CHEMICAL REVIEWS

REVIEW

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Transition Metal Catalyzed Cycloisomerizations of 1,*n*-Allenynes and -Allenenes

Corinne Aubert,* Louis Fensterbank,* Pierre Garcia, Max Malacria,* and Antoine Simonneau

Institut Parisien de Chimie Moléculaire (UMR CNRS 7201), UPMC Univ Paris 06, 4 place Jussieu, C. 229, 75005 Paris, France

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1. INTRODUCTION

Allenes have always fascinated chemists because of the intriguing features of the cumulated diene function such as the higher reactivity compared to simple alkenes and the peculiar axial chirality of the elongated tetrahedron system. For a long period, allenes have been considered more as chemical curiosities and unstable unsaturated moieties than reliable partners which has retarded the development of their synthetic applications. However, allenes have become increasingly popular over the last twenty years. They have notably been involved in fields where their use was previously limited, such as radical chemistry or transition metal-mediated reactions. Since the 1980s monographs on allenes, a series of books and an important flow of reviews and current articles have appeared,[1] reflecting the growing interest about the synthesis and the reactivity of allenes. It is also worthy of note that at the same time, isolation and characterization of allenic natural compounds have been pursued and about 150 natural products containing an allenic or a cumulenic structure are now known,[2] which has provided incentive for their synthesis.[3]

Thus, allenes have been proved to be reactive toward transition metals and good selectivities have been obtained by playing with the nature of the metal and the ligands. Therefore, important organometallic processes have been examined. In particular, the high density of unsaturations of allenes makes them premium candidates for cycloisomerizations which are among the most popular methods for the construction of carbo- and heterocyclic compounds. Beside their mechanistic interests, these reactions also serve at the starting point of new synthetic strategies and allow an increasing of molecular complexity in a context of atom-, step-, and redox- economy[4] and development of greener reactions conditions. While the cycloisomerizations of 1,*n*-enynes have been often described,[5] the number of transition metal-mediated cyclizations involving allenes has considerably increased since a few years.[6]

This review will summarize advances on the cycloisomerizations of 1,*n*-allenynes and 1,*n*-allenenes. Herein, cycloisomerization will refer to the formation of new carbon−carbon bonds to accomplish the assembly of carbocyclic rings or heterocyclic rings for precursors containing heteroatoms based tethers. The synthesis of heterocyclic rings through the generation of C−X bond (X = O, N) has been excluded because of its large scope, and therefore, we will only consider the cyclizations taking place between allenes and other C−C multiple bond rather than with a nucleophile (alcohols, amines, etc.). On the basis of genuine cycloisomerization processes, we have not retained cyclocarbonylation as well as processes necessitating a preliminary hydro-, carbo-, or heterometalation. We have however dealt with π-acid catalyzed processes involving a preliminary, intermediate or final nucleophilic trapping, because these totally new reactions bear some new and highly conceptual value.

This review is organized considering the mechanistic possibilities that have been proposed for the cycloisomerization of 1,*n*-allenynes and -allenenes depending on the metal nature or more precisely on the choice of the precatalyst and on reaction conditions (Scheme 1). Over the several studies we have selected for this work, we initially chose to divide them into two distinct

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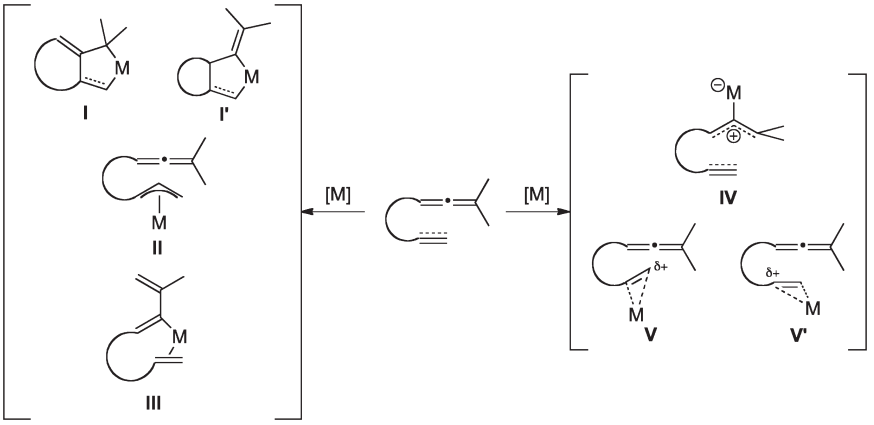
Scheme 1. Different Mechanistic Pathways for Allenynes/Allenenes Cycloisomerizations



parts according to the coordination mode of the metal onto the substrate. On one hand, metals that doubly coordinate to the allenyne/ene and give rise to intermediates of types **I**, **I**′ (metallacycles), **II** (π-allylmetal), or **III** (vinylmetal, Scheme 1, left side) with a change of the oxidation state of the latter are the object of the first part of this review. On the other hand, the metals that activate selectively one of the insaturations and act as formal Lewis acids that lowers the electronic density on the substrate are the object of the second part. These metals, grouped together under the appellation "π-acids", can give rise to allylic cation **IV** upon coordination onto the allene, or make appear positive charges on one carbon of an activated triple bond (depicted as slipped alkyne-metal complexes **V** and **V**′, Scheme 1, right side).

To bring the final touch to this introduction, and for more clarity, we want to inform the reader about the nomenclature we chose to name the cyclization precursors which also correspond to the commonly met appellation in the literature: 1,*n*-allenynes are numbered from the external carbon atom of the triple bond (Figure 1, left side), 1,*n*-allenenes from the external carbon atom of the allene moiety (Figure 1, middle side) and 1,*n*-bisallenes from both internal carbon atoms of the allene moiety.

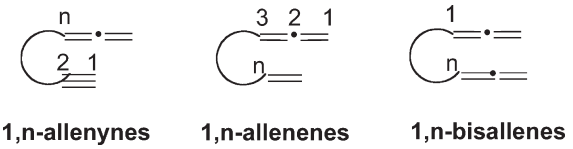


Figure 1. Nomenclature.

2. METALLACYCLES, Π-ALLYL METAL COMPLEXES, AND VINYLMETALS

2.1. Metallacycle Pathway

2.1.1. 1,*n*-Allenenes. In 1978, the report of a Pd(0) catalyzed vinylallene dimerization[7] opened a new area in the transformations of unsaturated allenes. Ito and Murakami in the nineties followed on that seminal work and provided evidence that transition metals can react with vinylallenes such as **1** to generate metallacyclopentenes complexes **2a** and **2b** (Scheme 2).[8] Since then, the metallacycle pathway has been widely invoked in allenynes and allenenes metal-catalyzed cycloisomerization.[9] Beyond the obvious disposition of allenes to generate metallacyclopentane derivatives, these authors reported remarkable use of such metallacycles for rhodium-catalyzed carbonylative [4 + 1] cycloaddition,[10] palladium- and rhodium- catalyzed [4 + 2] cycloaddition,[11,12] as well as palladium-catalyzed [4 + 4 + 1] and [4 + 4] cycloadditions.[13,14]

1,7-Allenenes, unlike vinylallenes (1,4-allenenes), which generally require an additional reagent such as CO to react, undergo efficient cycloisomerization (Scheme 3). Indeed, when reacted in the presence of dimeric rhodium complex $[RhCl(cod)]_2$ and phosphite ligands, various 1,7-allenenes **3** featuring a wide range of tethers (e.g., X = CE_2, NTs, NBn, O) have been efficiently transformed into the corresponding 1,4- and 1,5-dienic five-membered carbocycles **4**−**8**.[15]

Several points should be underlined. The reaction shows some stereospecifity as illustrated by the transformation of the *Z*- and *E*-styryl precursors **3** giving the *Z* and *E*-exobenzylidene products **6** and **7**, respectively. Interestingly also, it should be noted that the corresponding unsubstituted 1,6-diene (with Y = $C(E)_2$) showed no reactivity with this catalytic system suggesting the crucial role of the allene function. Presumably, initial coordination of the internal double bond of the allene and of alkene moiety by a mononuclear rhodium(I) phosphite complex as in **10** would result, after oxidative cyclization, in the generation of a rhodacyclopentane(III) of type **11** (Scheme 4). Regioselective subsequent β-H elimination involving H_b because of a better overlap of the C−H_b bond with the Rh−C bond would generate intermediate **12**. When R_3 or R_4 is a methyl group, the β-elimination is favored on that group and gives product **8**. For substrates bearing a monosubstituted allene unit (R^1 or R^2 = H or alkyl, R^3 = R^4 = H), a *E*-stereoselective formation of **5** (Scheme 3) is observed for which no obvious rationalization could be given. The reaction is compatible with different tethers as illustrated by the formation of products **4**. Interestingly also, on changing the catalytic species, that is, using Wilkinson complex or even better $[RhCl(CO)_2]_2$, precursors **3** with R^1 = R^2 = Me and R^3 = R^4 = H, led to cycloheptadiene products **9** in high yields, notably under CO atmosphere. This diverging reactivity could be explained by the intervention of a π-allyl rhodium-hydride originating from a preliminary allylic C−H activation, as detailed in section 2.2.1.

With the same approach, the authors have reported one example of conversion of a 1,8-allenene **13** into a 6-membered

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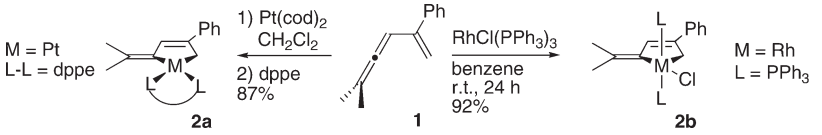
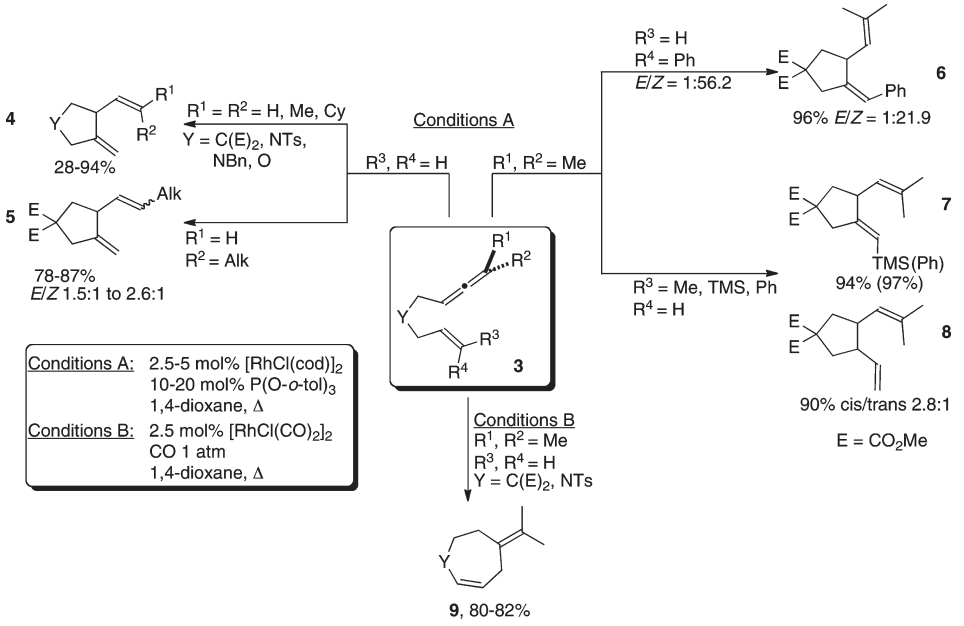
Scheme 2. Synthesis of Metallacyclopentene



Scheme 3. [RhCl(cod)]$_2$-Catalyzed Cycloisomerizations of 1,7-Allenenes



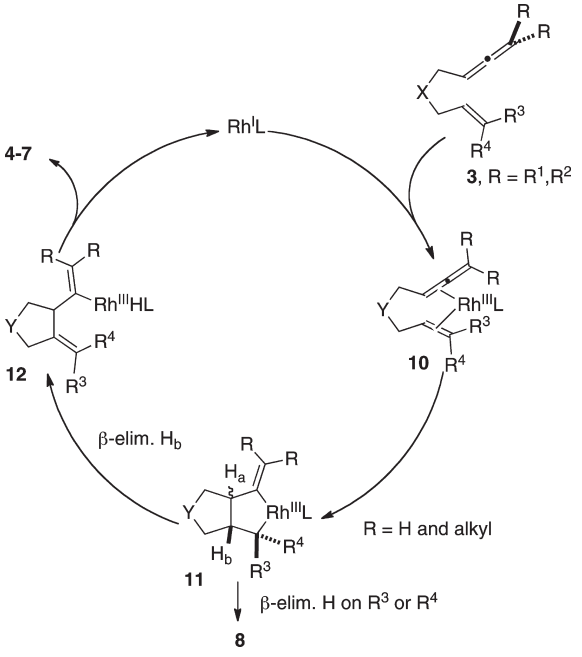
carbocycle **14**, however in the presence of 10 mol % of catalyst, which corresponds to 20 mol % of rhodium (Scheme 5).

1,5-Bisallenes are a subclass of 1,7-allenenes possessing an additional external double bond. From ones bearing terminally unsubstituted allenes (**15a**), Ma reported that palladium catalysis furnishes bicyclo [3.2.0] compounds **16** presenting a 1,4-butadiene pattern (Scheme 6).[16] Formation of the four-membered ring has been rationalized by a favored reductive elimination (as in **18** to **19**) because of the I^- ligand coming from tetrabutylammonium iodide (TBAI).[17,18] Interestingly, when X is a chiral L-valine ester derivative, an almost enantiomerically pure compound is obtained (**19**, 99% *ee*). These findings prompted the authors to propose a diastereoselective model involving coordination of palladium to the nitrogen lone pair.

On varying the rhodium precatalysts or the substitution of bisallenes **15**, different reactivity patterns have been observed. Indeed, using *trans*-RhCl(CO)(PPh$_3$)$_2$, dimerization through an initial formation of a bicyclic rhodacyclopentane, followed by coordination of an other allene part of the starting bisallene and subsequent insertion affords steroid like structures **20**,[19] substituted 1,5-bisallenes furnish seven-membered ring trienic systems **21** with either [RhCl(CO)$_2$]$_2$, [RhCl(cod)]$_2$ or [RhCl(CO)dppp]$_2$ complexes (Scheme 7) .[20,21]

In the same vein, Mukai has studied the behavior of 1,*n*-bis(sulfonylallenes) under Rh catalysis (Scheme 8). While 1,6-bisallene substrates under carbonylative conditions in the presence of 1 atm of CO furnish efficiently bicyclo[6.3.0]undecanedienones Pauson Khand (PK) adducts, reactions under N_2 could give high yields of cycloisomerization products incorporating a cyclooctene subunit. Even undecatetraene precursors **22** could provide good yields of exobisdienes **23** sometimes accompanied by bicyclo[7.2.0] products **24**.

Scheme 4. Mechanism for the [RhCl(cod)]$_2$-Catalyzed Isomerization of 1,7-Allenenes



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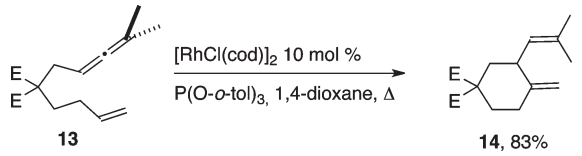
Ma has rationalized the formation of seven-membered cross-conjugated trienes **21** through a mechanism sequence involving: (1) formation of a rhodacyclopentane **25**, (2) regioselective hydride elimination to give **26**, and (3) reductive elimination (path A, Scheme 9).[20] In the case of bis(sulfonylallenes), the recent studies by Mukai[21] converge to the following mechanistic manifold. After formation of the initial rhodacycle **25**, a direct reductive elimination can afford the formal [2 + 2] adduct **27**. The latter, which is hardly available through thermal conditions, is not an intermediate in the formation of the cross-conjugated triene **29** since no interconversion was observed in the presence of the rhodium catalyst. Alternatively, a thermal 1,5-H shift[22] on the starting rhodacyclopentane bearing an internal 1,3-diene would furnish rhodacyclopentene **28**, which then undergoes reductive elimination giving cross-conjugated trienes **29**. As outlined by Mukai,[21b] a third pathway from an allylic C−H activation/carbometalation/reductive elimination (π-allylmetal path) cannot be ruled out. In this mechanistic proposal, it is noteworthy that the initial metallacycle formation involves the external allene double bonds which differs significantly from the works of Itoh,[15] where the internal bond is reacting (see Scheme 4).

Ring closing metathesis of allenynes (see section 2.1.2 and Scheme 25)[23] or allenenes[24] is very little described. Interestingly, these substrates can lend themselves to nonmetathetic diverging pathways upon exposure to Grubbs' catalyst as discussed now.[25] The first attempt to perform RCM on 1,*n*-allenenes was reported in 2001 by the group of Rutjes.[26] In the presence of both first and second-generation Grubbs' catalysts, 1,8-allenenes **30** were unsuccessfully reacted affording starting material or isomerized diene **31** (Scheme 10).

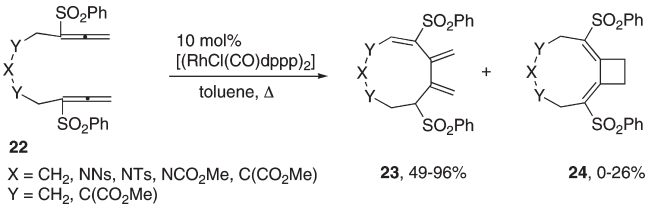
Considering the results of Scheme 10, Mukai has investigated in 2006 the transformation of 1,7-allenenes **32** with Grubb's catalyst.[27] Seven-membered rings were expected as a result of an initial isomerization as in Rutjes' work followed by RCM. Incidentally, cyclohexene derivatives **33** were observed thanks to an intermediate ruthenacyclopentane formation (**34**) involving the external allene bond (Scheme 11).[28] Of note is the absence of reactivity of persubstituted allenes and 1,8-allenenes under these conditions and the fact that an ene-type mechanism for the formation of **33** was discarded.

2.1.2. 1,*n*-Allenynes. Malacria reported the first transition metal-mediated isomerization of allenynes (Scheme 12).[29−31] In the presence of a stoichiometric amount of $CpCo(CO)_2$, 1,6-allenynes **36** afford 2:3 mixtures of the formal Alder-ene six-membered carbocycle **37** and of cobalt complex **38**. Even if reactions involving bisalkyne-allenes have been reported to furnish [2 + 2 + 2] cycloadducts under cobalt catalysis,[32] here no such cycloadducts were detected.[33] Presumably, a sequence of standard cyclometalation (**39**), β-H elimination (**40**), reductive elimination takes place. The formation of the cobalt complex **38** would originate from a cobalt-mediated migration of the double bond via a η^3-allyl hydride complex **41**.[34] Even if cobalt was the first metal to exhibit interesting properties and give seminal results, no catalytic transformation with the latter metal has been reported.[35]

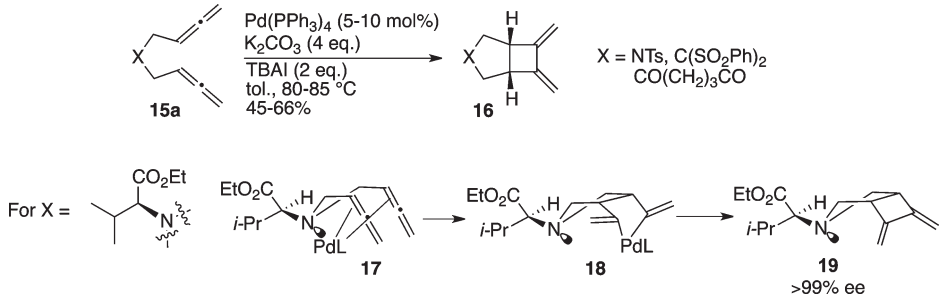
Scheme 5. 1,8-Allenene Cycloisomerization



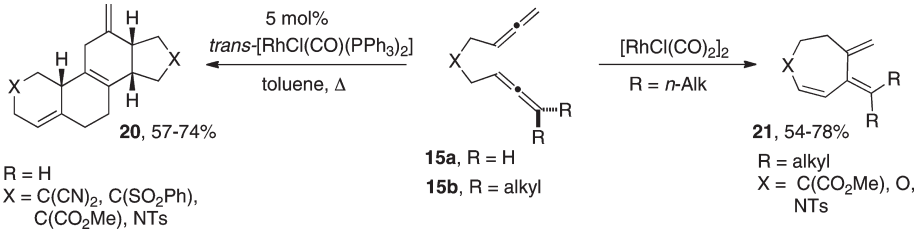
Scheme 8. Rhodium^{I}-Catalyzed Transformation of 1,7-Bisallenes



Scheme 6. Palladium-Catalyzed 1,5-Bisallenes Cycloisomerization



Scheme 7. Rhodium^{I}-Catalyzed Transformation of 1,5-Bisallenes



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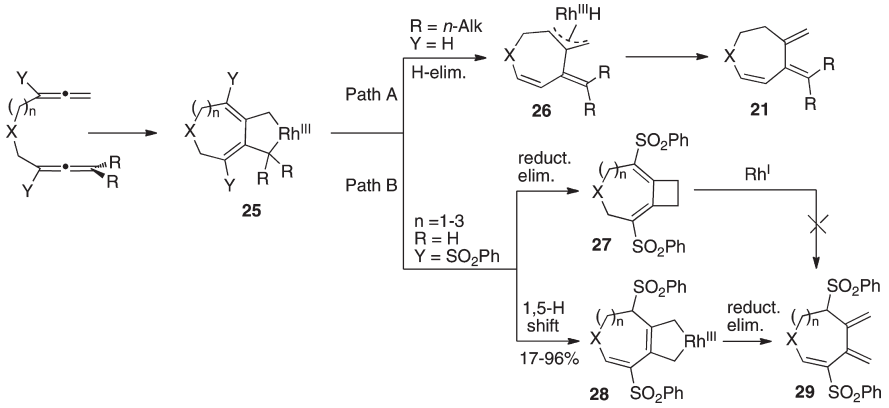
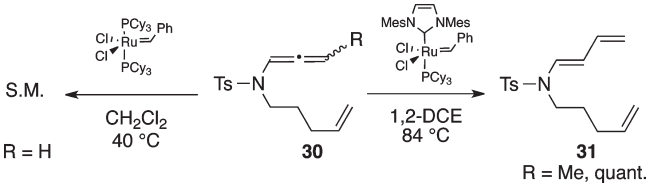
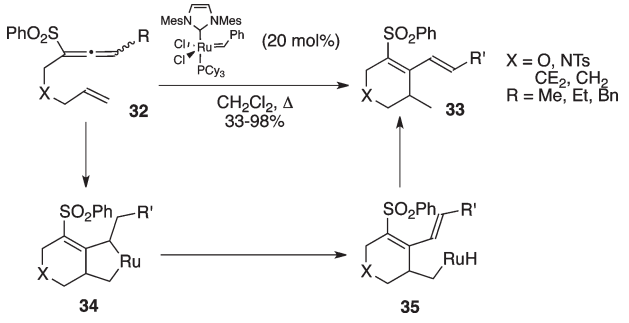
Scheme 9. Rh^{I}-Catalyzed Isomerization of 1,*n*-Bisallenes



Scheme 10. Unsuccessful RCM of Allenenes



Scheme 11. Second-Generation Grubbs' Catalyst Cyclo-isomerization of 1,7-Allenenes

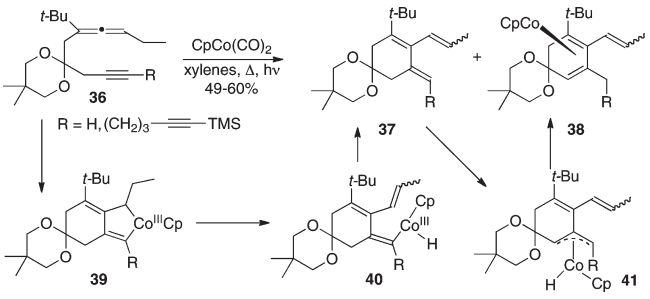


In that context, rhodium has so far owned the leadership of metal-catalyzed 1,*n*-allenynes isomerization as far as a metallacycle pathway is concerned.

Postulating that the metallacycle intermediate invoked in the PK reaction could be the opportunity of diverging routes, Brummond and Shibata moved from carbon monoxide atmospheres to inert ones to avoid CO insertion. Cross-conjugated trienes **43** were efficiently generated through either $[RhCl(CO)_2]_2$, $[RhCl(cod)]_2$ or Wilkinson catalysts from 1,6-allenynes **42** (Scheme 13),[36−38] and it should be noted that the complex $[IrCl(cod)]_2$ along with 20 mol % of $AgBF_4$ could also be used to obtain the formal Alder-ene processes.

On the basis of the exclusive *E* stereochemistry of the exocyclic olefin, Brummond proposes the formation of a rhodacyclopentene intermediate, such as **46**, which after β-H and reductive elimination gives the cross-conjugated triene. As a proof of this proposal,

Scheme 12. First Metal-Mediated Isomerizations of 1,*n*-Allenynes



submission of the deuterated allenyne **44** afforded the corresponding cycloadduct **45** with complete deuterium transfer (Scheme 14).

Brummond's labeling experiment cannot, however, exclude a starting competitive formation of a η^3-allyl rhodium hydride complex. The latter, as we will discuss in the next part, could also furnish the same Alder-ene cycloadduct. Ma brought interesting new elements in his study dealing with the cycloisomerization of propargylic 2,3-dienoates **48**.[39] While the application of $[RhCl(CO)_2]_2$ led to the cleavage of the propargylic ester linkage, the use of *trans*-$RhCl(CO)(PPh_3)_2$ catalysis provided either dimeric (**50** and **epi-50**) or monomeric (**51**) cycloisomerization α,β-unsaturated δ-lactone products depending on the substitution of the 1,6-allenynes (Scheme 15). With the metallacycle path in mind and considering the propensity of rhodium complexes to mediate [2 + 2 + 2] cycloadditions, addition of 3-methoxyprop-1-yne yields aromatic lactone **53** through two possible regioisomeric rhodacycloheptadienes **52a** and **52b**. This latter result strongly suggests that under rhodium catalysis, allenynes react through the metallacycle pathway. The author proposes that the formation of **50** and **epi-50** proceeds via a similar scheme through coordination of the acetylenic moieties of **48** to **49**, followed by an intramolecular Diels−Alder reaction.

From the wide range of catalysts, tethers and substitutions pattern of the substrates shown in Scheme 13, cycloisomerization of allenynes by rhodium salt appears as a robust transformation. Varying the size of the link is also highly compatible and allows an easy access of five to seven-membered cycles.[40,41] Indeed,

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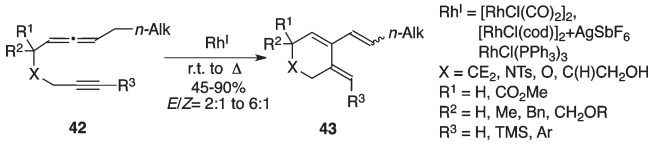
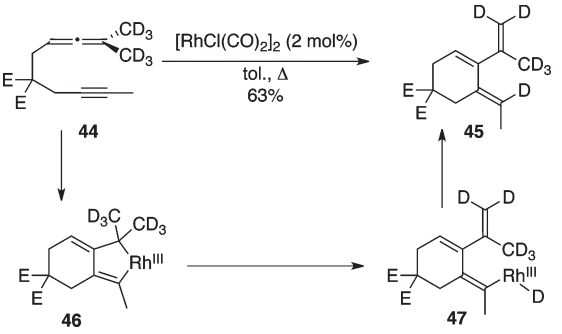
Scheme 13. Rhodium-Catalyzed 1,6-Allenyne Isomerization



Scheme 14. Mechanism of the Rhodium-Catalyzed 1,6-Allenyne Isomerization



cycloisomerization of allene-ynones **54** by $[RhCl(CO)_2]_2$ afforded cyclopentenones **55**, as well as cyclohexenones **56**, in fairly good yields (Scheme 16).

The observation that during the rhodium-catalyzed PK reaction of 3-phenylsulfonyl-1,6- and 1,7-allenynes a low carbon monoxide pressure yields unexpected six- or seven-membered carbocycles without CO incorporation drove Mukai to a specific study dedicated to their selective formation.[42] For instance, reacting allenenynes **57** under inert atmosphere with $[RhCl(CO)_2]_2$ or $[Rh(CO)dppp]_2$ afforded new cross-conjugated trienes **58** or cyclobutenes **59** (Scheme 17). Cycloheptenes **58** are obtained via the standard metallacycle pathway shown in Scheme 14, whereas bicyclo[5.2.0]nonedenes **59** originate from a thermal 4π-electronic rearrangement of **58**.

The selective rhodium-catalyzed cycloisomerization of 1,6-allenynes over 1,7 ones was evidenced by Brummond when using branched bisalkyne-allenes **60** (Scheme 18).[43] Whatever the nature of the tether and catalyst, complete selectivity for the six-membered Alder-ene cycloadduct **61** is observed. This set the stage for further refinement as up to two successive subsequent Rh-catalyzed intramolecular Diels−Alder reactions could take place, furnishing pentacyclic adducts **63** in good yields with dr up to 5:1.

The regio- and stereoselectivity of the β-hydride elimination in rhodium-catalyzed cycloisomerization of 1,6-allenynes is the other fundamental step studied by Brummond et al.[44] On using sulfonyl allenynes bearing two different alkyl groups at the allene termini, three different Alder-ene cycloadducts were isolated (Scheme 19). Thus, treatment of sulfonyl allenynes **64** with $[RhCl(CO)_2]_2$ led to *Z*-**65** as the major compound, which is not usual in such Alder-ene reactions. Indeed, based on the necessary cis relationship between the carbon−metal and the carbon−hydrogen bond for the β-elimination, two competitive metallacycles **67** and **68**, leading to *E*- and *Z*- isomers, respectively, have to be considered. In the conformation of the metallacycle **67** leading to *E*-**65**, an eclipsing interaction between the methyl and butyl groups is developed combined with a possible steric interaction between the butyl group and the ligands on the rhodium. Both interactions are released for metallacycle **68**, which delivers preferentially *Z*-**65** even if $A^{1,3}$ strain is developed. Substantial amounts of cross-conjugated triene **66** were also isolated. The selectivity between the different isomers (*E*/*Z*-**65** vs **66**) has been rationalized by the higher ability of methylene group than the methyl one to stabilize the partial positive charge which is developed in the β-elimination step. Finally, the use of cationic rhodium (or iridium) complex induces dramatic change in the selectivity since ***E*-65** and **66** are obtained in a 1:1 mixture without formation of *Z*-**65**.

Consistent with the observation that the metal center plays a huge role in the cycloisomerization of allenynes, by moving down the ninth column of the periodic table and using iridium salts, a remarkable improvement of the *E*/*Z* selectivity of the olefin side chain is guaranteed on products **71** (Scheme 20).[36,44]

Formation of bicyclo[4.2.0]octadienes from 1,6-allenynes has often been found to proceed under thermal conditions.[11,45] However, in some cases, metal catalysis was found to be essential in this [2 + 2] cycloaddition. Indeed, while trying to accomplish PK reactions on *gem*-difluoroallenyne **72**, Hammond found an unexpected and efficient synthesis of bicyclo[4.2.0]octadienes **73** strictly under molybdenum catalysis (Scheme 21).[46] It was shown that the reductive elimination is favored over carbonylation since even in the presence of 1.5 equiv of $Mo(CO)_6$, no PK product was detected.

Another similar result was later reported by Alcaide[47] through a domino alkyne homocoupling/double [2 + 2] allenyne cycloaddition. In this example, under a dual Pd/Cu catalyst system, an initial dimerization of the alkyne moiety of precursors **74** and **78** through either copper or palladium catalysis affords diynes **76**. Then, the formation of metallacyclopentene **77** and the subsequent reductive elimination furnish bicycloadducts **75** and **79** (Scheme 22).[48]

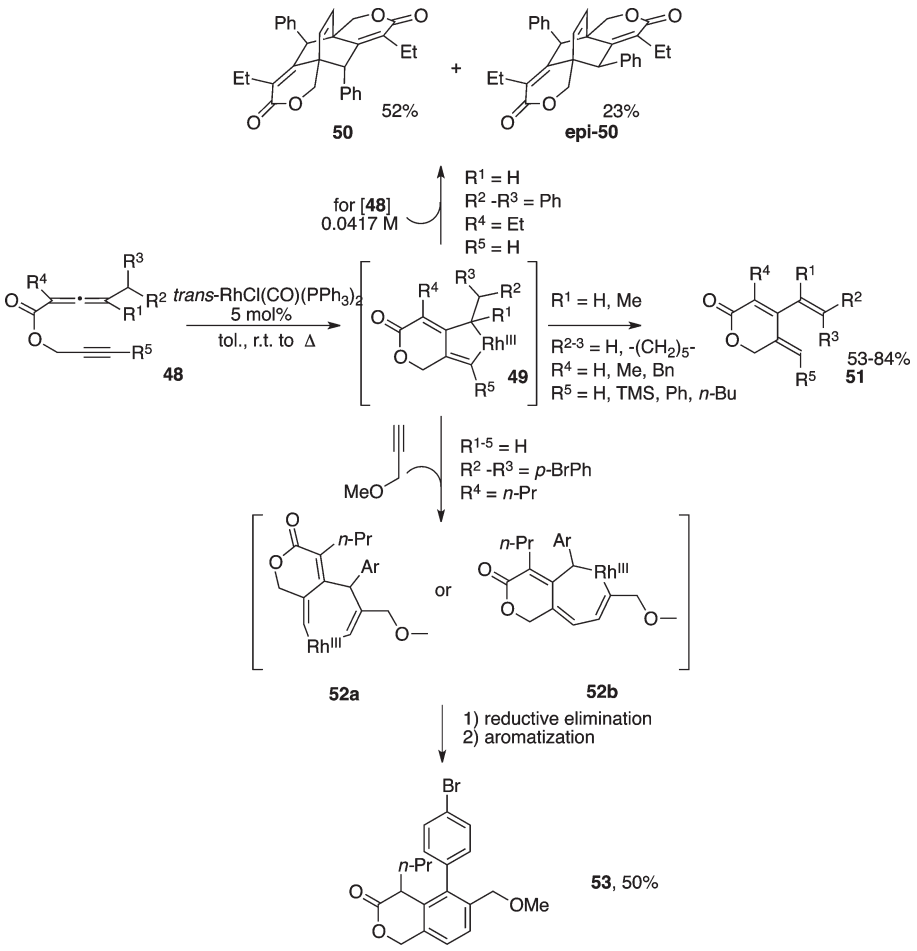
Metallacyclopentene formation from 1,6-allenynes generally involves the external double bond of the allene, as far as cycloisomerization is concerned. However, in the presence of a ruthenium catalyst,[49] 1,6-allenynes can react with either internal or external bond, depending on the solvent employed.[50] Exposure of 1,6-allenynes **80**, to Cp*Ru(cod)Cl in toluene leads to dimerized adducts **81** bearing a pentacyclic core (Scheme 23). Mechanistically, oxidative coupling between the internal allene bond and the triple bond of the acetylenic partner gives birth to metallacyclopentene **82**, which then undergoes reductive coupling to the assembly of a bicyclo[3.2.0]heptadiene intermediate **83**. Two molecules of the latter realize another oxidative coupling yielding ruthenacyclopentane **84** and after reductive elimination affords the dimeric pentacyclic adduct **81**.[50a]

When these substrates (**80**) were submitted to similar catalytic conditions but using protic media, bicyclo[4.2.0]octadienes **85** were isolated in very good yields (Scheme 24). To explain the dramatic change of the outcome of the cyclization, the authors invoke an in situ formation of a cationic ruthenium.[51] Indeed, when reacted with cationic Cp*Ru(cod)OTf in THF, quantitative yield of the corresponding bicyclo[4.2.0]octadienes was obtained.[50b]

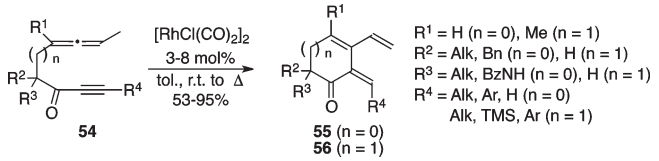
Reacting these unsaturated substrates with ruthenium could constitute an entry into metathesis type of transformations. However, as far as allenynes such as **86** are concerned, the latter transformation has been only reported through the use of Schrock catalyst, a molybdenum based complex.[23a,52] This transformation delivers vinylallenes **87** through an intermolecular, yet unclear, mechanism possibly transiting via intermediates

dx.doi.org/10.1021/cr100376w |*Chem. Rev.* 2011, 111, 1954–1993

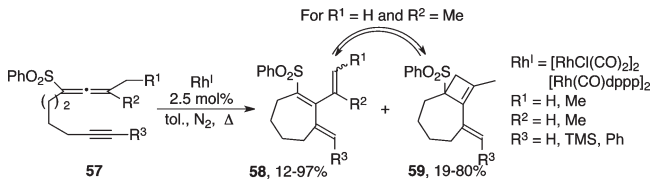
Scheme 15. Evidence of Rhodacyclopentene Intermediate



Scheme 16. Synthesis of Cyclopentenones and Cyclohexenones under $[RhCl(CO)_2]_2$ Catalysis



Scheme 17. Synthesis of Seven-Membered Rings under Rh^I Catalysis



88 and 89 as demonstrated by crossover experiments with precursors 90 and 91 (Scheme 25). No reaction takes place with unsubstitued allenes or with internal alkynes, as well as in the presence of oxygenated or longer tethers, making this transformation highly substrate dependent.

No formal metathesis was observed by Malacria in the $PtCl_2$-catalyzed cycloisomerization of allenynes 94 (Scheme 26).[53] Instead, unprecedented types of cycloisomerized products were observed as illustrated by the formation of 96 and 97. All products could be rationalized by the initial regioselective generation of a platinacyclopentene intermediate 98. From 98, two different β-H eliminations are accessible. With a terminal alkyne, formation of a vinyl platinahydride 99 would be followed by either reductive elimination, affording cross-conjugated triene 95 or by a steric hindrance-promoted carboplatination yielding to a five-membered platinahydride 100 and furnishing bicyclo[4.3.0]nonadiene 96 after reductive elimination.[54] Contrary to Brummond's report,[36] for R^2 = Me, the elimination involves only an allylic hydrogen atom, furnishing vinylallenes derivatives 97. Such a difference between rhodium and platinum might be attributed once again to the different geometries of the cyclopentene complexes.

2.2. π-Allylmetal Pathway

Another mechanistic option for the isomerization of 1,*n*-allenenes or allenynes is the pathway *via* a π-allylmetal. Here, we will focus on π-allylmetal promoted cyclizations (i.e., π-allyl complex generated before cyclization) and not on

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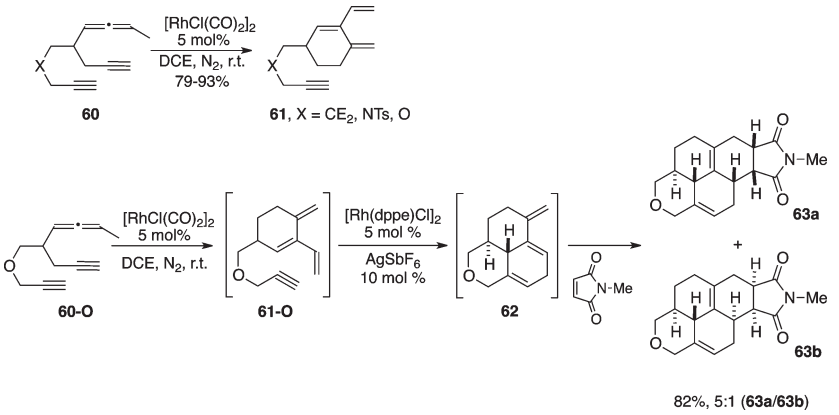
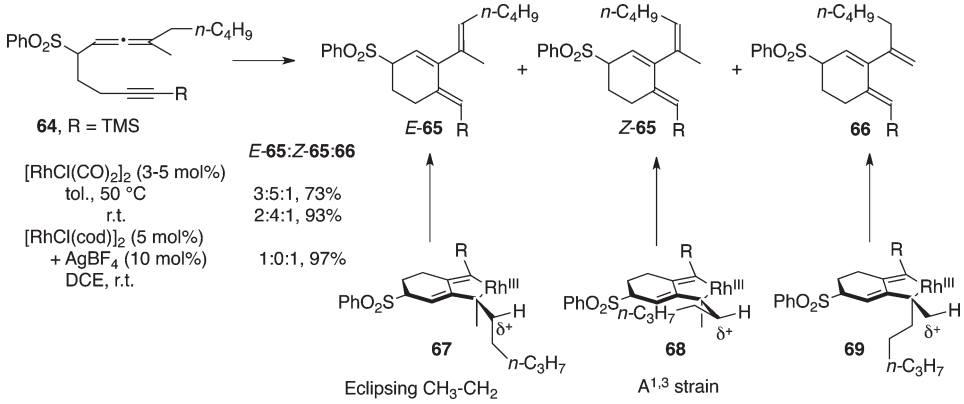
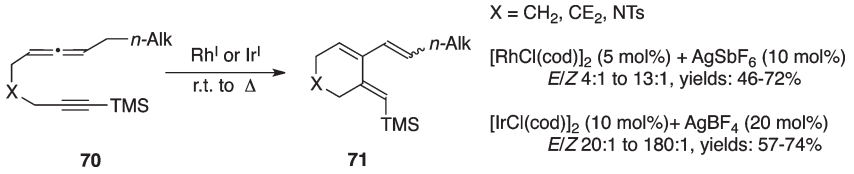
Scheme 18. Rh^I Selectivity for 1,6-Allenynes Isomerization



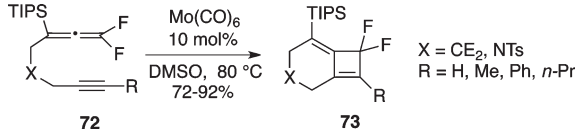
Scheme 19. β-H Elimination Selectivity in Rh^I-Catalyzed 1,6-Allenynes Cycloisomerization



Scheme 20. Rh^I- vs Ir^I-Catalyzed 1,6-Allenynes Cycloisomerization



Scheme 21. Synthesis of Bicyclo[4.2.0]difluoroctadienes by $Mo(CO)_6$ Catalyst



its resulting formation through cyclization of the two partners. Since this review is dedicated to catalytic cycloisomerizations process, we will not include the generation of π-allyl complex by initial hydro-,[55] carbo-,[56] or hetero-[57] metalation of the allene nor completion of the reaction by reductive coupling with an external agent.[58]

2.2.1. 1,*n*-Allenenes. During his study on the carbonylative behavior of 1,7-allenenes bearing an allylic acetate moiety, Yamamoto observed for the first time a transition metal-catalyzed cycloisomerization of allenenes via a π-allyl mechanism.[59] Indeed, in the presence of Pd(0), allylacetate **102** gives birth to a 1,6-allene-π-allylpalladium intermediate **103**. The latter reacts through the central *sp* carbon of the allene by means of double bond insertion into the π-allylpalladium moiety, thus generating a new π-allylacetate species **104**. Reductive elimination affords a five membered-ring allylic acetate **105**. It is noteworthy that even under a carbon monoxide atmosphere, which was found to be crucial to guarantee some conversion, no CO insertion was detected. In contrast, a 1,7-allene-π-allylpalladium intermediate reacts through the internal sp^2 carbon of the allene and the completion of the catalytic cycle requires an external agent (CO) to undergo reductive elimination (Scheme 27).

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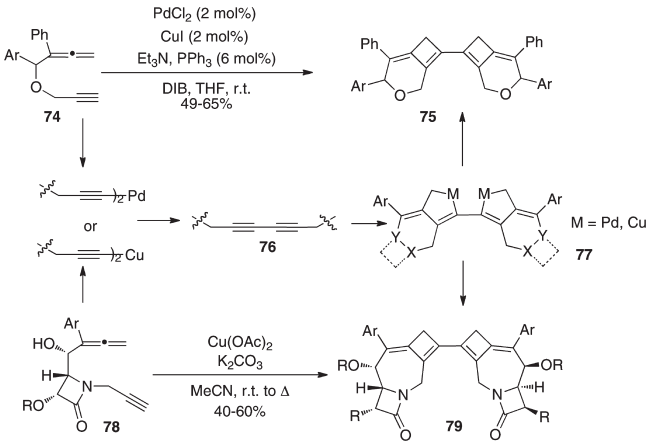
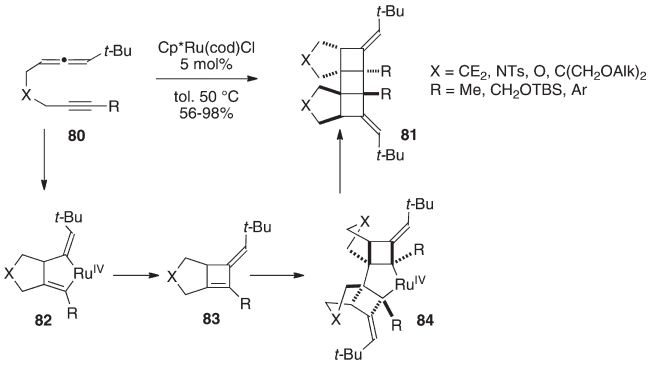
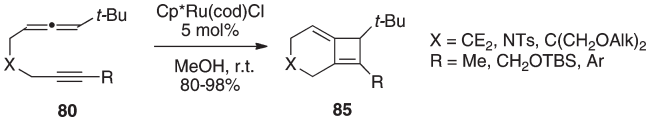
Scheme 22. Domino Alkyne Homocoupling/Double [2 + 2] Allenyne Cycloaddition



Scheme 23. Ruthenium-Catalyzed Cyclodimerization of 1,6-Allenynes



Scheme 24. Ruthenium-Catalyzed [2 + 2] Cycloaddition of 1,6-Allenynes



Itoh also noted the influence of carbon monoxide as a ligand of rhodium salts on the cyclization of 1,*n*-allenenes.[15] On moving from $[RhCl(cod)]_2$ to $[RhCl(CO)_2]_2$, seven membered rings **109** were exclusively produced (Scheme 3 and Scheme 28). A CO atmosphere proved to be a key factor to guarantee good yields. Mechanistically, a π-allyl rhodium intermediate **110a** generated from the allyl moiety was proposed. The latter undergoes insertion into the allene moiety to give π-allyl **110b**. Brummond who obtained similar formation of 7-membered rings confirmed this mechanistic hypothesis by deuterium labeling.[60,61]

Very recently, Shi and Li disclosed the same type of behavior for allenenes based on diarylvinylidenecyclopropanes.[62] Indeed, the cyclization of **111** was achieved in the presence of $[RhCl(CO)_2]_2$ in a mixture of solvents toluene/acetonitrile (2/1) and afforded bicyclo[5.1.0]octylenes **112** in very good yields (Scheme 29). MeCN plays a crucial role because in its absence the reaction delivered [2 + 2] cycloaddition adducts. The proposed mechanism is similar to the one described above, acetonitrile and the tethered terminal alkene can be coordinated to the metal to generate the intermediate **113**. Subsequent oxidative addition of the rhodium(I) complex into the neighboring allylic C−H bond gives a π-allyl rhodium−hydrogen species **114**, which affords a seven-membered carbocyclic rhodium−hydrogen intermediate **115** through an intramolecular cyclization to the allene moiety. Finally, a reductive elimination delivers the trans-fused bicyclic product **112**.

By studying the palladium-catalyzed carbocyclization of allenic allylic carboxylates,[63] the contribution of Bäckvall has been of great importance for the understanding of the π-allylmetal pathway in the cycloisomerization of allenenes. When refluxed in toluene, cyclohexenes *cis*-**116** underwent rapid cyclization leading to bicyclic adducts *cis*-**117** in fairly good yields (Scheme 30). In all cases, benzoates and acetates exhibit a higher reactivity than pivalates. When R^3 presents a double bond at the terminal position of the chain, the reaction proceeds regioselectively giving **118**, probably since the pendant alkene acts as an intramolecular ligand for palladium.

Seven-membered *cis*-cycloalkenes **119** exhibited the same reactivity and produced efficiently bicyclo[5.3.0]decadienes cis-**120** (Scheme 31). However, the formation of these compounds requires a higher catalytic loading (5 mol % instead of 2 mol %), as well as longer reaction time (20 h instead of 2 h) and higher reaction temperature (refluxing decane instead of toluene) to avoid the formation of the byproduct **121** which were identified as reduced derivatives.[63]

The cyclization of the trans-substrates is also feasible but limited to seven-membered ring substrates like *trans*-**119**, which give *trans*-bicycloadducts **120**, under the conditions used for the *cis*-substrates ($Pd(dba)_2$, toluene). A reduced side product **122** was also isolated. High selectivity in favor of *trans*-**120** and good yields were only reached when the reaction was performed in refluxing decane (Scheme 32). The catalytic cycle for the formation of **122** is not established but it is believed to involve a palladium-hydride species.

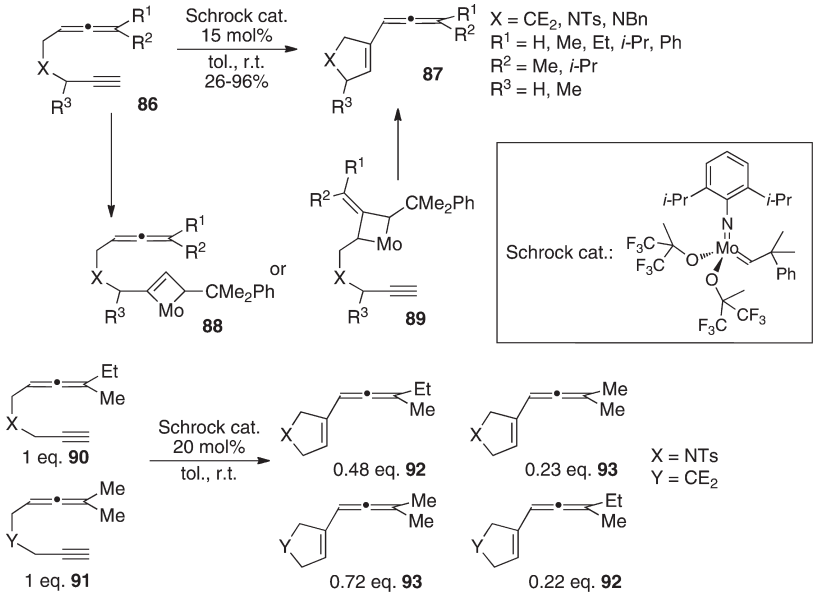
For the formation of bicyclic products *cis*-**120** or *trans*-**120**, a π-allyl complex, respectively intermediate *trans*-**123** or *cis*-**123**, originating from the oxidative addition into the C-*O*-acyl bond of the precursor is at work. Logically, the cyclization of cycloheptene carboxylates is stereospecific since *cis*- and *trans*-precursors **119** give *cis*-**120** and *trans*-**120**, respectively. The carbon−carbon bond formation occurs syn with respect to the leaving group and proceeds through a nucleophilic trans allene attack on the (π-allyl)palladium intermediate furnishing the cycloadduct (Scheme 33).

The same type of intermediates is proposed in the cyclization of *cis*-**116** which could undergo an *anti*-allene attack type mechanism to provide *cis*-six membered ring substrates **117** (Scheme 30). In the case of the trans precursor **116**, no anti attack would be possible on the *cis*-(π-allyl)palladium intermediate because of a too strained transition state.

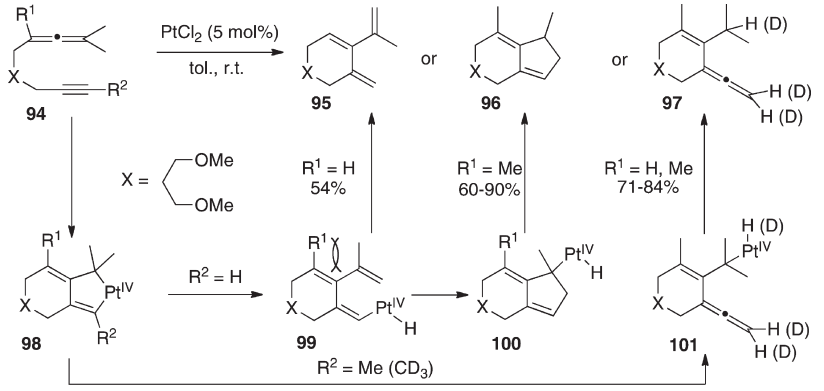
Taking this into account, the use of acetonitrile as a solvent allows the cyclization of *trans*-**119** leading to *cis*-**120**, as well as the cyclization of *trans*-**116** into *cis*-**117**. Acetonitrile now renders possible the insertion of the allene into the neighboring π-allylpalladium **124** (Scheme 34). This result is particularly interesting as it shows that a simple change of the solvent allows a total control of the stereochemistry of the product.

The crucial importance of the nature of the ligand on palladium was also underlined when maleic anhydride (mah) was added to *cis*-**116**. In that case, isolation of *cis*-**129**, usually accompanied by minor amounts of *cis*-**117**, enables to furnish the

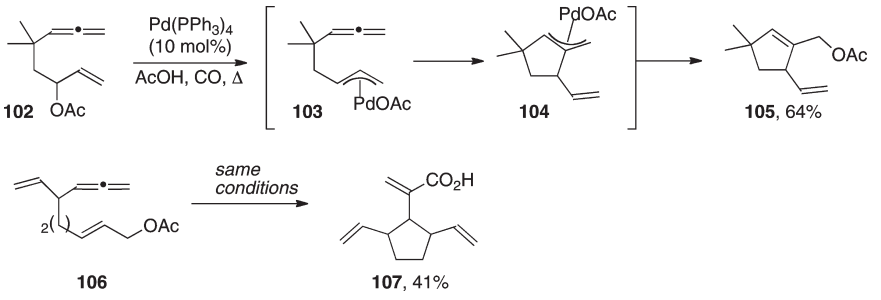
Scheme 25. Molybdenum-Catalyzed RCM of 1,6-Allenynes



Scheme 26. Platinum-Catalyzed Isomerization of 1,6-Allenynes



Scheme 27. First π-Allylmetal Pathway Evidence on the Cycloisomerization of 1,*n*-Allenenes



last key of the mechanism (Scheme 35). After oxidative addition of the allylic carboxylate with inversion of configuration, *anti*-allene attack produces **127**. Subsequent allylic cation trapping by Pd(0) affords π-allylpalladium **128**. The latter, depending on the electron-withdrawing properties of L, can be activated toward nucleophilic attack from the carboxylate anion (L = mah) to furnish *cis*-**129** or can undergo β-H elimination yielding *cis*-**117**.

Finally, it is worthy of note that the five-membered ring cis precursor as the substrates with an additional carbon between the allylic moiety and the allene in the case of the six- or seven-membered ring precursor failed to undergo any reaction.

Wender intensively studied the intramolecular rhodium(I)-catalyzed [5 + 2] cycloaddition of allenes and vinylcyclopropanes (VCPs) to afford fused systems of five- and seven-

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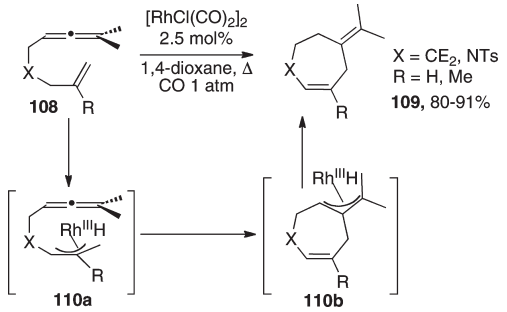
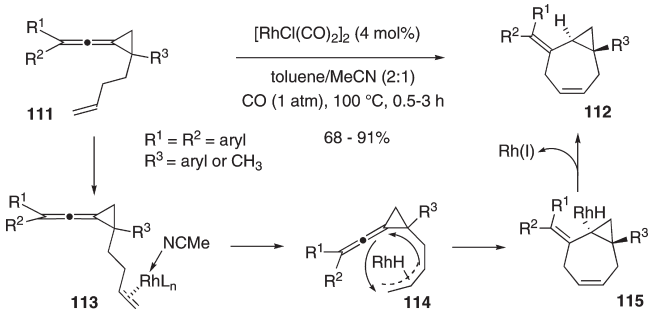
membered rings.[64] Indeed, 1,7-allenenes **130**, flanked with a vinylcyclopropane moiety in the presence of $RhCl(PPh_3)_3$ or $[RhCl(CO)_2]_2$, with or without silver triflate, produce bicyclo[5.3.0]decane derivatives **131** in high yields. The use of $[RhCl(CO)_2]_2$ instead of the Wilkinson catalyst allows the selective obtention of the cis-fused bicyclic compound whereas addition of silver triflate to the $RhCl(PPh_3)_3$ was found to facilitate the reaction.[64a] Over the range of substrates tolerated as depicted in Scheme 36, particular attention was dedicated to chirality transfer from the allene.[65] Thus, enantioenriched starting 1,7-allenene **130a** (R^1 = *t*-Bu, R^2 = H, 91% ee) was converted into the corresponding azulene derivative **131a** with total chirality transfer. From the recent mechanistic advances on the VCP reactivity in presence of unsaturated partners,[65] the first step of this cycloisomerization should be the formation of π-allyl rhodacyclohexene **133**. Then, insertion on the internal double bond of the allene affords rhodacyclooctene **134** which upon reductive elimination gives the bicyclo[5.3.0]decene **131**.

A nice application of this methodology was then reported through the total synthesis of the two natural products: (+)-dictamnol **136** and (+)-aphanamol **138** (Scheme 37), from precursors **135** and **137**, respectively.[64b,c]

Scheme 28. Rhodium-Catalyzed Synthesis of Seven-Membered Rings from 1,7-Allenenes



Scheme 29. Rhodium^I-Catalyzed Formation of Bicyclo[5.1.0]octylenes



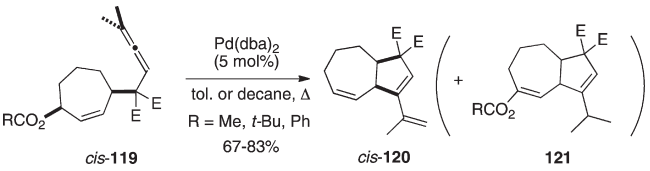
1,8-Allenenes displaying a VCP in internal position such as **139** follows an identical reactivity pattern affording the bicyclo[3.3.0]decane **140** albeit in lower yield. Contrary to former examples, the vinyl moiety is only involved in the cleavage of the cyclopropane ring and remains available for further functionalization (Scheme 38).[66]

The Wender group also undertook an extension of their study to the synthesis of eight-membered rings.[67] After initial attempts to use vinylcyclobutane, as an equivalent of VCP and observation of the unproductiveness of the transformation, the employment of a vinylcyclobutanone moiety as in **141** yielded the desired transformation.[68] Therefore, a broad range of bicyclo[6.3.0]-undecane derivatives presenting an exocyclic double bond were obtained still through $[RhCl(CO)_2]_2$ catalysis, as in the cycloisomerization of 1,7-allenene **141** to **142** (Scheme 39).

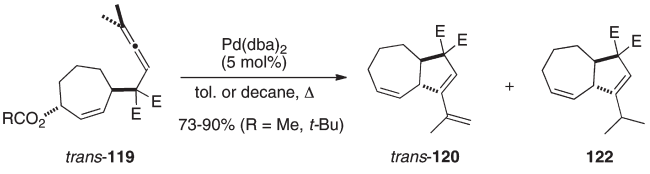
2.2.2. 1,*n*-Allenynes. Reports on the cycloisomerization of 1,*n*-allenynes through the π-allylmetal pathway are quite scarce since to date, and as far as we are aware, only two examples have been published. The first one, which is not a genuine isomerization process, relies on a disposable tether (CO_2) ensured by a carboxylate function. Nevertheless, it is of synthetic value. The corresponding buta-2,3-dienyl 2′-alkynoate precursors **143** provide 2-alkynyl buta-1,3-dienes **144** (Scheme 40).[69] Presumably, the reaction is initiated by an oxidative addition of $Pd(PPh_3)_4$, resulting in the formation of π-allylpalladium intermediate **145**. Nucleophilic addition of the carboxylate anion to the palladium center furnishes **146**, which after a decarboxylative process generates **147**. The latter intermediate undergoes reductive coupling, producing final dienynes **144** (Scheme 40).

Mukai recently introduced allenylcyclopropanes (ACPs) in the cycloisomerization of 1,6- and 1,7-allenynes **148** catalyzed by rhodium salts (Scheme 41).[70] This isomerization that involves an

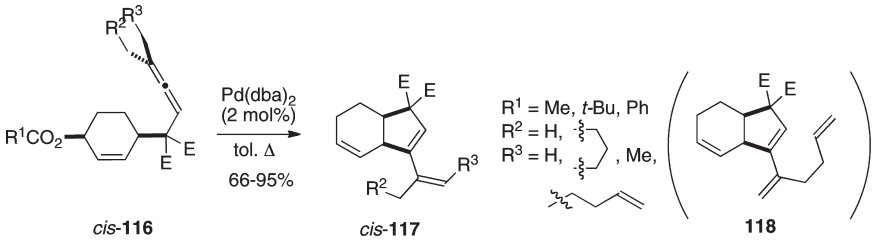
Scheme 31. Palladium^0-Catalyzed Cyclization of *cis*-Cycloheptene Carboxylates



Scheme 32. Palladium^0-Catalyzed Cyclization of *trans*-Cycloheptene Carboxylates



Scheme 30. Palladium^0-Catalyzed Cyclization of *cis*-Cyclohexene Carboxylates



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intramolecular [5 + 2] cycloaddition of alkynes and ACPs can be efficiently performed using substituted or unsubstituted alkynes as well as all-carbon tethers or heteroatom bearing ones.

By analogy with the mechanism of VCP opening (see Scheme 36), the transformation might follow an initial formation of a π-allyl rhodacyclohexene **150** from the ACP.[71] Evidenced from the isolation of the cyclopentene **151**, which would originate from the direct reductive elimination, the latter intermediate reacts with the pendant alkyne via insertion into the Csp^2—Rh bond, giving rhodabicyclotriene **152**. Reductive elimination ended the catalytic cycle by furnishing **149**.

2.3. Vinylmetal Pathway

Experimental conditions are of outmost importance in the mechanistic path followed by 1,*n*-allenenes under palladium catalysis. Indeed, whereas an acidic medium will promote hydropalladation of the allene part,[55c] nonprotic systems allow oxidative carbocyclizations that do not require any addition of external agent to the substrate.[72] Treatment of cycloalkenes derivatives **153** with $Pd(O_2CCF_3)_2$ in the presence of *p*-benzoquinone (BQ) yields[73] bicyclodienes **154** or **155** via oxidative cyclization (Scheme 42).[72a] Even if five to eight-membered carbocycles are efficiently transformed, the cycloisomerization process is often poorly regioselective. The cycloheptene-based derivative gives only a trans-fused ring system, whereas others systems with shorter or longer carbocyclic platforms give only cis-fused ring systems.

In a similar manner, acyclic substrates **156** also produce efficiently cyclopentenes derivatives **157** and **158** under Pd^{II} catalysis (Scheme 43).[72]

It is of note that under these conditions *trans*-allylic pivalate **126** led to the formation of *cis*-**160**. This latter result unambiguously shows that the isomerization process differs when Pd(0) and Pd(II) are used since no *cis*-**117** was formed (Scheme 44).[63]

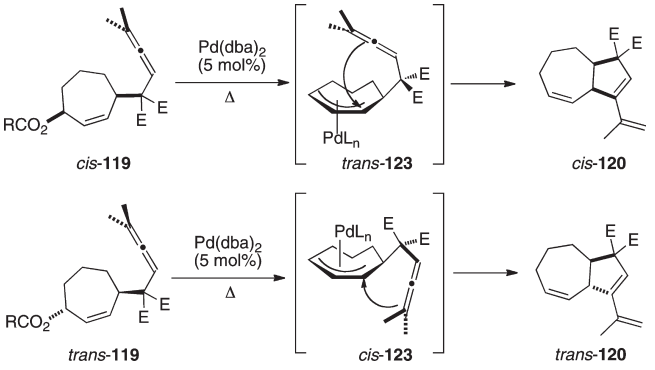
Mechanistically, after formation of a (π-alkene)palladium complex **151**, subsequent nucleophilic attack of the allene on palladium (**152**) followed by olefin insertion afford **153**. The latter would undergo regioselective β-H elimination, giving the final trienic products (Scheme 45). An alternative pathway could involve a π-allyl intermediate **154.** The reactivity of some acyclic compounds (Scheme 43) and the fact that **155**, which should afford a similar π-allyl intermediate, gave no conversion brings some support to the vinylmetal path of this transformation.[72a]

3. ALLENYNES AND ALLENE-ENES CYCLOISOMERIZATIONS UPON Π-ACIDIC METALS CATALYSIS

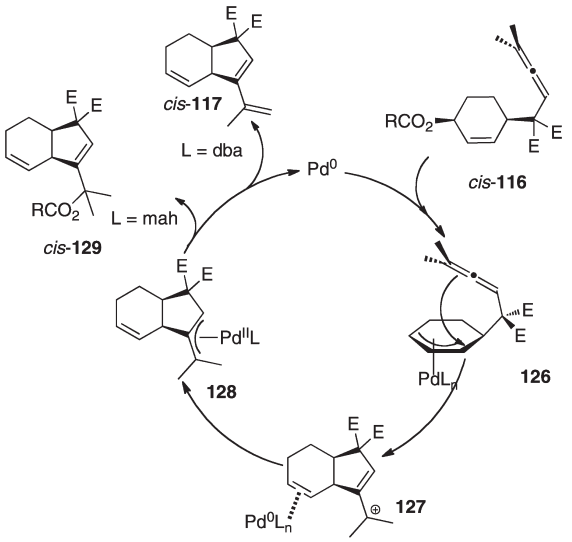
Since the seminal work of Trost in 1987,[74] dealing with the reactivity of electrophilic palladium catalysts onto enyne systems, cycloisomerization processes involving skeletal rearrangements have witnessed tremendous development in the past decade and this chemistry has been recently reviewed.[75] For that purpose, some platinum and then gold complexes have proved to be exquisite catalysts. Recently also, gallium, silver, iridium and mercury have raised interest from the scientific community toward cycloisomerizations reactions.[5e]

This section of the review will deal with the cyclization reactions of allenynes and allenenes with these metals, whose particularity stands in the coordination of the metallic center to only one π-bond of the considered systems. This results in a loss of π-electron density thus enhancing the electrophilicity of the bound π-ligand and triggering a nucleophilic attack from the second partner. These specific Lewis acid properties bring these metals together under the "π-acids" appellation.[76]

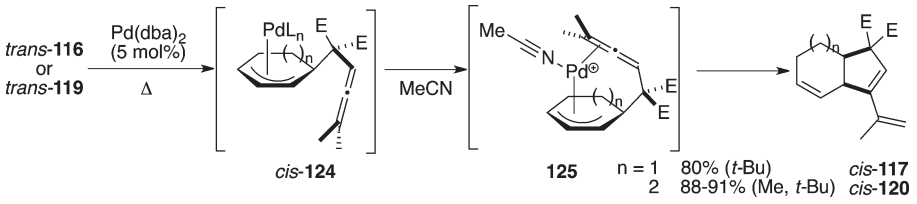
Scheme 33. Cyclization of *cis*- and *trans*-Cycloheptene Precursors via *anti*-Allene Attack



Scheme 35. Mechanism of the Cyclization of cis Six-Membered Ring Substrates 116



Scheme 34. Stereocontrol through Solvent Tuning



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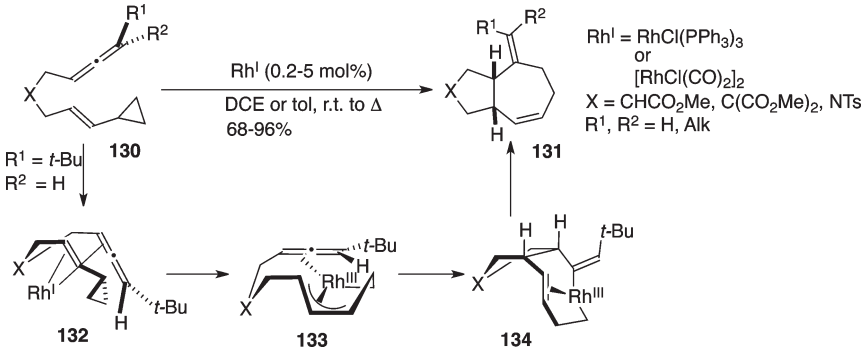
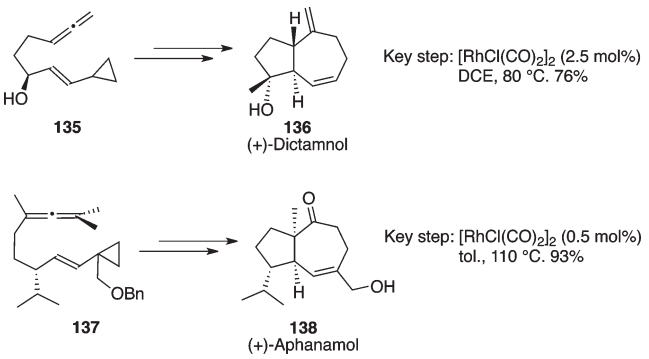
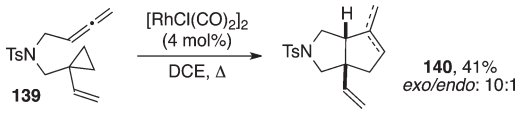
Scheme 36. Rh^I-Catalyzed [5 + 2] Cycloaddition of Allenes and Vinylcyclopropane



Scheme 37. Rh^I-Catalyzed Synthesis of Natural Products



Scheme 38. Reactivity Pattern of 1,8-Allenene with Internal VCP

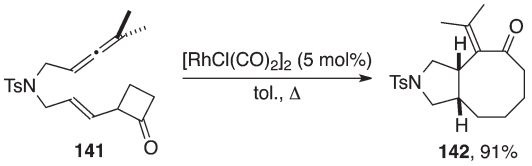


3.1. Allenynes Cycloisomerizations: A Rich and Highly Substrate-Dependent Mechanistic Issue

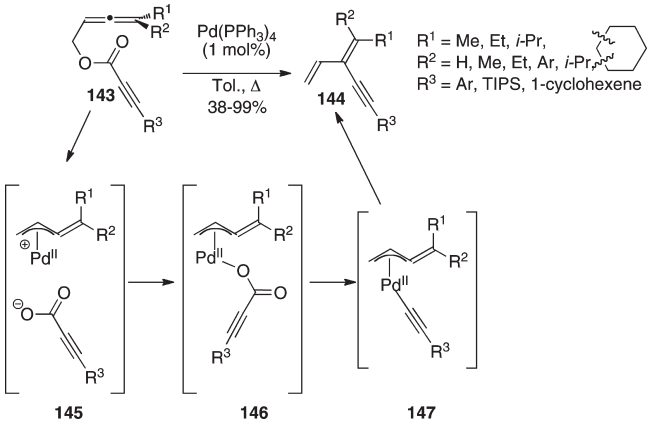
Trying to unify the mechanism of allenynes cycloisomerizations upon π-acid catalysis is quite a challenge as the outcome of such reactions is highly catalyst- and substrate-dependent. Therefore, this section will describe the different studies made in this field and the common points or differences in mechanistic pathways will be outlined. It is worthy insisting on the fact that theoretical chemistry has brought highly valuable information in the understanding of the cycloisomerizations mechanisms with such metals and shed light on some interesting mechanistic pathways.

3.1.1. Initial Electrophilic Activation of the Alkyne Partner. *3.1.1.1. 1,6-Allenynes Metathesis.* As we have seen above, the metathesis of allenynes was reachable with molybdenum complexes through a metallacycle pathway, affording vinylallenes (see 2.2.2, Part 1, II.2.). This kind of products was also obtained upon π-acids catalysis (gallium and mercury) by the group of Chung,[77] through a completely different mechanism, starting from compound **166** (Scheme 46).

Scheme 39. Rh^I-Catalyzed Synthesis of [6.3.0] Fused Bicycle



Scheme 40. Pd^0-Catalyzed Decarboxylative Rearrangement of Buta-2,3-dienyl 2′-alkynoates



The proposed mechanisms, supported by deuteration experiments, share common steps and similar intermediates, and both begin by activation of the alkyne moiety[78] (Scheme 47). With gallium, coordination of the metal to the triple bond generates a vinylmetalcation **168**, which subsequently evolves into bicyclic carbocation **169** upon 5-exo attack of the allene internal double bond onto the former. With mercury triflate,[79] an initial removal of one triflate ligand is necessary to allow the coordination of the metallic center to the alkyne. The mercury-alkyne complex **170** thus formed is in equilibrium with the experimentally observed mercury acetylide **173**. The authors proposed a continuation of the mechanism slightly different than with gallium: activation of the triple bond triggers the 5-exo attack, resulting in cationic vinylmercury species **171**. Bicyclic carbocation **169Hg** is then formed by vinylmercuration onto the vinylic carbocation. From this common intermediate, demetalation would afford highly strained cyclobutene **174**, which further rearranges to give the

dx.doi.org/10.1021/cr100376w |Chem. Rev. 2011, 111, 1954–1993

metathesis product **167**. For gallium catalysis, the authors also proposed a direct rearrangement (path b) from intermediate **169Ga** to product **167**. In some sporadic cases when substituted allenes were used another sigmatropic rearrangement of **174** can occur, leading to 1,3,5-trienes **175**.

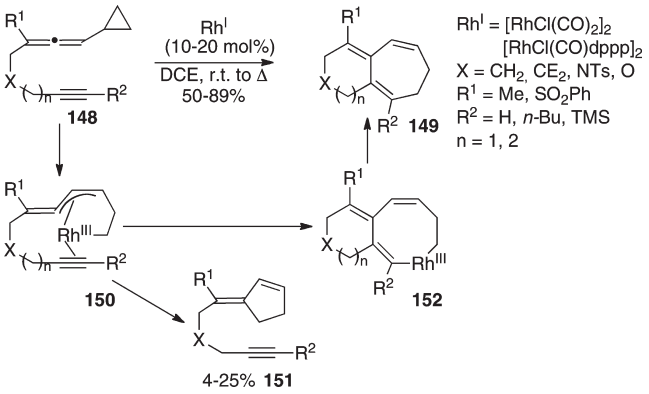
3.1.1.2. 1,5- and 1,6-Allenynes Cyclizations. First investigations along these lines were given by the Malacria group who studied the behavior of allenynes substrates upon $PtCl_2$ catalysis.[53] The same group then logically extended their investigations to gold catalysts, cationic Pt(II) complexes and $PtCl_4$,[80] which allowed them to get some new data that did not completely fit the platinacyclopentene mechanistic rationale initially proposed with $PtCl_2$[81] and supported by DFT calculations.[54] They first noticed that gold(I), gold(III), and platinum(IV) chloride salts could also promote the cyclization of precursor **94** (R = H) into the hydrindiene **96**, although the metallacyclopentene pathway is unlikely[82] for these metallic species (Scheme 48).

Changing from chloride salts to halide free cationic complexes of gold and platinum resulted in a dramatic change of reactivity, as the mixture of Alder-ene isomers **176** was obtained in good yields. It should be noted that Alder-ene-type products have been also obtained from allenynes in thermal conditions.[83] Such ligand effects are frequently met in gold catalysis and have recently been the object of a review.[84] Switching to methyl-substituted triple bonds allows the discovery of a third cycloisomerization pathway to give vinyl allenes **97**, which proved to be effective with the above-mentioned chloride salts and cationic halide-free complexes (Scheme 49).

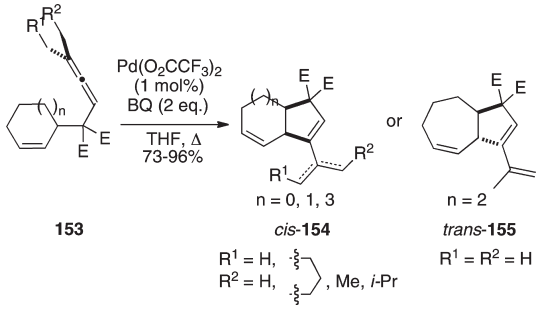
A cationic manifold was invoked as no metallacyclopentene appeared likely to occur.[85] Some additional experiments confirmed this hypothesis, such as trapping of intermediates with deuterated methanol, or substituting the allene moiety with a phenyl group to obtain Friedel−Crafts isomers (see below). The mechanisms proposed, supported by a computational study, starts for each product by a 6-exodig cyclization giving birth to a stabilized allylic carbocationic intermediate **178**/**180**. Then, depending on the substrate and the catalyst, diverging pathways were unveiled with DFT calculations. The Alder-ene products were computationally reachable if R = H and their formation proceeds through a direct 1,5-proton shift. The vinyl allenes **97** are also obtained in a single step by a 1,5-hydride shift[86] (Scheme 50).

As only chloride-containing catalysts could promote the formation of hydrindiene products, a mechanistic rationale was proposed involving isomerization of the vinyl metal species **178**, followed by elimination of HCl (Scheme 51). The next step is a

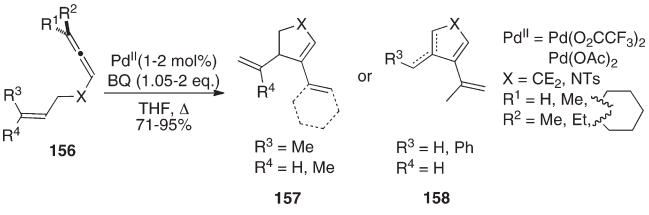
Scheme 41. Rh^I-Catalyzed Intramolecular [5 + 2] Cycloaddition of Yne-allenylcyclopropane



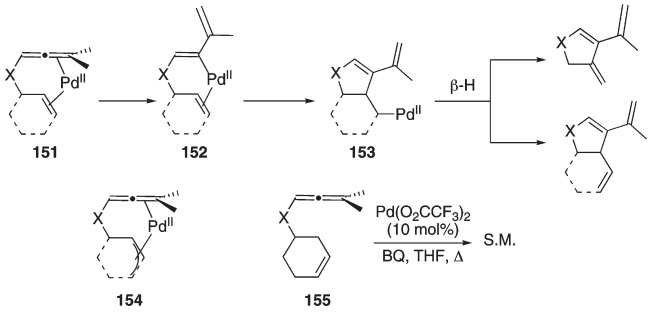
Scheme 42. Pd^{II}-Catalyzed Oxidative Carbocyclization of Allenic Cycloalkenes



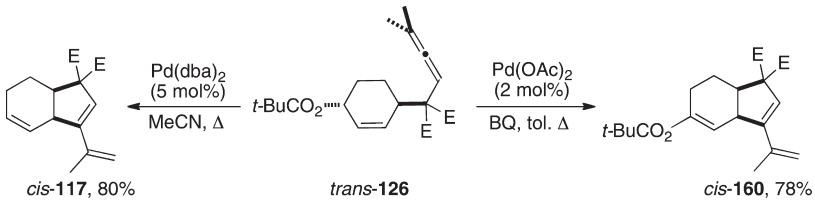
Scheme 43. Pd^{II}-Catalyzed Oxidative Carbocyclization of Allenic Alkenes



Scheme 45. Mechanistic Proposal and Evidences Agreeing for a Vinylmetal Pathway



Scheme 44. Distinct Reactivity Pattern between Pd^0 and Pd^{II}



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5-endo carboauration which after protolysis with HCl delivers the final product and restores the catalytic species. It is yet unclear why the isomerization of **178** into **183** is kinetically much more difficult from the computational point of view with $Au(PH_3)^+$.

In 2006, Murakami reported the platinum(II) chloride catalyzed cycloisomerizations of heteroatom tethered 1,6-allenynes **186** to give bicyclic cyclobutenes **187** (Scheme 52).[87]

The proposed mechanism starts as before with the activation of the triple bond by platinum(II), followed in this case by a 7-endodig cyclization giving rise to nonclassical carbocation **189**, depicted by resonance forms **189a**−**d**. Among them, the authors propose that **189a** is probably the most stable one because of its cinnamyl carbocation structure. After a proton abstraction by platinum (inter- or intramolecular), the cyclobutene product **187** is released through reductive elimination of the cyclobutenyl platinum hydride **190** (Scheme 53). Proton loss, followed by protodeplatination, could also explain the formation of compound **187** from intermediate **190**, nonetheless this pathway was not suggested by the authors.

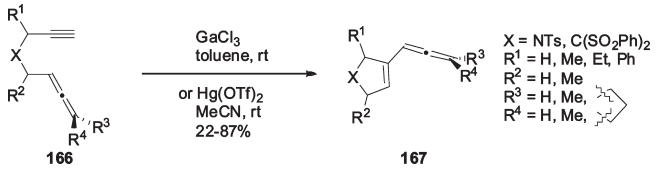
It is worthy of note that such a process is sensitive to the substitution of either the allene or the alkyne (disubstituted allenes and terminal alkynes led to complex mixture) and also to the nature of the tether (malonate tethered substrates showed no desired reactivity). The same reaction performed in refluxing methanol furnished hydratation compounds[88] **192** by trapping of the carbocationic species **189b** depicted in Scheme 53 (Scheme 54).

Intermediate **193** generated by nucleophilic trapping would then undergo a β-carbon elimination[89] to afford the vinyl platinum(IV) hydride **194**. Subsequent reductive elimination and hydrolysis of the enol ether **195** give the 3-acylpyrrolidine **192**.

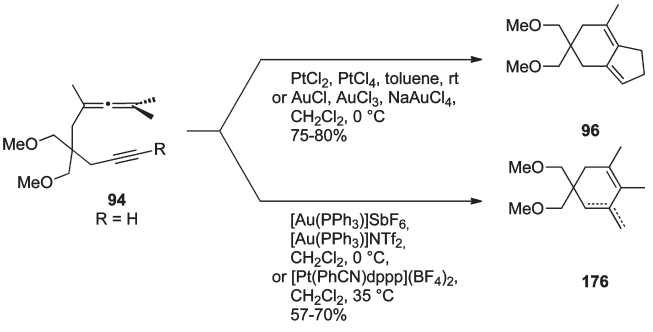
1,5-allenynes **200** can also react through a cationic manifold similar to the one observed for 1,6-allenynes. Thus, Liu et al. showed that subsequent to a 6-endodig ring closure, the resulting allylic-benzylic cation **202** undergoes a 4π Nazarov-type electrocyclization followed by rearomatization and final protodemetalation to afford the tricyclic products **201** which resemble the products **197**-**199** formed from phenyl substituted-1,6-allenynes **196** (Schemes 55).[90]

Hydroxylated 1,5 allenynes **206** were explored by Malacria and Fensterbank in the context of gold and platinum catalysis.[83a] Platinum chloride salts in refluxing toluene or gold chloride salts in toluene at room temperature gave unprecedented methylenebicyclo[3.1.0]hexan-3-ones **209** (Scheme 56) through a similar intermediate than resonance form **189d** proposed by Murakami in the platinum catalyzed cycloisomerization of 1,6 allenynes mechanism[87] (see Scheme 53). In these examples, the formation of a cyclobutene is not likely to occur as it would mean the formation of a highly strained [2.2.0]bicyclic intermediate

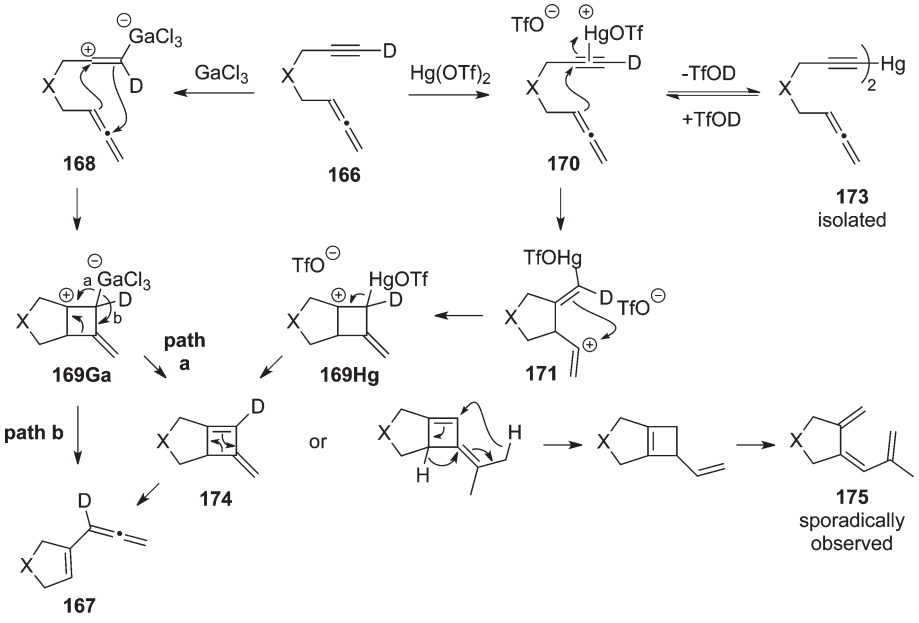
Scheme 46. Mercury- and Gallium-Catalyzed Allenyne Metathesis



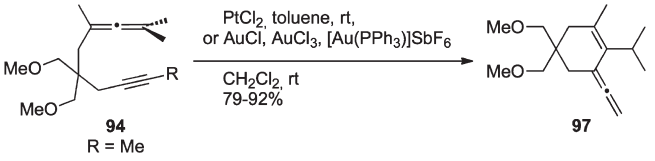
Scheme 48. Gold- and Platinum-Catalyzed Cycloisomerization of 1,6-Allenynes



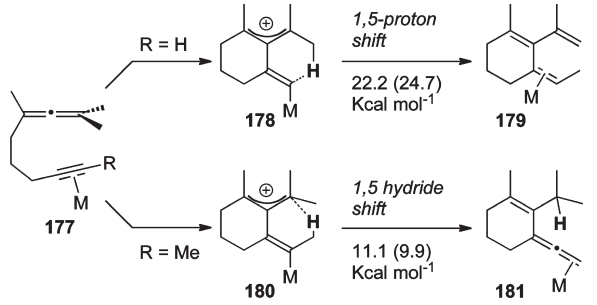
Scheme 47. Proposed Mechanisms for the π-Acid-Catalyzed 1,6-Allenyne Metathesis



Scheme 49. Particular Case of Methyl-Substituted Alkynes

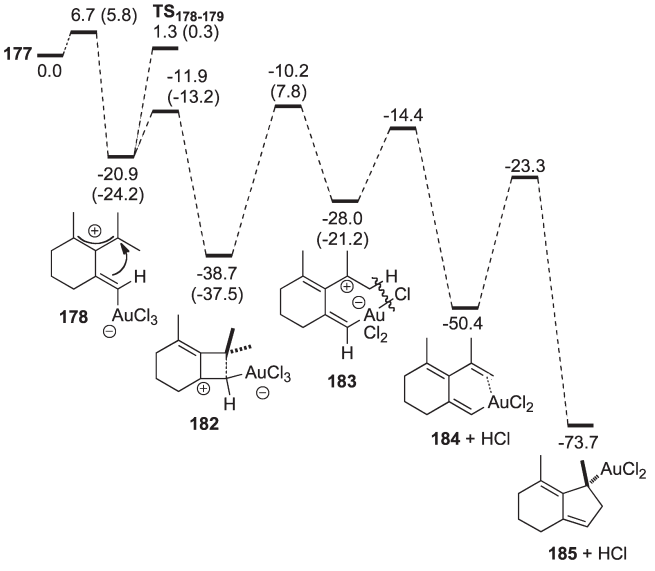


Scheme 50. Mechanistic Proposal for the Formation of Alder-Ene and Vinylallene Products[a]



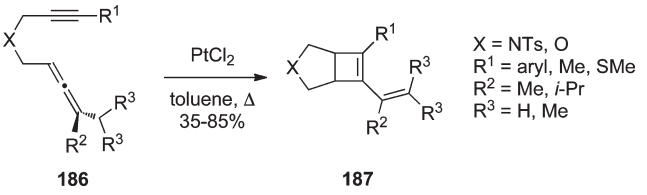
[a] ΔG°_{298} were calculated for M = $AuCl_3$ (and $AuPH_3^+$).

Scheme 51. Energy Profile [kcal mol^{-1}] for the Transformation of 177 into the Hydrindiene Precursor 185 Calculated for M = $AuCl_3$ (and $AuPH_3^+$)

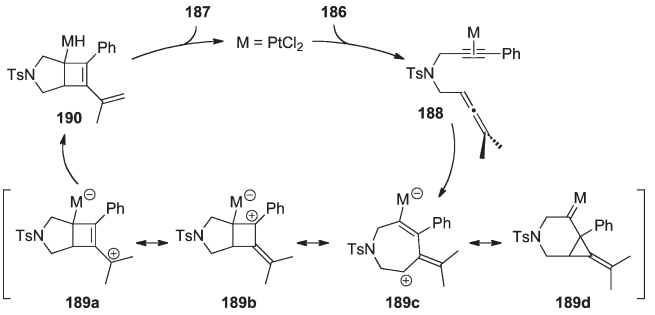


which is obviously not thermodynamically favorable. The methylenebicyclo[3.1.0]hexan-3-ol carbene **207** thus generated undergoes a β-hydride elimination to afford bicyclic ketone **209**. Surprisingly, either cationic phosphinegold catalysts in toluene or in refluxing dichloromethane or gold chloride salts in dichloromethane gave totally different products than those described above. These conditions led to dihydropyran derivatives **211** which formation can only be justified by an activation of the allene followed by an intramolecular nucleophilic addition of the hydroxyl group onto the former in a 6-endo manner resulting in oxonium **210** (Scheme 56).[91]

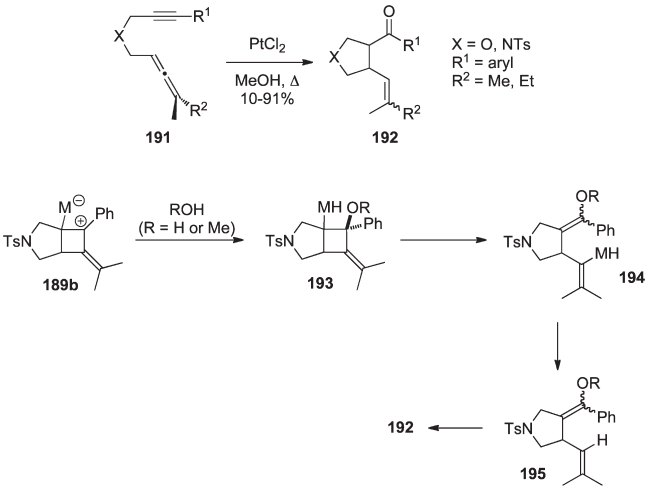
Scheme 52. Formation of Cyclobutenes upon Pt(II) Catalysis



Scheme 53. Mechanism Proposal for Cyclobutene Formation



Scheme 54. 1,6-Allenynes Cycloisomerizations in Hydrative Conditions



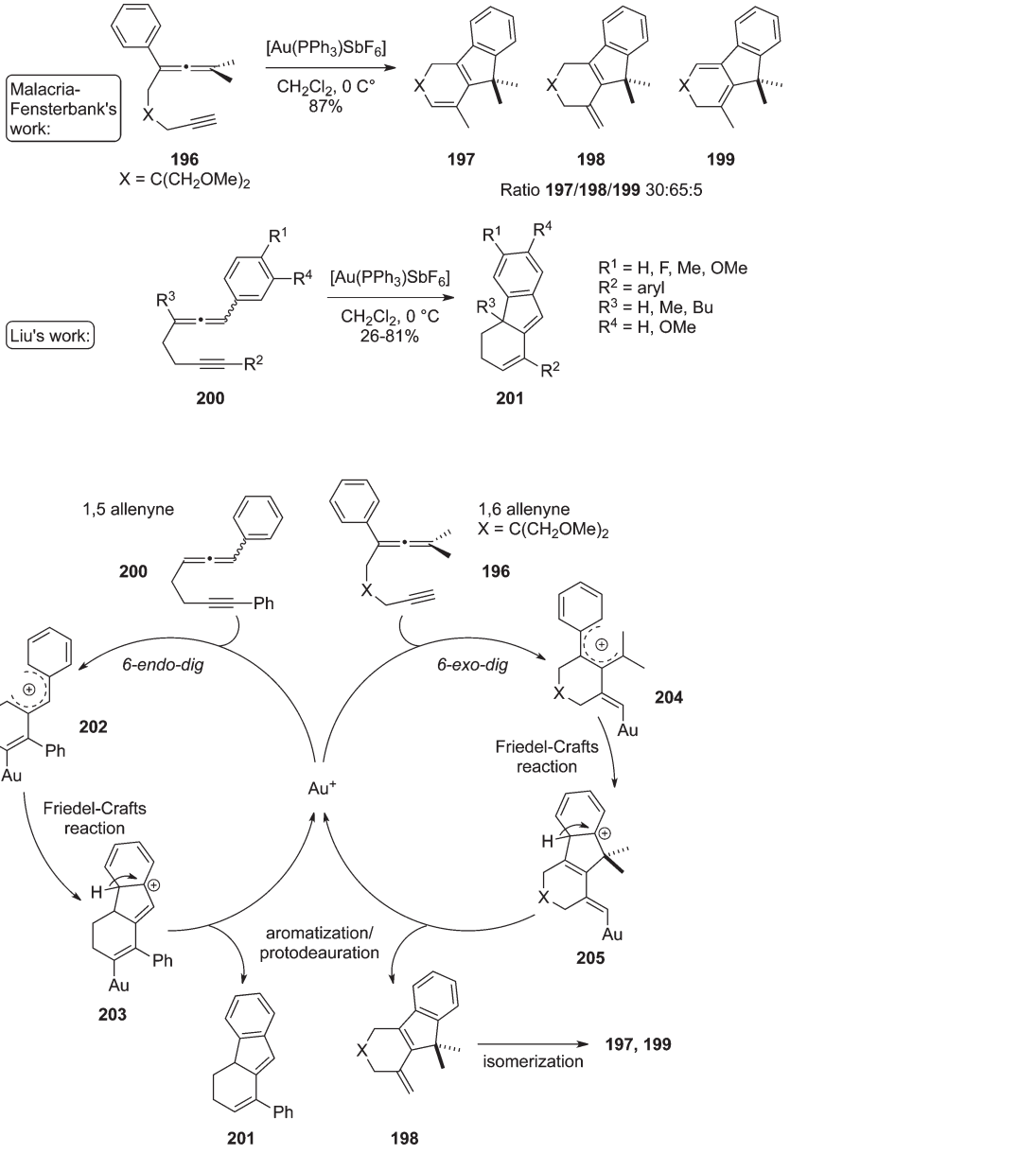
The reasons of such divergence in the cyclization mechanism depending on the catalyst remains unclear nonetheless this phenomenon, although rare, was precedently observed.[92]

Some other examples of allenynes cycloisomerization where coordination of the metal to the allene is preferred to alkyne coordination will be discussed below (see section 3.2)

3.1.1.3. Cyclization Reactions Involving Allenes Generated from Propargyl Esters. Unlike the previously discussed cycloisomerizations, the following examples will introduce reactions of allenyne substrates upon π-acids catalysis on which an allenylester moiety is generated in situ thanks to an initial catalyzed 1,3-*O*-acyl-migration, which corresponds also to a [3,3] sigmatropic rearrangement of the propargyl ester.[93] While this trick can undoubtedly saves

dx.doi.org/10.1021/cr100376w |*Chem. Rev.* 2011, 111, 1954–1993

Scheme 55. Phenyl-Substituted 1,5- and 1,6-Allenynes Cycloisomerizations



steps of allene synthesis, it also allows the introduction of an oxygenated function in the final cycloisomerization product. First example of this principle was given by Malacria et al. starting from propargyl ester **212** (Scheme 57).[53] First catalytic cycle with $PtCl_2$ yields to allenylester **214**, that can be further engaged in the previously mentioned cycloisomerization to provide the hydrindiene product **215**. Methanolysis liberates unsaturated ketone **213**.

In 2006, Toste reported a synthesis of aromatic ketones **217** based on a silver salt catalyzed tandem process (Scheme 58).[94] Following the generation of an allenyl ester **218**, activation of the triple bond by silver triggers a nucleophilic addition of the allenyl ester onto the alkyne that takes place in a 6-endodig manner, followed by hydrolysis of the acetate. This transformation is the first efficient[95] transition metal-catalyzed equivalent of the Myers−Saito cyclization that consists in the thermal cyclization of (*Z*)-allene-ene-yne systems through 1,4-biradical intermediates.[96]

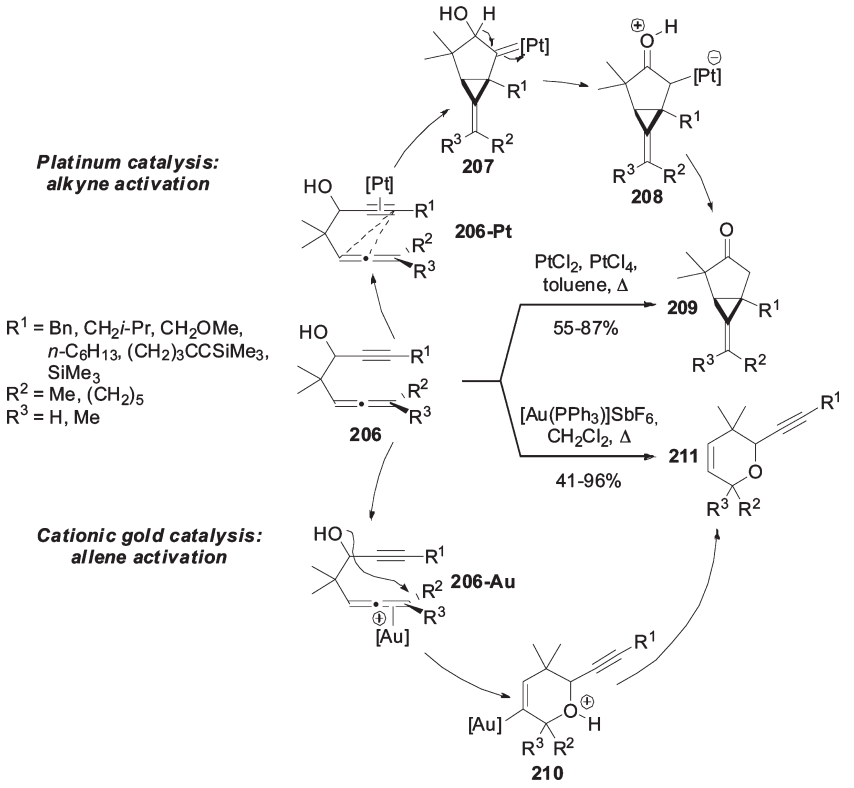
A similar approach for the construction of aromatic rings was lately designed by Liang, which relies on the coupling of a 1,6-enyne cycloisomerization and a [3,3] sigmatropic rearrangement of a propargylic ester upon platinum catalysis.[97] This allowed them to obtain bicyclic compounds **220** through a two-sequences mechanism (Scheme 59).

In a first catalytic cycle, the propargyl ester **219** undergoes the expected [3,3] sigmatropic rearrangement promoted by platinum to afford the allene **221** (Scheme 60). In a second catalytic cycle, the cyclization of the 1,6-enyne moiety occurs, giving rise to a cyclopropyl platinum carbene **222** that further rearranges[98] to give carbocation **223**. Finally, elimination of platinum followed by an isomerization/aromatization accompanied by acetic acid release furnish the aromatic ketone **220**, which formally corresponds to an intramolecular Diels−Alder reaction.

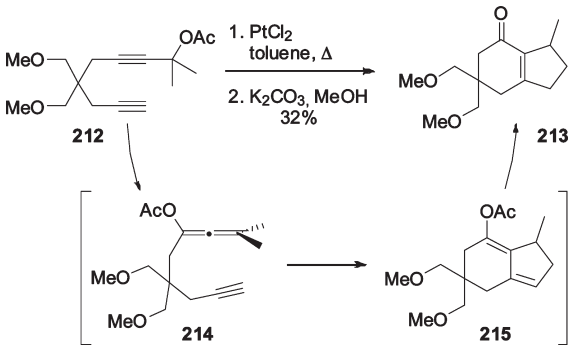
In 2009, Oh reported the gold-catalyzed hydrative rearrangement of 1,1-diethynylcarbinol acetates **224** into cyclopentenones **226**.[99]

dx.doi.org/10.1021/cr100376w |*Chem. Rev.* 2011, 111, 1954–1993

Scheme 56. Different Reaction Outcomes in Hydroxylated 1,5-Allenynes Cycloisomerization



Scheme 57. Cycloisomerization of in situ Generated Allenynyl Esters



At the beginning of their study, they observed a different reaction outcome of this gold-catalyzed rearrangement depending on the temperature, the catalyst loading and the reaction time (Scheme 61).

While **225** did not give cyclopentone **226** upon gold catalysis, the first steps of the rearrangement mechanism are nonetheless shared by both products **225** and **226**. First, a [3,3] sigmatropic shift of the propargyl acetate gives birth to a 1,3-allenyne system **227** (Scheme 62). Activation of the triple bond by gold then induces oxacyclization that generates the 1,3-dioxolium cationic intermediate **228**, which subsequently undergoes a nucleophilic attack by a molecule of water and protodemetalation to lead to intermediate **229**. Then, depending on conditions, the latter can evolve into two different fashions: kinetic conditions furnish allenone **225** after opening of the dioxole ring (path a), while thermodynamic conditions afforded cyclopentenone **226** (path b). This thermodynamic product probably results of a 5-endodig cyclization upon activation of the allene by gold giving intermediate **230**, which undergoes protodemetalation to deliver cyclopentenone **226**.

3.1.1.4. Intervention of Internal Oxygenated Nucleophiles on Allenyne Systems. The goal of this section is to describe the cycloisomerization of allenynes in which the latter system still undergoes an initial activation of the alkyne but followed by a competitive attack from an oxygenated nucleophile in the reaction conditions prior to the intervention of the allene moiety and C−C bond formation.

In 2008, Akita reported the gold(III)-catalyzed cycloisomerizations of 1-allenyl-1-ethynyl acetates **231** into 4-methylene-2-cyclopentenones **232** (Scheme 63),[100] which is formally an application of the Rautenstrauch rearrangement[101] to allenynes.

The mechanism proposed by the authors starts with the nucleophilic addition of the carbonyl oxygen of the propargylic acetate to generate the vinyl gold species **235a** probably in equilibrium with the gold carbene species **235b** (Scheme 64) that further cyclizes to furnish the intermediate delocalized carbocation **236**. The fulvene derivative **233** is released upon cationic gold(III) elimination and then undergoes methanolysis to give product **232**.

The following work, realized by Oh et al. in 2006, demonstrates that gold nanoparticles are as efficient as homogeneous catalysts to promote cyclization reactions with the undeniable advantages of catalyst recycling and low catalyst loading requirement in the context of the development of eco-friendly processes.[102,103] Indeed, fused polycyclic ketone **238** is obtained in good yields through the cyclization of 1,6-allenynebenzaldehyde **237** in the presence of gold nanoparticles (Scheme 65).

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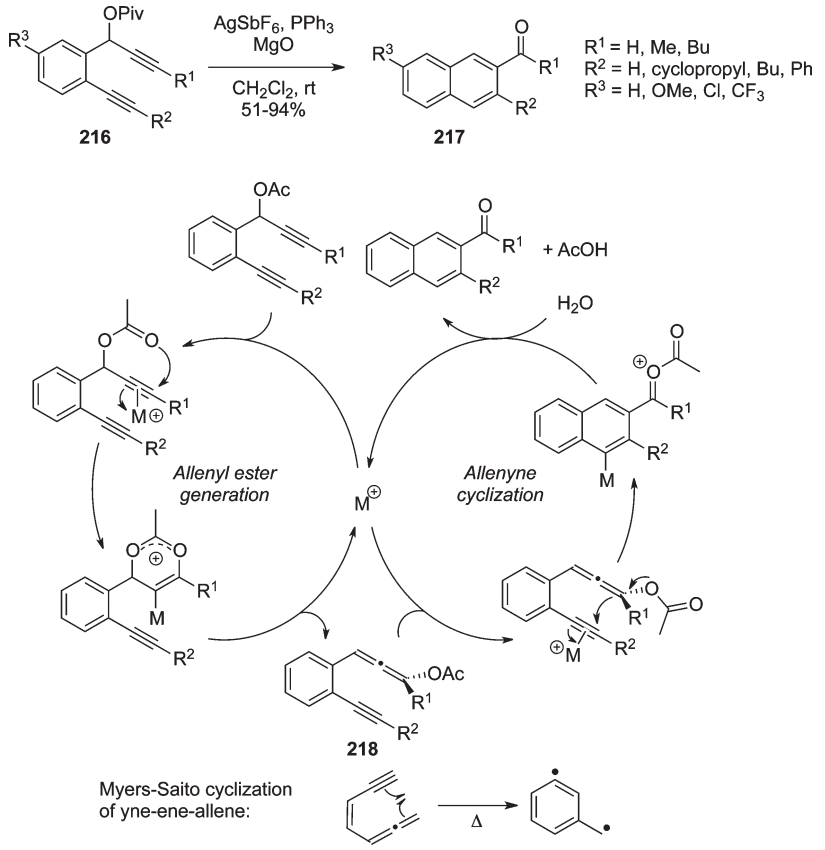
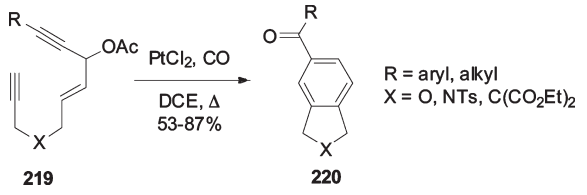
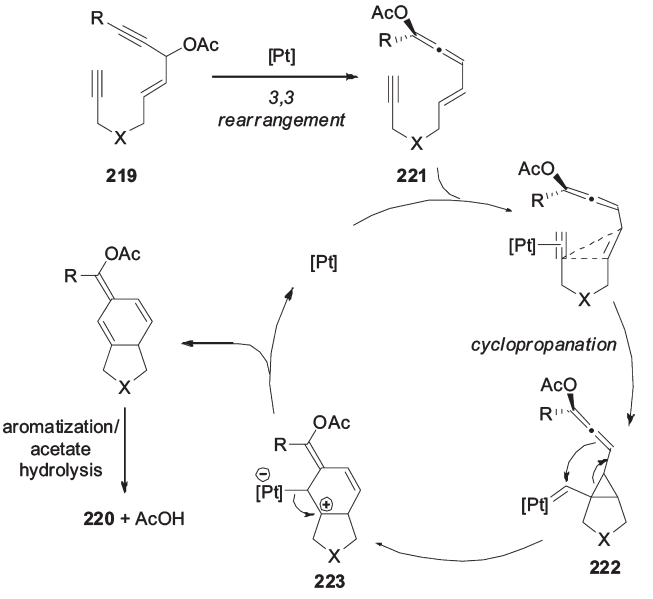
Scheme 58. Metal-Catalyzed and Thermal Biradical Myers−Saito Cyclizations



Scheme 59. Tandem Propargylic Ester Rearrangement/ Allene-ene-yne Cyclization



Scheme 60. Proposed Mechanism for the Cyclization of the Allene-ene-yne System

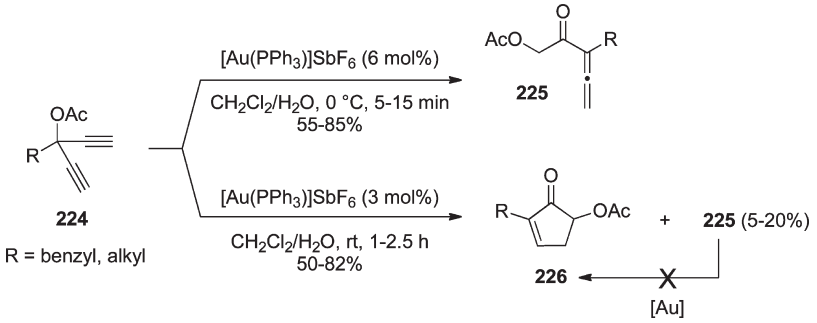


The first step of the proposed mechanism consists in a nucleophilic attack of the aldehyde oxygen onto the activated triple bond, thus giving rise to a zwitterionic intermediate **239** which rearranges into the polycyclic carbene **240** through a [3 + 2] dipolar cycloaddition. The latter undergoes the attack of water leading presumably to the adsorbed intermediate **241**[104] which desorption is accompanied by a molecular hydrogen release to afford compound **238** (Scheme 66).

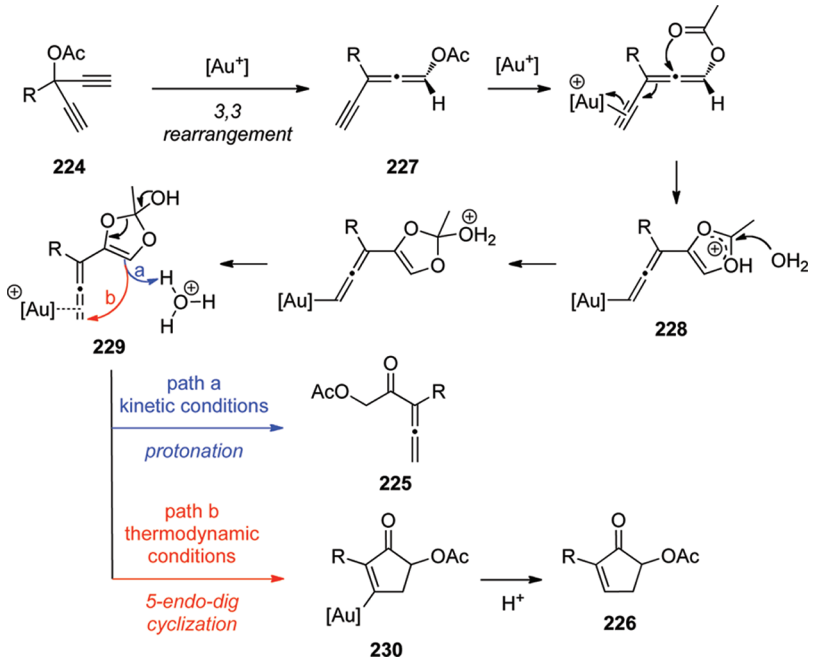
3.1.1.5. Activation of the Alkyne via Gold-Acetylide. In 2008, Toste and Houk reported a gold-catalyzed cycloisomerization of 1,5 allenynes **242**.[105] Herein, the difference stands in the choice of the catalyst, as the typical conditions for 1,5-enyne cycloisomerization[106] or those used before[80] (1 mol % Ph_3PAuCl, 1 mol % $AgSbF_6$ in CH_2Cl_2) rapidly resulted in the formation of a complex mixture. So, they chose to investigate the less reactive catalyst tris(phosphinegold)oxonium complex $[(Ph_3PAu)_3O]BF_4$, which allowed them to obtain Alder-ene products **243** as depicted in Scheme 67. Although Alder-ene products were also observed with 1,6 allenynes (Scheme 48), the originality of this transformation is based on its mechanism. A comprehensive theoretical study of the latter was conducted by Toste and Houk featuring different possible gold-substrate

dx.doi.org/10.1021/cr100376w |*Chem. Rev.* 2011, 111, 1954–1993

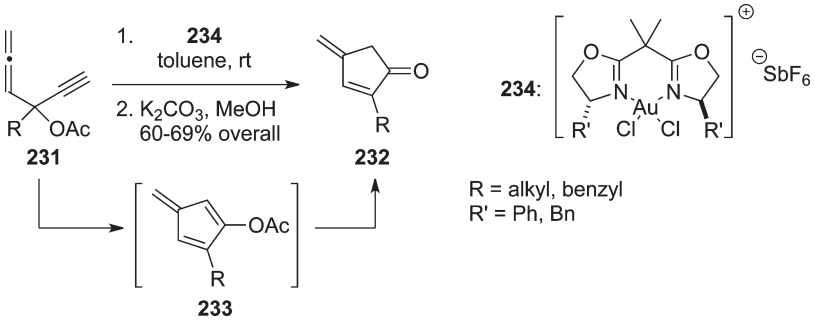
Scheme 61. Kinetic or Thermodynamic Outcome in Gold-Catalyzed Rearrangement of 1,1-Diethynylcarbinol Acetates



Scheme 62. Allenone or Cyclopentenone: Diverging Mechanistic Pathways



Scheme 63. Cycloisomerization of 1-Allenyl-1-ethynyl Acetates

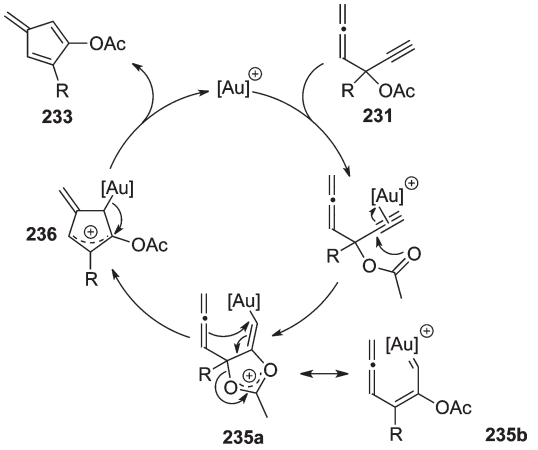


complexes and mechanistic pathways. Calculations demonstrated the unlikeliness of metallacyclopentene or vinylidene intermediates, single activation of the allene was unfavorable as well.

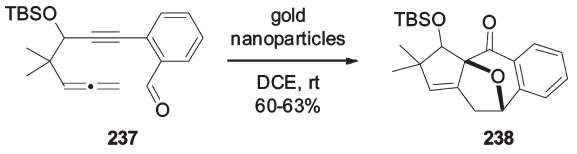
Nonetheless, they noticed that coordination of gold to the triple bond was favorable and the newly formed gold-substrate complex evolved to a gold acetylide[107] species upon which the coordination of a second gold cationic center is favorable

dx.doi.org/10.1021/cr100376w |*Chem. Rev.* 2011, 111, 1954–1993

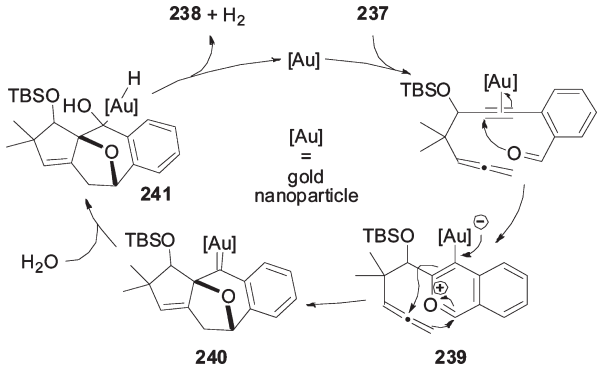
Scheme 64. Mechanism Proposal for 1-Allenyl-1-ethynyl Acetates Rearrangement



Scheme 65. Gold Nanoparticle-Catalyzed [3 + 2] Dipolar Cycloaddition



Scheme 66. Plausible Reaction Mechanism of the [3 + 2] Dipolar Cycloaddition

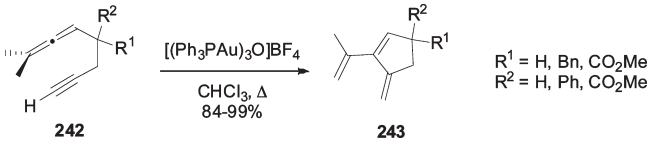


(Scheme 68). Exchange of deuterium at the terminal alkyne in cross labeled experiments, cyclization of the synthetic gold acetylide and inertness of substituted alkyne substrates constitute valuable clues of viability of the gold acetylide pathway.

The postulated mechanism is depicted in Scheme 69. C−C Bond formation occurs from the in situ generated gold acetylide in a 5-exodig manner upon activation of the triple bond by a phosphinegold cation to give a gem-diauraalkene **244**. The catalytic cycle is then terminated through the following sequence: 1,5 hydrogen shift, protodemetalation, and transfer of phosphine gold to another substrate.

3.1.2. Activation of the Allene. *3.1.2.1. Allene Activation in 1,4- and 1,6-Allenynes.* In 2008, Liu reported the gold-

Scheme 67. Gold-Catalyzed Alder-ene Reaction of 1,5-Allenynes



catalyzed hydrative carbocyclization of 1,4- and 1,6-allenynes.[108] The originality of this transformation stands in the fact that allene activation is preferred to alkyne activation, a divergence to the previously described processes that presumably relies on the presence of water. Depending on the number of carbon atoms that tethers the allene and the alkyne, two different types of products were obtained upon activation of the allene by the gold catalyst, resulting either of an endo- or an exocyclization (Scheme 70).

At this point, it is worthy of note that Murakami observed similar behaviors with 1,6-allenynes in hydrative conditions,[88] however no complexation to the allene was invoked (see section 3.1.1, Scheme 54). The proposed mechanism for the cyclization of 1,4 allenynes **245** starts with the formation of an allene-gold complex which undergoes a nucleophilic attack of the triple bond triggered by water in a 5-endo manner (Scheme 71). Cyclopentene derivatives **246a** and **246b** are released through subsequent protodemetalation. Concerning 1,6-allenynes **247**, the same allene activation is invoked, but this time the water-triggered attack of the triple bond takes place in a 5-exo manner. The vinylcation is then trapped by a water molecule and the following protodemetalation step affords cyclopentane derivatives **248a** and **248b**. This mechanistic proposal appears more plausible, as in contrast, the one proposed by Murakami[88] relies on a β-carbon elimination, a little described process which necessitates a parallel alignment of the fragmenting bonds which presumably cannot be the case on intermediate **193**.

Complexation of gold to the allene was confirmed by using an enantioenriched allene as the starting material, which resulted in a chirality transfer to the products (Scheme 72). This precludes the gold complexation to the triple bond as a complete racemization would presumably occur through such pathway.

The disubstituted allene (*S*)-**249** suffered partial racemization, while the disubstituted allene (*R*)-**251** cyclized with a total chirality transfer, which is probably because of the milder conditions used for the cyclization. This finding brings new complementary elements to the experimental and theoretical study on allenenes cycloisomerization performed by Malacria, Fensterbank, and Gandon[109] suggesting that electronically enriched disubstituted allenes racemize upon gold coordination (see section 3.2.3). A computational study of the 1,6-allenynes cyclization was also accomplished by Liu to support this work[108] (Scheme 73).

Although the presence of water was not taken into account, these computations gave some interesting information: first, an allene-metal complex appears as stable as an alkyne-metal complex for 1,6-allenynes (free energies of complexes **253** and **254** are around -50 ± 5 kcal mol^{-1}) so the discrimination of the two pathways would not rely on a preferred complexation of the metal.[110] According to the authors, the discrimination takes place in the second step of the mechanism as the cyclization of the cis-complexed intermediate *cis*-**253** to afford the vinylcation **255** is

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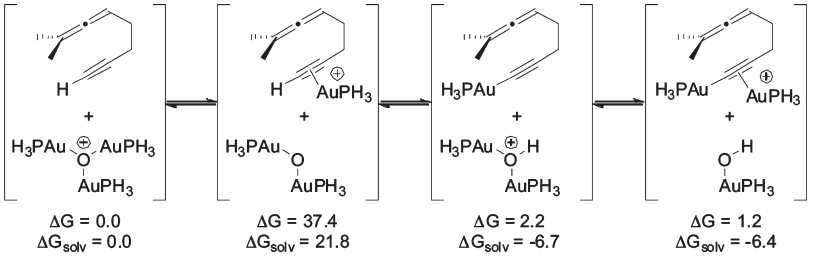
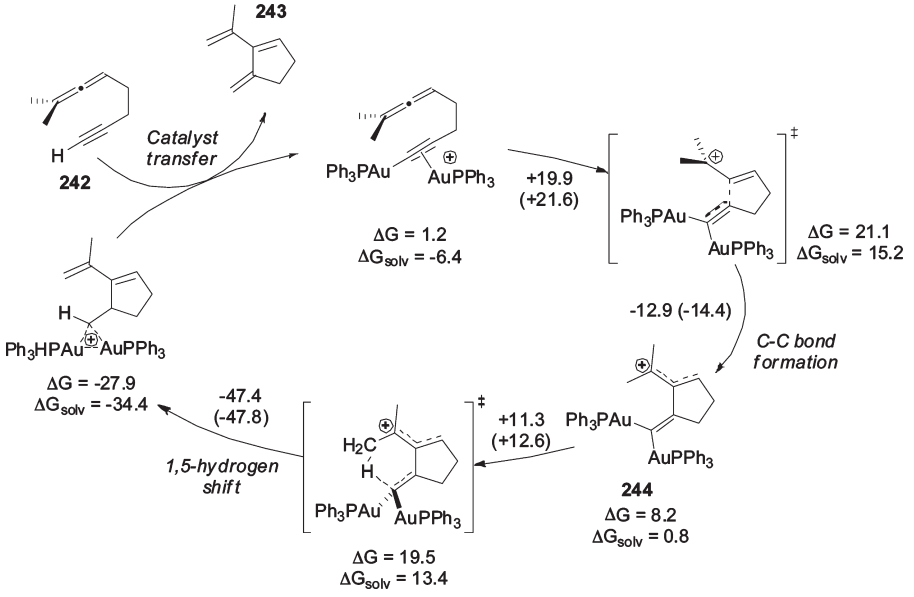
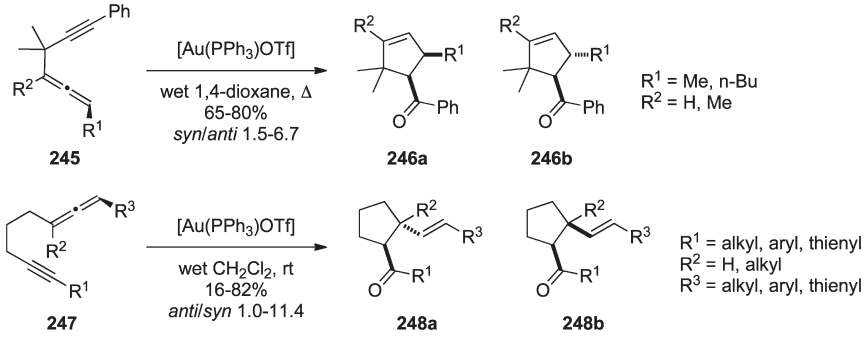
Scheme 68. Possible Gold−Substrate Complexes in Equilibrium (Free Energies Are Given in kcal mol^{-1})



Scheme 69. Computed Mechanism for the Cyclization of 1,5-Allenynes (Free Energies Are Given in kcal mol^{-1})



Scheme 70. Hydrative Cyclizations of 1,4- and 1,6-Allenynes



favored by about 6 kcal mol^{-1} than the cyclization of the alkyne complex **254** into carbocation **256**. Nonetheless, the pathway proposed by Murakami et al. seems to be thermodynamically favored over the allene complexation pathway (−73.34 kcal mol^{-1} for **256** versus −54.06 kcal mol^{-1} for **255**). Finally, the role of water remains unclear in this allenyne cyclization, and the factors that govern the cyclization pathway are not completely unveiled.

3.1.2.2. Intervention of Internal or External Oxygenated Nucleophiles on the Activated Allene. In 2009, Xu developed a tandem reaction using yne-allenylketones **257** to get naphthofurans **258** upon platinum catalysis (Scheme 74).[111]

The proposed mechanism of this reaction consists in two sequences (Scheme 75): first, a nucleophilic attack of the carbonyl oxygen takes place to generate a dihydrofuranyl platinum carbene **259**. As the authors proved that furanyne **261** was unreactive toward platinum catalysis, they logically proposed that this dihydrofuranyl carbene was the active species for the second sequence of the mechanism which consists in a 6π-electrocyclization type of process. The zwitterionic carbene **260** thus formed undergoes

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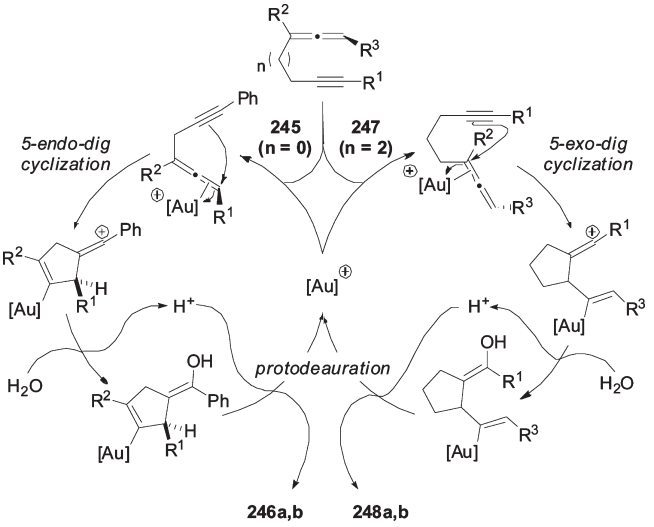
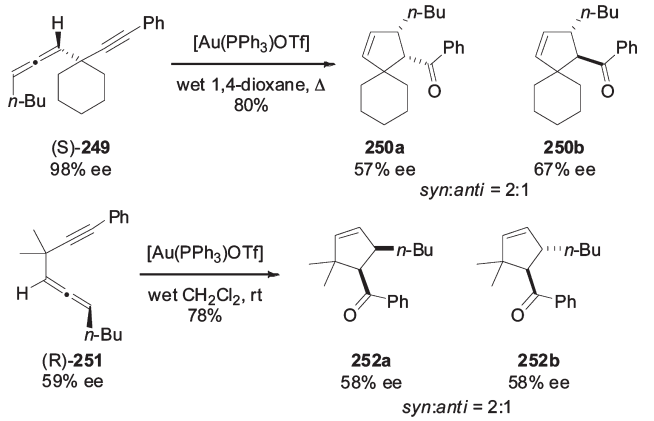
Scheme 71. Mechanism of Hydrative Cyclization of 1,4- and 1,6-Allenynes



Scheme 72. Axis-to-Center Chirality Transfer



rearomatization through a 1,3-hydride shift followed by deprotonation/protodemetalation processes to give tricyclic compound **258**.

Performing the reaction in the presence of D_2O gave a 56% deuterium incorporation at the C-3 position of the furan what is consistent with the above-described mechanism.

N-Allenamides revealed to be very reactive substrates giving several products upon gold and platinum catalysis. Thus, in 2009, Pérez-Castells et al. reported a synthesis of benzazepines **263** through a gold catalyzed cyclization of yne-*N*-allenamides **262** in the presence of external nucleophiles (Scheme 76).[112] Gold(III) chloride proved to be efficient at low temperature and allowed the authors to obtain selectively the desired benzazepine compounds **263** in moderate to good yields.

To account for their formation, the authors hypothesized activation of the allene by gold resulting in hydroalkoxylation of the latter to give the yne-enamine intermediate **264**. Then, upon activation of the triple bond, a 7-endodig cyclization takes place and the so generated nitrogen-stabilized carbocation **265** is finally trapped by an external nucleophile, and a simple protodemetalation affords the benzazepine **263**. Two pieces of evidence let the authors confirm that the allene complexation pathway is more likely to occur: in one hand, no products that could result from activation of the alkyne were isolated among the several products formed upon the different reaction conditions tested, and in the other hand, the isolated **264** intermediate furnished the benzazepine compound upon gold catalysis.

3.2. π-Acids Catalyzed Cycloisomerizations of Allenenes and Allenedienes

The goal of this section is to introduce the different mechanistic pathways of π-acids catalyzed reactions in which allene moieties react in an intramolecular manner with one or two double bonds. Whereas in the cyclizations of allenynes the coordination of the metal center to either the triple bond or the allene framework can raise problems of chemoselectivity, it is commonly accepted that allenenes or allenedienes cyclizations begins with activation of the allene. Hydroarylations reactions have been voluntarily omitted, since this subject deserves a review by itself,[113] but we nonetheless reported when comparable reactivities were observed with aromatic substrates.

3.2.1. 1,7- and 1,5-Allenenes Cyclizations. In 2007, Gagné and co-workers reported the cycloisomerization of 1,7-allenenes **266** catalyzed by chiral cationic gold(I) catalysts[114] (Scheme 77). The reaction proceeded smoothly to afford vinylcyclohexenes **267**[115] with low to moderate enantioselectivities (up to 77% *ee* when lowering the temperature to −12 °C).

The process is completely regioselective when sulfones or urea tethered substrates were used or when trisubstituted double bonds were employed as cyclization partners. Nonetheless, the authors noticed that monosubstituted olefins remained unreactive and substitution at the internal allene position led to poor yields and enantioselectivities and partial isomerization of the starting material. The mechanism of this cycloisomerization is supposed to begin with the electrophilic activation of the allene by the gold cation (Scheme 78). Nucleophilic attack of the double bond affords the vinylmetal intermediate **268**. Two competitive proton eliminations can then occur, followed by protodeauration to regenerate the catalyst.

Enols are also good partners for this kind of reactions. In 2003, Iwasawa reported the cyclization of allenyl silyl enol ethers **269** catalyzed by the electrophilic pentacarbonyl tungsten complex to give cyclopentenes and cyclohexenes derivatives[116] (Scheme 79).

Photoirradiation is necessary to generate the active catalytic species by dissociation of one carbonyl ligand, which can thus activate the external allene double bond. With the assistance of the siloxy group, a 5-endo cyclization takes place to give the vinyltungsten intermediate **271**. Three equivalents of water are generally needed to perform efficiently the last step of the mechanism, that is, hydrolysis of the siloxonium and protodemetalation, affording the bicyclic adduct **270**. Acyclic substrates reacted in a 6-endo manner, nonetheless with a higher catalyst loading. Importantly, the absence of water gives rise to a completely different reaction outcome, as the same substrates led to formal Cope rearrangement products upon $W(CO_6)/h\nu$ catalysis.[117]

Enols were also exploited by Ma and co-workers, who accomplished the first allene Conia-ene-type[118] reaction with allenylacetylacetates **272** in the presence of catalytic amount of a cationic phosphinegold(I) complex (Scheme 80).[119]

Coordination of gold to the external double bond of the allene framework would allow a 5-endo cyclization possibly through transition state **274** by analogy with the one proposed by Toste with alkynyl precursors.[118a] Subsequent protodeauration of the vinylgold species **275** regenerates the catalyst and affords cyclopentene derivatives **273**.

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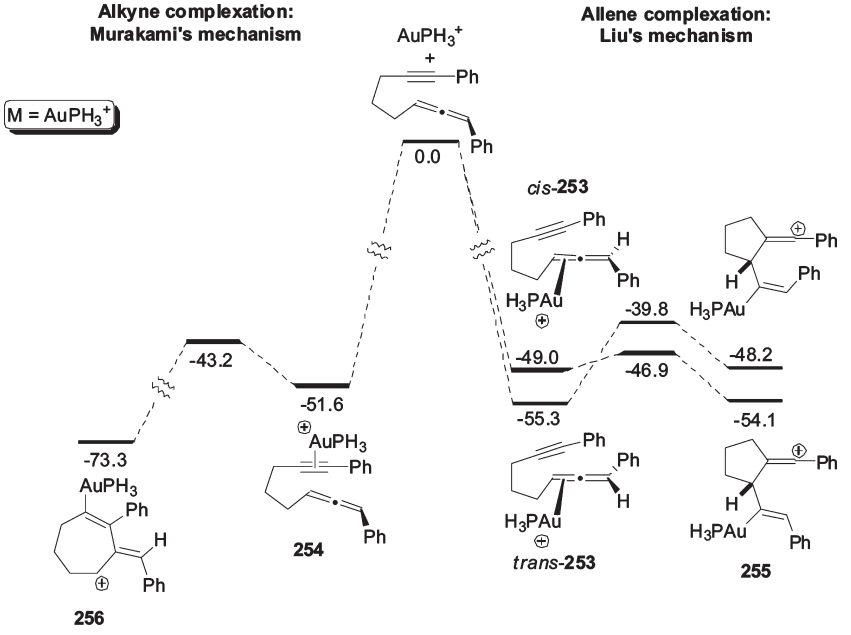
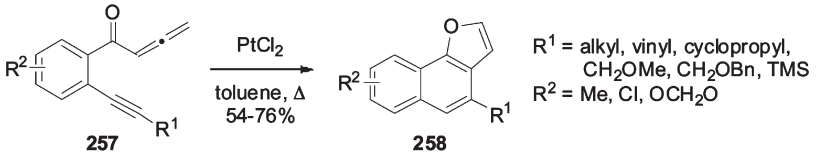
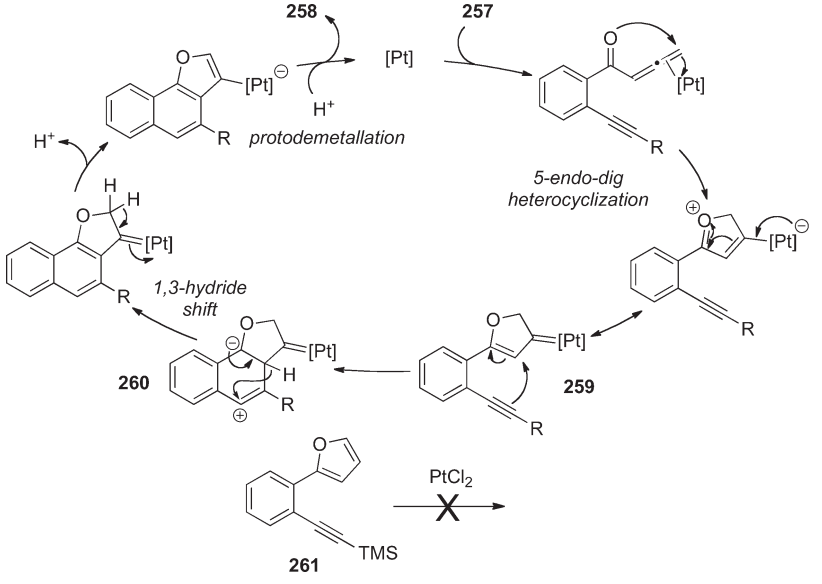
Scheme 73. Allene vs Alkyne Activation with $AuPH_3^+$: energy profiles (kcal.mol^{-1})



Scheme 74. Platinum-Catalyzed Cycloisomerization of Allenynes into Naphthofurans



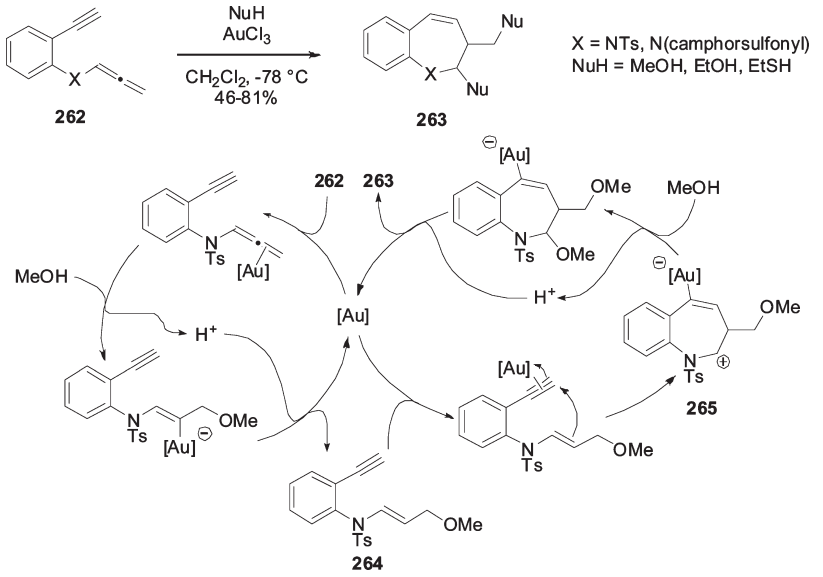
Scheme 75. Proposed Mechanism of Formation of Naphthofurans



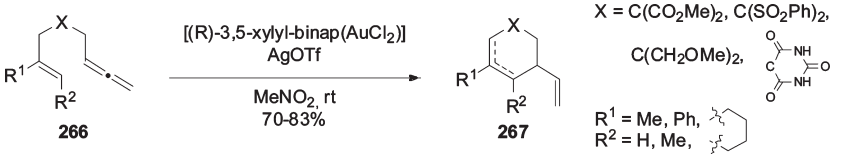
3.2.2. Cycloadditions of Allenenes and Allenedienes. *3.2.2.1. [3 + 2] Cycloadditions. 3.2.2.1.1. Allylallenes.* Between 2006 and 2007, two different groups explored the potential of 1,5-allenenes **276** toward gold catalysis. The Gagosz[120] and Zhang[121] teams both proposed a common intermediate in the cyclization of such substrates, that is, the bicyclic carbene **277**

dx.doi.org/10.1021/cr100376w |*Chem. Rev.* 2011, 111, 1954–1993

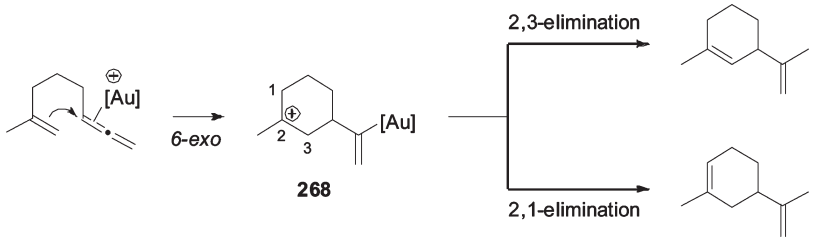
Scheme 76. $AuCl_3$-Catalyzed Cyclization of *N*-Allenamides into Benzazepines



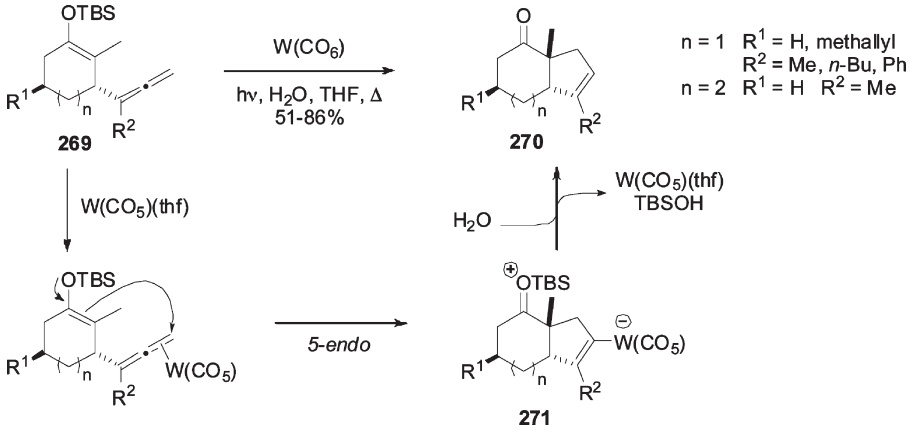
Scheme 77. Cycloisomerization of 1,7-Allenenes



Scheme 78. Proposed Mechanism for the Cycloisomerization of 1,7-Allenenes



Scheme 79. Tungsten-Catalyzed Cyclization of Allenyl Silyl Enol Ethers



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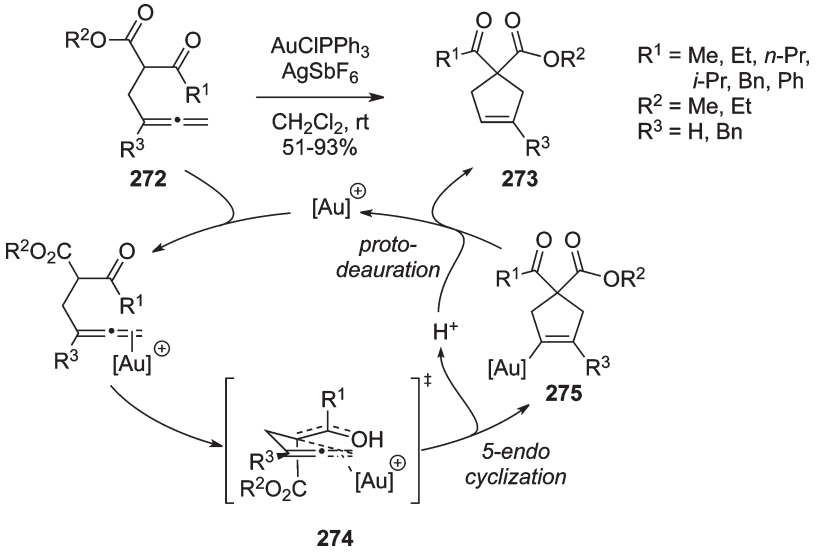
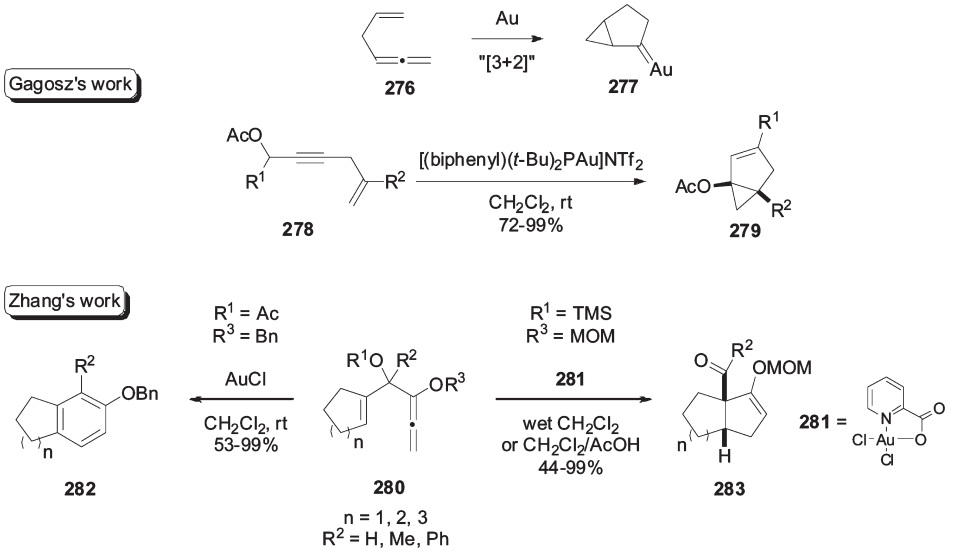
Scheme 80. Conia-ene-Type Cyclization of Allenylacetylacetates



Scheme 81. Generation of Bicyclo[3.1.0]carbenes from 1,5-Allenenes and Applications



(Scheme 81) resulting from a formal [3 + 2] cycloaddition of the allene and the alkene. A highly efficient preparation of bicyclo-[3.1.0]hexenes **279** bearing a tertiary acetate and of the corresponding 2-cycloalken-1-ones obtained after methanolysis was disclosed by Gagosz. In Zhang's work, the outcome of the reaction, namely products [3 + 3] products versus [3 + 2] products is dependent on the electron donating ability of the R1 group (ester versus ether).

A stepwise mechanism was first invoked by Gagosz (Scheme 82, right side): starting from propargyl acetates **278**, an initial gold promoted 3,3-rearrangement (see Part two, I.1.3) gives birth to the allylallene precursor **284**. A 6-endo cyclization upon activation of the allene by the cationic phosphinegold(I) catalyst would generate non classical carbocation **285** also viewed as cyclopropyl carbene intermediate **277**. The latter undergoes 1,2-hydride shift to deliver bicyclic product **278** and regenerate the gold catalyst.[122] Proof was made that **285** is a viable intermediate as trapping experiments with MeOH allowed the isolation of adduct **286**.

On the other hand, the mechanism proposed by Zhang (Scheme 82, left side) involves a concerted [3 + 2] cycloaddition from the 1,3-dipolar carbene **287** generated upon gold coordination to the allenol ether moiety.[123] The total stereospecificity obtained with a mixture of *Z*/*E* trisubstituted double bonds (*Z*/*E* 2.8:1 gave products with cis/trans ratio of 2.8:1) supports well this hypothesis. Nonetheless the 1,3-dipolar carbene intermediate is not consistent with the good chirality transfer observed by Gagosz et al. from enantioenriched propargyl acetates **278** to bicyclo[3.1.0]hexenes **279**. Carbene **277**[124] is a common intermediate for each pathway which can rearrange, depending on the conditions developed by Zhang: in presence of water, hydrolysis of the silylether and subsequent protodeauration afford aldehyde/ketone **283**. Replacing the silylether by the less electron-donating acetate and performing the reaction in dry conditions lead to another rearrangement of the

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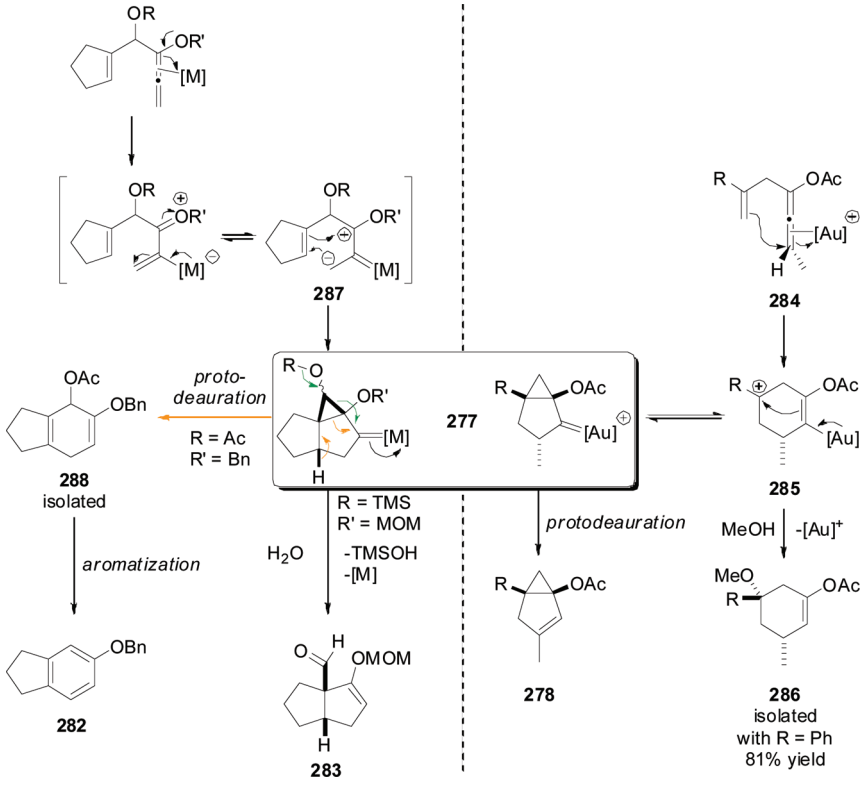
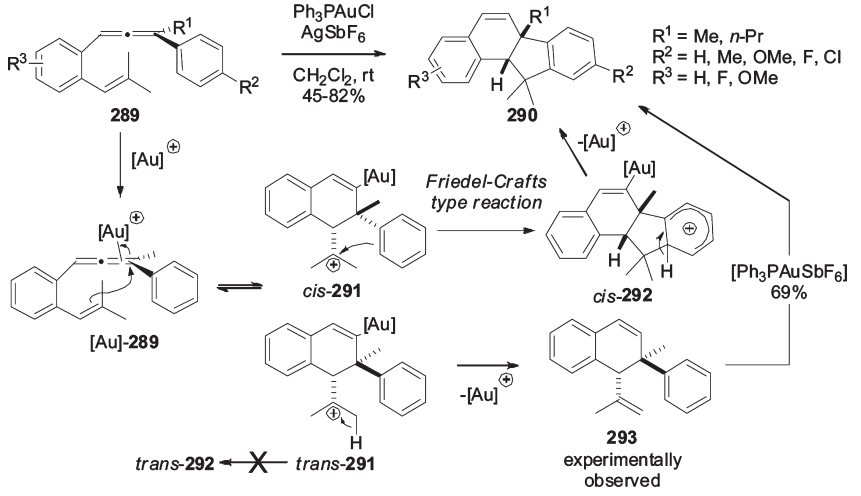
Scheme 82. Proposed Mechanisms of Allylallenes Cycloadditions



Scheme 83. Cycloisomerization of 1-Aryl-1,6-allenenes



cyclopropyl carbene to give 1,4-cyclohexadiene **288** (experimentally observed) that further aromatizes into compound **282**.[125]

3.2.2.1.2. 1-Aryl-1,6-allenenes. A particular case of [3 + 2] cycloadditions was reported by Liu who used phenyl-substituted 1,6-allenenes **289** as starting materials.[126] Only the external carbon of the allene is involved in the [3 + 2] process as the phenyl ring acts as a cycloaddition partner too (Scheme 83).

Upon gold coordination, two carbocationic stereoisomers, *cis*-**291** and *trans*-**291**, are generated from a 6-endo cyclization. These species, according to DFT calculations, are in equilibrium with [Au]-**289**. *cis*-**291** can evolve into *cis*-**292** through a 7.1 kcal mol^{-1} activation barrier, whereas for *trans*-**291**, 17.4 kcal mol^{-1} are needed to perform the second cyclization into *trans*-**292** (not depicted). Cycloadduct **290** is formed after demetalation of the Wheland intermediate *cis*-**292** but the authors also noticed that dihydronaphthalene **293**, resulting from proton elimination on *trans*-**291**, can also produce **290** when submitted to reaction conditions, probably through an isomerization/Friedel−Craft-type reaction sequence.

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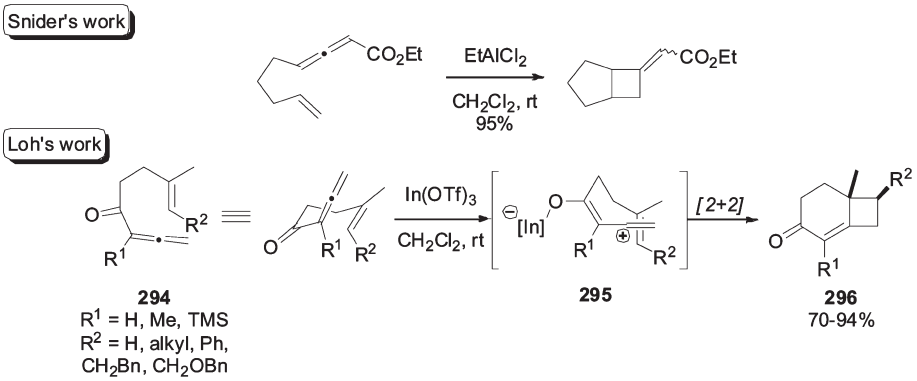
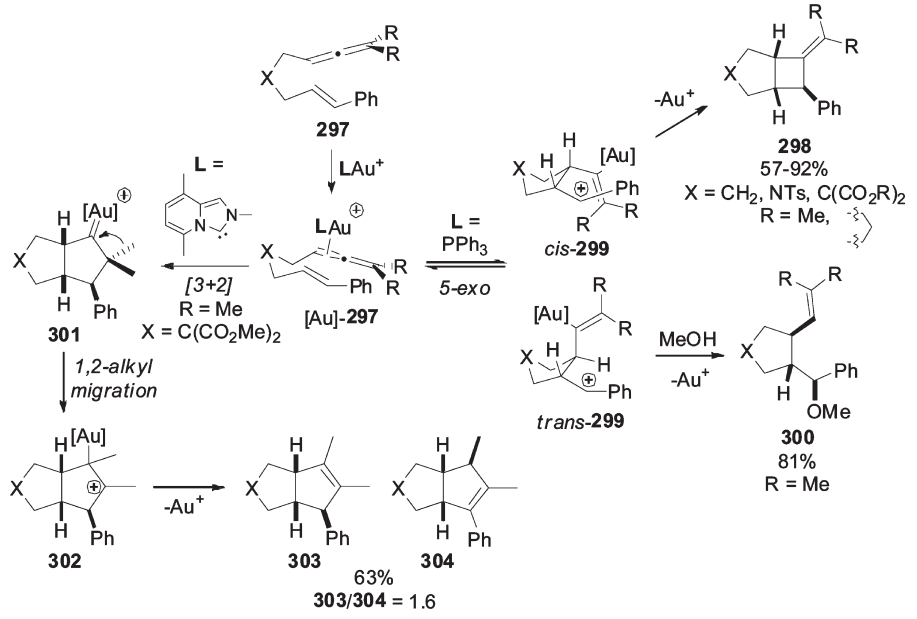
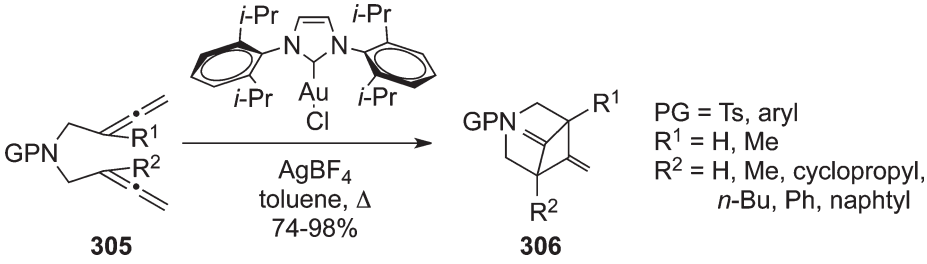
Scheme 84. Lewis-Acid-Catalyzed [2 + 2] Cycloaddition of Activated Allenenes



Scheme 85. [2 + 2] Cycloaddition of 1,7-Allenenes



Scheme 86. Gold-Catalyzed Transformation of 1,7-Bisallenes



3.2.2.2. Formal Head-to-Head 2+2 Cycloaddition. 3.2.2.2.1. 1,7-Allenenes. Inspired by the seminal works of Snider[127] and Hoffmann[128] who reported the inter- and intramolecular [2 + 2] between allenyl esters and alkene with catalytic amounts of $AlCl_3$ or $EtAlCl_2$, Loh and co-workers developed a Lewis acid catalyzed intramolecular [2 + 2] cycloaddition of allenyl ketones **294** and alkenes (Scheme 84).[129] As cationic phosphinegold(I) catalysts provided dimerization products or promoted only the cyclization of the ketone onto the allene, they switched to $In(OTf)_3$ salts to obtain selectively cycloadducts **296**. The proposed mechanism starts with coordination of the Lewis acid to the carbonyl oxygen of **294** which generates a formal positive charge at the central carbon of the allene. Then, based on the fact that their process was stereospecific (Z double bonds give only cis cycloadducts),

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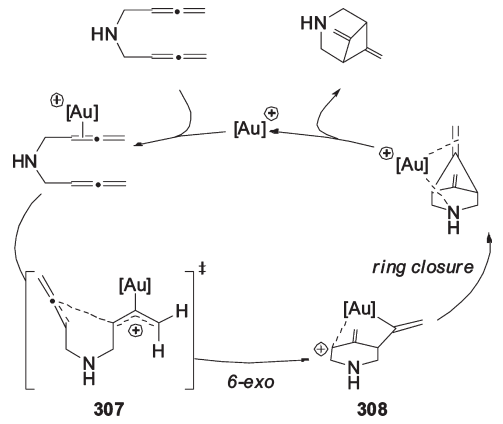
the authors suggested a concerted [2 + 2] cycloaddition occurring at the zwitterionic intermediate **295** to give the bicyclo-[4.2.0] compound **296**.

We have seen above that 1,7-allenenes cyclize upon activation of the allene by π-Lewis acids, such as gold, to give monocyclic compounds (Scheme 77).[114] Slight modifications on the starting 1,7-allenene can lead to a completely different reaction outcome, that is, [2 + 2] cycloaddition, thus allowing the formation of bicyclic adducts.[130] In 2007, Toste reported the gold-catalyzed [2 + 2] cycloaddition of 1,7-allenenes **297** in racemic and enantioselective version.[130a] Introducing a phenyl moiety at the external position of the double bond stabilizes the carbocation **299** generated from a 5-exodig cyclization of the double bond onto the activated allene (Scheme 85).

Scheme 87. Mechanism Proposal for the Cycloisomerization of 1,7-Bisallenes

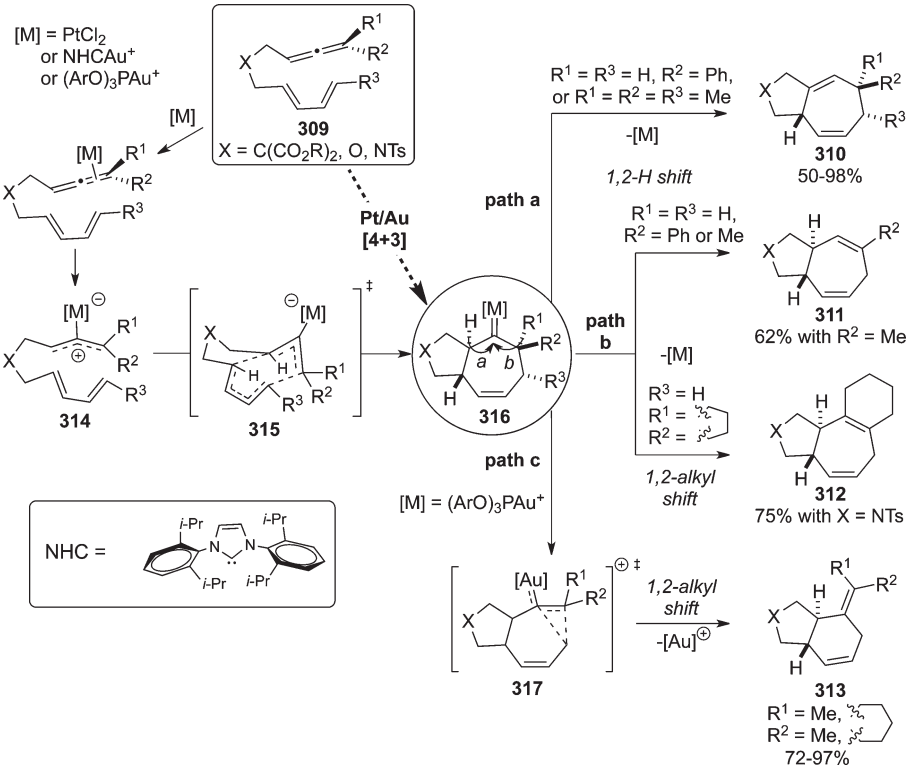


In this stepwise mechanism, two diastereomers are in equilibrium with [Au]-**297**: *cis*-**299**, which has the requisite geometry to give after demetalation cyclobutane **298**,[131] and kinetically formed *trans*-**299**, which affords *trans*-cyclopentane **300** if trapped by an exogenous nucleophile such as MeOH. Quite recently, Fürstner and co-workers show that the outcome of this reaction can be modified with an appropriate choice of ligand:[132] using strongly donor NHC ligands promotes the occurrence of a [3 + 2] pathway leading to carbene **301**. This intermediate then undergoes a 1,2-alkyl migration to give carbocation **302**. After demetalation, a mixture of [3 + 2] cycloadducts **303** and **304** are obtained. On the opposite, using more π-acceptor ligand lowers the electron density on the gold center, a carbene pathway is no longer likely to occur, and the [2 + 2] pathway is preferred.

3.2.2.2.2. Formal Head-to-Head [2 + 2] Cycloaddition of 1,7-Bisallenes. N-tethered 1,7-bisallenes **305** were explored toward cationic NHC-gold catalysis by Chung, Kang and co-workers.[133] The optimized conditions allowed them to obtain unprecedented 6,7-dimethylene-3-azabicyclo-[3.1.1]heptanes **306** (Scheme 86).

The mechanism of this transformation was studied by DFT calculations. Among the several mechanistic scenarios the authors envisioned, it appears that a concerted twisted head-to-head [2 + 2] cycloaddition was not likely to occur, and a stepwise process is preferred over a concerted one. The most probable pathway is depicted in Scheme 87 and begins with coordination of the cationic gold center to one allene. The latter, thus activated, undergoes a 6-exo attack of the uncomplexed allene internal double bond through transition state **307** to give a new type of long-range gold stabilized carbocation **308**. The gold coordination mode in **308** allows the positive charge and the vinylmetal to get close to each other and to perform the final ring closure. Thus, the newly formed 1,3-

Scheme 88. Behavior of Allenedienes with Platinum and Gold Catalysts



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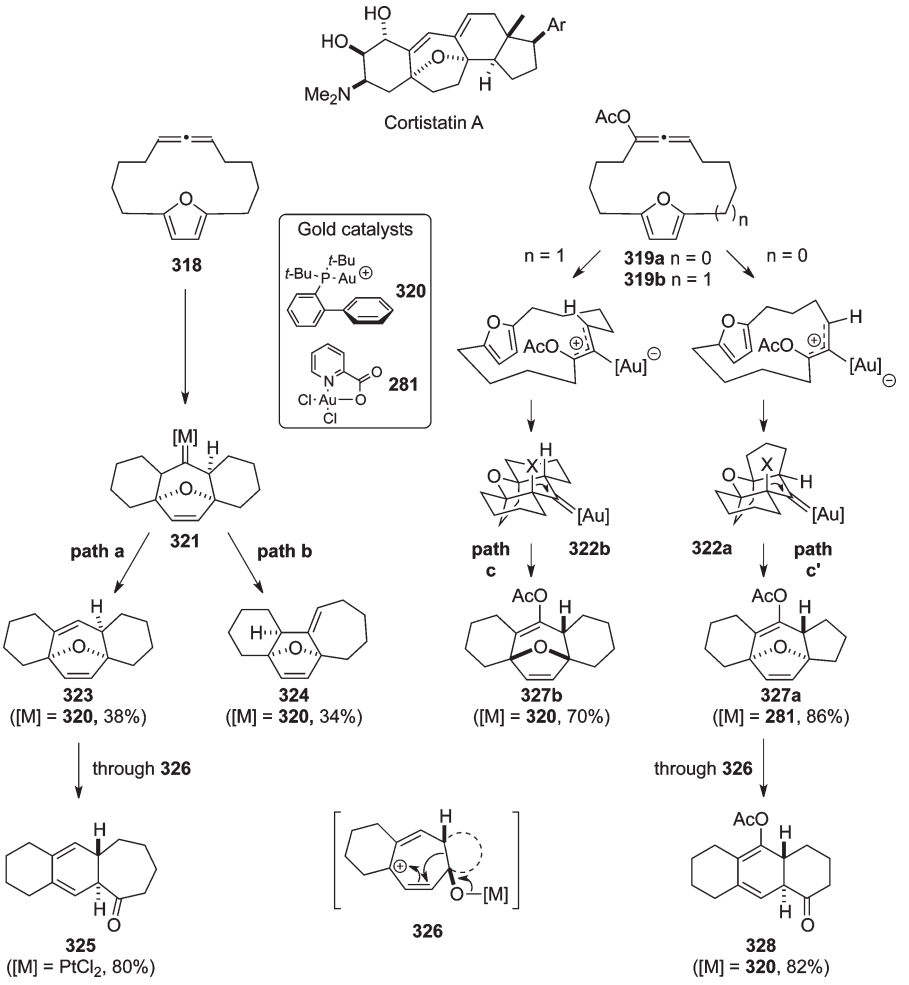
Scheme 89. Transannular [4 + 3] Cycloadditions



dimethylenecyclobutyl ring is released, and a new catalytic cycle can begin.

3.2.2.3. [4 + 3] versus [4 + 2] Cycloadditions of Allenedienes. The potential of allenedienes upon π-acid catalysts was extensively studied by the group of Mascarenas, whose work has been recently complemented by the contributions of the groups of Toste and Fürstner.[130b,132,134−138] One amazing feature of the [4 + 3] cycloaddition is that a judicious choice of the ligand (in case of gold salts) can drive to either [4 + 3] or formal [4 + 2] cycloadducts (Scheme 88).

Mascarenas first reported the platinum[134] and NHC-gold complexes[135] catalyzed reaction of allenediene **309** to give diastereoselectively 1,4-cycloheptadiene derivatives **310** or **311** (a 7:3 [respectively 1:2] mixture of **310** and **311** was obtained in the case of R^2 = Ph with Pt [respectively with Au]). The reaction is supposed to proceed first by coordination of the metal to the allene framework thus giving rise to allylic cation-metal complex **314**. A concerted [4 + 3] cycloaddition[136] then takes place probably through *exo*-like transition state **315** to explain the perfect diastereoselectivity of the process toward trans products. The so-generated cycloheptenyl carbene **316** can then evolve along path a (1,2-H shift followed by demetalation) to give **310** or path b (idem, upper arrow) to give **311** (sporadically observed). Notably, replacing R^1 and R^2 by a cyclopentyl allowed the authors to obtain polycyclic compound **312** through a 1,2-alkyl shift/demetalation sequence (path b, lower arrow). The authors noticed that the reaction was ineffective when using monosubstituted allenes (formation of **314** is not favored) or introducing a methyl at the most internal position of the diene, which raises the energy level of TS **315**. The group of Mascarenas, followed by Toste's one, observed that a different reaction outcome could be reached with gold salts, as some substrates gave mixtures of [4 + 3] and formal [4 + 2] cycloadducts.[137] Combined experimental and theoretical data suggested not only that lowering the electron density at the metal center can favor this pathway, but also that the mechanism of formation of cyclohexene derivatives **313** also begins with a [4 + 3] cycloaddition giving carbene **316**. The use of weak σ-donor phosphite ligands (or strong π-acceptor NHC ligands[132]) promotes selectively a ring contraction on carbene **316** through transition state **317** to yield compounds **313** (path c). DFT calculations show that with phosphitegold complexes, the 1,2-H shift (path a/b) is disfavored toward the ring contraction. Besides, it seems that the steric hindrance of the ligand can favor paths a/b over path c: the bulky biphenyl-di-*tert*-butyl phosphine ligand gives selectively [4 + 3] adducts. Finally, it is worthy of note that an enantioselective version of this methodology was achieved using chiral phosphoramidite[130b] or phosphite[138] ligands.

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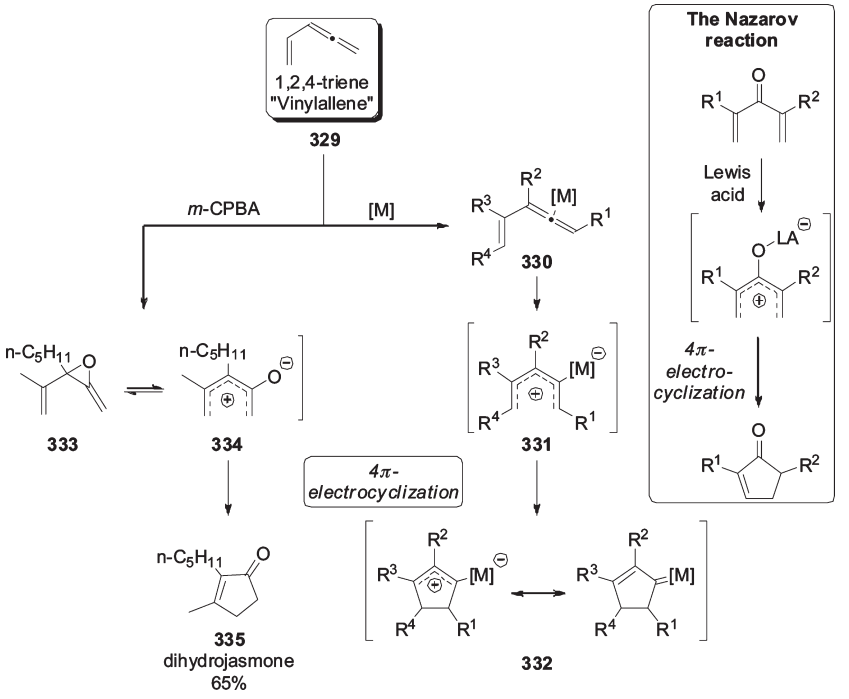
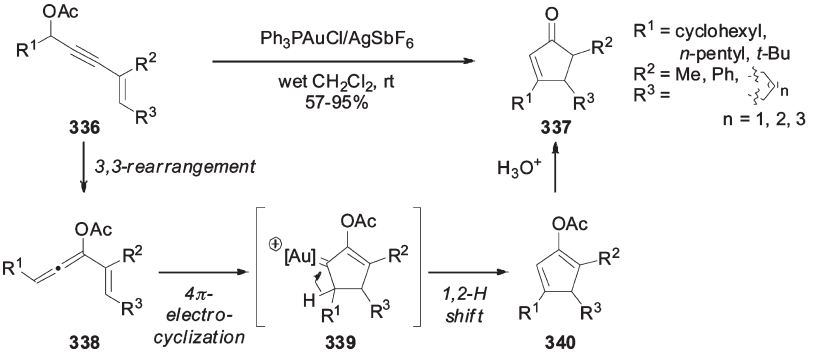
Scheme 90. Oxidative and Metal-Catalyzed Rearrangement of Vinylallenes



Scheme 91. Zhang's Metalla-Nazarov of Vinylallenes



The [4 + 3] cycloaddition was latterly exploited by Gung and co-workers in a transannular version.[139] Their work was aimed at the rapid construction of the tetracyclic core of Cortistatin A, a potent antiangiogenesis natural product.[140] Starting from allene **318** or allenylacetates **319a**, **319b** (generated through a gold-catalyzed 3,3-rearrangement from the corresponding propargyl acetates, not depicted), the above-mentioned cycloheptenyl carbenes are formed upon coordination of the metal to the allene moiety. With allenylacetates, depending on the ring size, a different diastereoselectivity is observed. The conformation of the allylic cation-metal complexes before the cycloaddition takes place explains well this difference. From carbene **321**, with the bulky gold catalyst **320**, a 1:1 mixture of products **323** and **324** is obtained, respectively through a 1,2-H shift (path a in Scheme 89) or through ring contraction (path b in Scheme 89). With $PtCl_2$, only product **325** (and variable amounts of its rearomatized equivalent, not depicted) is obtained through a metal promoted rearrangement of the 2,5-dihydrofuran framework on compound **323** (intermediate **326**). From carbenes **322a** and **322b**, a 1,2-acetate shift occurs (path c and c′ in Scheme 89, respectively), followed by demetalation to give cycloadducts **327a** and **327b**. The outcome of this reaction was shown to be strongly dependent on the gold catalyst: for allenylacetate **319a**, using gold(I) catalyst **320** led only to the rearranged product **328**, whereas for **319b** the polycyclic compound **327b** was obtained selectively in a good yield. Gold(III) catalyst **281** was the best candidate to avoid a further rearrangement of **327a** into **328**.

3.2.3. Metalla-Nazarov Reaction of Vinylallenes. 1,2,4-Trienes, also called vinylallenes, were shown to display a particular reactivity when submitted to π-acid catalysts (Scheme 90). Starting from a generic vinylallene **329**, coordination of the metal center to the allene moiety gives rise to delocalized cation **331** which then undergoes a 4π-electrocyclization to give carbene/metal-stabilized carbocation **332** (Scheme 90, right side). An obvious parallel can be made with

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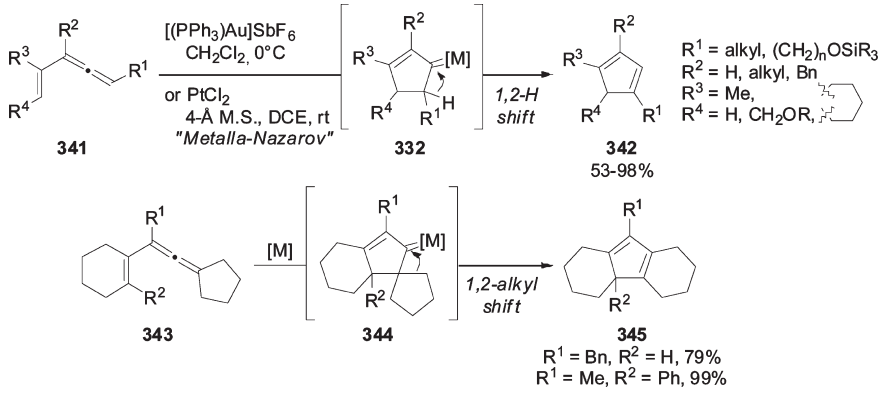
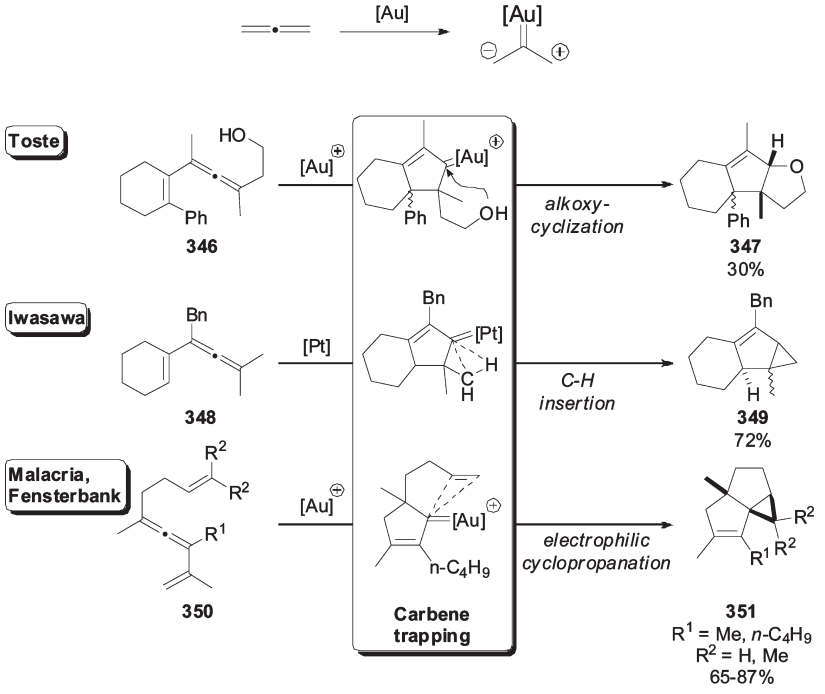
Scheme 92. Gold- and Platinum-Catalyzed Cyclizations of Vinylallenes



Scheme 93. Carbene-Trapping Strategies in the Metalla-Nazarov



the Nazarov reaction[141] (Scheme 90, box) and a closer one with the rearrangement of vinylallene oxides generated by oxidation with *m*-CPBA of the aforementioned vinylallene[142] (Scheme 90, left side). Ene-vinyloxirane **333** is in equilibrium with its zwitterionic opened form **334** that resembles to delocalized cation **331** and reacts in a comparable manner, that is, 4π-electrocyclization, to give cyclopentenone **335**.

Zhang and co-workers were the first to report this rearrangement[143] with gold catalysis, starting from propargyl acetates **336**. An initial gold-catalyzed 3,3-rearrangement is necessary to generate the desired vinylallene **338**, which undergoes the subsequent metalla-Nazarov cyclization to give carbene **339**. After a 1,2-H shift/protodeauration step, cyclopentadiene **340** is released, which is further hydrolyzed to furnish cyclopentenone **337** in a short reaction time (Scheme 91).

One year later, the groups of Toste[144] and Iwasawa[145] independently reported respectively the gold- and platinum-catalyzed cyclization of vinylallenes. In these studies, the allene moiety is not generated in situ and vinylallenes **341** were used as starting materials (Scheme 92). After the metalla-Nazarov step (Scheme 90), cyclopentadienes **342** are released form carbene **332** through a 1,2-H shift/demetalation sequence that can be replaced, as noticed by both groups, by a 1,2-alkyl shift/demetalation sequence when cyclopentane substituted allenes **343** were used as substrates, affording tricyclic compounds **345**.

Trapping of intermediate **332** was achieved by both groups: using the tetrasubstituted allene **348** avoids a possible 1,2-H shift to occur and promotes a C−H insertion of the carbene[146] to give a mixture of diastereomers **349**. To its part, Toste's team managed to trap it in an intramolecular manner using precursor

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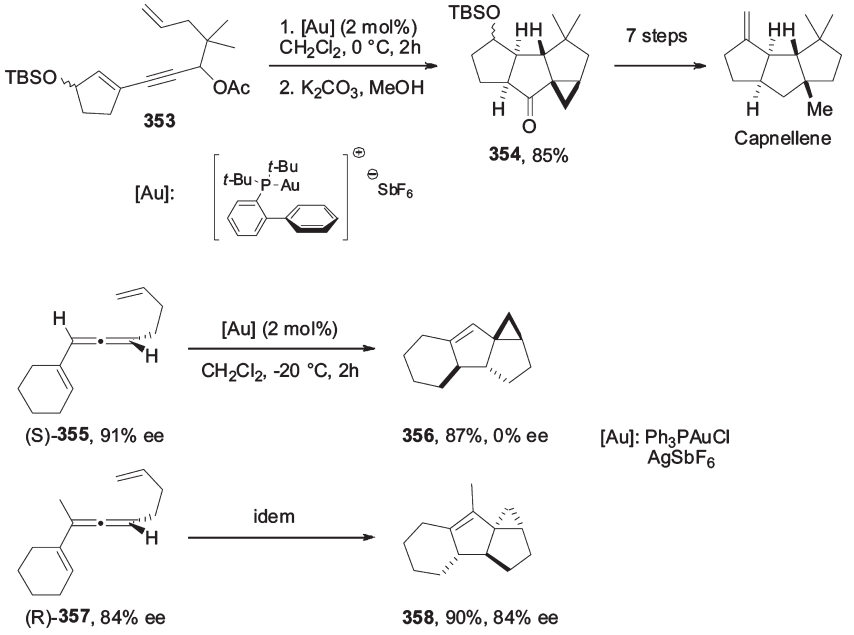
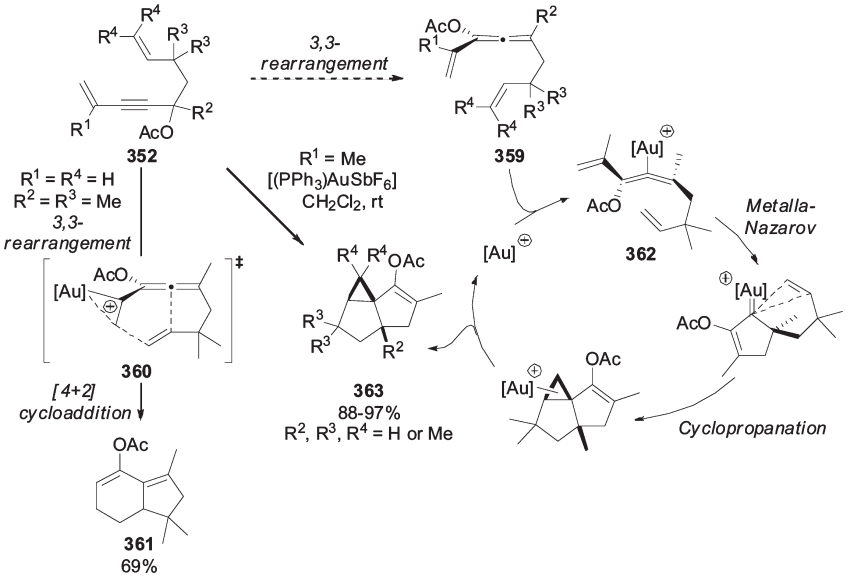
Scheme 94. Application in Total Synthesis and Chirality Transfer



Scheme 95. Mechanistic Rationale: Metalla-Nazarov/Cyclopropanation of Propargyl Acetates



346 bearing a free hydroxyl group to get the alkoxycyclized product **347**.

Aiming also at developing an expeditious trifunctionalization of the carbon atoms of the allene moiety, through a metalla-1,3-dipole as in intermediates **277** or **314**, Fensterbank, Malacria, and co-workers developed an efficient strategy that consists in trapping the carbene with a pendant double bond by electrophilic cyclopropanation, thus allowing them to build two more cycles from a linear vinylallene **350** (Scheme 93) and provides easy access to polyquinanes skeletons.[147]

This latter methodology was also extensible to propargyl acetates **352** (Scheme 95) and proceeds diastereoselectively. An application to the total synthesis of capnellene was accomplished from precursor **353** (Scheme 94).[147b] Excellent chirality transfers were achieved when enantioenriched propargyl acetates or allenes were used, but only in the case where the cyclizing allene is at least trisubstituted, as illustrated by the transformation of enantioenriched substrates **355** and **357**.[147b,109]

The mechanistic rationale of this transformation is depicted in Scheme 95.[147b] After initial 3,3-rearrangement, the allenyl ester **359** is generated, which can evolve along two distinct pathways: if the internal position of the 1,3-enyne framework is not substituted, a [4 + 2] cycloaddition pathway is favored over the metalla-Nazarov one and proceeds through transition state

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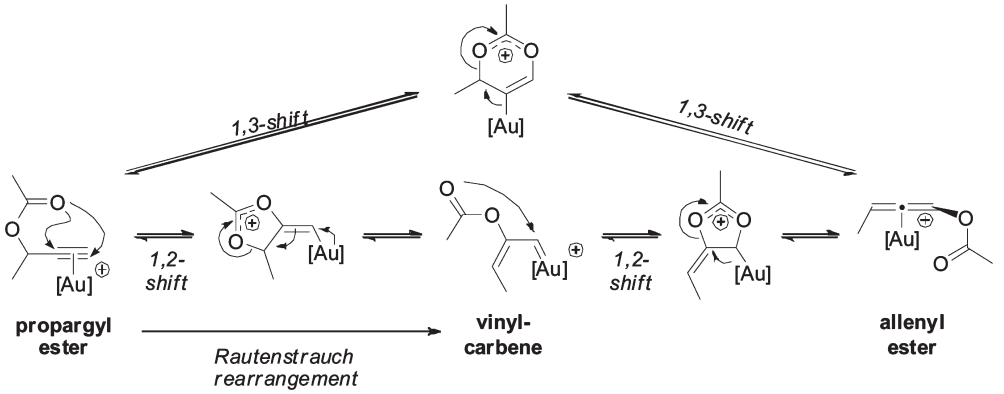
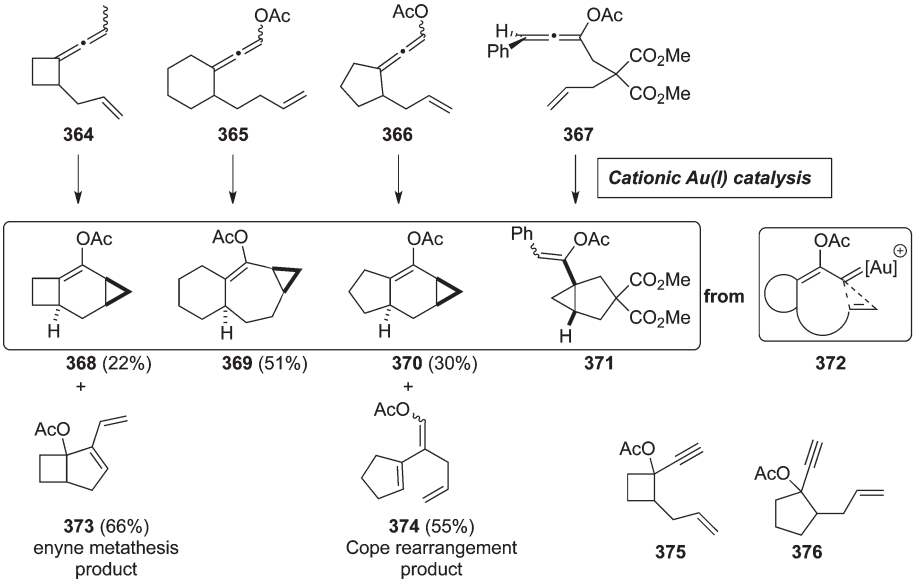
Scheme 96. Linked Reactivities of Propargyl- and Allenyl-Esters



Scheme 97. Cyclopropanation Products from Allenenyl Acetates



360 to give cycloadduct **361**. By contrast, when this position is substituted, the metalla-Nazarov/cyclopropanation sequence occurs to give polycyclic compound **363**. DFT calculations suggest that when a trisubstituted allene is involved in this transformation, a gold-"bent allene"[109,148] complex **362**, allowing retention of the chirality is involved, while with disubstituted allenes, allylic carbocations intervene and lead to racemization.

3.2.4. Cycloisomerizations of Allenenyl Esters. The final part of this section will focus on the particular reactivity of allenyl esters with gold and platinum catalysts. We saw above (see section 3.1.1.3) that propargyl acetates are good precursors of allenyl esters through a gold, silver or platinum catalyzed 1,3-sigmatropic shift but can also give rise to vinyl carbenoids through the well-known Rautenstrauch rearrangement.[101] The group of Malacria and Fensterbank has shown it was possible to give birth to vinyl carbenes upon complexation of gold or platinum onto the aforementioned allenyl ester, thus going back to the Rautenstrauch rearrangement product of the corresponding propargyl acetate.[122] This is consistent with DFT calculations by Cavallo,[149] showing that there was an equilibrium also coined as golden carousel, between propargyl acetates/allenyl acetates when submitted to catalytic amounts of gold salts, the pivotal intermediate between them being the vinyl carbene (Scheme 96).

Thus, it is possible to reach products **368**−**370** arising from electrophilic cyclopropanation of a gold carbenoid onto a tethered double bond, not starting from enynyl acetates but from allenenyl acetates **364**−**366** (Scheme 97). With precursor **364**, the metathesis product **373** was obtained as the major product, thus attesting the reversibility of the 1,2-/1,3-shift processes depicted in Scheme 96. A similar observation was also made by the group of Gung with comparable substrate **367** that gave selectively upon cationic gold(I) catalysis the cyclopropanation product **371**.[130c] It is worthy of note that engaging propargylic acetates precursor **375** leads to a mixture of **368** and **373** in the same ratio than starting from the corresponding allenyl ester **364**. On the opposite, starting from enyne **376** gives upon cationic gold(I) catalysis **370** as the major product (53% yield) and the enyne metathesis product (17% yield, not

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depicted), but no Cope rearrangement product **374** (predominant when starting from the corresponding allenenyl ester **366**) was observed, indicating that Rautenstrauch rearrangement/cyclopropanation sequence and the metathesis of this enyne system are kinetically more favorable than allenyl ester formation.

4. CONCLUSION

In conclusion, it appears that through all this review the transition metal-catalyzed cycloisomerization of allenenes and allenynes is not just a simple homologous version of the corresponding enyne or diene cycloisomerization reaction. The intrinsic features of the cumulenic moiety, such as the electronic richness, as well as the chirality guarantees that some highly specific transformations can be tailored. Our analysis of the reactivity of allenynes and allenenes based on mechanistic pathways also fully illustrates this fact. Thus, we have seen that metals can activate the allene and yne/ene partners at the same time, as well as activate selectively the allene or the yne partner in the presence of π-acidic metals. In the latter case, some substrates can even undergo both modes of activation depending on the reaction conditions as well as the nature of the catalyst. In terms of synthetic relevance, an obvious consideration lies in the fact that the obtained products are cyclic dienes and trienes which can be at the origin of various transformations, such as cycloadditions or further cyclization.

Most of this chemistry is less than twenty years old and has mainly relied on exploratory tracks focusing on different parameters such as the nature of the metal, the structural outfit of the polyunsaturated partner and reactions conditions. Nonetheless, as we have shown, several applications in total synthesis have been already accomplished. In terms of stereoselective synthesis, although some nice examples of chirality transfers or asymmetric catalysis have also been devised, more methodological developments are highly desirable.

It is quite likely that both aspects, targeted synthesis and stereoselectivity control, will still be pursued in the coming years and possibly merged. Further areas of possible progress lies in the preparation of the precursors. One-pot processes, which liberate in situ the reactive allene function, have been already very much utilized, as in the metal catalyzed 3,3-sigmatropic rearrangement of progargyl acetates to allenyl esters. Other synthetic tricks are welcome and one can envisage concurrent catalysis to achieve this goal.

Finally, the impact of DFT calculations in the rationalization of reactions and also for predictive outcomes has increased over the last years and renders this tool more and more complementary to bench studies and useful for the programming of research with the highly reactive allenene and allenynes entities.

AUTHOR INFORMATION

Corresponding Author

*Fax: (+33) 1 44 27 73 60. E-mail: corinne.aubert@upmc.fr (C.A.); louis.fensterbank@upmc.fr (L.F.); max.malacria@upmc.fr (M.M.).

BIOGRAPHIES

Corinne Aubert was born in Les Ardennes, France. After having studied chemistry at the University of Champagne-Ardennes, Reims, she graduated from the Ecole Nationale Supérieure de Chimie de Strasbourg. She defended her Ph. D. in 1985 under the supervision of Drs. J. F. Biellmann and J. P. Bégué from the University of Paris-Sud, Orsay. She was subsequently appointed by the CNRS in 1985 as Chargée de Recherches in the laboratory of Dr. J. P. Bégué and worked on fluorine chemistry. After doing two years of postdoctoral research at University of California, Berkeley with Professor K. P. C. Vollhardt, she joined the team of Professor Max Malacria at the Université Pierre et Marie Curie, Paris. In 2001, she was promoted Directeur de Recherches 2nd class and in 2009 Directeur de Recherches 1st class. Her current research interests focus on new developments of transition metal-mediated cyclizations and their application in synthesis, asymmetric catalysis, boron and silicon chemistry, and preparation of polyunsaturated systems for new molecular devices.

Louis Fensterbank was born in Poitiers in 1967 and raised in Tours. While graduating from the Ecole Superieure de Chimie Industrielle de Lyon (ESCIL) in 1990, he joined the team of Scott Sieburth at SUNY Stony Brook, worked on silicon-tethered reactions and obtained his Ph.D. in 1993. After a temporary lecturer position at the Université Pierre & Marie Curie (UPMC) in 1994, he was appointed by the CNRS in 1995 as a Chargé de Recherche in Max Malacria's team. In 2004, he obtained a professorship position at UPMC and in 2008, he was nominated junior member at the Institut Universitaire de France. His research

interests concern the discovery of new molecular transformations relying on radical or organometallic processes and their applications to the synthesis of substrates with relevant properties (natural products, probes, ligands...).

Pierre Garcia was born in Tarbes in 1983. He started studying chemistry for two years at IUT Chimie in Castres in 2001, after what he joined the Ecole Supérieure de Chimie Physique Electronique (ESCPE) in Lyon from which he received a Master's degree in Chemistry and Chemical Engineering in 2007. During the first part of his studies, he successively worked in Prof. A. Degl'Innocenti's group in Florence, Italy; at Bracco Imaging in Milan, Italy and in Prof. S. A. Glover's group in Armidale, Australia. He obtained his M. S. in Organic Chemistry in 2007 from the University Claude Bernard-Lyon 1 (UCBL), working in Prof. P. Goekjian's group. His PhD, granted by Sanofi-Aventis, was conducted under the supervision of Prof. Malacria and Dr. Aubert, aimed to study the formation of new pyridines systems through cobalt catalyzed [2 + 2 + 2] cycloadditions. He received his PhD degree in 2010, and he is now moving, as a postdoctoral researcher, to Prof. L. L. Schafer's group in Vancouver, Canada.

Max Malacria was born in 1949 in Marseille, France. He obtained his Ph. D. from the University of Aix-Marseille III with Professor Marcel Bertrand in 1974. He was appointed Assistant in 1974 at the University of Lyon I with Professor J. Goré. After almost two years as a postdoctoral fellow with Professor K. P. C. Vollhardt at Berkeley, he went back to the University of Lyon as a Maître de Conférences in 1983. In 1988, he was appointed Full Professor at the UPMC. In 1991, he was elected junior member of the Institut Universitaire de France, promoted to senior member in 2001. His research interests include the development of new domino processes in both organometallic and radical chemistry and applications in the synthesis, asymmetric synthesis, new stereoselective reactions involving heteroelements and developing physical chemistry interfaces. His work was rewarded with the prize from the French Chemical Society (Organic Chemistry division) (1997), the Grammaticakis-Neuman prize from the French Academy of Sciences (2000), médaille d'argent du CNRS (2001), and very recently, the Franco-Spanish prize Catalan-Sabatier from the Real Sociedad Española de Química (2009).

Antoine Simonneau was born in Vitry-sur-Seine in the suburbs of Paris in 1985. From 2005 to 2008, he studied chemistry at the École Nationale Supérieure de Chimie de Paris (ENSCP). In 2008 he received the M. Sc. in chemical science and engineering of the ENSCP, as well as the M. Sc. in organic and bioorganic chemistry of the Université Pierre et Marie Curie (UPMC), Paris, with honors. After a short period in Pr. Jaouen and Dr. Lebideau's laboratory, where he worked on rhenium carbonyl complexes, he joined in 2008 Prs. Malacria and Fensterbank's team to begin his PhD. His research interest stands in homogeneous organometallic catalysis with gold complexes in the field of cycloisomerization reactions.

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REFERENCES

(1) (a) *The Chemistry of Ketenes, Allenes and Related Compounds Part 1*; Patai, S., Ed.; Wiley: New York, 1980. (b) *Allenes in Organic Synthesis*; Schuster, H. F.; Coppola, G. M.; Wiley-Interscience: New York, 1984. (c) *Modern Allene Chemistry*; Krause, N., Hashmi, A. S. K., Eds.; Wiley-VCH: Weinheim, Germany, 2004; Vols. 1 and 2. (d) In *Science of Synthesis: Houben−Weyl Methods of Molecular Transformations*; Krause, N., Ed; 2007, Vol 44.For reviews, see:(e) Zimmer, R.; Dinesh, C. U.; Nanadanan, E.; Khan, F. A. *Chem. Rev.* **2000**, *100*, 3067. (f) Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **2000**, *39*, 3590. (g) Sydnes, L. *Chem. Rev.* **2003**, *103*, 1133. (h) Ma, S. *Chem. Rev.* **2005**, *105*, 2829. (i) Ma, S. *Aldrichim. Acta* **2007**, *40*, 91. (j) Belmont, P.; Parker, E. *Eur. J. Org. Chem.* **2009**, 6075. (k) Ma, S. *Acc. Chem. Res.* **2009**, *42*, 1679. (l) Alcaide, B.; Almendros, P.; Aragoncillo, C. *Chem. Soc. Rev.* **2010**, *39*, 783. (m) Krause, N.; Winter, C. *Chem. Rev.* **2011**, *111*, DOI: 10.1021/cr1004088.

(2) Hoffman-Röder, A.; Krause, N. *Angew. Chem., Int. Ed.* **2004**, *43*, 1196.
(3) Brummond, K. M.; Chen, H. In *Modern Allene Chemistry*; Krause, N., Hashmi, A. S. K., Eds.; Wiley-VCH: Weinheim, Germany, 2004; Vol. 2, pp 1041−1089.
(4) (a) Trost, B. M. *Science* **1991**, *254*, 1471. (b) Trost, B. M. *Angew. Chem., Int. Ed.* **1995**, *34*, 259. (c) Wender, P. A.; Croatt, M. P.; Witulski, B. *Tetrahedron* **2006**, *62*, 7505. (d) Burns, N. Z.; Baran, P. S.; Hoffmann, R. W. *Angew. Chem., Int. Ed.* **2009**, *48*, 2854.
(5) (a) Trost, B. M.; Krische, M. J. *Synlett* **1998**, 1. (b) Trost, B. M.; Toste, F. D.; Pinkerton, A. B. *Chem. Rev.* **2001**, *101*, 2067. (c) Aubert, C.; Buisine, O.; Malacria, M. *Chem. Rev.* **2002**, *102*, 813. (d) Lloyd-Jones, G. C. *Org. Biomol. Chem.* **2003**, *1*, 215. (e) Michelet, V.; Toullec, P.; Genêt, J.-P. *Angew. Chem., Int. Ed.* **2008**, *47*, 4268. (f) Bruneau, C. *Angew. Chem., Int. Ed.* **2005**, *44*, 2328. (g) Jiménez-Núñez, E.; Echavarren, A. M. *Chem. Rev.* **2008**, *108*, 3326.
(6) Hashmi, A. S. K. In *Modern Allene Chemistry*; Krause, N., Hashmi, A. S. K., Eds.; Wiley-VCH: Weinheim, Germany, 2004; Vol. 2, pp 877−923.
(7) Siegel, H.; Hopf, H.; Germer, A.; Binger, P. *Chem. Ber.* **1978**, *111*, 3112.
(8) (a) Murakami, M.; Itami, K.; Ito, Y. *J. Am. Chem. Soc.* **1996**, *118*, 11672. (b) Murakami, M.; Itami, K.; Ito, Y. *Organometallics* **1999**, *18*, 1326.
(9) Besides Pd, Rh, and Ru, one example of intramolecular formation of metallacylopentane with nickel salt has been reported. However, evolution of the reaction requires transmetallation with organozinc coupounds, see: Chevliakov, M. V.; Montgomery, J. *J. Am. Chem. Soc.* **1999**, *121*, 11139.
(10) (a) Murakami, M.; Itami, K.; Ito, Y. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2691. (b) Murakami, M.; Itami, K.; Ito, Y. *J. Am. Chem. Soc.* **1997**, *119*, 2950.
(11) For palladium catalysis, see: (a) Murakami, M.; Itami, K.; Ito, Y. *J. Am. Chem. Soc.* **1997**, *119*, 7163. (b) Murakami, M.; Minamida, R.; Itami, K.; Sawamura, M.; Ito, Y. *Chem. Commun.* **2000**, *118*, 2293.
(12) For rhodium catalysis, see: Murakami, M.; Ubukata, M.; Itami, K.; Ito, Y. *J. Angew. Chem., Int. Ed.* **1998**, *37*, 2248.
(13) (a) For [4 + 4 + 1] cycloaddition, see: Murakami, M.; Itami, K.; Ito, Y. *J. Angew. Chem., Int. Ed.* **1998**, *37*, 3418. (b) For [4 + 4] cycloaddition, see: Murakami, M.; Itami, K.; Ito, Y. *Synlett* **1999**, 951.
(14) A tandem approach from vinyl and propargyl halides upon Pd(0) was also reported, see: (a) Lee, P. H.; Lee, K. *Angew. Chem., Int. Ed.* **2005**, *44*, 3253. (b) Lee, P. H.; Lee, K.; Kang, Y. *J. Am. Chem. Soc.* **2006**, *128*, 1139.
(15) (a) Makino, T.; Itoh, K. *Tetrahedron Lett.* **2003**, *44*, 6335. (b) Makino, T.; Itoh, K. *J. Org. Chem.* **2004**, *69*, 395.
(16) Jiang, X.; Cheng, X.; Ma, S. *Angew. Chem., Int. Ed.* **2006**, *45*, 8009.
(17) For the synthesis of four membered cycles via reductive elimination, see: (a) Iyoda, M.; Tanaka, S.; Nose, M.; Oda, M. *J. Chem. Soc., Chem. Commun.* **1983**, 1058. (b) Pasto, D. J.; Huang, N.-Z.; Eigenbrot, C. W. *J. Am. Chem. Soc.* **1985**, *107*, 3160. (c) Pasto, D. J.; Huang, N.-Z. *Organometallics* **1985**, *4*, 1386. (d) Iyoda, M.; Tanaka, S.; Otani, H.; Nose, M.; Oda, M. *J. Am. Chem. Soc.* **1988**, *110*, 8494. (e) Iyoda, M.; Kuwatani, Y.; Oda, M. *J. Am. Chem. Soc.* **1989**, *111*, 3761. (f) Chao, K. C.; Rayabarapu, D. K.; Wang, C.-C.; Cheng, C.-H. *J. Org. Chem.* **2001**, *66*, 8804.
(18) In contrast, metal cyclobutadiene complexes araising from the parent metallacyclopentadienenes would not be produced by reductive elimination; see:Veiros, L. F.; Dazinger, G.; Kirchner, K.; Calhorda, M. J.; Schmid, R. *Chem.—Eur. J.* **2004**, *10*, 5860.
(19) (a) Ma, S.; Lu, P.; Lu, L.; Hou, H.; Wei, J.; He, Q.; Gu, Z.; Jiang, X.; Jin, X. *Angew. Chem., Int. Ed.* **2005**, *44*, 5275. (b) Ma, M.; Lu, L. *Chem. Asian. J.* **2007**, *2*, 199. (c) Lu., P.; Ma, S. *Org. Lett.* **2007**, *9*, 5319.
(20) Lu, P; Ma, S. *Org. Lett.* **2007**, *9*, 2095.
(21) (a) Inagaki, F.; Narita, S.; Hasegawa, T.; Kitagaki, S.; Mukai, C. *Angew. Chem., Int. Ed.* **2009**, *48*, 2007. (b) Kawamura, T.; Inagaki, F.; Narita, S.; Takahashi, Y.; Hirata, S.; Kitagaki, S.; Mukai, C. *Chem.—Eur. J.* **2010**, *16*, 5173.
(22) Hess, B. A., Jr.; Baldwin, J. E. *J. Org. Chem.* **2002**, *67*, 6025.
(23) For a molybdenum-catalyzed RCM of allenynes, see: (a) Murakami, M.; Kadowaki, S.; Matsuda, T. *Org. Lett.* **2005**, *7*, 3953. See also (b) Kim, K. H.; Ok, T.; Lee, K.; Lee, H.-S.; Chang, K. T.; Ihee, H.; Sohn, J.-H. *J. Am. Chem. Soc.* **2010**, *132*, 12027.
(24) A ruthenium-catalyzed tandem isomerization-RCM of 1,7-allenene has been reported, see: (a) Alcaide, B.; Almendros, P.; Martinez del Campo, T.; Rodriguez-Acebes, R. *Adv. Synth. Catal.* **2007**, *349*, 749. For allene cross-metathesis, see:(b) Ahmed, M.; Arnaud, T.; Barrett, A. G. M.; Braddock, D. C.; Flack, K.; Procopiou, P. A. *Org. Lett.* **2000**, *2*, 551. For RCM of bis-allenes, see:(c) Craft, D. T.; Gung, B. W. *Tetrahedron Lett.* **2008**, *49*, 5931.
(25) Alcaide, B.; Almendros, P.; Luna, A. *Chem. Rev.* **2009**, *109*, 3817.
(26) Kinderman, S. S.; van Maarseveen, J. H.; Schoemaker, H. E.; Hiemstra, H.; Rutjes, F. P. J. T. *Org. Lett.* **2001**, *3*, 2045.
(27) Mukai, C.; Itoh, R. *Tetrahedron Lett.* **2006**, *47*, 3971.
(28) Intermolecular coupling of MVK and allenes trough related ruthenacyclopentane has been reported earlier from CpRu(cod)Cl, see: (a) Trost, B. M.; Pinkerton, A. B. *J. Am. Chem. Soc.* **1999**, *121*, 4068. (b) Trost, B. M.; Pinkerton, A. B.; Seidel, M. *J. Am. Chem. Soc.* **2001**, *123*, 12466. For a similar work with cobalt catalyst, see:(c) Chang, H.-T.; Jayanth, T. T.; Cheng, C.-H. *J. Am. Chem. Soc.* **2007**, *129*, 4166.
(29) Llerena, D.; Aubert, C.; Malacria, M. *Tetrahedron Lett.* **1996**, *37*, 7027.
(30) One example of zirconium covalently mediated allenyne cyclization has been reported earlier. However, excess of external agents are required for zirconacyclopentene clivage, see: Negishi, E.; Holmes, S. J.; Tour, J. M.; Miller, J. A.; Cederbaum, F. E.; Swanson, D. R.; Takahashi, T. *J. Am. Chem. Soc.* **1989**, *111*, 3336.
(31) In a manner similar to that in ref 30, titanium-mediated allenyne cyclization have been reported, see: (a) Urabe, H.; Takeda, T.; Hideura, D.; Sato, F. *J. Am. Chem. Soc.* **1997**, *119*, 11295. (b) Urabe, H.; Sato, F. *Tetrahedron Lett.* **1998**, *39*, 7329. (c) Yamazaki, T.; Urabe, H.; Sato, F. *Tetrahedron Lett.* **1998**, *39*, 7333.
(32) (a) Llerena, D.; Aubert, C.; Malacria, M. *Tetrahedron Lett.* **1994**, *35*, 2341. (b) Llerena, D.; Buisine, O.; Aubert, C.; Malacria, M. *Tetrahedron* **1998**, *54*, 9373. (c) Buisine, O.; Aubert, C.; Malacria, M. *Synthesis* **2000**, *7*, 985.
(33) Competitive paths have been observed; see: (a) Petit, M.; Aubert, C.; Malacria, M. *Org. Lett.* **2004**, *6*, 3937. (b) Petit, M.; Aubert, C.; Malacria, M. *Tetrahedron* **2006**, *62*, 10582.
(34) (a) Dunach, E.; Haltermann, R. L.; Vollhardt, K. P. C. *J. Am. Chem. Soc.* **1985**, *107*, 1664. (b) King, J. A.; Vollhardt, K. P. C. *J. Organomet. Chem.* **1993**, *460*, 91.
(35) Cross-conjugated triene has been reported as by-product of PKR of 1,6-allenyne under $Co_2(CO_8)$ catalysis, see: Pagenkopf, B. L.; Belanger, D. B.; O'Mahony, D. J. R.; Livinghouse, T. *Synthesis* **2000**, *7*, 1009.
(36) Brummond, K. M.; Chen, H.; Sill, P.; You, L. *J. Am. Chem. Soc.* **2002**, *124*, 15186.
(37) Shibata, T.; Takesue, Y.; Kadowaki, S.; Takagi, K. *Synlett* **2003**, *2*, 268.
(38) Brummond, K. M.; Mitasev, B. *Org. Lett.* **2004**, *6*, 2245.
(39) Ma, S.; Jiang, X. *J. Am. Chem. Soc.* **2007**, *129*, 11600.
(40) For construction of five-membered cycles, see: (a) Brummond, K. M.; Chen, D.; Painter, T. O.; Mao, S.; Seifried, D. D. *Synlett* **2008**, *5*, 759. (b) Brummond, K. M.; Mao, S.; Shinde, S. N.; Johnston, P. J.; Day, B. W. *J. Comb. Chem.* **2009**, *11*, 486.
(41) For other examples of five- to seven-membered cycles starting from allenic propiolamides, see: (a) Brummond, K. M.; Painter, T. O.; Probst, D. A.; Mitasev, B. *Org. Lett.* **2007**, *9*, 347. Starting from yne-allenamides, see:(b) Brummond, K. M.; Yan, B. *Synlett* **2008**, *15*, 2303.
(42) For construction of seven-membered cycles, see ref 34 and (a) Mukai, C.; Inagaki, F.; Yoshida, T.; Kitagaki, S. *Tetrahedron Lett.* **2004**, *45*, 4117. (b) Mukai, C.; Inagaki, F.; Yoshida, T.; Yoshitani, K.; Hara, Y.; Kitagaki, S. *J. Org. Chem.* **2005**, *70*, 7159.
(43) Brummond, K. M.; You, L. *Tetrahedron* **2005**, *61*, 6180.

(44) Brummond, K. M.; McCabe, J. M. *Tetrahedron* **2006**, *62*, 10541.
(45) For selected recent works on thermal [2 + 2] intramolecular isomerization of allenynes; see: (a) Cao, H.; Van Ornum, S. G.; Deschamps, J.; Flippen-Anderson, J.; Laib, F.; Cook, J. M. *J. Am. Chem. Soc.* **2005**, *127*, 933. (b) Brummond, K. M.; Chen, D. *Org. Lett.* **2005**, *7*, 3473. (c) Mukai, C.; Hara, Y.; Miyashita, Y.; Inagaki, F. *J. Org. Chem.* **2007**, *72*, 4454. (d) Jiang, X.; Ma, S. *Tetrahedron* **2007**, *63*, 7589. (e) Ohno, H.; Mizutani, T.; Kadoh, Y.; Aso, A.; Miyamura, K.; Fujii, N.; Tanaka, T. *J. Org. Chem.* **2007**, *72*, 4378. (f) Buisine, O.; Gandon, V.; Fensterbank, L.; Aubert, C.; Malacria, M. *Synlett* **2008**, 751.
(46) Shen, Q.; Hammond, G. B. *J. Am. Chem. Soc.* **2002**, *124*, 6534.
(47) Alcaide, B.; Almendros, P.; Aragoncillo, C. *Chem.—Eur. J.* **2009**, *15*, 9987.
(48) In some palladium-catalyzed [2 + 2] cycloisomerization of allenynes performed at room temperature, strictly microwave irradiations where found to promote efficient isomerization, see: Oh, C. H.; Gupta, A. K.; Park, D. I.; Kim, N. *Chem. Commun.* **2005**, 5670.
(49) For seminal works on ruthenium catalyzed intermolecular reactivity of allenes and alkynes, see: (a) Yamaguchi, M.; Kido, Y.; Omata, K.; Hirama, M. *Synlett* **1995**, 1181. (b) Bai, T; Xue, P.; Zhang, L.; Ma, S.; Jia, G. *Chem. Commun.* **2008**, 2929.
(50) (a) Saito, N.; Tanaka, Y.; Sato, Y. *Organometallics* **2009**, *28*, 669. (b) Saito, N.; Tanaka, Y.; Sato, Y. *Org. Lett.* **2009**, *11*, 4124.
(51) Albers, M. O.; Robinson, D. J.; Shaver, A.; Singleton, E. *Organometallics* **1986**, *5*, 2199.
(52) One report on Cp*Ru(cod)Cl catalyzed transformation of allenynes has been reported. However, this transformation requires diazoalkane as external partner, see:Vovard-Le Bray, C.; Dérien, S.; Dixneuf, P. H.; Murakami, M. *Synlett* **2008**, 193.
(53) Cadran, N.; Cariou, K.; Hervé, G.; Aubert, C.; Fensterbank, L; Malacria, M.; Marco-Contelelles., J. *J. Am. Chem. Soc.* **2004**, *126*, 3408.
(54) For a DFT study dealing with mechanism of the $PtCl_2$ catalyzed cycloisomerization of allenynes; see:Soriano, E.; Marco-Contelles, J. *Chem.—Eur. J.* **2005**, *11*, 521.
(55) (a) Trost, B. M.; Tour, J. M. *J. Am. Chem. Soc.* **1988**, *110*, 5231. (b) Kang, S.-K.; Ko, B.-S.; Lee, D.-M. *Tetrahedron Lett.* **2002**, *43*, 6693. (c) Närhi, K.; Franzén, J.; Bäckvall, J.-E. *Chem.—Eur. J.* **2005**, *11*, 6937. (d) Pardo-Rodríguez, V.; Marco-Martínez, J.; Buñuel, E.; Cárdenas, D. J. *Org. Lett.* **2009**, *11*, 4548.
(56) For pioneering work on tandem carbopalladation-cycloisomerization, see: Ohno, H.; Miyamura, K.; Takeoka, Y.; Tanaka, T. *Angew. Chem., Int. Ed.* **2003**, *42*, 2647.
(57) For cyclizations through silastannylation, see: (a) Kang, S.-K.; Baik, T.-G.; Kulak, A. N.; Ha, Y.-H.; Lim, Y.; Park, J. *J. Am. Chem. Soc.* **2000**, *122*, 11529. (b) Kumareswaran, R.; Shin, S.; Gallou, I.; RajanBabu, T. V. *J. Org. Chem.* **2004**, *69*, 7157. For cylizations through germastannnylation, see:(c) Hong, Y.-T.; Yoon, S.-K.; Kang, S.-K.; Yu, C.-M. *Eur. J. Org. Chem.* **2004**, 4628.
(58) See ref 55 and (a) Zhu, G.; Zhang, Z. *Org. Lett.* **2004**, *6*, 4041. (b) Tsukamoto, H.; Kondo, Y. *Org. Lett.* **2008**, *10*, 2633. (c) Kammerer, C.; Prestat, G.; Madec, D.; Poli, G. *Chem.—Eur. J.* **2009**, *15*, 4224.
(59) Doi, T.; Yanagisawa, A.; Nakanishi, S.; Yamamoto, K.; Takahashi, T. *J. Org. Chem.* **1996**, *61*, 2602.
(60) Brummond, K. M.; Chen, H.; Mitasev, B.; Casarez, A. D. *Org. Lett.* **2004**, *6*, 2161.
(61) See also: Mao, S.; Probst, D.; Werner, S.; Chen, J.; Xie, X.; Brummond, K. M. *J. Comb. Chem.* **2008**, *10*, 235.
(62) Li, W.; Yuan, W.; Shi, M.; Hernandez, E.; Li, G. *Org. Lett.* **2010**, *12*, 64.
(63) (a) Franzén, J.; Löfstedt, J.; Dorange, I.; Bäckvall, J.-E. *J. Am. Chem. Soc.* **2002**, *124*, 11246. (b) Franzén, J.; Löfstedt, J.; Falk, J.; Bäckvall, J.-E. *J. Am. Chem. Soc.* **2003**, *125*, 14140.
(64) (a) Wender, P. A.; Glorius, F.; Husfeld, C. O.; Langkopf, E.; Love, J. A. *J. Am. Chem. Soc.* **1999**, *121*, 5348. (b) Wender, P. A.; Fuji, M.; Husfeld, C. O.; Love, J. A. *Org. Lett.* **1999**, *1*, 137. (c) Wender, P. A.; Zhang, L. *Org. Lett.* **2000**, *2*, 2323. (d) Wender, P. A.; Bi, F. C.; Gamber, G. G.; Gosselin, F.; Hubbard, R. D.; Scanio, M. J. C.; Sun, R.; Williams, T. J.; Zhang, L. *Pure Appl. Chem.* **2002**, *74*, 25.
(65) (a) Yu, Z.-X.; Wender, P. A.; Houk, K. N. *J. Am. Chem. Soc.* **2004**, *126*, 9154. (b) Yu, Z.-X.; Cheong, P. H.-Y.; Liu, P.; Legault, C. Y.; Wender, P. A.; Houk, K. N. *J. Am. Chem. Soc.* **2008**, *130*, 2378. (c) Liu, P.; Cheong, H.-Y.; Yu, Z.-X.; Wender, P. A.; Houk, K. N. *Angew. Chem., Int. Ed.* **2008**, *47*, 3939.
(66) Jiao, L.; Lin, M.; Yu, Z.-X. *Chem. Commun.* **2010**, *46*, 1059.
(67) Wender, P. A.; Correa, A. G.; Sato, Y.; Sun, R. *J. Am. Chem. Soc.* **2000**, *122*, 7815.
(68) For seminal work on rhodium insertion onto cyclobutenones, see: Huffman, M. A.; Liebskind, L. S. *J. Am. Chem. Soc.* **1993**, *115*, 4895.
(69) Sim, S.-H.; Park, H.-J.; Lee, S. I.; Ching, Y. K. *Org. Lett.* **2008**, *10*, 433.
(70) Inagaki, F.; Sugikubo, K.; Miyashita, Y.; Mukai, C. *Angew. Chem., Int. Ed.* **2010**, *49*, 2206.
(71) The authors report two competitive mechanisms: formation of π-allyl rhodacyclohexene or cyclometalation. By performing the reaction under carbon monoxide atmosphere (10 atm), 13% yield of a product arising from PK was isolated along with 48% of the expected product.
(72) (a) Franzén, J.; Bäckvall, J.-E. *J. Am. Chem. Soc.* **2003**, *125*, 6056. (b) Persson, A. K. Å.; Bäckvall, J. *Angew. Chem., Int. Ed.* **2010**, *49*, 4624.
(73) Impressive efforts have been made by Bäckvall's group to render catalytic the amount of BQ in such isomerizations, see ref 72b and also (a) Piera, J.; Närhi, K.; Bäckvall, J.-E. *Angew. Chem., Int. Ed.* **2006**, *45*, 6914. (b) Johansson, M.; Purse, B. W.; Terasaki, O.; Bäckvall, J.-E. *Adv. Synth. Catal.* **2008**, *350*, 1807. (c) Purse, B. W.; Tran, L.-H.; Piera, J.; Åkermark, B.; Bäckvall, J.-E. *Chem.—Eur. J.* **2008**, *14*, 7500. (d) Johnston, E. V.; Karlsson, E. A.; Lindberg, S. A.; Åkermark, B.; Bäckvall, J.-E. *Chem.—Eur. J.* **2009**, *15*, 6799.
(74) (a) Trost, B. M.; Tanoury, G. J. *J. Am. Chem. Soc.* **1987**, *109*, 4753. (b) Trost, B. M.; Tanoury, G. J. *J. Am. Chem. Soc.* **1988**, *110*, 1636. (c) Trost, B. M.; Chang, V. K. *Synthesis* **1993**, 824. (d) Trost, B. M.; Trost, M. K. *J. Am. Chem. Soc.* **1991**, *113*, 1850. (e) Trost, B. M.; Hashmi, A. S. K. *Angew. Chem., Int. Ed.* **1993**, *32*, 1085. (f) Trost, B. M.; Hashmi, A. S. K. *J. Am. Chem. Soc.* **1994**, *116*, 2183. (g) Trost, B. M.; Hashmi, A. S. K.; Ball, R. G. *Adv. Synth. Catal.* **2001**, *343*, 490.
(75) Diver, S. T.; Giessert, A. J. *Chem. Rev.* **2004**, *104*, 1317–1382.
(76) Fürstner, A.; Davies, P. W. *Angew. Chem., Int. Ed.* **2007**, *46*, 3410.
(77) With Ga: (a) Lee, S. I.; Sim, S. H.; Kim, S. M.; Kim, K.; Chung, Y. K. *J. Org. Chem.* **2006**, *71*, 7120. It was shown that this transformation was also effective with cationic phosphinegold(I) catalyst. With Hg: (b) Sim, S. H.; Lee, S. I.; Seo, J.; Chung, Y. K. *J. Org. Chem.* **2007**, *72*, 9818. For a theoretical study of the Ga-catalyzed metathesis of allenynes, see also: (c) Zhu, Y.; Guo, Y.; Xie, D. *J. Phys. Chem. A* **2007**, *111*, 9387.
(78) For pioneering works on Ga-catalyzed skeletal reorganization of unsaturated substrates, see: (a) Miyanohana, Y.; Chatani, N. *Org. Lett.* **2006**, *8*, 2155. (b) Chatani, N.; Oshita, M.; Tobisu, M.; Ishii, Y.; Murai, S. *J. Am. Chem. Soc.* **2003**, *125*, 7812. (c) Chatani, N.; Inoue, H.; Kotsuma, T.; Murai, S. *J. Am. Chem. Soc.* **2002**, *124*, 10294. (d) Inoue, H.; Chatani, N.; Murai, S. *J. Org. Chem.* **2002**, *67*, 1414.
(79) (a) Nishizawa, M.; Takenaka, H.; Hayashi, Y. *Chem. Lett.* **1983**, 1459–1460. (b) Nishizawa, M.; Takenaka, H.; Nishide, H.; Hayashi, Y. *Tetrahedron Lett.* **1983**, *24*, 2581.
(80) Lemière, G.; Gandon, V.; Agenet, N.; Goddard, J.-P.; de Kozak, A.; Aubert, C.; Fensterbank, L.; Malacria, M. *Angew. Chem., Int. Ed.* **2006**, *45*, 7596.
(81) For the mechanism of the $PtCl_2$-catalyzed cycloisomerization of enynes, see: (a) Fürstner, A.; Szillat, H.; Gabor, B.; Mynott, R. *J. Am. Chem. Soc.* **1998**, *120*, 8305. (b) Fürstner, A.; Szillat, H.; Stelzer, F. *J. Am. Chem. Soc.* **2000**, *122*, 6785. (c) Oi, S.; Tsukamoto, I.; Miyano, S.; Inoue, Y. *Organometallics* **2001**, *20*, 3704.
(82) Auracyclopentenes are a priori not viable species, as well as a platinacycle involving a platinum (VI) species. For a seminal work, see: (a) Tamaki, A.; Kochi, J. K. *J. Organomet. Chem.* **1972**, *40*, C81. (b) Tamaki, A.; Kochi, J. K. *J. Organomet. Chem.* **1973**, *51*, C39.
(83) See ref 45c and 45f and also (a) Zriba, R.; Gandon, V.; Aubert, C.; Fensterbank, L.; Malacria, M. *Chem.—Eur. J.* **2008**, *14*, 1482. (b) Ovaska, T. V.; Kyne, R. E. *Tetrahedron Lett.* **2008**, *49*, 376.

(84) Gorin, D. J.; Sherry, B. D.; Toste, F. D. *Chem. Rev.* **2008**, *108*, 3351.
(85) For a rare example of a gold metallacycle, see the Supporting Information of:Wu, J.; Kroll, P.; Rasika Dias, H. V. *Inorg. Chem.* **2009**, *48*, 423.
(86) For other examples of gold-promoted 1,5-hydride shift see: (a) Harrak, Y.; Simonneau, A.; Gandon, V.; Fensterbank, L.; Malacria, M. *Chem. Commun.* **2010**, *46*, 865. (b) Jurberg, I. D.; Obadachian, Y.; Gagosz, F. *J. Am. Chem. Soc.* **2010**, *132*, 3543. (c) Bolte, B.; Obadachian, Y.; Gagosz, F. *J. Am. Chem. Soc.* **2010**, *132*, 7294. (d) Kar-Yan, Lo, V.; Wong, M.-K.; Che, C.-M. *Org. Lett.* **2008**, *10*, 517.
(87) Matsuda, T.; Kadowaki, S.; Goya, T.; Murakami, M. *Synlett* **2006**, *4*, 575.
(88) Matsuda, T.; Kadowaki, S.; Murakami, M. *Helv. Chim. Acta* **2006**, *89*, 1672.
(89) (a) Murakami, M.; Takahashi, K.; Amii, H.; Ito, Y. *J. Am. Chem. Soc.* **1997**, *119*, 9307. (b) Nishimura, T.; Uemura, S. *Synlett* **2004**, 201. (c) Terao, Y.; Nomoto, M.; Satoh, T.; Miura, M.; Nomura, M. *J. Org. Chem.* **2004**, *69*, 6942. (d) Matsuda, T.; Makino, M.; Murakami, M. *Bull. Chem. Soc. Jpn.* **2005**, *78*, 1528. (e) Murakami, M.; Ashida, S.; Matsuda, T. *J. Am. Chem. Soc.* **2006**, *128*, 2166.
(90) Lin, G.-Y.; Yang, C.-Y.; Liu, R.-S. *J. Org. Chem.* **2007**, *72*, 6753.
(91) Such reactivity knows precedents: (a) Gockel, B.; Krause, N. *Org. Lett.* **2006**, *8*, 4485–4488. For related gold-catalyzed cycloisomerization of α-aminoallenes to 3-pyrrolines, see:(b) Morita, N.; Krause, N. *Eur. J. Org. Chem.* **2006**, 4634–4641. (c) Morita, N.; Krause, N. *Org. Lett.* **2004**, *6*, 4121–4123. For related gold-catalyzed cyclization of allene-substituted malonate esters, see:(d) Piera, J.; Krumlinde, P.; Strübing, D.; Bäckvall, J.-E. *Org. Lett.* **2007**, *9*, 2235–2237.
(92) For selected examples where Au and Pt displayed different reactivities on the same substrates see: (a) Zhang, G.; Catalano, V. J.; Zhang, L. *J. Am. Chem. Soc.* **2007**, *129*, 11358. See also:(b) Hashmi, A. S. K.; Kurpejovic, E.; Frey, W.; Bats, J. W. *Tetrahedron* **2007**, *63*, 5879.
(93) For Ag-catalyzed [3,3] rearrangement of propargyl esters see: (a) Saucy, G.; Marbet, R.; Lindlar, H.; Isler, O. *Helv. Chim. Acta* **1959**, *XLII*, 1945. (b) Schlossarczyk, H.; Sieber, W.; Hesse, M.; Hansen, H.-J.; Schmid, H. *Helv. Chim. Acta* **1973**, *56*, 875. (c) Oelberg, D. G.; Schiavelli, M. D. *J. Org. Chem.* **1977**, *42*, 1804. See also: (d) Cookson, R. C.; Cramp, M. C.; Parsons, P. J. *Chem. Commun.* **1980**, 197. (e) Bowden, B.; Cookson, R. C.; Davis, H. A. *J. Chem. Soc., Perkin Trans. 1* **1973**, 2634. (f) Sromek, A. W.; Kel'in, A. V.; Gevorgyan, V. *Angew. Chem., Int. Ed.* **2004**, *43*, 2280. For Pt, see:(g) Cariou, K.; Mainetti, E.; Fensterbank, L.; Malacria, M. *Tetrahedron* **2004**, *60*, 9745.
(94) (a) Zhao, J.; Hughes, C. O.; Toste, F. D. *J. Am. Chem. Soc.* **2006**, *128*, 7436. For the same reaction using gold salts see: (b) Oh, C. H.; Kim, A.; Park, W.; Park, D. I.; Kim, N. *Synlett* **2006**, *278*, 2781. For a related methodology developed for the synthesis of a library of pyrones, see: (c) Luo, T.; Schreiber, S. L. *Angew. Chem., Int. Ed.* **2007**, *46*, 8250. (d) Luo, T.; Schreiber, S. L. *J. Am. Chem. Soc.* **2009**, *131*, 5667.
(95) Mo-mediated carbonylation of allenyl arene-ynes gave by-products derived from the Myers−Saito rearrangement, see: Datta, S.; Liu, R.-S. *Tetrahedron Lett.* **2005**, *46*, 7985.
(96) For seminal works on the Myers−Saito rearrangement, see: (a) Myers, A. G.; Harrington, P. M.; Kwon, B. M. *J. Am. Chem. Soc.* **1992**, *114*, 1086. (b) Sugiyama, H.; Fujiwara, T.; Kawabata, H.; Yoda, N.; Hirayama, N.; Saito, I. *J. Am. Chem. Soc.* **1992**, *114*, 5573.
(97) Lu, L.; Liu, X.-Y.; Shu, X.-Z.; Yang, K.; Ji, K.-G.; Liang, Y.-M. *J. Org. Chem.* **2009**, *74*, 474.
(98) Comparable intermediates have invoked in the intramolecular Diels−Alder reaction of dienynes, see: Fürstner, A.; Stimson, C. C. *Angew. Chem., Int. Ed.* **2007**, *46*, 8845.
(99) Karmakar, S.; Oh, C. H. *J. Org. Chem.* **2009**, *74*, 370.
(100) Kato, K.; Kobayashi, T.; Fujinami, T.; Motodate, S.; Kusakabe, T.; Mochida, T.; Akita, H. *Synlett* **2008**, *7*, 1081.
(101) (a) Strickler, H; Davis, J. B.; Ohloff, G. *Helv. Chim. Acta* **1976**, *59*, 1328. (b) Rautenstrauch, V. *J. Org. Chem.* **1984**, *49*, 950. (c) Mainetti, E.; Mouries, V.; Fensterbank, L.; Malacria, M.; Marco-Contelles, J. *Angew. Chem., Int. Ed.* **2002**, *41*, 2132. (d) Miki, K.; Ohe, K.; Uemura, S. *J. Org. Chem.* **2003**, *68*, 8505. (e) Mamane, V.; Gress, T.; Krause, H.; Fürstner, A. *J. Am. Chem. Soc.* **2004**, *126*, 8654. (f) Shi, X.; Gorin, D. J.; Toste, F. D. *J. Am. Chem. Soc.* **2005**, *127*, 5802. (g) Fehr, C.; Galindo, J. *Angew. Chem., Int. Ed.* **2006**, *45*, 2901. (h) Fehr, C.; Winter, B.; Magpantay, I. *Chem.—Eur. J.* **2009**, *15*, 9773. (i) Watson, I. D. G.; Ritter, S.; Toste, F. D. *J. Am. Chem. Soc.* **2009**, *131*, 2056. For reviews, see:(j) Marion, N.; Nolan, S. P. *Angew. Chem., Int. Ed.* **2007**, *46*, 2750. (k) Marco-Contelles, J.; Soriano, E. *Chem.—Eur. J.* **2007**, *13*, 1350.
(102) Gupta, A. K.; Rhim, C. Y.; Oh, C. H.; Mane, R. S.; Han, S.-H. *Green Chem.* **2006**, *8*, 25.
(103) For reviews dealing with synthetic applications of gold nanoparticles, see: (a) Daniel, M.-C.; Astruc, D. *Chem. Rev.* **2004**, *104*, 293. (b) Corma, A.; Garcia, H. *Chem. Soc. Rev.* **2008**, *37*, 2096.
(104) It is worth noting that the same reactivity was observed with gold(III) salts, what would mean the occurrence of a gold(V) hydride during the catalytic cycle. As this oxidation state is rarely encountered with gold, such reactivity could probably arise from an in situ generated gold nanoparticles catalysis. Similar reactivities were observed with platinum by the same group with resembling enynes substrates, see: (a) Oh, C. H.; Lee, J. H.; Lee, S. J.; Kim, J. I.; Hong, C. S. *Angew. Chem., Int. Ed.* **2008**, *47*, 7505. (b) Oh, C. H.; Lee, J. H.; Lee, S. M.; Yi, H. J.; Hong, C. S. *Chem.—Eur. J.* **2009**, *15*, 71. (c) Oh, C. H.; Lee, S. J.; Lee, J. H.; Na, Y. J. *Chem. Commun.* **2008**, *44*, 5794. (d) Oh, C. H.; Lee, S. M.; Hong, C. S. *Org. Lett.* **2010**, *12*, 1308.
(105) Cheong, P. H.-Y.; Morganelli, P.; Luzung, M. R.; Houk, K. N.; Toste, F. D. *J. Am. Chem. Soc.* **2008**, *130*, 4517.
(106) Luzung, M. R.; Markham, J. P.; Toste, F. D. *J. Am. Chem. Soc.* **2004**, *126*, 10858.
(107) Such species have been invoked in gold catalyzed cyclization of diynes: Obadachian, Y.; Le Goff, X. F.; Gagosz, F. *Chem.—Eur. J.* **2009**, *15*, 8966.
(108) Yang, C.-Y.; Lin, G.-Y.; Liao, H.-Y.; Datta, S.; Liu, R.-S. *J. Org. Chem.* **2008**, *73*, 4907.
(109) Gandon, V.; Lemière, G.; Hours, A.; Fensterbank, L.; Malacria, M. *Angew. Chem., Int. Ed.* **2008**, *47*, 7534.
(110) Idem for enynes, see: Gorin, D. J.; Toste, F. D. *Nature* **2007**, *446*, 395.
(111) Wei, H.; Zhai, H.; Xu, P.-F. *J. Org. Chem.* **2009**, *74*, 2224.
(112) Gonzalez-Gomez, A.; Dominguez, G.; Pérez-Castells, J. *Eur. J. Org. Chem.* **2009**, 5057.
(113) For a review dealing with gold catalyzed hydroarylations, see: (a) Shen, H. C. *Tetrahedron* **2008**, *64*, 3885. See also :(b) Nevado, C.; Echavarren, A. M. *Synthesis* **2005**, 167.
(114) Tarselli, M. A.; Chianese, A. R.; Lee, S. J.; Gagne, M. R. *Angew. Chem., Int. Ed.* **2007**, *46*, 6670.
(115) Comparable products were obtained from arylallene compounds, see: (a) Zhang, Z. B.; Liu, C.; Kinder, R. E.; Han, X. Q.; Qian, H.; Widenhoefer, R. A. *J. Am. Chem. Soc.* **2006**, *128*, 9066. (b) Liu, C.; Widenhoefer, R. A. *Org. Lett.* **2007**, *9*, 1935. (c) Tarselli, M. A.; Gagne, M. R. *J. Org. Chem.* **2008**, *73*, 2439. (d) Weber, D.; Gagne, M. R. *Org. Lett.* **2009**, *11*, 4962. (e) Weber, D.; Tarselli, M. A.; Gagne, M. R. *Angew. Chem., Int. Ed.* **2009**, *48*, 5733. For an example of 6-endo hydroarylations of allenes, see also:(f) Mo, J.; Lee, P. H. *Org. Lett.* **2010**, *12*, 2570.
(116) Miura, T.; Kiyota, K.; Kusama, H.; Lee, K.; Kim, H.; Kim, S.; Lee, P. H.; Iwasawa, N. *Org. Lett.* **2003**, *5*, 1725.
(117) (a) Miura, T.; Kiyota, K.; Kusama, H.; Iwasawa, N. *Org. Lett.* **2005**, *7*, 1445. (b) Miura, T.; Kiyota, K.; Kusama, H.; Iwasawa, N. *J. Organomet. Chem.* **2007**, *692*, 562.
(118) For examples of transition metal-mediated Conia-ene reaction, see: (a) Conia, J. M.; Leperchec, P. *Synthesis* **1975**, 1. (b) Boaventura, M. A.; Drouin, J.; Conia, J. M. *Synthesis* **1983**, 801. (c) Balme, G.; Bouyssi, D.; Faure, R.; Gore, J.; Vanhemelryck, B. *Tetrahedron* **1992**, *48*, 3891. (d) McDonald, F. E.; Olson, T. C. *Tetrahedron Lett.* **1997**, *38*, 7691. (e) Kitagawa, O.; Suzuki, T.; Inoue, T.; Watanabe, Y.; Taguchi, T. *J. Org. Chem.* **1998**, *63*, 9470. (f) Bouyssi, D.; Monteiro, N.; Balme, G. *Tetrahedron Lett.* **1999**, *40*, 1297. (g) Renaud, J. L.; Aubert, C.; Malacria, M. *Tetrahedron* **1999**, *55*, 5113. (h) Kennedy-Smith, J. J.;

Staben, S. T.; Toste, F. D. *J. Am. Chem. Soc.* **2004**, *126*, 4526. (i) Kuninobu, Y.; Kawata, A.; Takai, K. *Org. Lett.* **2005**, *7*, 4823.

(119) Jiang, X. F.; Ma, X. J.; Zheng, Z. L.; Ma, S. *Chem.—Eur. J.* **2008**, *14*, 8572.

(120) Buzas, A.; Gagosz, F. *J. Am. Chem. Soc.* **2006**, *128*, 12614.

(121) (a) Huang, X. G.; Zhang, L. M. *J. Am. Chem. Soc.* **2007**, *129*, 6398. (b) Huang, X. G.; Zhang, L. M. *Org. Lett.* **2007**, *9*, 4627.

(122) Some [3 + 2] products were also observed by Malacria and Fensterbank in a study on enynyl esters, see: Marion, N.; Lemière, G.; Correa, A.; Costabile, C.; Ramon, R. S.; Moreau, X.; de Fremont, P.; Dahmane, R.; Hours, A.; Lesage, D.; Tabet, J. C.; Goddard, J. P.; Gandon, V.; Cavallo, L.; Fensterbank, L.; Malacria, M.; Nolan, S. P. *Chem.—Eur. J.* **2009**, *15*, 3243.

(123) A gold-catalyzed [3 + 2] cycloaddition was also observed with indoles as partners, see: (a) Zhang, G. Z.; Catalano, V. J.; Zhang, L. M. *J. Am. Chem. Soc.* **2007**, *129*, 11358. For a platinum-catalyzed intermolecular version, see: (b) Kusama, H.; Ebisawa, M.; Funami, H.; Iwasawa, N. *J. Am. Chem. Soc.* **2009**, *131*, 16352.

(124) For punctual examples of gold-catalyzed [3 + 2] cycloadditions of allylallenes, see ref 121 and also Horino, Y.; Yamamoto, T.; Ueda, K.; Kuroda, S.; Toste, F. D. *J. Am. Chem. Soc.* **2009**, *131*, 2809.

(125) A very similar reactivity was observed when replacing the double bond by an indole, see: (a) Kong, W.; Fu, C.; Ma, S. *Eur. J. Org. Chem.* **2010**, 6545. See also: (b) Park, C.; Lee, P. H. *Org. Lett.* **2008**, *10*, 3359. (c) Kong, W.; Fu, C.; Ma, S. *Chem. Commun.* **2009**, 4572.

(126) Chaudhuri, R.; Liao, H. Y.; Liu, R. S. *Chem.—Eur. J.* **2009**, *15*, 8895.

(127) Snider, B. B.; Ron, E. *J. Org. Chem.* **1986**, *51*, 3643.

(128) Hoffmann, H. M. R.; Ismail, Z. M.; Weber, A. *Tetrahedron Lett.* **1981**, *22*, 1953.

(129) Strong Brønsted acids were also effective. Zhao, J. F.; Loh, T. P. *Angew. Chem., Int. Ed.* **2009**, *48*, 7232.

(130) (a) Luzung, M. R.; Mauleon, P.; Toste, F. D. *J. Am. Chem. Soc.* **2007**, *129*, 12402. For an enantioselective version using phosphoramidite ligands, see: (b) Teller, H.; Flugge, S.; Goddard, R.; Fürstner, A. *Angew. Chem., Int. Ed* **2010**, *49*, 1949. Cyclobutanes were observed as cyclization products of ene-propargyl acetates upon gold catalysis, nonetheless an in situ generated allenene was not invoked:(c) Gung, B. W.; Bailey, L. N.; Craft, D. T.; Barnes, C. L.; Kirschbaum, K. *Organometallics* **2010**, *29*, 3450.

(131) Comparable products were obtained with allenyl indoles upon platinum catalysis, see: Zhang, L. M. *J. Am. Chem. Soc.* **2005**, *127*, 16804.

(132) Alcarazo, M.; Stork, T.; Anoop, A.; Thiel, W.; Fürstner, A. *Angew. Chem., Int. Ed.* **2010**, *49*, 2542.

(133) Kim, S. M.; Park, J. H.; Kang, Y. K.; Chung, Y. K. *Angew. Chem., Int. Ed.* **2009**, *48*, 4532.

(134) Trillo, B.; Lopez, F.; Gulias, M.; Castedo, L.; Mascarenas, J. L. *Angew. Chem., Int. Ed.* **2008**, *47*, 951.

(135) Trillo, B.; Lopez, F.; Montserrat, S.; Ujaque, G.; Castedo, L.; Lledos, A.; Mascarenas, J. L. *Chem.—Eur. J.* **2009**, *15*, 3336.

(136) During the redaction of this manuscript, a theoretical study was published highlighting the fact that with furanyl partners the [4 + 3] cycloaddition is indeed concerted, but stepwise with 1,3 butadienyl partners: Fernandez, I.; Cossio, F. P.; de Cozar, A.; Lledos, A.; Mascarenas, J.-L. *Chem.—Eur. J.* **2010**, *16*, 12147.

(137) (a) Alonso, I.; Trillo, B.; Lopez, F.; Montserrat, S.; Ujaque, G.; Castedo, L.; Lledos, A.; Mascarenas, J. L. *J. Am. Chem. Soc.* **2009**, *131*, 13020. (b) Benitez, D.; Tkatchouk, E.; Gonzalez, A. Z.; Goddard, W. A.; Toste, F. D. *Org. Lett.* **2009**, *11*, 4798.

(138) Gonzalez, A. Z.; Toste, F. D. *Org. Lett.* **2010**, *12*, 200.

(139) (a) Gung, B. W.; Craft, D. T. *Tetrahedron Lett.* **2009**, *50*, 2685. (b) Gung, B. W.; Craft, D. T.; Bailey, L. N.; Kirschbaum, K. *Chem.—Eur. J.* **2010**, *16*, 639.

(140) Aoki, S.; Watanabe, M.; Sanagawa, M.; Setiawan, A.; Kotoku, N.; Kobayashi, M. *J. Am. Chem. Soc.* **2006**, *128*, 3148.

(141) For recent reviews on Nazarov cyclization, see: (a) Frontier, A. J.; Collison, C. *Tetrahedron* **2005**, *61*, 7577. (b) Pellissier, H. *Tetrahedron* **2005**, *61*, 6479. (c) Tius, M. A. *Eur. J. Org. Chem.* **2005**, 2193. See also: (d) Habermas, K. L.; Denmark, S. E.; Jones, T. K. *Org. React. (N.Y.)* **1994**, *45*, 1–158.

(142) (a) Grimaldi, J.; Bertrand, M. *Tetrahedron Lett.* **1969**, *10*, 3269. (b) Grimaldi, J.; Bertrand, M. *Bull. Soc. Chim. Fr.* **1971**, *3*, 947. (c) Roumestant, M. L.; Malacria, M.; Goré, J.; Grimaldi, J.; Bertrand, M. *Synthesis* **1976**, 755. (d) Malacria, M.; Roumestant, M. L. *Tetrahedron* **1977**, *33*, 2813. (e) Doutheau, A.; Goré, J.; Malacria, M. *Tetrahedron* **1977**, *33*, 2393. (f) Malacria, M.; Goré, J. *J. Org. Chem.* **1979**, *44*, 885. (g) Malacria, M.; Goré, J. *Tetrahedron Lett.* **1979**, *20*, 5067. (h) Corey, E. J.; Matsuda, S. P. T.; Nagata, R.; Cleaver, M. B. *Tetrahedron Lett.* **1988**, *29*, 2555. (i) Kim, S. J.; Cha, J. K. *Tetrahedron Lett.* **1988**, *29*, 5613.

(143) (a) Zhang, L. M.; Wang, S. Z. *J. Am. Chem. Soc.* **2006**, *128*, 1442. (b) Shi, F. Q.; Li, X.; Xia, Y.; Zhang, L.; Yu, Z. X. *J. Am. Chem. Soc.* **2007**, *129*, 15503. See also ref 131 for a puntual example.

(144) Lee, J. H.; Toste, F. D. *Angew. Chem., Int. Ed.* **2007**, *46*, 912.

(145) Funami, H.; Kusama, H.; Iwasawa, N. *Angew. Chem., Int. Ed.* **2007**, *46*, 909.

(146) (a) Yates, P.; Danishefsky, S. *J. Am. Chem. Soc.* **1962**, *84*, 879. (b) Wrobel, J.; Takahashi, K.; Lannoy, G.; Cook, J. M.; Bertz, S. H.; Honkan, V. *J. Org. Chem.* **1983**, *48*, 139. (c) Kusama, H.; Yamabe, H.; Onizawa, Y.; Hoshino, T.; Iwasawa, N. *Angew. Chem., Int. Ed.* **2005**, *44*, 468. (d) Bhunia, S.; Liu, R. S. *J. Am. Chem. Soc.* **2008**, *130*, 16488.

(147) (a) Lemière, G.; Gandon, V.; Cariou, K.; Fukuyama, T.; Dhimane, A. L.; Fensterbank, L.; Malacria, M. *Org. Lett.* **2007**, *9*, 2207. (b) Lemière, G.; Gandon, V.; Cariou, K.; Hours, A.; Fukuyama, T.; Dhimane, A. L.; Fensterbank, L.; Malacria, M. *J. Am. Chem. Soc.* **2009**, *131*, 2993.

(148) (a) Chenier, J. H. B.; Howard, J. A.; Mile, B. *J. Am. Chem. Soc.* **1985**, *107*, 4190. (b) Tonner, R.; Frenking, G. *Angew. Chem., Int. Ed.* **2007**, *46*, 8695. (c) Kaufhold, O.; Hahn, E. E. *Angew. Chem., Int. Ed.* **2008**, *47*, 4057. (d) Dyker, C. A.; Lavallo, V.; Donnadieu, B.; Bertrand, G. *Angew. Chem., Int. Ed.* **2008**, *47*, 3206. (e) Fürstner, A.; Alcarazo, M.; Goddard, R.; Lehmann, C. W. *Angew. Chem., Int. Ed.* **2008**, *47*, 3210. (f) Lavallo, V.; Dyker, C. A.; Donnadieu, B.; Bertrand, G. *Angew. Chem., Int. Ed.* **2008**, *47*, 5411. (g) Yamaguchi, T.; Yamamoto, Y.; Kinoshita, D.; Akiba, K. Y.; Zhang, Y.; Reed, C. A.; Hashizume, D.; Iwasaki, F. *J. Am. Chem. Soc.* **2008**, *130*, 6894. (h) Kikuchi, Y.; Ishii, M.; Akiba, K.; Nakai, H. *Chem. Phys. Lett.* **2008**, *460*, 37. (i) Hanninen, M. M.; Peuronen, A.; Tuononen, H. M. *Chem.—Eur. J.* **2009**, *15*, 7287. (j) Melaimi, M.; Parameswaran, P.; Donnadieu, B.; Frenking, G.; Bertrand, G. *Angew. Chem.Int. Ed.* **2009**, *48*, 4792. (k) Tonner, R.; Frenking, G. *Organometallics* **2009**, *28*, 3901.

(149) Correa, A.; Marion, N.; Fensterbank, L.; Malacria, M.; Nolan, S. P.; Cavallo, L. *Angew. Chem., Int. Ed.* **2008**, *47*, 718.