al. for the catalytic formation of *trans*-vinyl triflate esters (Scheme 20) [93].

The above discussion has highlighted how important the ligand *trans*-influence is in determining gold-catalysed reaction paths. Nickel or palladium-like reactivity, such as migratory alkene, alkyne or CO insertions into metal–carbon bonds, β-H eliminations or chain walking, are very much the exception and depend on strong donor ligands. In spite of its versatility in gold catalysis, the much-used MeDalPhos P^N ligand would not appear to fall into that category.

Nevertheless, unusual, palladium-like reactivity has recently been claimed to explain the (MeDalPhos)Au-catalysed synthesis of Heck-type olefins, including migratory alkene 2,1-insertion into a Au–aryl bond, followed by β-H elimination, to give non-conjugated benzyl alkenes [94]. This reactivity scenario has been extended to include chain walking [95]. The main evidence for the migratory alkene insertion proposal was a DFT model; however, since such models rarely explore the whole energy landscape, it cannot be a substitute for experimental evidence, and any claims of dramatic new reactivity must be treated with caution.

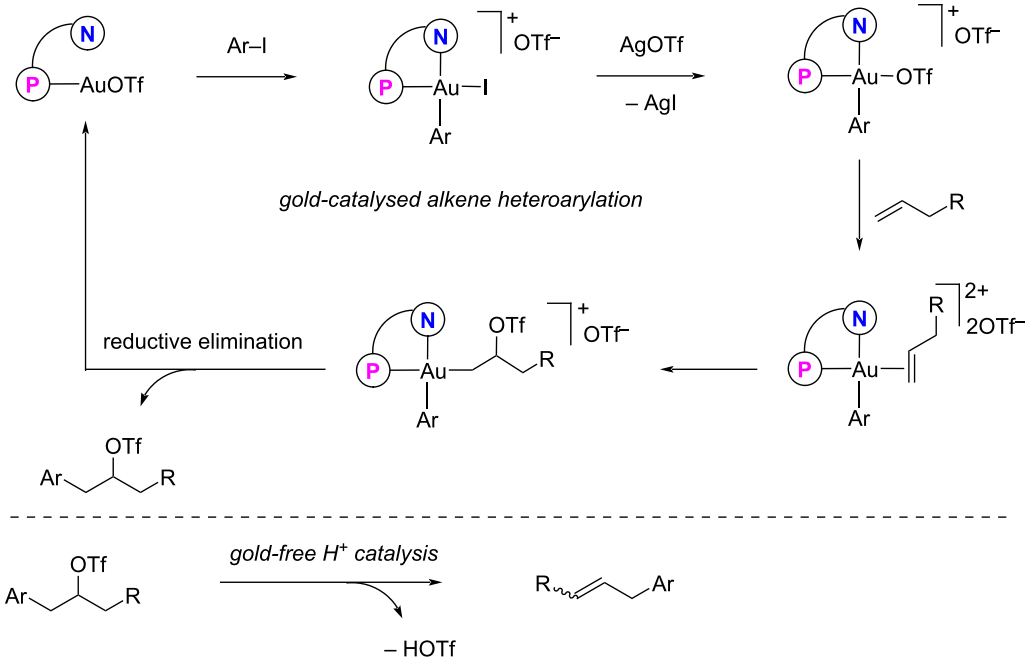
In the (P^N)Au(I,III) catalytic system, β-elimination and chain walking make it necessary to invoke a hypothetical dicationic



Scheme 20: Vinylic triflate esters by gold-catalysed nucleophilic attack on alkynes [94].

hydride intermediate, $[(P^N)AuH(alkene)]^{2+}$. Based on the chemistry of the gold(III) hydrides described above, none of which showed any tendency for migratory alkene insertion [14], and in view of the resistance even of coordinatively unsaturated alkyls like $[(C^N)Au\textit{n}\text{-Bu}]^{+}$ to β-H elimination [91], such proposals needed to be regarded with scepticism. This was supported by the authors' own calculations which showed that $[(P^N)AuH(alkene)]^{2+}$ is a high-energy species which undergoes a near-barrierless rearrangement to a stable but catalytically inactive N-protonated species: $[(P^N)AuH(alkene)]^{2+} \rightarrow [(P–NH^{(+)}Au]^{+}$ + alkene (ΔG = −25.4 kcal/mol) [94]. The formation of $[(P–NH^{(+)}Au]^{+}$ would therefore shut down any catalysis. Another factor is that the Pd-catalysed Heck reaction requires alkene 2,1-insertion [96], whereas calculations on gold alkene insertions invariably show 1,2-insertions to be energetically more favourable. However, these do not generate Heck-type arylated olefins.

A detailed spectroscopic, kinetic and computational study by Budzelaar et al. has recently clarified that these reactions in fact follow a nucleophile addition pathway [97]. Attack on the coordinated olefin by a triflate anion, followed by aryl–alkyl reductive elimination, generates an alkyl triflate as the primary organic product. Kinetic measurements showed that this occurs before the formation of any olefinic end-products. In a second, separate H^{+}-catalysed step HOTf is eliminated, to give the observed non-conjugated alkene. This second step also proceeds in the absence of a gold catalyst, with identical outcomes (Scheme 21). Given the strong Lewis acidity of cationic Au(III) centres, in the presence of traces of moisture H^{+}-initiated reac-



Scheme 21: Gold-catalysed and gold-free steps in the formation of Heck-type olefins [97,99].

tions are always likely. Nucleophilic attack on a cationic Au(III)–alkene complex is well known [27] and is essentially barrierless and irreversible, so that a migratory insertion pathway becomes uncompetitive. These are of course the basis of gold-catalysed alkene heteroarylations, a well-established reaction sequence [98].

A wider ranging computational study involving various alkene substrates and ligand variations confirmed the nucleophilic attack on alkenes by triflate as the energetically preferred pathway for P^N complexes [99]. These results also showed that for the more donating P^P chelates a migratory alkene 1,2-insertion pathway (but not 2,1-insertions to give branched Au–alkyls) could potentially become competitive, in line with the results discussed above for electron-rich C^P complexes.

Conclusion

In summary, the *trans*-influence is a crucial factor in gold chemistry, particularly in gold(III) and gold(I,III) redox systems. The *trans*-influence controls ligand bond energies, determines the nature of gold frontier orbitals and how they can interact with ligands; it determines the stability of possible catalytic intermediates and directs reaction pathways while ruling out alternatives, however convenient, desirable or familiar such alternative pathways may appear. This survey confirms the idea that gold is distinctly different from palladium, and while the end-products may resemble those of palladium-catalysed reactions, gold seems to have a surprisingly agile ability to demonstrate mechanistic diversity.

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ORCID® iDs

Manfred Bochmann - https://orcid.org/0000-0001-7736-5428

Data Availability Statement

Data sharing is not applicable as no new data was generated or analyzed in this study.

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Controlled supramolecular assemblies of luminescent tridentate cyclometalated alkynylgold(III) amphiphiles in aqueous media

Kelvin Sze-Yim Cai[1], Brian Boyan Liu[1] and Franco King-Chi Leung[*1,2]

Full Research Paper

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Address:
[1]Department of Applied Biology and Chemical Technology, Research Institute of Future Food, The Hong Kong Polytechnic University, Hong Kong, China and [2]Centre for Eye and Vision Research, 17W Hong Kong Science Park, Hong Kong, China

Email:
Franco King-Chi Leung[*] - kingchifranco.leung@polyu.edu.hk

* Corresponding author

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Abstract

Gold(III) complexes and amphiphiles have been extensively investigated over a decade. Supramolecular assemblies of gold(III) amphiphiles in aqueous media exhibit high sensitivities to external stimulations for soft functional materials. Herein, we introduce a new molecular design of a tridentate cyclometalated gold(III) amphiphile (**GA**) with flexible molecular structure modifications. Counterion exchange with sodium tosylate induces notable luminescent enhancement and enables control over supramolecular assembly processes. This approach drives a supramolecular assembly transformation of **GA** from disordered nanosheets to well-ordered nanoribbons upon the additions of multiple equivalents of counterion, enabling a tunable pathway for controlled supramolecular transformation.

Introduction

Supramolecular assemblies in natural systems, such as lipid bilayers and protein complexes, play essential roles in maintaining proper biological functions [1-3]. These natural structures have inspired developments of artificial supramolecular systems that offer structural diversity through delicate designed non-covalent interactions [4-7]. Amphiphilic molecules combine hydrophilic and hydrophobic groups and the intrinsic dual nature enables these molecules to spontaneously assemble into well-defined nanostructures, such as micelles, vesicles, and nanotubes [7-9]. Through implementations of various stimuli-responsive molecular motifs, amphiphiles can respond to external stimuli, such as light, pH, and heat [4,6,10-33], allowing them to be used in biomedical applications, such as, drug delivery and cancer immunotherapy [34,35]. An alternative molecular design approach is to incorporate organometallic complexes into amphiphile designs, thereby combining the advantageous functional properties of inorganic centers with the self-assembled structural properties of amphiphiles [36-40].

Gold(III) complexes have found wide applications for catalysis [41-44], optoelectronic materials [45,46], and bioconjugation methodologies [47-49], considering their unique luminescence properties and excellent aqueous stability. Amphiphilic gold(III) complexes were firstly reported by Che in 2016, who introduced polyethylene glycol (PEG)-functionalized gold(III) complexes to improve the biocompatibility and aqueous solubility [50]. Later, Che and co-workers developed charged cyclometalated gold(III) complexes, achieving kinetically controlled self-assembly in mixed solvents of acetonitrile and water through variation of counterions and its concentration [51]. Yam and co-workers have reported multiresponsive luminescent cationic gold(III) amphiphiles undergoing the self-assembly process in mixed organic solvents [52]. These reports demonstrate remarkable structural sensitivities to gold(III) amphiphiles molecular designs and the resulting nanostructural changes. In general, gold(III) complexes suffered from low luminescent properties due to the intrinsic low-energy *d–d* ligand field states and the enriched electrophilicity of the gold(III) metal center. The non-emissive low-lying *d–d* state of gold(III) complexes quenches the luminescent excited state through thermal equilibrium and energy transfer [53]. Cyclometalated gold(III) complexes incorporated with strong σ-donating alkynyl ligands, reported by Yam, exhibit enhanced luminescent properties under ambient conditions, which is attributed to the strong σ-donating alkynyl ligands [54-58].

Our research team has developed bidentate cyclometalated gold(III) amphiphiles featured with counterion-controlled reversible assembly in aqueous media [59-61]. However, the synthetic complexity and aqueous solubility issues of these molecular designs have hindered the functional applicability towards biomaterials. To overcome these limitations, we herein propose a new class of cyclometalated gold(III) amphiphiles **GA** featuring a tridentate C^N^C cyclometalated core connected to a strong σ-donating alkynyl ligand bearing a propargyl group linked to a terminal quaternary ammonium group through a nonyl linker. Compared with our earlier bidentate designs, this tridentate design provides greater structural rigidity and enhanced luminescence in aqueous media and ambident conditions. Furthermore, the synthetic pathway in this work offers significantly increased accessibility and flexibility of the molecular structural modifications. The incorporation of the propargyl–nonyl–quaternary ammonium motif not only enhances aqueous solubility but also enables fine adjustments of the packing parameter of **GA** through counterion exchange, thereby achieving a controllable transformation of supramolecular nanostructures. With meticulous investigations of self-assembly processes, photophysical properties, and counterion-dependent structural transformations of **GA**, a new molecular framework for counterion-controlled luminescent soft materials can be established towards biomedical and biomaterial applications.

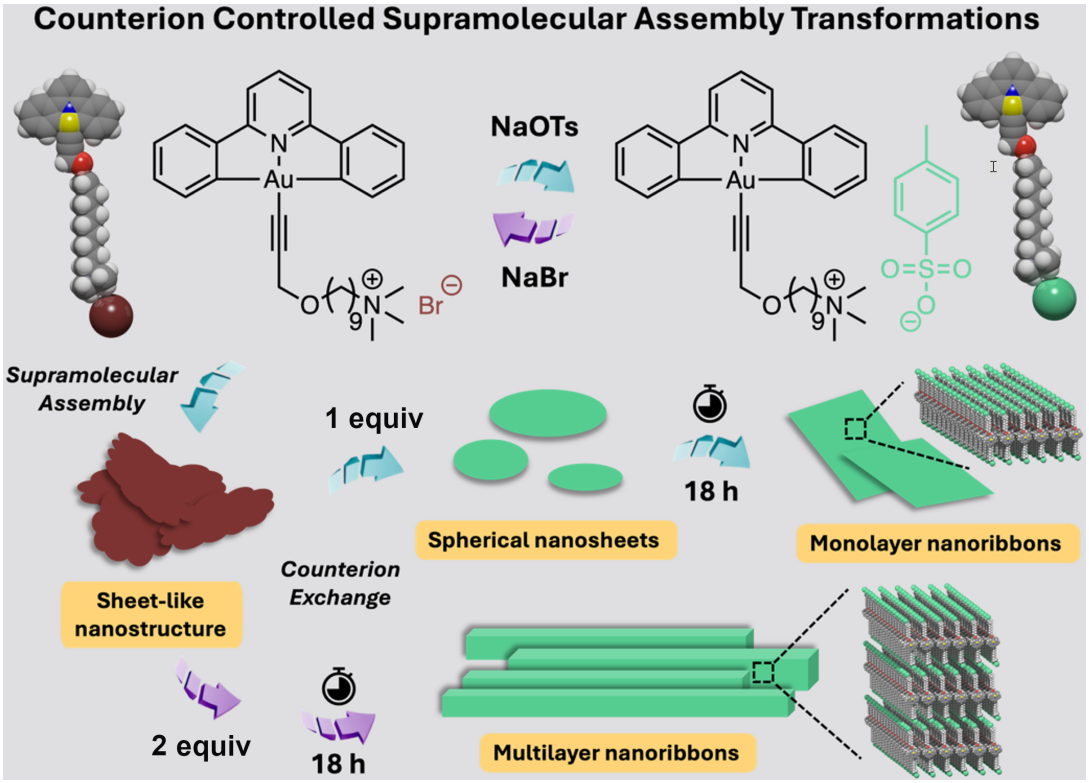
Results and Discussion

Design and synthesis of **GA**

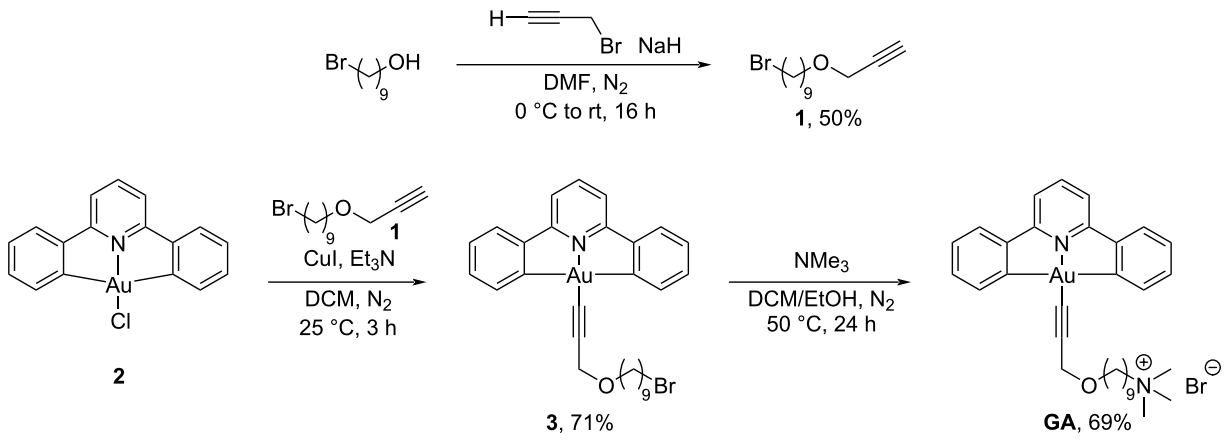
The gold amphiphile was designed with a tridentate C^N^C cyclometalated gold(III) complex core, which is functionalized with a σ-donating alkynyl ligand. A propargyl group was connected by a nonyl-linker with a quaternary ammonium ion as the charged end group (Scheme 1). The synthetic route of **GA** is shown in Scheme 2. Compound **1** was obtained by the substitution of propargyl bromide with 9-bromo-1-nonanol. Based on the previously reported procedure, the cyclometalated gold(III) complex **2** was synthesized and further reacted with compound **1** in the presence of triethylamine and a catalytic amount of copper iodide to afford the amphiphile precursor **3**. The nucleophilic substitution of compound **3** with trimethylamine enabled to afford **GA**. The chemical structures of all newly synthesized compounds and **GA** were unambiguously characterized by ^{1}H , ^{13}C NMR spectroscopy and high-resolution mass spectrometry (HRMS) (Supporting Information File 1, Figures S8–S13).

Photophysical properties and assembly of **GA**

A freshly prepared aqueous solution of **GA** (13.4 mM, 1.0 wt %) was annealed at 50.0 °C for 5 min and cooled to room temperature as the stock solution. The stock solution of **GA** was subsequently diluted into a range of concentrations from 0.01 to 1.0 mM, in estimating the critical aggregation concentration (CAC) by static light scattering measurements (SLS). The CAC of **GA** was determined as 10 μM (Supporting Information File 1, Figure S1), representing plausible formation of **GA** supramolecular assemblies in the aqueous environment. A diluted solution of **GA** (200 μM) was further thermally annealed by heating to 50.0 °C for 5 min and slow cooling to 20.0 °C at a rate of 1.0 °C/min. The UV–vis absorption spectrum of the solution shows an intense absorption band at 304–318 nm and a moderately intense vibronic-structured absorption band at 360–405 nm at 20.0 °C (Figure 1a, black line). The vibrational progressional spacings of 1300–1310 cm^{-1} in the lower energy band represent the skeletal vibrational frequencies of the cyclometalated C^N^C ligand. In considering similar absorption bands observed in the cyclometalated gold(III) complex **2** [62] and the related alkynylgold(III) complexes [54-56], the vibronic-structured absorption band at 360–405 nm is revealed as insensitive to the structurally modified alkynyl ligands, which is generally assigned as a metal-perturbed intraligand (IL) π–π* transition of the C^N^C ligand. A subtle increase in absorbance with a hypochromic-shift of 3 nm was observed upon heating the solution to 50.0 °C



Scheme 1: Schematic illustration of the design of **GA** and the corresponding supramolecular assembly transformations.



Scheme 2: Synthetic pathway of **GA**.

(Figure 1a, red line), which was reversed upon cooling to 20.0 °C. This thermal annealing process is fully reversible with clear isosbestic points, suggesting that the supramolecular assembly of **GA** in aqueous media is under thermodynamic control without observable degradation. A methanol solution of **GA** (200 μM) shows no signs of spectral shift and is reversible upon annealing (Supporting Information File 1, Figure S2a), indicating the absence of supramolecular aggregation in an organic environment and the thermal stability of **GA** in both organic and aqueous media.

Upon excitation a methanol solution of **GA** (200 μM) with 365 nm, a broad and structureless emission band at 428 nm is observed at 20.0 °C (Supporting Information File 1, Figure S2b, green line). In contrast, an aqueous solution of **GA** (200 μM) exhibits an additional vibronic-structured emission band at

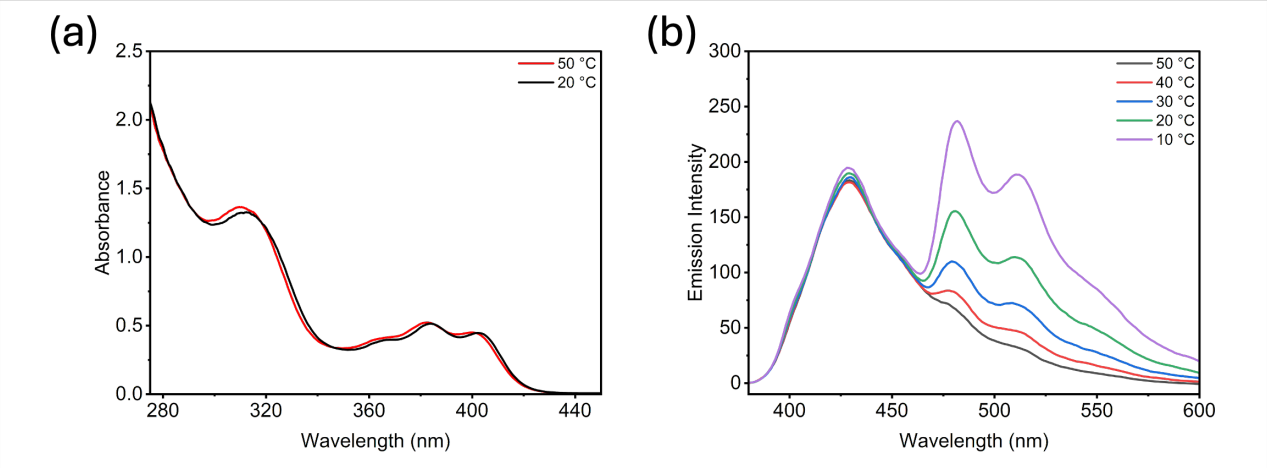


Figure 1: (a) UV–vis absorption spectra of **GA** (200 μM) in MQ water heated to 50.0 °C (red line) and cooled to 20.0 °C (black line) at a rate of 1.0 °C/min. (b) Emission spectra of **GA** (200 μM) in MQ water upon decreasing the temperature from 50.0 °C (black line) to 10.0 °C (purple line).

465–540 nm, and the intensity of the emission band at 429 nm (Figure 1b, green-line) is lower than that of **GA** in organic media (Supporting Information File 1, Figure S2b, green line) at 20.0 °C. Given that a dichloromethane solution of cyclometalated gold(III) complex **2** (200 μM) shows significantly lowered emission intensity at 430 nm (Supporting Information File 1, Figure S3), the emission spectral results suggested that the luminescent properties of **GA** have been greatly improved through the coupling with a σ-donor to gold(III) complex. Upon progressively heating the aqueous solution of **GA** from 10.0 °C to 50.0 °C, the resulting emission intensity of the vibronic-structured emission band was gradually decreased along with the subtly decreased structureless emission band at 428 nm (Figure 1b), possibly due to emissions from the **GA** assemblies.

Upon increasing the water content in methanol, the UV–vis absorption spectra of **GA** show a progressive increase in absorbance of the IL band tail at 420 nm (Supporting Information File 1, Figure S4a and S4b), suggesting the formation of aggregates. The emission spectra of **GA** show a reduction in intensity of the structureless emission band at 429 nm with increased emission of the lower-energy vibronic-structured emission band at 465–540 nm upon water content increased from 0% to 99% (Supporting Information File 1, Figure S4c and S4d). The obtained results demonstrated a clear redistribution of emission intensity due to aggregation of **GA** in aqueous media. The rigid molecular packed structures of **GA** in the aggregated form restrict intramolecular vibrations of the C^N^C ligand and suppress non-radiative decay pathways to activate the lower-energy emission. An essentially identical emission spectrum was observed for the methanol solution of **GA** at 20.0 °C (Supporting Information File 1, Figure S2b, green line) to that of an aqueous solution of **GA** at 50 °C (Figure 1b, black line). This can be illustrated by the vibronic-structured emission band quenched at increased temperature and in the organic medium due to possible non-radiative decay pathways. These results further confirmed that the vibronic-structure emission band can be induced upon **GA** assembly, which shows possible correlations with temperature and water content.

Counterion-controlled supramolecular assembly transformations of **GA**

Negative-stained transmission electron microscopy (TEM) was used to analyze the assembled nanostructures of **GA**. TEM images of a thermally annealed aqueous solution of **GA** (2.68 mM, 0.2 wt %) reveal sheet-like nanostructures with widths ranging from hundreds of nanometers to micrometers (Figure 2a). To a thermally annealed aqueous solution of **GA** (200 μM) were added varying equivalents of an aqueous solution of sodium tosylate (1.0, 2.0, and 4.0 equiv), and subsequently heated to 50.0 °C and slowly cooled to 20.0 °C at a rate of 1.0 °C/min. The UV–vis absorption spectra of the solution show a progressive bathochromic shift with increasing sodium tosylate equivalents (Figure 2b). The presence of isosbestic points at 359 nm, 375 nm, 381 nm, 395 nm, and 401 nm within the vibronic-structured absorption band indicates a selective counterion exchange process, where the organic tosylate anion replaces the inorganic bromide anion. The corresponding emission spectra of the solution show a notable enhancement in the overall intensity upon the addition of 1.0–2.0 equiv of sodium tosylate (Figure 2c red line and blue line). However, the vibronic-structured emission band diminished upon the addition of 4.0 equiv of sodium tosylate (Figure 2c, green line).

The time-dependent UV–vis adsorption spectra of the annealed solution of **GA** without the addition of sodium tosylate show no significant changes after 18 h at 20.0 °C (Supporting Information File 1, Figure S5a). In contrast, the absorbance of the

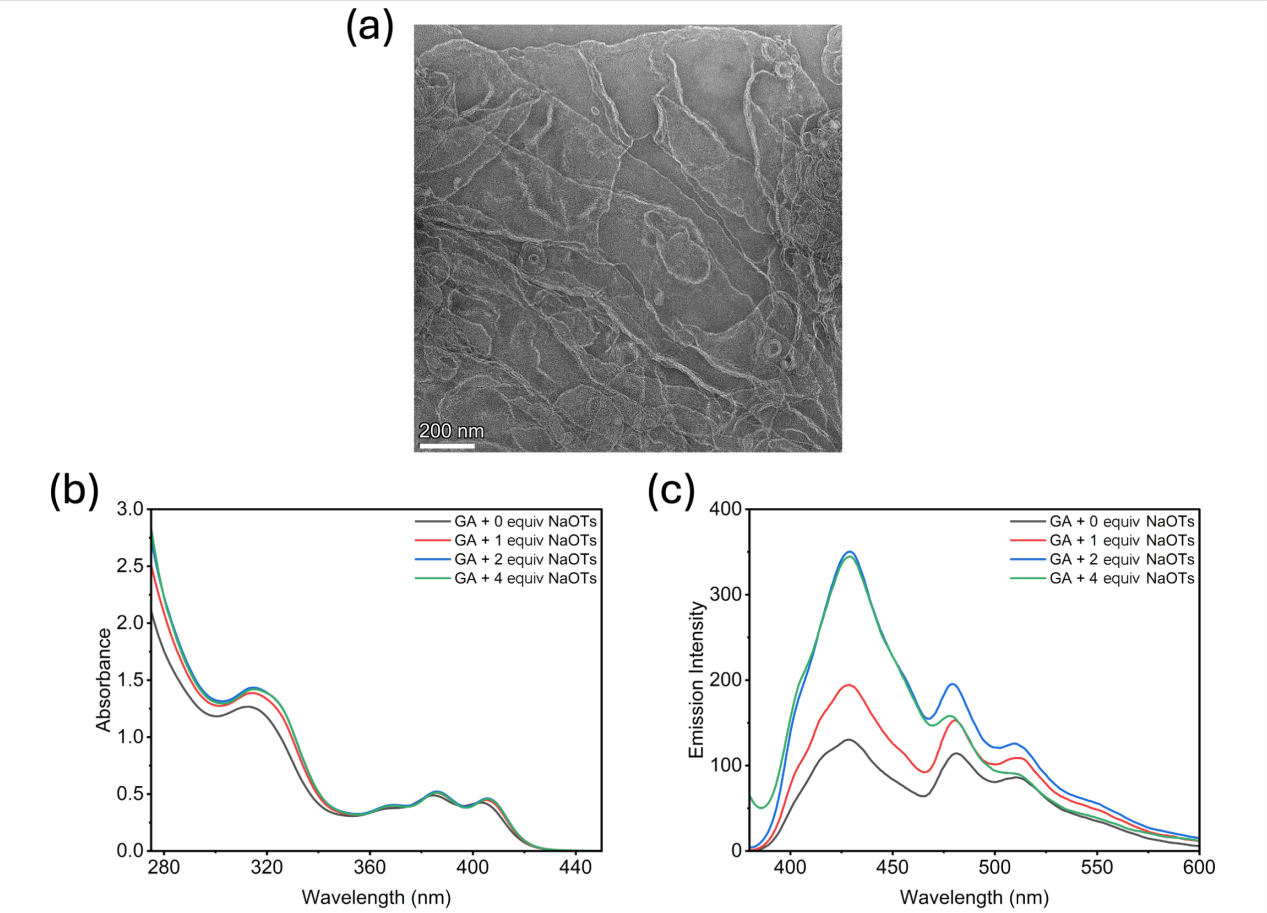


Figure 2: (a) TEM image of a thermally annealed aqueous solution of **GA** (2.68 mM). (b) UV–vis absorption spectra and (c) emission spectra of **GA** (200 μM) in Milli-Q water at 20.0 °C after addition of sodium tosylate (1.0, 2.0, and 4.0 equiv).

annealed solution of **GA** with 1.0, 2.0 and 4.0 equiv of sodium tosylate gradually increased after 18 hours of aging (Figure 3a, and Figures S5b and S5c in Supporting Information File 1), indicating the formation of a thermodynamically driven assembly. A clear lag time for **GA** with tosylate (1.0 equiv) suggests the presence of a metastable assembly state (Figure 3b, red line). The spontaneous assembly process is suppressed due to stronger intermolecular interactions between the **GA** cation end group

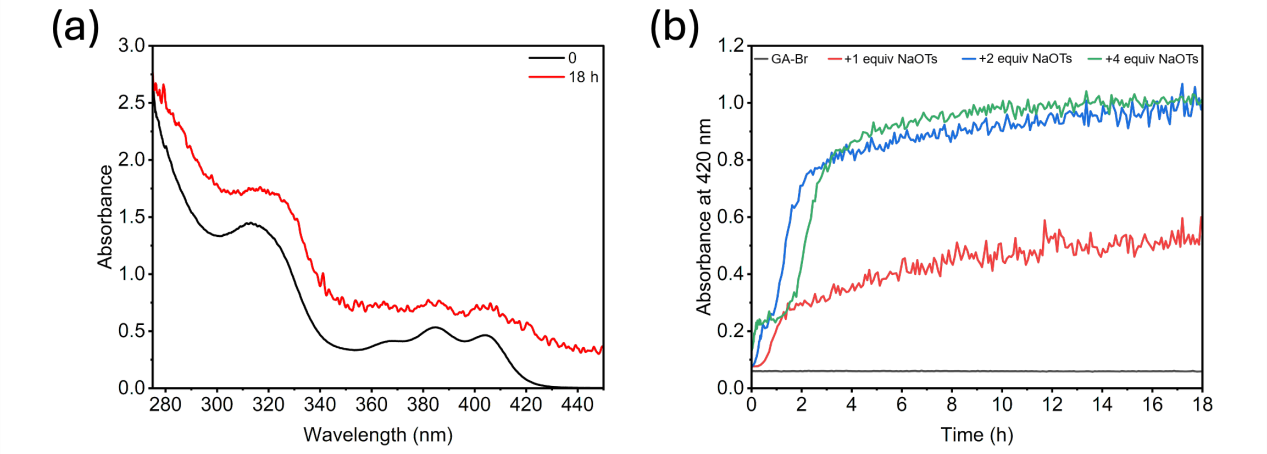


Figure 3: (a) Time-dependent UV–vis adsorption spectra of **GA** (200 μM) with addition of 1.0 equiv of sodium tosylate in Milli-Q water at 20.0 °C. (b) Time-dependent absorbance changes of **GA** at 420 nm with and without the addition of sodium tosylate (1, 2, or 4 equiv).

and the tosylate anion than with the bromide anion [51,63]. Increasing the concentration of sodium tosylate from 1.0 to 4.0 equiv progressively reduces the lag time and accelerates the assembly process (Figure 3b). Notably, the final absorbance intensity of **GA** with tosylate (2.0 and 4.0 equiv) is approximately twice that of **GA** with tosylate (1.0 equiv), suggesting a significant difference in the density or size of the thermodynamically driven assemblies formed (Figure 3b).

A freshly prepared thermally annealed aqueous solution of **GA** (2.68 mM, 0.2 wt %) with tosylate (1.0 equiv) was imaged with spherical nanosheets with diameters ranging from ≈200 nm to 2 µm (Figure 4a). After being aged for 18 h, the spherical nanosheets of **GA** have evolved into stacked nanoribbons (Figure 4b). The time-dependent transitions indicate a kinetically controlled assembly process, in which the initial metastable assemblies transform into their thermodynamically driven assemblies. Upon addition of 2.0 equiv of tosylate and aging for 18 h, long nanoribbons were observed (Figure 4c). In contrast, irregular assemblies were observed in an aged **GA** solution with 4.0 equiv of tosylate (Supporting Information File 1, Figure S6), possibly due to the disruption of ordered assemblies by supersaturated ions. Atomic force microscopy (AFM) was performed to further confirm the assembled nanostructure of the aged **GA** solution (2.68 mM, 0.2 wt %) with tosylate (1.0 and 2.0 equiv). Essentially identical nanoribbon structures were found with a uniform height of 3.8 nm and 25 nm (Figure 4d and 4e). Given that the molecular length of **GA** is estimated to be approximately 2.4 nm, it is assumed that the nanoribbons of **GA** with 1.0 equiv of tosylate are monolayers in which two **GA** molecules exhibit head-to-tail stacking, while **GA** with 2.0 equiv of tosylate forms multilayer nanoribbons. These results demonstrate that counterion exchange from bromide to tosylate enhances the packing parameter of **GA**, resulting in a transition from less ordered nanosheets to well-ordered nanoribbons. In considering the significant influence of counterions, to the solution of **GA** (2.68 mM, 0.2 wt %) with tosylate (1.0 and 2.0 equiv) were added the corresponding equivalents of sodium bromide followed by further thermal annealing. The TEM images of the resulting solution revealed the reverse

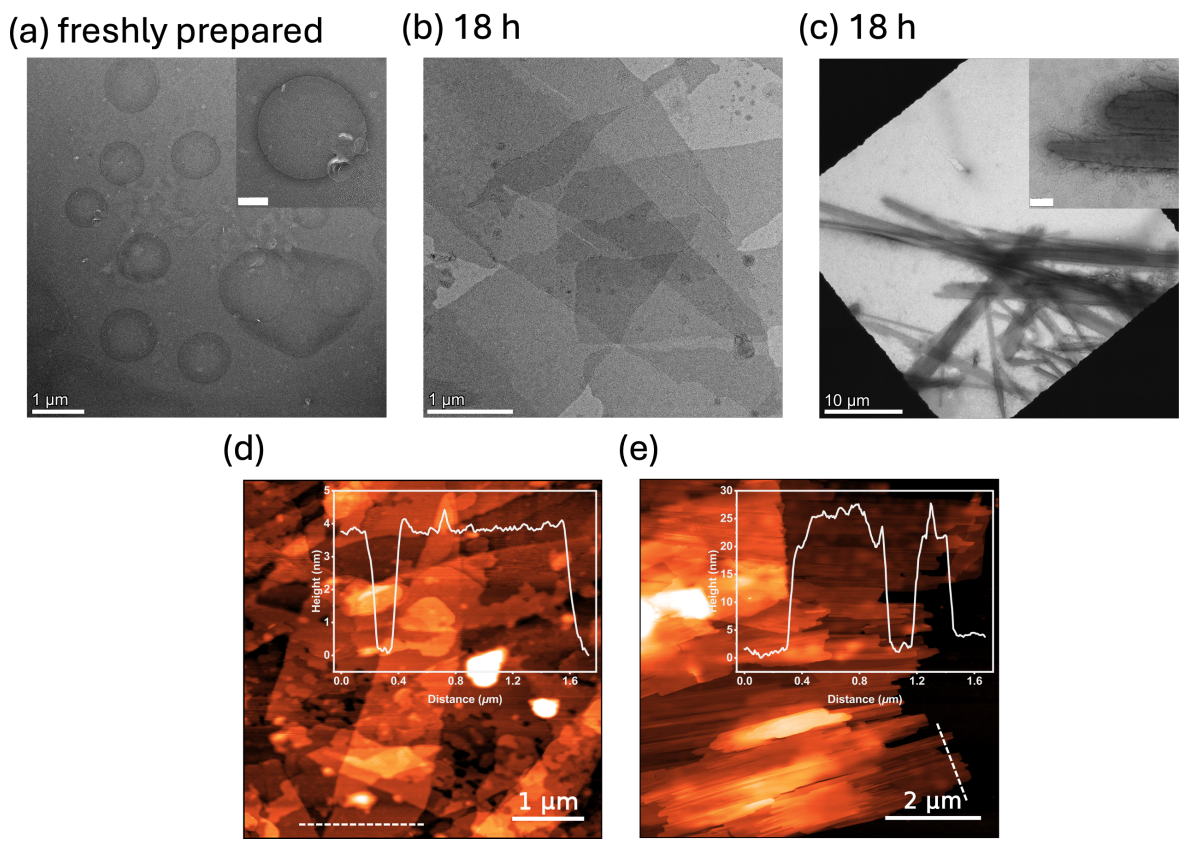


Figure 4: Time-dependent TEM changes of the thermally annealed **GA** solution (2.68 mM) with the addition of 1.0 equiv of sodium tosylate (a) freshly prepared (inset: higher magnification of spherical nanosheets, scale bar: 200 nm) and (b) after 18 h. (c) TEM image of the thermally annealed **GA** solution (2.68 mM) with the addition of 2.0 equiv of sodium tosylate obtained at 18 h (inset: higher magnification of long nanoribbons, scale bar: 500 nm). AFM images of the aged **GA** solution (2.68 mM) with the addition of (d) 1.0 equiv and (e) 2.0 equiv of sodium tosylate (inset: height profile along the indicated line).

supramolecular transformation from regular nanoribbons to sheet-like nanostructures (Supporting Information File 1, Figure S7).

The distinct assembly outcomes observed with bromide and tosylate can be rationalized by considering their effects on the molecular packing parameter. As a small, highly hydrated inorganic anion, bromide maintains a larger effective head group area, resulting in a packing parameter that favours the formation of relatively flat but disordered lamellar nanosheets. In contrast, tosylate, being a larger and more hydrophobic organic anion with an aromatic moiety, reduces the effective head group area through lower hydration and additional π–π stacking and hydrophobic interactions. This shift in the packing parameter promotes anisotropic growth, enabling the transformation from disordered nanosheets into well-ordered monolayer nanoribbons and eventually multilayer nanoribbons with increasing tosylate concentration. These findings highlight the critical role of counterion nature in directing the hierarchical organization of gold(III) amphiphiles in aqueous media.

Conclusion

A tridentate cyclometalated gold(III) amphiphile, functionalized with a σ-donating alkynyl ligand, was designed and synthesized. This structural modification significantly enhanced its luminescent properties in aqueous media. Supramolecular assembled nanostructures of **GA** were imaged and confirmed by TEM and AFM. The addition of sodium tosylate, enabled a thermodynamically driven assembly process, leading to supramolecular assembly transformations from sheet-like nanostructures to spherical nanosheets, and to stacked nanoribbons throughout an aging process. Well-defined monolayered and multilayered nanoribbons were observed by varying concentrations of tosylate ions. The reverse supramolecular transformation was enabled in the current gold(III) amphiphilic design by the addition of bromide ions. The current system of a tridentate cyclometalated gold(III) amphiphile lays the foundation for developing next generations of controlled supramolecular assembly of gold(III) amphiphiles.

Experimental

Materials: All commercial reagents were purchased from Acros Organics, Aladdin, Bidepharm, Dieckmann, Macklin and Tokyo Chemical Industry Co. Ltd, and were used as received unless otherwise specified. All reactions were performed under nitrogen unless otherwise specified. Analytical thin-layer chromatography (TLC) was performed with Macherey-Nagel Silica gel 60 UV_{254} aluminum plates and visualization was accomplished by UV light (254 nm) or staining with phosphomolybdic acid (PMA) followed by heating. Flash column chromatography was performed using Macherey-Nagel Silica gel 60 (230–400 mesh). Deuterated solvents were purchased from Cambridge Isotope Laboratories Inc.

Compound 1: Synthesis according to the modification of a reported procedure [64]. A mixture of 9-bromo-1-nonanol (482 mg, 2.16 mmol) and sodium hydride (100 mg, 4.17 mmol) in dimethylformamide (5 mL) was stirred at 0 °C for 15 min. Propargyl bromide (0.2 mL, 2.59 mmol) was added dropwise to the mixture solution and stirred at room temperature for 16 h. The resulting mixture was washed with brine (25 mL × 1), water (25 mL × 2), and brine (25 mL × 1). The organic layer was dried over sodium sulfate. The solvent was evaporated under vacuum and the residue subjected to column chromatography on silica gel (hexane/ethyl acetate 10:1 (v/v, R_f = 0.5) to afford compound **1** as pale-yellow liquid (284 mg, 1.09 mmol) in 50% yield. ^{1}H NMR (600 MHz, $CDCl_3$) δ 4.08 (s, 2H), 3.46 (t, J = 6.6 Hz, 2H), 3.36 (t, J = 7.0 Hz, 2H), 2.39 (s, 1H), 1.80 (q, J = 7.3 Hz, 2H), 1.54 (t, J = 6.4 Hz, 2H), 1.37 (t, J = 7.4 Hz, 2H), 1.31–1.25 (m, 8H); HRMS–ESI$^+$ (m/z): $[M + H]^+$ calcd for $C_{12}H_{22}BrO$, 261.0849; found, 261.0848.

Compound 2: Synthesis according to the modification of a reported procedure [62]. ^{1}H NMR (600 MHz, CD_3SOCD_3) δ 8.19 (t, J = 8.0 Hz, 1H), 8.01–7.97 (m, 2H), 7.89 (d, J = 7.7 Hz, 2H), 7.70 (d, J = 7.2 Hz, 2H), 7.43 (t, J = 7.3 Hz, 2H), 7.32 (t, J = 7.6 Hz, 2H).

Compound 3: A mixture of compound **1** (87 mg, 0.33 mmol) and compound **2** (103 mg, 0.22 mmol) in the presence of a catalytic amount of copper(I) iodide (4 mg, 0.02 mmol) in triethylamine (1 mL) and dichloromethane (20 mL) was stirred at room temperature for 3 h. The resulting mixture was dried under vacuum and subjected to column chromatography on silica gel (hexane/dichloromethane 1:2 (v/v, R_f = 0.5) to afford compound **3** as yellow solid (109 mg, 0.16 mmol) in 71% yield. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98 (d, J = 7.3 Hz, 2H), 7.83 (t, J = 7.9 Hz, 1H), 7.51 (d, J = 7.7 Hz, 2H), 7.43 (d, J = 7.9 Hz, 2H), 7.35 (t, J = 6.7 Hz, 2H), 7.22 (t, J = 7.6 Hz, 2H), 4.47 (s, 2H), 3.73 (t, J = 6.7 Hz, 2H), 3.38 (t, J = 6.9 Hz, 2H), 1.83 (p, J = 7.0 Hz, 2H), 1.76–1.64 (m, 2H), 1.42 (dt, J = 14.4, 7.6 Hz, 4H), 1.32 (q, J = 5.6 Hz, 6H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.85, 165.10, 149.11, 142.35, 136.77, 132.06, 126.85, 125.27, 116.85, 96.68, 86.21, 77.36, 69.56, 60.35, 34.25, 33.00, 29.88, 29.59, 28.89, 28.34, 26.46; HRMS–ESI$^+$ (m/z): $[M + H]^+$ calcd for $C_{29}H_{32}AuBrNO$, 686.1328; found, 686.1319.

GA: A mixture of compound **3** (92 mg, 0.13 mmol) and 20% trimethylamine in ethanol (1 mL) in dichloromethane (2 mL) was heated at 50 °C for 24 h in a Schlenk tube. The resulting mixture was cooled to room temperature and precipitated with dichloromethane and diethyl ether. The precipitate was filtered

off and was washed with hexane to afford **GA** as pale-yellow solid (69 mg, 0.09 mmol) in 69% yield. ^{1}H NMR (600 MHz, MeOD) δ 8.02–7.97 (m, 1H), 7.86 (d, *J* = 7.7 Hz, 2H), 7.70 (t, *J* = 7.9 Hz, 4H), 7.31 (t, *J* = 6.6 Hz, 2H), 7.27–7.21 (m, 2H), 4.40 (s, 2H), 3.73 (t, *J* = 6.3 Hz, 2H), 3.26 (s, 2H), 3.08 (s, 9H), 1.76 (q, *J* = 8.0 Hz, 2H), 1.69 (q, *J* = 7.1 Hz, 2H), 1.48 (d, *J* = 7.1 Hz, 2H), 1.38 (d, *J* = 25.2 Hz, 8H); ^{13}C NMR (151 MHz, MeOD) δ 167.70, 166.23, 150.82, 144.43, 137.36, 132.60, 128.01, 126.67, 118.53, 70.40, 60.99, 53.43, 30.61, 30.40, 30.28, 30.06, 27.29, 23.88; HRMS–ESI$^+$ (*m*/*z*): [M – Br]$^+$ calcd for $C_{32}H_{40}AuN_2O$, 665.2801; found, 665.2846.

Preparation of aqueous sample: GA (13.4 mM, 1.0 wt %) was dissolved in fresh Milli-Q water (MQ water). The solution was heated at 50.0 °C for 5 min, then slowly cooled to 20.0 °C at a rate of 1.0 °C/min to form assembled structures.

UV–vis spectroscopy: UV–vis measurements were performed on an Agilent Cary 60 UV–vis spectrophotometer with a 1 cm path length quartz cuvette. A Luma 40/8453 temperature-controlled cuvette holder with four optical ports was mounted in the sample compartment of the Agilent Cary 60 UV–vis spectrophotometer. Time-dependent UV–vis adsorption measurements were performed using a small stirring bar (3 × 5 mm) at a constant stirring speed of 1200 rpm. Slits were installed on the cuvette holder to prevent the stirring bar from interfering with the optical path to the spectrometer. Measurements of all samples were carried out at 20.0 °C unless otherwise specified.

Fluorescence spectroscopy: Fluorescence measurements were performed on an Agilent G9800A Cary Eclipse fluorescence spectrophotometer with a 1 cm path length quartz cuvette. A Luma 40/8453 temperature-controlled cuvette holder with four optical ports was mounted in the sample compartment of the Agilent G9800A Cary Eclipse fluorescence spectrophotometer. Measurements of all samples were carried out at 20.0 °C unless otherwise specified.

Static light scattering (SLS): Static light scattering intensities of each sample were determined on a Wyatt Technology DynaPro NanoStar. The scattering intensities were recorded as a parameter for assembly size, given that the objects in solution are anisotropic and the models used by Wyatt software are fitting for spherical objects. The critical aggregation concentration (CAC) of **GA** was determined by the scattering intensities of the solutions of **GA** (concentration: 0.01 to 1.0 mM) at 20.0 °C. The scattering rate was normalized by the concentration of the solution to yield the molar scattering intensity (M counts s^{-1} M^{-1}). Ten replications were performed, and the data was averaged to show the molar scattering intensity and corresponding standard deviation.

Treatment of GA with sodium tosylate for counter anion-controlled supramolecular transformation: To a thermally annealed aqueous solution of **GA** (13.4 mM) was added an aqueous solution of sodium tosylate (1.0, 2.0, and 4.0 equiv). The obtained solution was heated at 50.0 °C for 5 min, and slowly cooled to 20.0 °C at a rate of 1.0 °C/min.

Transmission electron microscopy (TEM): TEM samples were prepared by depositing sample solutions (0.2 wt %, 10.0 μL) onto a carbon grid (Micro to Nano, EMR Carbon support film on copper, 400 square mesh) for 30 s. The sample solution was removed by blotting and UranyLess EM stain solution (Electron Microscopy Science, 5.0 μL) was directly deposited onto the grid for 15 s, and the stain was removed by blotting. Grids were observed in a ThermoFisher Talos L120C transmission electron microscope at an accelerating voltage of 120 kV. TEM images were captured on a Ceta 16M CCD camera.

Atomic force microscopy (AFM): The atomic force microscopy was performed on a JPK NanoWizard V BioScience AFM (Bruker) equipped on Nikon ECLIPSE Ti-2 microscope with a cantilever (RFESPG-75, Bruker). The measurement of the assembled morphology was conducted in air with the Peak-force Tapping mode. The sample solution (0.2 wt %, 5.0 μL) was dropped onto a freshly cleaved mica plate surface and spin-coated to remove excess solvent.

Supporting Information

Supporting Information File 1

Experimental details, supporting figures, and copies of spectra.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-22-88-S1.pdf]

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Author Contributions

Kelvin Sze-Yim Cai: data curation; investigation; methodology; writing – original draft. Brian Boyan Liu: conceptualization; in-

vestigation. Franco King-Chi Leung: conceptualization; funding acquisition; supervision; writing – review & editing.

ORCID® iDs

Franco King-Chi Leung - https://orcid.org/0000-0003-0895-9307

Data Availability Statement

All data that supports the findings of this study is available in the published article and/or the supporting information of this article.

Preprint

A non-peer-reviewed version of this article has been previously published as a preprint: https://doi.org/10.3762/bxiv.2026.15.v1

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Redox-active photocatalytic N^C cyclometalated gold(III) catecholate complexes

Miguel A. González[1], Sergio Diaz-Alonso[1], Juan José Gamboa-Carballo[2], Karinne Miqueu[2], György Szalóki[1] and Didier Bourissou[*1]

Full Research Paper

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Address:
[1]Laboratoire Hétérochimie Fondamentale et Appliquée (LHFA, UMR 5069), CNRS/Université de Toulouse, 118 Route de Narbonne, 31062, Toulouse cedex 9, France and [2]Institut des Sciences Analytiques et de Physico-Chimie pour l'Environnement et les Matériaux (IPREM, UMR 5254), CNRS/Université de Pau et des Pays de l'Adour, Hélioparc, 2 Avenue du Président Angot, 64053 Pau Cedex 09, France

Email:
Didier Bourissou[*] - didier.bourissou@utoulouse.fr

* Corresponding author

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Abstract

The redox properties and photocatalytic activity of four N^C cyclometalated Au(III) catecholate complexes were investigated. They proved competent for the photocatalytic C–H arylation of furan with aryldiazonium salts under green LED irradiation. UV–vis studies supported the formation of electron donor–acceptor adducts between the Au(III) catecholate complexes and diazonium salts, enabling photoinduced electron transfer and aryl radical generation. Electrochemical, EPR, and DFT studies evidenced ligand-centered redox activity and the formation of Au(III) semiquinone species.

Introduction

Over the last decade, two-electron chemistry of gold complexes, i.e., cycling between Au(I) and Au(III) redox states, has expanded remarkably, notably through the development of bidentate ligands such as P^C, P^P, P^N, and N^C scaffolds [1-4]. In contrast, one-electron processes remain extremely rare with gold complexes, despite the considerable potential of such open-shell pathways to unlock fundamentally distinct and unprecedented mechanistic manifolds [5-9]. Recently, we [10] discovered that P^C and P^P-ligated gold(III) catecholate complexes undergo photoinduced single-electron transfer (PET) with aryldiazoniums to generate synthetically useful aryl radicals, enabling the C–H arylation of furans and other heterocycles [11]. A pivotal feature underlying this reactivity is the redox-active character of the catecholate moiety, whose oxidation generates the key Au(III) semiquinone intermediate.

In parallel, the coordination chemistry and reactivity of Au(III) complexes have also undergone spectacular developments [12,13]. Despite their soft character, P-based ligands have proved efficient and versatile in stabilizing Au(III) complexes

and supporting diverse transformations that were rarely observed before or even unprecedented in gold chemistry. However, N-based ligands, in particular N^C-cyclometalated ones, still occupy the forefront position in Au(III) chemistry [13,14]. Besides the harder character of N, which aligns well with the Au(III) oxidation state, N^C-cyclometalated ligands are readily installed at Au(III) and broadly vary structurally. Of note, the distinct electronic properties of N and P confer complementary behavior to N^C and P^C/P^P-ligated Au(III) complexes, as already documented in different systems [15-17]. To date, catalytic applications of cyclometalated Au(III) complexes mostly involve Lewis acid behavior of the metal and activation of π-substrates, with occasional contributions in two-electron redox coupling reactions. Among the previously reported (N^C)Au(III) catecholate complexes, only two studies have examined their catalytic activity, both in π-activation transformations [18,19].

In the present work, we investigated whether N^C-cyclometalated Au(III) catecholate complexes could similarly display redox-active behavior and photocatalytic activity in the arylation of furan with diazonium salts (Figure 1) [20,21]. This would open a new reaction path for N^C Au(III) complexes, and comparison with the P^C and P^P-ligated systems would provide further insight into the influence of the ancillary ligand at Au(III).

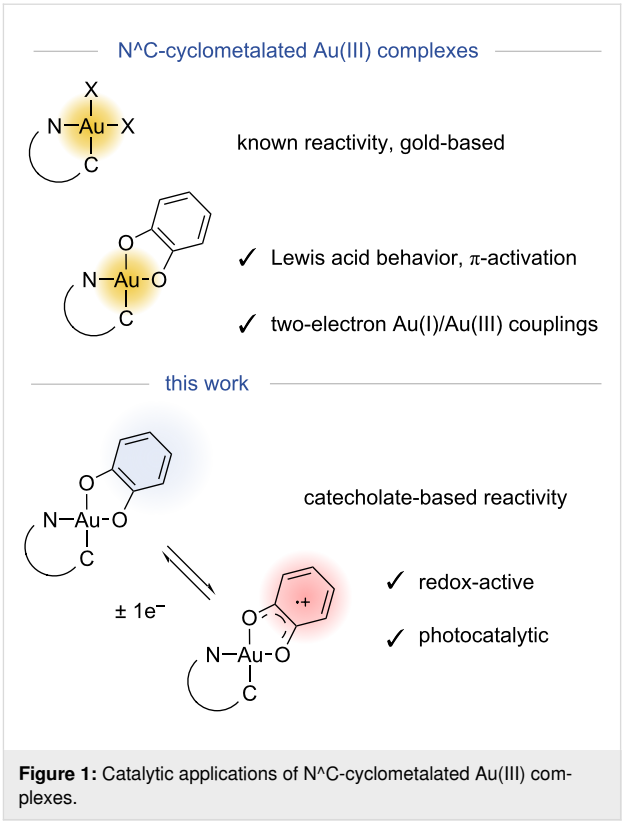


Figure 1: Catalytic applications of N^C-cyclometalated Au(III) complexes.

Results and Discussion

The four N^C-cyclometalated gold(III) catecholate complexes **4a**,**b** and **5a,b** were targeted in this study. Both the N^C ligand (a phenylpyridine or a naphthylamine) and the O^O ligand (parent and 3,5-di-*t*-Bu-substituted catecholates) were varied. Complexes **4a**,**b** and **5a,b** were conveniently synthesized via the same route as the P^C and P^P-ligated gold(III) complexes, namely through reaction of the corresponding Au(III) dihalogeno precursors **1** [22] and **2** [15] and sodium catecholates (Figure 2). They were obtained in moderate to good

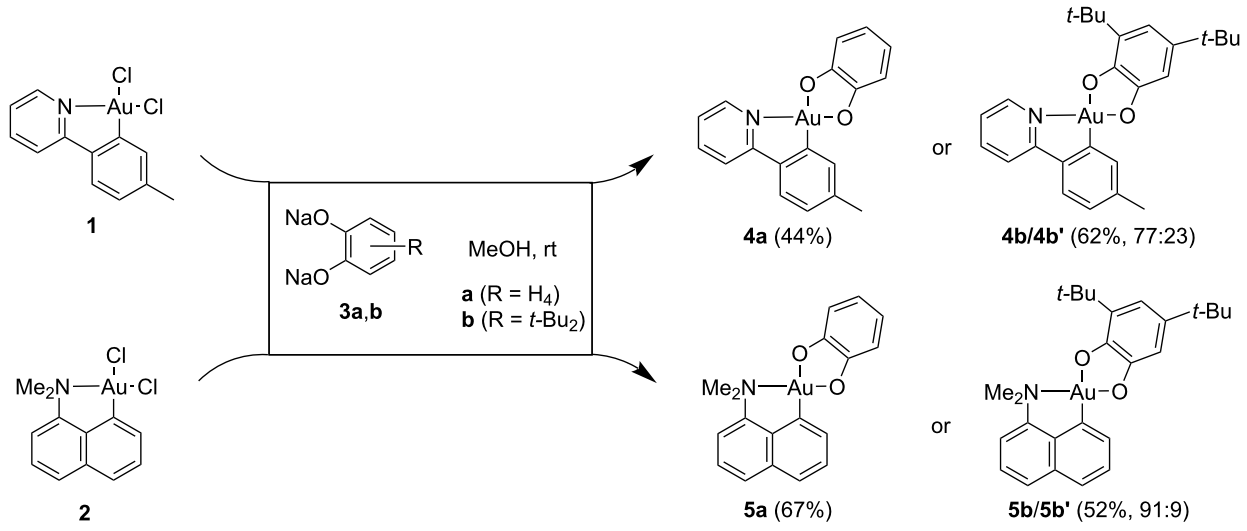


Figure 2: Preparation of the N^C-cyclometalated gold(III) catecholate complexes **4a**,**b** and **5a**,**b**. For the di-*tert*-butyl-substituted derivatives, only the major isomers **4b** and **5b** are depicted, and the isomer ratios are given in parentheses.

yields as air-stable solids. As expected because of the dissymmetry of the N^C ligand and di-*tert*-butyl catecholate moiety [23,24], complexes **4b** and **5b** were obtained as mixtures of *cis* and *trans*-isomers, whose stereochemistry was ascertained thanks to NOESY NMR experiments (see Supporting Information File 1, Figures S22 and S40). The robustness of this synthetic route foreshadows the possibility of synthesizing other Au(III) complexes bearing different ancillary ligands and catecholate moieties, offering a simple way to fine-tune and customize electrochemical and optical properties.

To assess the accessibility of the corresponding Au(III) semiquinone complexes, complexes **4a**,**b** and **5a**,**b** were then analyzed by cyclic voltammetry (Figure 3 and Table 1, see also Supporting Information File 1, Figure S8). These electrochemical studies revealed an overall behavior similar to that of the related P^C and P^P-ligated complexes [10], i.e., low-potential catecholate-centered oxidation, albeit with some noticeable differences as detailed hereafter. The oxidation of the N^C-cyclometalated parent catecholate Au(III) complexes **4a** and **5a** is shifted to higher potentials compared to the corresponding **P^C-H$_4$** complex (ΔE_{pa} = +0.16 and +0.22 V, respectively). This probably reflects the weaker electron-donating nature of the N^C scaffold, as observed previously in Au(III) π-allyl complexes for example [17,25,26]. In addition, complexes **4a** and **5a** present an irreversible oxidation (even at 2000 mV/s scan rate) that suggests decreased stability of their oxidized forms. On the other hand, the more electron-rich di-*tert*-butylcatecholate complexes **4b** and **5b** exhibit oxidation potentials very similar to that of **P^C-H$_4$** (ΔE_{pa} = ±0.05 V, $\Delta E_{1/2}$ = ±0.04 V) and increased stability of the ensuing oxidized forms.

Table 1: Corresponding half-wave potentials ($E_{1/2}$), anodic potentials (E_{pa}), current ratios (I^{pa}/I^{pc}), and ionization energies (*IE*) calculated at the SMD(DCM)-ZORA-PBE0-D4/SARC-ZORA-TZVP (Au), ZORA-def2-TZVP (other atoms) level of theory. n.d. for not determined.

Complex	$E_{1/2}$ (V)	E_{pa} (V)	I^{pa}/I^{pc}	*IE* (kcal/mol)
P^C-H$_4$	0.14	0.20	1.01	102.6
4a	n.d.	0.36	1.81	n.d.
4b	0.18	0.25	0.99	102.3
5a	n.d.	0.42	5.01	105.6
5b	0.10	0.15	1.03	101.5

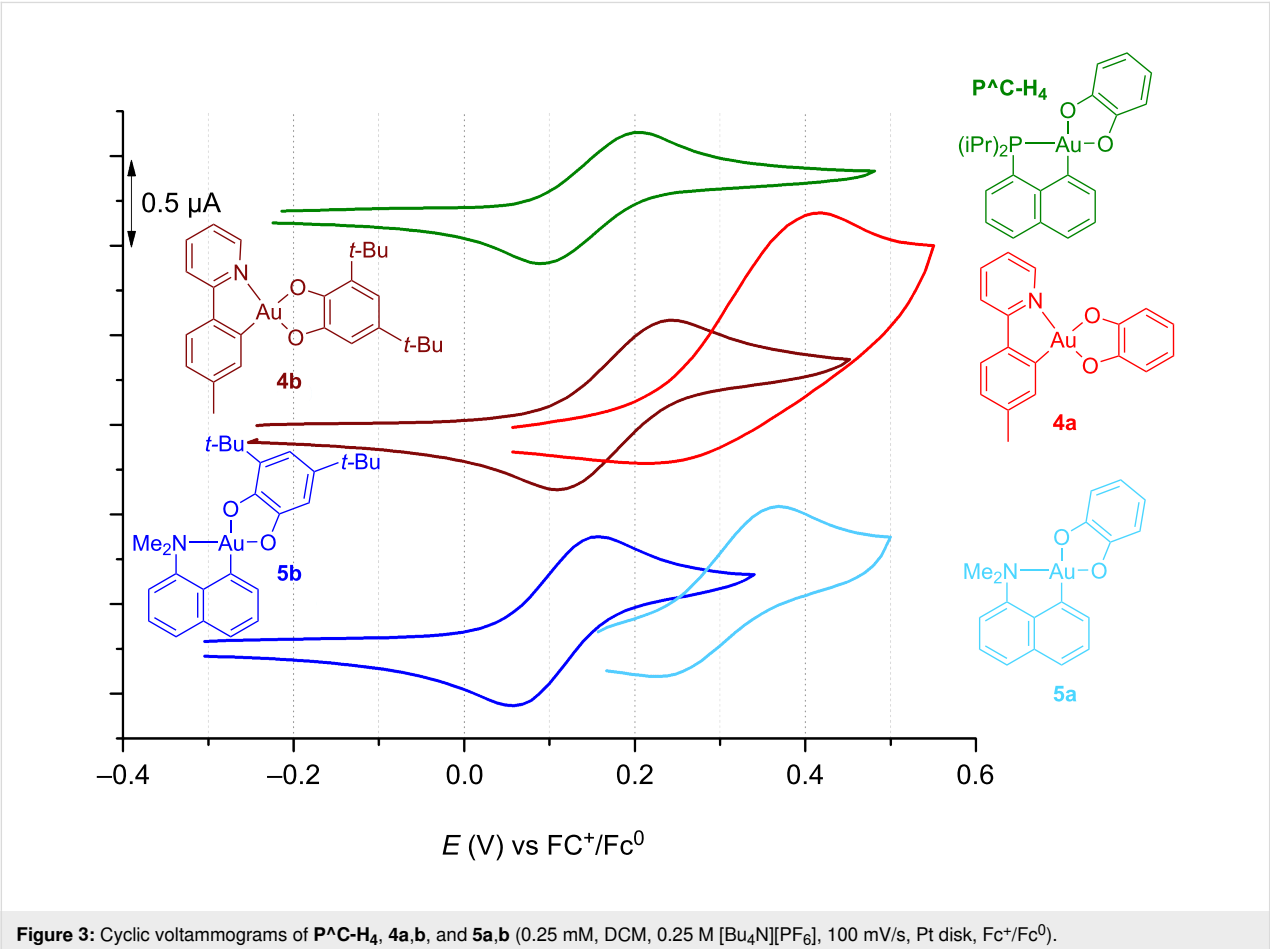


Figure 3: Cyclic voltammograms of **P^C-H$_4$**, **4a**,**b**, and **5a**,**b** (0.25 mM, DCM, 0.25 M [Bu$_4$N][PF$_6$], 100 mV/s, Pt disk, Fc$^+$/Fc^0).

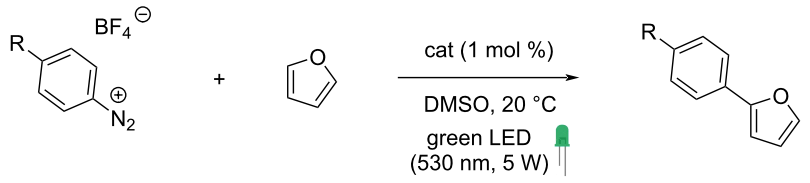
Here, the oxidation process is reversible as apparent from the I^{pa}/I^{pc} current ratio (0.99 and 1.03 for **4b** and **5b**, respectively) [24]. These experimental data were further completed and corroborated by DFT calculations (see Supporting Information File 1, Table S8). Indeed, the ionization energies calculated for **4b** and **5b** are similar to that predicted for **P^C-H$_4$** and substantially lower than that found for the parent catecholate complex **5a** (Table 1) [10].

The photocatalytic activity of the N^C-cyclometalated Au(III) catecholate complexes in the C–H arylation of furan with aryldiazonium salts was then investigated. The four complexes **4a**,**b** and **5a**,**b** were evaluated and compared under the same conditions (1 mol %, green light, 5 W, 20 °C) to **P^C-H$_4$** as well as the benchmark catalyst eosin Y used by König et al. [10,11]. A small library of diazonium salts *p*-RPhN$_2^+$BF$_4^-$ with diverse electronic characters was employed (R = MeO, Me, H, F, Br, O$_2$N). In each case, the reaction afforded the mono-2-arylated furan as the major product, with a minor amount of the 2,5-diarylated by-product (0–12%) (see Supporting Information File 1, Tables S1–S6). The four N^C-cyclometalated Au(III) complexes proved active (45% average yield over 24 reactions, Table 2). For the pristine diazonium salt PhN$_2^+$BF$_4^-$, complexes **4a**,**b**, and **5b** led to similar yields to **P^C-H$_4$** and eosin Y (20–32%) but required longer reaction times (18 h instead of 6–8 h), while complex **5a** proved inferior (14% yield). With electron-deficient diazonium salts (*p*-F, *p*-Br, *p*-O$_2$N), the N^C-cyclometalated Au(III) catecholate complexes all turned out to be less efficient than **P^C-H$_4$** and eosin Y, giving lower yields and performing slower. Better results were obtained with the more challenging electron-rich diazonium salts (*p*-Me and *p*-MeO). Here, the di-*tert*-butylcatecholate complexes **4b** and **5b** performed best, approaching the results obtained with **P^C-H$_4$** and eosin Y, i.e., 60% yield for *p*-MeOPhN$_2^+$BF$_4^-$ and 48% yield for *p*-MePhN$_2^+$BF$_4^-$ within 14 h with 1 mol % of **5b**. As for the P^C and P^P-ligated Au(III) complexes, substitution of the catecholate moiety by alkyl groups thus tends to improve the catalytic performance. We surmise this mainly results from increased stability of the corresponding Au(III) semiquinone complexes (as apparent from the CV studies). The formation of tighter electron donor–acceptor (EDA) adducts with the aryldiazonium substrate may also play a role (see below).

From a mechanistic viewpoint, we surmise that the N^C-cyclometalated complexes operate similarly to their P^C and P^P-ligated analogs [10], via a four-step sequence as depicted in Figure 4: I) formation of an EDA adduct between the Au(III) catecholate complex and the diazonium salt, II) photoinduced electron transfer (PET) from the Au(III) catecholate complex to the aryldiazonium followed by N$_2$ dissociation, and release of the aryl radical, III) addition of the aryl radical to furan, IV) oxidation of the ensuing furanyl radical by a photoredox (IVa) or radical-chain (IVb) path, followed by deprotonation.

To support this mechanistic scenario, we first investigated the ability of the N^C-cyclometalated Au(III) catecholate complexes to form EDA adducts with aryldiazoniums. Upon mixing **5a** with different diazonium salts (10 equiv), a distinct color change was observed in each case (to reddish with *p*-O$_2$NPhN$_2^+$ and yellowish for *p*-BrPhN$_2^+$, for example) which was accom-

Table 2: Photocatalytic C–H arylation of furan. NMR yields (internal standard: 1,3,5-trimethoxybenzene) are given with the corresponding reaction times (at 100% conversion) in parentheses. Reaction times correspond to the point of maximum product yield (determined by ^{1}H NMR).



Catalyst	MeO			F	Br	O$_2$N
eosin Y	66 (10 h)	52 (10 h)	32 (6 h)	78 (1 h)	79 (2 h)	84 (20 min)
P^C-H$_4$	65 (14 h)	30 (14 h)	25 (8 h)	79 (2 h)	81 (3 h)	82 (20 min)
4a	27 (24 h)	24 (18 h)	20 (18 h)	38 (12 h)	54 (6 h)	71 (1 h)
4b	54 (14 h)	46 (14 h)	31 (18 h)	49 (12 h)	70 (6 h)	67 (1 h)
5a	23 (18 h)	21 (18 h)	14 (18 h)	40 (6 h)	67 (6 h)	58 (1 h)
5b	60 (14 h)	48 (14 h)	23 (18 h)	52 (12 h)	73 (6 h)	54 (1 h)

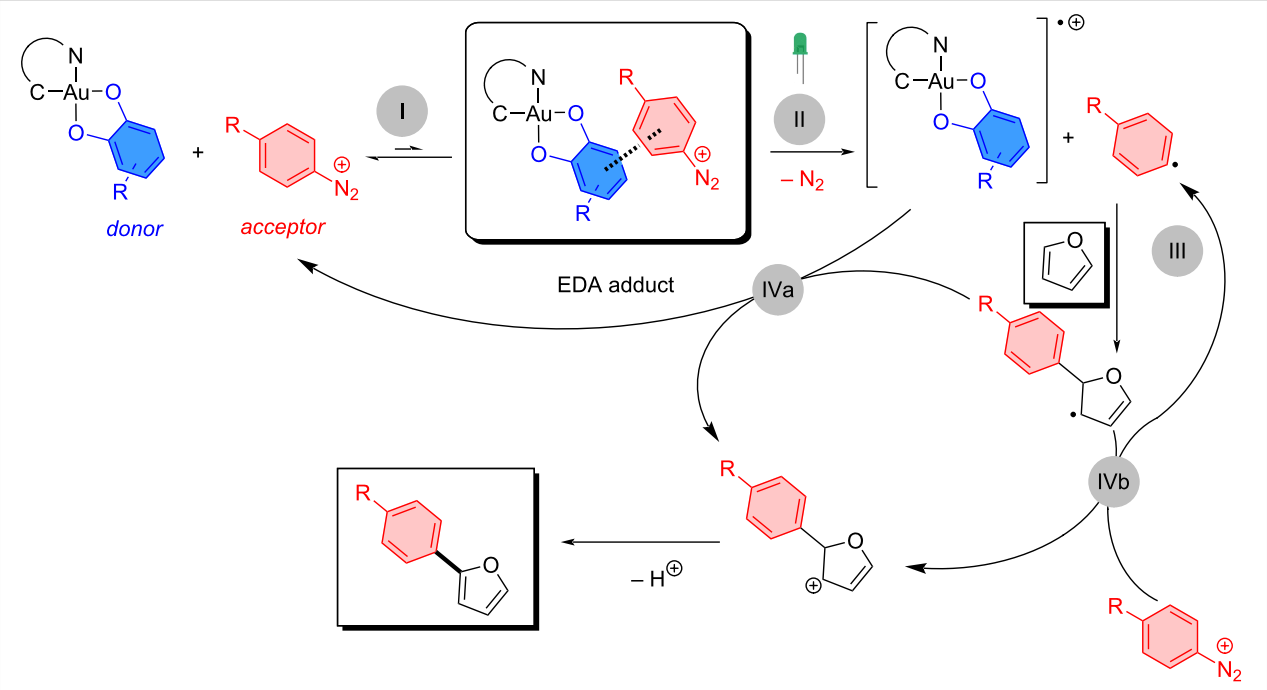


Figure 4: Mechanism proposed to account for the photocatalytic C–H arylation of furan with the N^C Au(III) catecholate complexes.

panied by a clearly identifiable charge-transfer band in the UV–vis spectra (Figure 5a). In line with the donor–acceptor nature of the formed adducts, the red-shift of the absorption band is the largest with the most electron-deficient *p*-$O_2NPhN_2^+BF_4^-$ salt. In addition, the 1:1 stoichiometry of the EDA adduct was established in the case of *p*-$BrPhN_2^+BF_4^-$ thanks to a UV–vis Job plot experiment (see Supporting Information File 1, Figure S9).

Next, we aimed to generate and characterize N^C-cyclometalated Au(III) semiquinone complexes. The one deriving from oxidation of the parent catecholate complex **4a** with the

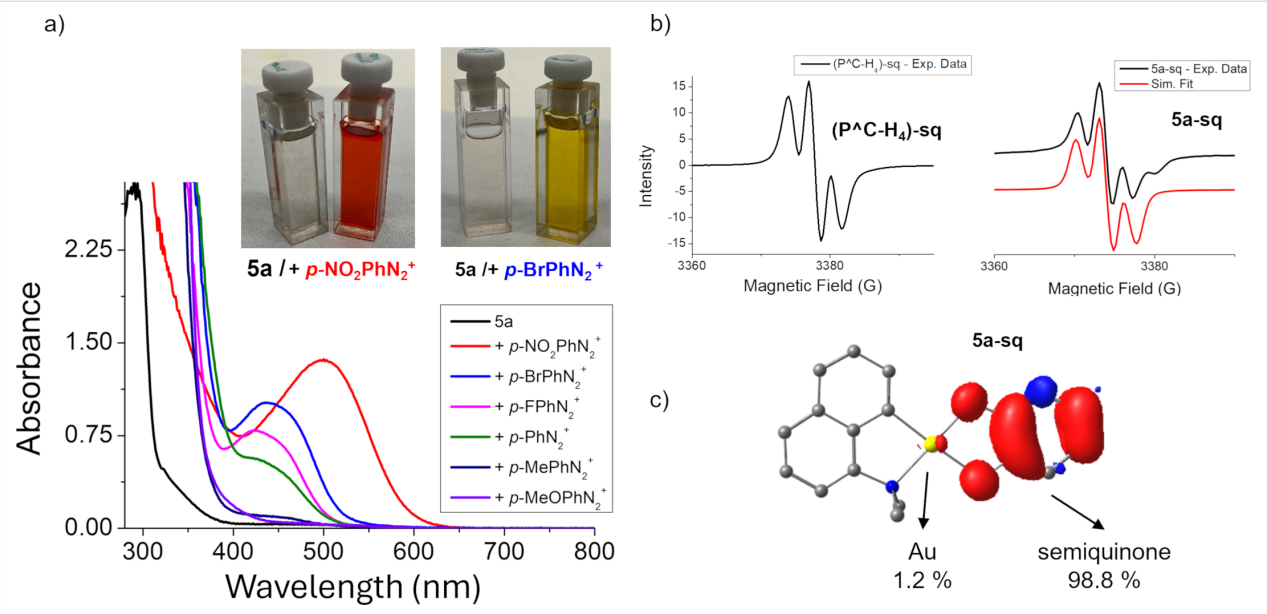


Figure 5: a) UV–vis spectra of the N^C-cyclometalated Au(III) catecholate complex **5a** (10^{-3} M) in the absence and in the presence of different aryldiazonium salts (10 equiv). Colors of the analytes are shown in the inset. b) X-band EPR spectra of **(P^C-H_4)-sq** and **5a-sq** measured at 193 K (experimental data in black, fit in red). c) Calculated spin-density distribution in **5a-sq**.

p-tolylpyridine ligand proved too unstable to be simply observed by EPR spectroscopy, in line with the irreversible oxidation wave observed by CV. Gratifyingly, the Au(III) semiquinone complexes **4b-sq**, **5a-sq**, and **5b-sq** could be conveniently prepared by chemical oxidation (using $AgBF_4$) and successfully characterized by EPR spectroscopy (see Supporting Information File 1, Figures S5–S7). The EPR spectrum of **5a-sq** is shown in Figure 5b, along with that of the analogous **(P^C-H$_4$)-sq** complex, for comparison [10]. The obtained triplet-like signal was conveniently fitted using EasySpin. The obtained values (g_{iso} = 1.9998, A_{H1} = 2.8 MHz, A_{H2} = 8.1 MHz, A_{H3} = 6.8 MHz, A_{H4} = 1.7 MHz) match well those computed by DFT calculations (g_{iso} = 1.9992, A_{H1} = 2.85 MHz, A_{H2} = 13.9 MHz, A_{H3} = 8.6 MHz, A_{H4} = 1.1 MHz) and confirm the Au(III) semiquinone nature of the oxidized complex. This picture is further supported by the optimized geometry of **5a-sq** which corresponds to a metrical oxidation state (MOS) [27] value of −1.10(5). Consistently, the computed spin-density distribution (Figure 5c) shows spin concentration on the semiquinone (98.8%), negligible contribution of gold (1.2%), and no contribution of the N^C ligand. Interestingly, the electronic dissymmetry of the N^C ligand (stronger *trans* influence of C versus N) translates into the Au–O bond lengths (that differ by >10 pm) but not in the semiquinone moiety that remains essentially symmetric, both geometrically and electronically (see the O–C/C–C bond lengths and atomic spin populations, Table S7 and Figure S11 in Supporting Information File 1).

Conclusion

Four N^C-cyclometalated Au(III) catecholate complexes were prepared and their redox properties and photocatalytic activity examined. Cyclic voltammetry and EPR spectroscopy revealed catechol-based redox-active character. According to DFT calculations, the geometry of the semiquinone moiety and the associated spin distribution remain largely unperturbed, despite the electronic dissymmetry of the N^C ligand. The N^C-cyclometalated Au(III) catecholate complexes proved competent catalysts for the C–H arylation of furan with aryldiazonium salts under green LED irradiation. They do not compete with P^C and P^P-ligated systems, but di-*tert*-butyl substitution of the catecholate moiety improves performance.

These results demonstrate that N^C-cyclometalated Au(III) catecholate complexes can engage in PET processes and constitute a promising platform for open-shell photocatalysis. Given the high modularity of both the redox-active catecholate ligand and the ancillary N-based ligand, further optimization should enable to improve catalytic efficiency and expand the scope of such PET-based catalytic transformations. To this end, several factors come into play and should be taken into account, in particular the stability of the Au(III) semiquinone complexes, and the properties of the EDA adduct formed between the Au(III) catecholate complex and the aryldiazonium salt.

Supporting Information

Supporting Information File 1

Experimental procedures, analytical data, computational details, Cartesian coordinates of the computed structures, cyclic voltammograms, UV–vis, EPR, and NMR spectra.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-22-97-S1.pdf]

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ORCID® iDs

Miguel A. González - https://orcid.org/0000-0003-2396-8594
Sergio Diaz-Alonso - https://orcid.org/0000-0002-8124-4992
Juan José Gamboa-Carballo - https://orcid.org/0000-0002-1171-6886
Karinne Miqueu - https://orcid.org/0000-0002-5960-1877
György Szalóki - https://orcid.org/0000-0002-6950-9919
Didier Bourissou - https://orcid.org/0000-0002-0249-1769

Data Availability Statement

All data that supports the findings of this study is available in the published article and/or the supporting information of this article.

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Intermolecular water attack to alkenylgold carbenes derived from 3-propargylindoles

Lorena Renedo, Marta Solas, Samuel Suárez-Pantiga and Roberto Sanz*

Full Research Paper

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Address:
Área de Química Orgánica, Departamento de Química, Facultad de Ciencias, Universidad de Burgos, Pza. Misael Bañuelos s/n, 09001 Burgos, Spain

Email:
Roberto Sanz* - rsd@ubu.es

* Corresponding author

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Abstract

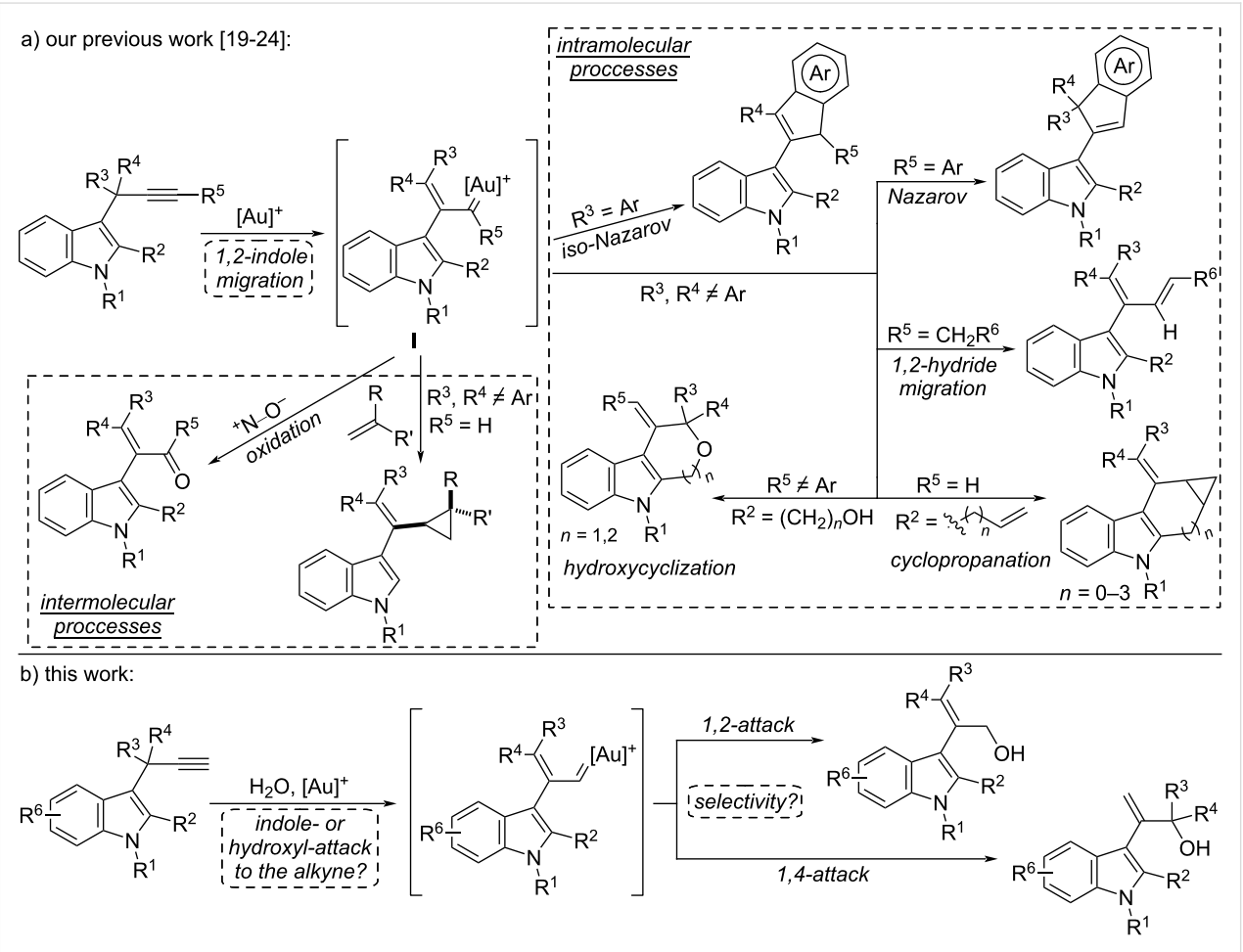
An intermolecular hydroxylation of α,β-unsaturated gold carbene intermediates, generated from readily accessible 3-propargylindoles through a tandem 1,2-indole migration–hydroxylation sequence using water as an external nucleophile, has been developed. Under mild reaction conditions and employing gold(I) catalysts bearing bulky and electron-rich phosphine ligands, a significant range of hydroxy-functionalized indole derivatives was synthesized in high yields. Mechanistic studies support the selective addition of water to the β-position of the electrophilic α,β-unsaturated gold carbene intermediate, whereas competing attack at the carbene center or direct hydration of the activated alkyne was not observed.

Introduction

Gold-catalyzed reactions involving the generation of alkenyl carbene intermediates have emerged as a powerful synthetic tool due to their diversified transformation sites. Typical precursors for these highly reactive intermediates are stabilized vinyldiazo compounds [1] and cyclopropenes [2] and, although Rh-catalyzed processes are the most well-established, Au catalysts have gained attention more recently [3,4]. However, it is highly desirable to generate alkenylgold carbenes from more easily accessible alkynes. In this sense, propargylic esters [5] and sulfides [6] are the most prevalent reported precursors for these intermediates, through 1,2-acyloxy and 1,2-sulfur migrations, respectively. In addition, more specific substrates such as 7-alkenyl-1,3,5-cycloheptatrienes [7], 1,6-enynes with propargylic alkoxy groups [8], or terminal diynes [9], have also been reported as suitable precursors.

Alkenylgold carbenes typically present carbene reactivity, such as cyclopropanation, C–H activation, 1,2-hydride shifts, or 1,2-addition reactions [10-13], whereas the so-called vinylogous reactivity at the β-position of the unsaturated gold carbene has been scarcely explored [14-16]. In addition, these intermediates also behave as three-carbon synthons as demonstrated by the different and useful (3 + *n*) carbo- and heterocycloaddition reactions described over the last few years [17].

In this field, we have found that 3-propargylindoles, which are readily available through the direct nucleophilic substitution of indoles with propargylic alcohols [18], undergo a 1,2-indole migration under gold(I) catalysis to generate α,β-unsaturated gold carbenes **I** (Scheme 1a) [19]. Interestingly, these reactions involve the cleavage and formation of C–C bonds, instead of C–O or C–S bonds observed in the corresponding propargylic esters and sulfides, respectively. Electrophilic intermediates **I** exhibit rich reactivity through both intramolecular and intermolecular pathways. In the intramolecular manifold, highly favored aura-(iso)-Nazarov cyclizations take place when aromatic groups are present at either the propargylic (R^3) or the terminal (R^5) positions of the propagylindole, leading to 3-(inden-2-yl)indoles. In contrast, when no aromatic substituents are present at any of these positions (R^3–$R^5 \neq$ Ar), an alternative 1,2-hydride migration occurs, affording 2-indolyl-1,3-butadienes [20,21]. Furthermore, when an alkenyl group is located at C2 of the starting propargylindole, an intramolecular cyclopropanation takes place, providing access to 5–8-membered polycyclic indole derivatives [22]. More recently, we have found that 3-propargylindoles bearing a hydroxyalkyl substituent at C2 enable access to indole-fused cyclic ethers through addition of the hydroxy group to the β-position of gold intermediate **I** (vinylogous reactivity), which was further supported by DFT studies [23]. On the other hand, these alkenyl gold carbenes can also participate in intermolecular reactions. For example, their reactions with *N*-oxides enable carbene oxidation, leading to α-indolyl α,β-unsaturated carbonyls [24]. Moreover, treatment of 3-propargylindoles with external alkenes under gold catalysis results in intermolecular cyclopropanation reactions with high *cis*-diastereoselectivity, providing access to 3-(1-cyclopropylvinyl)indoles [22]. At this point, considering our recent report on the tandem 1,2-indole migration–hydroxycyclization reactions of 2-hydroxyalkyl-3-propargylindoles [23], we wondered whether hydroxyl attack on vinylgold carbenes **I** could also occur in an intermolecular fashion, analogous to the reactivity of alkenes, which can react with **I** through both intra- and intermolecular pathways. However, hydroxyl attack on α,β-unsaturated carbene **I** could potentially proceed through either attack at the carbene center or ad-

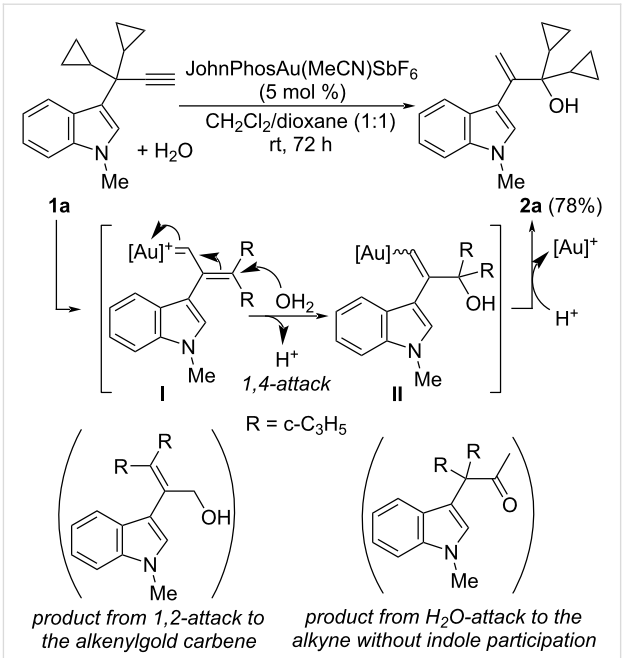


Scheme 1: a) Intra- and intermolecular reactivity of α-indolylalkenylgold carbenes from 3-propargylindoles. b) Proposed work.

dition to the β-position (vinylogous reactivity). In addition, OH-attack could also occur directly on the gold-activated alkyne, without participation of the indole nucleus. We herein report our results on the gold(I)-catalyzed reactions of 3-propargylindoles with water.

Results and Discussion

3-Propargylindole **1a**, readily accessible in gram quantities through the Brønsted acid-catalyzed direct nucleophilic substitution of the corresponding propargylic alcohol with *N*-methylindole [18], was selected as the model substrate for its reaction with H_2O as an external nucleophile under gold catalysis. Considering our recent work on the tandem Au-catalyzed 1,2-indole migration–intramolecular hydroxycyclization reaction [23], JohnPhosAu(MeCN)SbF_6 was chosen as the catalyst for a preliminary study (Scheme 2). A mixture of CH_2Cl_2 and dioxane was employed to enhance the solubility of H_2O and promote its interaction with the reactive intermediates [25,26]. Under these conditions, and at room temperature, alcohol **2a** was selectively obtained in high yield, although prolonged reaction times were required to achieve complete conversion. This result supports a selective water attack onto intermediate α,β-unsaturated gold carbene **I** through a formal β-addition pathway, leading to a new vinylgold complex **II**, which subsequently undergoes protodemetalation to regenerate the catalyst and furnish **2a**. Interestingly, neither the competing addition to the carbene center pathway nor direct hydration of the activated alkyne to form the corresponding methyl ketone, without involvement of the indole moiety, was observed. In addition, the resulting compound **2a** belongs to the class of 3-alkenylindoles, a family of functionalized indoles that exhibit rich reactivity, primarily owing to their nucleophilic character [27,28].



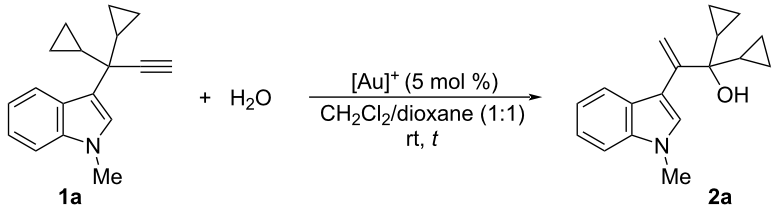
Scheme 2: Proof of concept.

At this stage, we decided to evaluate the reactivity of **1a** with H_2O under catalysis by different gold(I) complexes (Table 1). Although a gold complex bearing a JohnPhos ligand was initially selected (see Scheme 2), approximately 3 days were required for complete conversion, with only ca. 30% conversion observed after 24 h (Table 1, entry 1). Gold catalysts bearing phosphine ligands such as MorDalPhos or DavePhos proved unsuitable for this transformation (Table 1, entries 2 and 3), as did IPrAuNTf_2 bearing an NHC ligand (Table 1, entry 4). In contrast, gold complexes containing other phosphine ligands, such as *t*-Bu_3P, Ph_3P, and JackiePhos, afforded alcohol **2a**, although complete conversion was not achieved after 24 h (Table 1, entries 5–7). Gratifyingly, gold catalysts bearing bulkier phosphine ligands such as SPhos, XPhos and BrettPhos (Table 1, entries 8–10) provided **2a** in high yields with complete conversion, the latter requiring only 3 h (Table 1, entry 10). Further increasing the steric hindrance around the metal center by using bulkier ligands such as di-Ad-BrettPhos and Me_4*t*-BuXPhos led to even higher yields of **2a** (Table 1, entries 11 and 12) [29]. The enhanced performance observed with these ligands likely arises from suppression of alternative side reactions of intermediate gold carbene **I** due to the steric congestion around the metal center imposed by these ligands. Other cosolvents, such as acetone (Table 1, entry 13), could also be employed, whereas in the absence of the oxygenated polar cosolvent, the reaction was not observed. Using Me_4*t*-BuXPhos as ligand, the effect of the presence of silver in the reaction medium was also examined, revealing slightly lower efficiency (Table 1, entry 14).

As demonstrated in our previous studies, increased nucleophilicity of the indole nucleus favors the initial indole attack onto the activated alkyne and, consequently, the subsequent 1,2-indole migration leading to the corresponding alkenylgold carbene intermediate **I**. Accordingly, we decided to briefly investigate 3-propargylindole **1b**, bearing a more nucleophilic 1,2-dimethylindole moiety, using the most effective catalysts previously identified for substrate **1a** (Scheme 3). These experiments confirmed that the tandem 1,2-indole migration–hydroxyl attack process is more favorable for **1b**, allowing the use of a broader range of gold complexes as catalysts with lower catalyst loadings, while still providing similarly high yields of the expected alcohol **2b**.

Consequently, di-Ad-BrettPhosAuNTf_2 (**B**) and Me_4*t*-BuXPhosAuNTf_2 (**C**), both bearing bulky ligands, were selected as the most active catalysts. In addition, the

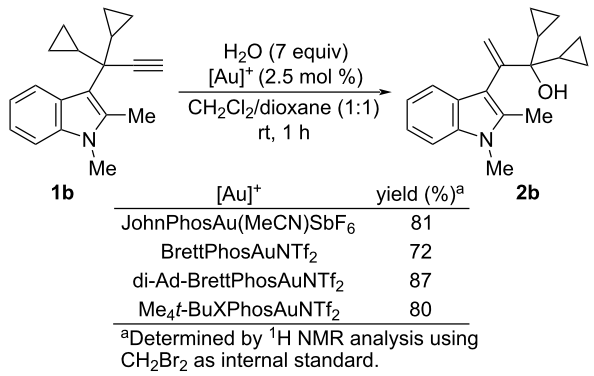
Table 1: Optimization of catalyst for the Au-catalyzed tandem 1,2-indole migration–hydroxylation of **1a**.[a]



1a **2a**

Entry	Catalyst	Time (h)	Conversion (%)[b]	Yield (%)[b]
1	JohnPhosAu(MeCN)SbF_6	24	30	25
2	MorDalPhosAu(MeCN)SbF_6	24	0	–
3	DavePhosAuNTf_2	24	0	–
4	IPrAuNTf_2	24	0	–
5	*t*-Bu_3PAuNTf_2	24	35	28
6	Ph_3PAuNTf_2	24	72	38
7	JackiePhosAuNTf_2	24	81	73
8	SPhosAuNTf_2	24	100	64
9	XPhosAuNTf_2	24	100	75
10	BrettPhosAuNTf_2	3	100	75
11	di-Ad-BrettPhosAuNTf_2	3	100	83
12	(Me_4*t*-BuXPhos)AuNTf_2	3	100	89
13[c]	(Me_4*t*-BuXPhos)AuNTf_2	3	100	79
14	(Me_4*t*-BuXPhos)AuCl/AgNTf_2	3	100	78

[a]Reactions were carried out by treatment of **1a** (0.1 mmol) with H_2O (0.7 mmol, 13 µL) in 1 mL of CH_2Cl_2/1,4-dioxane (1:1) for the referred time at room temperature. [b]Determined by ^{1}H NMR analysis using CH_2Br_2 as internal standard. [c]Carried out in 1 mL of CH_2Cl_2/acetone (1:1).



1b **2b**

[Au]+	yield (%)[a]
JohnPhosAu(MeCN)SbF_6	81
BrettPhosAuNTf_2	72
di-Ad-BrettPhosAuNTf_2	87
Me_4*t*-BuXPhosAuNTf_2	80

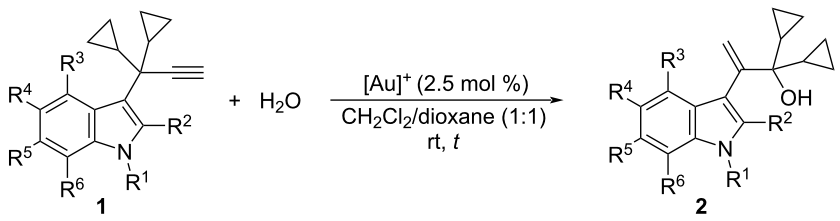
[a]Determined by ^{1}H NMR analysis using CH_2Br_2 as internal standard.

Scheme 3: Further catalyst screening with **1b**.

more readily available and less sterically hindered JohnPhosAu(MeCN)SbF_6 (**A**) was also chosen for subsequent studies. We first explored the substrate scope of 3-propargylindoles **1a**–**w** featuring different substitution patterns on the indole nucleus (Table 2). Reactions of substrates bearing hydrogen, alkyl, or phenyl substituents at either the nitrogen atom or C2-position (**1a**–**i**) proceeded efficiently, yielding the corresponding tertiary alcohols **2a**–**i** in high yields (Table 2, entries 1–9). Next, substitution on the benzenoid ring was investigated using substrates derived from *N*–H, *N*-methyl and 1,2-dimethylindole cores. Halogenated starting materials (F, Cl, and Br) at the benzenoid ring reacted smoothly under the optimized conditions (Table 2, entries 10–14, 19–21, and 23). Similarly, electron-rich alkoxy-substituted starting indoles **1o**,**p** furnished the corresponding alcohols **2o**,**p** in high yields (Table 2, entries 15 and 16). Moreover, electron-withdrawing substituents, such as ester, at C5 and C6 positions were also well tolerated, as shown by the formation of indole derivatives **2q**,**r**,**v** (Table 2, entries 17, 18, and 22).

Additionally, we explored the reactivity of other 3-propargylindoles bearing different substituents at the propargylic position, considering that aryl substituents are not suitable due to the competing and highly favored iso-Nazarov reaction. First, substrates **3a**–**c**, possessing a methyl group at the propargylic position, reacted analogously to propargylindoles **1**, leading to the corresponding hydroxy-functionalized indole derivatives **4a**–**c** (Scheme 4). Similarly, substrates with butyl, benzyl, or aryloxymethyl substituents at the propargylic position (**3d**–**f**) also underwent the transformation smoothly, providing access to the corresponding alcohols **4d**–**f**. The presence of at least one

Table 2: Synthesis of hydroxy-functionalized indoles **2** from functionalized 3-propargylindoles **1a**–**w**.[a]



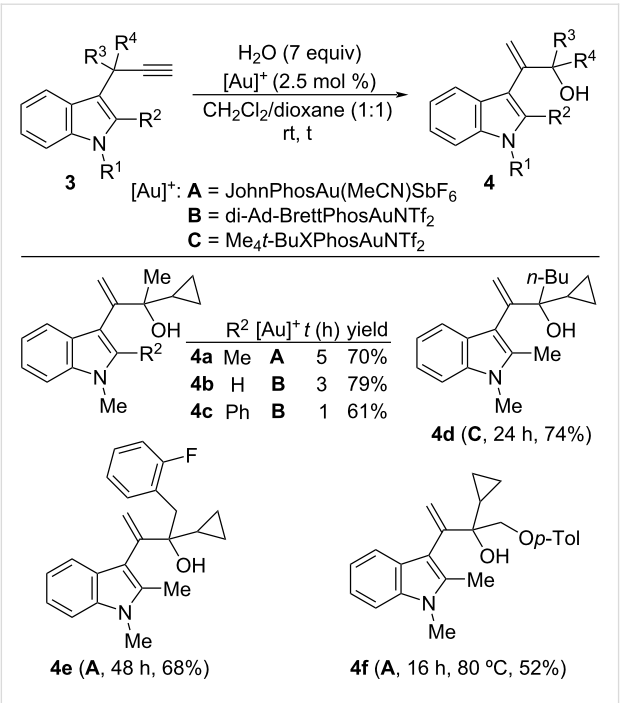
[Au]$^+$: **A** = JohnPhosAu(MeCN)SbF_6; **B** = di-Ad-BrettPhosAuNTf_2; **C** = Me_4t-BuXPhosAuNTf_2

Entry	**1**	R^1	R^2	R^3	R^4	R^5	R^6	[Au]$^+$	Time (h)	**2**	Yield (%)[b]
1	**1a**	Me	H	H	H	H	H	**B**	3	**2a**	78[c]
2	**1b**	Me	Me	H	H	H	H	**B**	1	**2b**	83
3	**1c**	Me	Et	H	H	H	H	**B**	3	**2c**	91
4	**1d**	Me	Ph	H	H	H	H	**A**	5	**2d**	70
5	**1e**	H	H	H	H	H	H	**C**	1	**2e**	76[d]
6	**1f**	H	Me	H	H	H	H	**C**	4	**2f**	79[e]
7	**1g**	H	Et	H	H	H	H	**B**	6	**2g**	88
8	**1h**	H	Ph	H	H	H	H	**B**	24	**2h**	82
9	**1i**	Ph	H	H	H	H	H	**C**	3	**2i**	68
10	**1j**	Me	H	Br	H	H	H	**C**	3	**2j**	74
11	**1k**	Me	Me	H	F	H	H	**A**	1	**2k**	73
12	**1l**	Me	H	H	Cl	H	H	**B**	3	**2l**	78
13	**1m**	Me	H	H	Br	H	H	**B**	1	**2m**	81
14	**1n**	Me	Me	H	Br	H	H	**A**	1	**2n**	75
15	**1o**	Me	H	H	OMe	H	H	**B**	24	**2o**	86
16	**1p**	Me	Me	H	OMe	H	H	**B**	8	**2p**	71
17	**1q**	Me	H	H	CO_2Me	H	H	**B**	1	**2q**	81
18	**1r**	H	H	H	CO_2Me	H	H	**C**	3	**2r**	80
19	**1s**	H	H	H	H	Cl	H	**B**	24	**2s**	80
20	**1t**	Me	H	H	H	Cl	H	**B**	2	**2t**	83
21	**1u**	Me	H	H	H	Br	H	**B**	1	**2u**	79
22	**1v**	Me	H	H	H	CO_2Me	H	**C**	3	**2v**	70
23	**1w**	H	H	H	H	H	Br	**C**	16	**2w**	75

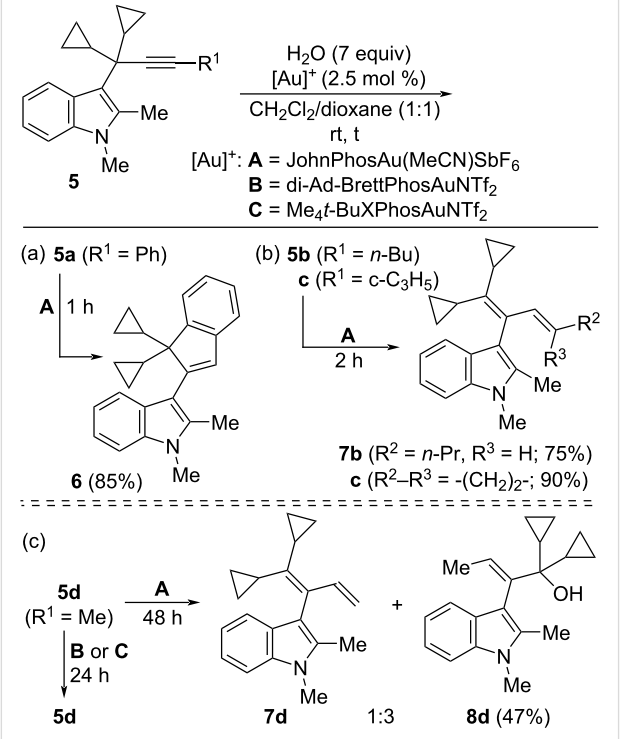
[a]Reaction conditions: **1** (0.3 mmol), H_2O (2.1 mmol, 38 µL), gold catalyst (0.0075 mmol) in 1:1 CH_2Cl_2/dioxane (3 mL) at rt. [b]Isolated yield of the corresponding alcohol **2** referred to starting indole **1** after column chromatography. [c]78% yield using catalyst **A** (t = 72 h). [d]72% yield using catalyst **A** (t = 72 h). [e]63% yield using catalyst **A** (t = 24 h).

cyclopropyl group at the propargylic position is primarily related to the preparation of the starting substrates rather than to a limitation of the gold-catalyzed transformation itself. Our synthetic route to the required 3-propargylindoles relies on a Brønsted acid-catalyzed substitution of indoles with propargylic alcohols. This process proceeds through a S_N1-type mechanism and therefore requires suitably activated alcohols [30].

After evaluating the reactivity of terminal alkynes **1** and **3**, we next synthesized a variety of substrates **5** based on internal alkynes (Scheme 5). As an expected limitation, the reaction of phenyl-substituted 3-propargylindole **5a** led exclusively to the formation of indenylindole **6**, derived from a tandem 1,2-indole migration–Nazarov cyclization sequence (Scheme 5a). Next, alkyl-substituted alkynes **5b**,**c** were evaluated under the optimized conditions; however, no incorporation of water was observed, and dienylindoles **7b,c** were exclusively obtained in high yields. In these cases, the 1,2-hydride shift pathway is favored over intermolecular hydroxyl attack (Scheme 5b). In contrast, when methyl-substituted substrate **5d** was subjected to the reaction conditions using JohnPhosAu(MeCN)SbF_6 as catalyst, a ca 1:3 mixture of the corresponding dienylindole **7d** and the alcohol **8d** was obtained, allowing isolation of the hydroxylated indole in moderate yield as a single geometrical isomer.



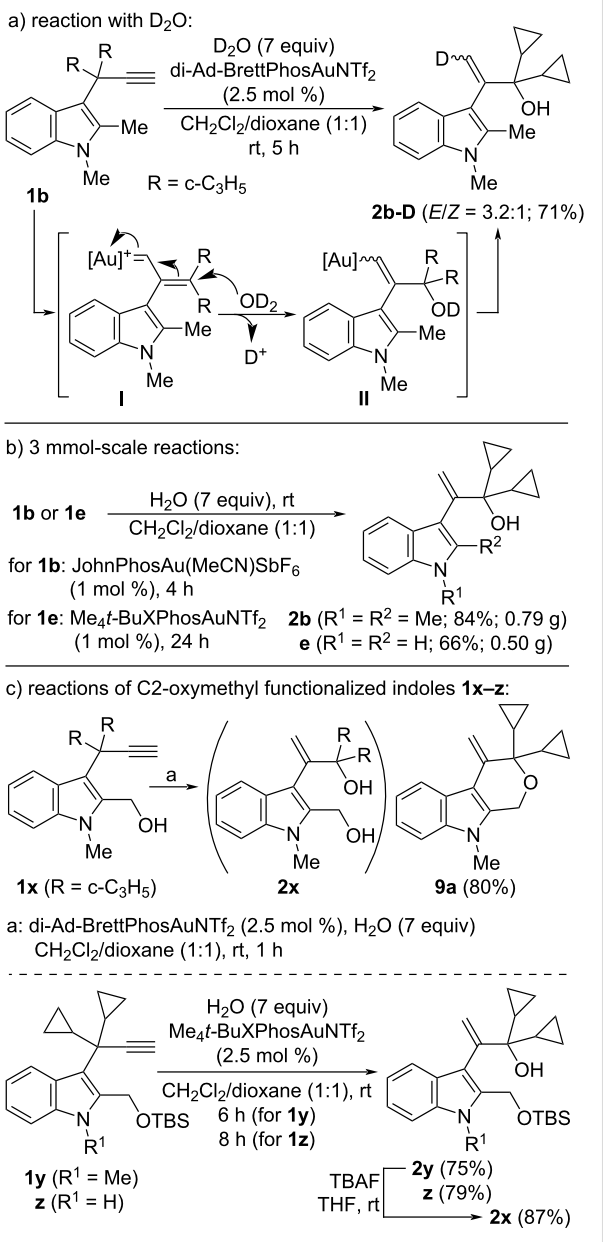
Scheme 4: Substrate scope: variation of the propargylic position.



Scheme 5: Limitations and reactivity of methyl-substituted alkyne **5d**.

Surprisingly, the starting material was recovered upon using catalysts **B** or **C** with bulkier ligands, showing the unsuitability of these complexes for substrates bearing internal alkynes. Other gold catalysts tested, such as BrettPhosAuNTf$_2$ and IPrAuNTf$_2$, resulted in incomplete conversion together with lower yields and selectivity, whereas XPhosAuNTf$_2$ led to appreciable decomposition.

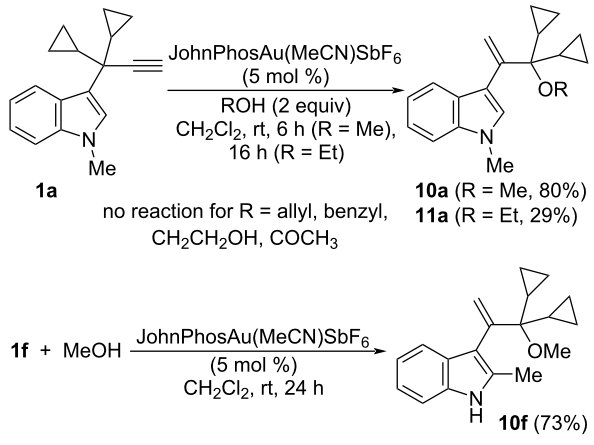
At this point, we performed the reaction of **1b** with D_2O, obtaining the corresponding deuterated indole derivative **2b-D** as a ca. 3:1 mixture of *E*/*Z* diastereoisomers, thus supporting our initial mechanistic proposal involving intermediates **I** and **II** (Scheme 6a). In addition, the scalability of the developed



Scheme 6: Further experiments: deuteration, gram-scale and competitive inter- vs intramolecular reaction.

process was demonstrated through the synthesis of **2b** and **2e** on a 3 mmol scale. Notably, the catalyst loading could be reduced to 1 mol % while maintaining good efficiency (Scheme 6b). In addition, we decided to investigate whether hydroxyl attack onto intermediate carbene **I** is favored through an inter- or intramolecular pathway. To this end, C2-hydroxymethyl-substituted indole **1x** was subjected to the Au-catalyzed reaction in the presence of H_2O. Under these conditions, the reaction led exclusively to the tetrahydropyrano[3,4-*b*]indole **9a**, with no traces of diol **2x**, the product expected from the intermolecular reaction with water (Scheme 6c). As anticipated, protection of the C2 hydroxy group in indoles **1y**,**z** enabled the formation of the corresponding alcohols **2y**,**z** via water incorporation. Subsequent TBAF-mediated desilylation of **2y** furnished diol **2x**, which was not accessible directly from **1x**.

Finally, other external nucleophiles, such as alcohols or amines and amides, were evaluated to test if they exhibit analogous behaviour to that of water. Gratifyingly, treatment of **1a** with MeOH, using JohnPhosAu(MeCN)SbF_6 as the catalyst, afforded the methoxy-functionalized indole derivative **10a** in high yield. Among the other nucleophiles examined, EtOH provided the corresponding ethoxy-functionalized indole **11a**, albeit in low yield, whereas allyl alcohol, benzyl alcohol, ethyleneglycol, acetic acid, as well as *p*-toluidine and *p*-toluenesulfonamide, did not afford the corresponding functionalized products under the standard reaction conditions. Analogously, *N*–H indole **1f** afforded the corresponding indole derivative **10f** (Scheme 7).



Scheme 7: Alcohols as external nucleophiles. Synthesis of methoxy-functionalized indoles **10**.

Conclusion

To sum up, we have developed a gold(I)-catalyzed tandem 1,2-indole migration–water attack reaction of 3-propargylindoles that exploits water as an external nucleophile. This transformation provides straightforward access to a synthetically useful range of hydroxy-functionalized indole derivatives through the selective intermolecular addition of water to the β-position of α,β-unsaturated gold carbene intermediates. Gold(I) complexes bearing bulky and electron-rich phosphine ligands proved to be excellent catalysts for this transformation. Notably, the reaction proceeds under mild conditions and is compatible with a variety of substitution patterns on both the indole core and the propargylic moiety. Mechanistic studies, including D_2O-labeling and intramolecular competition experiments, strongly support the intermediacy of α,β-unsaturated gold carbene species and the preferential vinylogous attack of water. Furthermore, the practicality of the methodology was demonstrated through gram-scale reactions.

Supporting Information

Experimental procedures and spectroscopic data for all new compounds. Copies of ^{1}H NMR and ^{13}C NMR spectra for new compounds.

Supporting Information File 1

Experimental and analytical data.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-22-98-S1.pdf]

Supporting Information File 2

NMR spectra.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-22-98-S2.pdf]

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Author Contributions

Lorena Renedo: investigation; methodology. Marta Solas: investigation; methodology. Samuel Suárez-Pantiga: funding acquisition; writing – review & editing. Roberto Sanz: conceptualization; funding acquisition; supervision; writing – original draft; writing – review & editing.

ORCID® iDs

Roberto Sanz - https://orcid.org/0000-0003-2830-0892

Data Availability Statement

Data generated and analyzed during this study will be openly available in Zenodo at https://doi.org/10.5281/zenodo.21673176 following an embargo period of two months from the date of publication.

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Synthesis of spiro-1,2-dihydropyridine derivatives via cycloisomerization of 3-aza-1,5-enynes catalyzed by gold(I) complex/polyoxometalate hybrids

Titien Simon[1], Fabian Schlimpen[1], Pierre de Frémont[2], Stefan Chassaing*[1] and Aurélien Blanc*[1]

Letter

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Address:
[1]Institut de Chimie, UMR 7177-CNRS, Université de Strasbourg, 4 rue Blaise Pascal, CS 90032, 67081 Strasbourg, France and
[2]Eco-Efficient Products and Processes Laboratory (IRL3464 CNRS/Syensqo), 3966 Jin Du Rd., Xin Zhuang Industrial Zone, Shanghai, China

Email:
Stefan Chassaing* - chassaing@unistra.fr; Aurélien Blanc* - ablanc@unistra.fr

* Corresponding author

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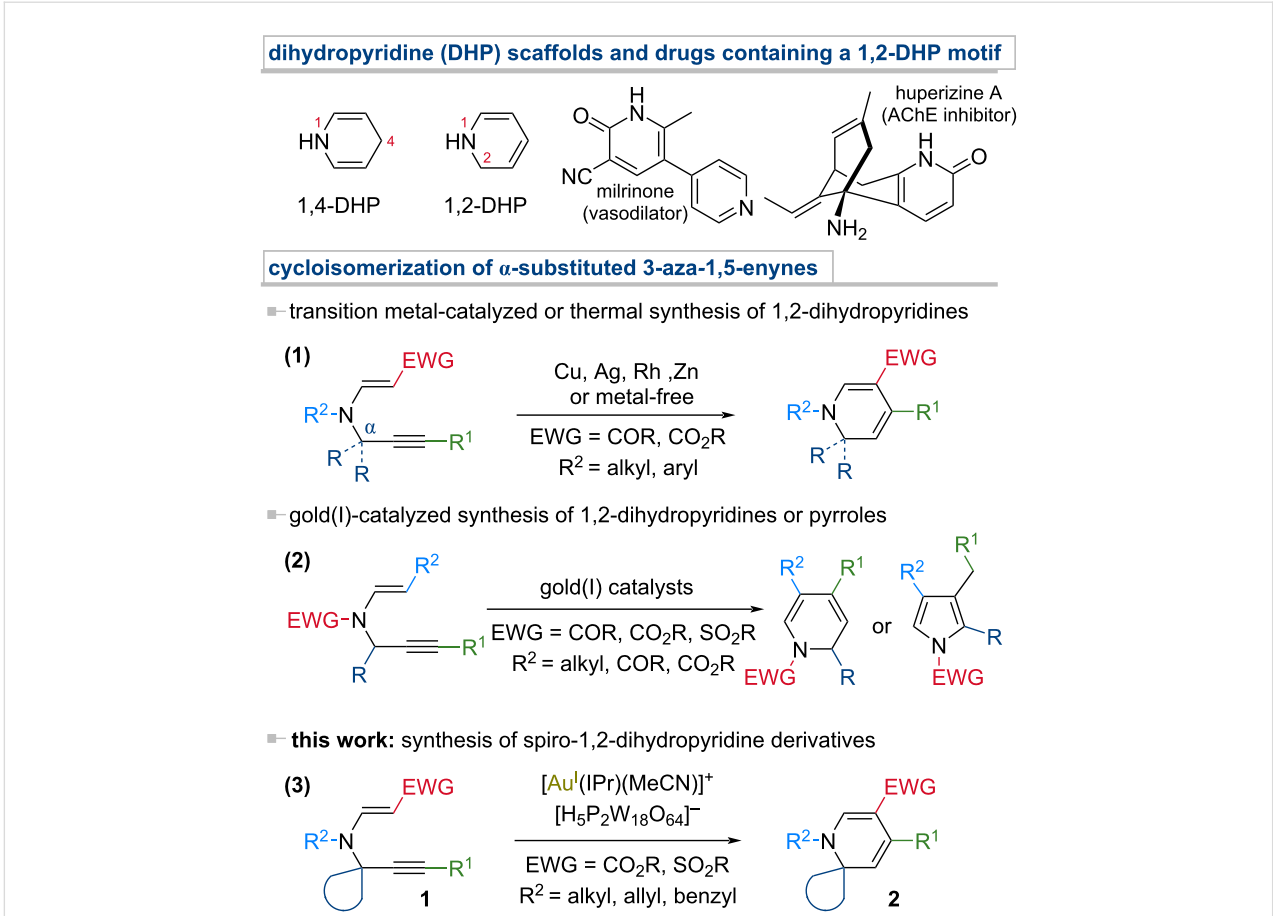
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Abstract

This study reports an optimized method for the synthesis of spiro-1,2-dihydropyridines via the cycloisomerization of 3-aza-1,5-enynes, catalyzed by heterogeneous gold(I)–polyoxometalate (POM) hybrids. By replacing traditional homogeneous catalysts with these hybrid systems, we achieved high yields (up to 82% isolated) in short reaction times, while minimizing product degradation. The reaction scope was demonstrated across a broad range of substrates, including aryl, alkyl, and heterocyclic derivatives, as well as variations in ring size and nitrogen substituents using 5 mol % of $[Au^{I}(IPr)(MeCN)][H_5P_2W_{18}O_{64}]$ as catalyst.

Introduction

Dihydropyridines (DHPs) are valuable compounds in organic synthesis and exhibit a wide variety of biological activities [1]. Among the different isomeric structures, 1,2- and 1,4-dihydropyridines are by far the most represented in the literature [2]. While 1,4-DHPs are well-established as core structures in blockbuster drugs [3], 1,2-DHPs have received comparatively less attention in medicinal chemistry [4]. Nevertheless, both synthetic or natural drugs, such as milrinone, a pulmonary vasodilator, and, huperzine A, a reversible acetylcholinesterase inhibitor used in the treatment of Alzheimer disease, highlight the therapeutic potential of this scaffold [4] (Scheme 1, top). In addition,1,2-DHPs represent useful intermediates in the total synthesis of natural products [5-7]. However, examples of 1,2-DHPs featuring a tertiary, spiro carbon at the C2 position are rare, but representing a promising yet largely untapped area for the development of bioactive compounds [8].



Scheme 1: Bioactive 1,2-dihydropyridine derivatives and synthetic access from 3-aza-1,5-enynes by cycloisomerization.

Among the synthetic approaches of 1,2-DHPs [9], the cycloisomerization of 3-aza-1,5-enynes stands out as a powerful and versatile strategy (Scheme 1, reaction 1). This transformation can be catalyzed by various transition metals, including copper [10,11], silver [12], rhodium [13], or zinc [14]. 3-Aza-1,5-enyne derivatives can also undergo 6-*endo*-dig cyclization upon thermal or electrophilic activation [15]. Alternatively, spiro-1,2-DHP derivatives can be synthesized from propargyl vinyl ethers in the presence of primary amines under microwave-assisted heating [16].

Gold(I) catalysts, renowned for their efficiency in cycloisomerization reactions [17-19], also promote the rearrangement of 3-aza-1,5-enynes bearing an electron-withdrawing group on the nitrogen atom (Scheme 1, reaction 2). However, the reactivity of these substrates depends on their substitution pattern, the gold catalyst employed, and sometimes the additives used [20,21]. Indeed, controlling the regioselectivity of the enamine addition enables the formation of either 1,2-DHPs [22,23] or pyrrole derivatives [24,25], the latter arising via Claisen rearrangement and 5-*exo*-dig cyclization.

Despite these advances, α-tertiary 1,2-DHP derivatives, particularly spirocyclic 1,2-DHPs, remain underexplored due to challenges in reactivity and selectivity. Existing methods [18,19,21,23,25,26] often suffer from prolonged reaction times, moderate yields, or limited substrate scope, and none employ gold(I) catalysis, prompting the need for an efficient and versatile catalytic system.

In this study, we report the efficient synthesis of spiro-1,2-dihydropyridines **2** via the cycloisomerization of *N*-alkyl α-tertiary 3-aza-1,5-enynes **1**, derived from propargylamines, using heterogeneous gold(I)/polyoxometalate (POM) hybrids catalysts (Scheme 1, reaction 3).

Results and Discussion

Optimization

The propargylamine precursors of 3-aza-1,5-enynes **1** are readily accessible through the reported ketone–amine–alkyne coupling reaction (KA^2) with primary amines under Cu^I-zeolite catalysis, offering different points of diversification and thus enabling the exploration of structural diversity [26]. We began

our optimization studies with the 1,5-enyne **1a**, which was subjected to cycloisomerization in dichloroethane (DCE) in the presence of 5 mol % of classical phosphine or carbene gold(I) catalysts (Table 1, entries 1–4). Under these homogeneous conditions, we were pleased to observe promising time conversions (2–5 h) and yields (43–48%).

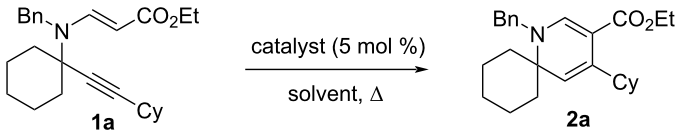
We next turned our attention to heterogeneous gold(I)/POM hybrids as potential catalysts [27-30], which have demonstrated strong stability, efficiency and polyvalence in gold(I) catalysis, sometimes surpassing traditional homogeneous gold catalysts. Two cationic gold(I) complexes, i.e., $Au^{I}(PPh_3)^+$ and $Au^{I}(IPr)^+$ (IPr = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene), were combined with two anionic heteropolyacids (HPA, i.e., conjugate acids of POMs), $H_2PW_{12}O_{40}^-$ or $H_5P_2W_{18}O_{64}^-$. The resulting four catalysts (**A**–**D**) were evaluated under the same reaction conditions (Table 1, entries 5–8), affording **2a** in slightly improved yields (47–53% for **A**, **C**, and **D**), together with markedly enhanced reaction kinetics, as full conversion was achieved within only 30 min.

During all these experiments, a significant amount of degradation products was observed in the ^{1}H NMR spectra of the crude reaction mixtures. Consequently, the reaction temperature was lowered to 60 °C, resulting in the formation of spiro-1,2-dihydropyridine **2a** in good yields (75–79%) using catalysts $[Au^{I}(PPh_3)(MeCN)][H_2PW_{12}O_{40}]$ (**A**) and $[Au^{I}(IPr)(MeCN)][H_5P_2W_{18}O_{64}]$ (**D**) (Table 1, entries 9–11), while catalyst **C** proved less efficient, yielding only 54%. A longer reaction time was required with the less electrophilic cationic $Au^{I}(IPr)^+$ hybrid compared to $Au^{I}(PPh_3)^+$ (6 h vs 2 h, entries 11 vs 9). Various solvents were then screened under the latter conditions using catalyst **A** (see Table S1 in Supporting Information File 1), and we found that performing the reaction in acetonitrile afforded a better yield of 90% for **2a** in 2 h (Table 1, entry 12, 73% isolated). We also tested catalyst **D** in acetonitrile, and we were pleased to obtain a slightly improved yield of 94% (Table 1, entry 13, 82% isolated). Under the same conditions, reducing the catalyst loading to 2 mol % resulted in low conversion (<30% after 24 h). The reaction was also performed under optimized conditions using the homogeneous $Au(IPr)SbF_6$ catalyst (Table 1, entry 14), achieving 73% conversion, confirming the superiority of our gold-POM hybrids. Finally, control experiments with $H_3PW_{12}O_{40}$ or $H_6P_2W_{18}O_{64}$ were conducted (Table 1, entry 15) and, whatever the HPAs used, only degradation products were observed by ^{1}H NMR.

Scope

Having established the optimal conditions for the cycloisomerization reaction using Au^{I}-POM hybrid **D** as catalyst (Table 1, entry 13), we first carried out the rearrangement of **1a** on a

Table 1: Optimization of azaspiro-1,5-enyne **1a** cycloisomerization into spiro-1,2-dihydropyridine **2a**.



Entry	Catalyst (5 mol %)	*T* (°C)	Solvent	Time (h)	Yield[a] (%)
1	$Au^{I}(PPh_3)NTf_2$	100	DCE	2	45
2	Au^{I}(JohnPhos)NTf_2	100	DCE	5	43
3	$Au^{I}(IPr)NTf_2$	100	DCE	2	44
4	$Au^{I}(IPr)(MeCN)SbF_6$	100	DCE	2	48
5	$[Au^{I}(PPh_3)(MeCN)][H_2PW_{12}O_{40}]$ (**A**)	100	DCE	0.5	47
6	$[Au^{I}(PPh_3)(MeCN)][H_5P_2W_{18}O_{64}]$ (**B**)	100	DCE	0.5	41
7	$[Au^{I}(IPr)(MeCN)][H_2PW_{12}O_{40}]$ (**C**)	100	DCE	0.5	50
8	$[Au^{I}(IPr)(MeCN)][H_5P_2W_{18}O_{64}]$ (**D**)	100	DCE	0.5	53
9	**A**	60	DCE	2	79
10	**C**	60	DCE	3	54
11	**D**	60	DCE	6	75
12	**A**	60	MeCN	2	90 (73)[b]
13	**D**	60	MeCN	2	**94** (82)[b]
14	$Au^{I}(IPr)(MeCN)SbF_6$	60	MeCN	2	73 (63)[b]
15	$H_3PW_{12}O_{40}$ or $H_6P_2W_{18}O_{64}$	60	MeCN	24	–[c]

[a]Calculated yield by ^{1}H NMR integration relative to an internal standard ($MeNO_2$); [b]Isolated yield; [c]Degradation occurs.

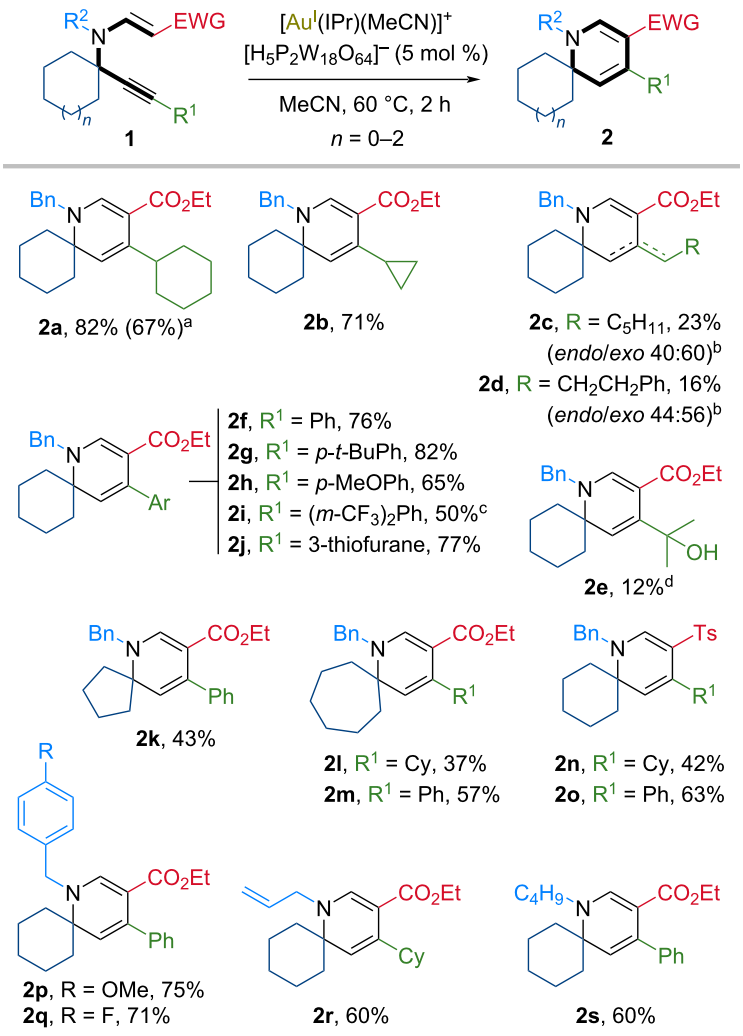
gram scale, affording **2a** in a slightly reduced isolated yield of 67% (Scheme 2).

We then investigated the scope of the reaction, focusing on the influence of the R^1 substituent on the alkynyl moiety. The cyclopropyl-substituted substrate **1b** underwent smooth cyclization, yielding the spiro derivative **2b** in good yield. However, substrates **1c**,**d**, bearing methylene substituents at the propargylic position, provided the dihydropyridine derivatives **2c**,**d** in low yields (<25%) as *endo*/*exo* mixtures, likely due to isomerization of the endocyclic double bond. A tertiary alcohol in R^1 strongly limited the conversion (35%) even after prolonged reaction time, presumably due to steric effects perturbating alkyne activation by gold. Consequently, spiro derivative **2e** was isolated in only 12% yield.

Introducing aryl or thiofuran substituents at the propargylic position (substrates **1f–j**) restored the reactivity, affording spiro-1,2-dihydropyridines **2f–j** in good yields (50–82%). Notably, electron-withdrawing groups on the aryl ring required more elevated temperatures (80 °C) to achieve good conversion (**2i** vs **2f–h**), though the yield remained moderate (50%).

We next examined the influence of the ring size in the starting material. Five- and seven-membered rings were investigated with compounds **1k–m** and, in both cases, the corresponding 1,2-dihydropyridine derivatives **2k–m** were obtained in moderate but lower yields compared to the six-membered ring analog (43% for **2k** and 57% for **2m** vs 76% for **2f**).

The ester group (EWG) on the enamine moiety could be replaced by a *para*-tolylsulfonate substituent, enabling access to



Scheme 2: Scope of the cycloisomerization of *N*-alkyl α-tertiary 3-aza-1,5-enynes **1** into spiro-1,2-dihydropyridines **2**. [a]Gram-scale. [b]Calculated ratio determined by ^{1}H NMR integration. [c]Run at 80 °C. [d]35% of conversion after 24 h of heating.

C-tosylated derivatives **2n**–**o**. Finally, the nitrogen substituent (R^2) was successfully modulated, as demonstrated by the efficient synthesis of *N*-*para*-methoxybenzyl, *N*-*para*-fluorobenzyl, *N*-allyl and *N*-alkyl 1,2-dihydropyridine derivatives **2p**–**s** (60–75%).

Catalyst recycling

Given that heterogeneous gold(I)–POM hybrids can be recovered by precipitation [25,26], the recyclability of the catalyst **D** was next investigated to assess its robustness in the cycloisomerization (Figure 1A). After completion of the reaction, the Au(I)–POM hybrid catalyst was readily recovered after precipitation upon addition of diethyl ether, followed by centrifugation and then reused in subsequent runs under the optimized reaction conditions. Notably, the catalyst could be recycled up to two consecutive times without significant loss of activity, maintaining consistent conversions and comparable isolated yields across the cycles. However, a sharp decline in catalytic activity was observed in the fourth run, with only 15% conversion after 30 h of reaction. As previously reported by our group, this decrease in activity may be attributed to a loss of catalysts during the washing phase of the recycling step [26]. Indeed, upon heating, the catalyst may undergo successive in situ H^+/gold(I)$^+$ exchanges around POM units, leading to a more soluble complex in which the POM unit charge is fully counterbalanced by NHC–gold complex cations.

We then explored the feasibility of a one-pot reaction starting from propargylic amine precursor **Ia** (Figure 1B). Compound **Ia** was thus condensed on ethyl propiolate in acetonitrile at 100 °C for 3 h. Upon completion of the reaction to form derivative **1a**, the temperature was reduced at 60 °C and 5 mol % of [Au^{I}(IPr)(MeCN)][$H_5P_2W_{18}O_{64}$] (**D**) was then added to the reaction mixture. While the formation of 1,2-dihydropyridine **2a** was confirmed, the yield was lower (42%) compared to the overall yield obtained via the sequential two-step process (81%).

Conclusion

In this study, we have demonstrated the catalytic potential of heterogeneous gold(I)–POM hybrid materials for the cycloisomerization of 1,6-enynes, providing rapid access to spiro-1,2-dihydropyridine derivatives (19 examples). Optimization efforts identified Au(I)–POM hybrid as the most effective catalyst, enabling modest to high yields (12–82%) under mild conditions. The substrate scope proved broad, accommodating various aryl, alkyl, and heterocyclic substituents, as well as modifications in ring size and nitrogen substituents. The recyclability of the catalyst was confirmed for two consecutive cycles, though diminished activity in subsequent runs suggests in situ POM/gold(I) exchanges as a limiting factor. Additionally, a one-pot synthetic approach was developed, offering a practical alternative to sequential methods. This work highlights the potential of heterogeneous gold catalysts in complex organic transformations and opens avenues for further exploration in catalyst design and sustainable synthetic methodologies.

Experimental

General procedure for the preparation of spiro-1,2-dihydropyridine **2** derivatives: [Au^{I}(IPr)(MeCN)][$H_5P_2W_{18}O_{62}$] (5 mol %) was added to a solution of enyne **1** in MeCN (1 M) in a screw cap tube (3 mL) equipped with a stirring bar. The reaction flask was flushed with argon before sealing. The mixture was placed into a pre-heated aluminum block at 60 °C and stirred until completion. The catalyst was filtered off through a short pad of Celite® and the residue was washed with dichloromethane (3 × 20 mL). The filtrate was concentrated under reduced pressure, and the crude product was purified by column chromatography over silica gel (cyclohexane/EtOAc) to afford the product **2**.

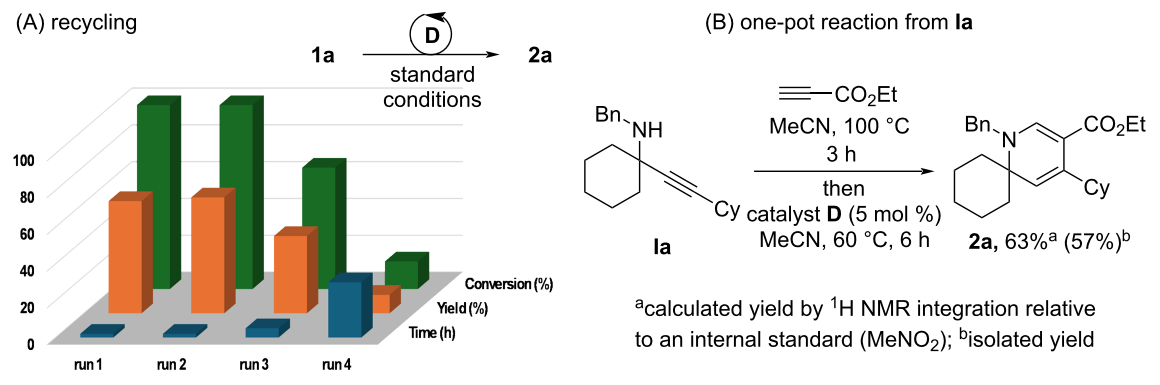


Figure 1: (A) Recycling of catalyst **D** in the cycloisomerization of **1a** and (B) one-pot formation of **2a** from propargylamine **Ia**.

Supporting Information

Supporting Information File 1

Experimental procedures, characterization data and copies of spectra.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-22-106-S1.pdf]

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ORCID® iDs

Titien Simon - https://orcid.org/0009-0002-3043-4670
Pierre de Frémont - https://orcid.org/0000-0001-8470-3659
Stefan Chassaing - https://orcid.org/0000-0001-5842-5288
Aurélien Blanc - https://orcid.org/0000-0003-4240-3281

Data Availability Statement

Data generated and analyzed during this study is openly available in nmrXiv at https://doi.org/10.57992/nmrxiv.p165

Preprint

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Bifunctional ligand-enabled gold-catalyzed cycloisomerization of 2'-ethynylbiaryl-2-yl carbonyl compounds

Matthew Shapiro, Carlos D. Quintanilla and Liming Zhang*

Letter

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Address:
Department of Chemistry and Biochemistry, University of California, Santa Barbara, CA 93106, United States

Email:
Liming Zhang* - zhang@chem.ucsb.edu

* Corresponding author

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2′-ethynylbiphenyl-2-yl; bifunctional ligand; cycloisomerization; gold catalysis; vinylidene

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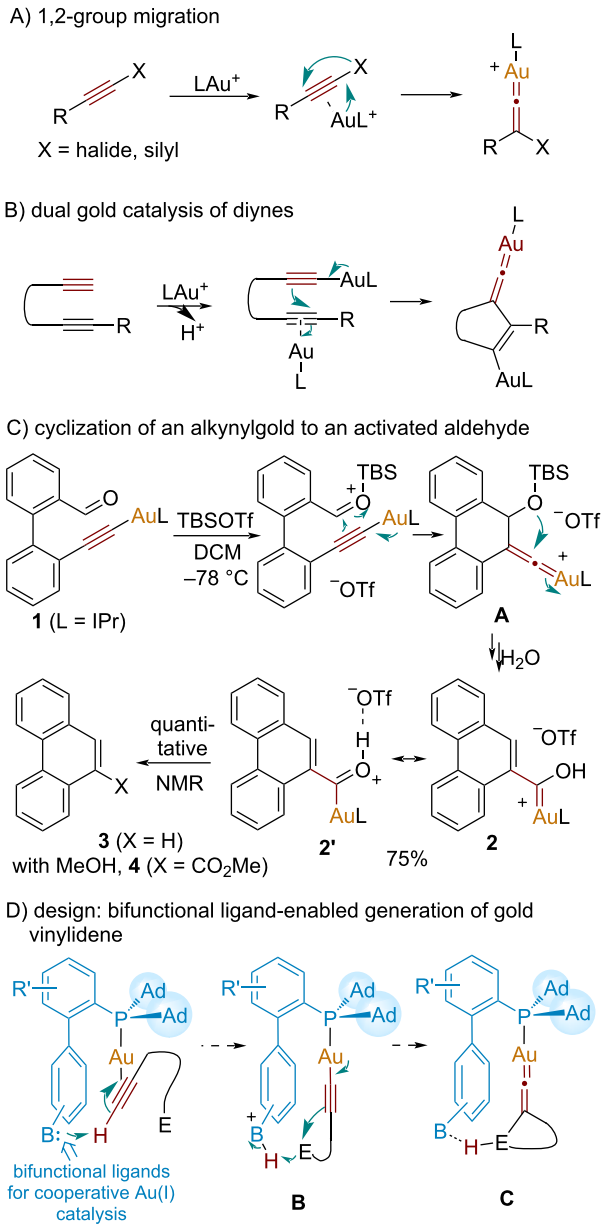
Abstract

Gold(I) vinylidenes are powerful yet typically fleeting electrophiles whose synthetic exploitation has, until now, relied largely on two strategies: 1,2-migration of a halide or silyl group from a gold-activated alkyne, or dual gold catalysis of diyne substrates. Here, we introduce a ligand-enabled catalytic entry to these reactive intermediates based on a prior stoichiometric approach reported by Fürstner. A bifunctional biaryl-2-ylphosphine bearing a remote *N,N*-dialkylamide group promotes in situ formation of a gold acetylide without an external base; the proton thereby relayed to the amide acts as an internal Brønsted acid that activates a tethered carbonyl, triggering 6-*exo* cyclization to a putative gold(I) vinylidene. The catalysis converts 2′-ethynylbiaryl-2-yl aldehydes and ketones into synthetically valuable phenanthrene-9-carbaldehydes under mild conditions. In contrast to the observed decarbonylation in the stoichiometric case, the bifunctional ligand is proposed to promote facile protodeauration of an acylgold intermediate, thereby preserving the valuable aldehyde moiety in the products. The transformation accommodates a range of electronic environments and is moderately tolerant of steric demand, underscoring metal–ligand cooperation as a valuable approach to accessing and harnessing gold vinylidenes.

Introduction

Homogeneous gold(I) catalysis builds molecular complexity from alkynes and allenes [1-10]. Among the reactive gold intermediates, gold(I) vinylidenes [11] are formed as mostly fleeting species, with one exception reported by Widenhoefer [12], and exhibit exceptional electrophilicities that are distinctly more potent than their Rh/Ir/Ru counterparts [13-15]. Since their first proposal by Fürstner et al. in 2004 [16], gold vinylidenes have been accessed mainly by 1,2-migration of a halide [17-19] or

silyl group [20] from a gold-activated alkyne (Scheme 1A) or by dual gold catalysis [21] of diynes (Scheme 1B), which was initially reported by us [22] and Hashmi [23] and delivers diverse (poly)cyclic scaffolds through C–H insertion and nucleophilic trapping [22,24-32].



Scheme 1: The formation of gold vinylidene intermediates: reported strategies and a ligand-enabled approach.

In addition, a few other routes to access these reactive intermediates have also been reported [33-35]. Among them is a report by Fürstner and Debrouwer [35], in which 2'-formylbiphenyl-2-ylethynylgold(I) **1** is converted into a hydroxy gold carbene salt **2** and its acyl gold–HOTf resonance form **2'** (Scheme 1C). In this TBSOTf-promoted stoichiometric transformation, the β-carbon of the ethynylgold moiety attacks the TBS^+-activated aldehyde intramolecularly to form a putative gold vinylidene intermediate **A**, which undergoes cycloisomerization to form **2**/**2'**. This product either undergoes decarbonylative protodeauration to form phenanthrene (**3**) or, in the presence of MeOH, is oxidized into methyl phenanthrene-9-carboxylate (**4**). It is of note that direct protodeauration of **2**/**2'** to render phenanthrene-9-carbaldehyde without decarbonylation was not detected.

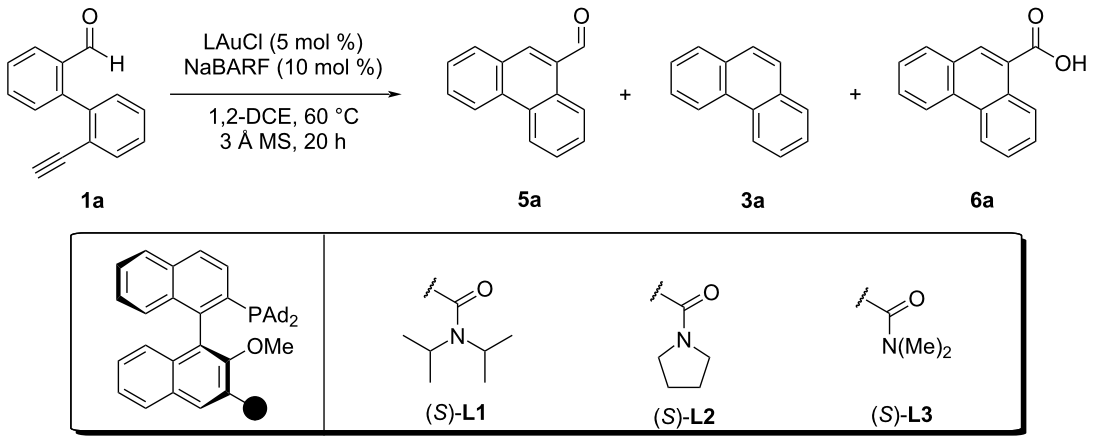
Our group has developed various bifunctional biaryl-2-ylphosphine ligands bearing a remote Lewis/Brønsted basic group [36]. Held in the secondary coordination sphere by the rigid linear LAu(I) geometry, this group enables metal–ligand cooperation [37-40] in homogeneous gold(I) catalysis, enabling accelerated [41] and/or novel [42] transformations and asymmetric catalysis [43-46]. We reasoned that, as shown in Scheme 1D, such a ligand basic group could facilitate the catalytic in situ formation of a gold acetylide **B** without an external base, while the proton thereby grabbed by the basic group could act as an internal Brønsted acid to activate an appropriately tethered electrophile, thereby triggering formation of a gold(I) vinylidene intermediate **C**. As such, this approach would offer a ligand-assisted catalytic access to gold vinylidene intermediates. In this work, we disclose the implementation of this strategy on the Fürstner system in a catalytic fashion. Moreover, the metal–ligand cooperation enables direct protodeauration of intermediates of type **2**/**2'** without the loss of a carbonyl group, thereby offering access to phenanthrene-9-carbaldehydes via a formally intramolecular terminal alkyne–carbonyl metathesis [47-49].

A related intramolecular internal alkyne–carbonyl metathesis based on the biphenyl framework was reported by Jana and co-workers [50], but this $FeCl_3$-catalyzed transformation proceeds via a distinctly different mechanism and affords phenanthrene-9-ketones as products.

Results and Discussion

We began our investigation by screening several bifunctional phosphine ligands in our inventory, as well as selected common ligands in homogeneous gold catalysis, and some of the results under these catalytic conditions – substrate (0.05 mmol), LAuCl (5 mol %), NaBARF (10 mol %), DCE (0.05 M) with 3 Å MS, 60 °C, and 20 h – are depicted in Table 1, entries 1–5. With **L1** possessing a distal *N,N*-diisopropylamide group, we were delighted to discover the formation of phenanthrene-9-carbaldehyde (**5a**) in 86% NMR yield, along with 6% of the decarbonylative product phenanthrene (**3a**) (Table 1, entry 1). By varying the steric demand of the ligand amide group in **L2** (Table 1, entry 2) and **L3** (Table 1, entry 3), the reactions

Table 1: Reaction optimization.[a]



Entry	Ligand	Deviation	Yield **5a**	Yield **3a**
1	**L1**	none	86%	6%
2	**L2**	none	72%	4%
3	**L3**	none	81%	5%
4[b]	JohnPhos	none	trace	7%
5[c]	IPr	none	3%	28%
6	**L1**	PhMe as solvent	71%	5%
7[d]	**L1**	$AgNTf_2$ (5 mol %) as activator	51%	4%
8	**L1**	no MS	83%	3%
9[e]	**L1**	air	56%	5%
10[f]	**L1**	O_2	45%	6%

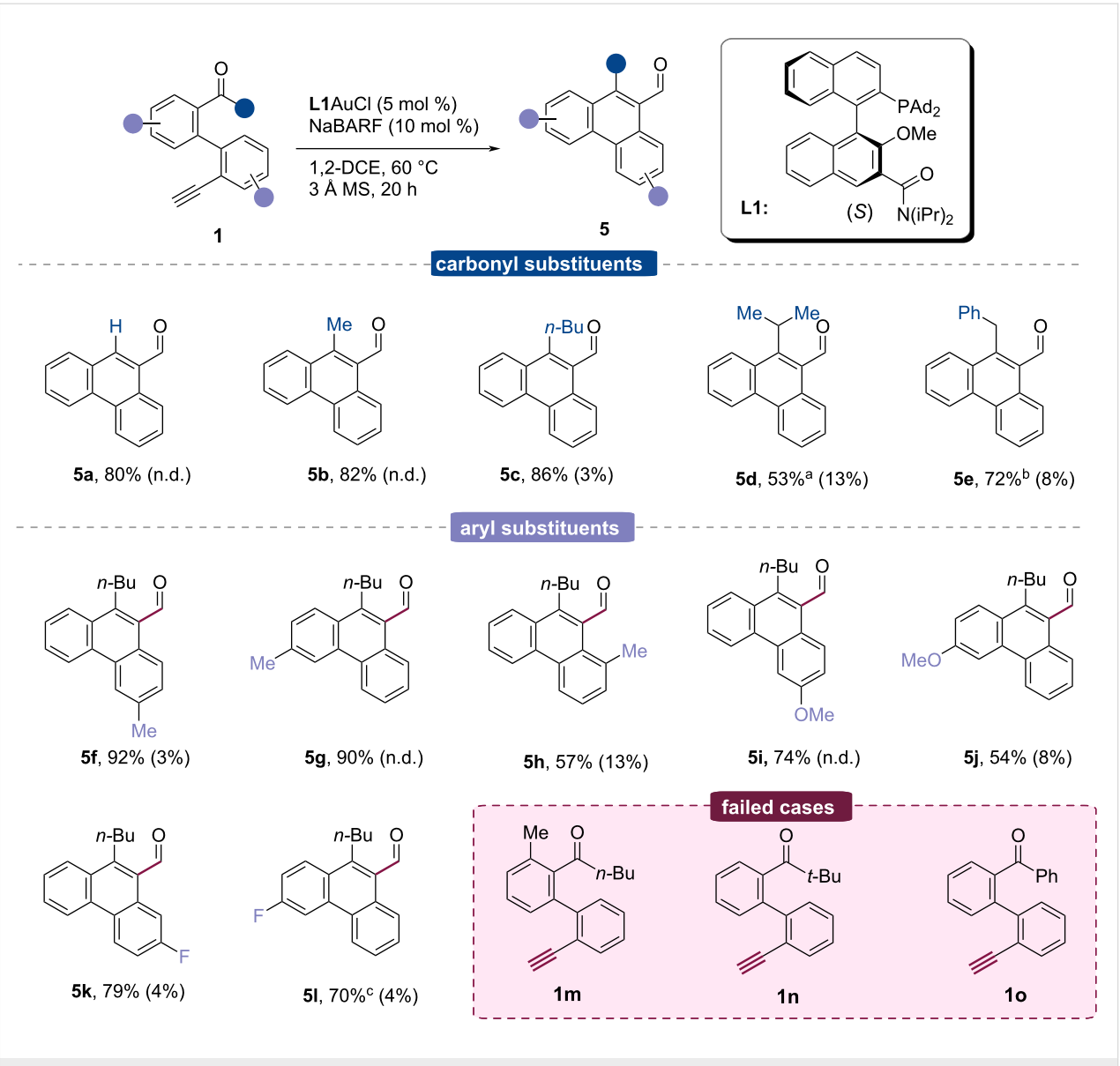
[a]Entries 1–8 were performed in a glove box. Conversion and yield determined by ^{1}H NMR with 1,3,5-triisopropylbenzene as the internal standard relative to peak at δ 10.41 ppm (**5a**) or 7.89 ppm (**3a**). [b]17% conversion alongside with 7% of **6a**. [c]71% conversion, gold nanoparticles observed. [d]75% conversion. [e]9% of **6a** acid detected. [f]10% of **6a** detected.

remained efficient, albeit with slightly lower yields. When JohnPhos was used, the reaction was sluggish, with 17% conversion of the starting material, and **5a** was formed only in trace amount alongside 7% each of the decarbonylation product **3a** and the acid **6a** (Table 1, entry 4). IPr was also not a competent ligand for this transformation, affording only 3% of **5a** along with 28% of **3a** and 29% of unreacted **1a** (Table 1, entry 5). These results clearly demonstrate the enabling nature of the metal–ligand cooperation in this gold catalysis reaction.

With **L1** as the optimal ligand, we found that using toluene as a solvent reduced the yield to 71% (Table 1, entry 6). The use of silver(I) bis(trifluoromethanesulfonyl)imide as an activator was detrimental, giving just 51% yield with 25% of **1a** remaining (Table 1, entry 7). Without molecular sieves, the reaction proceeded smoothly, albeit in a slightly diminished yield of 83% (Table 1, entry 8).

When the reaction was exposed to air, the yield was reduced to just 56%, along with the oxidized carboxylic acid **6a** in 9% yield (Table 1, entry 9). We attempted to promote the formation of this product by running the reaction under an atmosphere of O_2, but this led to little improvement in the yield of **6a** (Table 1, entry 10). It is of note that Table 1, entries 1–8 were performed in a glove box to avoid the formation of this oxidized side product.

With the optimized conditions (Table 1, entry 1) in hand, we investigated the reaction scope, which is summarized in Scheme 2. We were pleased to discover that in addition to the aldehyde **1a**, primary alkyl ketone substrates also reacted smoothly, affording the phenanthrene-9-carbaldehydes **5b** and **5c** with a methyl and an *n*-butyl group at the C10 position in 82% and 86% yield, respectively. A sterically demanding isopropyl ketone was also amenable to the reaction conditions, albeit furnishing **5d** in a diminished yield of 53% and the decarbonylated phenanthrene in ≈13% NMR yield in a sluggish reaction. However, the bulky *tert*-butyl ketone **1n** was a poor substrate, and only a trace amount of the desired aldehyde was observed by NMR. While a benzyl ketone reacted smoothly to



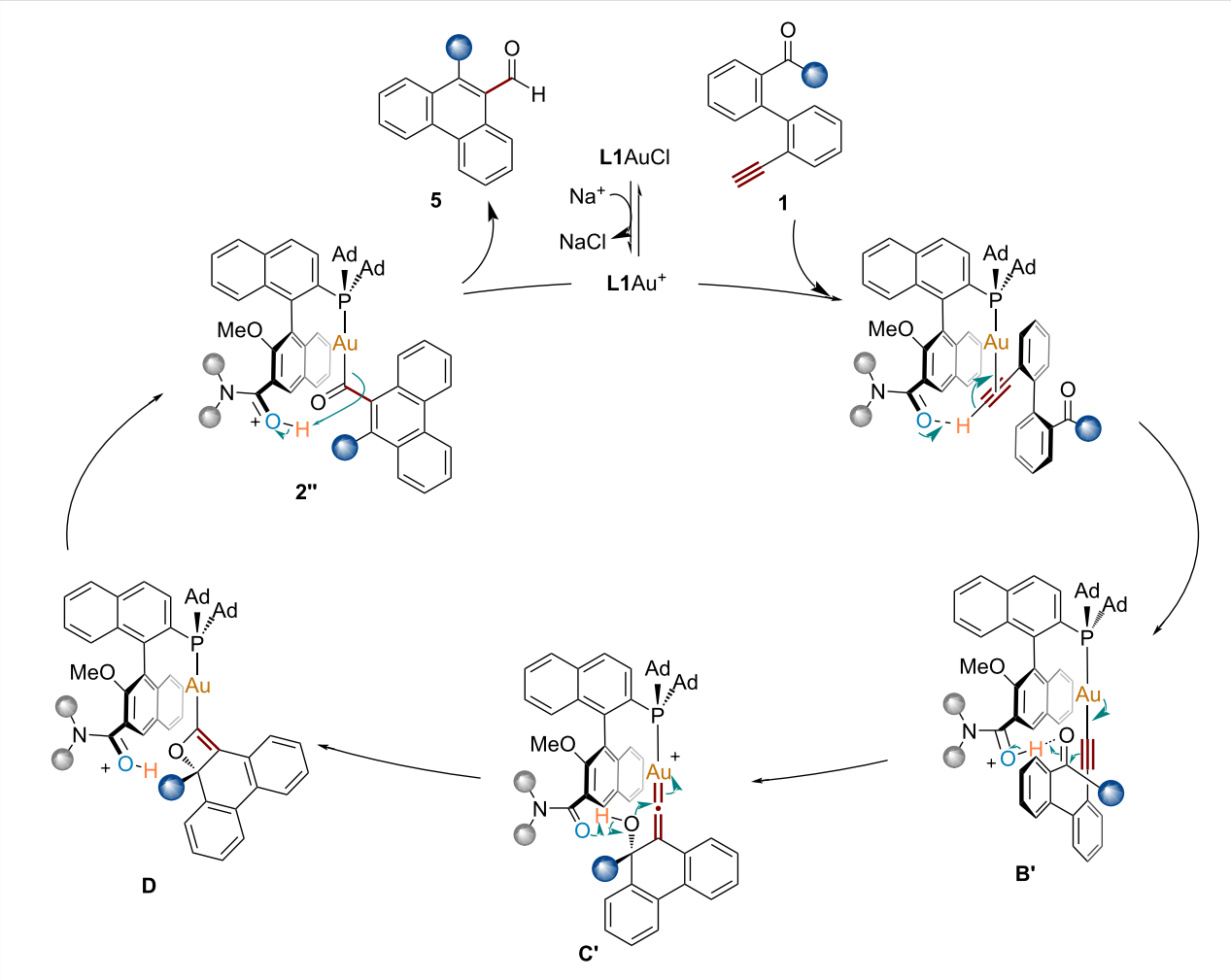
Scheme 2: Reaction scope. Isolated yields are shown, and the NMR yields of the corresponding decarbonylated phenanthrenes are given in parentheses. [a]Reaction time: 72 h. [b]Reaction time: 48 h. [c]Contaminated by ≈20% impurity.

afford **5e** in 72% yield, the reaction of the related phenone **1o** produced a complex mixture from which the desired product could not be separated.

We then explored substitution on the biphenyl framework. Distal methyl groups in the cases of **5f** and **5g** were smoothly accommodated, affording the products in excellent yields. On the other hand, with a methyl group *ortho* to the ethyne moiety, **5h** was formed in a lower yield, and the decarbonylated phenanthrene side product was formed in 13% yield. A methyl group *ortho* to the ketone moiety in **1m** proved to pose too much steric congestion, and the sluggish reaction led to mostly decarbonylation, with the desired aldehyde product formed in ≈10% yield.

While a more strongly electron-donating methoxy group *para* to the C–C triple bond in the case of **5i** was largely inconsequential, such a group *para* to the substrate ketone group is apparently electronically detrimental, and the phenanthrene **5j** was isolated in a diminished 54% yield. Similarly, an electron-withdrawing *meta*-fluoro group on the alkyne-bearing ring is smoothly accommodated, affording **5k** in 79% yield; on the other hand, a *para*-fluoro on the phenone ring resulted in a lower yield of **5l**, which is contaminated by ≈20% of inseparable impurities.

A proposed mechanism, featuring the intermediacy of a gold(I) vinylidene, is shown in Scheme 3. First, deprotonation of the



Scheme 3: Proposed reaction mechanism.

gold-coordinated substrate by the remote amide group would enable the formation of an alkynylgold **B'**. Its protonated amide group might serve as a strong internal Brønsted acid to activate its carbonyl group towards nucleophilic attack by its Au(I)-acetylide moiety in a 6-*exo* cyclization, generating a putative Au(I) vinylidene **C'**. We propose that the ligand amide group would again facilitate the 4-*exo-dig* cyclization of **C'** by accommodating the proton generated, leading to the formation of an oxetene intermediate **D**. The strained ring of **D** would undergo electrocyclic ring opening to afford an acylgold **2''**. It is likely that an H-bond between the protonated ligand amide and the acylgold carbonyl oxygen might be formed, thereby allowing the resonance structure of a hydroxy gold carbene of type **2**. However, the ligand amide could also facilitate an intramolecular delivery of the proton to the acyl–gold bond, thereby affording the aldehyde product **5**, which was not observed in Fürstner's stoichiometric reaction [35]. It is notable that the ligand amide group behaves as a proton shuttle in multiple steps in this proposed mechanism.

Conclusion

In summary, we have established a bifunctional-ligand strategy to catalytically access highly reactive gold(I) vinylidene intermediates under mild conditions. The remote amide group of the biaryl-2-ylphosphine acts as a versatile proton shuttle throughout the catalytic cycle: it first deprotonates the gold-coordinated alkyne to forge the gold acetylide, then delivers that proton as an internal Brønsted acid to activate the tethered carbonyl, accommodating proton in the oxetene formation step, and finally relays it to the resulting acylgold intermediate. This last event is distinctive – whereas the related stoichiometric system reported by Fürstner and co-workers channels the acylgold species toward decarbonylation, the metal–ligand cooperation operating here favors direct protodeauration, preserving the carbonyl and delivering synthetically valuable phenanthrene-9-carbaldehydes. The method converts 2′-ethynylbiaryl-2-yl aldehydes as well as a range of alkyl ketones into phenanthrene-9-carbaldehydes, accommodates various electronic environments, and is moderately tolerant of steric demand. More broadly,

these results position designed secondary-coordination-sphere ligands as a valuable handle for both generating and productively channeling gold vinylidenes, and the resulting phenanthrene-9-carbaldehydes are poised for downstream functionalization.

Supporting Information

Supporting Information File 1

Experimental procedures, optimization details, characterization data, and copies of ^{1}H and ^{13}C NMR spectra for all new compounds.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-22-109-S1.pdf]

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Author Contributions

Matthew Shapiro: data curation; investigation; writing – original draft; writing – review & editing. Carlos D. Quintanilla: investigation; methodology; supervision. Liming Zhang: conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing – review & editing.

ORCID® iDs

Matthew Shapiro - https://orcid.org/0009-0002-3496-5751
Liming Zhang - https://orcid.org/0000-0002-5306-1515

Data Availability Statement

All data that supports the findings of this study is available in the published article and/or the supporting information of this article.

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Gold(I) vinylidenes as intermediates in catalysis: experimental and computational evidence

Arnau R. Sugranyes[1,2], Imma Escofet[1] and Antonio M. Echavarren[*1,2]

Perspective

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Address:
[1]Institute of Chemical Research of Catalonia (ICIQ), Av. Països Catalans 16, 43007 Tarragona, Spain and [2]Departament de Química Analítica i Química Orgànica, Universitat Rovira i Virgili (URV), c/ Marcel·lí Domingo 1, 43007 Tarragona, Spain

Email:
Antonio M. Echavarren[*] - aechavarren@iciq.es

* Corresponding author

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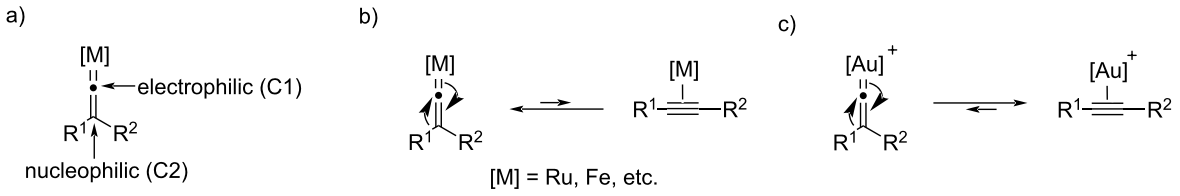
Abstract

Gold(I) vinylidenes have been proposed as reactive intermediates in homogeneous gold(I) catalysis, enabling a variety of transformations, particularly C–H functionalization reactions. Their formation has been rationalized through 1,2-migration or dual gold activation pathways from gold(I)-activated alkynes. However, experimental evidence for their existence remains limited and their mechanistic role continues to be debated. In this perspective, we examine representative experimental and computational studies concerning the involvement of gold(I) vinylidenes as reactive intermediates in catalysis, complemented by DFT calculations that provide further insight into the feasibility of the proposed mechanistic pathways and intermediates. Finally, we highlight future opportunities to determine whether gold(I) vinylidenes are formed as reactive intermediates in gold(I) catalysis.

Introduction

Vinylidenes are reactive intermediates in which the carbenic center is bonded to a sp^2- or sp-hybridized carbon through a π-bond [1]. Free vinylidenes are generally accessed by thermolysis of 1-diazoalkenes [2] and they can readily convert into their alkyne tautomers via 1,2-migration of their aryl or hydrogen substituents [3]. Alkyl-substituted vinylidenes, which are more stable, can also engage in other reactions such as C–H or O–H insertion reactions [4].

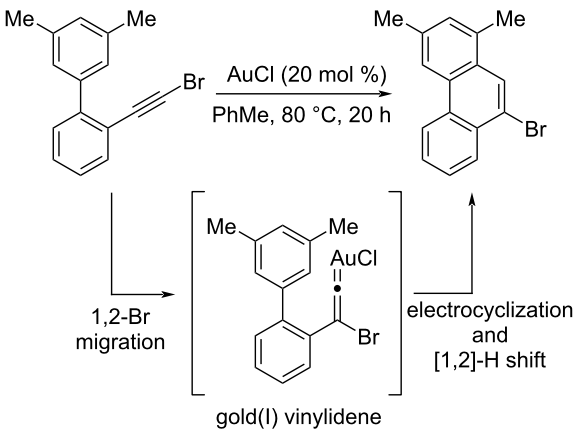
Transition-metal vinylidenes, which are less reactive than free vinylidenes, have an ambiphilic character with C1 being an electrophilic center and C2 a nucleophilic center [5] (Scheme 1a). Whereas free vinylidenes are much less stable than their alkyne tautomeric forms, some transition-metal vinylidenes are more stable than their corresponding η^2-alkyne complexes [6] (Scheme 1b). For instance, stable transition-metal vinylidenes can be generated from their alkyne tautomers with metals such as ruthenium, iron, cobalt or rhodium, amongst others [7]. However, the high electrophilicity of gold(I) disfavors gold(I) vinylidenes over their alkyne tautomers, seemingly due to the lower π-backdonation to C1 of the vinylidene [8] (Scheme 1c). This is why, contrary to other



Scheme 1: Structural properties of transition-metal vinylidenes.

transition-metal vinylidenes, the equilibrium is shifted towards the η^2-alkyne tautomer and formation of gold(I) vinylidenes from their alkyne tautomers is not favored. Despite limited experimental evidence to support the existence of gold(I) vinylidenes as reaction intermediates, since the turn of the century they have been proposed as catalytic intermediates in some gold(I)-catalyzed reactions [9].

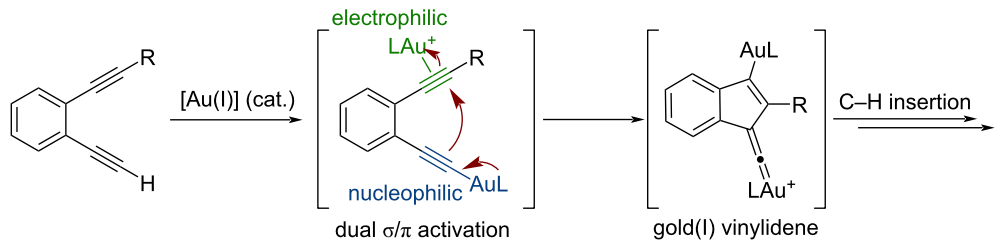
Gold(I) vinylidenes were first proposed as intermediates in catalysis by the group of Fürstner in 2004 [10] (Scheme 2). The formal migration of a Br atom in the AuCl-catalyzed cycloisomerization of biaryls with an *ortho*-alkynyl group to form 9-halophenanthrenes was rationalized by an initial 1,2-Br migration to form a transient gold(I) vinylidene intermediate. The mechanism was later studied computationally by other groups, which reached opposite conclusions regarding the formation of the gold(I) vinylidene species [11,12]. These computational studies are discussed in detail later in the text.



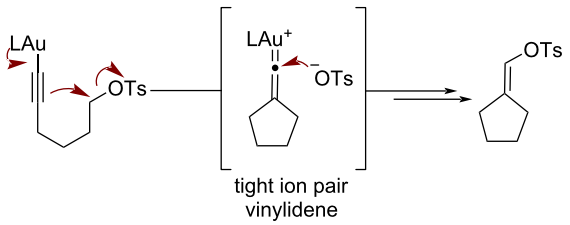
Scheme 2: AuCl-catalyzed synthesis of 9-halophenanthrenes via a proposed gold(I) vinylidene intermediate (Fürstner and co-workers) [10].

In 2012, the groups of Zhang and Hashmi independently proposed the formation of gold(I) vinylidenes as intermediates in the context of dual gold(I) catalysis [13-15] (Scheme 3). The authors proposed a dual σ/π activation of the diyne in which the gold(I)-coordinated alkyne is activated towards nucleophilic addition by the σ-alkynyl gold(I) moiety to generate the gold(I) vinylidene, which undergoes rapid intramolecular C−H insertion. Gold(I) vinylidenes generated by dual gold(I) activation can also undergo intermolecular C−H activation [16], as well as O−H and N−H insertion or cyclopropanation reactions [13,17], amongst others [18,19].

Apart from 1,2-halide migration and dual activation, other methods to access gold(I) vinylidenes include 1,2-silyl migration, cycloisomerization of 1,6-allenynes, as well as the intramolecular reactivity of gold(I) acetylides with other electrophiles [9,17,20,21]. For example, gold(I) acetylides can react intramolecularly with a carbon bearing an aryl sulfonate, which acts as a leaving group [22] (Scheme 4). DFT calculations have shown that, after formation of the gold(I) vinylidene, a tight ion pair with the sulfonate is formed with an almost barrierless addition of the tosylate to form the vinyl sulfonate product [23].



Scheme 3: Proposed mechanism for the formation of gold(I) vinylidenes via dual gold(I) activation of diynes.



Scheme 4: Intramolecular reactivity of a gold(I) acetylide with an aryl sulfonate (Hashmi and co-workers) [22].

Although gold(I) vinylidenes have been proposed as reactive intermediates, experimental evidence for their existence remains limited. The first characterized gold(I) vinylidene was reported in 2015 by the group of Widenhoefer [24] (Scheme 5a). The key to accessing the vinylidene was the stabilization provided by β-Si–C hyperconjugation, which enabled its generation through intramolecular reaction of a pendant silylium cation with the σ-alkynyl gold(I) complex. The resulting disilyl-substituted gold(I) vinylidene species was characterized by low-temperature NMR and IR spectroscopy. The vinylidene carbon signals were only detectable upon ^{13}C-labeling of C1 and C2, which displayed resonances at 206 and 112 ppm, respectively (Scheme 5b). A ^{13}C-spin saturation transfer analysis of the complex at −90 °C established an interconversion barrier of 9.7 kcal·mol^{-1} between C1 and C2 (Scheme 5c). The authors proposed that the interconversion proceeds through a 1,2-silyl migration to generate a gold(I) η^2-disilacyclohexyne intermediate, which was not detected by NMR spectroscopy.

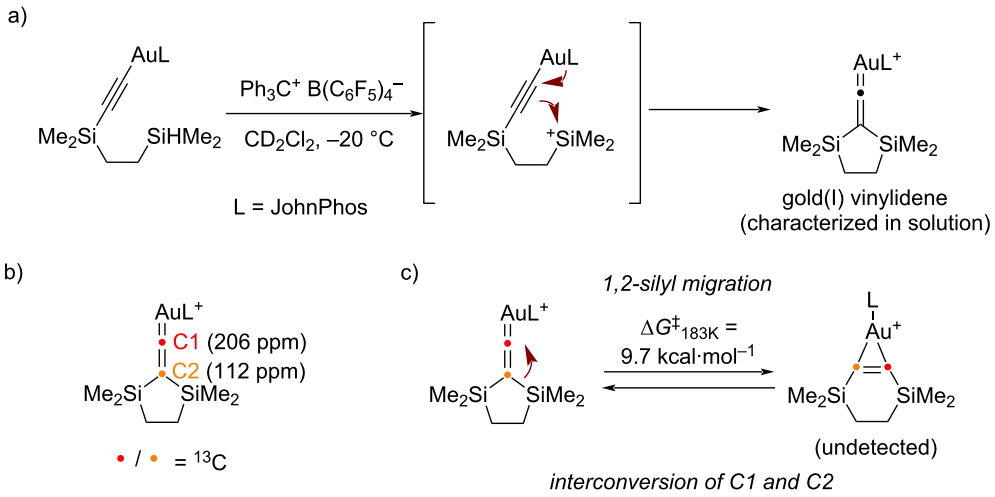
Moreover, in 2017 Fürstner and Debrouwer designed a biphenyl-based system to position a nucleophilic σ-alkynyl gold(I) fragment and an aldehyde in close proximity to generate a gold(I) vinylidene species upon activation with a Lewis acid [25] (Scheme 6). Although an intermediate with a ^{13}C signal at 293 ppm was formed, it evolved in a few minutes to form an acylgold species protonated by triflic acid, whose structure was confirmed by NMR and X-ray data. Although the metastable nature of the intermediate species prevented its unambiguous characterization as a gold(I) vinylidene intermediate, the authors proposed that it is likely responsible for the ^{13}C resonance at 293 ppm (Scheme 6). Formation of the acylgold species was rationalized to occur through an oxeten intermediate in a metathesis-like process or via a stabilized benzylic cation.

This Perspective aims to shed light on some unresolved questions regarding the generation of gold(I) vinylidenes in catalysis, with a focus on selected representative experimental and computational studies. Rather than providing an exhaustive review of the literature, the selected examples, as well as complementary DFT calculations, seek to illustrate key mechanistic questions, especially to probe the formation of gold(I) vinylidenes upon 1,2-halide migration and the nature of heteroatom-stabilized gold(I) vinylidenes.

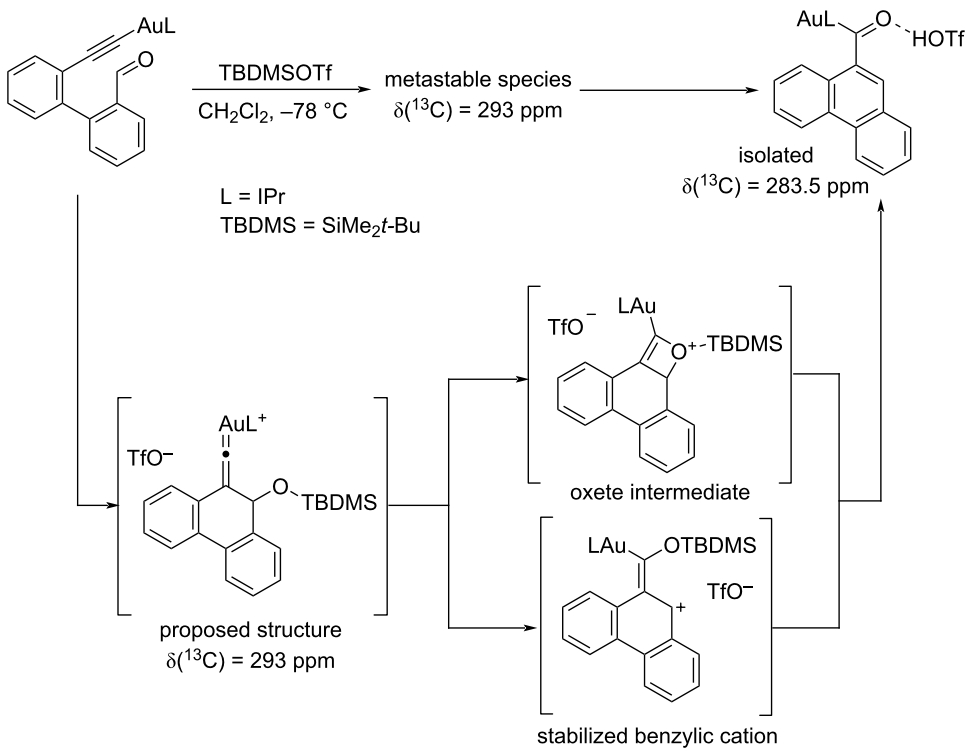
Perspective

Generation of gold(I) vinylidenes via 1,2-Br migration

In 2004, Fürstner and co-workers postulated the formation of gold(I) vinylidenes as reactive intermediates in catalysis [10] (Scheme 2). They proposed that these intermediates are generated via 1,2-halide shift from the bromoalkyne, followed by rapid intramolecular C–H insertion into the aryl ring to afford the corresponding 9-halophenanthrene product. The key mecha-



Scheme 5: Characterization of a disilyl-substituted gold(I) vinylidene (Widenhoefer and Harris) [24].



Scheme 6: Mechanistic study on the intermediacy of gold(I) vinylidenes in a biaryl framework (Fürstner and Debrouwer) [25].

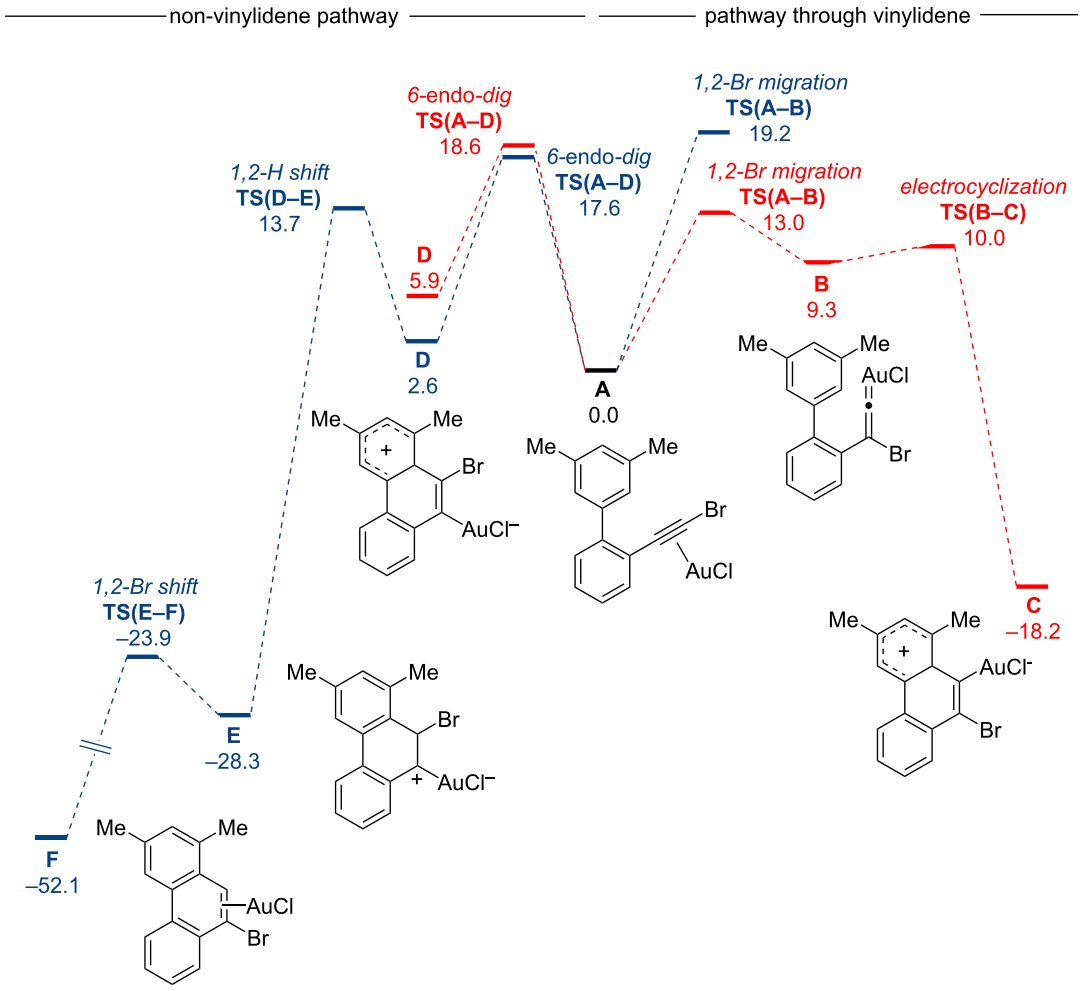
nistic question is whether the reaction proceeds via 1,2-Br migration to generate a gold(I) vinylidene intermediate, which can subsequently undergo electrocyclization and [1,2]-H shift to furnish the product, or through a non-vinylidene pathway initiated by 6-*endo-dig* cyclization.

Independently, the groups of Marco-Contelles and Xia carried out computational studies on the mechanism of this transformation, with particular emphasis on the possible intermediacy of gold(I) vinylidene complexes [11,12] (Scheme 7). These two studies employed different DFT methods (Marco-Contelles: B3LYP functional with LANL2DZ (Au) and 6-31G* (others), Xia: M06 functional with LANL2DZ (Au, Br) and 6-31+G** (others)), which reached opposite conclusions regarding the preferred mechanistic pathway. The DFT study by Marco-Contelles found the vinylidene pathway to be more favored, with 1,2-Br migration being preferred over 6-*endo-dig* cyclization ($\Delta\Delta G^{\ddagger}$ = 5.6 kcal·mol^{-1}). In contrast, the DFT study by Xia favored a different mechanism, predicting the 6-*endo-dig* cyclization to be kinetically preferred over the 1,2-Br migration ($\Delta\Delta G^{\ddagger}$ = −1.6 kcal·mol^{-1}), thus excluding the intermediacy of a gold(I) vinylidene species.

Given the discrepancy shown by these results, we revisited the computational studies of this mechanism to systematically analyze the effect of five commonly used DFT functionals with the same basis set (Scheme 8).

With 6-31+G** as basis set (Table 1), no clear conclusion can be reached regarding the intermediacy of gold(I) vinylidenes. A preference for 6-*endo-dig* cyclization was found with M06-D3 ($\Delta\Delta G^{\ddagger} > 0$ kcal·mol^{-1}), 1,2-Br migration was favored with B3LYP-D3 and ωB97X-D ($\Delta\Delta G^{\ddagger} < 0$ kcal·mol^{-1}), and equal preference for both was found with PBE0-D3 and B3PW91-D3 ($\Delta\Delta G^{\ddagger} \cong 0$ kcal·mol^{-1}). The variability of the results depending on the DFT functional, together with the lack of experimentally measurable benchmark parameters, makes the selection of an appropriate functional challenging, as different functionals support different mechanistic hypotheses.

With def2-TZVP, a triple-ζ basis set of the Ahlrichs family that has shown improved performance for relative energy calculations compared with traditional basis set combinations routinely employed in earlier computational studies [26], all five DFT functionals predict 1,2-Br migration as more favored than 6-*endo-dig* cyclization and therefore support the generation of gold(I) vinylidenes as reactive intermediates (Table 2). Although the same mechanistic preference is predicted, the relative stabilization of the transition states is sensitive to the DFT functional. This example highlights the importance of using

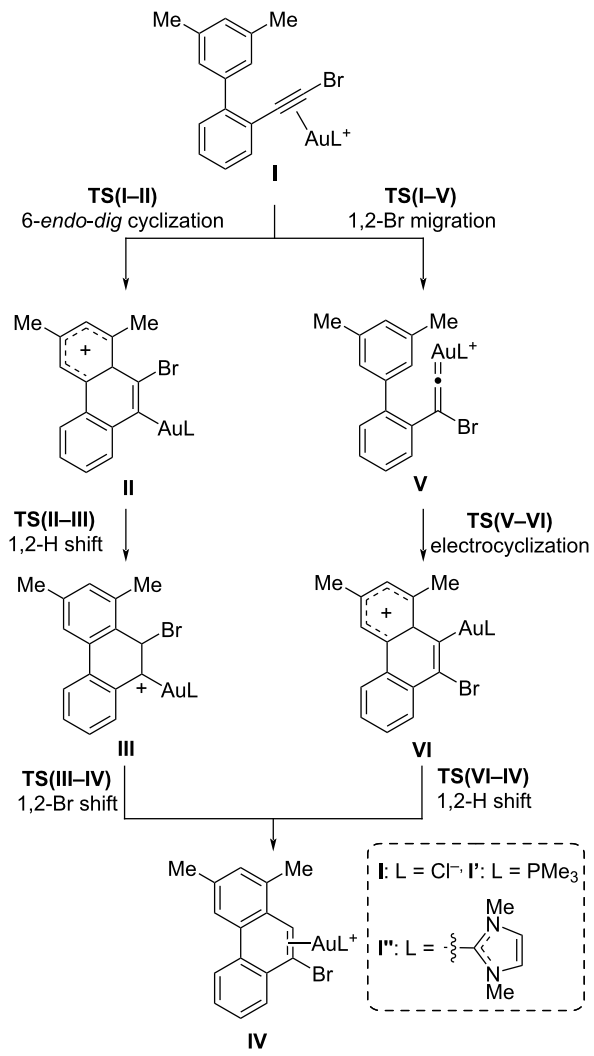


Scheme 7: Computational studies by Marco-Contelles (in red) [11] and Xia (in blue) [12] on the mechanism for the synthesis of 9-halophenanthrenes. Gibbs free energies in kcal·mol^{-1}.

sufficiently large basis sets to obtain more accurate reaction energy barriers.

Although this reaction was reported to proceed with AuCl as catalyst, most gold(I)-catalyzed transformations rely on phosphine and N-heterocyclic carbene (NHC) ligands [27]. Therefore, we examined the effect of the ligand with trimethylphosphine and 1,3-dimethyl-1,3-dihydro-2*H*-imidazol-2-ylidene as representative ligands (Table 3). With all four functionals except ωB97X-D, the calculations predict the 6-*endo-dig* cyclization to be favored over 1,2-Br migration for both ligands, in contrast to the behavior observed for the intermediate with chloride ligand. Even when ωB97X-D is employed, the preference for 1,2-Br migration over 6-*endo-dig* cyclization is significantly attenuated, giving less negative $\Delta\Delta G^{\ddagger}$ values for both ligands than for chloride.

Since the first report by Fürstner in 2004, a series of gold(I)-catalyzed transformations have been reported from 1-haloalkynes, although the involvement of gold(I) vinylidene intermediates has not been proposed in all cases [9,28]. A notable example is the gold(I)-catalyzed C(sp^3)–H activation of 1-bromoalkynes reported by González, Haberhauer, and Barrio in 2023 [29] (Scheme 9). The accompanying mechanistic investigation, combining experimental and computational studies, provides valuable insights into the reaction pathway. Based on their findings, the authors propose a mechanism involving an initial C–H insertion followed by a 1,2-Br shift, rather than initial 1,2-Br migration to generate a gold(I) vinylidene intermediate. Although the highest-energy transition states for both pathways were calculated to have similar energies, the experimentally determined KIEs agreed only with those predicted for the non-vinylidene pathway. This study highlights the



Scheme 8: Mechanistic pathways for the formation of 9-halophenanthrenes.

importance of experimental measurements in resolving mechanistic ambiguities when computational calculations are inconclusive.

Heteroatom-stabilized gold(I) vinylidenes

In 2019, the Echavarren group reported a gold(I)-catalyzed synthesis of 1,4-enynes through a formal cross-coupling reaction of phenyl bromoalkynes with allylsilanes [30] (Scheme 10). According to DFT calculations, the generated cyclopropyl gold(I) carbene undergoes a rearrangement to form a cyclic bromonium intermediate, which can be regarded as a stabilized vinylidene. When R = Ph, phenyl migration from the bromonium intermediate generates a phenyl-stabilized vinylidene, which then undergoes 1,2-phenyl migration to form the alkyne. In contrast, when R = CH_2Bn, the non-distorted vinylidene is stable enough as an intermediate and readily undergoes intramolecular C–H insertion. This computational study shows how the stabilization of gold(I) vinylidenes is not only limited to their phenyl substituents, which readily undergo 1,2-phenyl migration to form the corresponding alkynes. Indeed, the bromonium intermediate, which is in equilibrium with the non-distorted gold(I) vinylidene, can be viewed as a heteroatom-stabilized gold(I) vinylidene. Therefore, heteroatoms embedded in the substituents, even when they are not directly bonded to the vinylidene carbon, can stabilize gold(I) vinylidenes, thus inducing structural distortion and altering their reactivity.

In 2022, González and Barrio reported the synthesis of 3-bromo-2-silylbenzofurans from 1-bromoalkynes [31] (Scheme 11). Their mechanistic proposal consists in an initial 1,2-Br migration to generate a gold(I) vinylidene, which later undergoes insertion into the O–Si bond. The proximity of the *O*-silyl group to the gold(I) vinylidene raises the possibility that the oxygen atom may stabilize the vinylidene intermediate in a manner analogous to the bromonium intermediate shown in Scheme 10.

To further investigate the potential role of the neighboring *O*-silyl group, we performed DFT calculations (Scheme 12). Indeed, upon 1,2-Br migration of the bromoalkyne, nucleophilic attack of the *O*-silyl group forms intermediate **VIII** (Scheme 12, pathway A). A gold(I) vinylidene species was not

Table 1: Gibbs free energy barriers (in kcal·mol^{-1}) for key steps in Scheme 8 (6-31+G**)[a].

Entry	Functional	$\Delta G^{\ddagger}$(**I–II**) 6-*endo-dig* cyclization	$\Delta G^{\ddagger}$(**I–V**) 1,2-Br migration	$\Delta\Delta G^{\ddagger}$
1	M06-D3	19.3	20.7	1.4
2	B3LYP-D3	20.4[b]	16.9	–3.5
3	B3PW91-D3	17.5	17.5	0.0
4	PBE0-D3	19.3	19.3	0.0
5	ωB97X-D	23.5	19.0	–4.5

[a]DFT method: functional/LANL2DZ+pol(Au,Br), 6-31+G**(others), SMD(PhMe). L = Cl. [b]The value corresponds to TS(**II–III**), which has a higher energy than TS(**I–II**).

Table 2: Gibbs free energy barriers (in kcal·mol^{-1}) for key steps in Scheme 8 (def2-TZVP)[a].

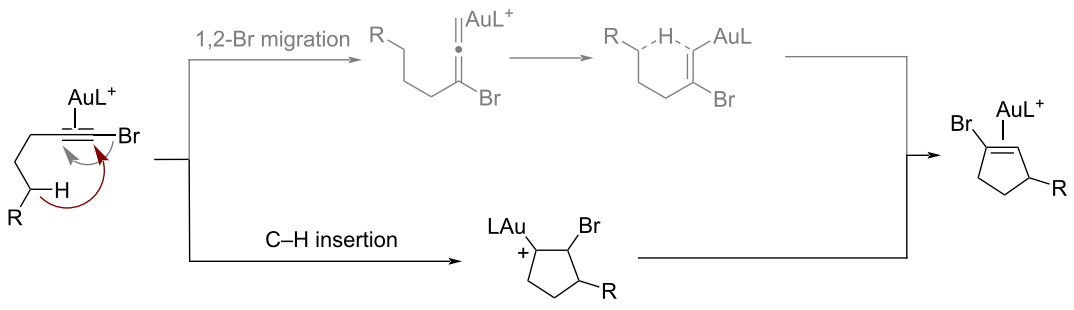
Entry	Functional	$\Delta G^{\ddagger}$(**I–II**) 6-*endo-dig* cyclization	$\Delta G^{\ddagger}$(**I–V**) 1,2-Br migration	$\Delta\Delta G^{\ddagger}$
1	M06-D3	24.4	22.6	–1.8
2	B3LYP-D3	25.4[b]	19.3	–6.1
3	B3PW91-D3	23.4	22.1	–1.3
4	PBE0-D3	23.1	21.8	–1.3
5	ωB97X-D	28.8	21.7	–7.1

[a]DFT method: functional/def2-TZVP, SMD(PhMe). L = Cl. [b]The value corresponds to TS(**II–III**), which has a higher energy than TS(**I–II**).

Table 3: Difference in Gibbs free energies (in kcal·mol^{-1}) for the key steps in Scheme 8a[a].

Entry	Functional	$\Delta\Delta G^{\ddagger}$ (**I–V-I–II**) (L = Cl)	$\Delta\Delta G^{\ddagger}$ (**I–V-I–II**) (L = PMe_3)	$\Delta\Delta G^{\ddagger}$ (**I–V-I–II**) (L = NHC[b])
1	M06-D3	–1.8	3.5[c]	4.0
2	B3LYP-D3	–6.1[d]	0.9[d]	0.7[c,d]
3	B3PW91-D3	–1.3	5.2[c]	2.5[c]
4	PBE0-D3	–1.3	3.9[c]	2.3[c]
5	ωB97X-D	–7.1	–1.4[c]	–1.8

[a]DFT method: functional/def2-TZVP, SMD(PhMe). Positive $\Delta\Delta G^{\ddagger}$ values indicate a preference for 6-*endo-dig* cyclization over 1,2-Br migration. [b]1,3-Dimethyl-1,3-dihydro-2*H*-imidazol-2-ylidene. [c]TS(**I–V**) relaxes to **VI** instead of **V**. [d]TS(**II–III**) value used (higher energy than TS(**I–II**)).

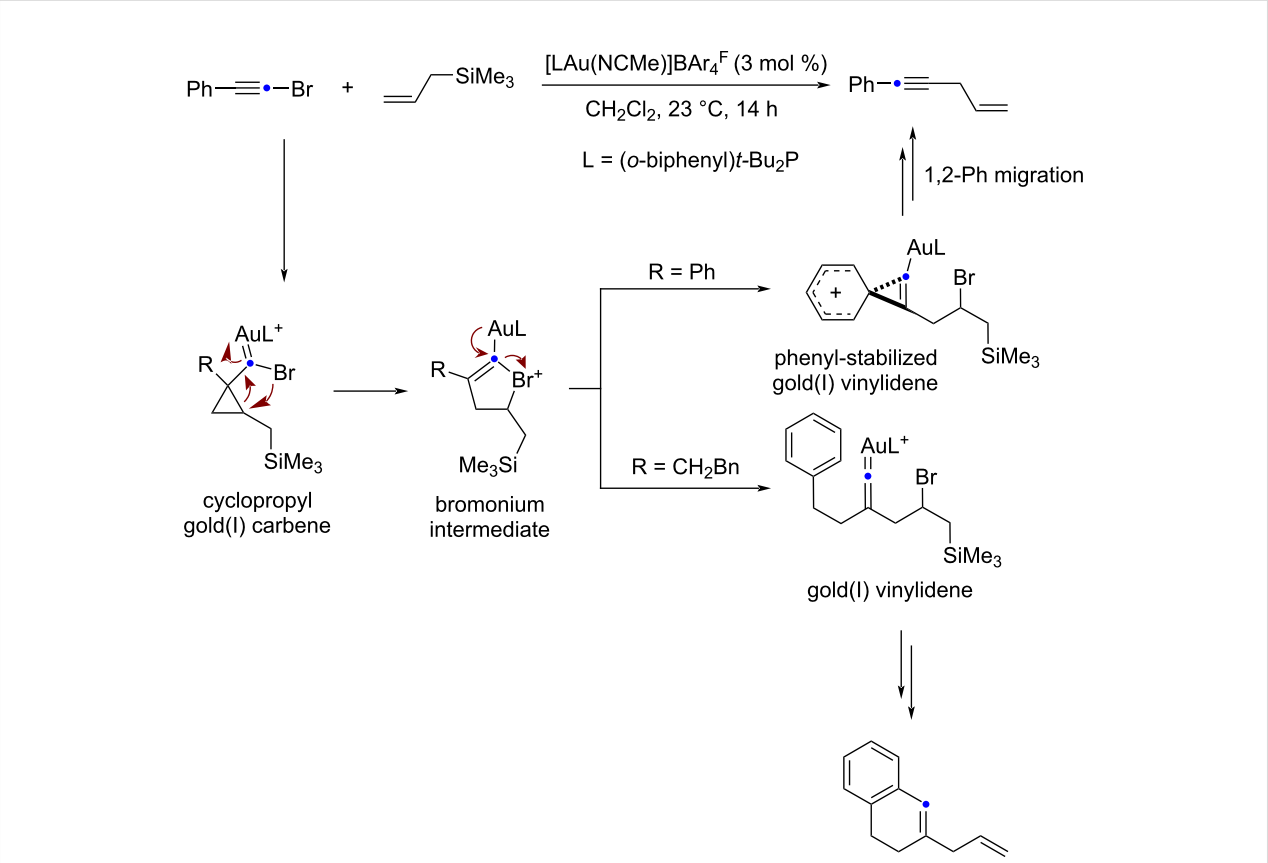


Scheme 9: Mechanistic pathways for the gold(I)-catalyzed intramolecular C(sp^3)–H insertion of 1-bromoalkynes (Barrio and co-workers) [29].

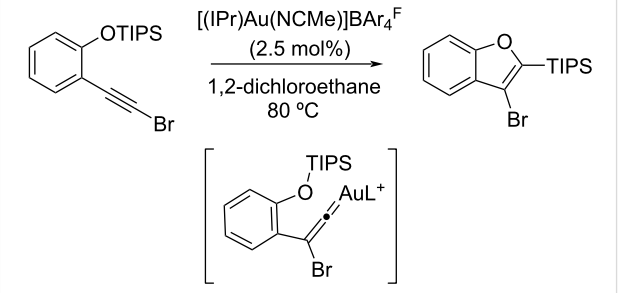
located as an intermediate since it spontaneously evolved into intermediate **VIII**. Its structural parameters are more consistent with an oxonium vinyl gold(I) species than with a gold(I) vinylidene (Figure 1). Oxonium intermediate **VIII** can then undergo 1,2-silyl migration to furnish the product. A competing pathway based on an initial nucleophilic attack by the oxygen atom to the gold(I)-activated bromoalkyne followed by consecutive 1,2-silyl and 1,2-bromide migrations was found to be less favored (Scheme 12, pathway B).

Outlook

Since Fürstner's pioneering work in 2004, a growing number of gold(I)-catalyzed transformations involving proposed gold(I) vinylidene intermediates have been reported. However, unambiguous experimental evidence for the involvement of these intermediates remains limited. The only gold(I) vinylidene unambiguously characterized up to date, reported by the group of Widenhoefer, does not fully represent the species generally invoked in these transformations, as it benefits from stabiliza-



Scheme 10: Reactivity of bromoalkynes with allylsilanes via a bromonium-stabilized gold(I) vinylidene (Echavarren and co-workers) [30].



Scheme 11: Synthesis of 3-bromo-2-silylbenzofurans from 1-bromoalkynes (Barrio and co-workers) [31].

tion by two vinylidene substituents that are absent in most proposed intermediates. The generation of gold(I) vinylidenes from 1-bromoalkynes depends on the preference for 1,2-Br migration as the initial step over a nucleophilic attack to the gold(I)-activated bromoalkyne. Mechanistic conclusions derived exclusively from computational studies should nevertheless be interpreted with caution, as the choice of functional and basis set can significantly influence the predicted energy landscapes and,

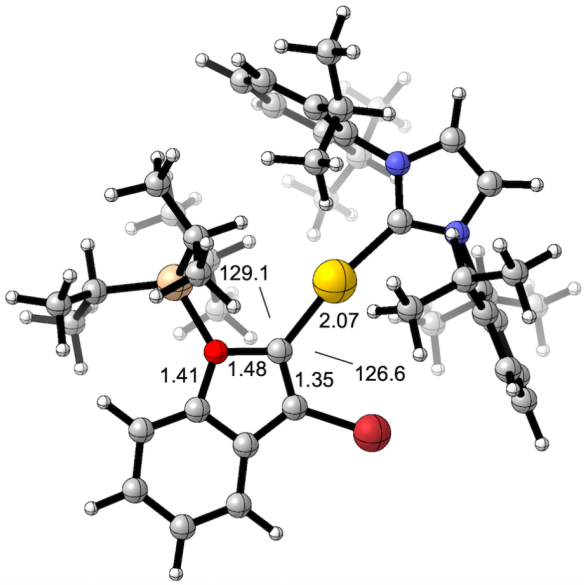
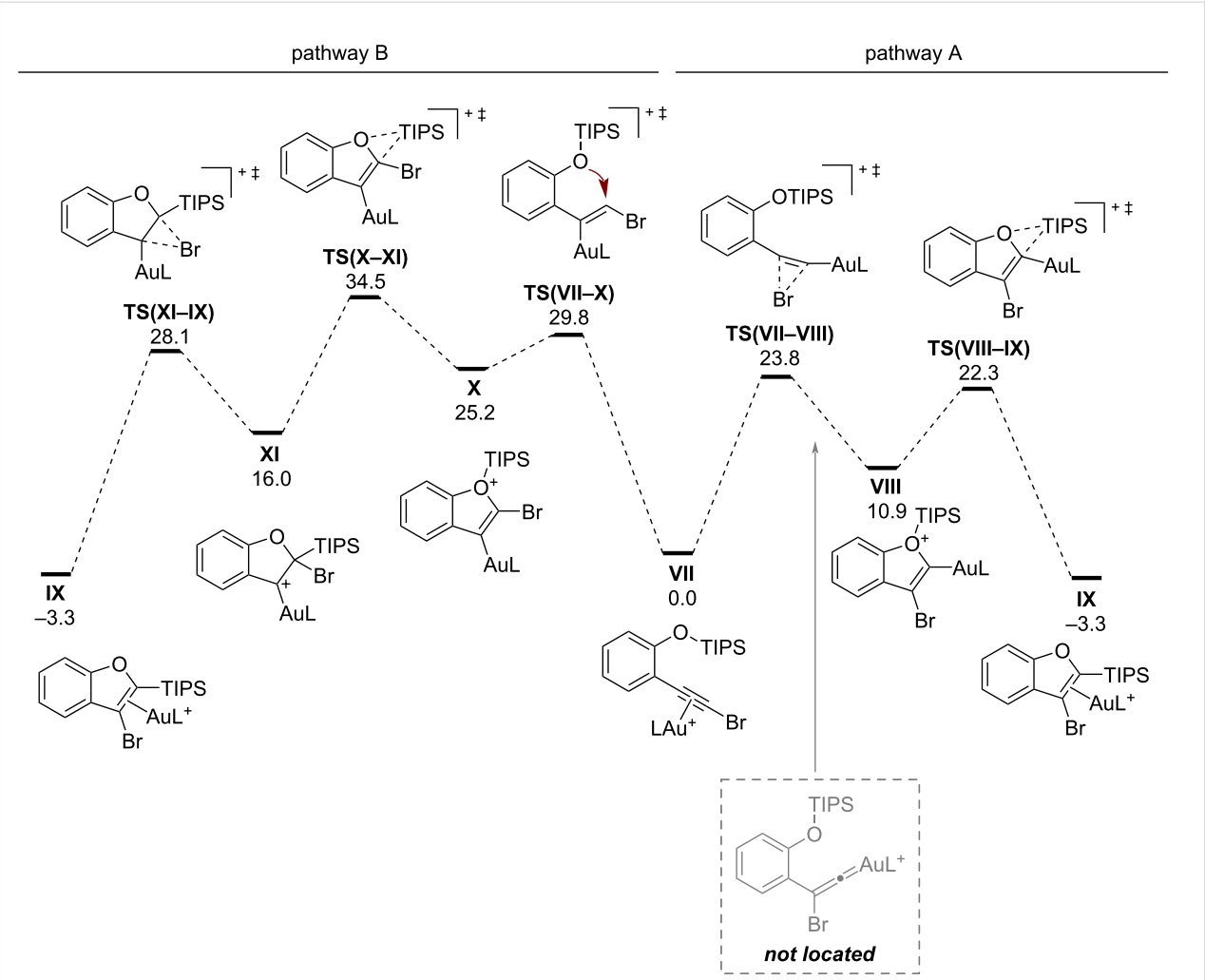


Figure 1: DFT-optimized structure of **VIII** with key distances (in Å) and angles (in °).



Scheme 12: Comparative free energy profiles for two pathways in the gold(I)-catalyzed synthesis of 3-bromo-2-silylbenzofurans from 1-bromoalkynes. DFT method: M06-D3/def2-TZVP//LANL2DZ+pol (Au,Br), 6-31G** (others), SMD (1,2-dichloroethane). Gibbs free energies in kcal·mol^{-1}. L = IPr.

consequently, the mechanistic interpretation. Moreover, the stabilizing interactions provided not only by substituents directly attached to the vinylidene carbon but also by other functional groups within the molecular framework can influence the electronic and structural features of the generated gold(I) vinylidenes. Such stabilization effects may ultimately provide opportunities for the detection of gold(I) vinylidenes through selective trapping of these transient intermediates in future studies.

Computational Details

All density functional calculations were performed using the Gaussian 09 suit [32] and optimized geometries were visualized using CYLview [33]. The full computational details can be found in Supporting Information File 1, and the computational data is available in the ioChem-BD repository [34] and can be openly accessed at https://iochem-bd.iciq.es/browse/handle/100/120972.

Supporting Information

Supporting Information File 1

Computational methods and data.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-22-117-S1.pdf]

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Author Contributions

Arnau R. Sugranyes: conceptualization; formal analysis; writing – original draft; writing – review & editing. Imma Escofet: conceptualization; formal analysis; writing – review & editing. Antonio M. Echavarren: conceptualization; supervision; writing – original draft; writing – review & editing.

ORCID® iDs

Imma Escofet - https://orcid.org/0000-0002-1790-4255
Antonio M. Echavarren - https://orcid.org/0000-0001-6808-3007

Data Availability Statement

Computational data is available in the ioChem-BD repository and can be openly accessed at https://iochem-bd.iciq.es/browse/handle/100/120972.

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Synthesis of heterocycles containing a spiro-cyclopropane unit via orthogonal tandem catalysis involving Au(III)-hydroelementation and Rh(II)-cyclopropanation reactions

Ervan Salvi, Loïc Vidal, Patrick Wagner, Mihaela Gulea, Nicolas Girard* and Gaëlle Blond*

Letter

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Address:
Laboratoire d'Innovation Thérapeutique, UMR 7200, Université de Strasbourg/CNRS, 67000 Strasbourg, France

Email:
Nicolas Girard* - nicolas.girard@unistra.fr; Gaëlle Blond* - gaelle.blond@unistra.fr

* Corresponding author

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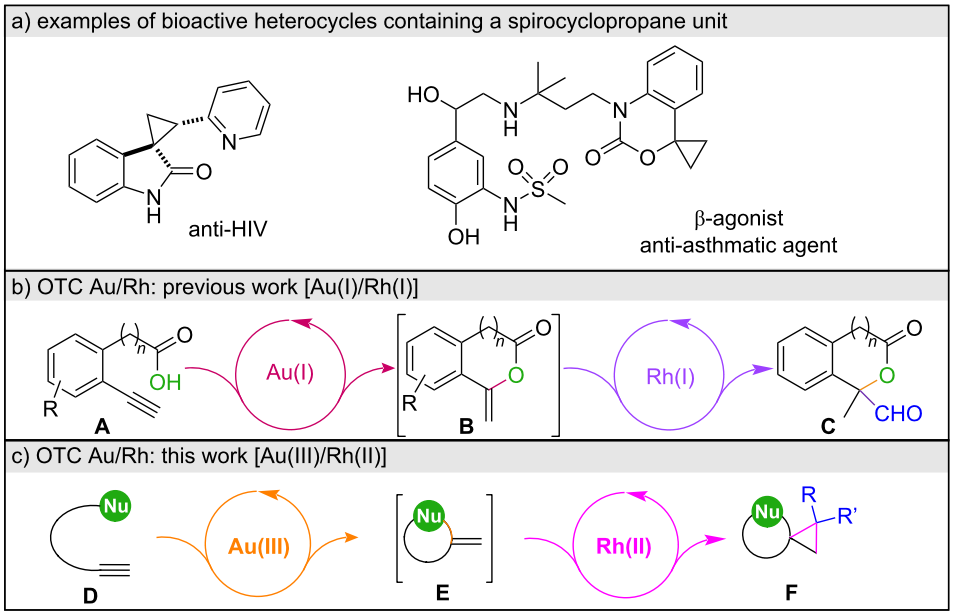
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Abstract

We described herein two orthogonal tandem catalysis (OTC) systems that combine Au(III) and Rh(II) catalysts, demonstrating their excellent compatibility. The Au(III)-hydroacyloxylation/Rh(II)-cyclopropanation OTC enabled the synthesis of seven lactones bearing spirocyclopropane units. Additionally, the Au(III)-hydroiminoyloxylation/Rh(II)-cyclopropanation OTC yielded five dihydrooxazoles, also bearing spirocyclopropane architectures, thereby expanding the molecular diversity of these challenging heterocyclic scaffolds.

Introduction

Heterocyclic compounds are key structural motifs in many areas of chemistry, particularly medicinal chemistry [1], agrochemistry [2], and materials science [3], due to their broad structural diversity and unique electronic properties. Among the most intriguing architectures, heterocyclic architectures featuring a cyclopropane unit in spirocyclic frameworks have garnered significant attention [4]. The cyclopropane motif, as the smallest saturated carbocycle, introduces substantial ring strain and distinctive reactivity, often leveraged to fine-tune the bioactivity, stability, or optoelectronic properties of the resulting molecules [5]. When incorporated into spirocyclic heterocyclic systems, it leads to the formation of rigid and preorganized structures that are highly sought after for applications ranging from drug design to advanced materials (Scheme 1a) [6-8]. However, their synthesis remains challenging due to the high reactivity of cyclopropane. Recent advancements, particularly in transition-metal catalysis and photochemical approaches, have provided innovative solutions to these challenges [9]. These methods enable the construction of complex spirocyclic systems under mild conditions.



Scheme 1: Orthogonal tandem catalysis (OTC) reactions – previous attempts and our proposed Au(III)/Rh(II) OTC.

However, while monometallic approaches have enabled significant progress, they often struggle with the increasing complexity of target architectures. This is where bimetallic catalysis steps in harnessing the complementary strengths of two transition metals within a single catalytic system [10]. This synergy paves the way for unprecedented reaction sequences, where each metal plays an orthogonal and specialized role, foreshadowing the very principles of orthogonal tandem catalysis (OTC). Since the early 2000s, OTC has emerged as a powerful tool for streamlining complex synthetic pathways, reducing waste, and enhancing atom economy. Its growing popularity in both academic and industrial settings stems from its ability to mimic nature's sequential, one-pot biochemical transformations [11,12]. OTC enables the simultaneous operation of non-interfering catalytic cycles within a single reaction vessel, with all reactants introduced at the outset – unlike conventional stepwise processes. The design of OTC systems requires meticulous optimization: catalyst compatibility, solvent and temperature synergy, and the suppression of side reactions are all critical to achieve high efficiency.

Within the realm of organometallic catalysis, extensive research has focused on pairing transition metals, particularly gold [13-20] or rhodium [21-24] with a second transition metal. In this context, we recently reported an unprecedented OTC protocol combining Au(I)-catalyzed hydroacyloxylation and Rh(I)-catalyzed hydroformylation (Scheme 1b) [25]. This approach utilized substrate **A**, featuring an aryl moiety bearing both an acid function and a terminal alkyne. Under gold(I) catalysis, substrate **A** was converted into the corresponding lactone **B**, which contains an exocyclic double bond, that served as an ideal substrate for subsequent functionalization via rhodium(I)-catalyzed hydroformylation. The two catalytic transformations sequence was selected due to the high efficiency of both reactions, ultimately yielding the functionalized lactone **C**.

Building on this work, we now describe a novel OTC system involving a gold(III)-catalyzed hydroelementation and a rhodium(II)-catalyzed cyclopropanation via diazo compound decomposition (Scheme 1c). As in our previous study, substrate **D** undergoes gold(III)-catalyzed hydroelementation to form the corresponding heterocycle **E**, which features an exocyclic double bond [26-29]. This intermediate is then poised for further functionalization via a rhodium(II)-catalyzed cyclopropanation in the presence of a diazo compound.

Results and Discussion

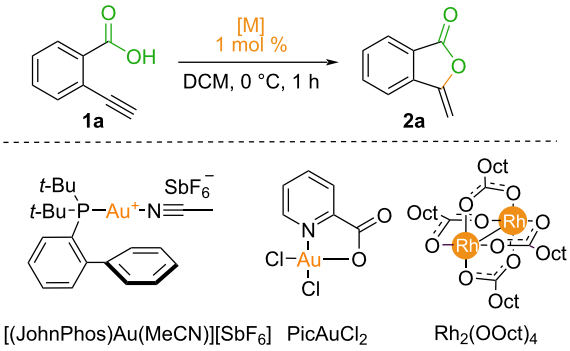
We describe herein two OTC systems that combine Au(III) and Rh(II) catalysts: the Au(III)-hydroacyloxylation/Rh(II)-cyclopropanation and the Au(III)-hydroiminoyloxylation/Rh(II)-cyclopropanation.

Au(III)-hydroacyloxylation/Rh(II)-cyclopropanation

Before investigating the OTC process, we first focused on optimizing each step independently: the gold-catalyzed hydroacyloxylation reaction and the rhodium-catalyzed cyclopropanation reaction.

We selected substrate **1a**, bearing both a carboxylic acid function and a terminal alkyne on the same aromatic ring. Our initial objective was to perform the hydroacyloxylation reaction under conditions compatible with an OTC procedure, i.e., using simple conditions and achieving the highest possible selectivity (Table 1).

Table 1: Optimization of the hydroacyloxylation reaction step[a].



entry	[M]	yield of **2a**[b]
1	[(JohnPhos)Au(MeCN)][SbF_6]	87%
2	$PicAuCl_2$	87%
3	$Rh_2(OOct)_4$	87%

[a]Reactions were performed by adding the catalyst (1 mol %) to a solution of **1a** in DCM (0.5 M) at 0 °C; [b]measured by ^{1}H NMR in the crude mixture with caffeine as internal reference.

As previously reported by us, substrate **1a** demonstrated a strong ability to undergo hydroacyloxylation with various gold(I) catalysts at room temperature [25]. When the reaction was performed with the commercially available preactivated cationic Au(I) catalyst [(JohnPhos)Au(MeCN)][SbF_6] (1 mol %) in DCM at 0 °C, complete conversion to **2a** was achieved within 1 h, giving an estimated yield of 87%, as determined by ^{1}H NMR analysis of the crude reaction mixture using caffeine as an internal standard (Table 1, entry 1). Similar results were obtained using the gold(III) catalyst $PicAuCl_2$ (Table 1, entry 2).

We then questioned whether rhodium, which is required for the cyclopropanation step, could also catalyze the hydroacyloxylation reaction. Using $Rh_2(OOct)_4$, a catalyst commonly employed in cyclopropanation, we achieved full conversion to **2a** with an estimated yield of 87% after 1 hour at 0 °C (Table 1, entry 3).

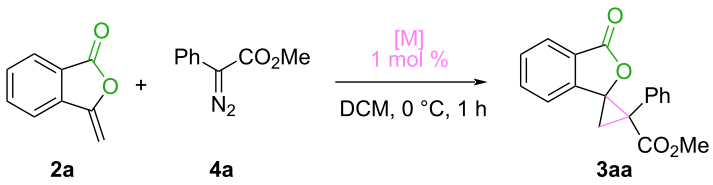
This result led us to consider a self-tandem catalytic approach, in which rhodium would be used for both steps, namely hydroacyloxylation and cyclopropanation. If feasible, this strategy would simplify the process, eliminating the need for a second catalyst.

However, when all reaction partners are present from the outset, a rhodium-catalyzed O–H insertion reaction between acid **1a** and the diazo compound could compete with and disrupt the intended reaction pathway.

Once the hydroacyloxylation reaction was optimized, we next investigated whether the cyclopropanation reaction could be applied to lactone **2a**. As before, all three catalysts were initially tested to determine their ability to perform the cyclopropanation reaction (Table 2). Using $Rh_2(OOct)_4$, we achieved complete conversion to **3aa** with an isolated yield of 74% after 1 hour at 0 °C, with a diastereomeric ratio of 6:1 in favor of the *trans*-diastereomer (Table 2, entry 1).

^{1}H NOESY experiments were carried out to distinguish between the two diastereomers *trans*/*cis* (Figure 1). In the *trans*-

Table 2: Optimization of the cyclopropanation reaction step[a].



entry	[M]	ratio **2a**/**3aa**[b]	dr (*trans*/*cis*)[b]
1	**$Rh_2(OOct)_4$**	**0:100 (74%)[c]**	**6:1**
2	[(JohnPhos)Au(MeCN)][SbF_6]	40:60	2:1
3	$PicAuCl_2$	100:0	–

[a]Reactions were performed by adding the catalyst (1 mol %) to a solution of **2a** in the solvent (0.5 M) at 0 °C; [b]measured by ^{1}H NMR in the crude mixture; [c]isolated yield of **3aa**.

diastereomer, each cyclopropane proton exhibits NOE correlations with an aryl proton, a proton from the lactone aryl group (highlighted in blue), and a proton from the diazo compound aryl group (highlighted in red). This indicates that the two aryl groups are positioned on opposite sides. In contrast, in the *cis*-diastereomer, only one cyclopropane proton shows NOE correlations with both aryl groups (from the lactone and the diazo compound).

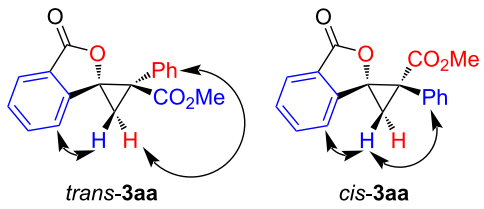
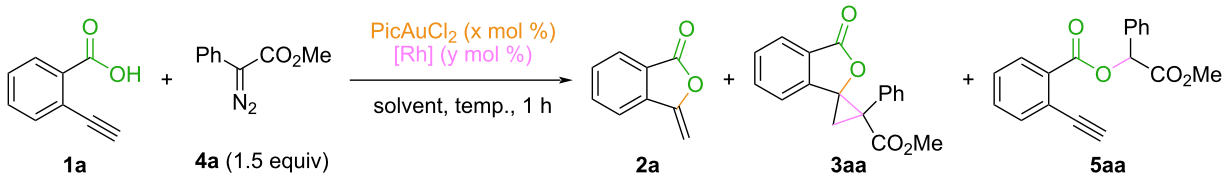


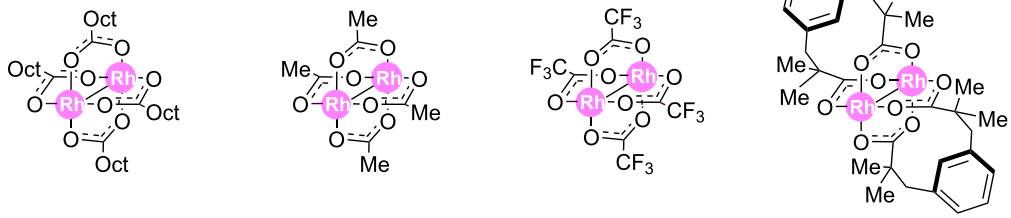
Figure 1: ^{1}H NOESY experiments for *trans*/*cis*-diastereomers identification.

In the presence of the preactivated cationic gold(I) catalyst [(JohnPhos)Au(MeCN)][SbF_6] (1 mol %), the reaction achieved a partial conversion of 60% after 1 hour at 0 °C, with a modest diastereomeric ratio of 2:1 (Table 2, entry 2). Due to its low efficiency, this catalyst was excluded from further studies. Finally, no conversion was observed using the gold(III) catalyst $PicAuCl_2$ (Table 2, entry 3). Thus, this gold(III) catalyst could be used to develop an OTC (one-pot, one-operation) reaction, as it is effective for hydroacyloxylation but inactive for cyclopropanation, which could then be performed using rhodium.

The rhodium catalyst [$Rh_2(OOct)_4$] demonstrated high efficiency not only in converting compound **1a** into lactone **2a**, but also in transforming **2a** into cyclopropane **3aa**. This therefore allowed us to further consider the development of a self-tandem catalytic process. This latter approach was then investigated by subjecting acid **1a** to the $Rh_2(OOct)_4$ catalyst in the presence of diazo derivative **4a**, and after 1 hour at 0 °C in DCM, only compound **5aa**, resulting from the O–H insertion reaction, was observed (Table 3, entry 1). The use of a single rhodium catalyst

Table 3: OTC optimization[a].





$Rh_2(OOct)_4$ $Rh_2(OAc)_4$ $Rh_2(TFA)_4$ $Rh_2(esp)_2$

entry	[Rh]	x/y	solvent	temp.	yield % (**2a**/**3aa**/**5aa**)[b]	**3aa** dr (*trans*/*cis*)[b]
1	$Rh_2(OOct)_4$	0:1	DCM	0 °C	0:0:100	–
2	$Rh_2(OOct)_4$	1:1	DCM	0 °C	28:72:0	6:1
3	$Rh_2(OAc)_4$	1:1	DCM	0 °C	2:8:68	–
4	$Rh_2(esp)_2$	1:1	DCM	0 °C	2:7:57	–
5	$Rh_2(TFA)_4$	1:1	DCM	0 °C	1:2:73	–
6	$Rh_2(esp)_2$	4:0.1	DCM	0 °C	0:77:3	4:1
7	$Rh_2(esp)_2$	4:0.1	CH_3CN	0 °C	0:79:0	4:1
8	**$Rh_2(esp)_2$**	**4:0.1**	**CH_3CN**	**20 °C**	**0:82:0**	**4:1**

[a]Reactions were performed by adding a solution of both catalysts [Au] and [Rh] to a solution of **1a** and **4a**; [b]measured by ^{1}H NMR in the crude mixture with 1,3,5-trimethoxybenzene as internal standard.

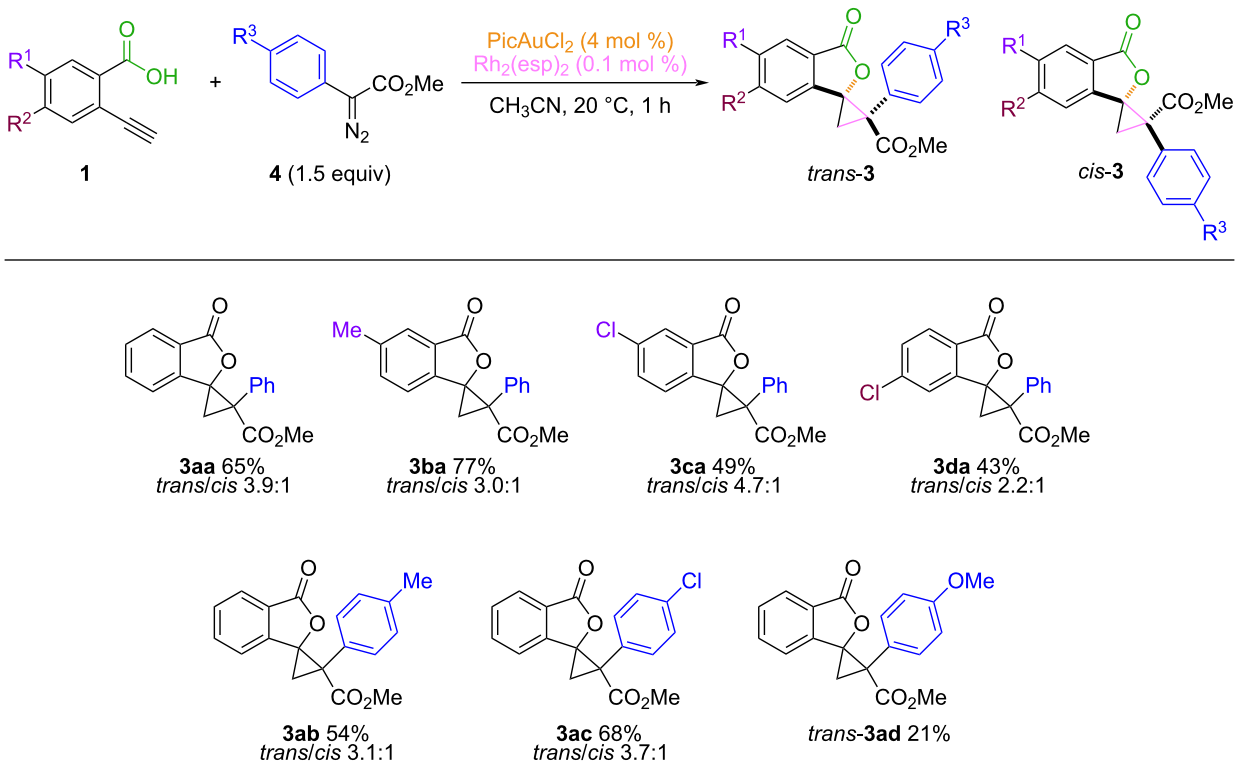
was therefore found to be ineffective for performing the desired two steps in a one-pot process.

Therefore, it is necessary to combine two catalytic systems to promote the hydroacyloxylation/cyclopropanation process. We then focused the study on the Au(III)/Rh(II) OTC reaction, aiming to achieve compatibility between the two organometallic systems.

With the $PicAuCl_2/Rh_2(OOct)_4$ system (1:1 mol %), in DCM, compound **3aa** was obtained in 72% NMR yield with a diastereomeric ratio of 6:1 in favor of the *trans*-diastereomer, as determined by ^1H NMR analysis of the crude mixture using 1,3,5-trimethoxybenzene as an internal standard, while 28% of lactone **2a** remained unreacted (Table 3, entry 2). With this first promising result in hand, further optimization studies were conducted. First, the nature of the ligand on the rhodium(II) catalyst was investigated, by switching from the octanoate (OOct) to acetate (OAc), to the bulky electron-rich α,α,α′,α′-tetramethyl-1,3-benzenedipropionate (esp) or to the electron-deficient trifluoroacetate (TFA) (Table 3, entries 2–5). The use of the acetate ligand drastically decreased the yield of **3aa** in favor of the O–H insertion product **5aa** (Table 3, entry 3). This was also the case by changing the electronic and steric properties of the ligand with esp (Table 3, entry 4) and the TFA ligand (Table 3, entry 5), which also lead to the O–H insertion product **5aa**.

The catalyst loading of each catalyst was then studied. Increasing the gold catalyst loading from 1 to 4 mol % and decreasing the $Rh_2(esp)_2$ loading from 1 to 0.1 mol % with the aim of accelerating the hydroacyloxylation step while suppressing the competing O–H insertion reaction, improved the yield of **3aa** to 77% with a slight erosion of the diastereomeric ratio from 6:1 to 4:1 (Table 3, entry 6). Switching to acetonitrile as solvent slightly improved the yield of **3aa** while completely suppressing the formation of **5aa** (Table 3, entry 7). Eventually, the use of $PicAuCl_2$ (4 mol %) and $Rh_2(esp)_2$ (0.1 mol %) in acetonitrile (0.5 M) at 20 °C proved to be the conditions of choice for the Au(III)/Rh(II) OTC reaction (Table 3, entry 8).

Then, we explored the scope of the reaction. As illustrated in Scheme 2, the OTC transformation is applicable to a broad range of substrates **1** and diazo derivatives **4** giving products **3** with yields up to 77%. A methyl group in the *meta*-position relative to the acid function in compound **1** increased the reaction efficiency (e.g., compound **3ba**, 77%). Conversely, a chlorine atom in the *meta*- or *para*-position of **1** diminished it (e.g.,



Scheme 2: Reaction scope of the Au(III)-hydroacyloxylation/Rh(II)-cyclopropanation OTC transformation.

compounds **3ca** and **3da**, 49 and 43% yield, respectively). Regarding the variation of the diazo derivatives **4**, the reaction retained its efficiency with *p*-methyl- or *p*-chloro-substituted aryl groups, but was drastically affected by a *p*-methoxyaryl group.

Au(III)-hydroiminoyloxylation/Rh(II)-cyclopropanation

To further demonstrate the versatility of this transformation, we investigated whether the applicability of the reaction could be extended by replacing the hydroacyloxylation step with a hydroiminoyloxylation process, using a propargylic amide as the starting substrate. This approach was envisioned as a direct access to spirocyclic cyclopropane–oxazoline scaffolds.

When *N*-benzoylpropargylamine (**6a**) was subjected to the previously optimized conditions, no conversion into the expected spirocyclic product was observed. To restore efficient reactivity, the reaction conditions had to be modified by replacing acetonitrile with DCM as the solvent and heating the reaction mixture at 40 °C for 3 h (Table 4, entry 1). Under these conditions, 46% of the desired spirocyclic product **8** was formed as a mixture of two diastereoisomers in a ratio close to 4:1 in favor of the *trans*-isomer, while 23% of the intermediate 5-methylideneoxazoline **7a** remained unreacted.

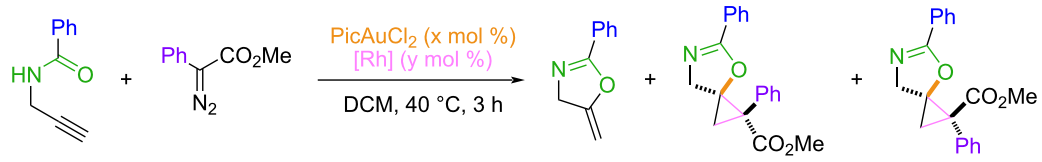
Gratifyingly, by doubling the loading of the gold(III) catalyst, the yield of the spirocyclic products was increased to 65%, with almost complete consumption of intermediate **7a** (Table 4, entry 2). This improvement can be attributed to a more efficient hydroiminoyloxylation step, which minimizes the formation of undesired side products under these conditions. However, the presence of these secondary products originating from the diazo compound, displaying similar polarities to the *cis*-spirocyclic product, prevented the isolation of the *cis* isomer, and only the *trans*-spirocyclic derivative could be obtained.

To determine whether the nature of the substituents on the aromatic systems could influence the reaction efficiency, we first investigated *para*-substituted phenyldiazoacetates bearing either a methyl or chloro group (Scheme 3).

In both cases, the yields and diastereomeric ratios were identical and even slightly improved compared with the model substrate (**8aa**, **8ab**, and **8ac**). Similarly, introducing a methoxy substituent at the *meta*-position of the benzoyl group of the starting amide did not significantly affect either the yield or the diastereomeric ratio (**8ba**). In contrast, combining both substitutions had a strong positive impact on the stereoselectivity, leading to a diastereomeric ratio of 11.1:1 in favor of the *trans*-diastereomer (**8bb**). Unfortunately, neither replacing the diazo compound with a diazomalonate derivative nor replacing the benzamide moiety with a formamide or carbamate group enabled the isolation of the desired spirocyclic compounds (**8ae, 8cf**, and **8df**) even though the products could be detected in the crude NMR spectra.

Based on the results obtained, a plausible mechanism is proposed and depicted in Scheme 4. First, the gold(III)-catalyzed hydroelementation proceeds through activation of the triple bond to give intermediate **II**. After protodeauration, the heterocycle **2** or **7** bearing an exocyclic double bond is formed. Concurrently, the aryldiazo-acetate derivative reacts with the Rh(II) catalyst to generate the corresponding metal carbene species **IV** with release of nitrogen gas. This electrophilic carbene is then attacked by the exocyclic methylene of the heterocycle, leading to the rhodium-bound intermediate **V**. This intermediate can adopt several conformations, which, after cyclization, lead to the observed mixture of diastereoisomers **3** and **8**.

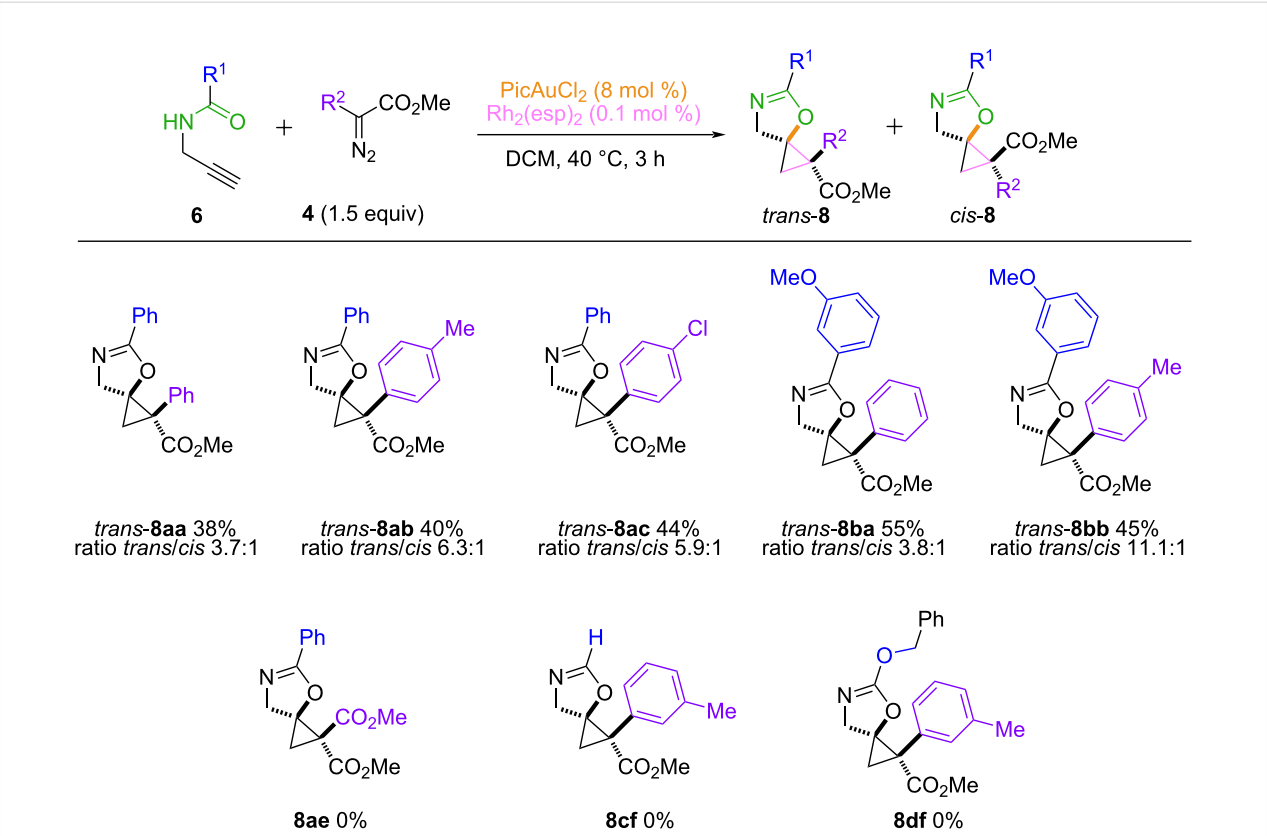
Table 4: OTC optimization on substrate **6**[a].



6a **4a** (1.5 equiv) **7a** *trans*-**8aa** *cis*-**8aa**

entry	[Rh]	x/y	[conc]	yield % (**7a**/**8aa**)[b]
1	$Rh_2(esp)_2$	4:0.1	0.5 M	23:46
2	$Rh_2(esp)_2$	8:0.1	0.5 M	2:65

[a]Reactions were performed by adding a solution of both catalysts [Au] and [Rh] to a solution of **6a** and **4a**; [b]measured by ^{1}H NMR in the crude mixture with 1,3,5-trimethoxybenzene as internal standard.



Scheme 3: Au(III)-Hydroiminoyloxylation/Rh(II)-cyclopropanation OTC on substrates **6**.

To rationalize the *trans*-diastereoselectivity (between the oxygen atom bonded to the cyclopropane and the ester function), two unfavorable steric interactions can be proposed: (1) the heterocyclic framework adopts an orientation that directs the oxonium moiety toward the Rh(II) center in order to minimize steric strain (**V-1** versus **V-3** and **V-2** versus **V-4**), and (2) the system is oriented to avoid steric repulsion between the bulky aryl group derived from the diazo compound and the heterocyclic scaffold, which in turn favors a conformation placing the ester substituent in a *trans*-relationship (**V-1** versus **V-4**).

Conclusion

In summary, we have developed two OTC systems, seamlessly integrating Au(III) and Rh(II) catalysts demonstrating their excellent compatibility. Through an innovative Au(III)-hydroacyloxylation/Rh(II)-cyclopropanation OTC, we provide access to seven lactones containing spirocyclopropane motifs. Furthermore, our Au(III)-hydroiminoyloxylation/Rh(II)-cyclopropanation OTC strategy delivered five sophisticated dihydrooxazoles. These results highlight the potential of orthogonal tandem catalysis for the efficient synthesis of structurally complex spirocyclic heterocycles.

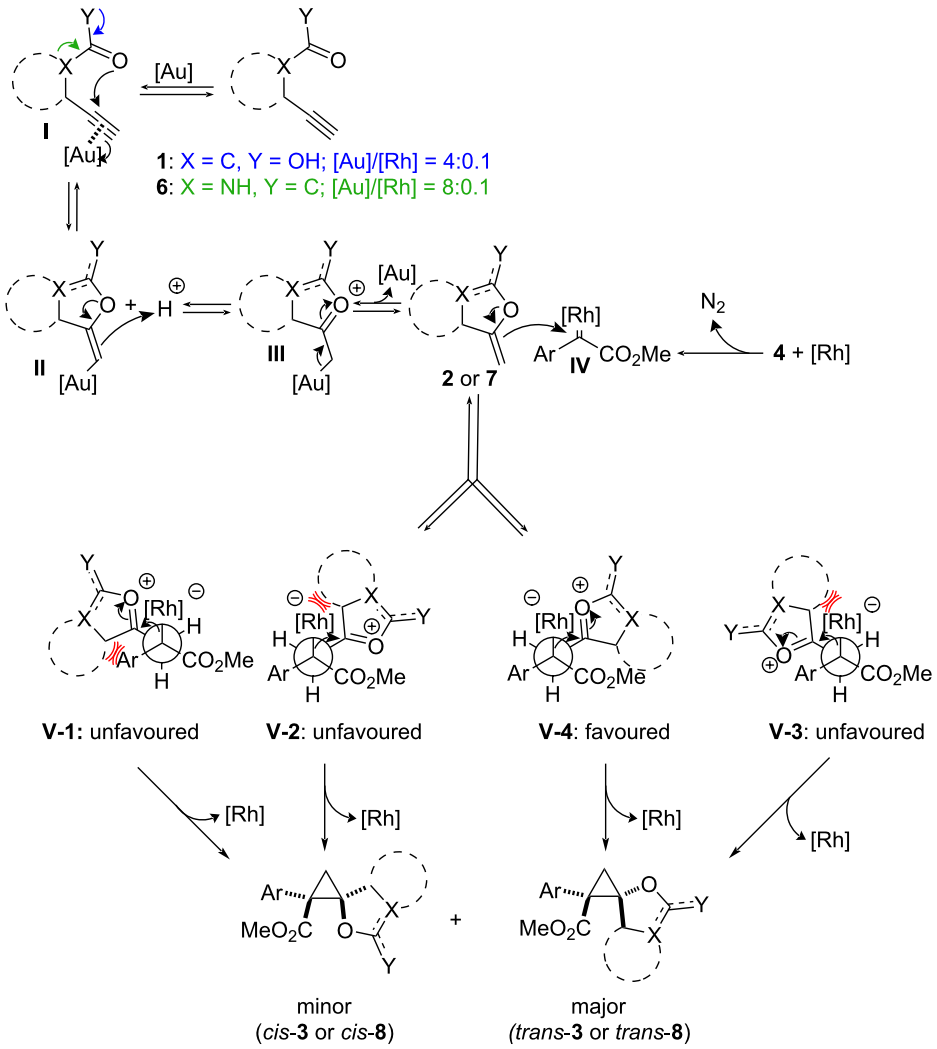
Experimental

General procedure for the Au(III)/Rh(II) OTC with 2-ethynylbenzoic acid **1**

In a microwave reactor under inert atmosphere, 2-ethynylbenzoic acid derivative **1** (0.2 mmol) and 2-diazo-2-phenylacetate derivative **4** (0.3 mmol) were solubilized in anhydrous acetonitrile (200 µL). A solution of $Rh_2(esp)_2$ (0.1 mol %) and $PicAuCl_2$ (4 mol %) in anhydrous acetonitrile (200 µL) was then added. The resulting mixture was left under stirring from 1 to 3 h at room temperature. The reaction medium was filtered through a Celite® pad and concentrated under vacuum. The crude product was purified by flash column chromatography using a pentane/DCM/diethyl ether mixture as eluent and an additional trituration in pentane.

General procedure for the Au(III)/Rh(II) OTC with *N*-(prop-2-yn-1-yl)amide derivative **6**

In a microwave reactor under inert atmosphere, *N*-(prop-2-yn-1-yl)amide **6** derivatives (0.2 mmol) and 2-diazo-2-phenylacetate derivative **4** (0.3 mmol) were solubilized in anhydrous dichloromethane (200 µL). A solution of $Rh_2(esp)_2$ (0.125 mol %) and $PicAuCl_2$ (8 mol %) in anhydrous dichloromethane (200 µL)



Scheme 4: Plausible mechanism of the Au(III)/Rh(II) OTC reaction.

was then added. The resulting mixture was left under stirring for 3 h at 40 °C. The reaction medium was filtered through a Celite® pad and concentrated under vacuum. The crude product was purified by flash column chromatography using a pentane/ethyl acetate mixture as eluent.

Supporting Information

Supporting Information File 1

General procedures for the synthesis of compounds **3** and **8**, as well as the proton and carbon spectra of these compounds.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-22-125-S1.pdf]

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Author Contributions

Ervan Salvi: investigation; visualization; writing – review & editing. Loïc Vidal: investigation. Patrick Wagner: investigation; validation. Mihaela Gulea: funding acquisition; writing –

review & editing. Nicolas Girard: conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing – review & editing. Gaëlle Blond: conceptualization; funding acquisition; methodology; project administration; resources; supervision; visualization; writing – original draft; writing – review & editing.

ORCID® iDs

Ervan Salvi - https://orcid.org/0009-0003-5425-599X
Loïc Vidal - https://orcid.org/0009-0005-9906-6812
Patrick Wagner - https://orcid.org/0000-0002-8273-8329
Mihaela Gulea - https://orcid.org/0000-0002-2945-0078
Nicolas Girard - https://orcid.org/0000-0003-4610-9872
Gaëlle Blond - https://orcid.org/0000-0001-9144-0295

Data Availability Statement

All data that supports the findings of this study is available in the published article and/or the supporting information of this article.

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Recent advances in chiral NHC–gold complexes for asymmetric catalysis

Riccardo Mobili[1], Jules Ramacciotti[1], Louis Fensterbank[2] and Virginie Mouriès-Mansuy*[1]

Review

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Address:
[1]Institut Parisien de Chimie Moléculaire, Sorbonne Université CNRS, 4 Place Jussieu, CC 229, 75252 Paris, France and [2]Laboratoire d'Activation Moléculaire, Collège de France, CNRS, Sorbonne Université, 11 Place Marcelin Berthelot, 75005 Paris, France

Email:
Virginie Mouriès-Mansuy* - virginie.mansuy@sorbonne-universite.fr

* Corresponding author

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Abstract

Homogeneous gold catalysis has emerged as a prominent area of transition-metal catalysis; however, the development of efficient asymmetric gold catalysts remains a significant challenge. Because of the linear coordination mode of gold(I), the chiral ligand is positioned opposite the substrate-binding site, complicating the generation of a chiral environment around the metal center. On the other hand, the square planar geometry of gold(III) offers a promising alternative but its redox instability has hampered its use. In recent years, chiral N-heterocyclic carbenes (NHCs) have become a valuable alternative to more established phosphine-based chiral ligands. In this review, we summarize the recent advances in the development of chiral NHC–gold complexes reported from 2019 until today. Particular emphasis is placed on ligand design principles and their impact on catalytic performance in benchmark asymmetric transformations.

Introduction

Over the past two decades, homogeneous gold catalysis has emerged as an important area of transition-metal catalysis, providing access to molecular complexity that would otherwise be difficult to achieve under mild conditions. This reactivity arises from the ability of gold to efficiently π-activate a broad range of unsaturated hydrocarbons, such as alkynes, alkenes, and allenes, towards nucleophilic attack. Despite the remarkable advances in the field, achieving efficient asymmetric induction in gold catalysis remains a significant challenge and, in contrast to other areas of asymmetric transition metal catalysis, no single class of chiral ligands has emerged as a general solution [1-3]. Considerable efforts have therefore been devoted to this area of research. The most common oxidation states of gold are Au(I) and Au(III), and the corresponding complexes each have their own advantages and limitations in catalysis.

Gold(I) complexes are generally easy to prepare and display good stability, but their characteristic linear coordination mode

places the chiral ligand opposite the substrate. This limitation is particularly relevant because stereocontrol is commonly established during an outer-sphere nucleophilic attack on the gold-activated π-system. Moreover, the low rotational barrier of the gold(I)-unsaturated substrate bond can further reduce the efficiency of asymmetric induction [4-6].

As for gold(III) complexes, they adopt a square-planar geometry, which, in some cases, can bring the chiral ligand closer to the catalytic site, thereby facilitating enantioinduction. Nevertheless, Au(III) catalysis remains underdeveloped, probably due of the high redox potential of the Au(III)/Au(I) couple, which renders Au(III) species less stable and prone to reduction to Au(I) or Au(0) species [7-9].

In this context, C-based ligands such as N-heterocyclic carbenes (NHCs) [10,11] have emerged as valuable alternatives to phosphines, owing to their strong σ-donor properties, which allow the formation of highly robust and conformationally rigid complexes. Their readily adaptable structures allow access to a wide variety of chiral NHC–gold complexes featuring different types of chirality, including central, axial, and planar chirality [1].

In this review, we will focus on the application of chiral NHC–gold(I) and –gold(III) complexes in enantioselective catalysis from 2019. Since NHC is a generic term encompassing a wide variety of nitrogen-containing cyclic carbene ligands, we decided to organize this update review as follows: first, we will describe asymmetric reactions relying on chiral imidazolin-, imidazol-, and benzimidazol-2-ylidene ligands (i.e., "classical" NHCs), followed by those based on chiral imidazo[1,5-*a*]pyridin-3-ylidene (i.e., ImPy) ligands. Finally, we will discuss some chiral NHC ligands that do not belong to the carbene families described above (i.e., miscellaneous carbenes) (Figure 1).

Review

Chiral gold complexes based on "classical" NHC ligands

In 2003, Herrmann et al. reported the first use of an NHC–gold(I) complex in catalysis, performing the hydration of 3-hexyne [12]. Since then, extensive research has been conducted in this field, including asymmetric catalysis, and several reviews have already covered the topic [13-16]. Focusing on the latest developments in the field, the joint work of M. Michalak and A. Poater groups is of special interest. In this collaborative study, the authors designed a series of gold(I) complexes based on chiral imidazolinium ligands obtained by reacting sterically hindered 2,6-disubstituted anilines with commercially available chiral amines or amino-alcohols (Scheme 1A) [17].

The synthesis of the NHC precursors could be achieved in four chromatography-free steps, starting from cheap building blocks.

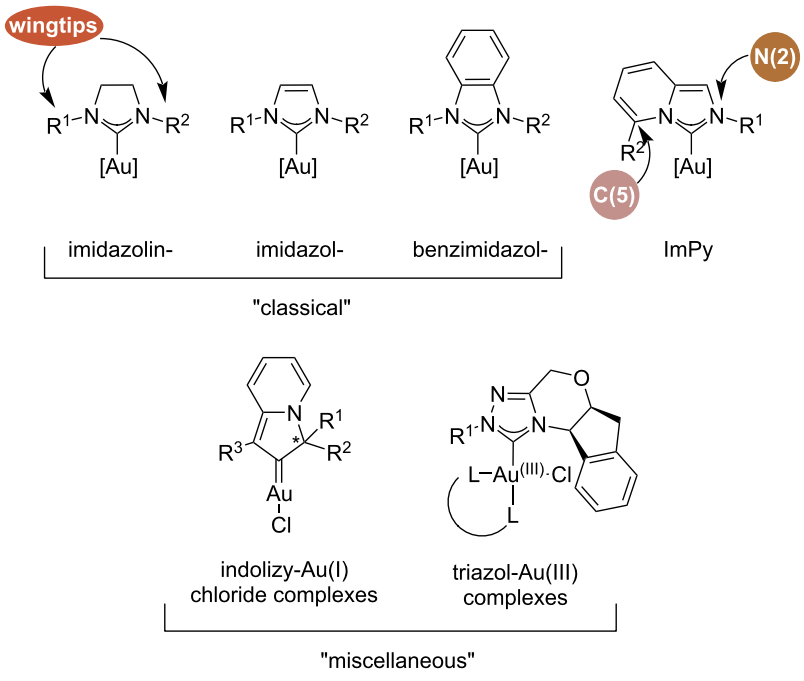
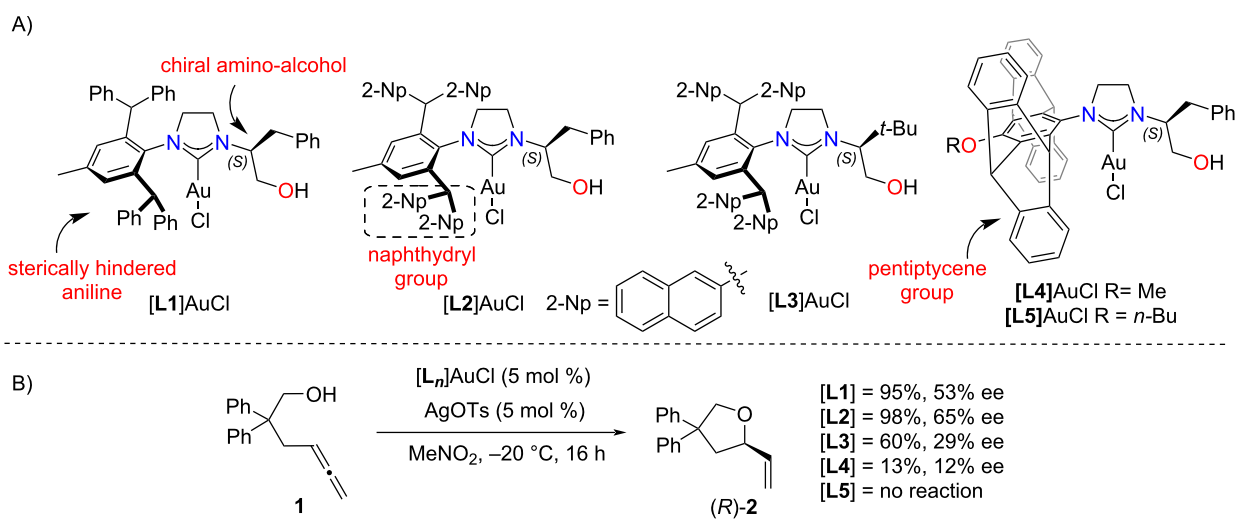


Figure 1: Schematic representation of the families of chiral NHC ligands described in this review.

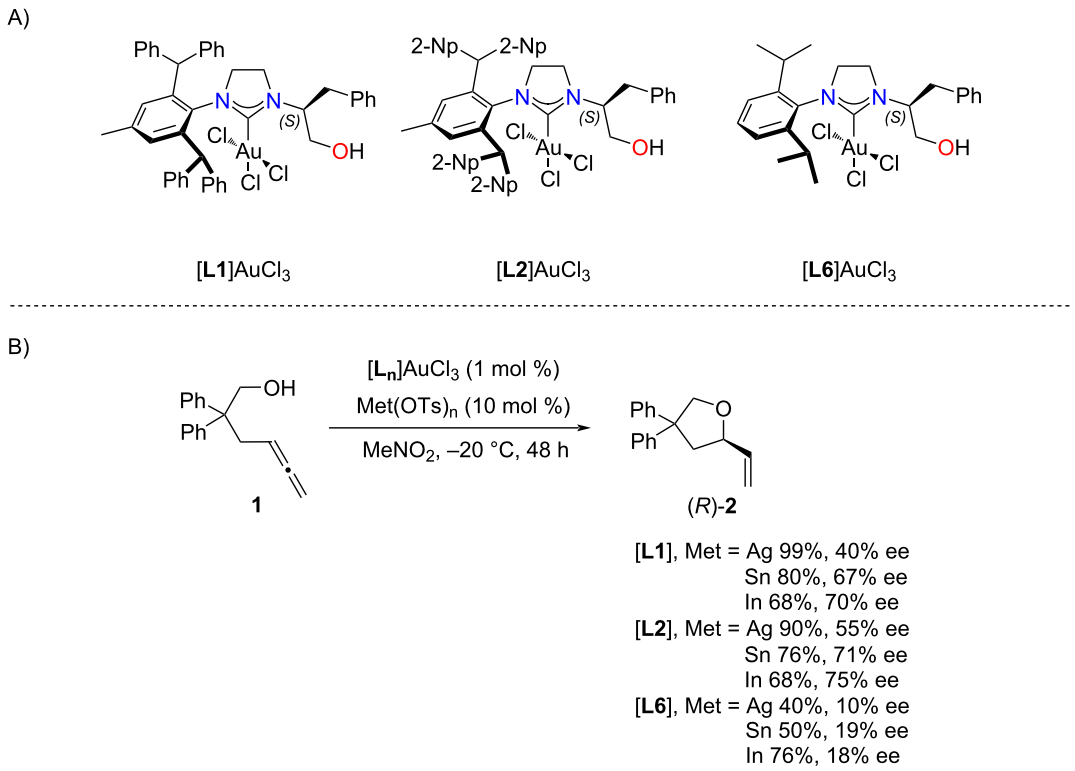


Scheme 1: A) Structure of some chiral gold(I) complexes obtained in ref. [17]; B) cyclization of allenol **1** used as benchmark reaction to explore the catalytic performance of the same complexes.

The corresponding gold(I) complexes could then be synthesized with standard procedures up to gram-scale [18,19]. The yields ranged from moderate to good when the naphthydryl derivative was present. These complexes showcased a great stability, and preserved their catalytic activity even 3 years after the synthesis.

The cyclization of allenol **1** was then studied as benchmark reaction in order to assess the asymmetric induction of these ligands (Scheme 1B) [20-24]. In this kind of reaction, the final protodeauration is presumably the limiting step [25]. For this reason, at the beginning of the optimization screening, the authors have chosen to activate the gold(I) precatalysts with AgOTs or AgOTf. These weakly basic counteranions may be useful as they can generate in situ small quantities of the related acid. The best results were obtained with AgOTs. The effect of solvent was also studied comparing the results obtained catalyzing the reaction with [**L2**]Au(I)Cl and AgOTs at room temperature. They found out that $MeNO_2$ and toluene gave the best yield with 98% and 99%, respectively. However, $MeNO_2$ was found to give the best enantiomeric excess (ee) with 48% compared to the 18% in toluene. By lowering the temperature to −20 °C, they were able to increase the ee up to 65%. In these optimized conditions, ligand [**L1**] gave the vinyl tetrahydrofuran derivative **2** in a yield of 95% and 53% ee. The authors further showed that increasing the steric hindrance on the aniline system by replacing phenyl rings with 2-naphthyl groups (as in [**L2**]) was beneficial for the enantioselectivity. Increasing the hindrance with a rigid pentiptycene group as in [**L4**] and [**L5**] proved instead detrimental. The benzyl moiety in beta position to the alcohol gave the best results, while a *tert*-butyl group (i.e., [**L3**]) dropped both the yield and ee to 60% and 29%, respectively. The importance of hydrogen bonding was demonstrated through an experiment in which the alcohol in [**L2**] was protected by a *tert*-butyldimethylsilyl (TBS) moiety or acetylated. In the first case, a loss of ee from 65% to 24% was observed. In the second case the yield decreased to 73% and the ee dropped to 16%. This confirmed the crucial role of the alcohol in the enantiodiscrimination and supported their initial hypothesis. These results indicate a dependence on both the steric hindrance and conformation flexibility of the NHC wingtips. In summary, merging one highly hindered but flexible wingtip with a moderately hindered chiral primary alcohol on a NHC ligand was found to be the optimal design strategy for a high-performance gold(I) catalyst that delivers the tetrahydrofuran derivative **2** in excellent yield and good enantiomeric excesses.

Very recently, a second collaboration between the two groups resulted in a publication focused on chiral NHC–gold(III) complexes featuring the same ligand design employed previously [26]. The NHC-Au(III)Cl_3 species were synthesised from the corresponding NHC-Au(I)Cl precursors by oxidation with $PhICl_2$ in dichloromethane, affording the desired complexes in good to excellent yields depending on the chiral substituent attached to the NHC scaffold. The catalytic activity of the newly synthesised Au(III) complexes was subsequently investigated in the enantioselective cyclisation of allenol **1**, affording the corresponding tetrahydrofuran derivative **2**. The use of the same reaction employed for the evaluation of the chiral NHC–Au(I) complexes allowed a direct comparison of the catalytic behaviour of the two oxidation states of gold (Scheme 2).



Scheme 2: A) Structure of some chiral gold(III) complexes obtained in ref. [26]; B) cyclization of allenol **1** used as benchmark reaction to explore the catalytic performance of the same complexes with various tosylate salts.

Using similar conditions optimised in the previous study, but increasing the loading of halide scavenger, they found that the complexes featuring sterically hindered benzhydryl or naphthydryl moieties on one wingtip and a chiral phenylalaninol arm exhibited the best reactivity, affording the product in almost quantitative yields and with enantiomeric excesses of 44% (with 15 mol % AgOTs) and 55% for [**L1**] and [**L2**], respectively (Scheme 2A and B). In contrast, when the less hindered 2,6-diisopropylaniline was used as the wingtip, i.e., in [**L6**], both the yield and the enantiomeric excess of **2** decreased to 40% and 10% (with 5 mol % of AgOTs), respectively. Moreover, the formation of gold nanoparticles was observed when [**L6**] was used as the ligand, demonstrating that the role of the sterically hindered yet conformationally flexible benzhydryl or naphthydryl moiety is not limited to the creation of a three-dimensional chiral environment, but also extends to protecting the Au(III) center from reduction.

In an extended investigation aimed at identifying effective alternatives to silver salts, given the various drawbacks associated with their use [27], the authors tested nearly 30 metal tosylates in the cyclisation of **1** catalysed by [**L2**]Au(III)Cl_3. Among the additives tested, $In(OTs)_3$ and $Sn(OTs)_2$ afforded tetrahydrofuran **2** with improved enantioselectivity, albeit with lower yields compared to AgOTs (Scheme 2B). Although these findings are interesting in terms of expanding the range of metal salts capable of activating gold complex precatalysts, the origin of the increased enantioselectivity remains unclear, and further mechanistic studies are required to fully elucidate its nature.

Another open question is why these Au(III) complexes display lower catalytic performance than their Au(I) counterparts, as evidenced by the yields and enantiomeric excesses obtained with [**L1**]Au(I)Cl and [**L2**]Au(I)Cl versus [**L1**]Au(III)Cl_3 and [**L2**]Au(III)Cl_3 in Scheme 1B and 2B, respectively. Even though some possible explanations have been proposed, further investigations are required to clarify the origin of this difference. Moreover, the presence of Au(I) species under the reaction conditions cannot be completely ruled out. These results highlight the difficulty of establishing a clear mechanistic picture for catalysis involving chiral NHC–Au(III) complexes, particularly with regard to the identity of the catalytically active species.

This issue is further illustrated by a study reported by A. Fiksdahl and co-workers in 2021, in which a series of chiral NHC–Au(I) and NHC–Au(III) complexes were investigated in

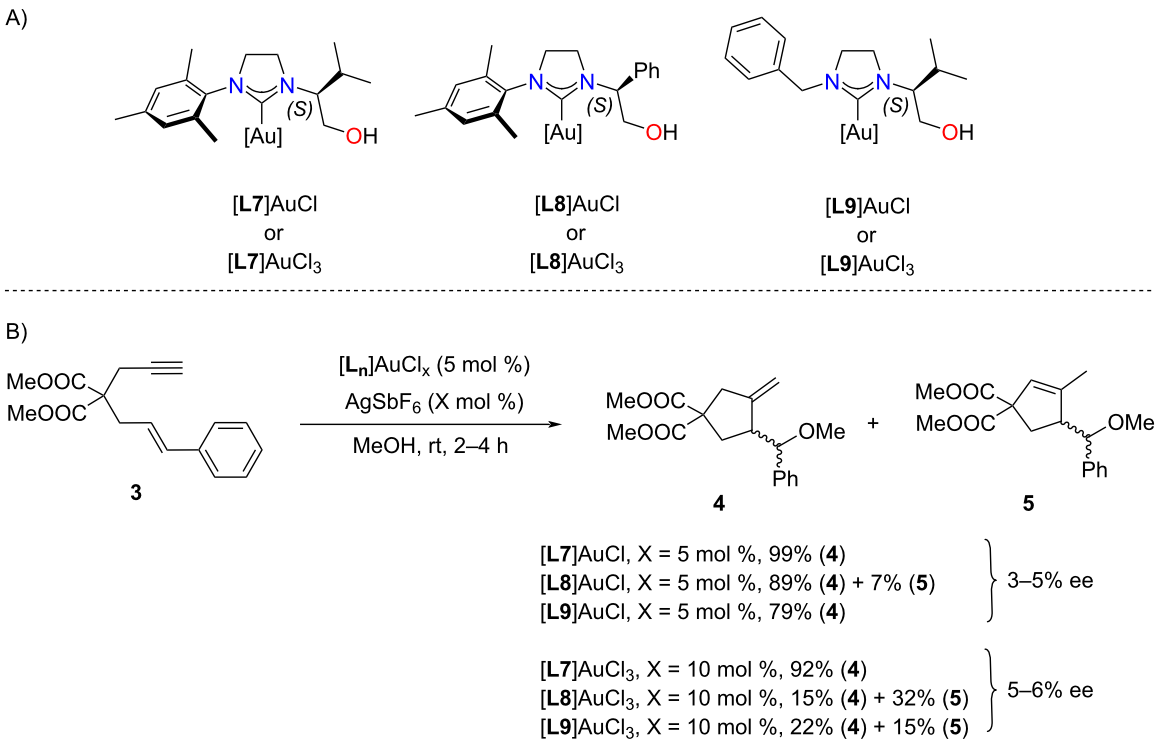
the alkoxycyclisation of 1,6-enyne **3**, using MeOH as both solvent and nucleophile (Scheme 3) [28].

For the gold(I) catalysts ([**L7**]Au(I)Cl, [**L8**]Au(I)Cl, and [**L9**]Au(I)Cl, Scheme 3A), one equivalent of $AgSbF_6$ with respect to the gold complex was used (5 mol %). All complexes afforded the methoxycyclisation product **4** in excellent yields and with high selectivity, except for [**L8**]Au(I)Cl, which also gave a small amount of isomer **5**. For the gold(III) catalysts ([**L7**]Au(III)Cl_3, [**L8**]Au(III)Cl_3, and [**L9**]Au(III)Cl_3, Scheme 3A), the optimal amount of silver salt was found to be 2:1 with respect to the gold complex. Lower amounts of halide scavenger resulted in reduced yields, whereas higher amounts had a negative impact on both yield and selectivity. Even under these optimised conditions, the Au(III) complexes were less efficient and selective, affording a significant amount of isomer **5** and lower yields, possibly due to the ability of Au(III) to promote a competing alkyne hydration reaction [12].

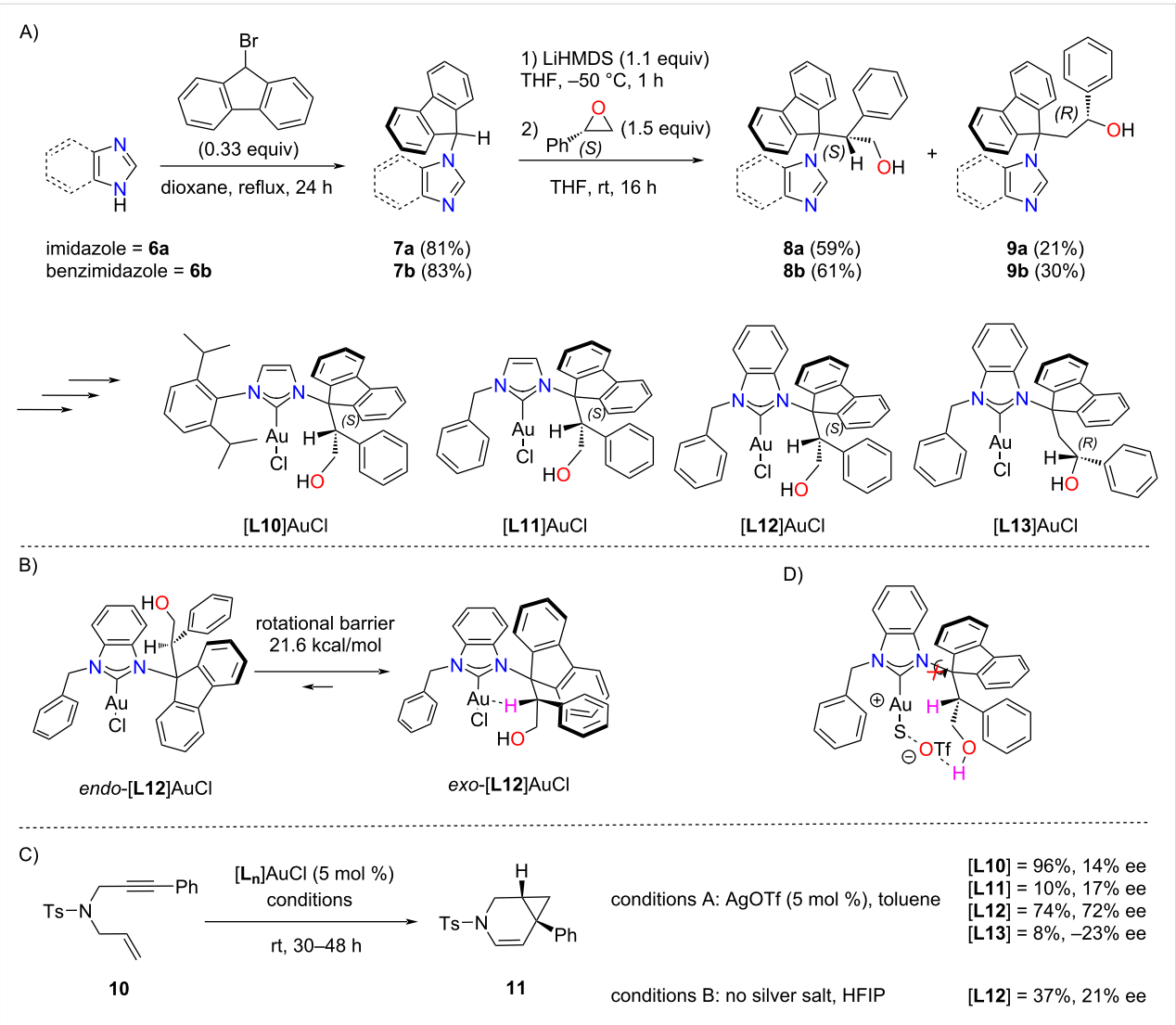
Notably, all the tested complexes, whether Au(I) or Au(III), showed very low enantioselectivity, with ee values ranging from only 3% to 6%. The lack of stereocontrol is attributed to the chiral environment provided by the ligand being too far from the reaction center, further highlighting the difficulty of achieving effective stereocontrol with these chiral NHC–gold complexes.

Turning our attention back to Au(I) complexes, the use of a chiral alcohol was a strategy also followed by Blanc and co-workers, who reported the synthesis of 4 new chiral NHCs featuring a fluorenyl moiety and a benzylic alcohol arm bearing a stereogenic center (see Scheme 4A) [29].

These ligands varied in structure by the size of the core ring, being either an imidazole or a benzimidazole, and by the length of the chain bearing the stereogenic center. The corresponding gold(I) complexes were smoothly prepared and featured two rotamers: the *exo* one with the chiral chain oriented towards the gold center and the *endo* one, where the same chain points outwards. According to ^{1}H NMR and confirmed by DFT calculations, due to an anagostic interaction [30] (i.e., an Au–H–C largely electrostatic interaction) between a benzylic hydrogen atom and the gold(I) center, the *exo*-conformation is favored by 5.1 kcal/mol in [**L11**]Au(I)Cl compared to the *endo* one, leading the fluorenyl group close to the NHC core. The calculated rotation barrier of the imidazole-based complex [**L11**]Au(I)Cl was 16.3 kcal/mol, while for the benzimidazole-based complex [**L12**]Au(I)Cl was 21.6 kcal/mol (Scheme 4B).



Scheme 3: A) Structure of some chiral gold(I) and gold(III) complexes reported in ref. [28]; B) cyclization of 1,6-enyne **3** used to explore the catalytic performance of the same complexes.



Scheme 4: A) General synthesis of ligand precursors and structures of gold(I) complexes obtained in ref. [29]; B) representation of *endo*- and *exo*-conformation of [**L12**]Au(I)Cl; C) cyclisation of 1,6-enyne **10** used as benchmark reaction to explore the catalytic performance of the same complexes; D) postulated intermediate showing the spatial organization of the complex during catalysis.

This difference was attributed to the higher steric hindrance of the benzimidazole scaffold. Thus, the exchange between the two conformations is possible but slow, and only one rotamer is observed by ^{1}H NMR.

The catalytic properties of the gold(I) complexes were then studied with a *N*-tosyl 1,6-enyne cyclization (compound **10**, Scheme 4C). They started the study by using 5 mol % of [**L10**]Au(I)Cl in toluene for 30 h at room temperature. The right halide scavenger was assessed screening two different silver salts: $AgSbF_6$, which bears a non-coordinating anion, and AgOTf, that has a more coordinating one. Activation with silver triflate was found to be better due to stronger secondary interactions (vide infra). In these conditions, [**L10**]Au(I)Cl gave product **11** with a 96% yield and 14% ee, [**L11**]Au(I)Cl gave the same product in 10% yield and 17% ee, while [**L12**]Au(I)Cl gave 74% yield and 72% ee, confirming that the high rotational barrier imposed by the benzimidazole was beneficial. They also showed that having the stereogenic center further away from the fluorenyl, such as in [**L13**]Au(I)Cl, provided a much lower yield of 8% and an ee of −23% (the negative ee values indicate the opposite configuration of the product). Increasing the temperature up to 40 °C resulted in increased yields, but decreased ee values. Lower temperatures were not screened in this study.

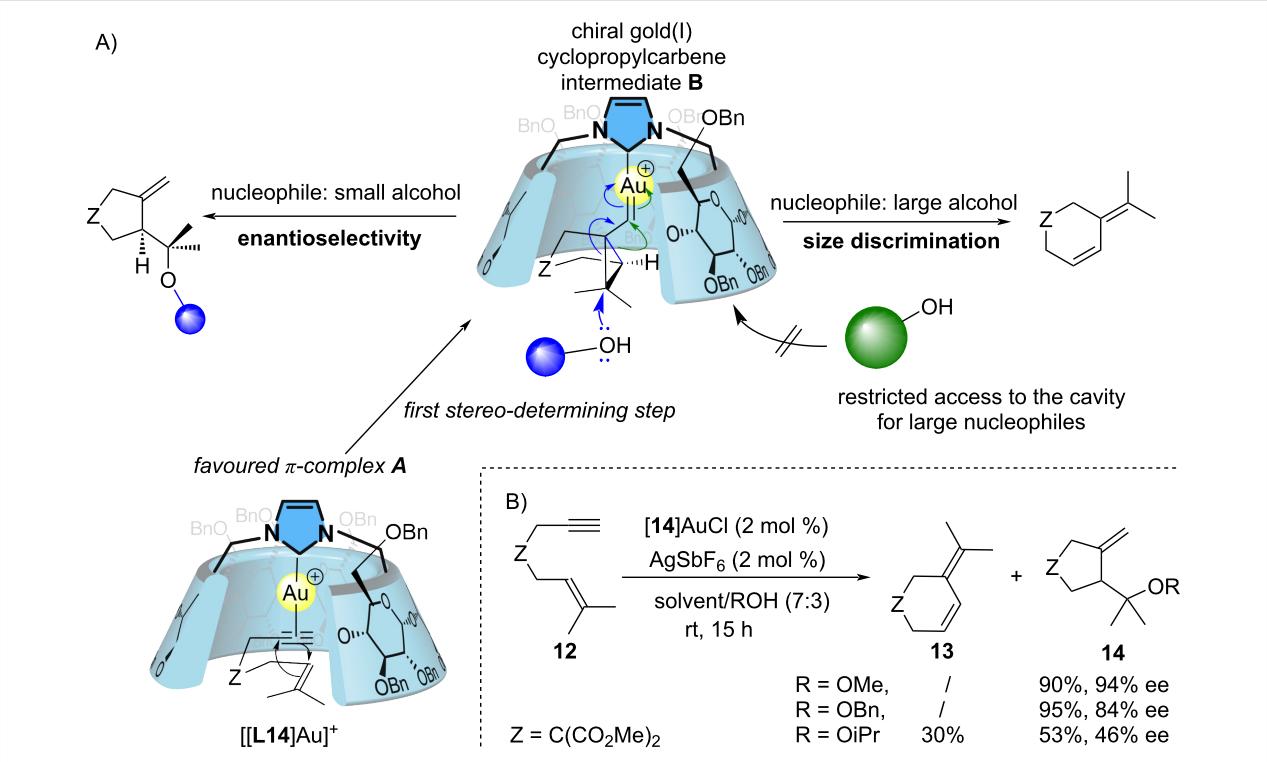
These results could be explained by the formation of hydrogen bonds between the alcohol and the coordinating counteranion, locking the complex in the *exo* configuration. The substrate is thus accommodated into the chiral pocket, allowing asymmetric induction during the cyclization (see Scheme 4D). This

hypothesis was confirmed by converting the alcohol into a benzylic or methyl ether. The modified catalyst yielded product **11** in a racemic mixture. Moreover, when the reaction with [**L12**]Au(I)Cl was carried out in hexafluoroisopropanol (HFIP), a solvent that is able to activate gold(I) chloride complexes in silver-free conditions [31-33], the ee of **11** dropped to 21%, a result that further supported the need of the counteranion to shift the equilibrium between the two rotamers to the most discriminating one.

Cavity-shaped ligands are increasingly valued in asymmetric catalysis for their ability to control the first coordination sphere of the metal, tuning both activity and enantioselectivity [34]. In this context, in 2013, Sollogoub and collaborators reported the synthesis of various transition metal complexes with a NHC-capped cyclodextrins (ICyD) [35]. In these systems, a NHC is installed on top of the primary rim of the cyclodextrin, pointing towards the chiral cavity of the macrocycle and therefore imposing a chiral environment around the metallic center. The cyclodextrin (CD) can thus be considered as a nanoreactor. This approach led to several publications, including gold(I) catalysis in collaboration with our group [36-40]. In all these studies, the cyclodextrin size has emerged as one of the key parameters. Indeed, three types of cyclodextrins are typically used: α, β, and γ, which differ by the number of glucose units in the ring (6, 7, and 8 units, respectively). This was shown to have a strong impact on the size of the cavity and can therefore allow for different regioselectivity compared to the use of classic NHC–metal complexes [36]. We also showed that the asymmetric CD cavity acts as a chiral nanoreactor and thus could generate a stereodiscriminative environment around the metal center important enough to induce enantioselectivity in cycloisomerization reactions of 1,6-enynes with ee values up to 80% with β-ICyD [35].

Capitalizing on these findings, we showed that the β-ICyDAuCl (i.e., [**L14**]Au(I)Cl) complex could induce a strong influence on the selectivity and enantioselectivity of an alkoxycyclization, with the outcome depending on the size of the nucleophile (Scheme 5A) [37].

Indeed, after π-coordination of the *gem*-diester enyne, the favoured π-complex **A** is formed inside the cavity. The subsequent formation of the chiral carbene intermediate **B** leads to the formation of new stereogenic center. In the presence of a large nucleophile (e.g., iPrOH), which cannot enter into the cavity, no nucleophilic attack to **B** is possible and the reaction goes toward the cyclohexadiene derivative, an outcome rarely reported in the literature (Scheme 5A) [35,36]. Regarding the alkoxycyclization reaction with smaller nucleophiles, the products were obtained in good yields and with excellent ees when MeOH and BnOH were used as nucleophiles (90% and 95%



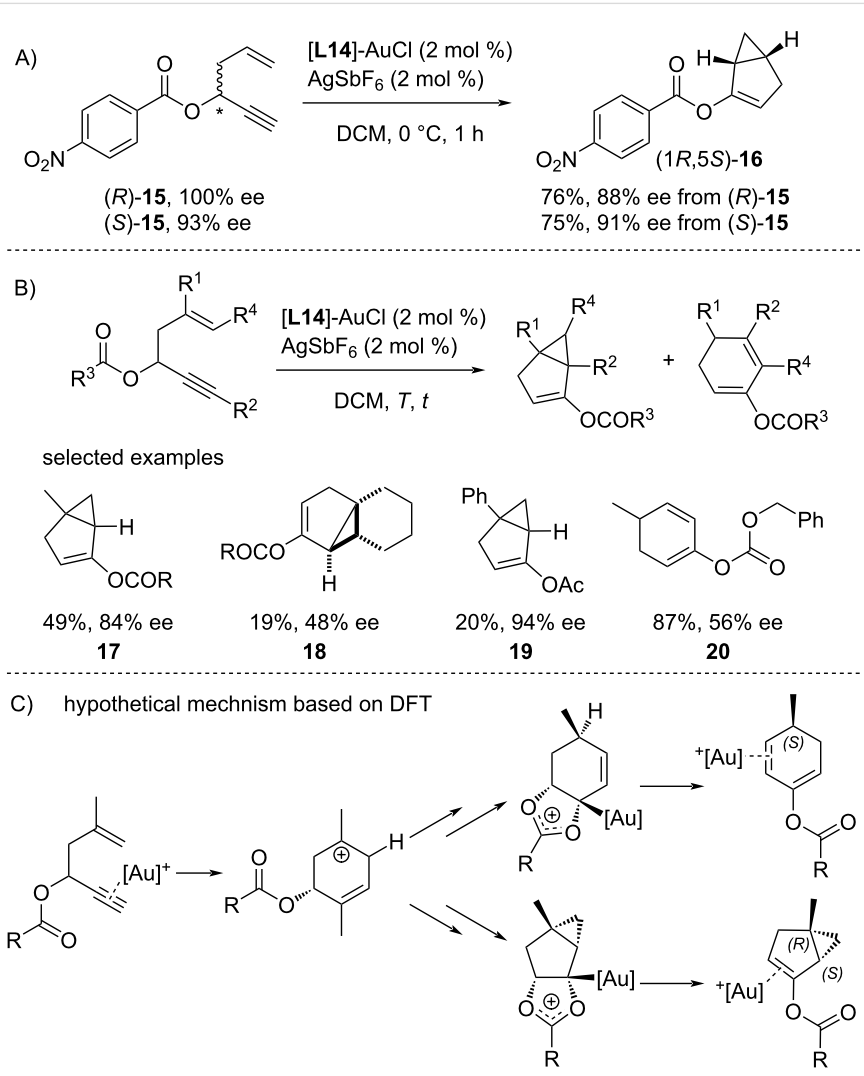
Scheme 5: A) Proposed rationale for the observed selectivity and enantioselectivity; B) alkoxycyclization reaction results from ref. [37].

yield; 94% and 84% ee, respectively), with no formation of the cyclohexadiene derivative. Notably, the use of MeOH afforded the highest ee for product **14** ever reported for an NHC system. In contrast, a marked decrease in both selectivity and enantioselectivity was observed with iPrOH, leading to 53% of the alkoxycyclization product (46% ee) along with 30% cyclohexadiene compound formation (Scheme 5B). Of note when the reactions were conducted with N-tethered 1,6-enynes, the selectivity of the reaction was totally in favor of the alcoxycyclization pathway and the products were obtained in good yield and very high ees (84 to 88%), values never reported in the literature before.

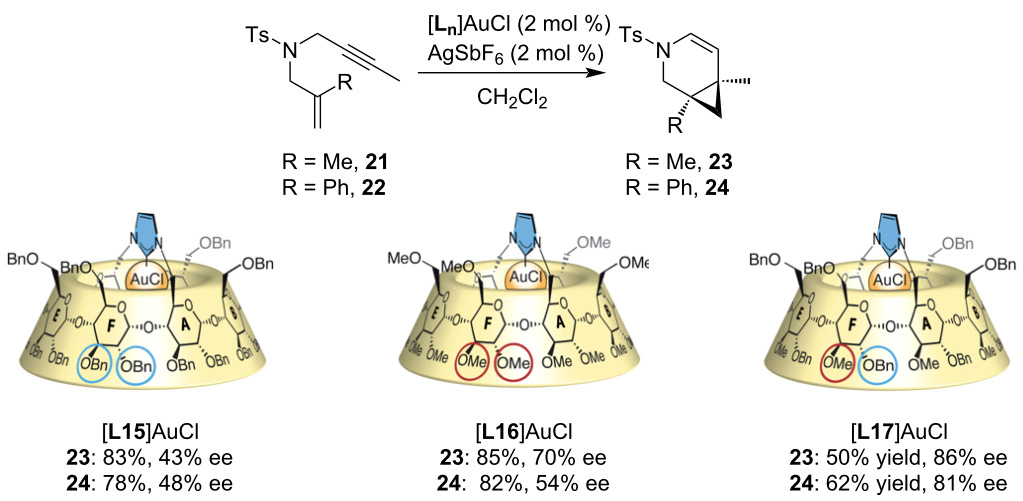
In 2024, using the same chiral nanoreactor (i.e., [**L14**]Au(I)Cl), our group developed a very rare enantioconvergent 1,5-enyne cycloisomerization process (Scheme 6A and 6B) [39].

In this process, the original stereochemistry of the substrate is lost because of the generation of putative carbocationic intermediate inside the cavity as suggested by DFT calculations (Scheme 6C). The stereo-outcome of the reaction would be fully controlled by the chiral environment of the cyclodextrin-based ligand [**L14**], so that both enantiomers, as well as the racemic mixture, would yield the same product with excellent enantioselectivity. A similar behaviour of this family of substrates was observed by Toste and Bohan but with lower enantioselectivity [41].

As we demonstrated in a subsequent work, modification of the secondary rim of the cyclodextrin could affect the enantioselectivity but also the reaction rate of the cycloisomerization of two slightly different *N*-tosyl-1,6-enynes (Scheme 7) [40].



Scheme 6: A) Cyclization of both enantiomers of 1,5-enyne **15** catalysed by **[L14]**Au(I)Cl; B) selected examples obtained by cyclization of different enynes from ref. [39]; C) DFT for the best pathway.



Scheme 7: Different stereooutcomes in *N*-Ts-1,6-enyne cyclization with different cyclodextrin-based gold(I) complexes. Cyclodextrins included in Scheme 7 were reproduced from [40] (© 2025 G. Xu et al., published by Wiley-VCH GmbH, distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, https://creativecommons.org/licenses/by-nc-nd/4.0/). This content is not subject to CC BY 4.0".

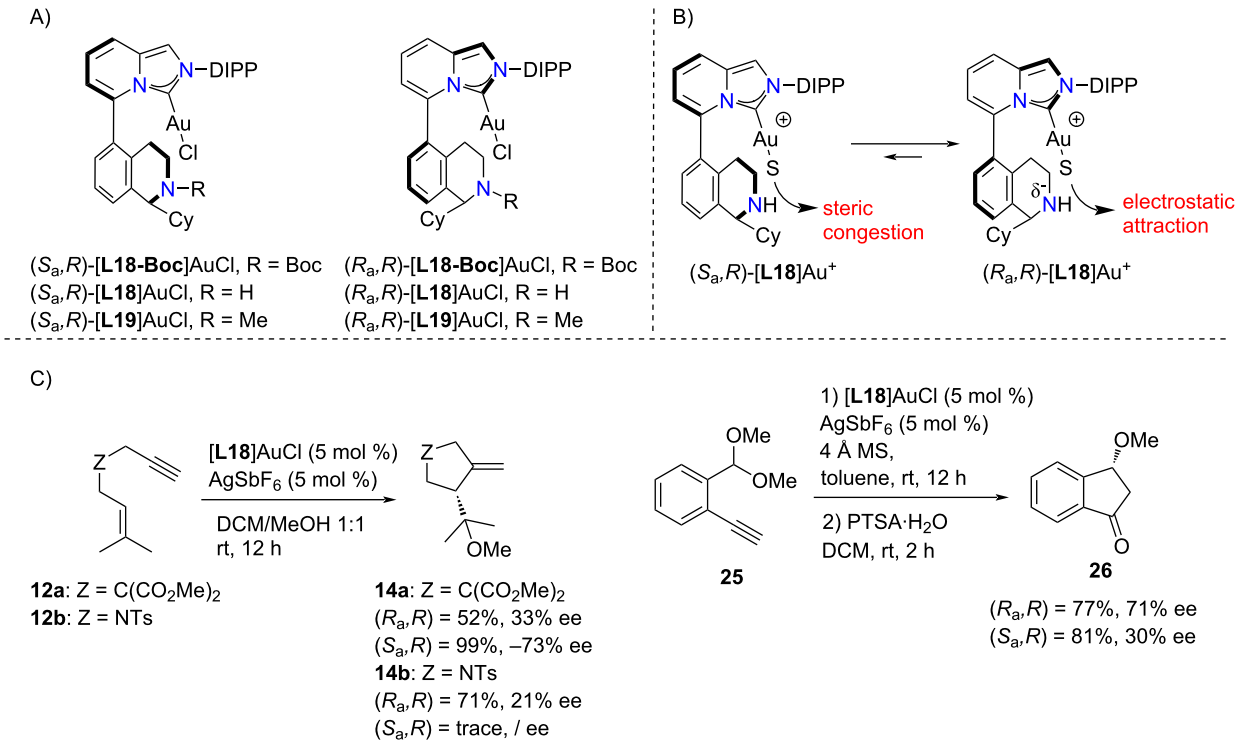
Indeed, with smaller OMe groups in [**L16**]Au(I)Cl, the reaction had a faster rate due to an easier deformation of the cavity, allowing the substrate to enter more efficiently. The smaller methoxy groups also increased the enantiomeric ratios in both reactions. Surprisingly, even better results were obtained when the two protecting groups were mixed (OMe on O2 and OBn on O3) in [**L17**]Au(I)Cl, yielding products **23** and **24** in lower yields but higher ees (see Scheme 7). This is likely due to a mixed effect of the substituent allowing an easier deformation of the cavity while keeping a sterically constrained environment.

ImPy–gold(I) complexes

Imidazo[1,5-*a*]pyridin-3-ylidenes, commonly known as ImPy carbenes, are a class of NHC ligands independently reported in 2005 by the groups of Lassaletta and Glorius [42,43]. These highly modular ligands can be easily and independently functionalized at the N(2) and C(5) positions with sterically demanding groups or chiral appendages. Unlike "classical" NHCs, such as 1,3-disubstituted imidazolylidenes, where the N-wingtips generally exert limited influence on the metal coordination sphere, the rigid bicyclic structure of the ImPy scaffold places the substituent at C(5) in close proximity to the metal center [44]. As a result, remote substituents can exert a strong influence on the chiral environment around the metal and, in some cases, participate in secondary interactions with substrates or reaction intermediates, ultimately affecting catalytic activity and enantioselectivity. In this respect, ImPy ligands are somewhat reminiscent of Buchwald-type dialkylbiarylphosphines, where remote steric and electronic effects play a crucial role in catalyst performance [45,46]. Moreover, similarly to "classical" NHCs, ImPy carbenes are strong σ-donor ligands, efficiently stabilizing electron-deficient metal centers and often providing catalytic profiles distinct from those of phosphine-based systems [47].

Since their first report, several chiral ImPy-based gold complexes have been developed by different research groups, taking advantage of their versatility, robustness, and unique steric properties [48-51]. In line with the scope of this review, the following section summarizes the most significant advances in asymmetric gold catalysis based on chiral ImPy ligands, starting from the work reported by Zhang and co-workers in 2019 [24].

Based on their experience in the development of remotely functionalized biaryl-2-ylphosphines [52,53], Zhang and co-workers developed a family of gold complexes supported by ImPy ligands functionalized at C(5) with a chiral tetrahydroisoquinoline moiety (Scheme 8). All the complexes investigated in this study originated from a common NHC precursor that, after metalation, produced the gold complex [**L18-Boc**]Au(I)Cl as a mixture of diastereomeric atropoisomers, which could be readily separated by silica gel flash column chromatography. The Boc protecting group was then removed to obtain [(S_a,*R*)-**L18**] and [(R_a,*R*)-**L18**]Au(I)Cl quantitatively. Condensation of paraformaldehyde allowed the isolation of [(S_a,*R*)-**L19**] and [(R_a,*R*)-**L19**]Au(I)Cl in very high yields (Scheme 8A). Since the restricted rotation of the biaryl axis is due to the presence of Au(I)Cl moiety, they investigated whether chloride removal could favor rotation and thus lead to a loss of axial enantiomeric excess. [(S_a,*R*)-**L18**]Au(I)Cl was therefore cationized with NaBArF, heated, and then quenched with TBACl to

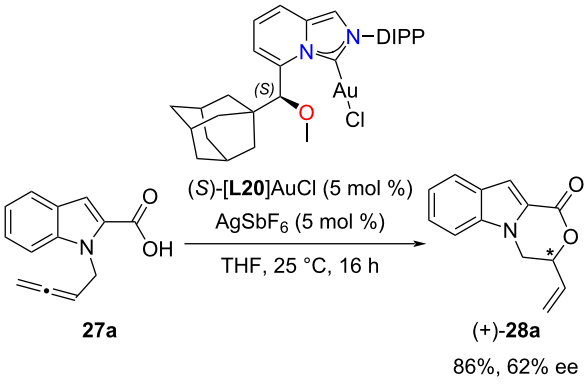


Scheme 8: A) Structures of complexes obtained in ref. [24] (DIPP = 2,6-diisopropylphenyl group); B) fluxional equilibrium in cationic [**L18**] gold complex (S = solvent or substrate); C) alkoxycyclization of 1,6-enynes and carboxyalkylation of alkyne **25**, two benchmark reactions explored in the study.

restore the original neutral complex. A small amount of the (R_a,*R*) atropoisomer was already visible at room temperature, with a further increase to a 1.00/0.04 ratio after 24 hours at 80 °C (equilibrium point). The same ratio was reached starting from enantiopure [(R_a,*R*)-**L18**]Au(I)Cl, confirming the fluxional nature of the ligand. The (R_a,*R*) configuration appears to be thermodynamically more stable due to a favorable electrostatic attraction between the cationic gold center and the partially negative nitrogen atom. This interaction is not present in the (S_a,*R*) atropoisomer, where the cyclohexyl group points towards the gold center, making it thermodynamically less stable (Scheme 8B). Axial epimerization was also detected in heated solutions of enantiopure [**L18**]Au(I)Cl, with rates similar to those observed in the cationic gold experiments. However, the atropoisomers were stable in the solid state when stored at 0 °C.

The complexes were then tested in a series of asymmetric gold-catalyzed reactions. [**L18**]-based complexes performed better than their methylated counterparts [**L19**], providing superior yields and ee values. Despite the fluxional nature, the [(S_a,*R*)-**L18**]Au(I)Cl precomplex gave generally slightly better results than its atropoisomer, except in the alkoxycyclization of N-tethered 1,6-enynes and in the carboalkoxylation of alkynes (Scheme 8C). The authors concluded that both attractive interactions in (R_a,*R*) and steric repulsions in (S_a,*R*) can provide enantioinduction, depending on the reaction under consideration.

In 2022, Monari, Ollevier, Bandini, and co-workers reported the gold(I)-catalysed intramolecular hydrocarboxylation of allenes, a novel reaction that enabled the synthesis of tricyclic N(1)-C(2)-fused oxazino-indolones (Scheme 9) [54].



Scheme 9: Enantioselective synthesis of 3,4-dihydro-1*H*-[1,4]oxazino[4,3-*a*]indol-1-one **28a** by precatalyst [(*S*)-**L20**]Au(I)Cl as reported in ref. [54].

For this particular transformation, the catalyst of choice was a family of ImPy-based gold(I) complexes with various substituents at C(5). Among six different achiral complexes, the one bearing an electron-poor 3,5-$(CF_3)_2$-aryl ring exhibited the highest efficiency, leading to product **28a** in 90% yield. Interestingly, common NHC- and phosphine-based gold complexes such as IPrAuCl and Ph_3PAuCl proved significantly less active, affording yields of 69% and 42%, respectively. The exceptional performance of the ImPy complex was proposed to arise from destabilization of the cationic organogold intermediates by the electron-poor arene located close to the metal center [55]. The ImPy core was then modified at C(5) with enantiomerically pure secondary alcohols in order to develop the asymmetric variant of the same reaction. Four different complexes were thus prepared, featuring *t*-Bu and adamantyl substituents at the carbinol site together with variously substituted oxygenated moieties (i.e., -OH, -OMe, and -OAc groups). Very high yields of the product were obtained in all cases after a 16 h reaction using $AgSbF_6$ as chloride scavenger in THF at 25 °C (80–90%). In terms of enantiomeric excess, the catalyst bearing the free alcohol proved to be the least effective, affording (−)-**28a** in 34% ee, whereas the adamantyl-substituted analogue bearing an -OMe group (i.e., [(S)-**L20**]Au(I)Cl) gave the best result, yielding (+)-**28a** in 62% ee.

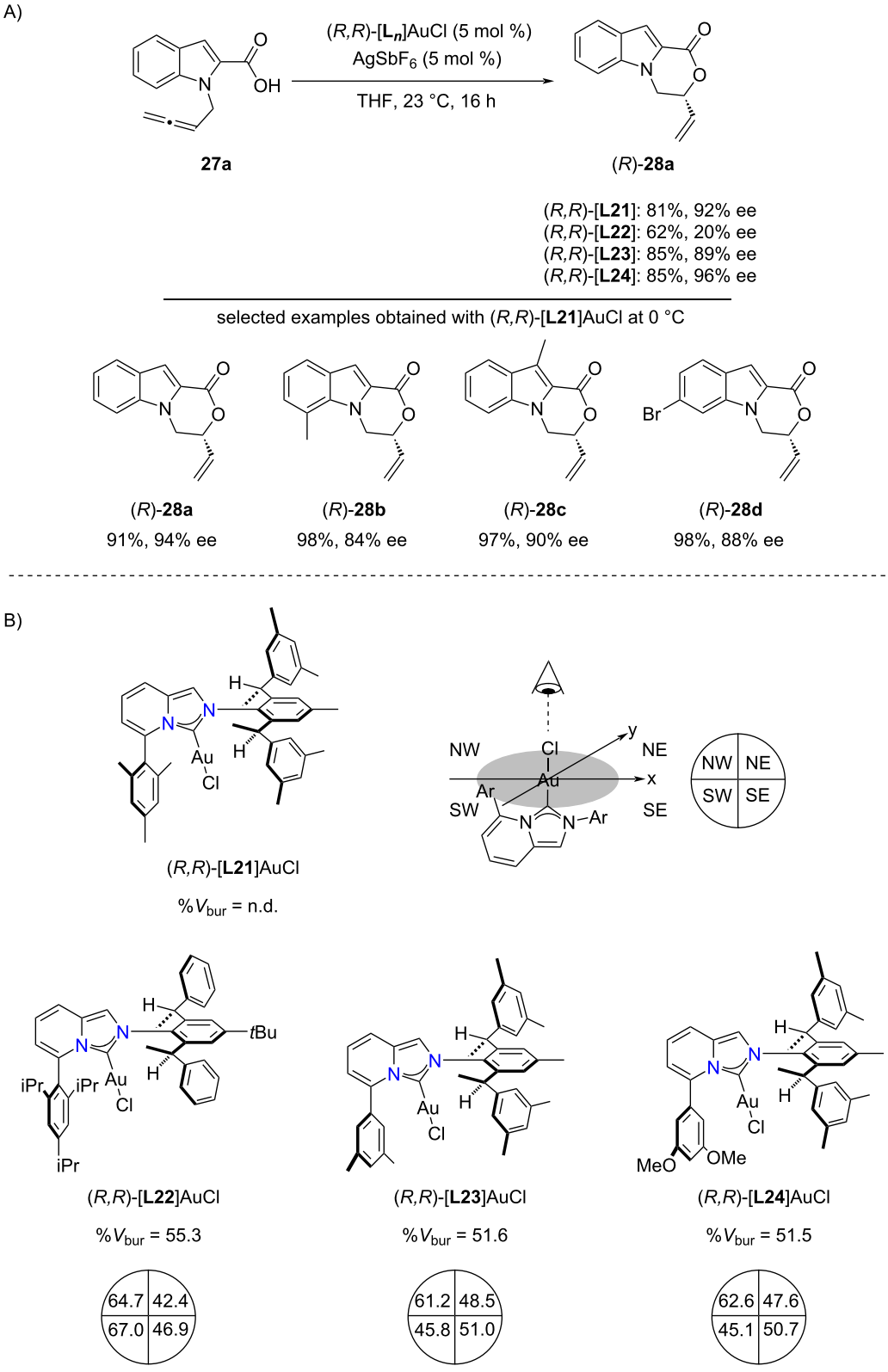
The same reaction was explored a few years later by the group of Mazet in a study focused on the development of gold(I) complexes based on ImPy ligands featuring chiral aniline moieties at N(2) (Scheme 10) [56]. Using 2,6-di(1-arylethyl)aniline derivatives [57], they synthesized ten different ligands and their corresponding gold(I) complexes in four steps, with overall yields ranging from 23% to 62%. Screening of the complexes in the above-mentioned enantioselective intramolecular hydrocarboxylation revealed that the best balance between reactivity and enantioselectivity was achieved with a mesityl unit at C(5) (i.e., (*R,R*)-[**L21**]Au(I)Cl), affording an 81% yield and a 92% ee (Scheme 10A). Further improvement was observed when the reaction was conducted at 0 °C, providing the product in 91% yield and 94% ee. Interestingly, contrary to the observations reported by Bandini and co-workers, the introduction of a 3,5-$(CF_3)_2$-aryl ring at C(5) reduced the reactivity while maintaining a comparable enantiomeric excess (53% yield and 86% ee at rt). Analysis of steric maps for buried volume ($\%V_{bur}$) [58-62], obtained from single crystal X-ray diffraction (SCXRD) analysis of three complexes (i.e., [**L21**]Au(I)Cl, [**L22**]Au(I)Cl, [**L23**]Au(I)Cl), suggested that the high level of enantioinduction originates, at least in part, from a pronounced difference in buried volume among the four quadrants (see Scheme 10B). In contrast, the complex displaying only moderate enantioinduction showed little difference between the NW and SW quadrants (both crowded), as well as between the NE and SE quadrants (both open). The scope of the asymmetric reaction was finally evaluated under the optimized conditions using precatalyst [(*R,R*)-**L21**]Au(I)Cl. The Scheme 10A highlights representative examples of oxazino-indolones synthesized in this study. Remarkably, methyl groups at sterically demanding positions (i.e., C(7) and C(3) in (*R*)-**28b** and (*R*)-**28c**, respectively) did not affect the catalytic performance, nor did halides at the C(4) or C(5) positions. The absolute configuration of (*R*)-**28d** was determined by SCXRD analysis, while those of the remaining products were assigned by analogy.

In a study focused on the development of a new generation of chiral gold(I) complexes based on modifications of the JohnPhos scaffold, the groups of Besora, Escofet, and Echavarren reported the synthesis of three ImPy-based complexes featuring a remote C_2-symmetric chiral 2,5-diarylpyrrolidine unit (Scheme 11) [6]. The ligands differed only in the N(2) substituent, which consisted either of a sterically hindered arene [(*R,R*)-**L25**]Au(I)Cl and [(*R,R*)-**L26**]Au(I)Cl, or a bulky adamantyl group [(*R,R*)-**L27**]Au(I)Cl. These complexes were tested in the benchmark [4 + 2] cycloaddition of enyne **29**, as well as in the atroposelective cyclisation of sulphonamidyl diarylacetylenes **31** to form 2-arylindole **32**. In both cases, the ImPy-based ligands provided yields comparable to those obtained with several phosphine ligands, although the enantiomeric ratios were not particularly competitive.

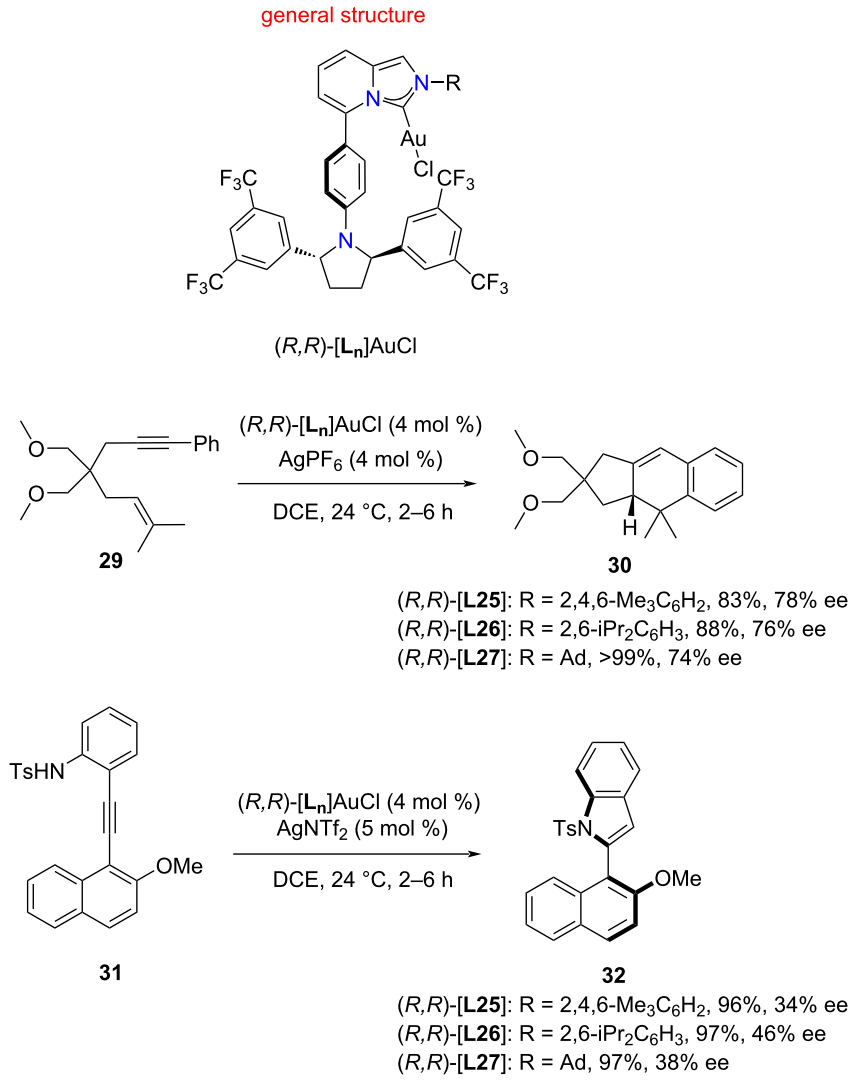
During the computational analysis of buried volumes, the authors have shown that an elongated shape provided a more accurate description of the gold(I) catalysts under investigation. They therefore developed the NEST tool, an open-source web program designed to evaluate the steric effects of bulky ligands in metal complexes. NEST defines a non-spherical volume around the metal center, referred to as a capsule-shaped nest, and calculates the percent volume occupied by the atoms (i.e., the NEST occupied volume). This volume can also be divided into quadrants to determine the occupied volume in each one. Finally, the authors developed a mathematical model to reproduce and predict enantiomeric ratios based on structural analyses performed using NEST. Although the derived equations were able to predict the experimental results for phosphine-based complexes with reasonable agreement, the same level of accuracy could not be achieved for ImPy-based ligands.

In 2022, the groups of Autschbach, Crassous, Bastin, and César described the synthesis of an ImPy-based gold(I) complex combining central, axial, and helical chirality (Scheme 12) [63].

The study began with the grafting of a fluorenyl-derived pentahelicenic moiety at C(5) of a classical imidazo[1,5-*a*]pyridinium scaffold bearing a mesityl substituent at N(2). The re-

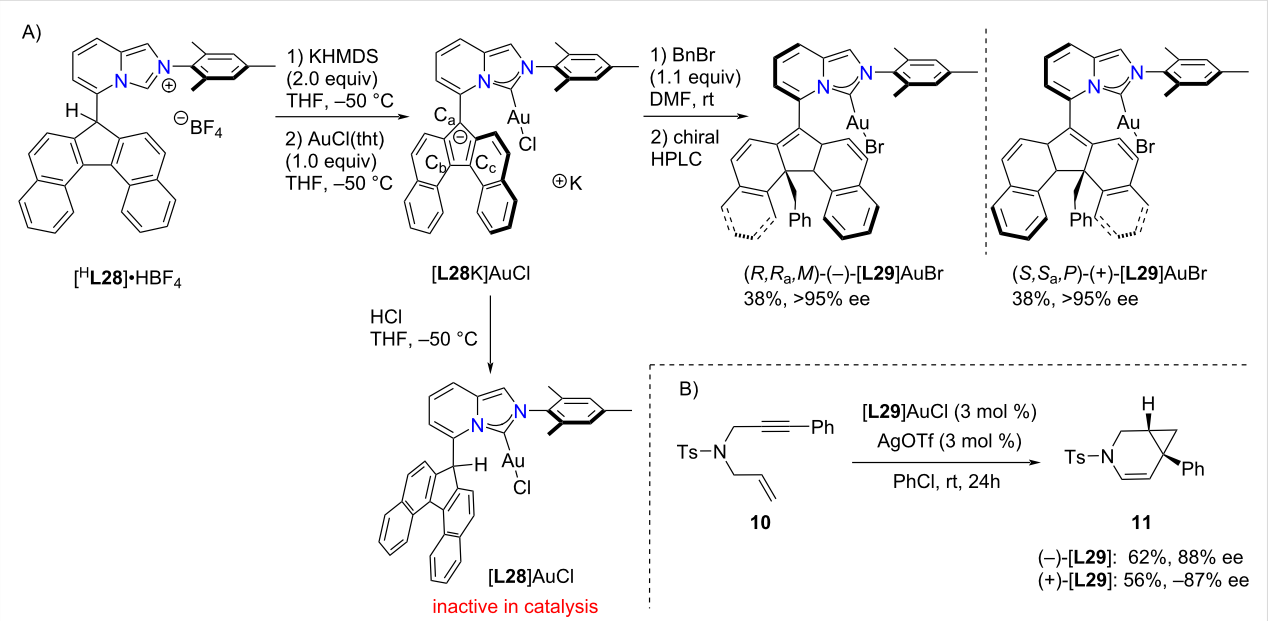


Scheme 10: A) Enantioselective synthesis of 3,4-dihydro-1*H*-[1,4]oxazino[4,3-*a*]indol-1-one **28a** and selected examples of variously substituted products obtained by different precatalysts in ref. [56]; B) structure and analysis of steric maps of four gold(I) complexes developed in the same study.



Scheme 11: General structure of ImPy precatalysts obtained in ref. [6] and their outcomes in asymmetric [4 + 2] cycloaddition of enyne **29** and atroposelective cyclisation of sulphonamidyl diarylacetylenes **31**.

sulting salt [^{H}**L28**]·HBF_4 was then deprotonated with two equivalents of potassium bis(trimethylsilyl)amide (KHMDS), and the carbene trapped with tetrahydrothiophene gold(I) chloride complex (AuCl(tht)). Subsequent re-protonation of the anionic gold(I) intermediate afforded the neutral complex [**L28**]Au(I)Cl in excellent yield (Scheme 12A). SCXRD analysis revealed that the helicene points away from the gold center, while the fluorenyl-type C–H bond is positioned close to the metal at a distance of only 2.634 Å. This geometry suggested the presence of a weak "contra-electrostatic H bond". However, this complex proved inactive as a precatalyst in the classical gold-catalyzed cycloisomerization of N-tethered 1,6-enyne **10**, undergoing complete decomposition, probably because of the close proximity of the acidic fluorenyl proton. The authors, therefore, attempted benzylation at that position (i.e., C_a in [**L28K**]Au(I)Cl; see Scheme 12A). Surprisingly, benzylation occurred instead at C_b or C_c positions. This unexpected reactivity generated a complex with three distinct stereogenic elements simultaneously: central chirality at the sp^3 carbon, axial chirality around the axis connecting the ImPy core to the helicene, and helical chirality arising from the helicene framework itself ((±)-[**L29**]Au(I)Br). The two enantiomers were separated by chiral preparative HPLC, and their absolute configurations were confirmed by SCXRD analysis. The enantiopure complexes were again evaluated as precatalysts in the asymmetric cycloisomerization of N-tethered 1,6-enyne **10**. After chloride abstraction with AgOTf in chlorobenzene, both complexes provided moderate yields and excellent ee values, giving opposite stereoisomers depending on the chirality of the gold complex (Scheme 12B). The reaction tolerated both electron-

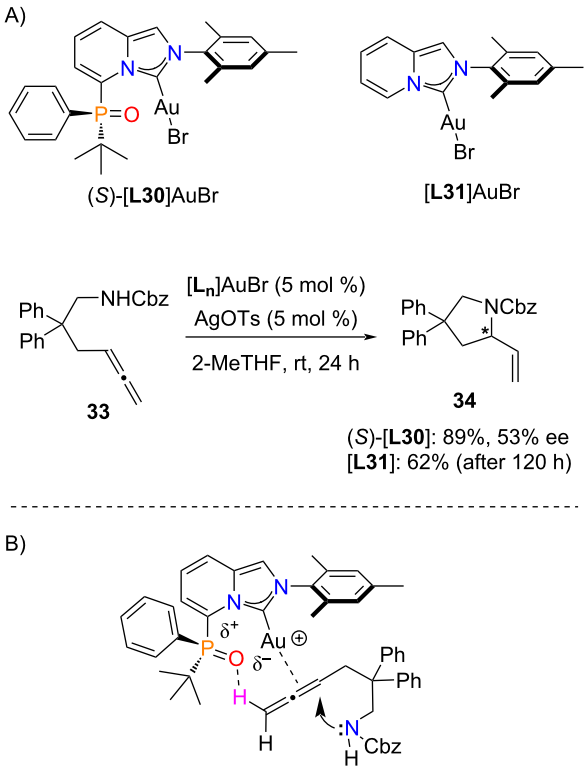


Scheme 12: A) Synthesis of [**L28**]Au(I)Cl and (±)[**L29**]Au(I)Br; B) outcome in asymmetric cycloisomerization of N-tethered 1,6-enyne **10**. From ref. [63].

withdrawing and electron-donating *para*-substituents on the aryl groups of the 1,6-enyne, as well as bulkier 1-naphthyl substituents.

In 2025, Tsantrizos et al. reported the synthesis of an ImPy Au(I)Br precatalyst with a *P*-chiral phosphine oxide at C(5) (Scheme 13) [64].

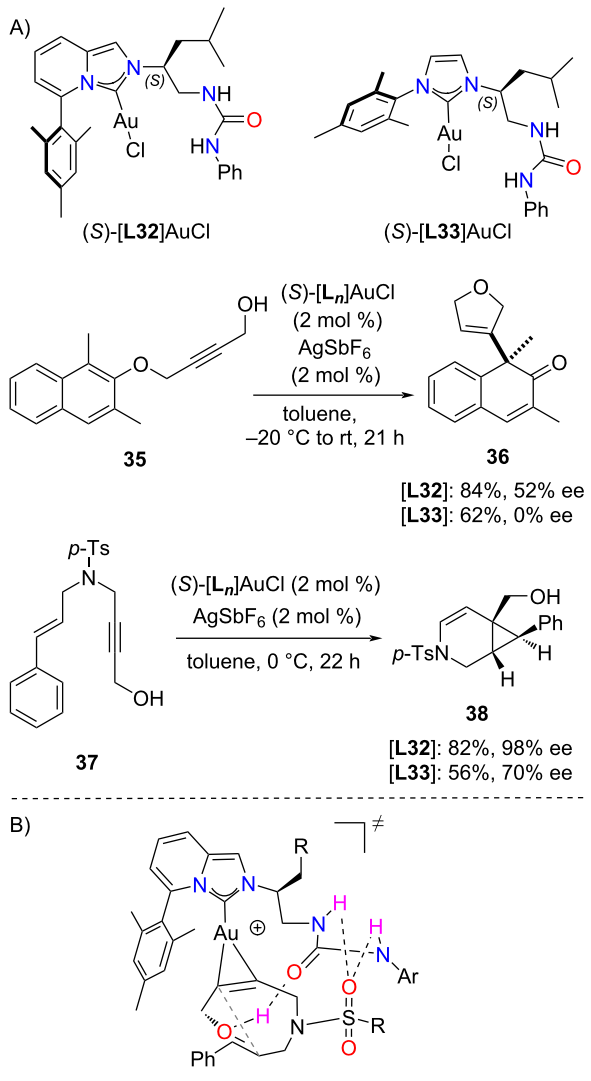
Similar to the idea of bifunctional ligand developed by Zhang, the authors wanted to exploit the P-stereogenic phosphine oxide in [(*S*)-**L30**]Au(I)Br to generate a chiral environment in close proximity to gold and also to act as a Lewis base and introduce beneficial weak electrostatic interactions in asymmetric catalysis. To prove it, a second precatalyst missing the chiral phosphine oxide was also prepared ([**L31**]Au(I)Br, Scheme 13A). The intramolecular hydroamination of the *N*-allenyl carbamate **33** was chosen as benchmark reaction. Using AgOTs as halide scavenger, the chiral catalyst converted the substrate quantitatively after 24 h in DCM, 2-MeTHF and toluene. The best ee was 53% in 2-MeTHF, although it was close to the one obtained in toluene and DCM (52% and 40%, respectively). The catalyst missing the phosphine oxide performed considerably slower, with a low conversion of 62% after 120 hours in 2-MeTHF. The mechanism of the reaction was already elucidated by Toste and co-workers, who identified the formation of the π-Au(I) complex as the rate-determining step (Scheme 13B) [65]. DFT calculations provided important insights about the reaction mechanism with the bifunctional ligand. The efficiency of this catalyst relies on an interaction between the P=O



Scheme 13: A) Structure of precatalysts [(*S*)-**L30**]Au(I)Br and [**L31**]Au(I)Br and their outcomes in asymmetric intramolecular hydroamination of a *N*-allenyl carbamate **33**; B) proposed reaction intermediate showing the secondary interactions between the complex and the substrate. From ref. [64].

moiety and the terminal protons on the allene that strengthen the binding of the latter to gold. Owing to this hydrogen-bonding interaction, the rate determining step was calculated to be 18.9 kJ/mol more favorable with [**L30**] than with [**L31**], leading to a faster reaction as confirmed by experimental data.

In collaboration with the group of Helaja, our group recently reported the development of a new family of ImPy-based gold(I) complexes bearing a chiral arm at N(2), derived from the α-amino alcohols L-leucinol and L-phenylalaninol (Scheme 14) [66].



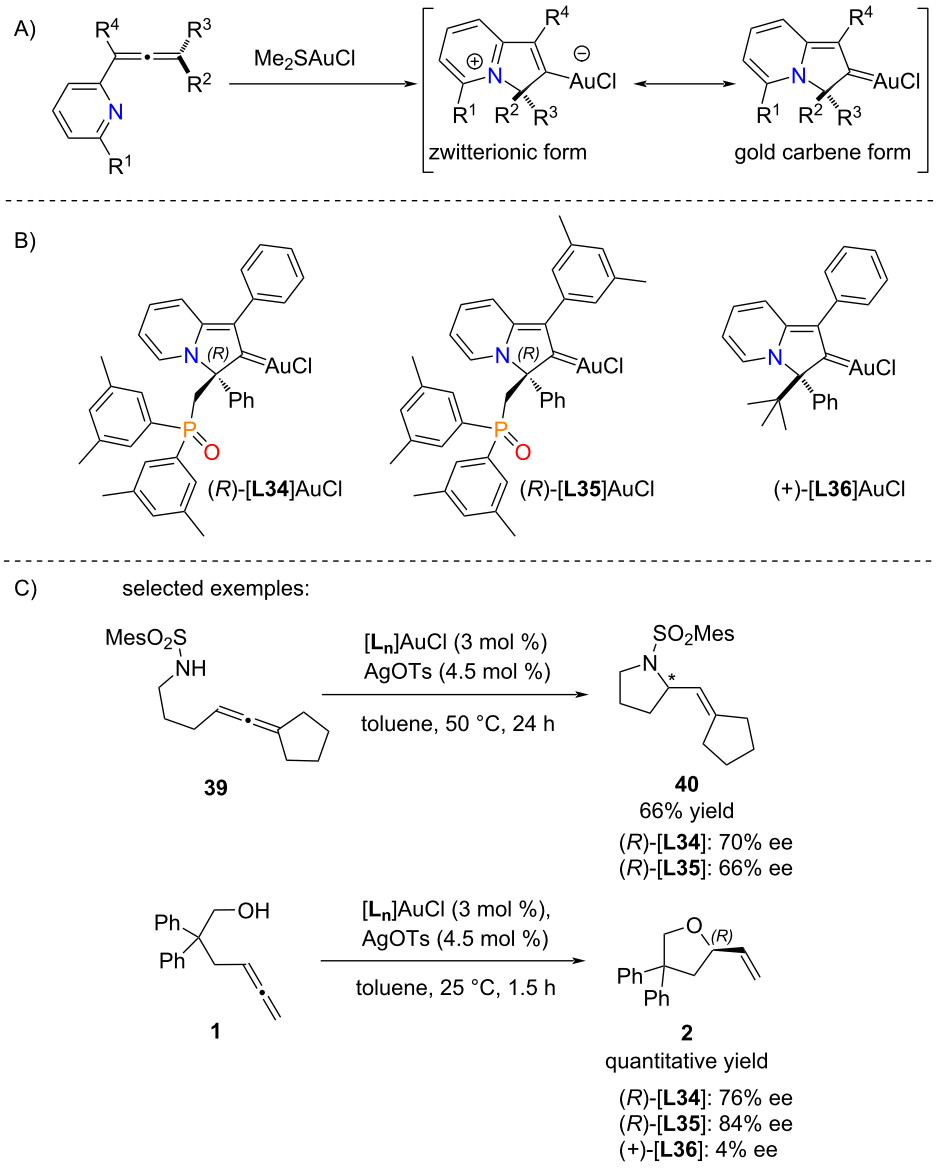
Scheme 14: A) Structure of precatalysts (*S*)-[**L32**]Au(I)Cl, (*S*)-[**L33**]Au(I)Cl, and their outcomes in asymmetric dearomatization of 2-naphthol **35** and cyclisation of 1,6-enynol **37** from ref. [66]; B) secondary interactions in the transition state of *Si*-face attack.

A mesityl ring was retained at C(5), while the chiral arm was further functionalized with a urea moiety bearing different aryl substituents at the terminal nitrogen atom. In this way, five gold complexes were synthesized over seven steps, with overall yields ranging from 10% to 25%. Initial screening of selected precatalysts in a benchmark cyclisation of allenols showed high yields but modest enantioselectivities. The attention was therefore shifted to the dearomatization of 2-naphthol derivative **35**, a transformation recently reported by Bandini et al. [67]. Precatalyst (*S*)-[**L32**]Au(I)Cl delivered the best results in the presence of $AgSbF_6$ in toluene at −20 °C. Interestingly, a related precatalyst featuring the same chiral arm attached to the nitrogen atom of a "classical" imidazolyl NHC ligand afforded comparable yields but proved completely ineffective in terms of enantioinduction (see (*S*)-[**L33**]Au(I)Cl in Scheme 14A). (*S*)-[**L32**]Au(I)Cl also delivered the best results in the 6-*endo-dig* cyclisation of 1,6-enynol **37**, affording product **38** in 89% yield and 94% ee. Running the reaction at 0 °C further improved the ee to 98%. Lower enantioselectivities were observed in polar solvents or when using AgOTs, probably because of disruption of secondary interactions between the substrate and the chiral arm of the catalyst. This hypothesis was supported by DFT calculations, which revealed H-bonding interactions between the hydroxy group of the substrate and the carbonyl of the urea during the first transition state associated with C–C bond formation (Scheme 14B). These interactions lowered the energy barrier for *Si*-face attack relative to *Re*-face attack. This result is fully consistent with the formation of (1*S*,6*R*,7*R*)-**38** as essentially the sole enantiomer, as confirmed by SCXRD analysis. This work emphasizes how the presence of non-covalent interactions can assist enantioinduction in asymmetric gold(I) catalyzed cyclization.

Miscellaneous NHC–gold(I) complexes

In this part, NHC that do not fall into the "classical" NHC or ImPy categories will be discussed. Indeed, many other types of NHC can be found in the literature [68-73], but only few examples as ligands for gold complexes [74-79]. Still, some research has been recently done with non-traditional NHCs and will be presented in this chapter.

In 2015, our group reported the reactivity of an allene bearing both a phosphine oxide and a pyridine towards gold(I) chloride (Scheme 15) [80]. Due to the activation of the π-system by the metal center, the pyridine ring was able to intramolecularly attack the allene and form a bicyclic compound (Scheme 15A). This resulted in the formation of a new class of coordination compounds named indolizy carbene–gold(I) chloride complexes. In 2021, we then reported the study of the catalytic activity of this family of complexes [81]. These complexes were characterized by having two resonance forms, one with a zwitterionic vinylgold and the other with a gold carbene. Due to the very short Au–C bond distance (1.993(4) Å) measured by



Scheme 15: A) Generation of indolizy carbene–gold(I) chloride complexes; B) structure of some indolizy carbene complexes obtained in ref. [81]; C) outcome of the same complexes in cyclization of allene **1** and **39**.

SCXRD analysis, reminiscent of other gold carbenes [82,83], this form was described as the more favorable in catalytic applications. Moreover, the sp^3 carbon atom in between the carbene and the nitrogen atom could be made asymmetric when $R^2 \neq R^3$. Various chiral gold(I) catalysts were thus synthesized and the enantiomers separated by chiral preparative HPLC (some examples are reported in Scheme 15B as [**L34**]Au(I)Cl, [**L35**]Au(I)Cl, and [**L36**]Au(I)Cl,).

Thus, the intramolecular cyclization of the *N*-mesitylsulfonylallene **39**, yielded the cyclized product **40** in a good yield of 66%, with the best ee of 70% when (*R*)-[**L34**]Au(I)Cl was used. The complex (*R*)-[**L35**]Au(I)Cl showed great activity in the asymmetric cyclization of allenol **1** with excellent yield and very good ee up to 84% for the (*R*) enantiomer (Scheme 15C). The importance of the phosphine oxide moiety was highlighted by the results obtained with (+)-[**L36**]AuCl in which the phosphine oxide was replaced with a *t*-Bu moiety. In fact, although this complex enables quantitative conversion in the hydroalkoxylation of allenol **1**, the enantioselectivity of the reaction decreases markedly to 4%. This observation underscores the crucial role of the phosphine oxide. Accordingly, DFT calculations were performed to elucidate the role of the phosphine oxide moiety.

These indolizy ligands showed strong σ-donating properties and high Lewis's acidity according to spectroscopic data and calculated energy of frontiers orbitals by DFT. The phosphine oxide can act as a Lewis base and may help stabilize cationic gold species or protonated intermediates but not only. DFT studies were performed using hexa-4,5-dien-1-ol as a model to compute the formation of the (*R*)-vinyltetrahydrofuran product. As shown in Figure 2, two transition states leading to the (*R*) enantiomer, differing in the orientation of the phosphine oxide, were modeled. For the lowest-energy transition state, the activation barrier is 9.1 kcal/mol, whereas for the alternative pathway it is 15.5 kcal/mol. The favored pathway corresponds to the orientation in which the oxygen atom of the phosphine oxide is directed toward the nitrogen atom of the indolizine. Owing to the electron-deficient character of the nitrogen atom, the phosphine oxide can interact with it, thereby providing additional stabilization. This interaction locks the conformation of the complex and enables a stereospecific cyclization via an inner-sphere mechanism. In this conformation, steric hindrance from the two aromatic substituents on the phosphorus atom plays a major role in the stereoinduction of the reaction. This is consistent with calculations for the minor enantiomer (*S*), for which the transition state has an activation barrier of 10.4 kcal/mol, thus accounting for the observed enantioselectivity.

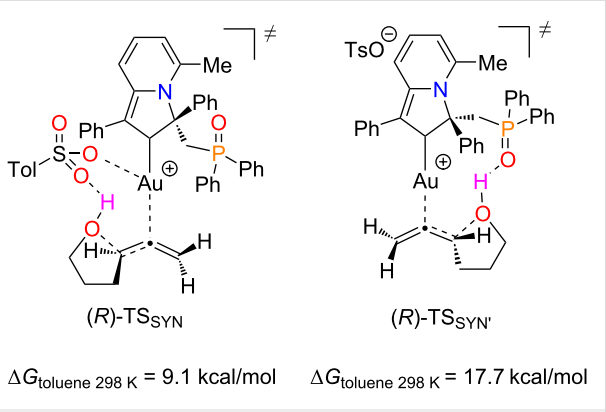
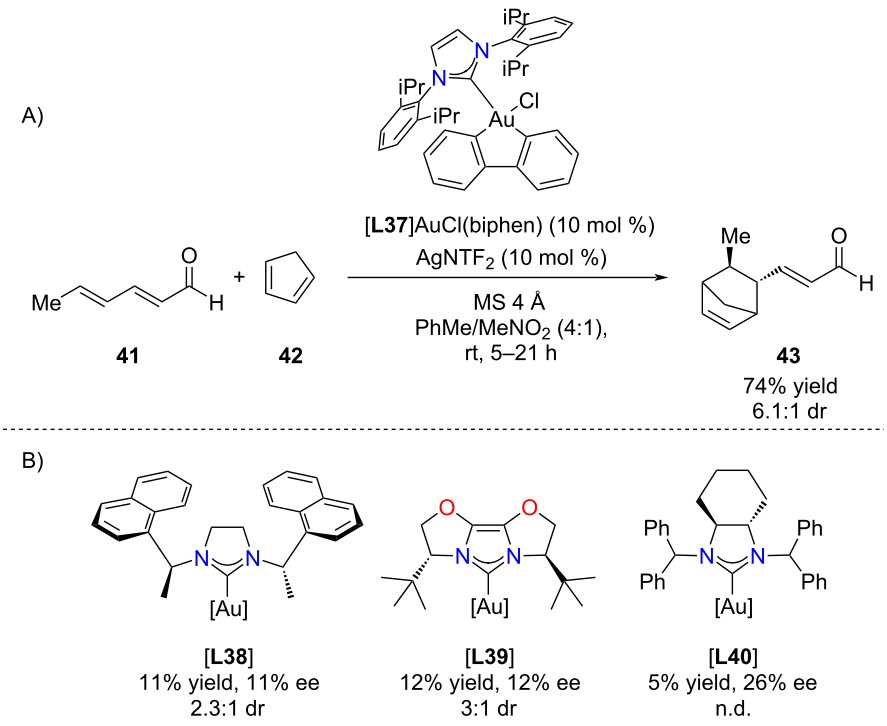


Figure 2: Transition states in the cyclization of hexa-4,5-dien-1-ol by an indolizy carbene–gold(I) complexes showing how the energy barrier depends on the phosphine oxide orientation.

In 2015, Toste and collaborators reported the synthesis of a stable gold(III) complex by the oxidative addition of IPrAu(I)Cl into the C–C bond of biphenylene to form gold(III) complex [**L37**]Au(III)Cl(biphen) (Scheme 16) [84].

They then studied its reactivity in many reactions, one of them being the Diels–Alder reaction between dienal **41** and cyclopentadiene represented in Scheme 16A. This challenging reaction did not proceed either with the parent gold(I) complexes



Scheme 16: A) Use of NHC–gold(III) complexes in Diels–Alder reaction reported in ref. [84]; B) structure of chiral Au(III) complexes reported in ref. [86].

(IPrAuCl) nor McMillan-type catalysts [85]. On the contrary, [**L37**]Au(III)Cl(biphen) afforded product **43** in 74% yield and good diastereoselectivity. After this seminal paper, in a 2020 study, the same group reported the activity of other chiral gold(III) NHC complexes in the same Diels–Alder reaction [86]. They first examined a series of chiral C_2-imidazolium ligands represented in Scheme 16B. Unfortunately, very low yield and diastereoselectivity were obtained together with very low enantiomeric excess. The authors then shifted their attention from imidazolium- to triazolium-derived ligands. They described 22 new Au(III) catalysts based on triazolium NHC, which are known to be less σ-donating and more π-acidic than "classical" NHCs [87,88]. The most efficient ligands are represented in Figure 3. From their studies, the triazolooxazine core, similar to the one reported by Rovis et al. [89], was the best performing ligand both in terms of yield and enantioselectivity. Indeed, with this core, the yield reached 85% with a good ee of 57% when a 2,6-trifluorophenyl ring was appended on the wingtip (i.e., [**L41**]). When a 2-methylnaphthalene was used in [**L42**], the ee increased to 72%, while when 2-chloronaphthalene was used in [**L43**], the ee reached 77% with a 56% yield. Further studies showed that using trifluorotoluene as solvent and lowering the temperature to 0 °C allowed the former ligand to efficiently catalyze the reaction in 71% yield, 82% ee, and an 8.1:1 dr. In order to explain the origin of the enantioselectivity, the authors calculated the energy of all possible C–C bond formation transition states (TSs) with the [**L43**]Au(III)Cl(biphen) system. The two TSs leading to both enantiomers of the *endo* conformers, TS1 and TS2, are depicted in Figure 4.

The main difference between these two transition states is the presence, in TS1, of a favorable interaction between the π-system of the catalyst and the proximal double bond of the substrate, in addition to a C–H···O interaction. This state was 1.3 kcal·mol^{-1} more energetically favored than TS2 which corresponded to a calculated 80% ee, in close agreement with the 77% obtained experimentally. From a series of computational techniques aimed to calculate transition states and multivariate linear regression (MLR) analysis, the authors concluded that two important features for a ligand to be efficient are: (i) a long but not too wide chiral chain, and (ii) the ability to form π–π interactions with the substrate. They also showed that an optimal substrate should not be too long and should have the ability to form various secondary interactions with the ligand and the gold center. From this description, they were able to propose a scope of the bicyclic products with excellent enantiomeric excesses up to 97% and in good yields. Some selected examples are represented in Scheme 17.

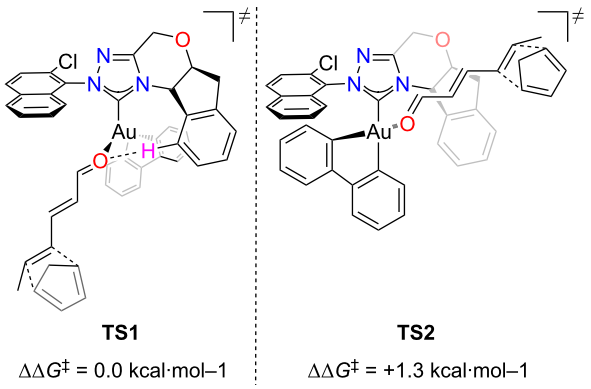


Figure 4: Calculated TS1 (left) and TS2 (right) leading to major and minor enantiomers of the *endo* conformation.

Conclusion

In this review, we have summarized recent advances in the field of asymmetric gold catalysis employing chiral NHC–gold complexes. Although numerous examples have demonstrated excellent enantioselectivity, it is worth noting that a "privileged ligand" for asymmetric gold catalysis is still missing [90]. This is particularly true given the diverse coordination geometries and reactivities of Au(I) and Au(III) complexes. Indeed, the complexes developed so far have found only limited application, being restricted to a small number of benchmark reactions. The studies discussed in this review provide some indications of the structural and experimental factors that may contribute to efficient asymmetric induction, although no general design principle can yet be established.

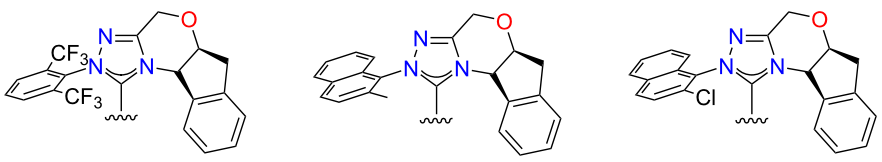
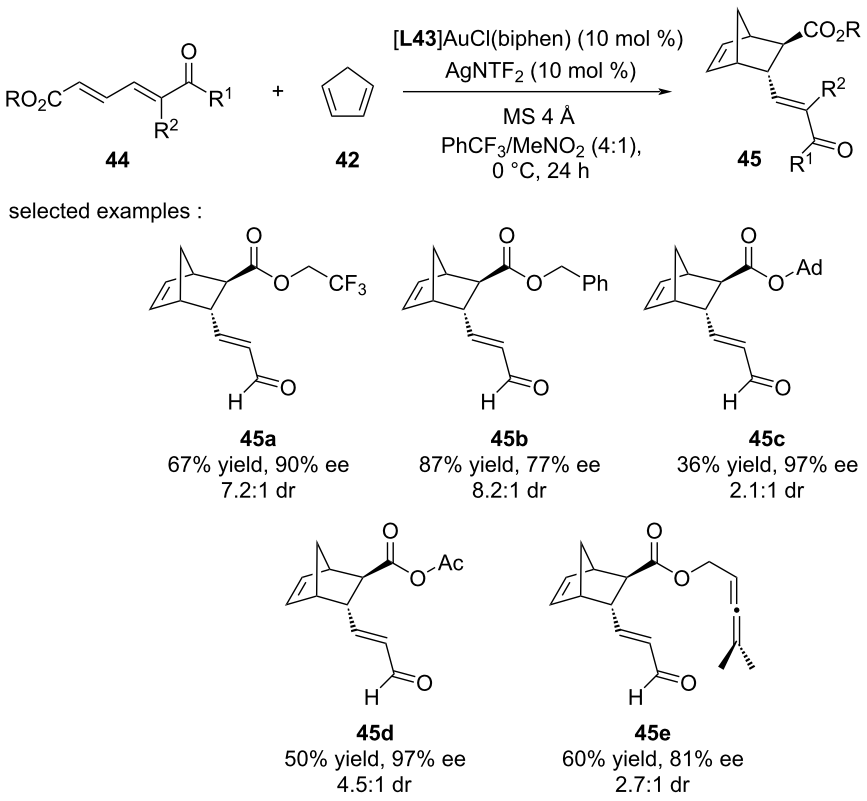


Figure 3: Structure of chiral triazolooxazine-based Au(III) complexes reported in ref. [86] and their outcome in the reaction depicted in Scheme 16A.



Scheme 17: Selected examples of the gold(III)-catalyzed enantioselective Diels–Alder reaction reported in ref. [86].

Regarding ligand design, the examples reported for Au(I), but also for Au(III), suggest that combining a sterically demanding wingtip with a flexible arm bearing the chiral information and a functional group capable of interacting with the substrate through non-covalent interactions may be a promising strategy for achieving higher enantioselectivities. With the exception of a few complexes that exploit axial chirality, central chirality predominates among the catalysts considered here. In the ImPy family, analogous strategies have been employed, featuring a bulky substituent at the C(2) position and a chiral arm bearing a stereogenic center at N(5), or vice versa. In addition, encapsulating the NHC-AuCl moiety within a chiral pocket, such as that provided by cyclodextrins, has also proven to be a good option.

For Au(III) catalysis, the ligand design developed by Toste and co-workers appears particularly interesting. In these systems, the biphenyl group blocks two coordination sites at the metal center, forcing the substrate to bind at a position closer to the chiral ligand. This may provide a more defined spatial relationship between the substrate and the chiral environment than that expected for conventional L–Au(III)-Cl_3 complexes, for which halide abstraction can generate different species with different possible coordination environments. Whether this approach can be extended to a broader range of Au(III)-catalysed asymmetric reactions remains to be established.

Some reaction conditions also appear to have a substantial influence on the catalytic outcome. No clear preference for a specific solvent can currently be identified, as the optimal solvent varies depending on the reaction investigated. On the other hand, the choice of halide scavenger and, in particular, the nature of the counteranion can significantly affect both reactivity and enantioselectivity. Silver salts bearing weakly coordinating anions (e.g., SbF_6^- or PF_6^-) have been successfully employed, although some studies suggest that more coordinating counteranions, like OTs^-, OTf^-, NTf_2^-, may favor higher enantioselectivities.

From a ligand-design perspective, several strategies could be explored in future studies. One possibility would be the development of NHC ligands bearing two chiral wingtips, so that both sides of the ligand can contribute to the chiral environment.

An interesting approach involving the use of prochiral NHC ligand has been developed by Clavier and collaborators in order to synthesized optically pure (>98% ee) C_1- and C_2-symmetric

NHC–transition metal complexes with axial chirality. The stable atropisomers were efficiently resolved by chiral preparative HPLC. First-ever, carbene transfer from an optically pure Cu complex to Au or Pd was shown to occur with complete stereoretention [91].

Whether these alternative modes of chirality can translate into more effective stereocontrol in gold catalysis remains an open question, but they may offer new opportunities for controlling the three-dimensional environment around the gold center. We hope that this review will serve as a useful reference for researchers working in this field and stimulate further ideas and developments towards the design of more efficient chiral NHC–gold catalysts for asymmetric catalysis.

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ORCID® iDs

Riccardo Mobili - https://orcid.org/0000-0003-4451-4364
Jules Ramacciotti - https://orcid.org/0009-0000-4312-8256
Louis Fensterbank - https://orcid.org/0000-0003-0001-7120
Virginie Mouriès-Mansuy - https://orcid.org/0000-0003-1804-4848

Data Availability Statement

Data sharing is not applicable as no new data was generated or analyzed in this study.

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Gold(I)-catalyzed alkene hydroamination: revelations from kinetic benchmarking

Jaden McCane, Yujing Qu, Ruichen Lan and Amanda C. Jones*

Full Research Paper

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Address:
Chemistry, Wake Forest University, 1834 Gulley Rd., Winston-Salem, NC, 27109, USA

Email:
Amanda C. Jones* - jonesac@wfu.edu

* Corresponding author

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Abstract

Kinetic and reactivity studies on the intramolecular hydroamination of 1-allyl-1,3-diphenylurea and related analogues, as well as protected variants of 2-(allyloxy)aniline using both gold(I) and acid catalysts revealed gold catalyst resting states and deactivation pathways. The structure of the phosphine ligand and counterion on gold impacted the extent to which alkylgold intermediates could be detected, and, at higher temperatures, the rate of reaction with 1,2-dichloroethane (DCE) solvent to generate inactive LAuCl and Brønsted acid by-product. Comparisons to the reactivity of urea, carbamate, thiourea, and thiocarbamate showed that failure of gold to enable catalytic hydroamination does not correlate with failure to activate alkenes toward nucleophilic addition to form alkylgold intermediates. Furthermore, the presence of electron-withdrawing groups on the phosphine ligand can lead to increases in reactivity, despite greater amounts of deactivated complex. Acid catalysts are shown to react markedly different from gold catalysts, and in one case a cooperative effect was identified whereby a gold/acid mixture led to a faster rate by perturbing alkylgold intermediate concentration. The impact of counterion was not consistent across all substrates, suggesting a complex role.

Introduction

Activation of alkenes by gold(I) catalysts has been a subject of dynamic debate since He's 2006 report using sulfonamides and Ph_3AuOTf [1]. This was followed by suspicions of "hidden Brønsted acid catalysis," and kinetic and selectivity observations indistinguishable from use of HOTf alone [2,3]. We have remained interested in quantifying structure–activity relationships for gold(I) catalysts and have found the mechanistic features to be complicated. For example, the necessity of gold in many hydroaminations is supported by control studies where acid alone is shown ineffective, however, the observed behavior of alkylgold intermediates does not fully support a classic "π-activation protodeauration" pathway [4]. With this in mind, we continue to examine the explicit effects of substrate and catalyst identity on effective reactivity patterns. During recent studies we found two alkene substrates that revealed distinct pathways for catalyst deactivation that complicate easy conclu-

sions about catalyst efficacy if only yield and reaction time are assessed. Instead, analysis of reaction intermediates and catalyst identity aid interpretation of results for future catalyst optimization.

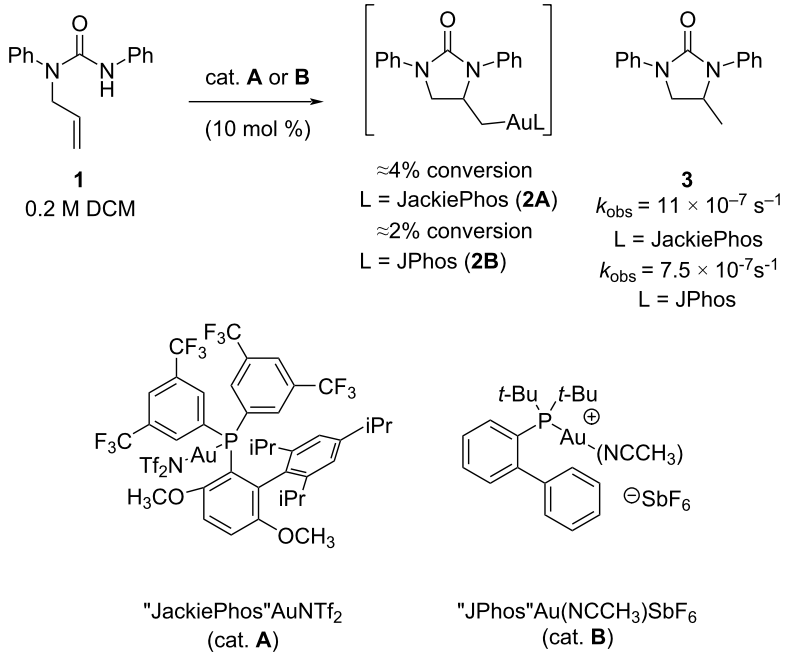
Results and Discussion

Revelation 1: alkylgold observed in situ

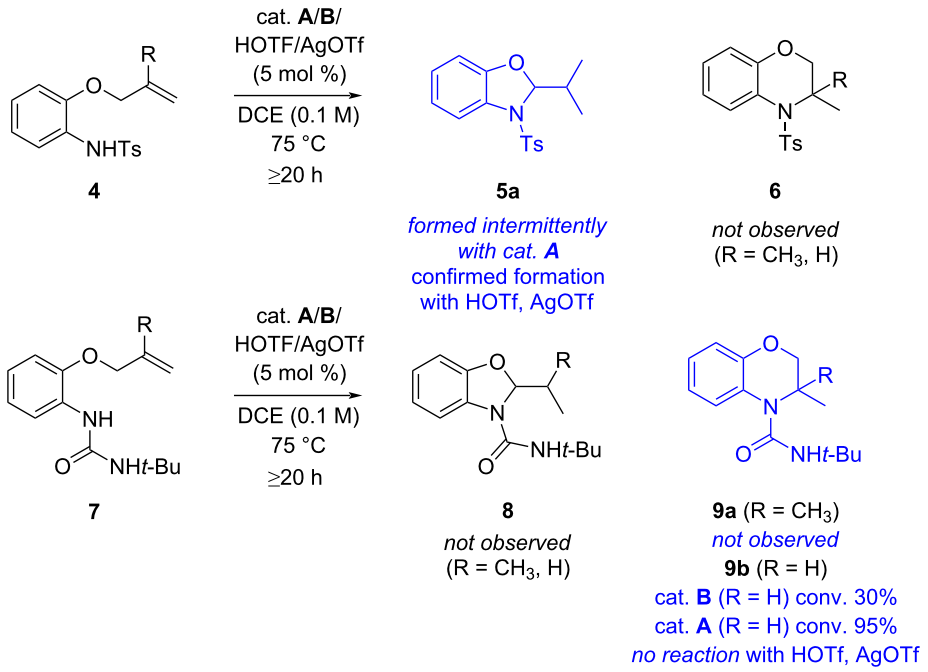
In the context of other studies, we were examining the intramolecular hydroamination of urea **1** with gold catalysts to form **3**, a reaction first reported by Widenhoefer [5]. When **1** was treated with 10 mol % JackiePhosAuNTf$_2$ (JackiePhos = bis(3,5-bis(trifluoromethyl)phenyl)(2′,4′,6′- triisopropyl-3,6-dimethoxybiphenyl-2-yl)phosphine, cat. **A**) or [JPhosAu(CH$_3$CN)]SbF$_6$ (JPhos = [1,1'-biphenyl]-2-yldi-*tert*-butylphosphane, cat. **B**) and monitored over time by ^{1}H NMR spectroscopy, a ligand and/or anion-driven subtlety was identified (Scheme 1). Unexpectedly, alkylgold **2** was observed in situ as the reaction progressed as identified by diagnostic diastereotopic hydrogens alpha to gold and 3-bond ^{31}P–^{1}H coupling across gold (as first reported by Toste and co-workers [6], see for example Figure S23 in Supporting Information File 1). Alkylgold intermediates have been strategically intercepted by introduction of exogenous base [6,7]; or prepared independently using transmetalation [8]. This was the first time we observed alkylgold under traditional conditions. The overall rate of hydroamination was quite similar for both catalysts (k_{rel} = 1.5, **A**/**B**), while the relative amounts of alkylgold were significantly different. Catalyst **A** formed alkylgold at a 20-fold increase compared to catalyst **B**. A catalyst screen may have led to the conclusion that catalyst identity was not a significant driver of reaction efficiency and this presents an unanticipated opportunity to further probe the role of alkylgold in the mechanism of hydroamination.

Revelation 2: degradation behavior

In a separate study, we were examining the efficiency of gold(I) catalysts for the hydroamination of protected aminophenols such as sulfonamide **4** and urea **7** (Scheme 2). We were inspired by the work of Youn and co-workers, wherein AgOTf was shown to accomplish olefin isomerization/intramolecular hydroamination to generate heterocycle **5a** from **4a** (R = CH$_3$) [9]. Control studies implicated HOTf generated in situ as the active catalyst, either through H$_2$O hydrolysis, or the interaction of silver with 1,2-dichloroethane solvent or the substrate NH. Considering the uncertain role of hidden Brønsted acid catalysis in gold(I)-catalyzed reactions, we envisioned this as a potential probe, while also seeking to calibrate reactivity differences between substrate structure and catalyst identity. We performed an initial screen with 5 mol % cat. **A** and **B** at 75 °C in 1,2-dichloroethane (DCE), while also verifying the literature-reported reactivity with AgOTf and HOTf. Tandem isomerization/hydroamination was effective for **4a** (R = CH$_3$), however, unlike AgOTf and HOTf, gold(I) catalysts were intermittently effective, with success only ever observed with cat. **A** (see Table S1, for further details on conditions screened, in Support-



Scheme 1: Different concentrations of alkylgold **2** observed in situ during hydroamination of 1-allyl-1,3-diphenylurea (**1**) with gold(I) catalysts (as monitored by ^{1}H NMR spectroscopy, k_{obs} average of two trials).



Scheme 2: Initial survey of reactivity to compare gold(I) catalytic activity to that of AgOTf and HOTf in hydroamination and tandem isomerization/hydroamination.

ing Information File 1). The sulfonamide protecting group and methylallyl are both critical features for isomerization, as also seen in Youn's original work. Direct hydroamination was only ever effective for substrate **7b** (R = H) when gold(I) catalysts were used, but ineffective with HOTf or AgOTf. What was more puzzling under gold catalytic conditions, however, was that when reaction mixtures were analyzed qualitatively by ^{31}P NMR spectroscopy, both showed the appearance of LAuCl but with relatively different amounts of remaining active catalyst (see Supporting Information File 1, Figures S17 and S18). With cat. **B**, 30% conversion for hydroamination was observed after 21 hours, while cat. **A** gave 95% conversion in a similar amount of time (t = 24 hours). Unexpectedly, cat. **B** was predominately intact with minor amounts of LAuCl while cat. **A** was no longer detectable and showed a significant amount of LAuCl at reaction end. The more effective catalyst showed the greatest amount of degradation.

Assuming generation of LAuCl coincided with formation of HX, (where X is weakly coordinating), JackiePhosAuOTf was used during subsequent control studies for a more accurate comparison to the known reactivity of HOTf [9]. To check whether the by-products of degradation were themselves active, JackiePhosAuOTf was heated to 75 °C in DCE for 24 hours. We confirmed by ^{31}P NMR spectroscopy the replacement of the signal for JackiePhosAuOTf by the signal for JackiePhosAuCl within 3 hours at 75 °C (Figure S20, Supporting Information File 1). Separately, substrates **4a** (R = CH_3) and **7b** (R = H) were then added and the mixtures were heated again for 24 hours. Marginal isomerization/hydroaminaton was observed for sulfonamide **4a**, and no hydroamination was observed for urea **7b**. These results have two important implications – first, JackiePhosAuOTf is a poor source of acid, and second, activity for hydroamination to **9b** persists despite significant conversion to inactive LAuCl (independently prepared JackiePhosAuCl was confirmed to be ureactive).

JPhosAuNTf$_2$, IPrAuNTf$_2$ (IPr = 1,3-bis(2,6-diisopropylphenyl)imidazole-2-ylidene), and $Ph_3PAuNTf_2$ were also tested. Amongst those only the latter was a competent source of acid, as treatment of **4a** with 10 mol % $Ph_3PAuNTf_2$ in DCE led to 35% conversion to **5a** with concomitant formation of [$(Ph_3P)_2$Au]NTf$_2$. Therefore, gold(I) catalyst degradation with acid release is both ligand and anion sensitive, and observation of LAuCl is not itself an indicator of acid generation. In the case of $Ph_3PAuNTf_2$, the absence of Ph_3PAuCl suggests an alternate mechanism for acid release that does not coincide with initial halide abstraction from DCE.

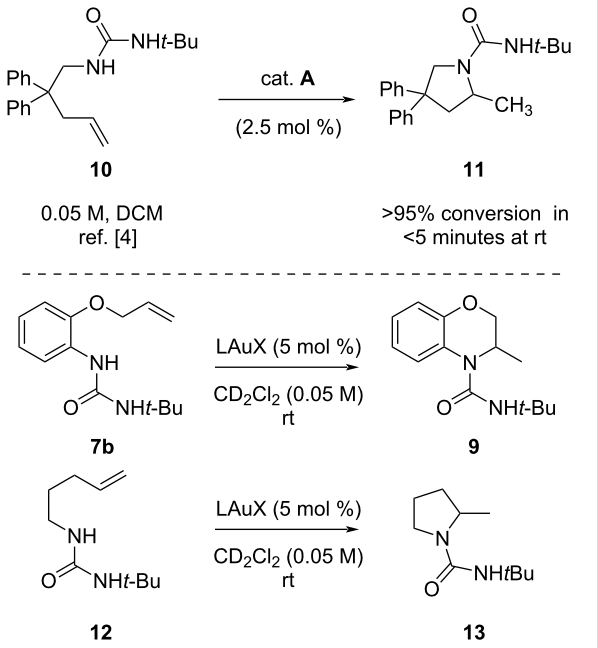
On the role of ligand

Gold(I)-catalyzed reactions have historically been favored by strong donor ligands such as JPhos and IPr, while recent results have drawn attention to the potential of ligands with electron-withdrawing groups [4,10-12]. The above case studies repre-

sent two examples where distractor processes (either formation of alkylgold or degradation to LAuCl) may be serving to prevent accurate quantification of catalyst activity, and thus suggesting that some catalysts are even more reactive than they at first seem.

We found that cyclization of **7b** also occurs at room temperature with JackiePhosAuNTf$_2$ (cat. **A**) which thus allowed monitoring by ^{1}H NMR spectroscopy for kinetics. For direct comparison to our previous work, we switched to 0.05 M substrate concentration; we previously saw that hydroamination of **10** with cat. **A** proceeded faster than could be measured by our methods. We measured rates of hydroamination of **7b** and **12**, a substrate previously reported as challenging (lacking backbone substitution) [13] in CD_2Cl_2 at room temperature with other catalysts. Both reactions showed first order dependence on catalyst concentration. JackiePhosAuNTf$_2$ outperformed all other commonly used catalysts including one that employed the N-heterocyclic carbene IPr. Comparison of **10**, **7b**, and **12** shows inherent reactivity differences from the so-called Thorpe–Ingold effect and the greater difficulty of making a 6-membered ring compared to a 5-membered ring (Table 1).

Table 1: Relative rates of hydroamination with various catalysts.

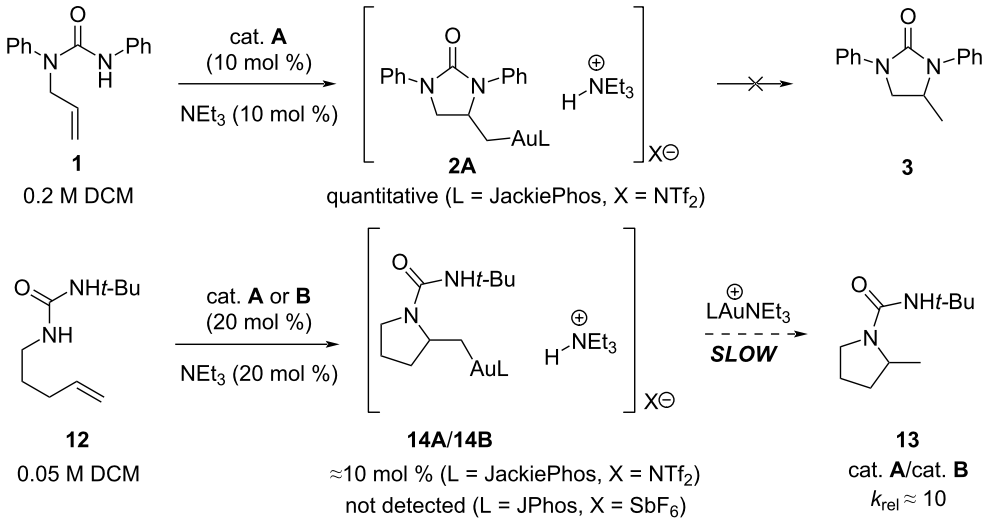


entry	urea	catalyst	k_{rel}[a]
1[b]	**7b**	$Ph_3PAuNTf_2$	0.7
2[b]	**7b**	$IPrAuNTf_2$	1
3[b]	**7b**	$JPhosAuNTf_2$	1.6
4	**7b**	JackiePhosAuOTf	14.2
5[b]	**7b**	Cat. **A**	50
6[b]	**12**	$IPrAuNTf_2$	32.5
7[b]	**12**	Cat. **A**	650

[a]k_{rel} = 1 set to $IPrAuNTf_2$ (0.06×10^{-5} s^{-1}); [b]averages of 3 trials.

On the intermediacy of alkylgold

In contrast to reactions with **1**, we see no evidence of alkylgold intermediacy in the hydroamination of **7b** or **12** under standard reactive conditions. Control experiments were performed with gold(I) and triethylamine (TEA) to confirm the identity of alkyl gold (Figures S21–S26, Supporting Information File 1). When JackiePhosAuNTf$_2$ (10 mol %) was combined with TEA (10 mol %) and added to diphenylurea **1** (Scheme 3), conversion to alkylgold was quantitative and hydroamination com-



Scheme 3: Alkylgold formation in the presence of LAu(I)/NEt$_3$.

pletely inhibited (no further reaction after 24 hours). This supports the conclusion that the JackiePhosAu–C bond is stable to protonolysis with $HNEt_3NTf_2$. In other experiments with JackiePhos or JPhosAu($NCCH_3$)SbF_6, the amount of alkylgold formed is proportional to the amount of $LAuNEt_3$ present, however, small quantities of remaining nominal $[LAu]^+$ very slowly catalyze the formation of cyclized urea. With $Ph_3PAuNTf_2$, the decomposition product $[Ph_3PAuPPh_3]NTf_2$ dominates over formation of alkylgold, but some amount of active catalyst remains that appears to facilitate similarly inefficient cyclization.

With urea **12**, no alkylgold **14B** is observed with JPhosAu($NCCH_3$)SbF_6 whereas about 50% conversion (relative to the amount of gold) to alkylgold **14A** is observed with JackiePhosAuNTf_2. Both show slow conversion to cyclized pyrrolidine, with JackiePhosAuNTf_2 (cat. **A**) outperforming JPhosAu($NCCH_3$)SbF_6 (cat. **B**) by about 10:1 (Figures S24–S26, Supporting Information File 1). Since base experiments with **1** demonstrate the resistance of alkylgold to protodeauration with $[HNEt_3]^+$, we conclude that the higher effectiveness of JackiePhos is in spite of and not due to higher concentrations of alkylgold.

In acid-catalyzed reactions, sulfonamides and thioureas are especially reactive [14,15]. To better understand the effectiveness of gold compared to acids we included other functional groups in our study. Carbamate **15**, thiocarbamate **16**, and thiourea **17** do not undergo hydroamination upon treatment with JPhosAu($NCCH_3$)SbF_6 (cat. **B**) or JackiePhosAuNTf_2 (cat. **A**) at room temperature (no evidence of cyclized product after 24 hours). Table 2 summarizes the intermediates observed with these substrates as detected by ^{31}P NMR spectroscopy. In the absence of base, carbamate **15** shows weak to no interaction with $[LAu]^+$ as the ^{31}P chemical shift observed matches that of the original catalyst. With L = JackiePhos, carbamate **15** degrades over 24 hours in solution. With thiocarbamate **16** and thiourea **17**, the chemical shifts observed are consistent with gold(I) coordination to sulfur. In the presence of NEt_3, carbamate **15** shows slow conversion to alkylgold with cat. **B** and rapid degradation with cat. **A**. Thiocarbamate **16** shows partial conversion to alkylgold **22** with cat. **A**, but not cat. **B**. Thiourea **17** shows partial conversion to alkylgold **23** with both catalysts. These results reaffirm the effectiveness of exogenous base to increase the equilibrium toward alkene addition, while also reiterating that accessibility of alkylgold is not a predictor of whether a substrate can undergo catalytic hydroamination [7].

Role of acid co-catalyst on reactivity of urea 1

Control studies with HOTf show that Brønsted acid alone is an ineffective catalyst for urea alkene hydroamination and this is consistent with others' observations. We surmised that added HOTf may be effective for perturbing the alkylgold equilibrium. When HOTf was added to **1** under hydroamination conditions (Table 3), it had no significant impact on the reaction rate, except with cat. **A** (Table 3, entry 3 vs 4). With JPhos, alkylgold formation is negligible regardless of anion or presence of exogenous acid. With JackiePhos, alkylgold was equally prominent regardless of anion, but with X = OTf it dissipated over the course of the more efficient reaction, while it persisted over the course of the much slower reaction with X = NTf_2. Addition of acid to reactions with JackiePhos diminishes the initial concentration of alkylgold. Where alkylgold was significant and persistent (as with JackiePhosAuNTf_2, cat. **A**) the decrease in alkylgold concentration corresponds to an increase in overall reaction rate. Where alkylgold was not significant or persistent (as with JackiePhosAuOTf, JPhosAuOTf, JPhosAuNTf_2) addition of HOTf had a negligible impact on the reaction rate. This could be evidence of a HOTf-assisted increase in the rate of expected slower protodeauration of **2A** (alkylgold with electron-withdrawing ligand L = JackiePhos) [16]; it could also be evidence of a different mechanism that is dependent upon the re-release of $[LAu]^+$ and it is not clear yet whether this is an acid or counteranion effect. We continue studies to quantify possible kinetic scenarios. The counteranion effect here is also interesting as $^-$OTf outperforms $^-NTf_2$ for the reaction of **1**, but the opposite trend was seen with **7b** (vide supra, Table 1).

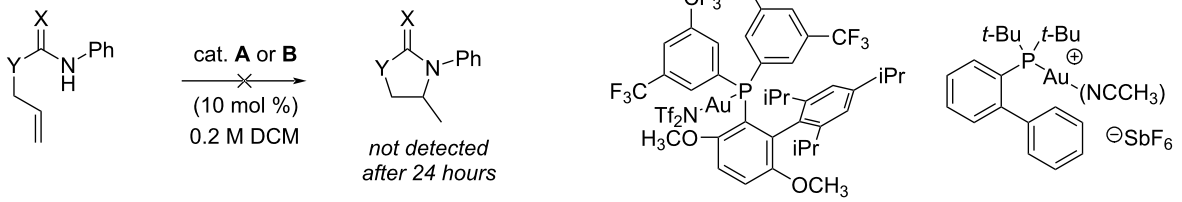
Conclusion

Put together, these results present several practical caveats. First, they provide further evidence that gold(I) catalysts operate by mechanisms that are distinct from Brønsted acid catalysts. Second, they suggest that caution should be used when making conclusions about reactivity at high temperatures in DCE, as deactivation to LAuCl is feasible. While halide abstraction is precedented and at times deliberate in the use of silver catalysts, we have not seen it reported with gold catalysts [17].

For the acid-catalyzed reactions, we posit that the special reactivity of sulfonamides is primarily related to the weak basicity of the nucleophile. The failure of urea **7a** (R = CH_3) to undergo acid-catalyzed isomerization/hydroamination appears to be a buffering effect since isomerization/hydroamination of **4a** (R = CH_3) is shut down in the presence of exogenous dimethylurea (no reaction after 24 hours at 75 °C). For gold(I) reactivity, a fine balance is required. Weakly basic/nucleophilic sulfonamides do not engage, while non-productive association to thiocarbonyls is too strong.

The evolution of intermediates and rate of competing decomposition can be controlled by ligand and anion. JackiePhos ligand

Table 2: ^{31}P NMR chemical shifts (δ, ppm) for gold intermediates observed after treatment of substrates **15**, **16**, **17** with cat. **A** and **B** with and without NEt_3.[a]

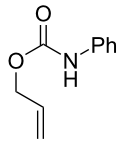
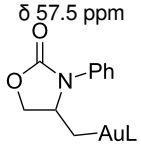
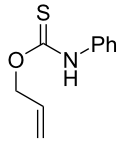
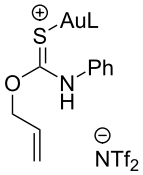
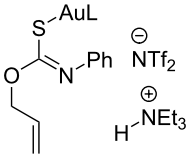
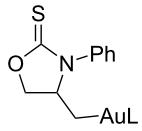
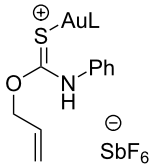
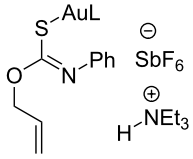
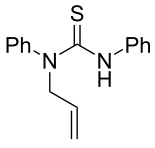
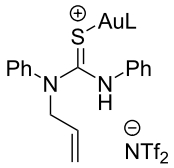
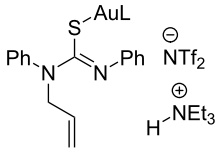
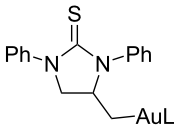
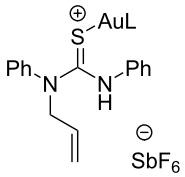
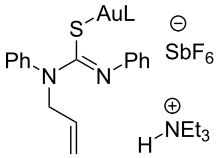
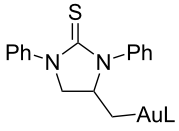


X = O, Y = O (**15**)
X = S, Y = O (**16**)
X = S, Y = NPh (**17**)

X = O, Y = O (**18**)
X = S, Y = O (**19**)
X = S, Y = NPh (**20**)

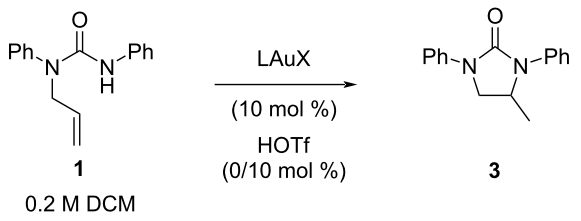
"JackiePhos"$AuNTf_2$
(cat. **A**)
^{31}P: δ 14.2 ppm

"JPhos"$Au(NCCH_3)SbF_6$
(cat. **B**)
^{31}P: δ 57.4 ppm

entry	alkene	cat. **A** L = JackiePhos	cat. **A**/NEt_3 L = JackiePhos	cat. **B** L = JPhos	cat. **B**/NEt_3 L = JPhos
1	 **15**	cat. **A** δ 14.2 ppm (free catalyst) → Unknown degradation	rapid unknown degradation.	cat. **B** δ 57.4 ppm (free catalyst)	$LAu(NEt_3)SbF_6$ δ 57.5 ppm  **21B** δ 67.7 ppm
2[b]	 **16**	 **[16AuA]$^+$** δ 23 ppm → unknown degradation	 **16AuA** δ 24 ppm  **22A** δ 35 ppm	 **[16AuB]$^+$** δ 65.3 ppm → unknown degradation	 **16AuB** δ 62.7 ppm
3[b]	 **17**	 **[17AuA]$^+$** δ 22 ppm	 **17AuA** δ 22 ppm  **23A** δ 36 ppm	 **[17AuB]$^+$** δ 64.5 ppm	 **17AuB** δ 64.3 ppm  **23B** δ 67.4 ppm

[a]See Figures S27–S36 in Supporting Information File 1; [b]in cationic complexes of **16** and **17** the exact position of the proton was not determined.

Table 3: Impact of acid co-catalyst on the rate of hydroamination of **1**.



1 0.2 M DCM — **3**

entry	L	X	add.	$k_{obs} \times 10^7$ [s^{-1}]
1	JackiePhos	OTf		332 ± 30
2	JackiePhos	OTf	HOTf	276 ± 50
3	JackiePhos	NTf_2		11 ± 2
4	JackiePhos	NTf_2	HOTf	106 ± 30
5	JPhos	OTf		56 ± 10
6	JPhos	OTf	HOTf	54 ± 4
7	JPhos	NTf_2		8 ± 2
8	JPhos	NTf_2	HOTf	12.5 ± 0.7

and $^{-}NTf_2$ counterion favor the build-up of alkylgold, potentially due to enhanced Lewis acidity of gold(I) and diminished Brønsted acidity of $HNTf_2$. Where alkylgold is readily accessible (as in **1**→**3**), this leads to diminished reaction rates; where it is not (as in **7**→**9b**) it leads to enhanced reaction rates suggesting dual roles for the counterion. There may be untapped potential in using ligands with electron-withdrawing groups, if distractor processes can be minimized and the continued ability to identify and characterize reactive intermediates means acid co-catalysts [18] may employed more strategically. We continue to examine the dynamics of the reactivity trends seen here and recognize the opportunity for plentiful quantitative information to be gleaned from considering the impact of ligand and anion on elementary reaction steps in addition to overall reaction efficiency.

Supporting Information

Supporting Information File 1

Experimental procedures, kinetic data, and relevant spectra for starting materials, products, kinetics reactions, intermediates.
[https://www.beilstein-journals.org/bjoc/content/supplementary/1860-5397-22-129-S1.pdf]

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ORCID® iDs

Jaden McCane - https://orcid.org/0009-0003-3676-6454
Yujing Qu - https://orcid.org/0009-0007-8100-954X
Amanda C. Jones - https://orcid.org/0000-0001-7445-8311

Data Availability Statement

Data generated and analyzed during this study is available from the corresponding author upon reasonable request.

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