Gold Vinylidenes as Useful Intermediates in Synthetic Organic Chemistry

Fabien Gagosz*

Department of Chemistry and Biomolecular Sciences, University of Ottawa, K1N 6N5, Ottawa, Canada
fgagosz@uottawa.ca
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Abstract Gold vinylidenes have recently emerged as useful intermediates in synthetic organic chemistry. These species, which can principally be accessed by a 1,2-migration process from a gold-activated alkyne or by dual gold catalysis on a diyne substrate, can react with nucleophilic partners or by C–H insertion to produce a variety of functionalized (poly)cyclic compounds. This short review covers the synthetic approaches developed so far to access gold vinylidenes and the different reactivities these species can exhibit.

1 Introduction

Since its emergence more than 15 years ago, homogeneous gold catalysis has developed into a very active area of research. The straightforward access to various gold complexes, their ease of use and general high stability, allied to the variety of selective and unusual transformations they can allow, have enabled homogenous gold catalysis to become a synthetic tool of choice for the generation of molecular diversity and structural complexity. Since gold catalysts are electrophilic in nature and particularly prone to activate carbon–carbon systems, a large number of the synthetic transformations reported to date involve cationic intermediates, whose reactivity can be modulated, to some extent, by the presence of the gold moiety. Gold carbenes of type 1, for instance, have been intensively studied (Scheme 1). They can be accessed from a variety of substrates, under different reaction conditions and following a range of mechanistic pathways. In sharp contrast, and while their first appearance in the literature as potential intermediates in a synthetic transformation dated from 2004, gold vinylidenes species 2 have comparatively attracted less attention. Such a situation can probably be imputed to a long-standing lack of synthetic processes to access them in an easy and selective manner.

Key words vinylidene, reactive intermediate, gold, catalysis, dual catalysis, nucleophilic trapping, C–H insertion
The context changed in 2012 when the groups of Hashmi and Zhang discovered that arenediynes substrates could be used for the generation of gold vinylidenes, and that these species demonstrated interesting reactivities. Since then, more attention has been focused onto the field and a variety of synthetic transformations based on their involvement as key reactive species have been reported.

The aim of this short review is to give the reader an overview of the synthetic approaches developed so far to access gold vinylidenes and the various reactivities these species can exhibit. It is organized by means of gold vinylidene generation: 1) 1,2-migration processes, 2) dual gold catalysis, and 3) other unrelated processes. The reactivities of gold vinylidenes are illustrated for each transformation by a short selection of representative examples.

2 1,2-Migration Processes

The treatment of an alkyne substrate 3 bearing either a halogen atom (Br, I) or atrialkylsilyl (SiR₃) substituent with an electrophilic gold species is probably the most straightforward manner to generate vinylidene gold species (Scheme 2). Indeed, upon activation of the C≡C bond by gold, the X group can perform a 1,2-migration to deliver a vinylidene gold intermediate 4 that can then react via nucleophilic trapping or C–H bond insertion.

The very first example of such a reactivity (and involvement of a vinylidene gold species in a synthetic process) was reported by Fürstner and co-workers in 2004. While working on the synthesis of substituted phenanthrene by cycloisomerization of o-alkynylbiaryl derivatives, they observed that bromo- and iodoalkynes 5Br and 5I were rearranged selectively into phenanthrene 6Br and 6I in the presence of AuCl (Scheme 3). This reactivity was attributed to the involvement of a vinylidene gold species 7 that cyclizes onto the pendant aryl motif. DFT studies performed by So-rio and Marco-Contelles brought support to the proposed mechanism. Interestingly, the use of InCl₃ as the catalyst led to a divergent reactivity with the selective formation of the regiosomeric 10-halophenanthrenes 8.

The same concept of 1,2-halogen migration was exploited by the group of González for the formation of dehydroiodoquinolines from iodopropargyl amide derivatives 9 (Scheme 4). The authors found that the selectivity was dependent on the nature of the gold(I) complex employed. The use of [(IPr)Au]NTf₂ (13) as the catalyst favored the iodine migration product 11, while a phosphite-based gold complex 14 led majorly to the product of direct cyclization 12. This divergence in selectivity was explained by considering the difference of electrophilicity between the two catalysts and the ability of NHC-based gold complexes to more favorably stabilize the vinylidene gold intermediate 10. The reaction was shown to be particularly selective in the case of substrates possessing electron-withdrawing aryl substituents, as the competitive direct cyclization was slowed down in such cases. The same authors also reported that the 1,2-iodine migration process could also be employed for the selective synthesis of 3-iodo-2H-chromenes (Scheme 4).

More recently, González and co-workers demonstrated that aryldiaalkynes 15 could also be employed as substrates for the synthesis of functionalized indenes 17. In this case, the intermediate gold iodoalkynilide species 16 cyclizes following a concerted C–H bond insertion at the benzylic position of the substrate (Scheme 5). This procedure represents a particularly efficient entry to iodoindenes.

The group of Hashmi also proposed the involvement of similar gold iodoalkynilide intermediates in a synthesis of 1,3-diodonaphthalenes 20 from 1,2-bis(iodoethyl)arenes 18 (Scheme 6). In this transformation, the electrophilic species 19 was proposed to cyclize onto the pendant iodoalkyne thus inducing the nucleophilic addition of benzene. This process could also be applied to enediyne or bromoalkyne derivatives.
Besides halogen atoms, it was also reported that silyl groups could undergo 1,2-migration upon activation of a silylalkyne with an electrophilic gold species. However, examples of such a reactivity remain rare. Seregin and Gevorgyan reported in 2006 that 2-propargylpyridine 21 could be rearranged into indolizine 23 when treated with AuBr₃ in toluene at 50 °C (Scheme 7).¹¹ This process was shown to be applicable to a series of other heterocyclic motifs. A mechanism involving the nucleophilic addition of the pyridine nitrogen atom onto an intermediate gold vinylidene 22 was initially proposed to explain the formation of 23. DFT calculations conducted later on by Li and Gevorgyan led to question the likelihood of such a mechanism while not ruling it out, though.¹²

A more recent and unambiguous example of 1,2-silyl group migration was reported by the group of Barriault.¹³ During their studies on the total syntheses of biologically active polyprenylated polycyclic acylphloroglucinols,¹⁴ the authors isolated an intriguing organogold complex 25 that was produced when ynone 24 was reacted with a catalytic amount of [(JohnPhos)Au(NCMe)]SbF₆ (Scheme 8). Intrigued by the structure of 25 and the relative position of the TBS group/the gold residue, the authors made a series of experiments which showed that: a) the process could be applied to other trialkylsilyl groups and b) alkenyl gold species of type 28 could be generated and isolated in the presence of various gold complexes. To explain this reactivity, a mechanism involving a gold vinylidene species 27, immediately produced by 1,2-migration of the silyl group on the gold-activated C≡C, was proposed. Interestingly, the use of di- and triphenylsilyl groups prevents the migration thus

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**Scheme 4** Synthesis of 3-iododehydroquinolines and -2H-chromenes

**Scheme 5** Synthesis of 2-iodoindenes via gold iodovinylidene intermediates

**Scheme 6** Synthesis of 1,3-diiodonaphthalenes

**Scheme 7** Postulated gold-mediated 1,2-silyl migration in the formation of fused pyrrole-containing heterocycles
leading to the formation of the regioisomeric organogold complex. The authors also demonstrated that 28 could be efficiently demetalated in the presence of electrophilic species thus allowing the formation of further functionalized compound 29.

While gold vinylidene species can be conveniently accessed by 1,2-migration from iodo- or silylalkynes, and subsequently involved in synthetically useful transformations, examples of such a reactivity remain rare in the literature. The migration process generally competes with the direct nucleophilic functionalization or with the dehalogenation/desilylation of the gold-activated alkyne.

3 Dual Gold Catalysis

A major breakthrough in the field of gold vinylidene chemistry was made when the group of Hashmi found in 2012\(^{15}\) that these reactive species could be conveniently generated by an intramolecular reaction between a nucleophilic goldacetylide 30 and a gold-activated alkyne 31 (Scheme 9). This important discovery paved the way to the development of a variety of dual gold-catalyzed processes\(^{16}\) which are based on the key generation of intermediate gold vinylidene species 32 from diyne substrates. These reactions are detailed in the following paragraphs.

The story started when Hashmi and co-workers studied the reaction of arenediyne 33 in the presence of the [(IPr)Au]NTf\(_2\) complex 13 in benzene (Scheme 10). When 33 was treated with 15 mol% of 13 at 20 °C, benzene adduct 34 was produced almost as a single product. It was proposed that 34 was formed by an initial diyne cyclization followed by the trapping of the resulting napthyl cation by a molecule of solvent.\(^{10,17}\) Surprisingly, when the reaction was conducted at reflux, another unexpected benzene adduct 35 was competitively formed. The authors discovered that the selectivity could even be completely shifted towards the formation of 35 in the presence of a basic additive (Et\(_3\)N). After an extensive and careful study of the influence of reaction conditions (nature of catalyst and loading, additive, temperature), as well as D-labeling experiments, the group of Hashmi proposed that the unexpected adduct 35 could be produced by an unusual mechanism involving the formation of an intermediate gold vinylidene species (Scheme 10).\(^{18}\)
fer and ring expansion. The catalytic cycle would be closed by a catalyst transfer from \( \text{40 to 36} \) that would liberate the reaction product \( \text{41} \) and regenerate the di-gold complex \( \text{38} \). It is worth noting that \( \text{40} \) could be isolated and was found to be catalytically active in the process.

By capitalizing on this result, and on the basis of their mechanistic investigations, the Hashmi group subsequently reported that dibenzopentalenes \( \text{43} \) could be synthesized by reacting diyne derivatives \( \text{42} \) in the presence of complex \( \text{13} \) (Scheme 11). In this transformation, the intermediate gold vinylidene \( \text{45} \), generated by dual gold catalysis, is trapped in an intermolecular manner by the pendant aryl group. Interestingly, no compounds derived from an intramolecular reaction of \( \text{45} \) with benzene (used as the solvent) was observed. The involvement of \( \text{45} \) in the process and the overall mechanistic proposal were supported by a series of computational studies. Of special interest is the catalyst transfer event, which was found to proceed between the gem-diaurated species \( \text{46} \) and \( \text{42} \) in a 3-step sequence comprising an initial \( \text{Au}^+ \) transfer, followed by a proton transfer and a second \( \text{Au}^+ \) transfer.\(^{20b}\)

\[ \text{Scheme 11 Synthesis of dibenzopentalenes by dual gold catalysis} \]

\[ \text{Au}^+ \text{(IPr)Au}^+ \text{NTf}_2 (\text{5 mol%}) \]

\[ \text{R} \quad \text{R} \]

\[ \text{Scheme 12 \( \sigma \),\( \pi \)-Acetylide digold complexes as traceless dual-activation catalysts} \]

Since the gold activation of the diyne is a required step prior to the formation of the gold vinylidene species (‘initiation’ step), Hashmi and co-workers designed a new class of \( \sigma,\pi \)-acetylide digold complexes \( \text{47} \) derived from propyne, which could act as traceless dual-activation catalysts (TDACs) (Scheme 12). These complexes were shown particularly active in a series of transformations as exemplified by the conversion of \( \text{48} \) into dibenzopentalene \( \text{49} \) (see additional examples in the following paragraphs).

The replacement of the aryl moiety at the alkyne terminus of the substrate by a substituted allyl or benzyl group allowed an easy access to fluorenes \( \text{51} \) and benzofluorenes \( \text{52} \) (Scheme 13). The reaction should proceed in a similar manner with the initial generation of gold vinylidene \( \text{50} \), which would then suffer a nucleophilic attack of the allyl or benzyl moiety to ultimately deliver cyclized aromatic products. The nature of the final product depends on the substitution pattern at the allyl/benzylic position of the substrate since an additional aromatization step can take place when this position is not fully substituted.

\[ \text{Scheme 13 Synthesis of fluorene derivatives by dual gold catalysis} \]

Besides undergoing nucleophilic trapping with carbon \( \pi \) systems, gold vinylidenes generated by dual gold catalysis can also be involved in C–H insertion processes. This reactivity was first demonstrated independently by the groups of Zhang and Hashmi in 2012 (Scheme 14). Zhang and co-workers employed a combination of \( \text{[[BrettPhos]Au]NTf}_2 \) as the catalyst and a pyridine oxide as a basic additive to convert arene diyne \( \text{53} \) into benzofulvene \( \text{57} \). While the reaction can be performed without this basic additive, its presence was shown to positively affect both the rate and the efficiency of the transformation. Hashmi and co-workers employed the catalytic system that was shown to be active in their previously reported synthesis of dibenzopentalenes. DFT calculations as well as D-labelling experiments support a mechanism in which a dual gold-catalyzed process allows the formation of an intermediate gold vinylidene species \( \text{55} \) that subsequently undergo a C–H insertion. The nature of the C–H bond activation process was studied by Hashmi, Knizia, and Klein. The group of Hash-
mi was also able to isolate and characterize a gem-diaurated species 56 that might participate in the catalytic cycle by transferring the Au moieties to the diyne substrate 53. The transformation proved to be applicable to a large variety of substrates allowing C–H insertion not only in primary or secondary C–H bonds but also in O–H and N–H bonds. With the very same substrate 33 that led to the initial discovery of gold vinylidene generation by dual gold catalysis (see Scheme 10), Hashmi and co-workers demonstrated that intermolecular reactions of gold vinylidene 61 with alkenes or alkenes was also accessible (Scheme 16).27 Reactions of 61 with cycloalkanes (employed as the solvent) led to the isolation of substituted naphthalenes 62 in moderate yields. The mechanism for this transformation was not detailed. The reaction was more efficient when the trapping of 61 was performed in the presence of linear or cyclic alkenes. In this case, fused cyclobutene derivatives 64, derived from the gold-catalyzed rearrangement of the intermediate alkylidenecyclopropane 63 could be isolated.

Interestingly, while arylidyines of type 65 were shown to undergo a dual gold-catalyzed 5-endo-dig cyclization leading to the formation of gold vinylidene species 66, it was demonstrated by the Zhang group that the cyclization event could alternatively proceed following a 6-endo-dig mode when the aryl group tethering the two alkyne moieties was replaced by an alkene 67 (Scheme 17).28 This shift in cyclization mode lead to the formation of intermediate orthoaurophenyl cations 68, which can also be regarded as carbones 69. These species were shown to react via C–H activation or with nucleophilic patterns to produce a variety of aromatic compounds. The same observation was made by the group of Hashmi with 2,3-dialkynlythiophene derivatives 70 (Scheme 17).29 Interestingly, the regioisomeric 3,4-dialkynlythiophenes 71 react similarly to arylidyines 65 following 5-endo-dig cyclization process leading to gold vinylidene intermediates.30 Computational studies by Hashmi and co-workers showed that this divergence in selective arises from electronic and not steric effect.

However, the presence of an unsaturated C=C motif between the two alkyne units is not a structural requirement to enable the dual gold-catalyzed generation and selective

The same C–H bond activation process could be applied to the cycloisomerization of iodoalkyne derivatives 58 (Scheme 15).26 In this case, iodozenofulvenes 59 were selectively obtained as the result of an iodine atom transfer from the substrate 58 to the gem-diaurated species 60. As described above, this transfer might proceed in 3 steps: AuL+ transfer from 60 to 58, followed by the iodine atom transfer, and a subsequent second AuL+ transfer. This transformation, which was shown to be relatively efficient, allows for further functionalization of the fulvene core by transition-metal-catalyzed cross-coupling reactions.

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reaction of gold vinylidenes. The group of Van der Eycken has reported for instance that diynamides 72, which can be obtained in a straightforward manner by an Ugi reaction, could be cyclized into cyclopentapyridone derivatives 74 in the presence of a catalytic amount of [(IPr)Au]OTf in 1,2-dichloroethane at 120 °C (Scheme 18). In this transformation, the gold vinylene species 73, produced intermediately by a dual gold-catalyzed cyclization of diyne 72, inserts into a primary or tertiary inactivated C–H bond to generate a new five-membered fused cycle.

In the same vein, Hashmi, Fuji, and Ohno demonstrated that dual gold catalysis could also be applied to the cycloisomerization of substrates 75 possessing a simple two carbon alkyl moiety tethers the two alkyne units (Scheme 19). Depending on the substitution pattern of the substrate linker, the intermediate gold vinylidene species 76 could evolve either via C–H activation or nucleophilic trapping. As for the reactivity trend, competition experiments showed that (1) the C–H activation pathway was more favorable than the nucleophilic trapping by an aromatic ring and (2) nucleophilic trapping by aromatics led preferentially to the formation of a new 6-membered (as compared to a 5-membered one). In a recent article, the group of Hashmi reported another example of selective nucleophilic trapping using polyarylated 1,5-hexadiyne substrates. Selected examples of such transformations are given in Scheme 19.

Gold vinylidene generated by dual gold catalysis also proved to be useful species for the synthesis of various nitrogen containing heterocyclic motifs. For example, and by analogy with the work performed with arylidyne substrates, the group of Hashmi developed a procedure for the synthesis of polycyclic fused pyridines 80 from pyridinium substrates 77 (Scheme 20). Initial tests showed that the cycloisomerization could not be directly performed from the ‘free’ pyridines, presumably due to their capacity to strongly bind to gold catalysts. It is also interesting to note that while simple methyl/pyridium salts exhibit a low to moderate reactivity, the benzyl ones 77 bearing either a...
PF$_6^-$ or NTf$_2^-$ counteranion, could be readily and efficiently converted into 79 by treatment with [(IPr)Au]NTf$_2$ at 55 °C in dichloromethane. The transformation, which involves the C–H insertion of gold vinylidene 78 as the key step, could be employed for the synthesis of a variety of polycyclic pyridinium 79. These salts could be subsequently hydrogenated and debenzylated to liberate the corresponding free pyridines 80. This protocol appears to be particularly useful as it allows a rapid access to structural motifs, which are found in molecules described to possess insecticidal or antimicrobial properties.

Several synthetic procedures have also been reported using ynamide derivatives as substrates for the synthesis of heterocyclic structures. Ohno, Hashmi, and Fuji have demonstrated that N-propargyl ynamide of type 81 could be converted in moderate to good yields into 3,4-disubstituted polycyclic pyrroles 83 and 84 (Scheme 21). The introduction of a nitrogen atom in the diyne tether does not affect the reactivity previously observed for substrates possessing an all-carbon linker. The intermediate gold vinylidene 82 was found capable of performing either C–H activation or nucleophilic trapping to produce pyrrole derivative 83 or 84, respectively. The C–H activation turned out to be generally more efficient than the arylation process. It is worth noting that the cyclization leading to 82 proceeds by umpolung via the addition of the nucleophilic goldacetylide to the carbon of the ynamide.

Recently, our group reported that structurally similar ynamide substrates 85 possessing a longer linker between the two alkyne units could similarly react to produce a variety of N-containing aromatic heterocycles 88 (Scheme 22). The use of [(RuPhos)Au]NTf$_2$ in refluxing chloroform was found to be a set of optimal catalytic conditions to perform the transformation. The use of a pyridine additive was observed to increase the reaction rates and in some cases to significantly improve the yields. In contrast to the previously reported dual gold-catalyzed reactions that proceed by 5-endo-dig cyclization, the given transformation singularly involves either a 5-, 6-, or 7-endo-dig cyclization. This process allows for the generation of a key gold vinylidene intermediate 86, which subsequently reacts in an intramolecular manner with a nucleophilic alkenyl or aryl moiety to produce a new substituted phenyl or naphthyl motif. Overall, this transformation can be regarded as an intramolecular gold-catalyzed formal dehydro-Diels–Alder reaction between an enyne and an alkyne. We also performed a series of D-labeling experiments and kinetic studies that support the involvement of a dual gold catalysis mechanism with species 86 and 87. The very same type of transformation was reported very recently by the group of Zi using [(IPr)Au]NTf$_2$ in combination with DIPEA. 

**Scheme 20** Access to polycyclic pyridinium salts and pyridines by dual gold catalysis

**Scheme 21** Synthesis of pyrrole derivatives by C–H activation or nucleophilic trapping of gold vinylidene species

**Scheme 22** Involvement of gold vinylidene species in formal dehydro-Diels–Alder reactions of ynamide derivatives
In a very recent article, Hyland and Pyne described an unusual cycloisomerization of an enediyne motif 89 that produces isoindolinones 94 (Scheme 23). The singularity of this process lies in the fact that the dual catalyzed cyclization event involves the initial addition of a nucleophilic goldacetylide on the alkene moiety of the gold-activated enyne (see 90 → 91). The resulting gold vinylidene species 91 subsequently cyclizes onto the allenylgold moiety to deliver a new gold carbene intermediate 92. The rearrangement of 92 into a six-membered cycle 93 followed by aromatization of the system finally produce 94. This mechanism was supported by a combination of D-labeling experiments and DFT calculations. An alternative direct pathway leading to 93 from 91 was also suggested. This transformation was found to perform best with the oxo [(Ph3PAu)2]BF4 gold complex in toluene at reflux to deliver a variety of isoindolinones 94 in high yields. Interestingly, the propiolamide substrates 89 could be easily obtained from the corresponding protected amino aldehydes 95 with high enantiopurity, and the gold-catalyzed transformation was found to retain this level of purity.

Besides performing C–H activation or undergoing nucleophilic trapping with C-nucleophiles, gold vinylidene species have also been demonstrated to react with oxygen-based nucleophiles. As reported by the group of Hashmi, a gold vinylidene 97 intermediately generated by dual gold catalysis from an arylidyne substrate 96 can, for instance, react with water (Scheme 24). This nucleophilic trapping generates an aurated enol 98 which then tautomerizes to the gold acyl species 99. A subsequent CO extrusion produces the alkylgold 100, which ultimately yield the indane product 101 either by protodemetalation or by catalyst transfer with substrate 96. The CO loss was confirmed by GC/MS spectrometry measurements using either 18O-labeled water or a substrate 13C-labeled at the alkyne carbon being removed by CO extrusion. Since the trapping of the vinylidene intermediate with water proceeds in an intramolecular fashion, a specific design of the substrate is required to prevent (or limit) any competitive intramolecular C–H activation or nucleophilic trapping. The reaction was shown to be the most efficient when it was performed with the [(IPr)Au]NTf2 as the catalyst in THF at room temperature with only 5 equivalents of water. The efficiency was, however, shown to be strongly dependent on the substrate substitution pattern.

Intramolecular transfers of alkoxy groups to gold vinylidene species is also feasible as reported by the Zhang group. When aryl diynes 102 possessing a methoxy group at the propargylic position were reacted with a catalytic amount of [(IPr)Au]NTf2 in a t-BuOH/DCE mixture at 70 °C, various polycyclic fused cyclopentenones 106 could be obtained (Scheme 25). To explain their formation, the authors proposed that a transfer of the methoxy group from the alkyne carbon to the gold vinylidene moiety could proceed in the immediately formed species 103. A subsequent isomerization of the resulting carbocation 104 would allow a Nazarov-type cyclization that would ultimately lead to the formation of 106 after hydrolysis of cyclopentadiene 105.

The same group later reported that gold vinylidene 108 derived from arylidyne 107, could also react with 3,5-dichloropyridine oxide to generate in situ a diaurated ketene 109 (Scheme 26). This species could subsequently suffer an intra- or intermolecular nucleophilic attack of an alcohol or even water to produce indene derivatives 111 bearing either a lactone, an ester, or a carboxylic acid functional group. The key oxidation step of 108 into 109 with the pyridine oxide was supported by DFT calculations, as well as the involvement of the gem-digold species 110. This three-

![Scheme 24](image-url)  
Intramolecular transfers of alkoxy groups to gold vinylidene species with water
component reaction, which can be regarded as an oxidative cyclization of a diyne, was shown to be efficient and applicable to a large variety of substrates.

As seen from the different examples of reactions compiled in this section, dual gold catalysis represents a particularly efficient means of generating gold vinylidene species from diyne substrates. Depending on the nature of the linker between the two alkyne units and the substitution pattern of the substrate, these reactive electrophilic intermediates can undergo C–H insertion at a non-activated position or react with carbon and oxygen nucleophiles to produce a variety of polycyclic (aromatic) compounds.

4 Other Processes

Besides 1,2-migration of iodine or silyl groups from the terminal position of a gold-activated alkyne or dual gold catalysis of diynes, a few other processes have been reported for the generation and use of gold vinylidene intermediates. These alternative methods are described in the following paragraphs.

The group of Zhang has reported in 2016 that TMS-protected yiones could be converted into 2-bromocyclo-pentenones by treatment of with a catalytic amount of (IPr)AuCl and AgSbF6 in the presence of N-bromoacetamide (NBA) as the brominating agent (Scheme 27). This transformation was shown to be high yielding, compatible with various commonly used functional groups and, regio- and stereoselective. While the mechanism has not been completely elucidated, the authors have proposed on the basis of experimental studies that the reaction proceeds via the intermediate formation of a bromovinylidene species. The latter can then undergo a C–H insertion at a non-activated position of a pendant alkyl group. As for the generation of it was suggested that under the reaction conditions, the silylalkyne first converts into the goldacetylide. Upon activation of the C=O bond in the acidic species, a gold allenylidene species would form and subsequently react with NBA to produce the corresponding bromoalkyne was demonstrated not to be an intermediate in this transformation, thus ruling out the possibility of a 1,2-migration process (see Section 2). The nature of the C–H insertion step was computationally studied by Hashmi, Knizia, and Klein.

Hashmi and co-workers also demonstrated that goldacetylides, generated in situ by reaction between a terminal alkyne and the gold pre-catalyst, could perform a nucleophilic attack at a position bearing an aryl sul-
fomate leaving group, thus allowing the formation of a gold vinylidene species 120 (Scheme 28). A subsequent attack of the sulfonate anion on 120 generates an aurated alkenyl intermediate 121, which, in turn, undergoes a catalyst transfer with the substrate to deliver the alkenyl sulfonate product 122 and regenerate the goldacylate 118. Both, 5 and 6-membered cycles could be produced in moderate to good yields following this procedure. The efficiency of the transformation was found to be dependent on the nature and substitution pattern of the chain tethering the alkyne moiety and the sulfonate group: geometrically restricted substrates were observed to be more reactive. While the scope of this transformation remains so far limited, the easy access to the substrates and the usefulness of the alkenyl sulfonate leaving group, thus allowing the formation of a gold vinylidene species 120 (Scheme 28). A subsequent attack of the sulfonate anion on 120 generates an aurated alkenyl intermediate 121, which, in turn, undergoes a catalyst transfer with the substrate to deliver the alkenyl sulfonate product 122 and regenerate the goldacylate 118. Both, 5 and 6-membered cycles could be produced in moderate to good yields following this procedure. The efficiency of the transformation was found to be dependent on the nature and substitution pattern of the chain tethering the alkyne moiety and the sulfonate group: geometrically restricted substrates were observed to be more reactive. While the scope of this transformation remains so far limited, the easy access to the substrates and the usefulness of the alkenyl sulfonate products makes this approach particularly attractive from a synthetic point of view.

Recently, Fürstner and Debrouwer reported another protocol for the generation of gold vinylidene species by an intermolecular nucleophilic attack of a goldacylate on an activated aldehyde (Scheme 29). While this study was not dedicated to the development of a new synthetic transformation, the described procedure undoubtedly possesse some synthetic potential. The authors have shown that the treatment of goldacylate 124, generated by reaction of the TMS-alkyne 123 with a stoichiometric amount of (IPr)AuOH, with TBSOTf at –78 °C led to the formation of a transient gold vinylidene species 125. This process probably involves the nucleophilic addition of the goldacylate moiety onto an O-silyloxocarbenium intermediate. Interestingly, 125 rapidly evolved at –78 °C via the formal transfer of the oxygen residue from the benzyl position to the carbenic one to produce the HOTf-acylgold complex 126. At 20 °C, 126 suffered an extrusion of CO that produced 127. Alternatively, its treatment with methanol delivered the corresponding ester 128. Both intermediates 125 and 126 could be detected using NMR spectrometry technics and the structure of 126 was confirmed by X-ray analysis.

Finally, Fensterbank, Gandon, and Gimbert have reported the involvement of intermediate gold vinylidene species 132 in the gold-catalyzed selective conversion of 1,6-allenynes 129 into hydrindienes 133 (Scheme 30). The singularity of the process, as compared to those presented above, lies in the mechanism leading to the formation of the gold vinylidene. The authors have proposed based on a series of D-labeling experiments and computational studies, that the alkenylgold species 131, initially produced by nucleophilic attack of the allene in 130 on the gold-activated alkyne moiety, could undergo a favorable 1,4-hydride shift. This unusual transfer would produce a gold vinylidene in-
Intermediate 132 which, in turn, could insert into a non-activated C-H bond to deliver compound 133. Interestingly, while this process was found to be very efficient with gold complexes bearing bulky phosphine or NH ligands [as well as gold(I)(III) halides], the use of gold(I) complexes possessing less sterically demanding ligands (Et₃P, Ph₃P) led to a divergence in selectivity with the formation of Alder-ene type products 134.

5 Conclusion

While gold vinylidenes species have been proposed as reactive intermediates in synthetic processes as early as 2004, the development of transformations based on their efficient generation and selective reaction has only started in 2012, after the groups of Hashmi and Zhang uncovered the synthetic potential of dual gold catalysis with diyne substrates. Although gold vinylidenes can be accessed by a 1,2-migration process from Au-activated halogeno- or silyl-alkynes (see Section 2), this route lacks generality. Depending on the reaction conditions and the substitution pattern of the substrate, the 1,2-migration pathway can be in competition with the direct nucleophilic functionalization of the alkyne and/or with the dehalogenation/desilylation of the gold-activated alkyne. In contrast, and as exemplified in Section 3, the use of dual gold catalysis with diyne substrates has been shown to be a far more robust and reliable way to produce gold vinylidenes. The reactivity principle lies in the possibility to generate in situ, from a terminal alkyne, a goldacyclide that would undergo an intramolecular nucleophilic addition onto a second gold-activated alkyne. The increased number of studies that have been made in the field of dual gold catalysis during the last 5 years have already allowed enlightening some unique and unsuspected reactivities of gold vinylidenes. These species have been demonstrated to react, for instance, with carbon or oxygen-based nucleophiles, by oxidation or by C–H insertion at a non-activated center. If one considers that the regioselective reaction of an electrophilic species at the carbon of a goldacyclide could theoretically generate a gold vinylidenyl species, the application of this simplistic reactivity principle with various electrophiles should lead in the future to new exciting discoveries and consequently to an increasing interest for the use of gold vinylidenes in synthetic organic chemistry.

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