Gold-Catalyzed Allylation Reactions

Gold Catalyzed Allylation Reactions

Arianna Quintavalla,[a] and Marco Bandini*[a]

Abstract: The allylation reaction is a well-established and indispensable tool for the development of chemical complexity/diversity in organic synthesis. Across the decades, this unique transformation renewed itself many times always aiming at more simple, selective and sustainable variants. Moving from stoichiometric amounts of metal additives to sub-stoichiometric and more recently catalytic loadings is only one of the chemical revolutions faced by the allylation reaction. In this context, homogeneous gold catalysis played a pivotal role, making unexpected reaction machineries, concerning unactivated unsaturated hydrocarbons, feasible. Among them, [Au(I)]- and [Au(III)]-assisted allylation reactions deserve a particular mention, due to their impact in the synthesis of key organic building blocks and added value compounds. An unprecedented survey across the development of allylating methodologies based on this coinage metal is documented in the present *Minireview*.

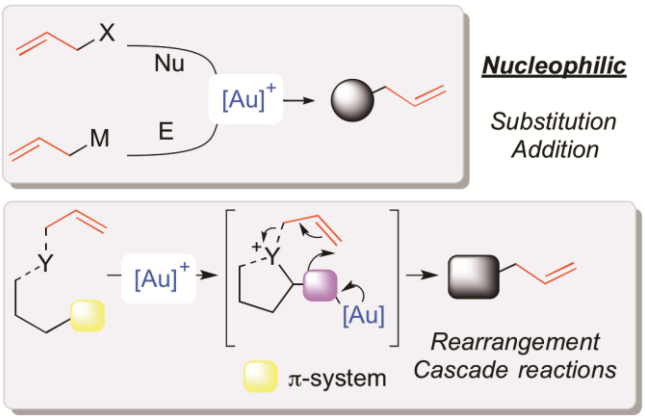
1. Introduction

The allylation reaction represents an undoubted milestone in the synthetic organic chemistry texture.[1] Within the scenario of the alkylating events, allylating methods deserve a particular mention due to the convenient embedment of synthetically flexible allylic units into molecular scaffolds in a chemo-, regio- and stereoselective fashion.

Across these years, allylating processes have faced a continuous evolution towards always more selective and environmentally acceptable variants. In this direction, the replacement of stoichiometric additives[2] with sub-stoichiometric or catalytic amounts of promoting agents (both metal and metal-free species) has represented a significant breakthrough in the field. Additionally, the substitution of undesired allylic alkylating agents (*i.e.* halides) with more environmentally acceptable alcohols[3] concurred to emphasize the sustainability of the protocol.

Allylation reactions can be firstly categorized based on the intrinsic reactivity of the allylic framework. In other words, the alkylating unit can feature electrophilic or nucleophilic profiles depending on the activation modes adopted in the process. Here, the employment of redox-active *hard* metal species generally results into the *in situ* formation of nucleophilic organometallic allylic agents. Contrarily, the use of *soft* metal catalysis commonly provides an electrophilic activation of the unsaturated framework causing the consequent nucleophilic attack by an external agent. The latter approach also comprises the use of metal-free acid catalysis occurring through S_N1, S_N2 and S_N2' reaction mechanisms.

Gold catalysis[4] proved particular competence in this segment[5] and contributed substantially in expanding the scope and applicability of the allylation reaction to densely functionalized compounds.[6] Additionally, the well-known attitude of gold species in promoting site-selective rearrangement reactions opened up a new frontier on the "indirect" insertion of allylic frameworks into molecular architectures. Key aspects such as dual-catalysis and stereoselectivity have been also extensively documented in the literature and will be discussed herein (Scheme 1).



Scheme 1. Pictorial sketch summarizing the gold catalyzed allylating strategies covered in the *Minireview*. (E: electrophile, Nu: nucleophile, Y: heteroatom or tethering unit, X: leaving group, M: metal).

Although gold(I) and gold(III) homogenous catalysis has been summarized in many circumstances main focus on allylation reactions is still absent and it will be targeted by the present *Minireview.* The manuscript is organized in several sections dealing with the type of reactivity profile of the allylating agent. In particular, i) nucleophilic substitution reactions, ii) rearrangement processes and iii) addition processes have been identified as main themes involving gold catalysis. Additionally, if applicable, sub-organization of the sections based on the nature of the new bond created (*i.e.* C-C, C-O, C-N, C-S) is realized.

Gold catalyzed hydro-functionalization of allenes, and nucleophilic addition to alkynes are useful and complementary approaches towards the indirect realization of allylic units. However, these transformations should be considered beyond the scope of the present literature survey. Readers are kindly readdressed to specific review articles for more insights into these protocols.[7,8] Last but not least, in order to emphasize the role of proposed or characterized organogold intermediates in the catalytic cycles, with respect to reaction partners and fully

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organic intermediates a dedicated labeling system (*i.e. roman numerals*) is provided.

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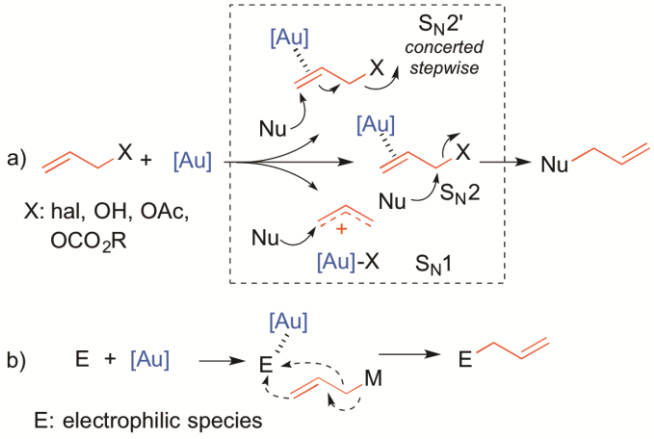
2. Allylic substitutions

The allylation reaction via catalytic nucleophilic substitution is by now the most popular and pursued reaction machinery to install allylic units into molecular skeletons. The process commonly evolves through the *in situ* formation of "electrophilic" allylic reagents that face inter- as well as intramolecular nucleophilic trapping. Depending on the structure of the allylic precursor (I, II or III halides, alcohols, acetates….) the overall reaction course can belong to the S_N1, S_N2 or S_N2' (concerted or stepwise) reaction profiles. Additionally, the well-known redox stability of [Au(I)] adducts generally prevents redox processes from taking place (*i.e.* different to classic Pd-assisted Tsuji-Trost allylic alkylation processes).[1a,b] As a consequence η^2-coordination modes[9] are prevalently involved in gold-mediated electrophilic activations of allylic units (S_N2 or S_N2' pathways, Scheme 2a). Alternatively, some examples of alkylating substitutions involving the combined use of organometallic allylating species and Lewis acid-based gold-catalysis have been reported and will be described at the end of the section 2.1.2 (Scheme 2b).



Scheme 2. Possible activation modes exerted by the gold catalysis in the allylic substitution reactions.

2.1. Electrophilic activation of the alkylating agent

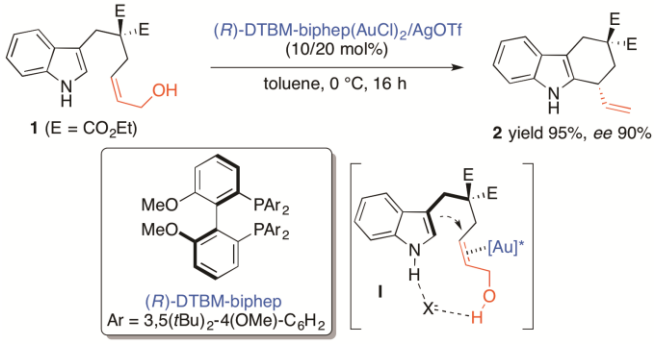
2.1.1. Alcohols as alkylating agents

The intrinsic and peculiar capability of homogenous gold catalysis in the electrophilic activation of unsaturated hydrocarbons has led to the extensive utilization of [Au(I)] and [Au(III)] species also in nucleophilic substitution reactions. Additionally, the well-known tolerance of gold species towards oxygenated moieties enabled the full development of allylating events based on alcohols without additional activating agents. The stoichiometric formation of water as the only byproduct concurs to emphasize the sustainability of the transformation.

The combination of gold catalysis and π-alcohols is so specific and unique that, frequently, analogous alkylating events involving more reactive allyl acetates, carbonates, halides do not take place or display significantly different reaction rates/outcomes under similar conditions.[10] Within this realm, both carbon-carbon and carbon-heteroatom bond forming procedures have been extensively investigated over the last few years with particular emphasis on controlling demanding issues such as chemo-, regio- and stereoselectivity.

2.1.1.1 C-C Bond forming processes

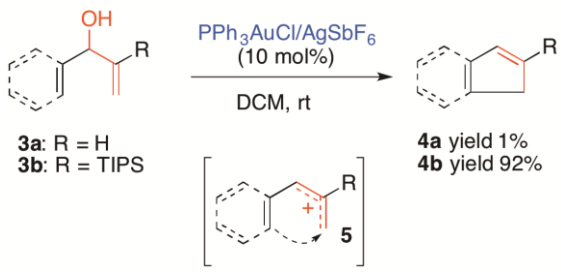
The formation of carbon-carbon bonds via gold catalyzed intramolecular allylations with alcohols found several pertinent examples in the Friedel-Crafts (FC) type alkylations.[11] Here, Bandini and coworkers (2009) documented on the synthesis of a range of α/γ-vinyl-tetrahydrocarbazoles (**2**), starting from readily available indolyl-alcohols **1**, by means of C(2) or C(3) site-selective alkylating steps (Scheme 3). DTBM-biphep$(AuCl)_2$/AgOTf (10 mol%) was the catalytic system of election.[12a] A stepwise S_N2'-type mechanism was elucidated via a combined experimental/computational investigation,[12d] providing undoubted evidences on the "folding effect" (**I**) exerted by the OTf counterion in bringing both reactive sites proximal (Scheme 3).[13]



Scheme 3. Enantioselective synthesis of tetrahydrocarbazoles **2** via gold assisted C-C forming ring closing event. The case of the C(2)-allylic alkylation is reported (X^- = OTf^-).

Subsequently, the same team applied the successful combination of gold-catalysis and allylic alcohols in the stereoselective allylic alkylation of enolizable aldehydes (2012). A binary metal/metal-free catalytic system (*i.e.* first generation MacMillan catalyst/[JohnPhosAu(ACN)SbF_6]) furnished a range of 5- and 6-membered rings in high chemical and optical yield.[14] The formation of new carbon-carbon bonds via gold-assisted intramolecular allylation reactions did not involve solely electron-rich indolyl cores but also different arenes and activated methylene groups.

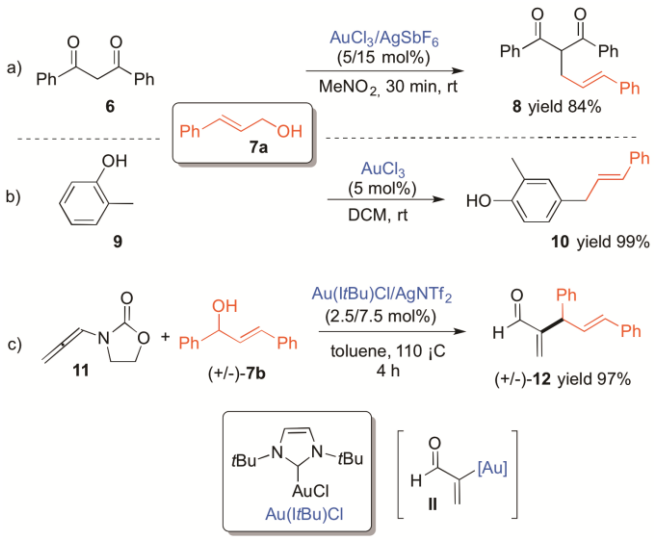
In the 2012, Yamamoto demonstrated the selective synthesis of indenyl-derivatives by introducing a bulky TIPS (triisopropylsilyl) group adjacent to the hydroxyl-moiety (**3**).[15] The induced stabilization of the reactive cationic intermediate **5**, by means of both steric as well as electronic aspects (*β*-silicon effect), permitted the synthesis of a variety of 1*H*-indenes **4** via FC-type allylic alkylation (Scheme 4). It is worthy of mentioning that, the methodology was also efficiently used for the preparation of densely substituted cyclopentadienes via allylic alkylation of olefins.



Scheme 4. Synthesis of 1*H*-indenes **4** via silyl-stabilized intermediates **5**.

Intermolecular variants generally involve highly reactive cinnamyl alcohols (**7a**) or 1,3-diaryl-propenols (**7b**) with the resulting formation of stabilized cationic intermediates. These species have been trapped with different C-based nucleophiles under gold regime and a collection of examples is depicted in the Scheme 5.

In particular, Chan worked (2008/09) extensively in the allylating processes of β-dicarbonyl compounds **6** and intermolecular FC-type alkylation of arenes **9**. The use of electrophilic $AuCl_3$ or $AuCl_3/AgSbF_6$ originated the new C-C bond linkage in excellent yield and relatively mild reaction conditions (Scheme 5a and b, respectively).[16] In the same segment, Bandini (2015) documented on the α-allylic alkylation of α,β-unsaturated carbonyls by condensing allenamides (**11**) and **7b**-type π-alcohols.[17a] The methodology (Au(I*t*Bu)Cl/$AgNTf_2$, 2.5/7.5 mol%) was efficiently applied to the alkylation of enals, enones and acylsilanes. Based on a previous work,[17b] the authors postulated the presence of an active nucleophilic organogold species (**II**) during the reaction course. Additionally the use of an excess of $AgNTf_2$ with respect to the gold complex (3:1) improved further the efficiency of the methodology, probably impacting onto the allylic alcohol activation (Scheme 5c).



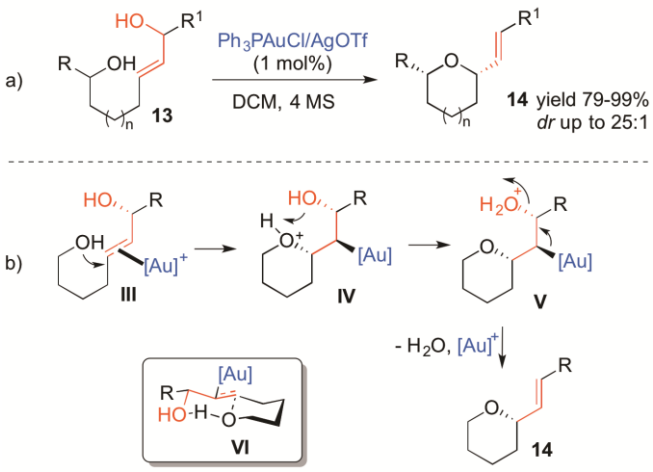
Scheme 5. Intermolecular allylations of active methylene compounds, arenes and α,β-unsaturated carbonyls promoted by [Au(III)] and [Au(I)] complexes.

Interestingly, the combined use of PPh_3AuOTf (5 mol%) and functionalized allylic alcohols was utilized by Harmata in the FC-type alkylation of furan and subsequent cycloaddition reaction.[18] Vinylthionium ions were considered as key intermediates in the cascade reaction.

2.1.1.2 C-O Bond forming processes

Concerning the formation of new C-O connections, Aponick and coworkers pioneered the field (2008) by describing the formation of tetrahydropyrans and tetrahydrofurans **14** via intramolecular oxa-allylic alkylation.[19a] Preference for the *in situ* formed PPh_3AuOTf with respect to AgOTf or TfOH was demonstrated, providing the cyclized product in high yields (up to 99%) and from moderate to good diastereoselectivity (Scheme 6). This work posed several interrogatives in terms of

reaction machinery (*i.e.* S_N2' *vs* S_N1) and stereoselection. Shortly after, the same team and others addressed these issues with dedicated investigations, underlining the role of hydrogen-bond interactions during the ring-closing process on both kinetics and stereochemistry.[19,c] The process proved to be governed by a stepwise S_N2'-type mechanism in which a sequence of outer-sphere *anti*-C-O bond forming process (**III** ⇒ **IV**), hydrogen transfer (**IV** ⇒ **V**) and *anti*-gold elimination (**V** ⇒ **14**) is taking place (Scheme 6b). Such a mechanism provided a reliable rational for the pivotal role played by the C=C configuration of the reacting diol (**13**) on the final stereochemistry of **14**.



Scheme 6. a) Pioneering gold-catalyzed oxa-allylic alkylation reaction. b) Insights into the mechanism of the intramolecular C-O bond forming process.

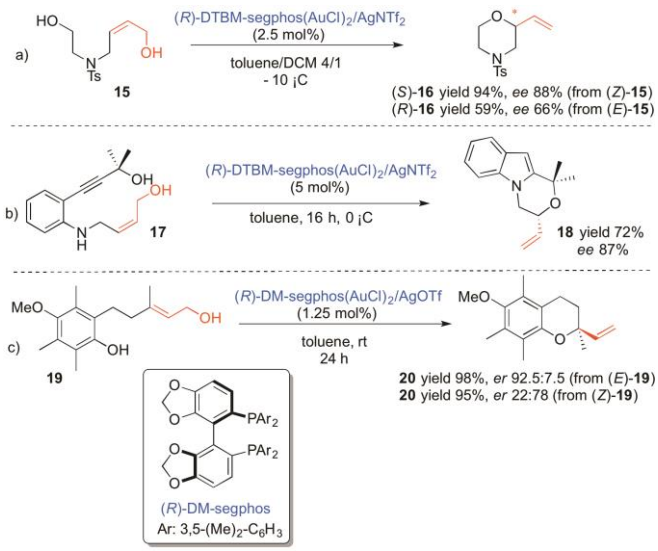
It is worth mentioning that such stepwise machinery was demonstrated to also be active in other C-C and C-X forming gold(I)-catalyzed allylic substitutions, proving a great homogeneity in terms of reaction mechanisms (*vide infra*). The same team (2010) discovered the possibility to obtain synthetically appealing *2H*-chromenes via gold assisted (JohnPhosAuCl/AgOTf 5 mol%, THF, reflux) *endo*-cyclization of phenols on allylic alcohols.[19d] Interestingly, the stereospecific gold catalyzed cyclization of monoallyl-diols ($PPh_3AuCl/AgOTf$) was also employed by Robertson for the total synthesis of (+)-isoaltholactone in good overall yield.[20]

Later on, Bandini (2011) and coworkers successfully exploited this methodology for the preparation of a library of densely functionalized γ-vinylbutyrolactones via intramolecular dealkoxylative oxa-allylic reaction. Au(IMes)Cl/AgOTf (5 mol %) proved competence in the titled reaction but modest diastereoselectivity was obtained (IMes: 1,3-bis(2,4,6-trimethylphenyl)imidazol-2-ylidene).[21]

Efforts towards the control of the stereochemical profile (*i.e.* enantioselection) of the reaction were devoted by several groups. In particular, the enantioselective synthesis of vinyl-morpholines (**16**) and seven-membered ring analogous was recorded, by reacting readily available monoallyl-diols **15** in the presence of DTBM-segphos$(AuCl)_2/AgNTf_2$.[22] Primary as well as tertiary alcohols worked smoothly as nucleophilic partners and the stereochemical course was drastically impacted by the configuration of the C=C of the allylic unit (Scheme 7a). As a matter of fact, diastereoisomeric *Z*-**15** and *E*-**15** provided the morpholine skeleton **16** with opposite absolute configuration by using the same enantiomer of the gold complex. The stereodivergence was rationalized in terms of formation of diastereoisomeric aggregates between the chiral metal complex and the C-C double bond.

The stereocontrolled allylic C-O bond forming process inspired the one-pot synthesis and enantioselective manipulation of indole scaffolds via gold-assisted cascade hydroamination of C-C triple bond and intramolecular dehydrative oxa-allylic alkylation.[23] The combination of propargylic and allylic alcohols in the same molecular framework (**17**) resulted in the synthesis of oxazino-indoles **18** in high enantiomeric excesses (up to 98%) in the presence of DTBM-segphos$(AuCl)_2/AgNTf_2$ as the chiral catalyst (Scheme 7b).

Similarly, Rueping and coworkers (2014) described the synthesis of chromans **20** featuring quaternary stereogenic centers in a stereochemically defined manner,[24] in the presence of DM-segphos$(AuCl)_2/AgOTf$ (1.25 mol%) and substituted phenols **19**. Also in this case, the absolute configuration of the C-C double bond governed the overall stereoinduction of the process with the *E*-stereoisomer being the most efficient one (Scheme 7c). Elegantly, the authors demonstrated the synthetic utility of the bicycled fused scaffold **20** in the synthesis of natural product analogous.

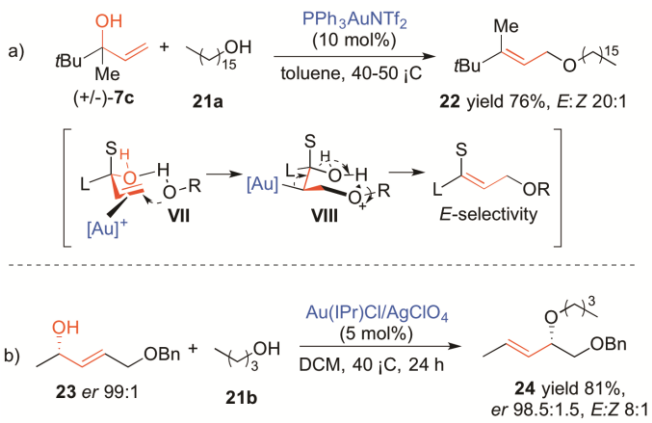


Scheme 7. Enantioselective variants of the gold-triggered dehydrative oxa-allylic alkylation. Applications in the synthesis of morpholines (**16**), oxazino-indoles (**18**) and chromans (**20**).

Several examples of regio- and stereospecific intermolecular dehydrative alkoxylation of allylic alcohols have been also reported under electrophilic gold(I) catalysis. Both

phenols and alkyl alcohols have been condensed with alkylating agents in order to obtain aliphatic as well as aromatic ethers. Lee (2013)[25] and Widenhoefer (2013)[26] were particularly active in this field, exemplifying the potential of the method as well as gaining insights into the mechanistic details.

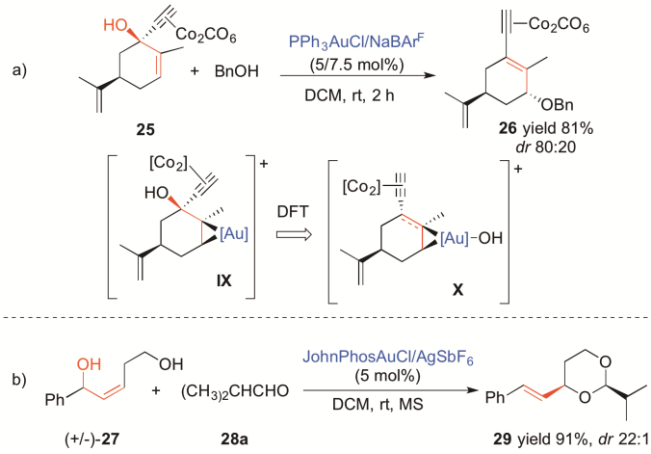
Lee documented on the direct etherification of allylic alcohols with primary, secondary and also tertiary alcohols **7**.[25] The high *E*-selectivity for the newly formed C-C double bond was rationalized in terms of a chair-like 6-membered ring transition state, stabilized by hydrogen bonding interactions (**VII** and **VIII** Scheme 8a). Stereospecific variants of this approach were further developed by Lee (PPh_3AuNTf_2, 10 mol%) [25d] and Widenhoefer ($Au(IPr)Cl/AgClO_4$, 5 mol%).[26] Here, a complete "transfer of chirality" from the enantiomerically enriched alcoholic precursors **23** (Scheme 8b) to the resulting ethers **24** was recorded. The configuration of the C=C bond on the allylating alcohols controlled the overall stereochemical profile of the process and the incoming nucleophile was found to approach the allylic unit *syn* with respect to the leaving OH group.



Scheme 8. Stereospecific synthesis of allylethers **22**/**24** via dehydrative condensation of alcohols with allylic congeners. S and L stand for small and large groups/substituents.

Interestingly, in 2013 Muñoz and Sierra described the first example of classic Nicholas reaction under gold(I) catalysis.[27] The protocol proved extreme competence towards the formation of new C-O and C-C bonds under allylating regime.[28] In the Scheme 9a a representative example of C-O bond forming reaction is presented along with the postulated trimetallic intermediates **IX** and **X**.

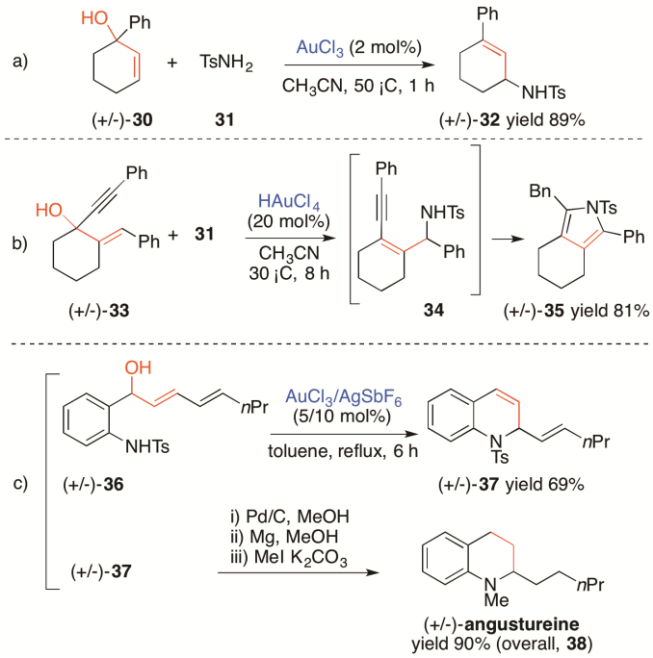
Finally, an elegant diastereoselective annulation reaction was very recently documented by Aponick and coworkers (2015) for the preparation of protected 1,3-diols.[29] In the latter approach ($JohnPhosAuCl/AgSbF_6$, 5 mol%), the condensation of racemic monoallyl-1,5-diols **27** with aldehydes (mainly *i*PrCHO, **28a**) or chloral hydrate provided 1,3-*syn* acetals **29** in high yield (up to 98%) and perfect *dr* (higher than 25:1, Scheme 9b). As before, *Z*-alcohols resulted as more performing with respect to the *E*-isomers in terms of reactivity and stereoselectivity.



Scheme 9. a) Gold-catalyzed Nicholas-type reaction. b) Synthesis of 1,3-*syn*-diols **29** via annulation reaction.

2.1.1.3 C-N Bond forming processes

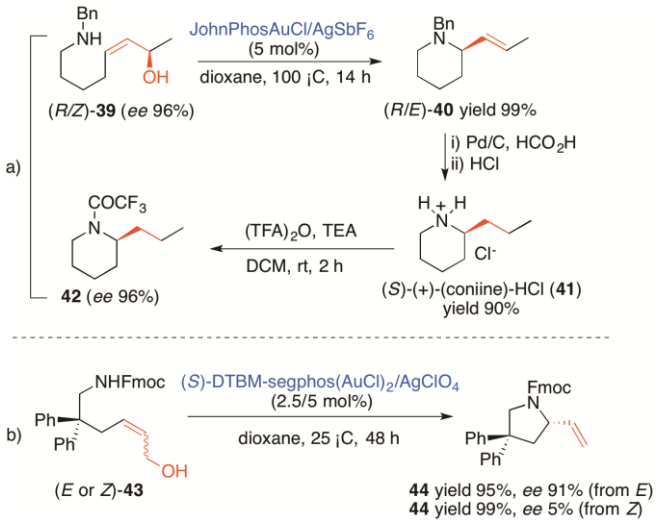
The transition metal promoted condensation of amino groups to alcohols, in absence of any additional stoichiometric Brønsted or Lewis acid source was first theorized by Ozawa (*i.e.* Pd-catalysis) in 2002 and subsequently expanded to other transition metal species. In 2007, Liu published the first intermolecular allylic amination of tosylamides **31** with alcohols (**30**) in the presence of catalytic amounts of $AuCl_3$ (2 mol%, Scheme 10a).[30a] Subsequently, similar strategy was also reported by Nájera and coworkers (2011).[30b]
An elegant use of gold-promoted dehydrative amination reaction was reported by Liang (2008) for the synthesis of densely functionalized pyrroles **35**.[31] Here, the combined use of predesigned 1-en-4-yn-3-ols **33** and $HAuCl_4{\bullet}4H_2O$ (20 mol%) led to *N*Ts-2,3,4,5-tetrasubstituted pyrroles **35** in moderate to very high yields (up to 96%). A site-selective dehydrative amination, followed by hydroamination of the pre-installed C-C triple bond, was accounted as the key mechanistic step (Scheme 10b).



Scheme 10. Examples of intermolecular (a and b) and intramolecular (c) gold catalyzed allylic amination reactions.

Subsequently, Chan and coworkers (2009) implemented this protocol in an intramolecular variant that turned out to be an efficient synthetic shortcut to many aza-heterocycles and in particular to (+/-)-angustureine **38**.[32] A combination of $AuCl_3$ (5 mol%) and $AgSbF_6$ (10 mol%) ensured optimal isolated yields in the desired dihydroisoquinoline **37**, delivering water as the only stoichiometric byproduct (Scheme 10c).

Progresses in the field were made by Widenhoefer (2011/2012) that elegantly addressed the stereochemical profile of the aminative course. In particular, diastereoselective (first) and enantioselective (subsequently) intramolecular condensations of *N*-protected nucleophiles on allylic alcohols were reported in the presence of JohnPhosAuCl/$AgSbF_6$ (5 mol%) and (*S*)-DTBM-segphos$(AuCl)_2$/$AgClO_4$ (2.5/5 mol%), respectively.[33] In the first study, transfer of stereochemical information from the acyclic reagent to the final aza-cycle was effectively exploited in the total synthesis of (*S*)-(+)-coniine•HCl **41**. A stepwise S_N2'-type mechanism (overall *syn*-substitution) was hypothesized via an *anti*-addition/*anti*-elimination sequence (Scheme 11a).[34]

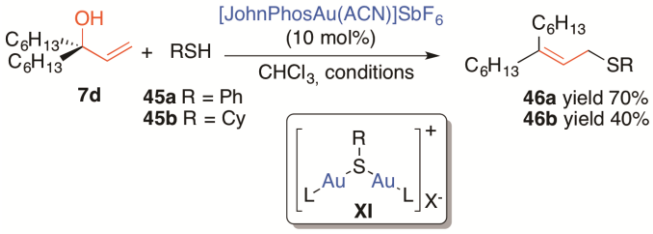


Scheme 11. Stereospecificity and enantioselectivity are accessible via allylic amination of alcohols and gold catalysis.

Subsequently, the enantioselective profile of the reaction course was efficiently governed by means of a gold complex based on enantiomerically pure DTBM-segphos as the chiral ligand. A wide range of 5- and 6-aza-membered rings (**44**) was obtained in very high enantiomeric excesses (up to 94%) with a specific preference for *E*-configured allylic alcohols **43** (Scheme 11b). This evidence is in marked contrast with previous findings in the analogous oxa-allylic alkylation reaction.[22]

2.1.1.4 C-S Bond forming processes

Soft sulfur-based nucleophiles are commonly considered unsuitable to LTM (late transition metal) catalysis due to poisoning effects. As a consequence, the gold catalyzed thioether formation has been far less investigated. Lee and coworkers (2014) documented on the synthesis of allylic thioethers **46**, by condensing π-alcohols (**7**) with unactivated thiols in the presence of [JohnPhosAu(ACN)]SbF_6 (Scheme 12).[35] Higher yields (up to 92%) were accessible by a portion-wise addition of the gold catalyst to the solution. Moreover, while thiophenols (**45a**) performed well at 35 °C (24 h), more basic aliphatic thiols (**45b**) required harsh reaction conditions (72 h, 45-60 °C). The authors justified this trend with the likely formation of the catalytically inactive species **XI** when aliphatic nucleophiles were employed. Finally, the high regioselective S_N2' mechanism was accounted via computational tools revealing that the reaction occurred under thermodynamic regime.



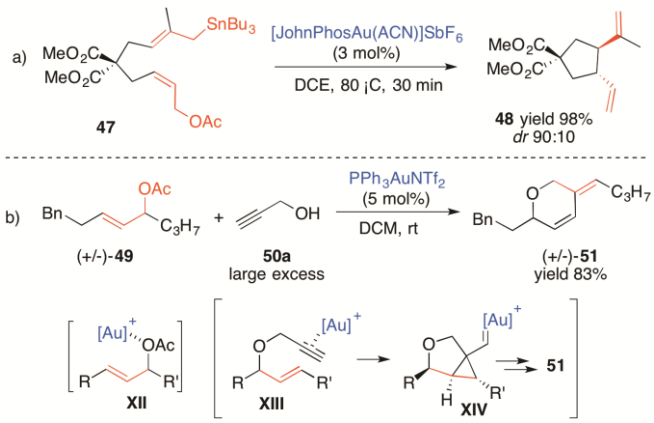
Scheme 12. Gold catalyzed allylic thioetherification of alcohols. **XI:** Catalytically inactive metal species. Conditions: **45a**, 24 h, 35 °C; **45b**, 72 h, 60 °C.

2.1.2. Other alkylating agents

2.1.2.1 Activation of allyl acetates

Albeit far less abundant than that the use of alcohols, more "classic" allylic alkylating agents (*i.e.* acetates) have found some leading applications in gold catalysis. This approach is probably less related to the intrinsic π-acidity of [Au(I)] and [Au(III)] adducts highlighted so far, and it relies mostly on their sigma-acidity content.

In this framework, Echavarren pioneered the field (2008) by documenting a valuable and elegant procedure for the synthesis of carbocyclic compounds **48** via nucleophilic trapping of incipient carbocations, originated by a Lewis acid gold activation of allylic acetates (**XII**), with allylstannanes (*i.e.* formal allyl-allyl coupling, Scheme 13a).[36] No traces of transmetallation between the organo-tin framework and the gold catalyst or oxidative insertion of the metal species on the allylic acetate were observed during the investigation (*vide infra*).



Scheme 13. Use of allylic acetates for the gold assisted inter- as well as intramolecular nucleophilic substitution.

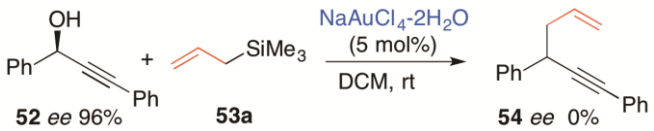
Besides the excellent chemical and stereochemical performances, this reaction stems as a clear example of complementarity between Au and Pd-catalyzed nucleophilic allylic substitutions. As a matter of fact, analogous protocol carried out in the presence of [Pd(0)]-species failed in providing the desired allyl-allyl coupling, when Pd-Sn transmetallation was forbidden due to geometrical issues.

Chen and Gou (2010) reported on the use of allylic acetates as initiators of a cascade synthetic sequence also involving propargylic alcohols. The methodology (PPh_3AuNTf_2, 5 mol%) resulted as a valuable one-pot synthetic route to densely functionalized diastereomerically pure oxygen-containing heterocycles **51** via intermolecular oxa-allylic alkylation followed by intramolecular cycloisomerization (Scheme 13b).[37] Additionally, the same team (2010/2011) reported a series of studies in which allylic acetates were employed for the effective formation of new C-C and C-O bonds via inter- as well as intramolecular condensation with arenes or malonyl-derivatives.[38] Allylic cationic intermediates were postulated as electrophilic active species during the reaction course via gold-based Lewis acid activation.

2.1.2.2 Nucleophilic allylating agents

Allylsilanes found numerous applications in the nucleophilic substitution reactions initiated by an electrophilic gold activation event.

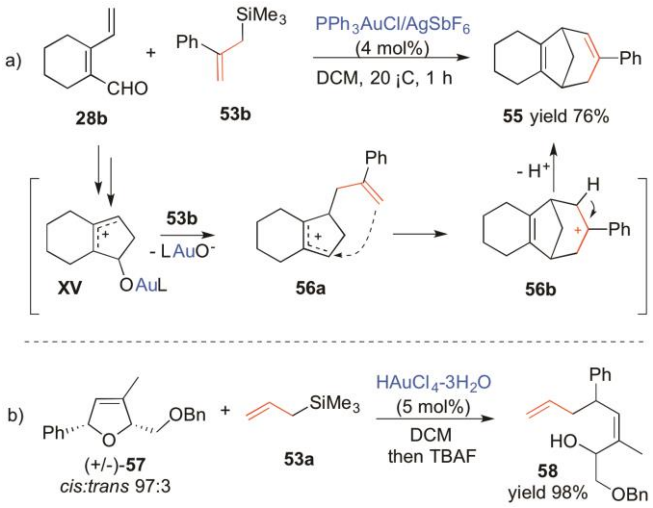
Champagne and coworkers (2005) provided a pioneering proof-of-concept on the condensation of allyltrimethylsilane **53a** and π-activated alcohols. In particular, the combination of **53a** and enantiomerically enriched secondary propargylic alcohol **52** (*ee* 96%) led to the substitution product **54** in racemic form in the presence of $NaAuCl_4$•$2H_2O$ (S_N1-type mechanism, Scheme 14).[39]



Scheme 14. The S_N1-type nucleophilic substitution published by Champagne in 2005.

In 2007 and 2008 Liu further explored this chemistry by presenting a one-pot synthesis of substituted cyclopentenes **55** via deoxygenative cyclization of dienals **28b**. Here, upon the initial gold-triggered intramolecular attack of the olefin to the aldehydic group, the allylsilane **53b** was responsible of intercepting the incipient carbocation intermediate **XV** (Scheme 15a).[40] Subsequently, the team also accounted an analogous tandem reaction involving allylsilanes and oxabicyclic benzenes to give formal [3+4]-annulated compounds.[40c]

Finally, the gold assisted allylation reaction involving allylsilanes was shortly-after consolidated by Krause and coworkers (2009), in the allylation of dihydrofurans **57** and dihydropyrans.[41] The methodology proved efficiency in delivering a range of 2,6-dien-1-ols **58** under extremely mild and convenient conditions ($HAuCl_4$•$3H_2O$, 5 mol%, Scheme 15b). The nucleophilic intercepting of a transient allylic carbocation by **53a** was postulated as the reaction mechanism.



Scheme 15. Examples of gold catalyzed allylation reaction employing allylsilanes as alkylating agents.

3. Rearrangement reactions

The gold catalyzed rearrangement reactions have emerged as an indispensable synthetic shortcut to effectively conjugate molecular complexity and chemical economy.[42] As a matter of fact, the wide range of viable reaction mechanisms and the possibility to design manifold domino sequences make the gold-catalyzed rearrangements one of the most useful synthetic strategy to construct diversely functionalized carbocyclic, heterocyclic and acyclic scaffolds.

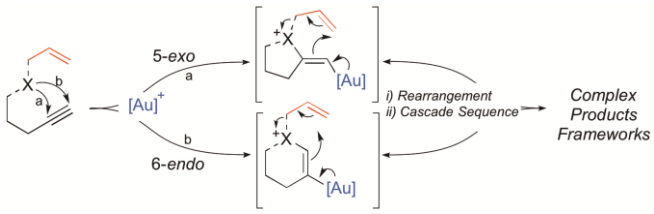
In this section, a survey of gold-promoted rearrangements engaging the transfer of "allyl" moieties is documented. The domino sequence is mostly initiated by a gold promoted event, such as the nucleophilic addition to an activated multiple bond or the rearrangement of a propargylic ester. A reactive intermediate is therefore generated, which typically undergoes concerted or stepwise allylic rearrangement followed by additional transformations under substrate-controlled regime.

3.1. Processes initiated by nucleophilic addition to alkynes

The unique ability of [Au(I)] and [Au(III)] catalysts to selectively activate alkynes towards the nucleophilic addition has found extensive applications, also becoming widely employed as the initial step of cascade processes involving rearrangements. The nature of the nucleophilic site and the interatomic distance between the atoms directly engaged in the migration process determine the subsequent mechanistic issues (*i.e.* chemo-, regio-, and stereoselectivity) of the chemical outcome.

3.1.1. Rearrangements of allyl vinyl onium-species

The addition of allyl-substituted heteroatoms to carbon-carbon triple bonds leads to the formation of reactive allyl vinyl onium-intermediates that commonly undergo gold-promoted allylic rearrangements (Scheme 16).

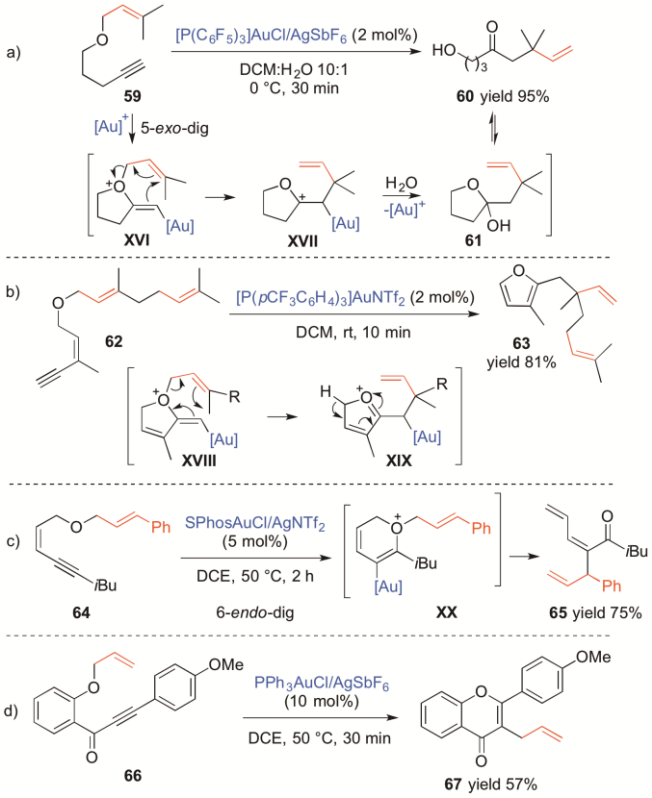


Scheme 16. Examples of gold-initiated cascade processes involving allylic rearrangement. Late-stage transformations lead to the synthesis of complex scaffolds.

3.1.1.1. Oxonium-species

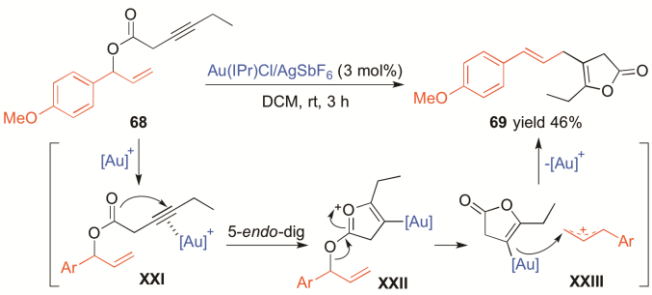
The intra- and intermolecular nucleophilic addition of oxygenated functions to gold-activated alkynes has been widely exploited to generate allyl vinyl oxonium species that can evolve through concerted or stepwise rearrangements. In particular, the intramolecular addition of ethers to gold-activated triple bonds with concomitant alkyl shift (formal intramolecular carboalkoxylation) attracted much attention, enabling the synthesis of a variety of furans and other heterocycles, as well as functionalized acyclic products.

Rhee and coworkers (2011) exploited the nucleophilic trapping of a cationic gold intermediate (**XVII**) to convert the 5-allyloxy-1-yne **59** into the corresponding γ-hydroxyketone **60**, via a hydration-terminated domino sequence involving alkoxycyclization/sigmatropic allyl migration (Scheme 17a).[43] An analogous 5-*exo*-dig approach applied to ynenyl allyl ethers **62** furnished substituted furans **63**, bearing a quaternary stereocenter (Scheme 17b).[44] Hashmi (2013) developed a complementary 6-*endo*-dig strategy, allowing internal ynenyl allyl ethers **64** to be transformed into 1,3,6-trien-4-yl ketones **65** via a [3,3]-sigmatropic rearrangement and a subsequent electrocyclic ring opening (Scheme 17c).[45] As last example, Gouault (2011) investigated the access to substituted chromones **67** by means of a 6-*endo*-dig ether-cyclization of alkoxy-arylalkynones **66**, followed by carbodemetallation via [1,3]-migration (Scheme 17d).[46]



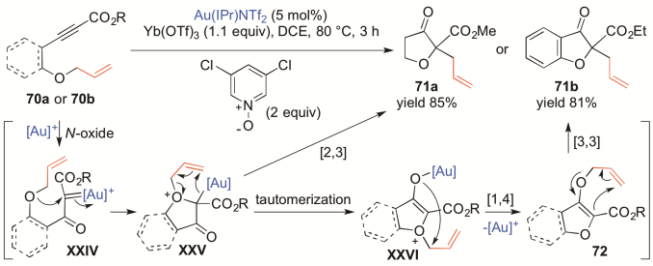
Scheme 17. Intramolecular gold(I)-mediated rearrangements of allyl vinyl oxonium intermediates generated from ethers.

Very recently (2015), Hashmi presented a novel synthesis of highly substituted γ-butyrolactones **69** achieved through a gold-catalyzed cascade reaction of benzyl esters **68** (Scheme 18).[47] The 5-*endo*-dig cyclization leads to an oxonium intermediate (**XXII**), which dissociates into a stabilized carbocation and a vinyl gold(I) species **XXIII**. The subsequent C-C coupling generated the lactone and released the catalyst. Although the process was proposed for propargyl esters, the reaction proceeds also on allylic substrates.



Scheme 18. Rearrangement of oxonium intermediate **XXII** generated from intramolecular ester addition to alkyne.

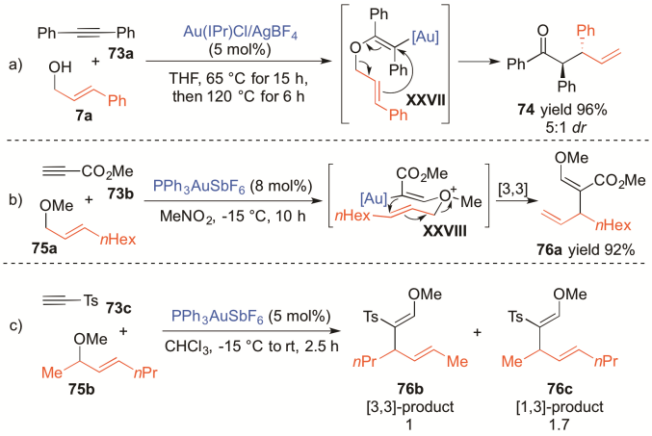
The rearrangement of allylic oxonium ylides was exploited by Yang and Tang (2013) to develop a novel synthetic approach to highly functionalized dihydrofuran-3-ones **71** (Scheme 19).[48] The strategy is based on the gold-catalyzed oxidation of allyl homopropargyl ethers **70** into α-oxo gold carbenes (**XXIV**), which can evolve through two different pathways. In particular, while aliphatic substrates preferably underwent a concerted [2,3]-sigmatropic rearrangement (product **71a**), aromatic analogous followed a stepwise mechanism, consisting of a tautomerization/1,4-allyl migration/Claisen rearrangement sequence (product **71b**). Disubstituted dihydrofuran-3(2*H*)-ones **71** were also obtained by Tae (2013) with the same approach employing slightly different substrates and catalytic system ($P(tBu)_2$(*o*-biphenyl)Au(ACN)SbF_6, 8 mol%).[49]



Scheme 19. Different rearrangement pathways for oxonium intermediates derived from gold(I)-catalyzed oxidation of allyl homopropargyl ethers to α-oxo gold carbenes **XXIV**.

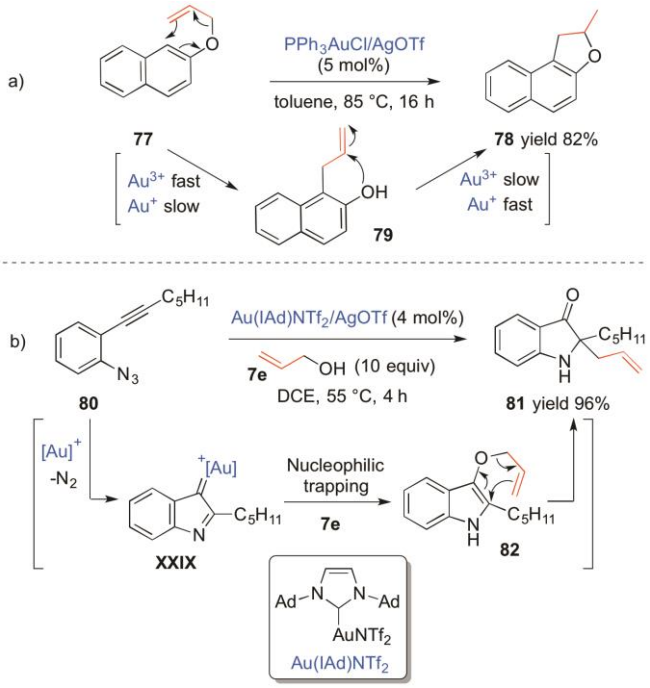
Despite the significant advancements achieved in homogeneous gold catalysis, the intermolecular coupling of alkynes with allylic systems is still a major challenge. In this regard, Aponick (2013) proposed a tandem intermolecular hydroalkoxylation/Claisen rearrangement, in which the key intermediate allyl vinyl ether **XXVII** is generated through the intermolecular gold-promoted addition of allyl alcohols to alkynes (Scheme 20a).[50] The enol ether olefin geometry was stereospecifically defined and substituted γ,δ-unsaturated ketones **74** were obtained in high yields and diastereoselectivity. Interestingly, Nolan and coworkers (2014) further investigated such a transformation, improving the environmental sustainability of the method and clarifying the reaction profile (*i.e.* gold assisted Claisen rearrangements) via computational tools.[51]

Shin and Rhee (2013) reported the gold(I)-catalyzed intermolecular coupling of allylic ethers with alkynoates **73b** [52] (Scheme 20b) and sulfonylacetylenes **73c** (Scheme 20c).[53] While in the case of alkynoates the [3,3]-sigmatropic rearrangement was strongly preferred, the sulfonylacetylenes underwent [1,3]- or [3,3]-rearrangement depending on the α-substituent of the ether.



Scheme 20. Oxonium-intermediate rearrangements achieved through intermolecular additions of allylic alcohols (a) and ethers (b, c) to alkynes (Ts: 4-methylbenzenesulfonyl).

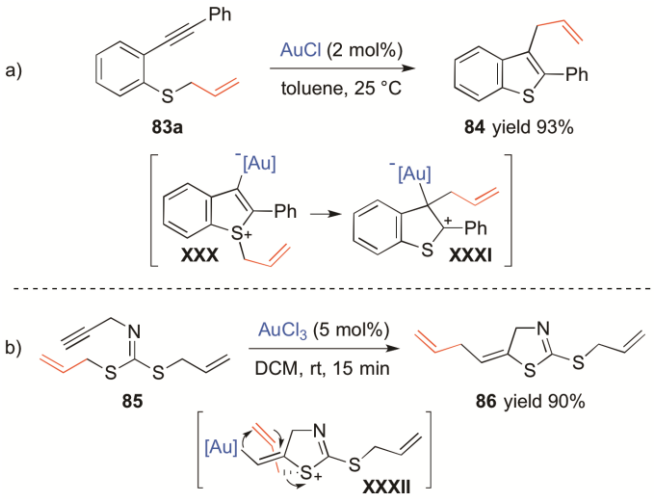
Examples of gold-catalyzed rearrangements taking place on allyl vinyl ethers (not oxonium) are showed in Scheme 21. A tandem process, consisting of a Claisen rearrangement followed by an oxalkylation of olefins, was proposed by He (2006) for the construction of dihydrobenzofurans **78**.[54] Although only [Au(I)]-based catalysts were able to promote both the reaction steps, the authors found [Au(III)]-species particularly efficient in the Claisen rearrangement (Scheme 21a). In 2011 Gagosz exploited the π-Lewis acid/electron donor properties of NHC gold(I)-catalysts to synthesize 3-oxindoles **81**, bearing a quaternary carbon center at C2 position (Scheme 21b).[55] The starting 2-alkynyl arylazide **80** was first converted into the α-imino gold carbene **XXIX**, which was trapped by an allylic alcohol acting as nucleophile. The subsequent gold(I)-promoted Claisen rearrangement cleanly provided the 2-allylindolin-3-one **81**. This remarkable transformation formally corresponds to the amino-oxy-allylation of the starting alkyne.



Scheme 21. Gold-promoted allylic rearrangements on allyl vinyl ethers.

3.1.1.2. Sulfonium-species

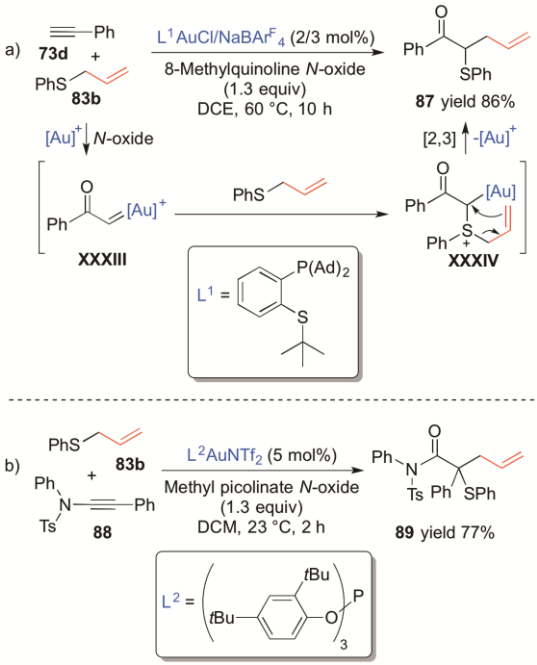
Nakamura and coworkers, in 2006, documented a seminal work on gold-catalyzed rearrangement/allyl migration sequence involving C-S bond forming processes (Scheme 22a).[56] This strategy enabled the direct synthesis of 2,3-disubstituted benzothiophenes **84** in excellent yields, starting from *ortho*-alkynyl benzenethioethers **83a**. The proposed mechanism retraces what is described for ethers in the previous section, but noteworthy is the absence of poisoning effects of sulfur-containing substrates on the gold catalyst. Stevens (2011) successfully applied a similar approach to *N*-propargylic dithiocarboimidates **85** to synthesize *E*-5-alkylidene-dihydrothiazoles **86** in a stereoselective manner (Scheme 22b).[57]



Scheme 22. [Au(I)] a) and [Au(III)] b) catalyzed rearrangements of allyl vinyl sulfonium-species.

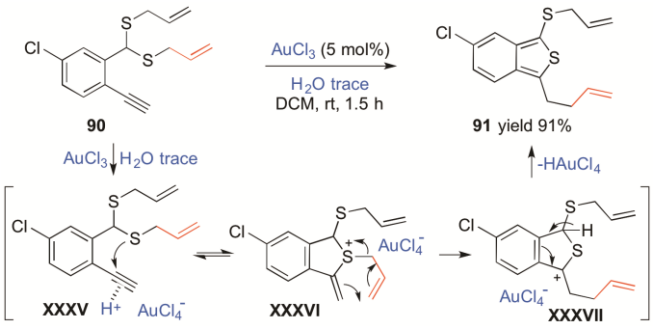
A few years later (2014), Zhang renewed the synthetic approach previously developed by Yang and Tang[48] (Scheme 19) involving the initial gold-catalyzed oxidation of alkynes into α-oxo gold carbenes (**XXXIII**, Scheme 23a).[58] Allyl thioethers were employed as external nucleophiles in the presence of a new generation of organometallic complexes. Here, the *P*,*S*-bidentate phosphine **L**^{1} enabled the formation of a tricoordinated, and hence more stable, α-oxo gold carbene intermediate **XXXIII** that efficiently promoted the final [2,3]-sigmatropic rearrangement to α-thio-γ,δ-unsaturated ketones **87**.

A further advancement in this direction was achieved by Davies (2014), by means of ynamides **88** that solved the issues of unsuitability related to terminal alkynes (Scheme 23b).[59] Here, densely functionalized tertiary thioethers **89** were isolated in good yield.



Scheme 23. Rearrangements of sulfonium-intermediates obtained from gold(I)-catalyzed intermolecular oxidation of alkynes to α-oxo gold carbenes.

A recent (2015) example of allyl vinyl sulfonium rearrangement was provided by Stevens (Scheme 24).[60] The authors demonstrated that the transformation of diallyl thioacetals **90** into the corresponding substituted benzo[*c*]thiophenes **91** was mediated by gold-superacid $HAuCl_4$, generated *in situ* from wet $AuCl_3$. Both the strong acidity and the nature of the counterion were crucial in order to prevent $AuCl_4^-$ from a detrimental covalent binding to **XXXVII**.

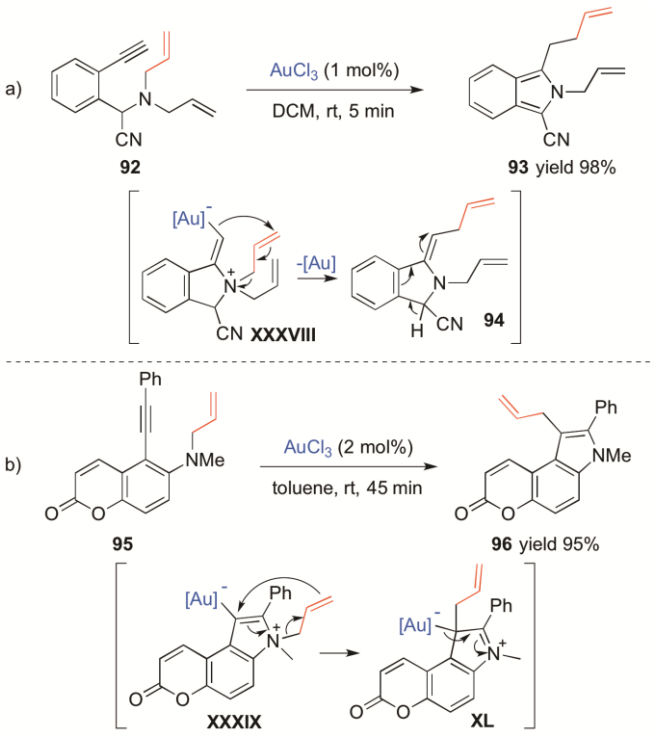


Scheme 24. Superacid-catalyzed intramolecular 5-*exo*-dig cyclization and allylic sulfonium rearrangement.

3.1.1.3. Ammonium-species

In 2009 Stevens and coworkers investigated the synthesis of 1-cyanoisoindoles **93** by means of $AuCl_3$-catalyzed 5-*exo*-dig heteroannulation reaction followed by [1,3]-alkyl migration and

1,5-prototropic aromatization (Scheme 25a).[61] Low catalyst loading and high efficiency were the peculiar features of this strategy. The authors hypothesized a concerted mechanism for the gold-catalyzed process, and a stepwise pathway for the analogous microwave-induced reaction. A similar approach was proposed by Majumdar (2011), who described the synthesis of allyl functionalized pyrrolocoumarins **96**, pyrroloquinolones and other indole-containing heterocycles (Scheme 25b).[62] In this case, a 5-*endo*-dig cyclization of substituted anilines takes place, instead of the 5-*exo*-dig ring closure reported by Stevens. The excellent yields achieved in short reaction time and mild reaction conditions make this protocol attractive for the construction of complex heterocycles.

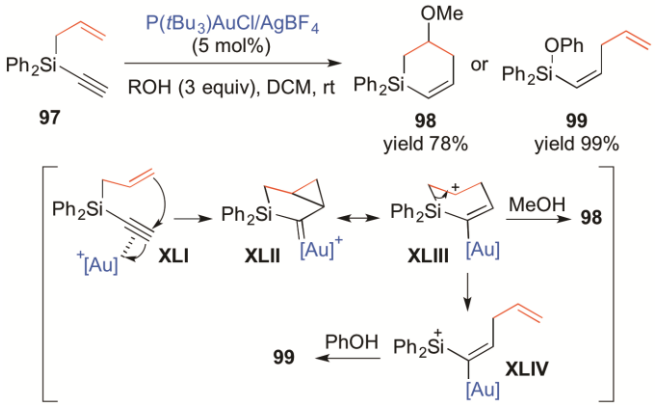


Scheme 25. Gold(III)-mediated rearrangements of allyl vinyl ammonium-intermediates.

3.1.2. Ene-Yne reactions on allyl silanes

The replacement of heteroatomic-based nucleophiles with electron-rich carbon-based π-systems (*i.e.* alkenes) resulted in an ene-yne condensation that found significant credits in cascade transformations involving allyl silanes.

In 2006 Toste proposed a gold(I)-promoted sila-Cope rearrangement of acetylenic allyl silanes **97**, proceeding through a cyclization induced rearrangement (CIR) mechanism.[63] The 6-*endo*-dig cyclization selectively provided the silacycle **98** in the presence of alkyl alcohols, whereas the preference was completely reversed to *cis*-1,4-dienyl silane **99** employing the less nucleophilic phenol (Scheme 26). Several substituents were tolerated on the alkyne, but variations on the allylic moiety often affected the product distribution negatively.

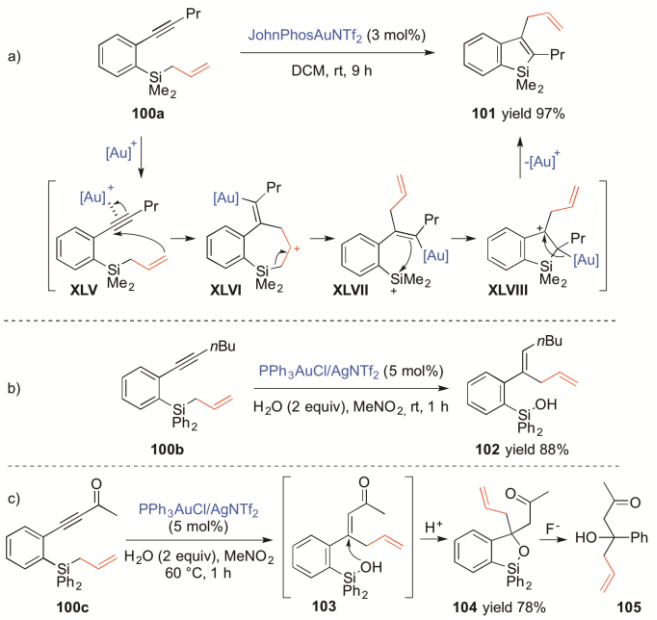


Scheme 26. Gold(I)-catalyzed ene-yne reaction and cyclization induced rearrangement (CIR) involving acetylenic allyl silanes.

In the same year, Lee studied the gold(I)-catalyzed stereoselective synthesis of alkoxy vinyl silanes via alcoholysis of alkynyl allyl silanes.[64] The authors, employing a slightly different catalytic system ($PPh_3AuCl/AgSbF_6$, 1 mol%), recorded the selective formation of the vinyl silanes for a range of alcohols and differently substituted acetylenic allyl substrates.

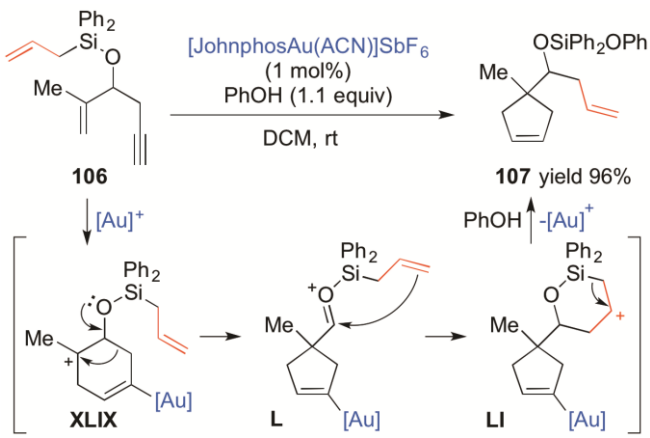
A related mechanism was proposed by Murakami (2008) for the construction of 3-allyl-1-silaindenes **101** via gold(I)-catalyzed *trans*-allylsilylation of silicon-tethered enynes **100a** (Scheme 27a).[65] The initial 7-*exo*-dig cyclization is followed by a ring opening to cationic silyl species **XLVII**, directly cyclized by the alkenylgold function present in the molecule. The final demetallation furnished the silaindene **101** and regenerated the catalyst. In 2014, Xia carried out a comprehensive DFT study providing insights into many aspects of the process mechanism, among them the divergent and substrate-dependent reaction pathways.[66]

Slight variations on the catalytic system and the presence of water in the reaction medium were documented by Kuroda (2010) in transforming analogues silicon-tethered enynes **100b** into 1,4-dienylsilanes **102** (Scheme 27b).[67] Afterwards, Horino (2014) applied the latter protocol on enynes **100c** bearing a ketone group in the propargylic position (Scheme 27c).[68] The combination of *in situ* formed Brønsted acid and water enabled the intramolecular conjugate addition providing bezoxasiloles **104**, which could be easily transformed in to β-carbonyl tertiary homoallylalcohols **105**.



Scheme 27. Examples of ene-yne reactions and subsequent rearrangements involving *ortho*-alkynyl phenyl allyl silanes.

At the end of this section, we report the manifold work presented by Lee in 2012.[69] A tandem sequence consisting of ene-yne carbocyclization/rearrangement to oxonium cation/allyl silane trapping was developed. The authors proposed first an intramolecular allyl transfer process (Scheme 28), and then an intermolecular version of the same reaction, in which two different oxonium intermediates were sequentially formed, respectively trapped by an alcohol and by an external allyl silane.

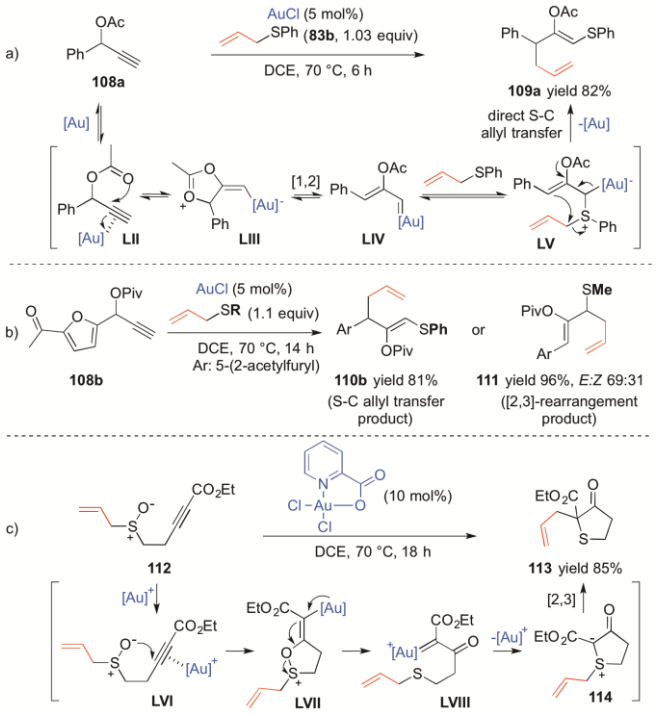


Scheme 28. Gold(I)-catalyzed ene-yne carbocyclization/rearrangement to oxonium cation/allyl silane trapping sequence.

3.1.3. Rearrangements on propargylic carboxylates

The gold-catalyzed rearrangements of propargylic carboxylates have been widely employed as starting point for a variety of efficient synthetic methodologies.[70] In particular, in this section we will document a series of cascade processes, in which a first propargylic carboxylate makes possible the subsequent allylic rearrangement.

In 2008, Davies presented a gold(I)-catalyzed intermolecular coupling between propargylic esters **108a** and allyl sulfides **83b** (Scheme 29a).[71a,b] The initial 1,2-rearrangement (**LIV**) was followed by the sulfide nucleophilic attck, generating the ylide **LV**. The final oxygen-assisted 1,4-shift provided the product **109a** only as *Z* isomer. Afterwards (2012), the authors applied the protocol to heteroaromatic substituted propargylic esters **108b** (Scheme 29b), obtaining two different products depending on the bulkiness of the non-migrating group (-R) on the sulfide.[71c] At last, Davies also proposed an interesting intramolecular related transformation starting from alkyne-tethered allyl sulfoxides **112** (Scheme 29c).[71d] An internal redox-combination allows the directly access to α-carbonyl gold-carbenoid **LVIII** and therefore the sulfur ylide **114**, which underwent the final [2,3]-rearrangement.

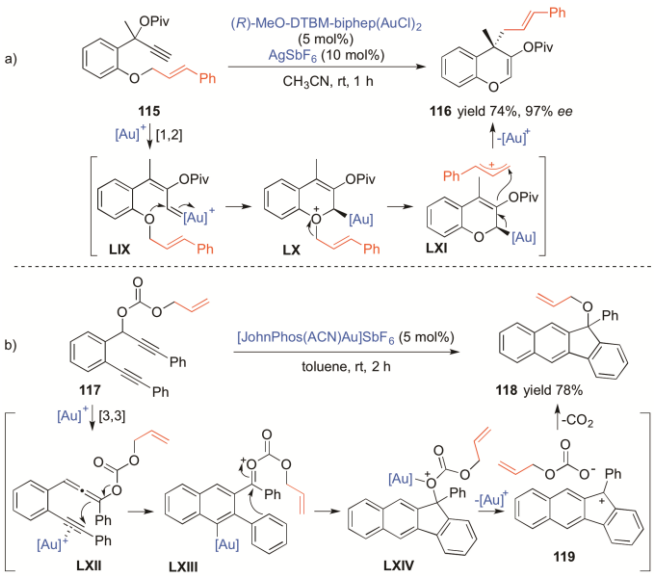


Scheme 29. Gold-promoted propargylic ester rearrangements as initiating step of tandem sequences involving allylic rearrangements.

In 2009, Toste developed the first enantioselective gold(I)-catalyzed carboalkoxylation of propargylic esters **115**, affording chiral benzopyrans **116** containing a quaternary stereocenter (Scheme 30a).[72] Initially, the 1,2-migration of propargylic ester provided the carbenoid-gold species **LIX** which was intramolecularly attacked by the ether oxygen. Experimental

evidences suggested that the oxonium intermediate **LX** evolved into an allyl cation **LXI**, which condensed intermolecularly with the allyl-gold nucleophile.

A few years later (2012), Liu reported a cascade cyclization of 1,6-diynyl carbonates **117** to benzo[*b*]fluorenes **118** (Scheme 30b).[73] In this case, the process was initiated by a [3,3]-rearrangement of the propargylic carbonate to carboxyallene **LXII**, which acted as nucleophile adding to the gold-activated alkyne. The generated oxocarbenium ion **LXIII** was sufficiently stabilized by the carbonate ion to be intramolecularly engaged in a FC-type alkylation. The subsequent gold-promoted decarboxylative etherification provided the expected product.



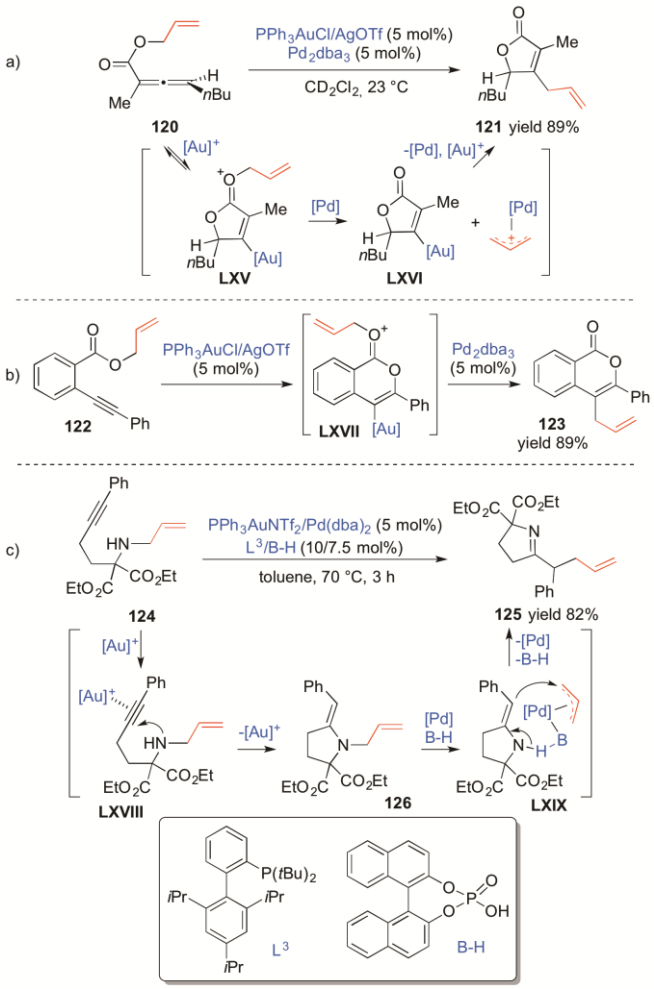
Scheme 30. Intramolecular cascade processes initiated by [1,2] a) or [3,3] b) propargylic carboxylate rearrangement and involving intermolecular allylic rearrangements.

3.1.4. Dual-catalyzed transformations

Dual-catalyzed reactions, which are promoted by the contemporary presence of two different metals, are particularly attractive as they enable innovative reactivity and selectivity with respect to single-metal based catalytic systems.[74]

In 2009, Blum and coworkers proposed the term *catalyzed catalysis*, to describe the ability of Au species to generate intermediates with increased reactivity toward oxidative addition by Pd-catalysts.[75] In many cases, the vinyl-gold species (**LXVI** in Scheme 31a) underwent protodemetallation. The introduction of a Pd-catalyst enabled the rearrangement with C-C bond formation, increasing the synthetic value of the transformation. The authors started applying the Au/Pd dual-catalytic system to the synthesis of substituted butenolides **121** from allenoates **120** (Scheme 31a) and to *o*-alkynyl allyl benzoates **122** (Scheme 31b). Crossover experiments proved the intermolecular nature of the allyl transfer. In this segment, it should also be highlighted that, in 2012, Hashmi reported on the efficiency of the gold-free [Pd(0)]/[Ag(I)] couple in the cross-coupling on allenoates.[76] Furthermore, while *o*-alkynyl benzyl benzoates were successfully transformed exclusively in the presence of [Au(I)]-catalysis, *o*-alkynyl benzoates **122** also reacted, even if in lower extent, under [Pd(II)] regime.

In the same year (2012), Gong proposed an interesting example of relay and cooperative catalysis, based on a gold/palladium/Brønsted acid ternary catalytic system.[77] Dihydropyrroles **125** were obtained in high yields via a tandem hydroamination/allylic alkylation process (Scheme 31c). The authors demonstrated that all the catalytic species were required: the gold-complex promoted the hydroamination step, while palladium and Brønsted acid cooperated in the "allyl" transfer.



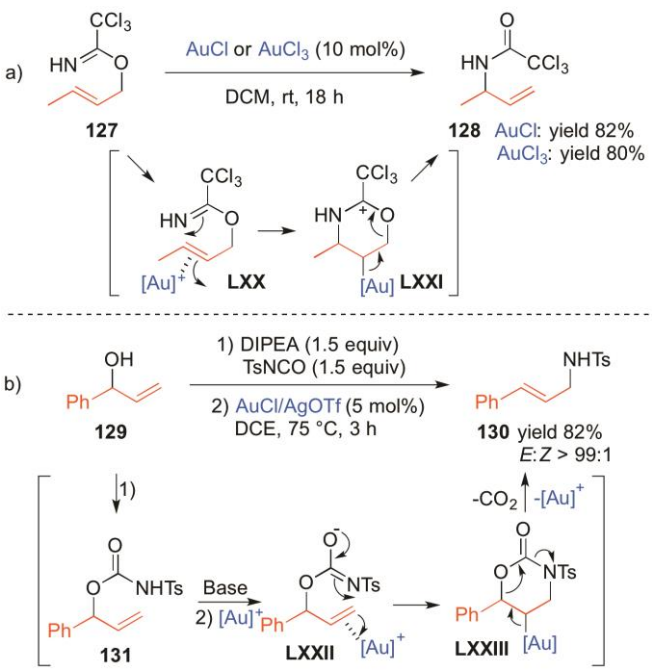
Scheme 31. Au/Pd dual catalytic systems applied to intermolecular allylic rearrangements (a and b). c) Ternary catalysis in the synthesis of dihydropyrroles **125**.

3.2. Processes initiated by nucleophilic addition to alkenes

The previously described capability of gold(I)/(III) species to interact with more challenging unsubstituted C=C frameworks prompted synthetic chemists to face and develop allylic rearrangements involving initial intramolecular nucleophilic additions to alkenes. Among many, the most diffuse application concerns the conversion of allyl alcohols into allyl amines.

3.2.1. From allyl alcohols to allyl amines

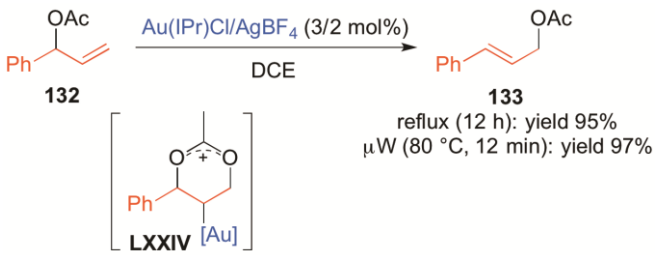
A series of Claisen-like rearrangements on allylic substrates have been described over the past decade. In 2005 Jirgensons reported on the transformation of *O*-allyltrichloroacetimidates **127** into *N*-allyltrichloroacetamides **128**, already known as the "Overman rearrangement", efficiently mediated by catalytic amounts of AuCl or $AuCl_3$ under mild conditions (Scheme 32a).[78] Several structurally diverse trichloroacetamides were obtained in moderate to good yields. The slightly better results recorded lowering the gold oxidation state supported the CIR mechanism, already proposed for the catalytic Overman rearrangement. This transformation was further developed by Yang (2011), who broadened the substrate scope and reduced the reaction time operating in water at 55 °C.[79a] The same authors also reported the gold(I)-catalyzed base-induced decarboxylative aza-Claisen rearrangement of allylic *N*-tosylcarbamates **131** (Scheme 32b).[79b,c] High yields and stereoselectivity in favour of the *E* isomers were obtained. The success of the reaction strongly depended on the NH acidity of the carbamate and on the presence of a base, which promoted the process and prevented side-reactions.



Scheme 32. Gold-catalyzed rearrangements converting allyloxy- into allylamino-derivatives.

3.2.2. From secondary to primary allyl acetates

The possible access to primary allyl acetates **133** from secondary congeners **132** was efficiently proved by Nolan and coworkers (2007, Scheme 33).[80] Here, the optimized catalytic system comprised sterically hindered NHC-based gold species and promoted the allylic rearrangement in satisfactory manner. Interestingly, the challenging construction of trisubstituted olefins in stereochemically defined fashion was finally accomplished. The CIR mechanism proposed by the authors was confirmed afterwards (2009) by a computational investigation on different reaction pathways.[81]

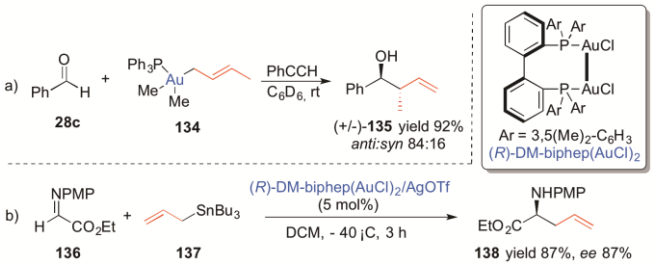


Scheme 33. Gold-catalyzed rearrangement converting secondary into primary allyl acetates.

4. Miscellaneous

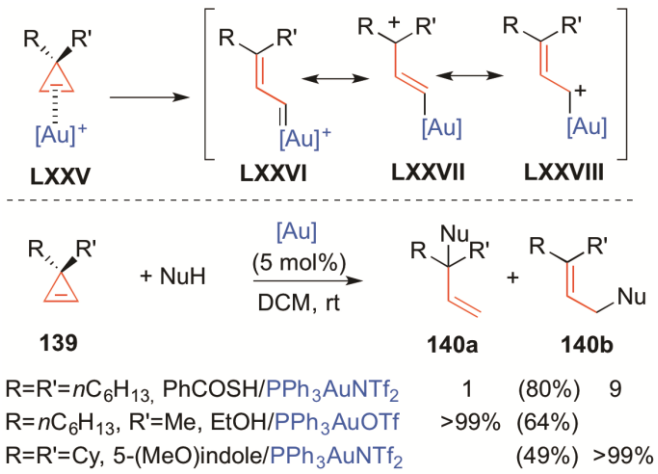
Homogenous gold catalysis has been also employed in allylating procedures dealing with Lewis acid promoted addition of allylstannanes to carbonyls. As a pioneering work, it should be cited that allyl-[Au(III)] species **134** has been reported to react with carbonyl compounds (*i.e.* benzaldehyde **28c**) in a S_N2'-fashion, delivering the corresponding homoallylic alcohols **135** in good extents (Scheme 34a).[82]

An elegant enantioselective allylation of imines was documented by Mikami and coworkers (2011) in the presence of enantiomerically pure *tropos*-DM-biphep$(AuCl)_2$ complexes.[83a] Interestingly, despite the intrinsically low-energy rotation barrier of unsubstituted biphenyl scaffolds, the complexation with gold atoms confers rigidity to the structure due to intramolecular attractive interatomic aurophilic interaction. This behavior enables the isolation and utilization of enantiomerically pure binuclear complexes upon resolution with chiral anions.[83b,c] Homoallylic secondary amines **138** deriving from glyoxylate imines **136** were isolated in moderate to high enantiomeric excesses (up to 87%) with 5 mol% of chiral catalyst (Scheme 34b).



Scheme 34. a) Seminal work on the nucleophilic allylation of carbonyls with stoichiometric organogold(III) species (**134**). Phenylacetylene was used as a proton source. b) Enantioselective synthesis of homoallylic amines **138** by means of enantiomerically pure atropoisomeric gold complexes.

The gold-assisted nucleophilic ring-opening of cyclopropenes (**139**) is an elegant and exploited methodology to allylated compounds.[84] In particular, the capability of electrophilic [Au(I)] complexes to deliver positively charged organogold intermediates, featuring carbocation (**LXXVII**/**LXXVIII**) and carbene (**LXXVI**) characters, was exploited in the regioselective formation of new C-C and C-X bonds. Some representative examples have been reported in the Scheme 35.

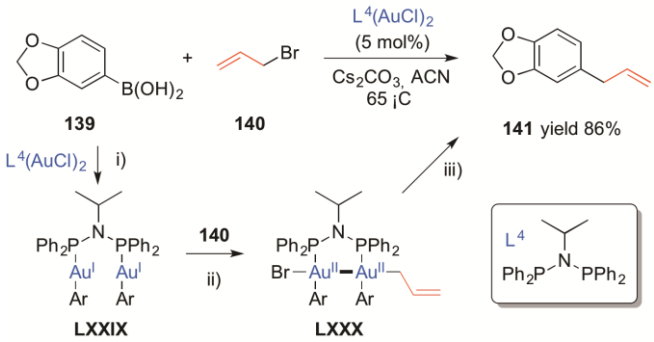


Scheme 35. Gold catalyzed regioselective nucleophilic ring-opening of cyclopropenes.

Last but not the least, a different direct and convenient approach to electrophilic gold alkenyl carbenoid species was documented by López. Here, Au(IPr)(ACN)SbF_6 (5 mol%) transformed vinyldiazoacetates into organogold allylating agents, that can be trapped both by substituted ferrocenes and ruthenocenes in good yields.[85]

Up to now, only allylating procedures involving gold species that did not modify their oxidation states during the catalytic cycle were presented. As a matter of fact, this aspect is still considered a crucial prerogative in homogenous gold catalysis. However, several synthetic applications of redox gold catalysis have been reported in the presence of sacrificial stoichiometric oxidants, mainly based on I^{3+} and F^{+} compounds.[86]

In the context of allylating reactions, Toste very recently described a notable cross-coupling methodology for the creation of new C_{sp3}-C_{sp2} bonds through the condensation of allyl bromide and aryl-boronic acids.[87] The principal limitation related to gold centered cross-coupling events (namely: slow alkyl-alkyl reductive elimination) was circumnavigated by addressing a much faster alkyl-aryl coupling and by employing a specific binuclear gold species. In particular, the amino-biphosphine ligand **L^4** is thought to facilitate the oxidative addition step by forming [Au(II)-Au(II)] intermediates instead of the expected [Au(III)] counterparts (Scheme 36). Under optimal conditions, a wide range of allylated arenes **141** was isolated in moderate to good yields. It is worth mentioning, based on mechanistic insights, the following catalytic sequence was proposed: i) [Au(I)]/boronic acid transmetallation, ii) oxidative addition with the allyl bromide and iii) reductive elimination.



Scheme 36. Oxidant-free gold catalyzed cross-coupling between boronic acids and allyl bromide. Proposed elementary steps for the catalytic cycle.

5. Conclusions

Homogeneous gold catalysis and allylation reactions represent two concrete realities in the synthetic organic chemistry panorama. The merging of these aspects contributed substantially to both sides: creating new opportunities to install “allylic” units into organic motifs and discovering new reactivity/activation modes of the metal species. This “autocatalytic” process has rapidly brought to a full comprehension and exploitation of gold-mediated allylating methodologies, paving the way for the realization of innovative and sustainable synthetic routes to chemical complexity.

From the examples collected in the *Minireview* the wide range of applicability of this protocol clearly emerged, ranging from natural product synthesis to methodology development.

A particular mention goes to the massive efforts devoted towards the comprehension of corresponding reaction profiles, by means of synergistic experimental, spectroscopic and computational tools, that keep prompting chemists towards the development of even more sustainable variants.

Certainly the game is not over. Challenging tasks such as the combination of enabling techniques (*i.e.* photoredox catalysis, flow-chemistry…) or tackling hot-topic transformations such as C-H activation are only few of the possible future goals on the use of homogeneous catalysis in allylation processes.

6. Acknowledgments

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Keywords: Allylation • Catalysis • Gold • Reaction mechanism • Selectivity

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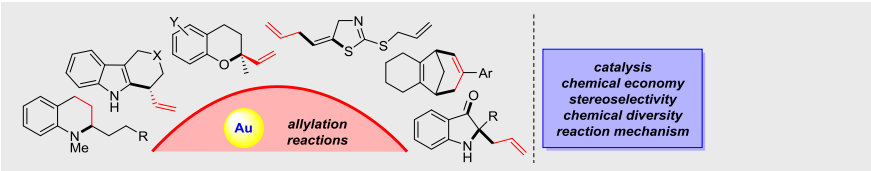

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Gold Catalyzed Allylation Reactions

Golden ***Ally***lation. Some of the most salient gold-mediated allylic alkylating protocols are presented. Features and limitations of the methodologies are highlighted with particular focus on the strategic role played by gold during the reaction machinery.