Advances in the metallotropic [1,3]-shift of alkynyl carbenoids

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Metal complexes of alkynyl carbenes undergo a [1,3]-bond shift known as a metallotropic shift. Since the discovery of the metallotropic [1,3]-shift of Rh-carbenoid, many more alkynyl carbene complexes with Ti, Cr, Mn, Mo, Ru, W, Re, Pt, and Au have been discovered to show metallotropic shift behavior. This article briefly summarizes the [1,3]-bond shift of alkynyl carbenes and their metal complexes.

1. Introduction

Carbene is one of the most versatile reactive intermediates in organic chemistry. Especially, the transition metal-complexed version known as metal-carbenoid has been extensively utilized in tandem reaction sequences to generate complex ring structures *via* the formation of carbon–carbon and carbon–heteroatom bonds.[1] The unique capacity to form and break more than two bonds in a concerted or sequential manner is characteristic of a "complex reaction", which is represented by "coarctate" electron-shifting topology compared to the linear and cyclic topologies of common organic reactions and pericyclic reactions, respectively.[2]

The typical reactivity of carbenes and carbenoids, represented by their insertion to C–C, C–H, N–H, O–H, Si–H bonds (addition to a single bond), addition to double and triple bonds (cyclopropane and cyclopropene formation), and rearrangement, is strongly influenced by the nature of substituents and the hybridization of carbenic carbons. Rearrangements in unsaturated carbene systems including vinylidenes,[3] allenylidenes[4] and alkynyl and vinyl carbenes[5] have been a long-standing subject for theoretical and experimental investigation. However, it is only recently that the interest in alkynyl carbenes has been renewed, leading to significant advances in our understanding of their structure and reactivity. Especially, the development of transition metal-based methods for their efficient generation directly from alkynes permits the study of [1,3]-carbenoid shift behaviors, which could be developed into synthetically useful processes.

The intention of this *Perspective* is to survey the metallotropic [1,3]-shift of metal-carbenoids with an emphasis on recent developments. Due to similarities between the chemistry of free carbenes and metal-carbenoids, the bond shift and structural features of free alkynyl carbenes (propynylidene and petadiynylidene) will be briefly introduced and the metallotropic [1,3]-shift of various transition metal-alkynyl carbenoids will be reviewed.

2. Bond shift of alkynyl carbenes

The rearrangement (bond shift) of acetylenic carbenes has long been a topic of interest from a range of perspectives. Since propynylidene, first generated photochemically by Skell and Klebe

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in 1960, showed equal reactivity at C1 and C3,[6] many experimental and theoretical efforts have been made to elucidate the bond shift behavior of various acetylenic carbenes (Fig. 1).

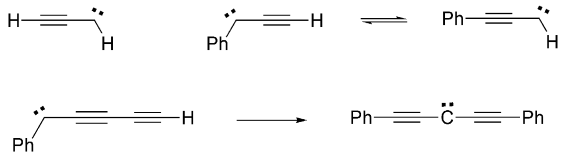
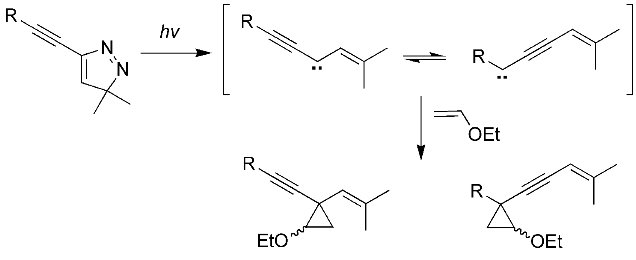


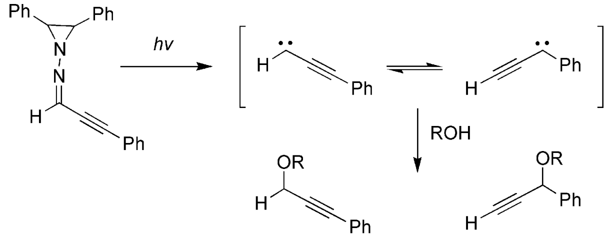
Fig. 1 Acetylenic carbenes.

The bond shift in free carbenes was inferred by the product distribution in trapping experiments with alkenes (Scheme 1)[7] and alcohols (Scheme 2)[8] as well as dimerization reactions (Scheme 3).[9] These results indicate that no straightforward rationale can be provided based on steric and electronic effects. Products are probably determined by the equilibrium ratios of the bond shift isomers and by their relative reactivities with the trapping agents or other carbenes.



R = H	34%	66%
R = Me	100%	0%
R = Br or CO_2Me	0%	100%

Scheme 1 Alkene trapping by an alkynyl carbene.

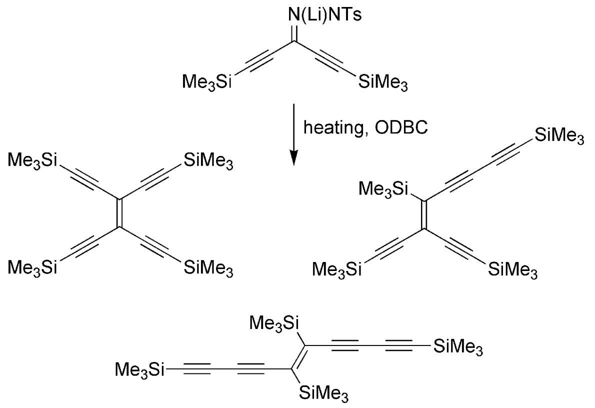


R = Me 2 (1) : 3 (10)
R = iPr 5 : 1

Scheme 2 Alcohol trapping by an alkynyl carbene.

In addition to experimental evidence supporting bond shift behaviors of alkynyl carbenes, several theoretical calculations were carried out to get more accurate structural information for these carbene species. Recently, studies of propynylidene (propargylene) by McMahon and coworkers provided conclusive evidence that, among linear carbenic structure,[10] C_2-symmetric bent allenic diradical,[11] and C_s-bent carbenic structure,[12] the C_2-symmetric bent allenic diradical with a bent angle of 155° is the best fit based on spectroscopic analyses (ESR/IR/UV–Vis) and *ab initio* calculations (Fig. 2).[13]

Electronic and structural information for pentadiynylidene (HC_5H), a prototype of diacetylenic carbenes RC5R′, was also obtained by McMahon and coworkers from the photochemical decomposition of 1-diazo-2,4-pentadiyne followed by matrix isolation and spectroscopic characterization.[14] From this study, the linear penta-1,4-diyne-3-ylidene structure with the largest unpaired spin density at the central carbon was ascribed to the major resonance contributor while the other degenerate resonance contributors are also important for describing the spin density at the terminal carbon. In contrast to HC_3H, the penta-1,2,3,4-tetraene-1,5-diyl structure bearing spin density at the terminal carbons is not a discrete minimum on the potential energy surface (Fig. 3).



Scheme 3 Dimerization of alkynyl carbenes.

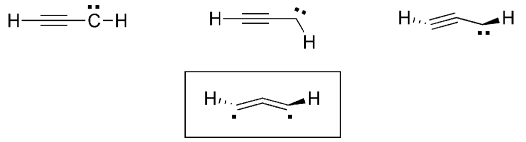


Fig. 2 Propargylene.

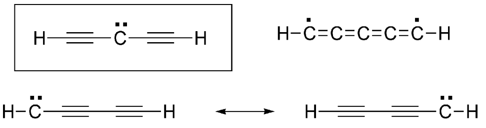
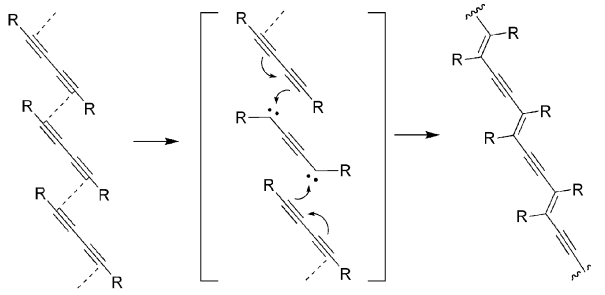


Fig. 3 Pentadiynylidene.

Interest in the alkynyl carbene species does not merely remain in the realm of curiosity and theoretical interest. Involvement of an alkynyl carbene is implicated in the polymerization of diynes to generate polydiacetylenes. Since 1969 it has been known that 1,3-diynes undergo polymerization in a topochemically controlled fashion under uv-irradiation (Scheme 4).[15] This polymerization process gives conjugate polymers with delocalized π-systems along the polymer backbone, which confers interesting optical, electronic, and photochemical properties to those polymers.[16] Carbene-mediated polymerization, a generally accepted mechanism, implies that a triple bond is a 1,2-dicarbene equivalent under suitable photochemical or thermal activation.[17] Due to the short lifetime of putative dicarbenes involved in this process, their generation within the well-organized topology of monomers is required to effect polymerization.[18]

Therefore, generation of stable yet reactive metal complexed equivalents of these carbenes would be expected to have significant impact on polymer chemistry and organic synthesis.

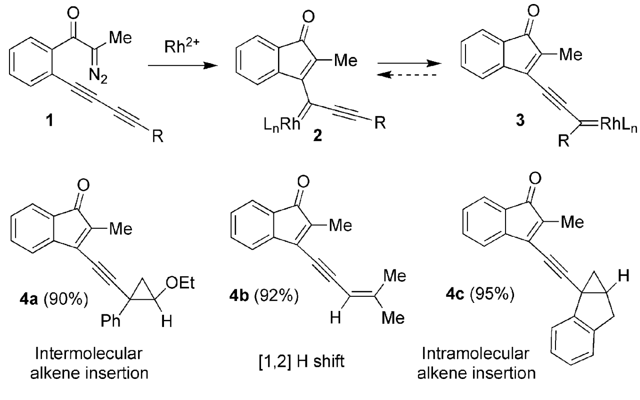


Scheme 4 Topochemical polymerization of 1,3-diynes.

3. Alkynyl carbenoids: metallotropic [1,3]-shift

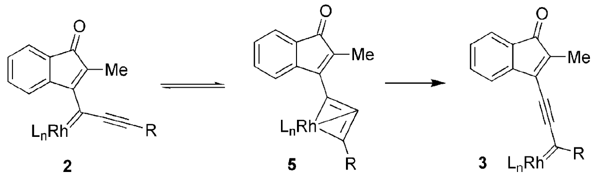
3.1. Rh-complex from diazoketone

The decomposition of diazoketones with various transition metal catalysts constitutes one of the most convenient methods to generate metal-carbenoids.[19] Padwa and coworkers treated a 1,3-diyne-tethered diazoketone **1** with $Rh_2(OAc)_4$, which generated vinyl alkynyl Rh-carbenoids **2** after addition of the initially formed α-keto-Rh-carbenoid to a proximal triple bond of the tethered 1,3-diyne.[20] The regioselectivity in trapping of alkynyl Rh-alkylidene intermediates was examined under various settings by using different trapping reagents (Scheme 5). The putative Rh-carbenoid **3** was first reacted with an external alkene such as ethyl vinyl ether to give the corresponding cyclopropanation product **4a** in 90% yield. Exclusive cyclopropanation was observed at the remote alkynyl site with no sign of regioisomeric cyclopropane on the proximal site, indicating the proclivity of a metallotropic [1,3]-shift of the initially formed alkynyl Rh-carbenoid. Since a [1,2]-hydrogen shift in a singlet carbene is known to form an alkene, a carbene species bearing a group capable of undergoing a [1,2]-hydrogen shift gave indenone **4b** in 92% yield. Similarly, an intramolecular cyclopropanation with a tethered alkene gave **4c** in 95% yield. The exclusive formation of **4a** could be explained by a higher rate of trapping of carbenoid **3** by ethyl vinyl ether, probably due to a lower steric hindrance at the remote site. Alternatively, the regioselectivity can be attributed to a more favorable equilibrium toward the fully conjugated, more stable phenyl substituted regioisomer.



Scheme 5 Rh-alkynyl carbene complex and its metallotropic [1,3]-shift.

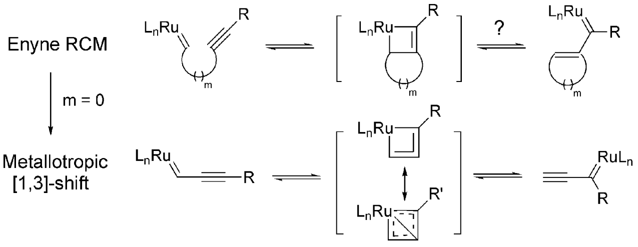
The alkynyl Rh-carbenoid is the first example of a metal complexed alkynyl carbene showing [1,3]-shift behavior, which was proposed to proceed through the formation of transient intermediate metallacycle **5** followed by structural rearrangement (Scheme 6). This transient intermediate undergoes ring opening to form a new Rh-carbenoid. The putative dehydrometalla cyclobutadiene complex shares a common structural feature with the tungstenadehydrocyclo-butadiene complex reported by Schrock and coworkers.[21]



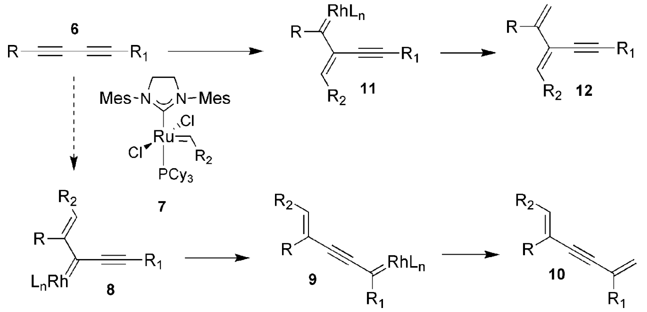
Scheme 6 Putative intermediates for metallotropic [1,3]-shift.

3.2. Ru-complex from metathesis (RCM)

Grubbs-type ruthenium alkylidene complexes are very efficient catalysts for enyne ring-closing and cross metathesis.[22] Due to the conceptual similarity between the enyne RCM and the metallotropic shift (Scheme 7), Lee and coworkers hypothesized that a reaction between a 1,3-diyne **6** and a ruthenium alkylidene **7** would form a regioisomeric intermediate **8**, which would then undergo the expected metallotropic [1,3]-shift to generate a new alkylidene **9** to provide a 1,5-diene-3-yne **10** as a final product (Scheme 8).[23] However, a 2-alkynyl-1,3-diene **12** was obtained from the cross metathesis reaction as the only observable product, a consequence of the formation of an inappropriate regioisomeric alkylidene intermediate **11** for the [1,3]-shift.

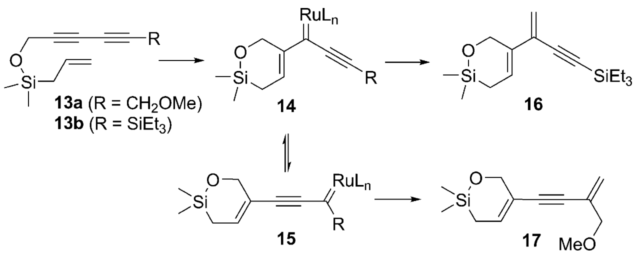


Scheme 7 Enyne RCM and metallotropic shift.



Scheme 8 Cross metathesis of 1,3-diynes without metallotropic shift.

It was hypothesized that generation of a Ru-alkynyl alkylidene species appropriate for the [1,3]-shift could be achieved by tethering an alkene to a diyne such that the formation of intermediates becomes intramolecular, providing an appropriate regioisomeric alkynyl alkylidene. This supposition was vindicated by the RCM of ene-diyne **13a**, which provided a single regioisomeric product **17** in quantitative yield (Scheme 9). On the other hand, the RCM of a similar ene-diyne **13b** containing a silyl group at the terminal position of the 1,3-diyne moiety generated a cross conjugated product **16** exclusively. We believe that an initial RCM from both substrates **13a** and **13b** generated an intermediate alkylidene **14** in equilibrium with another alkylidene **15**. The fate of these equilibrating intermediates to choose divergent reaction paths would depend on the nature of substituents.



Scheme 9 RCM of 1,3-diynes with an alkene tether.

The generality of the RCM followed by a metallotropic [1,3]-shift was further demonstrated with various enediynes **18a–d** (Table 1) that provided efficient metallotropic [1,3]-shifted products **19a–d**.

The enyne RCM reactions of **20a–e** reported by van Otterlo and coworkers provided products **21a–e** (Table 2).[24] The authors proposed that an eneyne RCM product such as **21a′** was initially formed, which then underwent ethylene extrusion due to thermodynamic reasons *via* an unknown mechanism. However, considering that a product such as **21a′** has never been isolated even in trace amounts, it is unlikely that **21a′** was formed and completely transformed to **21a**. It is more reasonable to assume that the products **21a–e** were formed *via* the aforementioned mechanistic steps involving an RCM-metallotropic [1,3]-shift sequence.

To further expand the scope of the RCM-metallotropic [1,3]-shift sequence, Lee and Kim designed a substrate that can undergo repetitive ring-closing metathesis–metallotropic [1,3]-shift (M & M) process, which can lead to the formation of oligoenynes (Scheme 10). The projected M & M sequence resulted in a highly efficient sequential bond-forming process, producing a variety of oligoenynes **22a–g** in reasonably good yield (Fig. 4).[25]

Table 1 RCM-induced metallotropic [1,3]-shift

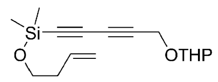
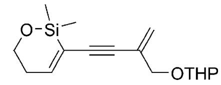
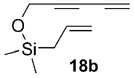
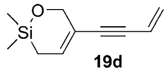
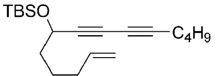
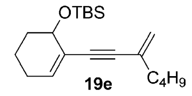
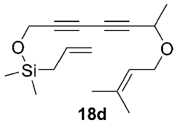
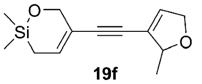
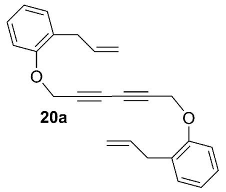
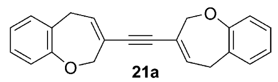
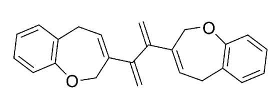
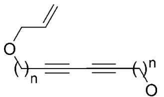
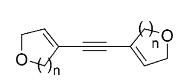
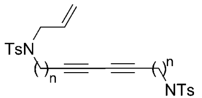
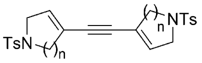
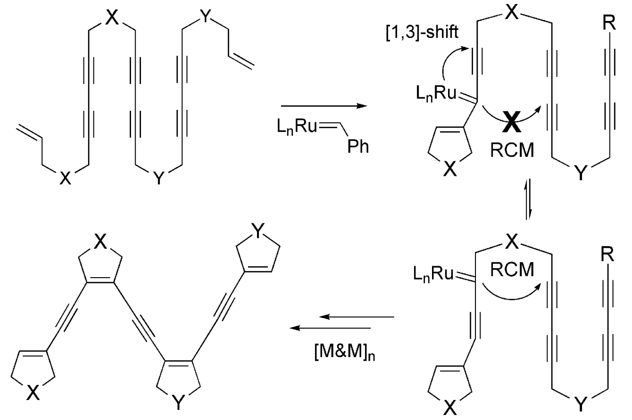
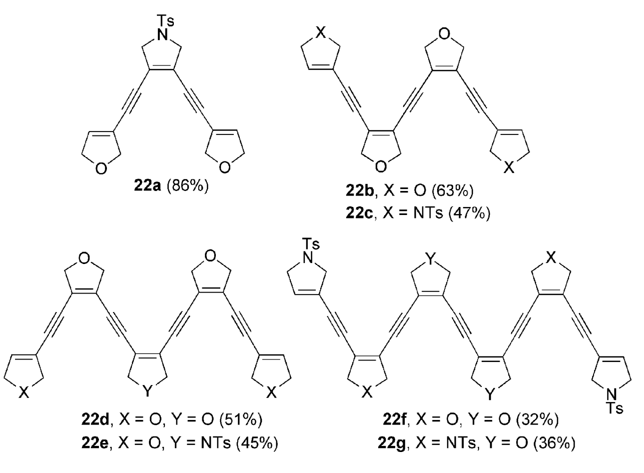
Enediyne	Product	Yield (%)
 **18a**	 **19b**	66
 **18b**	 **19d**	69
 **18c**	 **19e**	96
 **18d**	 **19f**	71

Table 2 van Otterlo's synthesis of bicyclic 1,5-diene-3-ynes

Dienediyne	Product	Yield (%)
 **20a**	 **21a**	54
	 **21a'**	0
 **20b** n = 1	 **21b** n = 1	88
20c n = 2	**21c** n = 2	58
 **20d** n = 1	 **21d** n = 1	32
20e n = 2	**21e** n = 2	53



Scheme 10 RCM and metallotropic [1,3]-shift (M & M).



22a (86%)

22b, X = O (63%)
22c, X = NTs (47%)

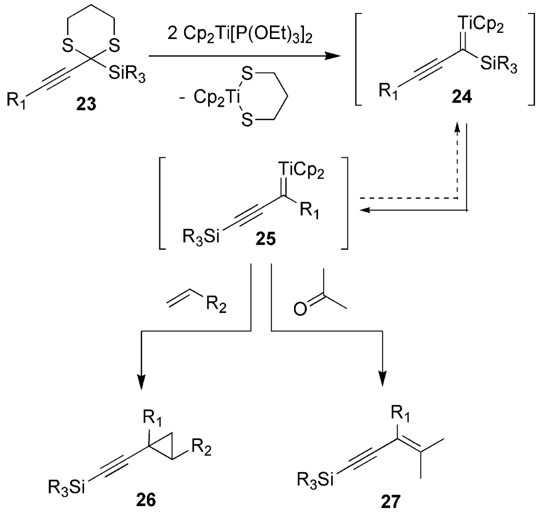
22d, X = O, Y = O (51%)
22e, X = O, Y = NTs (45%)

22f, X = O, Y = O (32%)
22g, X = NTs, Y = O (36%)

Fig. 4 Oligoenynes generated by M & M.

3.3. Ti-complex from titanation of thioacetals

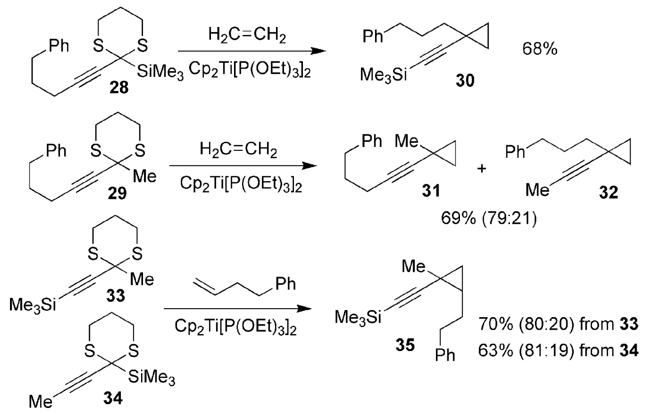
Takeda and coworkers utilized a thioacetal-titanocene(II) system to develop a range of transformations in which the active intermediate is assumed to be a titanium carbenoid.[26] Under these conditions, desulfurizative titanation of thioacetals and related organosulfur compounds with titanocene(II) reagent $Cp_2Ti[P(OEt)_3]_2$ could provide access to titanium carbenoids, which participate in various reactions such as cyclopropanation and carbonyl olefination. In particular, the reaction of thioacetal **23** with a bulky silyl group and a substituted alkyne moiety was expected to proceed *via* the less sterically encumbered titanium carbenoid **25** (Scheme 11).[27] The metallotropic [1,3]-shift of the initially formed carbenoid **24** would be driven by steric hindrance of the bulky silyl substituent in the carbenoid **24**.



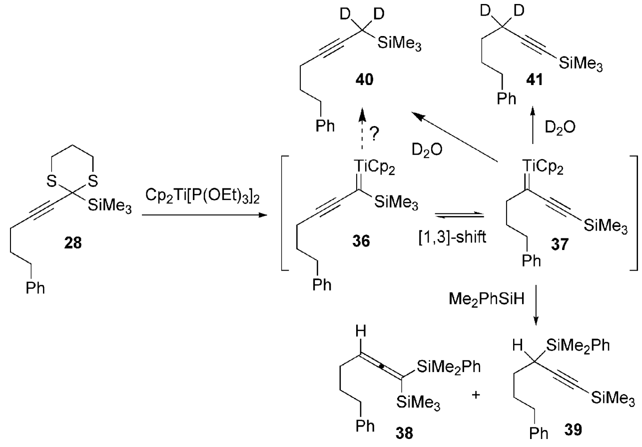
Scheme 11 Ti-alkylidenes and their metallotropic [1,3]-shift.

The titanocene-promoted cyclopropanation of silyl and methyl substituted thioacetals **28** and **29** was examined under ethylene. As expected, a single regioisomeric trimethylsilyl ethynyl substituted cyclopropane **30** was obtained in 68% yield from **28**, whereas a 79 : 21 mixture of regioisomeric alkynylcyclopropanes **31** and **32** was obtained from **29** in 61% yield in favor of the sterically less crowded cyclopropane. The cyclopropanation of regioisomeric acetylenic thioacetals **33** and **34** with 4-phenylbut-1-ene produced a single regioisomeric cyclopropane **35** with the same ratio of stereoisomers. These results indicate that regioselectivity of the cyclopropanation depends on the relative steric bulkiness of substituents on both sides of the alkynyl Ti-carbenoid (Scheme 12).

Mechanistically, cyclopropanation is assumed to proceed through a titanacyclobutane intermediate formed from a [2 + 2] cycloaddition between Ti-carbene and an alkene. Reductive elimination of titanium from this intermediate affords the observed cyclopropanes. To provide further evidence for the involvement of a metallotropic [1,3]-shift and the formation of trialkylsilylethynyl-substituted Ti-alkylidene **37**, an insertion reaction of this carbenoid with group 14 metal hydrides and deuteration reactions were explored (Scheme 13).[28] Desulfurizative titanation of **28** in the presence of dimethylphenylsilane produced propargylsilane **39** as a major product along with the allenylsilane **38**. It is apparent that these compounds are formed from trialkylsilylethynyl Ti-alkylidene **37** *via* [2 + 1] and [2 + 3] carbenoid insertion reactions. On the other hand, deuterium incorporation occurred from both alkylidenes to generate **40** and **41** in a 15 : 85 ratio. Although this result can be rationalized by the presumed sole intermediacy of **37**, another plausible explanation is that the products of these reactions are the consequence of the differential trapping rates of the alkylidene species **36** and **37** while they are undergoing rapid [1,3]-shifts.



Scheme 12 Reactivity and selectivity of substituted thioacetals.

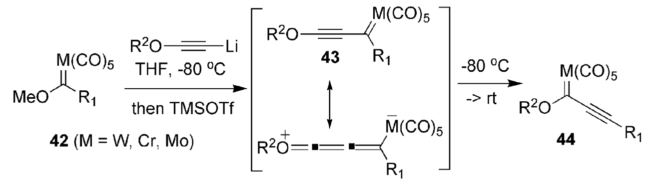


Scheme 13 Reactivity and selectivity of Ti-alkynylidenes.

3.4. Cr-, W-, Mo-Fischer carbene complexes

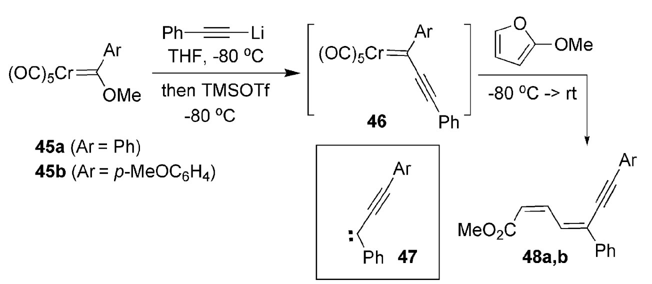
Since the discovery of a number of Fischer carbene complexes of group 6 metals, a variety of synthetic applications have been developed.[29] In the course of expanding the scope of Fischer carbene complexes to chiral alkynyl(alkoxy)carbenes,[30] Barluenga and coworkers reported the utilization of alkoxyacetylides.[31] This methodology did not just allow the easy implementation of the chiral alkoxy group to the metal carbene complexes but also provided an unprecedented example of [1,3]-migration of the metal center. Thus, when the carbene complex **42** was treated with an alkoxyethynyl lithium reagent, initially formed nonstabilized carbene **43** underwent rapid rearrangement, providing the more stable alkoxy carbene **44** as a final product (Scheme 14).

It was implied that the [1,3]-migration of the carbene center is an electronically controlled process for a given system. This facile process was not only applied to tungsten and chromium



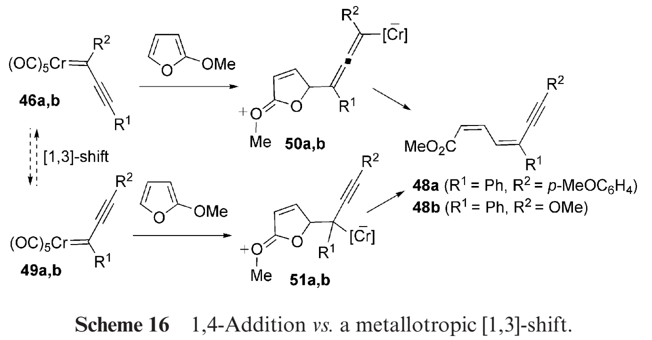
Scheme 14 Rearrangement of alkynyl carbenoids.

carbenes but also to a more elusive molybdenum carbene species. It is noteworthy that [1,3]-migration of metal carbene complexes was invoked as a possible pathway in a different type of reaction of alkynyl Fischer carbene complexes. Barluenga reported that metal alkynylcarbene complexes **45a**,**b** were synthetic equivalents of the electrophilic propargylcarbene species **47** (Scheme 15).[30] In this reaction, both stabilized and nonstabilized metal alkynyl carbene complexes **45a**,**b** were reacted with 2-oxyfurans. Olefination of these complexes gave the dienyne products **48a**,**b**, the formation of which involves a formal [1,2]-migration of the triple bond to give an overall regioselective olefination at C_β of the alkynylcarbene.

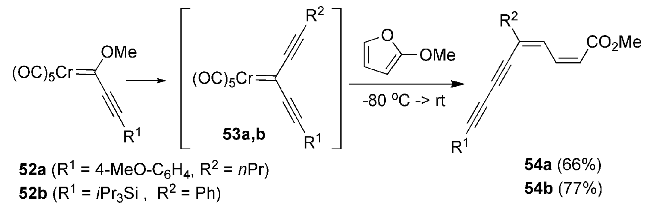


Scheme 15 Reactions of alkynyl Fischer carbene complexes.

The observed results were rationalized by a Michael-type addition of oxyfuran to the electron deficient alkynyl carbenes **46** to generate the zwitterionic allenyl intermediate **50**. Subsequent C–O bond cleavage by metal elimination regenerates the alkyne functionality conjugated to the (*Z*)-pentadienoate moiety. An alternative view invokes a [1,3]-$Cr(CO)_5$ shift to generate the rearranged metal carbene **49**, which undergoes 1,2-addition to form **51** followed by a ring-opening concomitant with metal elimination. The latter pathway seems less likely at least for the metal carbene **49b** (R^2 = OMe) due to its unfavorable equilibrium (Scheme 16). Expansion of the latter concept to more complex structures allows assessment of the ability of substituents to induce the [1,3]-carbene shift: substituent effects follow the order of alkyl > aryl > trialkylsilyl (Scheme 17).



Scheme 16 1,4-Addition *vs.* a metallotropic [1,3]-shift.

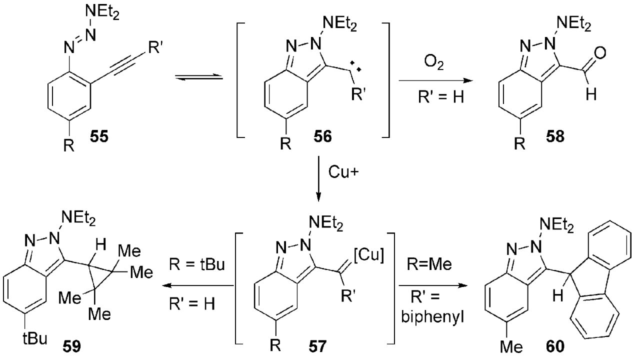


Scheme 17 Substituent effects on a [1,3]-carbene shift.

Product formation involving isomerization of the alkynyl moiety might not be a direct consequence of metal migration as alluded in the former mechanistic picture. However, as addressed by the authors, the metallotropic [1,3]-shift is a conceptually useful framework to view and design alkynyl carbene mediated reactions.

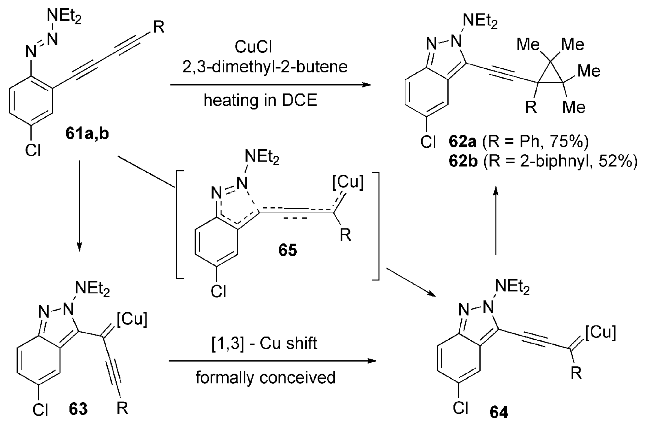
3.5. Cu-complex

Haley and co-workers reported the conversion of (2-ethynylphenyl)-triazenes into isoindazole aldehyde. Experimental and theoretical investigation led the authors to conclude that kinetic trapping of the reversibly formed carbene **56** intermediate with oxygen was responsible for the formation of the observed isoindazole aldehyde **58** (Scheme 18).[32] When copper salt was used as a catalyst, the carbene-mediated reaction manifold became more effective, generating products derived from typical carbene-mediated processes. Thus, use of a Cu-catalyst supports not only the involvement of carbene species but also provides a means to control chemoselectivity.[33]



Scheme 18 Reaction of isoindazolyl Cu-carbene complexes.

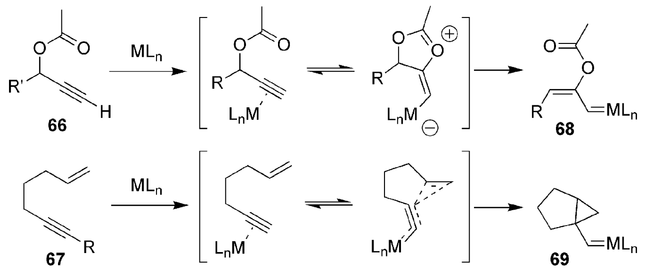
Having established a facile Cu-catalyzed cyclization of an azo-enyne substrate *via* isoindazolyl carbenoids, these authors pursued a sequential cyclization involving a [1,3]-shift of the Cu-carbenoid intermediate. Thus, the azo-enediyne compounds **61a** and **61b** were treated with CuCl in the presence of 2,3-dimethyl-2-butene. Upon heating in aprotic solvent, cyclopropane-containing products **62a** and **62b** were obtained in 75% and 52% yields, respectively.[34,35] The observed product formation can be rationalized by a sequence of events involving an initial formation of alkynyl carbenoid **63** followed by a [1,3]-shift to a more stable carbenoid **64** and its trapping by an external alkene. However, another plausible explanation involves electrophilic activation of the remote triple bond by coordination with CuCl to form an intermediate **65** with more extended electron delocalization. DFT-based computational study supported the latter resembling S_N2', which was calculated to have the lowest energy barrier (Scheme 19).[34]



Scheme 19 Cu-carbene complexes and their metallotropic [1,3]-shift.

3.6. Au-, Pt-, Ru-complex from diyne activation

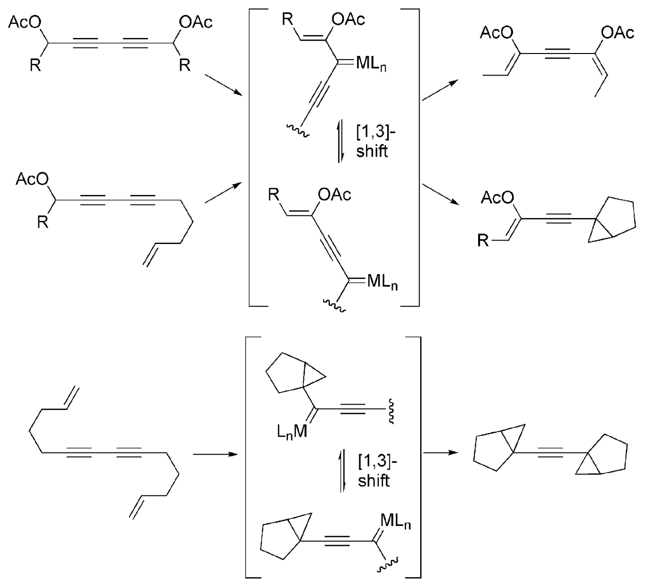
One of the most notable trends in metal-carbenoid chemistry is the use of triple bonds as a direct source of carbenes.[36] With the propargyl acetate **66** and the 1,6-enyne **67** shown to be valid precursors for carbenes **68** and **69**, respectively, under electrophilic metal catalysis (Scheme 20), substrates incorporating a 1,3-diyne could be envisaged for the generation of the alkynyl metal-carbene species and its [1,3]-shift. An alkyne moiety attached to the reacting alkyne of the propargyl carboxylate might be expected to behave as a controlling element for the formation of the requisite metal-carbenoid for the metallotropic [1,3]-shift (Scheme 21).



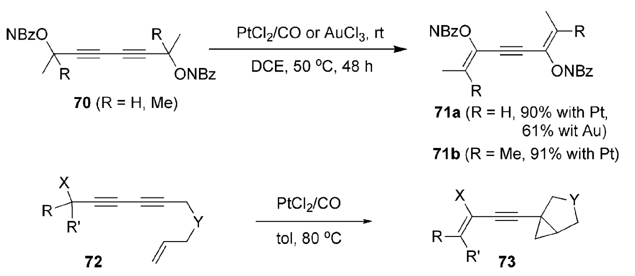
Scheme 20 Vinyl and cyclopropyl carbenoids generated from alkynes.

Recently, Lee and coworkers demonstrated an efficient metallotropic [1,3]-shift during bond reorganization of 1,3-diynes using platinum and gold catalysts.[37] The homo- and hetero-combinations of propargyl acetate and 6-heptene-1-yne moieties within the 1,3-diyne platform were employed for the formation of metal-alkylidenes followed by metallotropic [1,3]-shifts. Two salient reactivity features of these transformations are: acetate is a more reactive initiating functionality than the tethered alkene, generating [1,2]-acetate migrated alkylidene in the first step, and the tethered alkene is better than acetate as a terminating functionality to generate the cyclopropane moiety in the last step. Representative examples of three classes of 1,3-diyne rearrangement are depicted in Scheme 22.

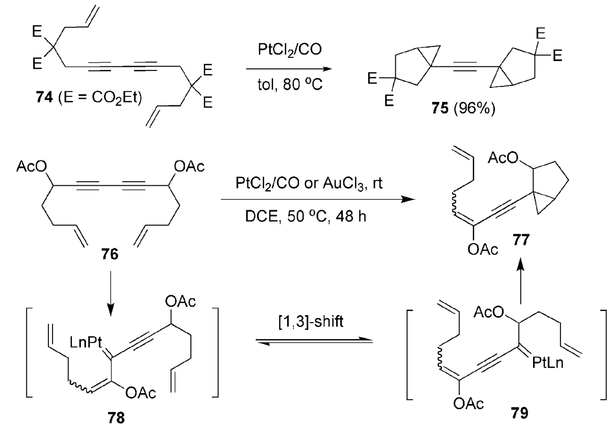
Ohe and co-workers also reported the Ru-catalyzed bond reorganization of 1,3-diynes.[38] They employed a 1,3-diyne **80** with propargylic acyl groups, which efficiently provided 1,5-dien-3-yne structure **81**. The bond reorganization and the stereochemistry of the product was rationalized to proceed *via* a metallotropic [1,3]-shift (**82** → **83**) as shown in Scheme 23.



Scheme 21 Formation of alkynyl carbene complexes from diynes and their metallotropic [1,3]-shifts.

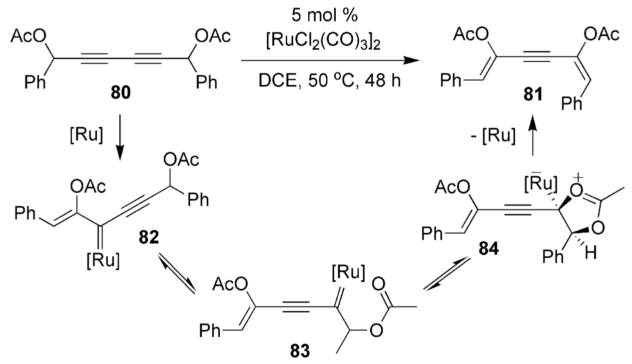


entry	72	X	R	R'	Y	yield of **73** (*E:Z*)
1	a	OAc	Me	H	C(CO$_2$Et)$_2$	67% (3.3:1)
2	b	OAc	Ph	H	C(CO$_2$Et)$_2$	92% (5.9:1)
3	c	OAc	Me	H	O	87% (2.7:1)
4	d	OAc	Me	H	NTs	46% (2.5:1)
5	e	ONBz	Me	Me	O	90%
6	f	ONBz	Me	Me	C(CO$_2$Et)$_2$	98%



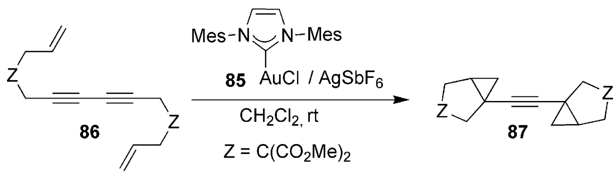
Scheme 22 Bond reorganization of 1,3-diynes Pt and Au.

An NHC-gold complex was employed by Echavarren and coworkers to induce the structural reorganization of **86** to **87** in 91% yield.[36] The authors invoked formation of an alkynyl Au-alkylidene intermediate followed by its metallotropic [1,3]-shift



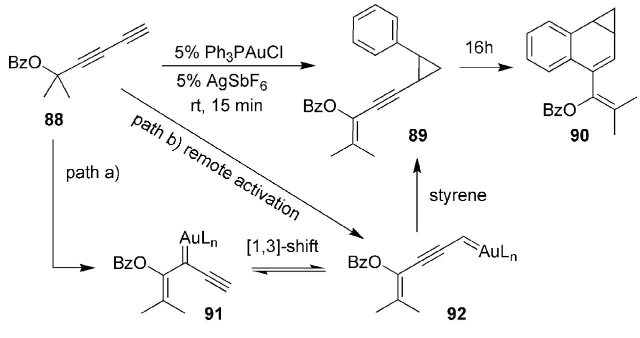
Scheme 23 Ohe's Ru-catalyzed bond reorganization of 1,3-diynes.

as the requisite steps for formation of the observed product (Scheme 24).



Scheme 24 NHC-gold complex-catalyzed bond reorganization.

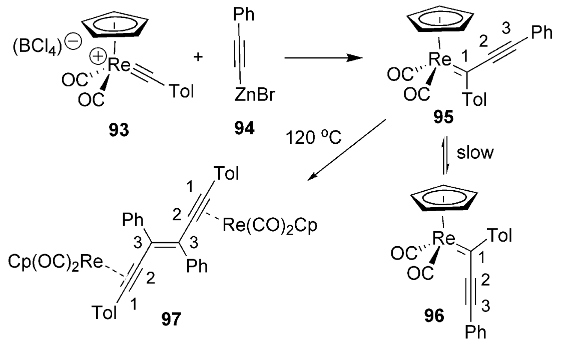
Toste and coworkers developed a tandem sequence for the synthesis of benzonorcardienes **90** by gold-catalyzed incorporation of the 1,3-diyne moiety **88** to styrene, where the enynyl cyclopropane **89** was observed as an isolable intermediate during the reaction course (Scheme 25).[39] Two pathways could be suggested for formation of the enynyl cyclopropane **89**. The first involves a metallotropic [1,3]-shift of the initially formed Au-carbene **91** to its regioisomeric intermediate **92** (path a). The second pathway proceeds *via* a cumulene intermediate derived from the coordination of cationic Au to the remote alkyne (path b).



Scheme 25 Toste's synthesis of benzonorcardiene.

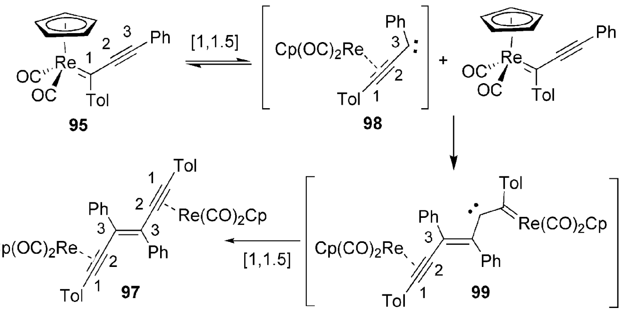
3.7. Mn-, Re-complex

The bond-shift behavior of alkynyl Mn- and Re-carbene complexes is slightly different from the typical metallotropic [1,3]-shift of other metal-carbenoids. However, the overall transformation results in product formation that always involves a formal [1,3] bond-shift of alkynyl carbenes. Casey and coworkers reported the dimerization of manganese and rhenium alkynyl carbene compexes.[40] The alkynyl Re-carbene complex **95** was prepared by addition of metal acetylide reagent **94** to the metal carbyne complex **93** and the mixture was heated at 120 °C in toluene (Scheme 26). They observed an unusual regioselective carbene-mediated dimerization at the remote alkyne carbon: a small amount of isomeric Re-carbene complex **96** resulting from [1.3]-migration was observable only spectroscopically.



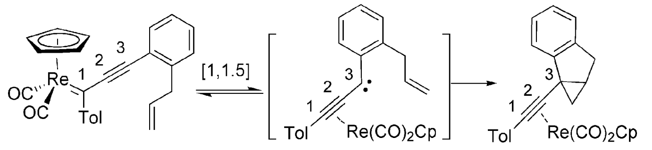
Scheme 26 Regioselective Re-carbene mediated dimerization.

The authors proposed a mechanism for the formation of the enediyne **97** invoking a [1,1.5]-shift of the rhenium moiety from C_1 of the carbene complex **95** to the midpoint between C_1 and C_2 of the resulting alkyne complex **98**. Thus, slow addition of the carbene center of the [1,1.5]-shifted carbene intermediate **98** to the C_3 center of another molecule of **95** generates a vinyl carbene intermediate **99**, which then undergoes another [1,1.5]-shift to give the final enediyne bis-Re-complex **97** (Scheme 27).



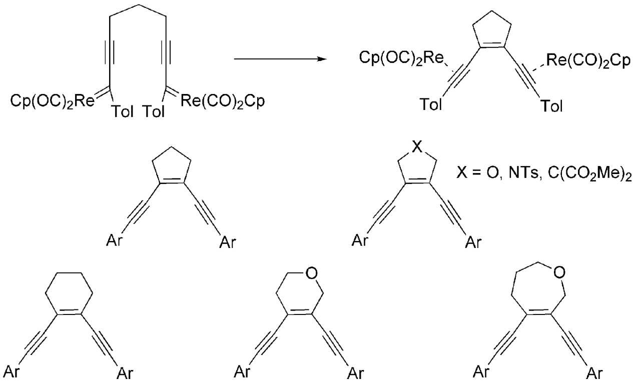
Scheme 27 Enediyne *via* [1,1.5]-Re shift.

The carbene character induced on the remote C_3 center of intermediate **98** was further verified by an intramolecular cyclopropanation with an alkene tethered to the C_3 position (Scheme 28).[41]



Scheme 28 η^2-Alkynyl Re-carbene complex from [1,1.5]-Re shift.

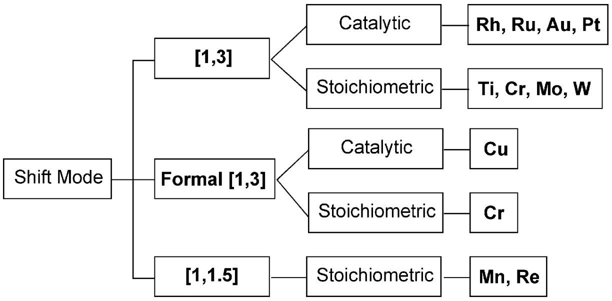
The synthetic utility of the [1,1.5]-shift of Re-carbene complexes was further demonstrated in the synthesis of various cyclic *cis*-enediynes (Scheme 29).[42]



Scheme 29 *cis*-Enediynes *via* dimerization of Re-carbenoids.

Conclusions

A survey of reactions involving various alkynyl metal carbenoids shows three characteristic reactivity patterns, which are graphically summarized in Scheme 30. Carbenoids generated by a catalytic amount of Rh-, Ru-, Au-, and Pt-complexes undergo facile [1,3]-shift at relatively low reaction temperatures. Similar bond shift behaviors were observed with Ti-, Cr-, W-, and Mo-carbenoids but they require a stoichiometric amount of the corresponding metal precursors. The Cu-catalyzed conversion of 1,3-diyne presursors to isoindazoles is considered to be a formal [1,3]-shift process because an alternative reaction that does not involve a [1,3]-shift was found to be a lower energy pathway. Also, the addition process of alkynyl Cr-carbenoids to 2-oxyfurans can be described under the framework of [1,3]-shift, although 1,4-addition is actually involved. Compared to a typical [1,3]-shift, the bond shift behaviors of Mn- and Re-complexes are viewed as [1,1.5]-shift. Only stoichiometic reactions involving these two carbenoids are reported.



Scheme 30 Comparison of various alkynyl carbenoids.

The emerging diversity in structure and reactivity of alkynyl carbenoids has promoted an increasing number of synthetic and mechanistic studies. Insights into the reactivity of different types of metal-stabilized alkynyl carbenoids from these studies will enable the designs of a host of new substrates of conceptual and practical interests. The metallotropic shift process allows for sequential bond-forming events leading to the efficient construction of multiply unsaturated complex molecular structures. Further spectroscopic, crystallographic, and computational studies are necessary to get a more accurate picture of the metallotropic [1,3]-shift and to characterize intermediates in the rearrangement process.

Direct application of the metallotropic [1,3]-shift in natural product synthesis is yet to be seen but its capacity to change and increase molecular complexity bodes well for its synthetic utility. Especially, enediyens and enynes, readily constructed by alkynyl metal carbenoids undergoing metallotropic [1,3]-shift, are substructures in many biologically important natural products as well as polymeric materials such as polydiacetylenes. Therefore, discovering the right match between alkynyl substrates and metal complexes that generate reactive yet selective alkynyl carbenoids will be one of the highest priorities in the field.

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