Recent Advances in Ruthenium-Catalyzed Carbene/Alkyne Metathesis (CAM) Transformations

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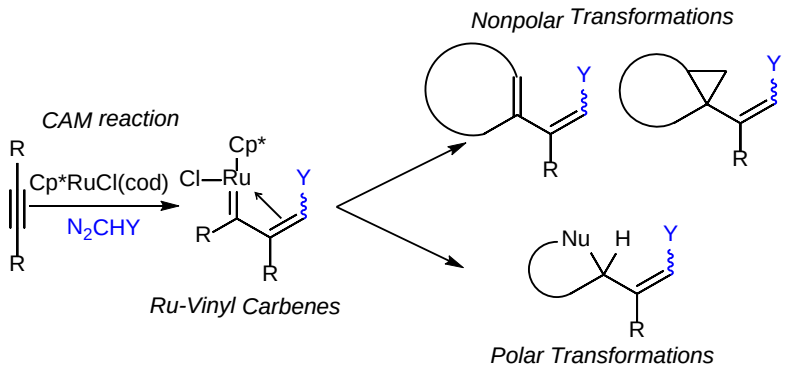

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Abstract Carbene intermediates have shown versatile applications in modern synthetic chemistry. Catalytic ruthenium carbene/alkyne metathesis (CAM) with readily available substrates renders an efficient procedure for the in situ generation of ruthenium vinyl carbene intermediates. Here, recent advances in synthetic applications of ruthenium-catalyzed carbene/alkyne metathesis (CAM) are highlighted.

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2 Ruthenium Vinyl Carbenes Through Carbene/Alkyne Metathesis (CAM)
3 Nonpolar Transformations of Ruthenium Vinyl Carbenes
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Key words alkynyl derivatives, carbenes, cyclization, heterocycles, metathesis, vinyl ruthenium carbenes

1 Introduction

The complexation of the neutral, divalent, sp^2-hybridized, 6e$^-$-carbon atom of carbenes to a metal center entails a significant stabilization of the otherwise extremely reactive intermediate. In this coordination, the carbene behaves as a neutral 2e$^-$ ligand generating a formal double bond with the metal. The stability, reactivity and bonding properties greatly depend on the nature of the metal, the ligands on the metal and the substituents of the carbene fragment, whereby the metal carbene complexes have been divided into two main groups:[1] Fischer-type carbenes (Figure 1, left), characterized by the interaction of a singlet carbene ligand with a metal fragment in the singlet state which leads to a significant carbene to metal σ donation ($sp^2 \rightarrow d$) and a weaker metal to carbene π back-donation ($d \rightarrow p_z$) that renders the carbene carbon electrophilic; and Schrock-type carbenes or alkylidenes (Figure 1, right), derived from the combination of a triplet carbene and a triplet metal fragment leading to a "covalent-like" double bond which is polarized towards the carbene moiety, making it nucleophilic.

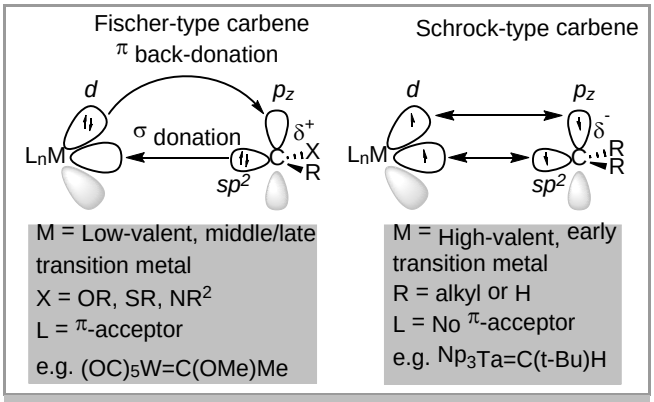


Figure 1 Classification of metal carbenes

Since the synthesis, isolation and characterization of the first metal carbene complex, a tungsten carbonyl methoxymethylcarbene, by E. O. Fischer and A. Maasböl in 1964,[2] metal carbenes have been used in many catalytic processes[3] like alkene and enyne metathesis,[4] alkyne polymerization,[5] cyclopropenation,[6] etc. In situ generated catalytic metal carbenes[1a,3,7] have been invoked as intermediates for cycloadditions, insertions or skeletal rearrangements.[8]

Substitution in carbenes has a significant influence on their reactivity. When the substituent is a vinyl group, it is governed by the combination of three factors: i) the presence of a three carbon-four electron π-system; ii) the existence of two electrophilic positions (α and γ positions) and iii) the possible existence of two coordination modes (η1 or η3 coordination) (Figure 2). Such features render metal vinyl carbenes valuable intermediates in organometallic chemistry with potential

applications in organic synthesis. In this account, we will highlight the main synthetic applications involving catalytic processes through ruthenium vinyl carbene intermediates.[9]

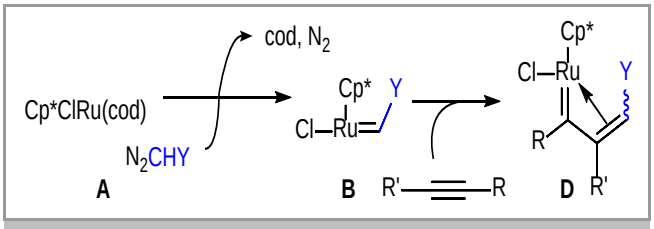
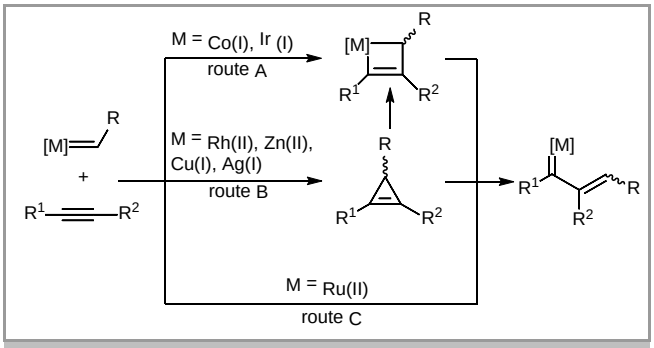


Figure 2 Characteristics of metal vinyl carbenes

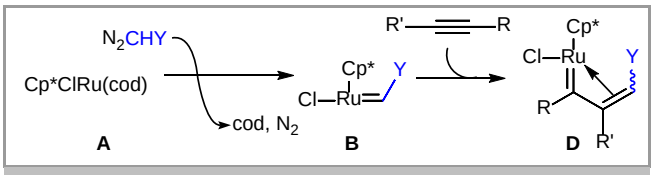
2 Ruthenium Vinyl Carbenes Through Carbene/Alkyne Metathesis (CAM)

In a metal mediated carbene/alkyne metathesis (CAM), a carbene fragment from a metal complex migrates to an alkyne with the concomitant generation of a metal vinyl carbene where a new carbon-carbon double bond and a new metal carbene are being formed.[10] Different mechanisms have been proposed for this process depending on the metal complex used and its oxidation state (Scheme 1). In the case of low-valent metals, such as Co(I)[11] or Ir(I),[12] the metal carbene undergoes a (2+2) cycloaddition with the alkyne to yield a metallacyclobutene intermediate which subsequently ring opens through a cycloreversion to give the metal vinyl carbene (Scheme 1, route A). Originally, this was considered the standard mechanism for CAM catalyzed by most transition metals; however, new experimental and theoretical data indicate that the mechanisms differ from one metal to another. Thus, cyclopropenes, formed through a concerted (2+1) cycloaddition between metal carbenes and alkynes (Scheme 1, route B),[13] or direct concerted reaction with alkynes to yield ruthenium vinyl carbenes (Scheme 1, route C)[14] have been identified or postulated.



Scheme 1 Mechanistic proposals for carbene/alkyne metathesis

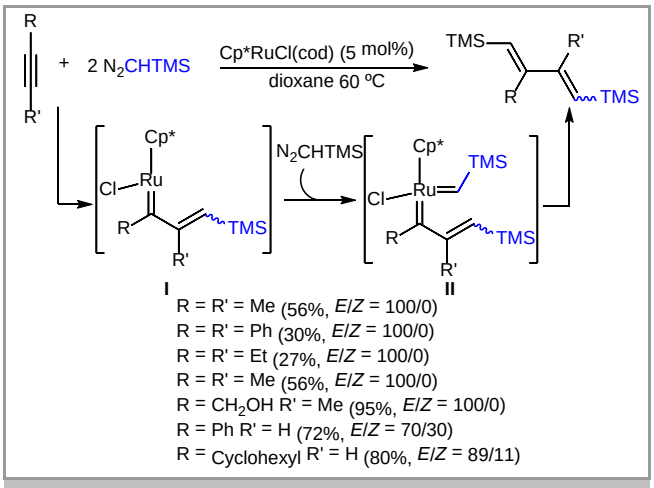
In 2000, Dixneuf and coworkers discovered a new methodology for the in situ generation of ruthenium vinyl carbenes by combining diazoalkanes and alkynes in the presence of catalytic amounts of Cp*RuCl(cod) (Scheme 2).[15] Catalytic ruthenium vinyl carbene intermediates have been invoked in a variety of transformations that will be presented in the next sections.



Scheme 2 Generation of ruthenium vinyl carbenes from Cp*RuCl(cod), diazocompounds and alkynes

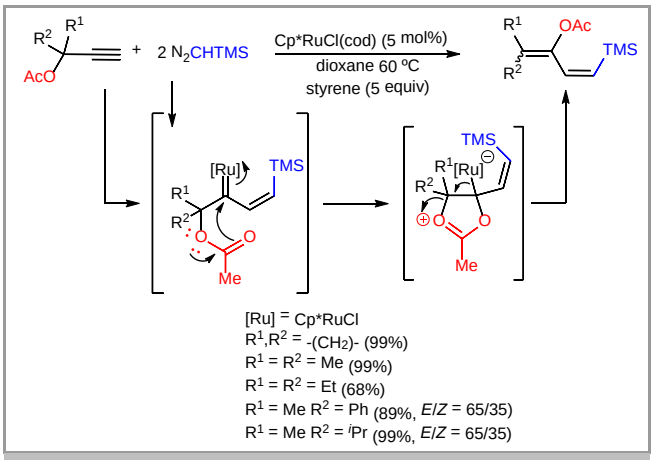
3 Nonpolar Transformations of Ruthenium Vinyl Carbenes

The reaction products formed via ruthenium vinyl carbene intermediates strongly depend on the nature of the alkyne.[16] Thus, non-functionalized alkynes generate 1,3-dienes via double diazoalkane carbene addition to the triple bond.[15,17] For example, reaction of mono- and disubstituted alkynes with two equivalents of trimethylsilyldiazometane in the presence of Cp*RuCl(cod) afford 1,4-bistrimethylsilylbuta-1,3-dienes through initial formation of ruthenium vinyl carbene **I** which interacts directly with a second unit of the diazocompound to afford the observed diene either directly or via the *cis* biscarbene **II** (Scheme 3).



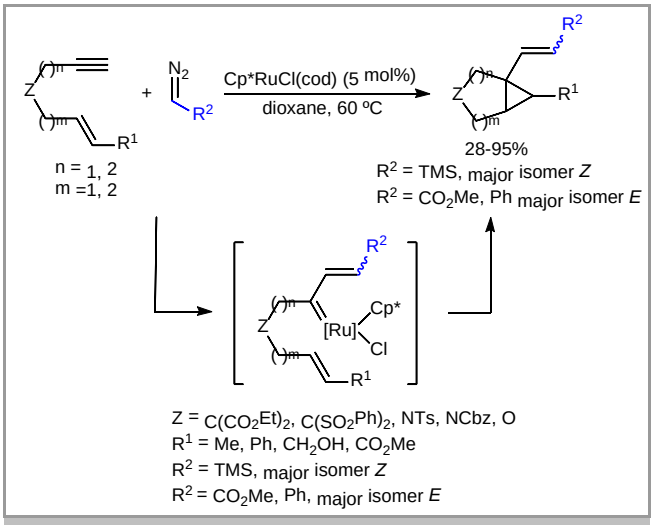
Scheme 3 1,3-Dienes by double diazoalkane carbene addition to alkynes catalyzed by Cp*RuCl(cod)

Functionalized 1,3-dienes could also be obtained by Rautenstrauch rearrangement of ruthenium vinyl carbenes **I**, generated in situ by reaction of propargylic carboxylates with diazoalkanes in the presence of catalytic Cp*RuCl(cod) (Scheme 4).[18]



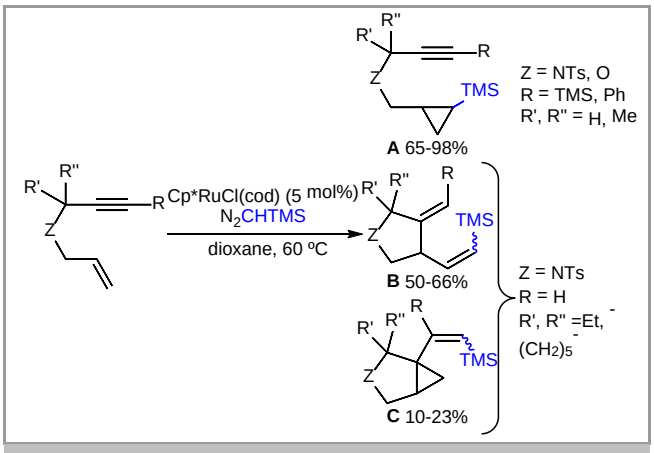
Scheme 4 Functionalized 1,3-dienes by Rautenstrauch rearrangement of ruthenium vinyl carbenes derived from diazoalkane, propargylic carboxylates and catalytic Cp*RuCl(cod)

Bicyclic [n.1.0] systems can also be achieved by using enynes in the presence of catalytic Cp*RuCl(cod) and diazocompounds. Alkenyl bicyclo[3.1.0]hexanes and bicyclo[4.1.0]heptanes can be ensembled by Cp*RuCl(cod)- catalyzed reaction between C-, N- and O-tethered 1,6- and 1,7-enynes and diazocompounds by initial formation of the corresponding ruthenium vinyl carbene through CAM followed by a concerted [2+1] reaction (cyclopropanation) of the carbene into de double bond of the alkene (Scheme 5).[19] Remarkably, when electron-rich N_2CHTMS was used the major diastereoisomer obtained had *Z* geometry, while with conjugated diazolkanes such as N_2CHCO_2Et and N_2CHPh the major isomer presented *E* geometry.



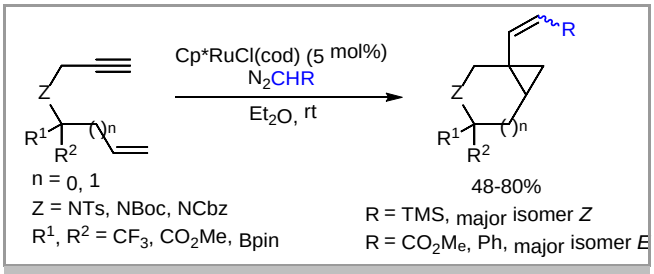
Scheme 5 Alkenyl bicyclic systems by Cp*RuCl(cod)-catalyzed reaction of 1,6- and 1,7-enynes with diazocompounds

Enynes bearing a substituted triple bond or with a propargylic substitution disfavor the tandem CAM process. Thus, cyclopropanes **A** are formed by direct cyclopropanation of the alkene moiety when the alkyne bears bulky substituents (Scheme 6); α-alkenyl alkylidene cyclopentanes **B** together with the expected alkenyl bicyclo[3.1.0]hexanes **C** are obtained when the enyne possess propargyl α,α-disubstitutions (Scheme 6).[19b]



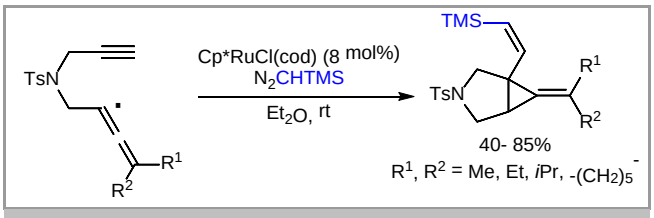
Scheme 6 Cp*RuCl(cod)-catalyzed reaction of enynes bearing propargylic α,α–disubstituted and internal/terminal alkynes with N_2CHTMS

Similarly, alkenyl bicyclo[3.1.0]hexanes and bicyclo[4.1.0]heptanes are obtained from 1,6- and 1,7-enynes with alkenyl/allylic substituted substrates (Scheme 7).[20]



Scheme 7 Cp*RuCl(cod)-catalyzed reaction of allylic substituted 1,6- and 1,7-enynes with diazocompounds

Furthermore, allenynes reacted under the same catalytic conditions to afford alkylidenebicyclo[3.1.0]hexanes having and adjacent bridgehead-substituted (*Z*)-CH=CHTMS group (Scheme 8).[21]



Scheme 8 Cp*RuCl(cod)-catalyzed reaction of allenynes with N_2CHTMS

4 Polar Transformations of Ruthenium Vinyl Carbenes

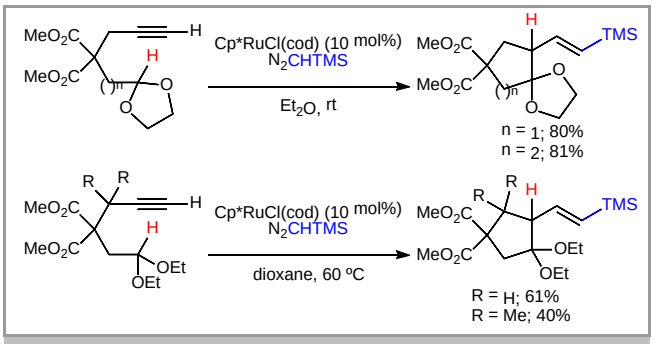
A decade ago we initiate a program in our group to evaluate the reactivity as electrophile of the ruthenium vinyl carbene intermediates to be applied in polar transformations.

4.1 Intramolecular Ruthenium Catalyzed [1,5]- and [1,6]-Hydride Transfer/Cyclization

During the last few years, metal-catalyzed C-H activation/functionalization has been positioned as a powerful tool for the step-economical construction of C-C and C-

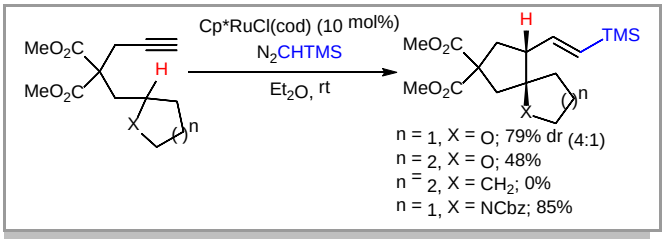
heteroatom bonds starting from hydrocarbons.[22] While extensive methodology has been developed for the functionalization of Csp2-H bonds, Csp3-H bonds remain more challenging due to its high bond dissociation energy.

A selective activation and direct functionalization of Csp^3-H bonds towards five- and six-membered carbo- and heterocycles has been devised by ruthenium-catalyzed redox, neutral [1,n]-hydride transfer/cyclization processes.[23] Ruthenium vinyl carbene intermediates derived from CAM reaction of trimethylsilyldiazomethane and alkynylacetals behave as hydride acceptors in intramolecular [1,n]-hydride transfers to afford functionalized carbo- and spirocycles.[24] Tertiary Csp^3-H of linear and cyclic acetal derivatives undergo [1,5] and [1,6]-hydride transfer/cyclizations in moderate to good yields (Scheme 9).



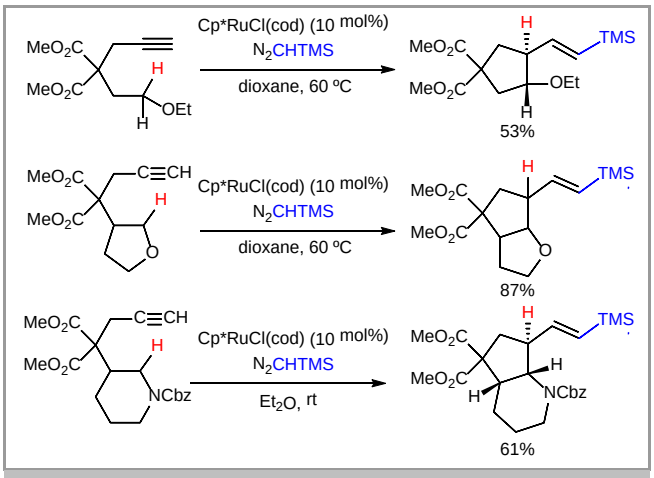
Scheme 9 Ruthenium-catalyzed [1,5]- an [1,6]-hydride transfer/cyclizations of tertiary Csp3-H of alkynylacetals

Even alkynyl tetrahydrofurans and pyrans (X = O, n = 1,2) and pyrrolidines (X = N), having less activated tertiary Csp3-H by single heteroatoms, underwent [1,5] and [1,6]-hydride transfer/cyclization processes to provide the bicyclic oxa- and azaspiranes in fairly good yields with high diastereoselectivities or as single diastereomer, respectively. Unfortunately, pure tertiary Csp3-H of cycloalkanes failed to react (Scheme 10).



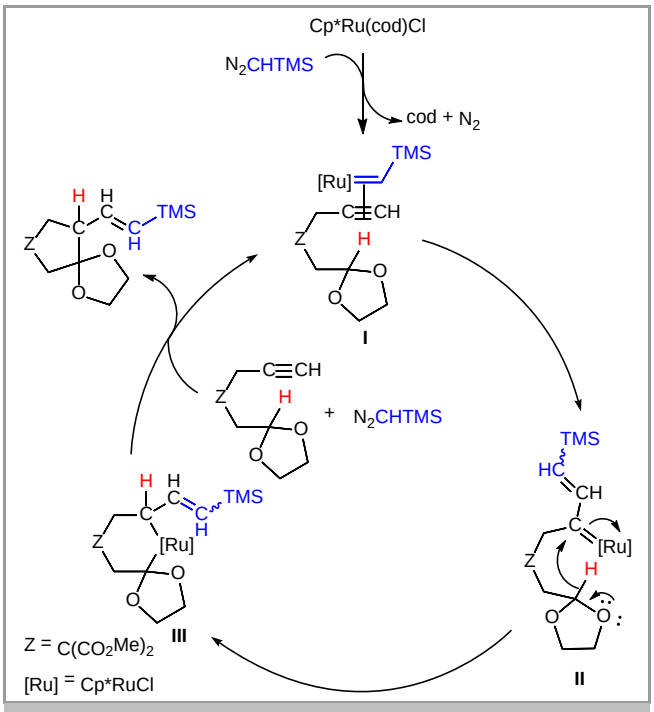
Scheme 10 Ruthenium-catalyzed [1,5]- and [1,6]-hydride transfer/cyclizations of tertiary Csp3-H in alkynyl heterocycles

Moreover, secondary linear Csp^3-H of alkynyl ethers also underwent [1,5]-hydride transfer/cyclization processes. *Trans* homoallylic ethers could be obtained from acyclic ethers and tetrahydrofurans in moderate to good yields (Scheme 11). Interestingly, activation of the secondary Csp^3-H of piperidines gave a single diastereoisomer of the corresponding bicyclic derivative.



Scheme 11 Ruthenium-catalyzed [1,5]-hydride transfer/cyclization of secondary Csp3-H in alkynyl ethers and heterocycles

The mechanistic hypothesis for the Ru-catalyzed [1,5]-hydride transfer/cyclization processes in cyclic alkynyl acetals is shown in Scheme 12. After initial formation of ruthenium carbene **I**, a CAM process arises to generate the vinyl ruthenium carbene **II**. Then, a [1,5]-hydride transfer assisted by the heteroatoms affords a transient zwitterionic species which is trapped to give the ruthenacycle **III**.[14a] A reductive elimination would finally afford the spiroacetal with recovery of the Ru(II) catalyst.

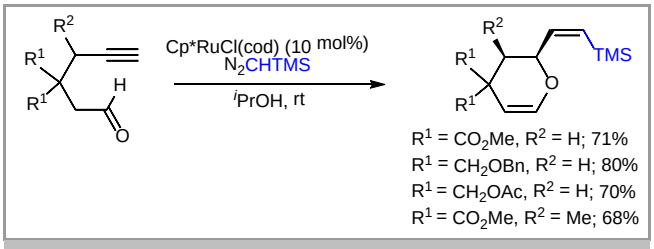


Scheme 12 Mechanistic hypothesis for the Ru-catalyzed [1,5]-hydride transfer/cyclization in cyclic alkynyl acetals

4.2 Heterocyclizations of Alkynals and Alkynones

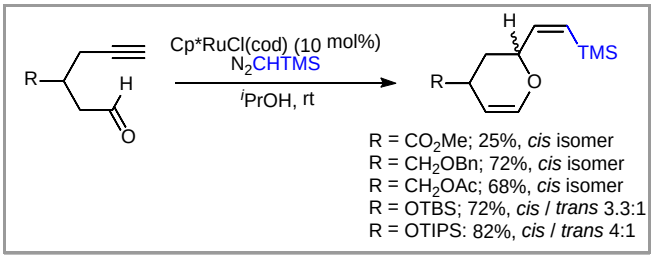
Electrophilic vinyl ruthenium carbenes derived from Cp*RuCl(cod)-catalyzed CAM reaction between alkynals/alkynones and trimethylsilyldiazomethane could be catched with O-nucleophiles from the carbonyl functionalities to give five- and six-membered oxaheterocycles.[25] 2-Vinyl-3,4-

dihydropyrans were obtained in good yields and high diastereoselectivities starting from 3,3- and 3,3,4-substituted alkynals (Scheme 13).[26]



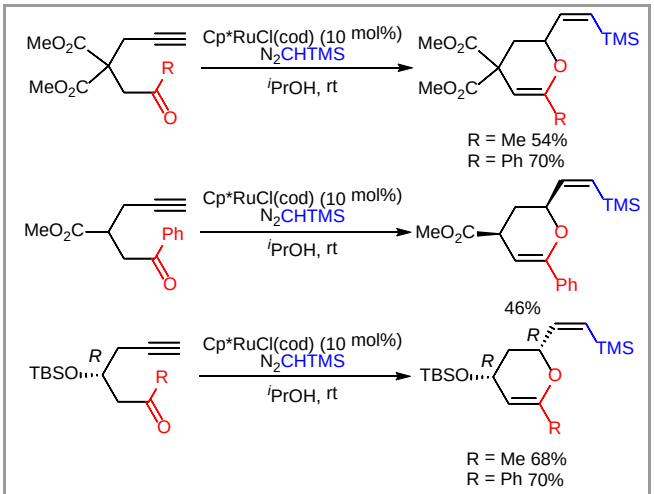
Scheme 13 Ruthenium-catalyzed heterocyclization of di- and trisubstituted alkynals to 2-vinyl-3,4-dihydropyrans

With a glimpse to future applications to the synthesis of bioactive tetrahydropyrans, we undertook the reevaluation of the diastereoselectivity of the reaction with 3-monosubstituted alkynals. Alkynals bearing ester and ether functionalities afforded, to our delight, the corresponding 2-vinyl-3,4-dihydropyrans as single *cis* diastereomers (Scheme 14). However, although alkynals bearing bulkier 3-silyloxy substituents were very well tolerated in terms of reactivity, they showed lower diastereoselectivities.



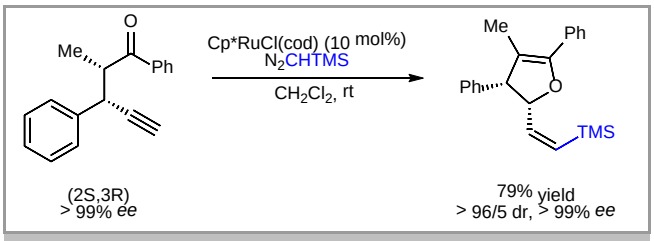
Scheme 14 Ruthenium-catalyzed heterocyclization of 3-alkynals to 2-vinyl-3,4-dihydropyrans

Similarly, alkynones were also capable to undergo ruthenium catalyzed heterocyclizations to 6-substituted 2-vinyl-3,4-dihydropyrans (Scheme 15). As before, 3-monosubstituted alkynones showed complete diastereoselectivity to give the *cis* 2,4,6-trisubstituted dihydropyrans, and also to the enantiomerically pure dihydropyrans if the starting alkynone was (*R*) 3-(*tert*-butylsilyloxy)alkynones (Scheme 15).



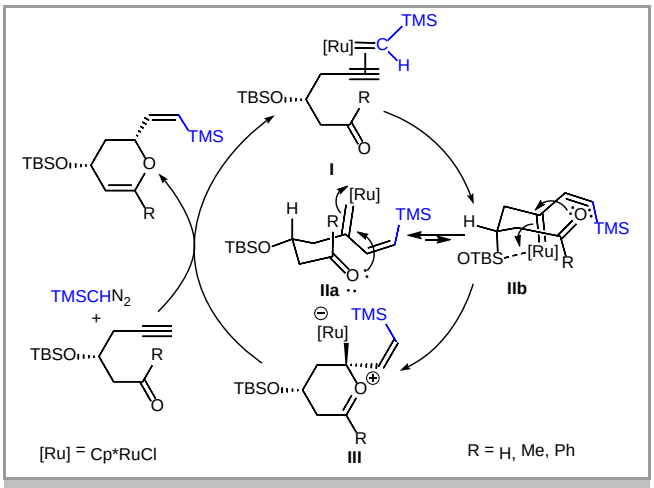
Scheme 15 Diastereo- and enantiomerically ruthenium-catalyzed heterocyclization of alkynones to 6-substituted 2-vinyl-3,4-dihydropyrans

Optically active 2,3-dihydrofurans, which are synthetically relevant structures for a plethora of natural and bioactive products,[27] can be easily accessed *via* Ru-catalyzed heterocyclization of (2*S*,3*R*)-1,4-alkynones derived from enantioselective propargylic alkylation of acyclic ketone enamines (Scheme 16).[28]



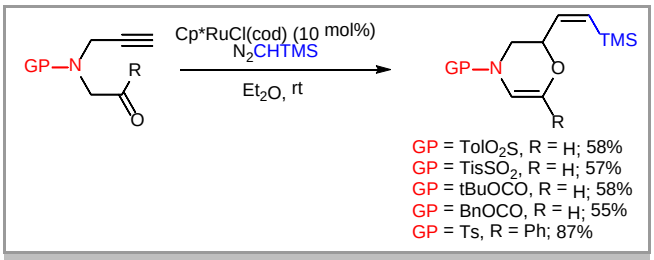
Scheme 16 Ruthenium-catalyzed heterocyclization of (2*S*,3*R*)-1,4-alkynones to active 2,3-dihydrofurans

The tentative mechanism for the Ru-catalyzed heterocyclization of alkynals and alkynones to give 2-vinyl-3,4-dihydropyrans is shown in Scheme 17. After initial generation of the electrophilic vinyl ruthenium carbene **II** through CAM reaction, a nucleophilic attack of the carbonyl would afford the zwitterionic intermediate **III**. The diastereoselectivity seems to be controlled on the nucleophilic attack of the carbonyl through the more stable chair-like conformer of carbene **IIa** with all the equatorial substituents. Final deprotonation and reductive elimination would give rise to the observed dihydropyran with regeneration of the active ruthenium species for the next catalytic cycle.



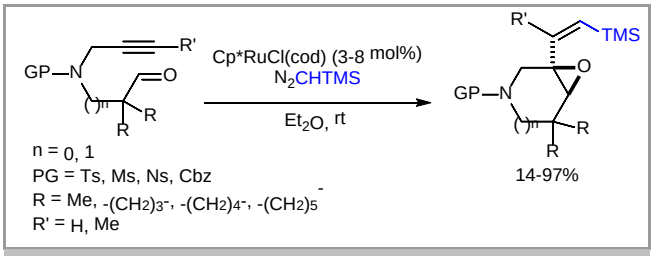
Scheme 17 Mechanistic hypothesis for the ruthenium-catalyzed heterocyclization of alkynal and alkynones

Likewise, *N*-tethered alkynals (aza-alkynals) and alkynones also underwent heterocyclizations to give the corresponding 2-vinyl-3,4-dihydro-2*H*-1,4-oxazines in moderate to good yields (Scheme 18).



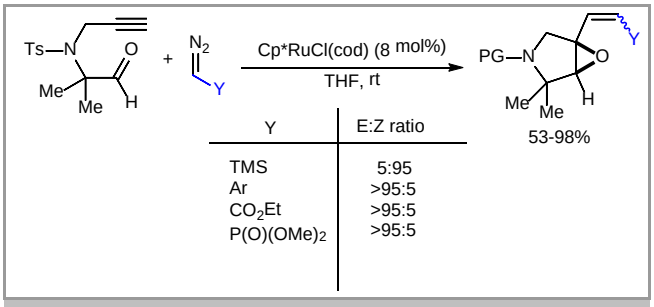
Scheme 18 Ruthenium-catalyzed heterocyclizations of *N*-tethered alkynals and alkynones to 2-vinyl oxazine derivatives

Remarkably, 2,2-disubstituted aza-alkynals undergo a divergent cyclization reaction leading to vinyl epoxypyrrolidines (n = 0) and epoxypiperidines (n = 1), valuable building blocks for the synthesis of bioactive compounds (Scheme 19).[29]



Scheme 19 Cp*Ru(cod)-catalyzed cyclization of α,α'-disubstituted aza-alkynals and trimethylsilyldiazomethane to epoxypyrrolidines and epoxypiperidines

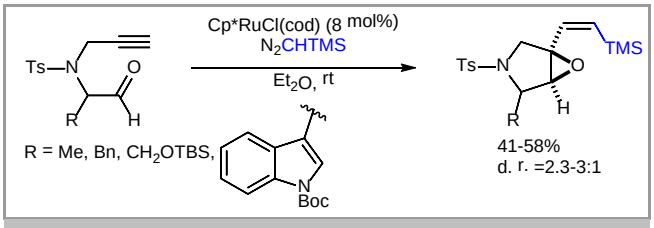
When conjugated diazoalkanes were used, the reaction also occurred but, interestingly, the geometry of the vinyl substituent changed to *E* instead of the *Z* observed when $TMSCHN_2$ was used (Scheme 20).



Y	E:Z ratio
TMS	5:95
Ar	>95:5
CO_2Et	>95:5
$P(O)(OMe)_2$	>95:5

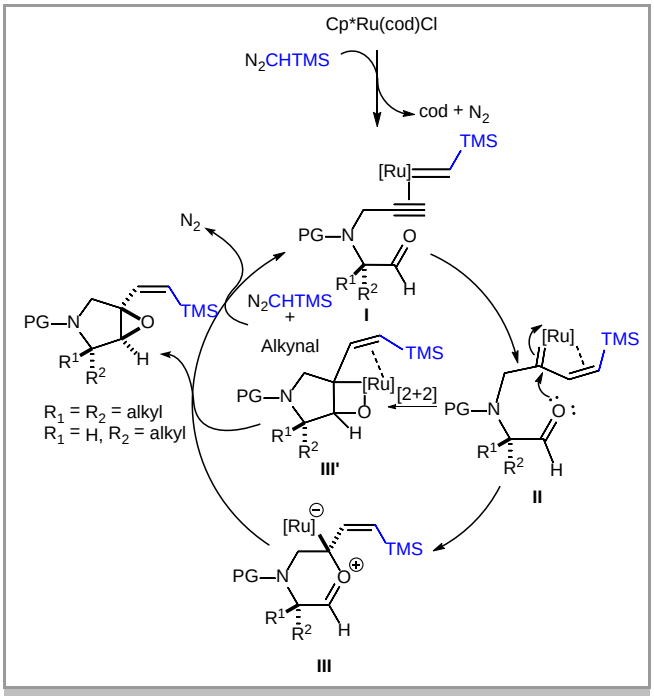
Scheme 20 Cp*Ru(cod)-catalyzed cyclizations of α,α'-disubstituted aza-alkynals and diazoalkanes to vinyl epoxypyrrolidines.

Interestingly, α-monosubstituted aza-alkynals reacted chemo- and diastereoselectively to give the corresponding epoxypyrrolidines in moderate yields (Scheme 21).



Scheme 21 Chemo- and diastereoselective formation of epoxypyrrolidines by Cp*Ru(cod)-catalyzed cyclization of α-monosubstituted alkynals and trimethylsilyldiazomethane

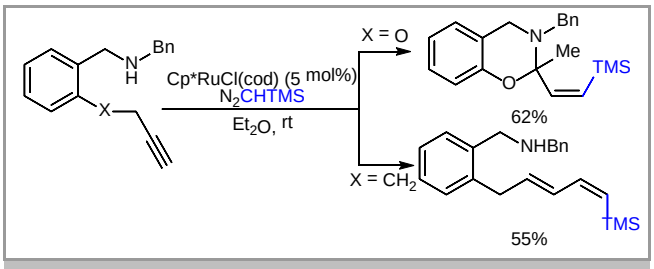
The mechanistic hypothesis for the Cp*RuCl(cod)-catalyzed epoxyannulation is shown in Scheme 22. The initially formed alkynal-carbene complex **I** would evolve through CAM to the electrophilic vinyl ruthenium carbene intermediate **II**. A subsequent nucleophilic attack by the carbonyl group gives rise to the oxonium species **III**, which finally ends up in the observed epoxypyrrolidine. In this particular case, the lack of hydrogens (or sterically hindered) at α position preclude or highly hamper the deprotonation/reprotonation step blocking the formation of dihydrooxazine. Evolution of the vinyl carbene **II** *via* a formal [2+2] cycloaddition to the oxaruthenacycle **III'** and final reductive elimination cannot be excluded.



Scheme 22 Mechanistic hypothesis for the Cp*RuCl(cod)-catalyzed epoxyannulation of alkynals with trimethylsilyldiazomethane

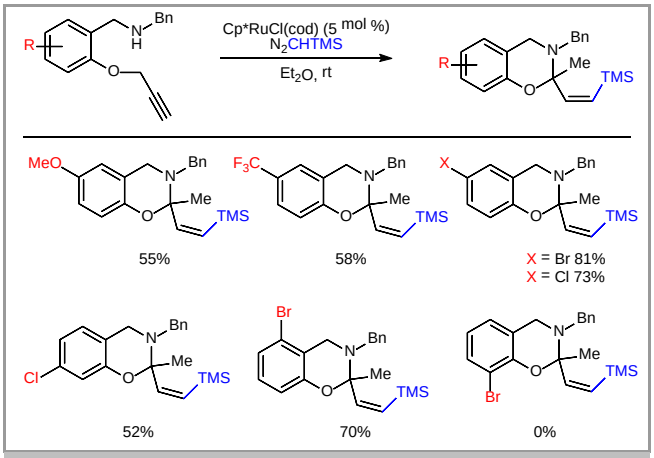
4.3 Heterocyclizations of *ortho*-(Alkynyloxy)benzylamines

Electrophilic ruthenium vinyl carbenes from Cp*RuCl(cod)-catalyzed CAM reaction between ω-alkynyl benzylamines and trimethylsilyldiazomethane could also be catch by *N*-nucleophiles of benzylamine derivatives.[30] Thus, ruthenium-catalyzed heterocyclization of *o*-(alkynyloxy)benzylamines afforded 2,2-disubstituted dihydro-1,3-benzoxazines, presumably by a nucleophilic attack of the amine to the ruthenium vinyl carbene followed by a sequential ring opening/ring closure rearrangement (Scheme 23).[31]



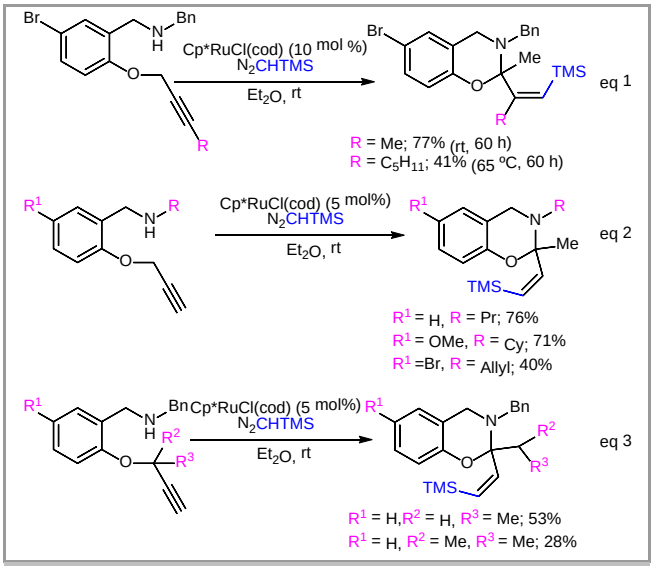
Scheme 23 Ruthenium-catalyzed reactions of C- and O-tethered *o*-alkynylbenzylamines

Substitution on the aromatic ring of benzylamines is well tolerated for these processes (Scheme 24). Both electron-rich and electron-poor aromatic rings are reactive enough to give the corresponding 1,3-benzoxazines in relatively good yields, a bit better for the electron-poor rings. Halo-1,3-benzoxazines are easily accessible except the sterically hindered *ortho*-bromo 1,3-benzoxazine, which might outlook future manipulations of these substrates.



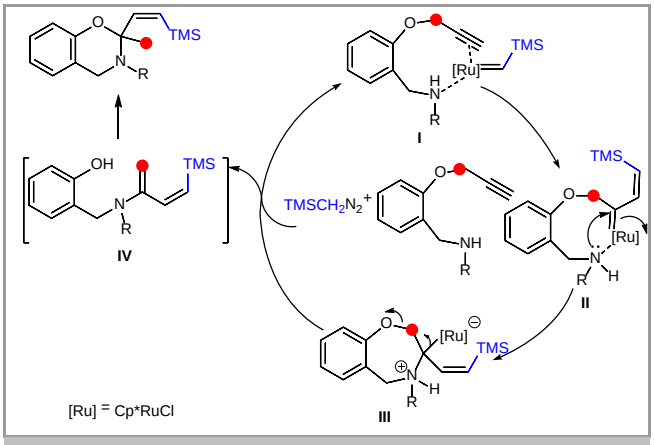
Scheme 24 Substituted 1,3-benzoxazines

Alkynyl substituted substrates also cyclized to give the corresponding 1,3-benzoxazines in moderate to good yields, although longer times and heating conditions are needed (Scheme 25, eq 1). On the other hand, primary and secondary benzylamines are also accepted affording the corresponding 1,3-benzoxazines in good yields. Polar interactions seem to control the reactivity of the carbene intermediate since *N*-allyl substituent on benzylamine remains intact during the reaction (Scheme 25, eq 2). Propargyl substituted alkynylamines are also well tolerated. Methyl monosubstituted and methyl disubstituted propargylic benzylamines gave rise to the rearranged 2-ethyl and 2-isopropyl substituted 1,3-benzoxazines in low to moderate yields. (Scheme 25, eq 3).



Scheme 25 Ruthenium-catalyzed heterocyclizations of internal alkynes, *N*-substituted and propargyl substituted *ortho*-(alkynyloxy)benzylamines to 1,3-benzoxazines

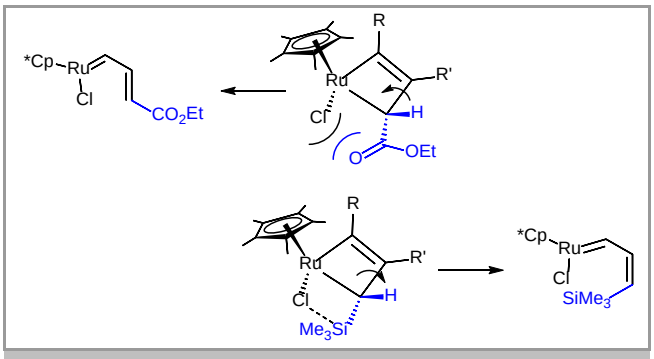
The proposed mechanism involves an initial formation of the alkynylamine-carbene complex **I** that would evolve through CAM to the electrophilic vinyl ruthenium carbene intermediate **II**. Saturation of ruthenium to give the 18 e⁻ complex by nitrogen coordination might be occurring. Then, a subsequent nucleophilic attack to the carbene would afford the zwitterionic species **III** that ring opens to a transient enamine **IV**. The acidic phenol would promote the final ring closing to afford the 2,2-disubstituted 1,3-benzoxazine (Scheme 26).



Scheme 26 Mechanistic hypothesis for the ruthenium-catalyzed heterocyclization of *ortho*-(alkynyloxy)benzylamines to 1,3-benzoxazines

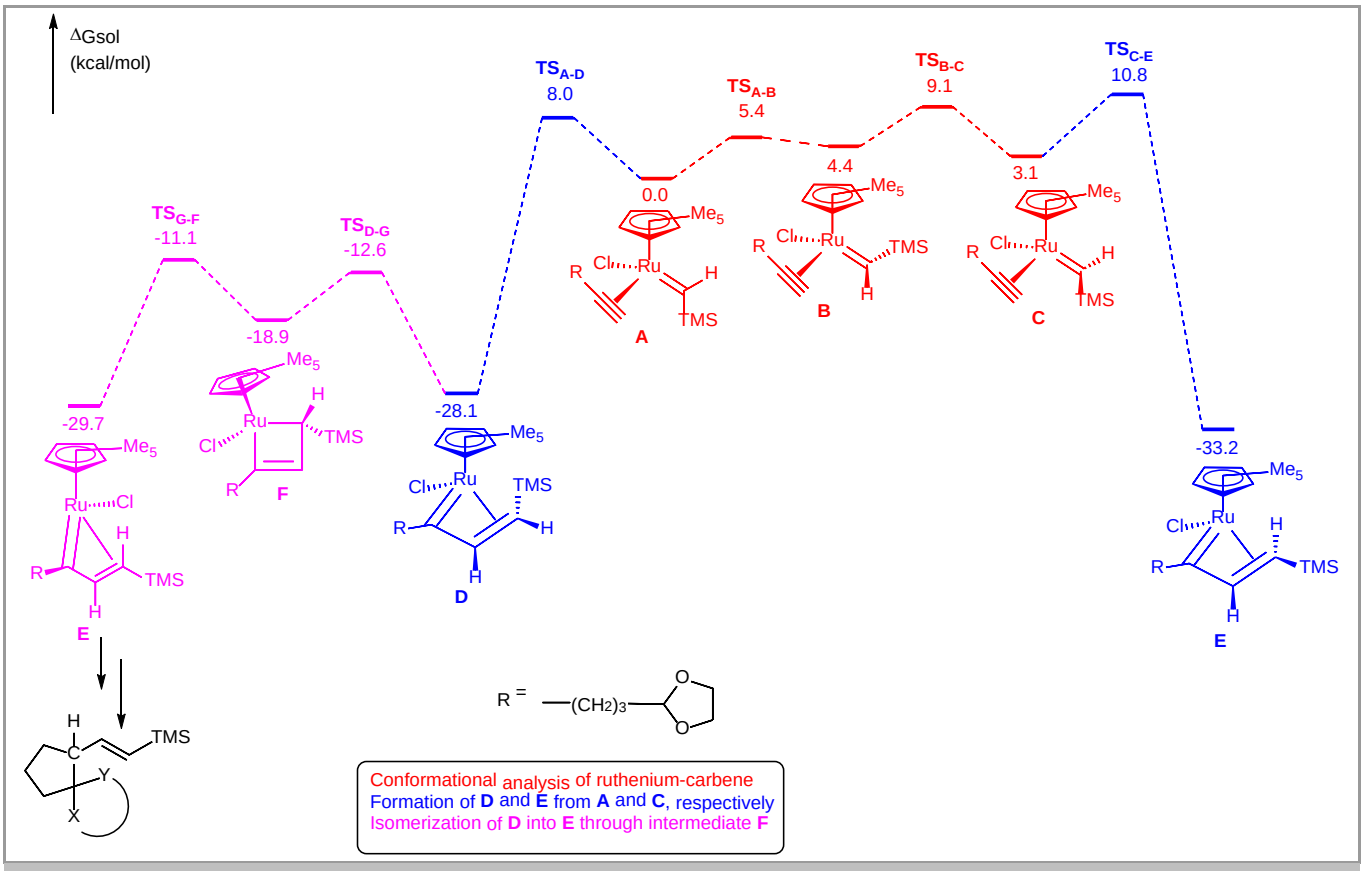
5 DFT Studies on the Stereoselectivity of the CAM Reaction

In all the nonpolar and the majority of polar transformations, the geometry of the double bond (stereoselectivity) of the ruthenium vinyl carbene intermediates through CAM reactions between trimethylsilyldiazomethane and alkynes and also in the final product is *Z* except for the polar [1,n]-hydride transfer/cyclization which was found *E*. Nevertheless, with conjugated diazoalkanes such as N_2CHCO_2Me or N_2CHPh, the geometry of the final product is *E* regardless of the type of transformation. A first premise to explain the stereoselectivity derives from the assumption of the vinyl ruthenium carbene formation during the electrocyclic opening of ruthenacyclobutene (Scheme 27), in which the Cp* and R groups should be *anti* to minimize detrimental steric interactions. If R = $SiMe_3$, intense attractive interactions should be operative between $SiMe_3$ and Cl groups compelling a favourable *Z* configuration after ring-opening. Conversely, if R ≠ $SiMe_3$ steric hindrance should be the boost for the torquoselectivity delivering favourable *E*-configuration of the double bond (Scheme 27) [15]



Scheme 27 Early hypothesis for the formation of *Z*- and *E*-vinyl ruthenium carbenes by ring-opening of ruthenacyclobutenes

To explain the appearance of the *E* geometry and to clarify properly these early premises for the formation of ruthenium vinyl carbenes, DFT calculations were performed for the [1,n]-hydride transfer/cyclization (Scheme 28).[14a] Three conformers in equilibria for the initial ruthenium carbene coordinated to the alkyne were observed: a) the conformer **A**, with the hydrogen pointing to the Cp*ring, being the more stable and b) the conformers **B** and **C**, with the TMS group pointing to the Cp* ring backwards and forward, respectively, being less stable.

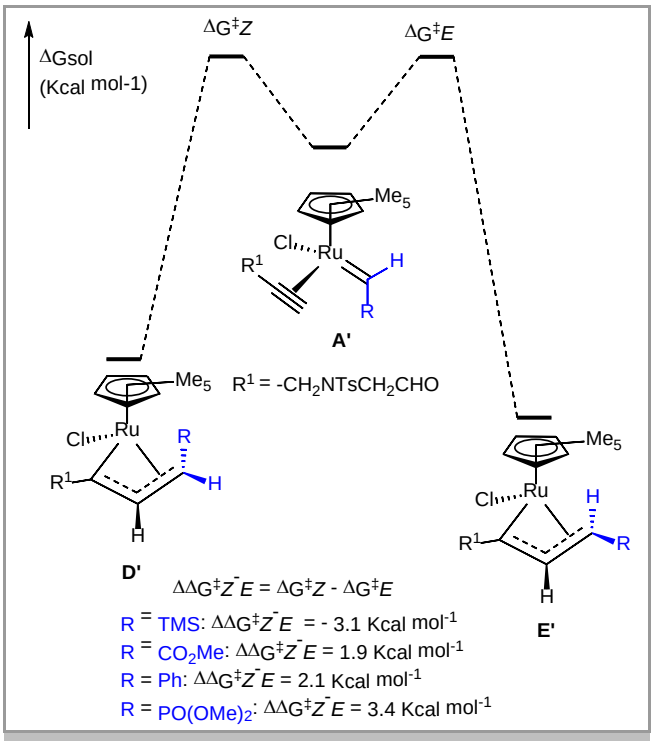


Scheme 28 Calculated potential free energy curve for the conformational equilibrium of alkyne coordinated Cp*RuCl carbene and its transformation into *Z* and *E* vinyl ruthenium carbenes **D** and **E**

Evolution either to the *Z*- or *E*- ruthenium vinyl carbenes **D** and **E** is favored to the *Z* isomer **D** since the transition state is lower by 2.8 Kcal mol^{-1}. The most favorable pathway involved the initial isomerization of *Z* isomer **D** to the *E* isomer **E** through ruthenacyclobutene intermediate **F**, which could justify the *E* geometry of the vinyl substituents found in the final products.

In the case of the other polar transformations, the most favorable pathway would start from intermediates of type **D** without isomerization, which would explain the appearance of the final products with *Z* geometry.

To explain the observed *E* stereoselectivity when conjugated diazoalkanes were used, DFT calculations for the transformation from alkyne-carbene complexes **A'** to *Z*- and *E*-ruthenium vinyl carbenes **D'** and **E'**, respectively, were performed (Scheme 29).[29]



Scheme 29 Calculated potential free energy curve for the generation of *Z*- and *E*- vinyl ruthenium carbenes by CAM reaction of several Cp*RuCl carbenes

From the results, trimethylsilyldiazomethane favor the formation of *Z*-vinyl ruthenium **D'** carbenes by 3.1 Kcal mol^{-1}, while conjugated diazoalkanes favor the formation of *E*-vinyl ruthenium carbenes **E'** (from 1.9 Kcal mol^{-1} for the CO_2Me to 3.4 Kcal mol^{-1} for the $PO(OMe)_2$). This stereochemical divergence might be attributed to the strong steric repulsion between the Cp* ligand and the bulky TMS group.

6 Conclusions

Recent advances in Ru-catalyzed synthetic applications involving carbene/alkyne metathesis (CAM) processes have been compiled. From the model schemes of this account, we can see the significant progress that has been accomplished in recent years. With the easy availability of ruthenium catalysts and the mild conditions needed, the use of CAM reactions for the development of new synthetic approaches is highly appealing. New challenges may focus on the preparation of structurally well-defined ruthenium vinyl carbenes as catalysts for the development of selective reactions, and also in the isolation and characterization of reactive Ru intermediates for a complete elucidation of reaction mechanism, which may provide insight for the design of new organic transformations. The development of chiral Ru vinyl carbene complexes for enantioselective transformations could be another interesting future task.

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(25) Alkynols do not undergo CAM processes since the diazocompound is inmmediately trapped with the hydroxyl group.

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Biosketches

Carlos Saá, born in Lugo (Spain), studied chemistry at the Universidad de Santiago de Compostela (Spain) where he received his PhD in 1985 under the supervision of Profs. L. Castedo, R. Suau and J. M. Saá. He spent two-year (1987-1988) as a NATO postdoctoral research associate at the University of California, Berkeley, working with Prof. K. P. C. Vollhardt in a Cobalt catalytic approach to ergot alkaloids. In 1990, he joined the faculty at the Universidad de Santiago de Compostela as Profesor Titular, and since 2004 has been a full Professor. His research interest centers on the discovery of new methodology of organometallic catalysis and their applications to the synthesis of bioactive compounds and organic conductive materials.

Biosketches

Jesús A. Varela was born in 1971 in Lugo, Spain, and studied chemistry at the Universidad de Santiago de Compostela, Spain. He completed his M. Sc. in 1994 and his Ph. D. thesis in 1999 (excellent award) both under the supervision of Prof. Dr. Carlos Saá for research on synthesis of oligopyridines via cobalt chemistry. He spent a predoctoral research training period in Harvard University under supervision of Prof. Dr. Matthew Shair working on polyol synthesis by C-H insertion of metal-carbenes. From 1999 to 2001, he spent a postdoctoral period as an Alexander Von Humboldt and Marie Curie Fellow with Prof. Dr. Paul Knochel at Ludwig Maximilians Universität in Munich (Germany), working on remote C-H activation via hydroboration. After that, he joined the faculty at the Universidad de Santiago de Compostela as Ramón y Cajal researcher, and since 2008 as Profesor Titular. His research interests are focused in organometallic catalysis towards the synthesis of biological active systems or molecular materials and its mechanistic study.

Biosketches

Damián Padín received his B.Sc. degree in Chemistry from the University of Santiago de Compostela in 2013. Then, he also obtained the M.Sc. in Advanced Chemistry from the same university in 2014 under the supervision of Prof. Carlos Saá and Prof. Jesús A. Varela. After a short research stay in Boston College working on copper-catalyzed transformations under the supervision of Amir H. Hoveyda in 2017, he got his PhD in Organic Chemistry in 2019 under the supervision of Prof. Carlos Saá and Prof. Jesús A. Varela for research on catalytic ruthenium vinyl carbenes. His research interests include the development of new catalytic transformations, elucidation of reaction mechanisms and total synthesis.