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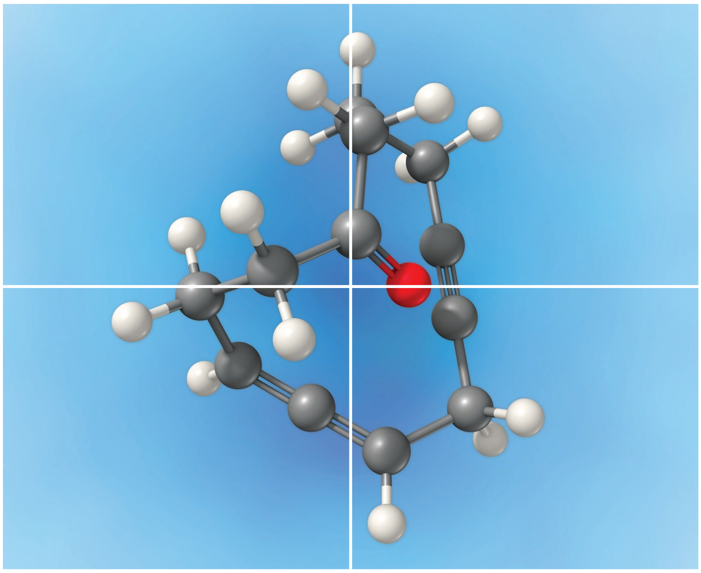

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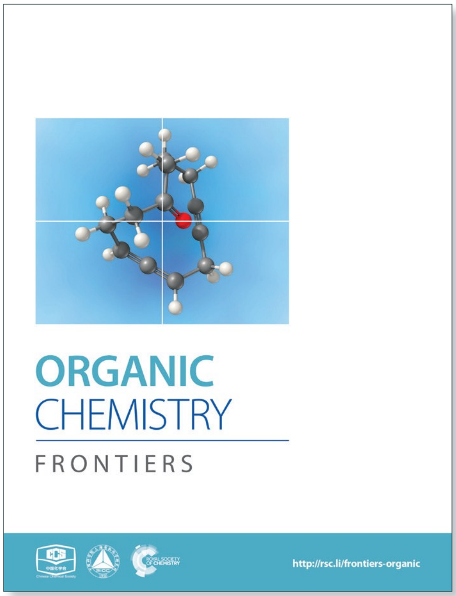

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ARTICLE

Beyond Fischer and Schrock Carbenes: Non-Heteroatom-Stabilized Group 6 Metal Carbene Complexes – A General Overview†

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Non-heteroatom-stabilized group 6 metal carbene complexes are a particular type of Fischer carbene complexes lacking the stabilizing heteroatom. The aim of this review is to provide a comprehensive overview of the usefulness of these organometallic reagents in organic synthesis. Thus, the diverse methodologies that have been developed for their synthesis are initially disclosed, followed by their reactivity. In this regard, their decisive role in early days of alkene metathesis and cyclopropanation and enyne metathesis is pointed out, as well as their participation in insertion reactions. However, the major part of the review highlights recent achievements in both stoichiometric and catalytic processes, which have led to the synthesis of structurally diverse carbo- and heterocycles, acyclic compounds, and even metal carbene complexes of other groups by transmetallation reactions.

1. Introduction.

A carbene complex can be defined as the organometallic species made up by the formal combination of a carbene and a metallic fragment. Some carbene complexes of metals of several groups in the periodic table are stable at room temperature and have been synthesized and employed as reagents or catalysts in many synthetic transformations. On the opposite, some others, less stable, have been just proposed, detected or, sometimes, isolated as synthetic intermediates. Although alkylidene complexes of group 6 metals in several oxidation states (0, +2, +4, +6) are known, carbene complexes are typically divided into two major categories:

a) *Schrock-type carbene complexes or Schrock carbenes*. In these carbenes the metal is in high oxidation state, they are nucleophilic in nature (the carbon atom of the carbene possesses negative charge) and have a short M–C-carbene bond.[1] The nucleophilicity of these compounds derives from the dominant orbital interactions between both a metal and a carbene in a triplet state (Figure 1).[2] The most relevant carbene complexes of this type are Mo(VI)– or W(VI)–based carbenes **1** (Figure 2). Indeed, despite their sensitivity to air and moisture, that forces to their handling under strict inert conditions (glove-box or by Schlenk techniques), molybdenum alkylidenes are amongst the most powerful olefin metathesis catalysts known to date. They are usually referred as Schrock catalysts or Schrock alkylidenes and, for instance, Schrock catalyst **4** or Schrock-Hoveyda catalyst **5** (Figure 2) are widely employed and commercially available.

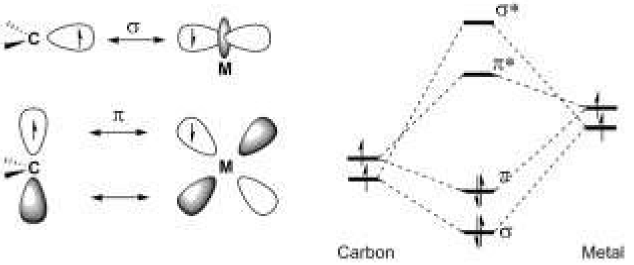


Figure 1 Dominant orbital interactions and bonding in Schrock-type carbene complexes.

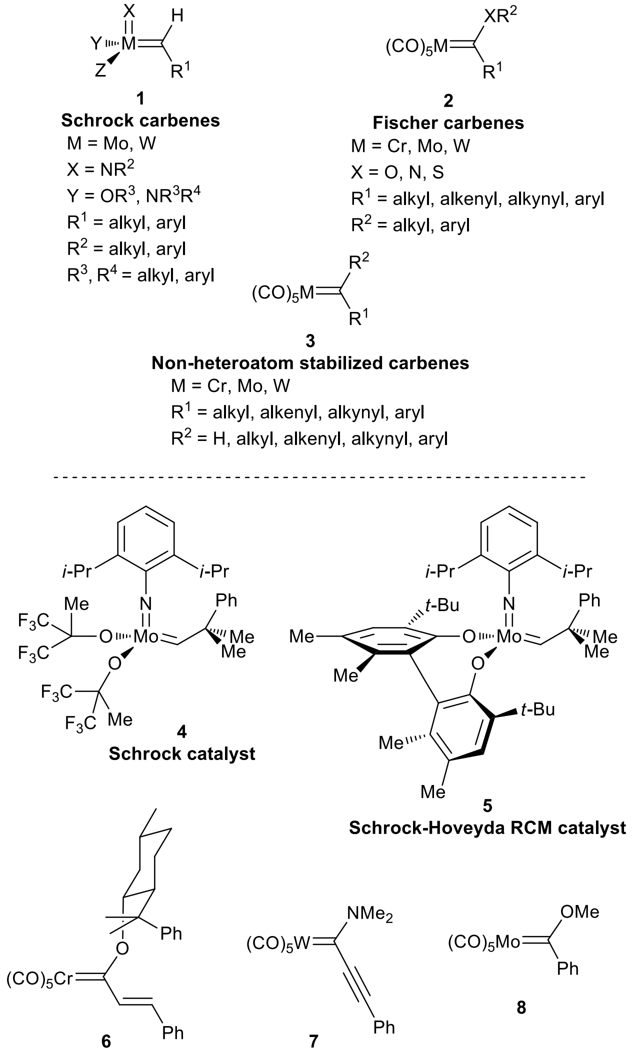


Figure 2 Group 6 metal carbene complexes: general structure and representative examples.

b) *Fischer-type carbene complexes or Fischer carbenes*. In contrast, for this type of carbene complexes the metal is in low oxidation state –usually they are metal(0) complexes–, they have a much longer M–C-carbene bond than the high-valent complexes, and the pair of electrons in the π-bonding MO resides mainly on the metal. In this case, the bond is explained as an interaction between a carbene carbon in a singlet state with σ-donation from the carbene ligand to the metal and π-back donation from the metal to the ligand (Figure 3).[2,3] This fact has the effect of generating a positive charge on the carbon atom and, as a result, they are: (1) electrophilic in nature and (2) stabilized due to the presence of an electron-donating heteroatom linked to the carbene carbon. They are highly valuable reagents in synthetic organic chemistry. Indeed, de Meijere coined the expression "chemical multitalents" to label these versatile complexes,[4] as they have displayed several patterns of reactivity which led to the construction of a large variety of highly functionalized structures in a regio- and stereoselective manner.[5] Usually they are employed as stoichiometric reagents, although they have occasionally been proposed as reactive intermediates in catalytic cycles.[6] Because of their balance of reactivity and stability combined with easy accessibility, chromium complexes have found, by far, the broadest application of group 6 Fischer carbenes. A possible reason lies in the fact that they are more prone to carbonyl insertion than their tungsten or molybdenum analogues, due mainly to the differences in metal-CO strength through backbonding. The general formula for Fischer carbenes **2** and, among them, several representative examples are depicted in Figure 2, including: (1) an alkoxy alkenylcarbene chromium complex bearing a chiral auxiliary **6**, (2) an amino alkynylcarbene tungsten complex **7**, and (3) an alkoxy arylcarbene molybdenum complex **8**.

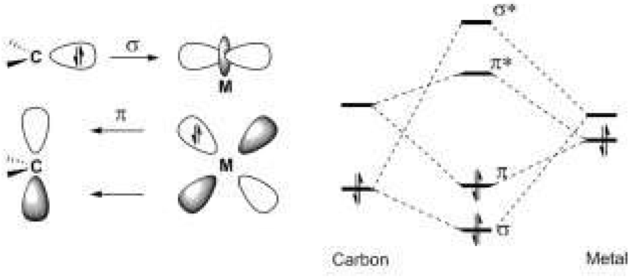


Figure 3 Dominant orbital interactions and bonding in Fischer-type carbene complexes.

Non-heteroatom-stabilized carbene complexes **3** (Figure 2) are a particular type of Fischer carbene complexes lacking the stabilizing hetereoatom. Therefore, they are low valent metal carbenes and electrophilic in nature; however, they have received much less attention mainly due to their low stability, particularly those having hydrogen at the carbene carbon. Although they have been frequently used as stoichiometric reagents, seminal contributions to the development of organic chemistry (i.e. alkene metathesis, enyne metathesis) as well as more recent transformations have arisen either from their employment as catalysts or by adopting a role as intermediates in catalytic processes.

The chemistry of non-heteroatom-stabilized carbene complexes has been partially reviewed[5a,7] but a comprehensive manuscript covering all aspects of their rich chemistry has not been published to date. In this manuscript, even though a chronologic line will not be strictly followed, an historical perspective will be used as starting point to outline the developed methods of synthesis for these carbene complexes. Then, their different synthetic applications will be disclosed, ranging from their useful participation and their tremendous impact in early days of alkene metathesis to the state of the art which includes the synthesis of structurally complex compounds under stoichiometric or catalytic conditions, and their role in multicomponent reactions, or as precursors to carbene complexes of other metals by transmetallation reactions.

Usually, the stabilizing heteroatom in Fischer carbene complexes is directly linked to the carbene carbon. However, vinylogous stabilization occurs when a double bond is placed between the heteroatom and the carbene.[8] Remoted *N*-heterocyclic carbene complexes (*r*NHCs) can also be included in this family.[9] Thus, although the carbene carbon is linked to two carbon moieties, they behave as stabilized carbenes and therefore, cases of vinylogous stabilization or *r*NHCs will not be treated in this review.

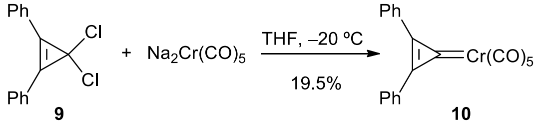
On the other hand, in a similar manner, arylogous stabilization occurs when an arene is placed between the heteroatom and the carbene carbon; these cases are scarcer than the vinylogous stabilization ones and have indeed been included in this review, mainly for the sake of comparison (i.e., for instance, to point out the striking differences between carbenes with two phenyl or two *p*-anisyl substituents).

2. Synthesis and stability.

The synthetic methods for non-heteroatom-stabilized carbene complexes fall into four strategies, as follows:

2.1 Reaction of a *gem*-dichlorocompound with sodium pentacarbonylchromate.

This approach was employed by Öfele to synthesize pentacarbonyl(2,3-diphenylcyclopropenylidene)chromium(0) **10** which was the first group 6 metal non-heteroatom-stabilized carbene complex prepared; it was isolated in 19.5% yield by treating 1,1-dichloro-2,3-diphenylcyclopropene **9** with sodium pentacarbonylchromate in THF at –20 ºC (Scheme 1). Carbene complex **10** was described as astonishingly stable, due to the aromaticity of the cyclopropenyl carbene moiety: thus, it is a solid stable to air, decomposes above 192 ºC in an inert atmosphere, and can be sublimed at 110 ºC in vacuum without decomposition.[10]

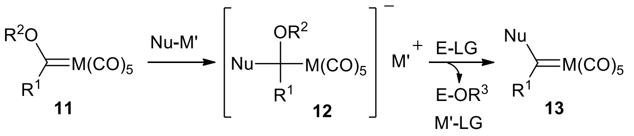


9 **10**

Scheme 1 Synthesis of pentacarbonyl(2,3-diphenylcyclopropenylidene)chromium(0) **10**.

2.2 Nucleophilic substitution of Fischer alkoxy carbene complexes.

The nucleophilic substitution is a well known reaction in the chemistry of heteroatom-stabilized Fischer carbene complexes; it is particularly useful as a procedure to synthesize a new stabilized carbene complex from a pre-existing one by addition an heteroatom nucleophile (alcohol, amine, thiol). This approach has been by far the most employed strategy for the synthesis of group 6 non-heteroatom-stabilized carbene complexes. Organolithium reagents, metal hydride complexes or enamines have been the nucleophiles employed. The reactions presumably proceed via nucleophilic addition to starting Fischer alkoxy carbene complex **11** leading to tetrahedral intermediate **12**, which upon addition of the electrophile evolves with elimination of the E-OR^3 moiety to generate non-heteroatom-stabilized carbene complex **13** (Scheme 2).



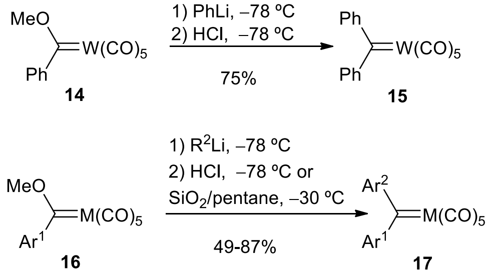
11 **12** **13**

Nu-M' = R^{3}Li, M"HB(OR$_3$)
Nu = R^3, H
E-LG = HCl, TFA, MeOTf, TMSOTf
E = H, Me, TMS

Scheme 2 General strategy for the synthesis of non-heteroatom-stabilized carbene complexes via nucleophilic addition to Fischer alkoxy carbene complexes.

2.2.1 Initiated by nucleophilic addition of organolithium reagents to Fischer carbene complexes.

Casey[11,12] was able to synthesize pentacarbonyl(diphenylmethylene)tungsten(0) **15** by adding phenyllithium to a solution of methoxy phenyl(methylene)tungsten(0) **14** (Scheme 3). In a similar manner, symmetrical and unsymmetrical diaryl (or heteroaryl) carbene complexes of chromium or tungsten **17** (Ar^1, Ar^2 = aryl, heteroaryl) were prepared by Casey[13] and Fischer[14] by adding aryl or heteroaryllithium compounds to methoxy aryl (or heteroaryl) carbene complexes **16**.



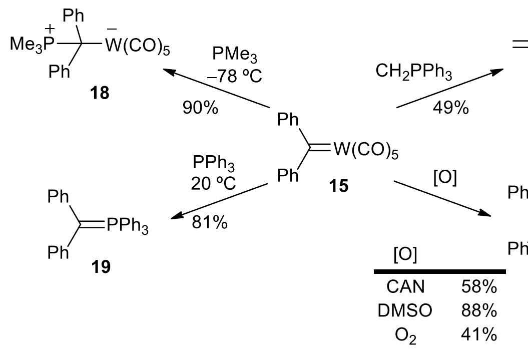
14 **15** **16** **17**

M = Cr, W
Ar^1 = Ph, *p*-Tol, 2-Furyl, 2-Thienyl
Ar^2 = Ph, *p*-Tol, *p*-CF$_3$-C$_6$H$_4$, 2-Furyl, 2-Thienyl, *N*-Me-Pyrrol-2-yl

Scheme 3 Synthesis of non-heteroatom-stabilized diaryl carbene complexes.

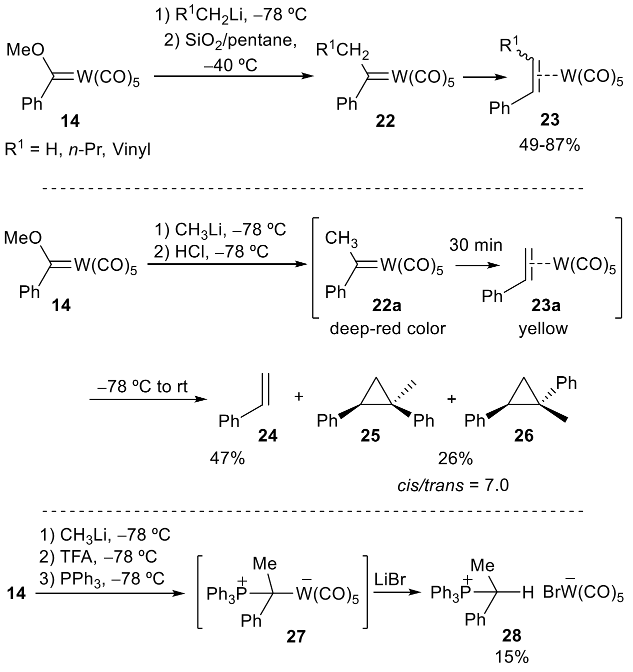
On the one hand, carbenes **17** are moderately air-stable solids although more thermally labile than their methoxy aryl (or heteroaryl) carbene complexes precursors **16**. For instance, thermal decomposition of pentacarbonyl(diphenylmethylidene) tungsten (0) **15** in heptane was complete in less than 2 hours at 100 ºC leading to W(CO)$_6$, diphenylmethane and tetraphenylethylene.[11a] On the other hand, the metal plays an important role in the stability of the carbene complex; thus, chromium carbene complexes are more labile than their analogous tungsten ones.[14]

Evidence for formation of carbene complexes was also obtained by several methods, as shown in Scheme 4 for carbene complex **15**: i) by trapping phosphine adducts **18**,**19** formed by its reaction with phosphines,[11b,15] ii) by oxidation to the corresponding carbonyl compounds, such as **20**, either with cerium ammonium nitrate (CAN), dimethyl sulfoxide (DMSO) or oxygen,[11b] iii) by methylenation with methylenetrimethylphosporane leading to 1,1-diphenylethylene **21**,[11b] or iv) by thermolysis (*vide supra*).[11b]



Scheme 4 Chemical evidences of carbene complex **15**.

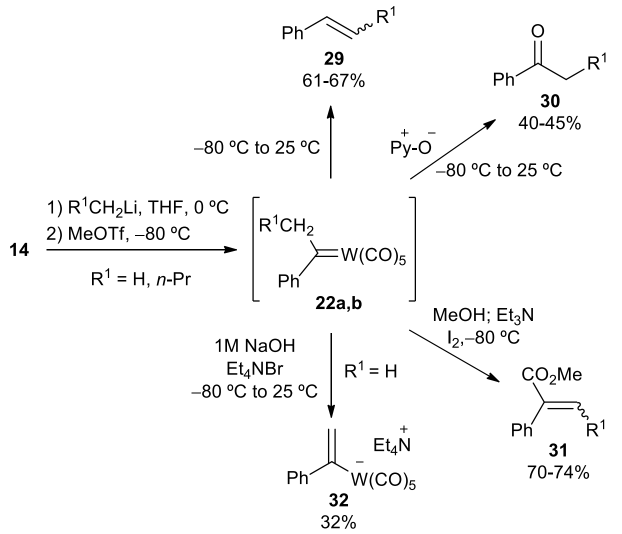
The formation of aryl alkyl carbene metal(0) complexes is more problematic as they are highly unstable and can be prepared but not isolated. After addition of alkyllithium to solutions of methoxy phenyl(methylidene)tungsten(0) **14** at –78 ºC followed by treatment with silica gel, a brown (or deep red) colour was observed that was attributed to the formation of the desired aryl alkyl carbene metal(0) complexes **22** (Scheme 5). However, it lightened into yellow under the low temperature reaction conditions leading to formation of pentacarbonyl π-olefin tungsten(0) complexes **23**, which could be isolated (Scheme 5; *top*).[16]



Scheme 5 Synthesis, stability and chemical evidences of formation of alkyl aryl carbene complexes.

Casey was also able to generate phenylethylidenecarbene complex **22a** by successive addition of methyllithium and HCl to methoxy phenyl(methylene)tungsten(0) **14** at –78 ºC but the deep red colour attributable to **22a** faded within 30 min at that temperature. Warming the reaction mixture to room temperature led to styrene **24** (47%) and *cis*- and *trans*-1-methyl-1,2-diphenylcyclopropane **25,26** (26%, in a *cis*/*trans* ratio of 7.0) formation (Scheme 5; *middle*). It was also demonstrated that the cyclopropane mixture did not result by direct cyclopropanation of styrene but it involved two different tungsten organometallic species.[17] Chemical evidence for the formation of carbene complex **22a** (R^1 = H) was achieved by reaction with PPh$_3$ to generate its phosphine adduct **27**, which was transformed into isolable tungsten complex **28** (Scheme 5; *bottom*).

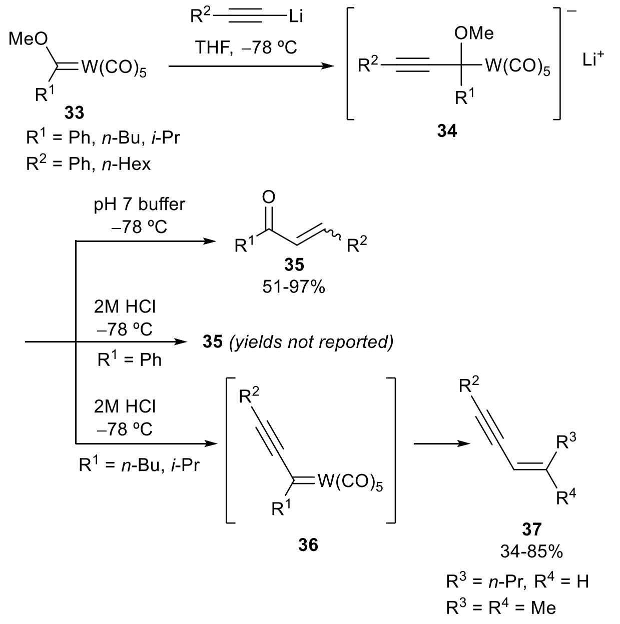
More recently, Barluenga generated non-heteroatom-stabilized tungsten carbene complexes **22a,b**, by adding methyl triflate at –80 °C to the lithium tungstate formed after treating **14** with alkyllithium species (R^1 = H, *n*-Pr), (Scheme 6).[18] As expected, non-stabilized carbene complexes **22a,b** could not be isolated nor characterized but they evolve to (i) furnish alkenes **29** when allowed to reach room temperature (61-67% yield, *E*:*Z* = 1:1) through 1,2-hydrogen migration and β-elimination reactions, (ii) afford phenones **30** (40-45% yield) when oxidized with pyridine oxide at –80 °C, (iii) produce methyl 2-phenylalkenoates **31** (70-74% yield, *E*:*Z* = 1:5), when treated under Iwasawa methoxycarbonylation conditions,[19] and (iv) give the stable tetraethylammonium alkenyltungstate **32** (R^1 = H, 32% yield), which was fully characterized, when allowed to reach room temperature in the presence of aqueous 1 M NaOH/Et$_4$NBr.



Scheme 6 Derivatization of alkyl phenyl tungsten carbene complexes **22**.

Iwasawa has pioneered the reaction of alkynyllithium species with Fischer tungsten carbene complexes **33**. Smooth addition took place at –78 ºC leading presumably to tetrahedral intermediate **34**, whose evolution depended on both reaction conditions and nature of R^1 carbene substituent[20] (Scheme 7). On the one hand, neutral aqueous workup followed by mild acid treatment led to enones **35**; on the other hand, acidic workup with

2M HCl or TFA produced enynes **37** in moderate to good yields, presumably via non-heteroatom-stabilized carbene complexes **36**, when R^1 bears acidic hydrogen atoms (R^1 = *i*-Pr, *n*-Bu). Alternatively, enones **35** are the major products, even under acidic conditions, when the β-elimination reaction cannot take place (R^1 = Ph).

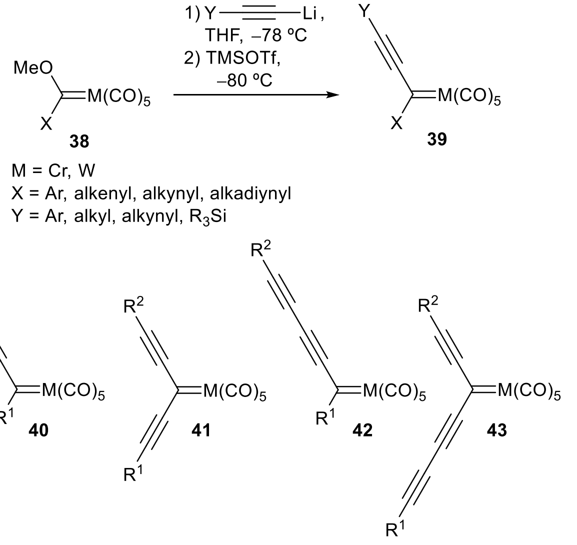


Scheme 7 Synthesis of non-heteroatom-stabilized alkynyl tungsten carbene complexes **36**.

Therefore, alkynyllithium addition is preferred to deprotonation even in cases of primary alkyl-substituted carbene complexes. Moreover, from these results it seems obvious that the use of alkynyllithium reagents is essential for the success of the addition reaction: carbene complexes **33** were recovered and no addition products formed when phenyllithium or *n*-octyllithium was employed.

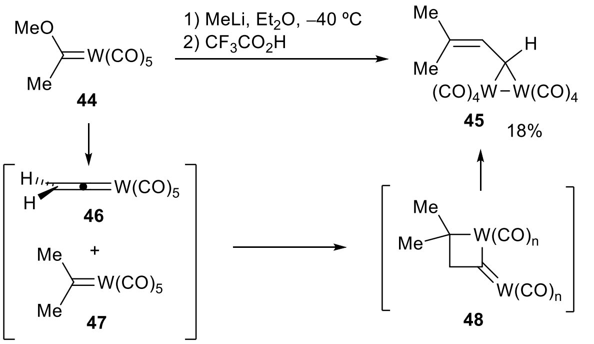
Following such pioneering work, Barluenga generated a plethora of chromium or tungsten non-heteroatom-stabilized alkynyl carbene complexes **39** at low temperature in THF, by sequential treatment of alkoxycarbene complexes **38** with various lithium acetylides and trimethylsilyl triflate (TMSOTf) at –80 ºC (Scheme 8).[21] In these transformations the change of colour is usually a good indicator of how the reaction was proceeding. For instance, once the addition of lithium phenylacetylide was completed the colour of the solution changed from orange or red to yellow. Then, after addition of TMSOTf, the solution suffers an instantaneous colour change, usually to deep blue. The presumed formation of alkynyl carbene complex by elimination of methyl trimethylsilyl ether from the tetrahedral addition species should account for the observed colour change.

Metal carbene scaffolds prepared this way are outlined in Scheme 8, and they have been classified according to the number of ethyne units in the dimer precursors: i) alkynyl carbene complexes **40**, ii) cross-conjugated diynyl carbene complexes **41**, iii) linear-conjugated diynyl carbene complexes **42**, and iv) cross-conjugated triynyl carbene complexes **43**.[22] The structure of these non-heteroatom-stabilized carbene complexes was unambiguously stablished by X-ray analysis of a chromium alkynyl and a tungsten cross-conjugated diynyl carbene complexes.



Scheme 8 Synthesis of non-heteroatom-stabilized alkynyl metal carbene complexes.

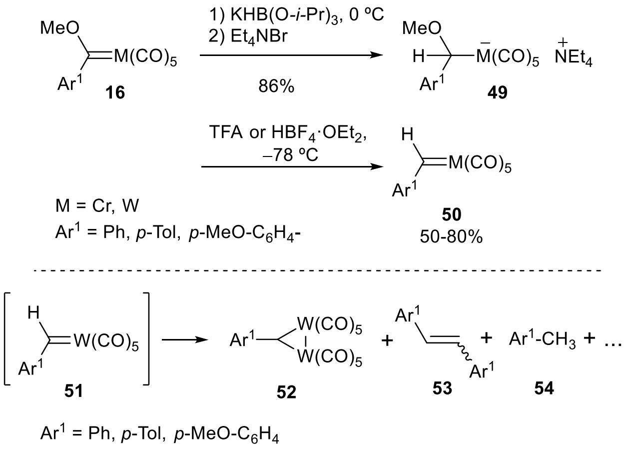
The formation of group 6 metal dialkyl carbene complexes remains rather elusive due to their high instability. Thus, the addition of methyllithium to 1-methoxyethylidene(pentacarbonyl)tungsten **44** resulted in the isolation of three-membered cyclic bimetallic compound **45**.[23] Its formation is proposed to proceed by [2+2]-cycloaddition between two intermediate tungsten complexes (ethynylidene **46** and pentacarbonyl dimethyl carbene complex **47**) leading to a four-membered tungstenacycle **48**, which should evolve into the final product (Scheme 9). Regarding the purpose of this review, dimethyl carbene tungsten complex **47** has been proposed as an intermediate but it could not be isolated nor detected.



Scheme 9 Reaction of MeLi with methoxy methyl tungsten carbene complex **44**.

2.2.2. Initiated by nucleophilic addition of borohydrides to Fischer carbene complexes.

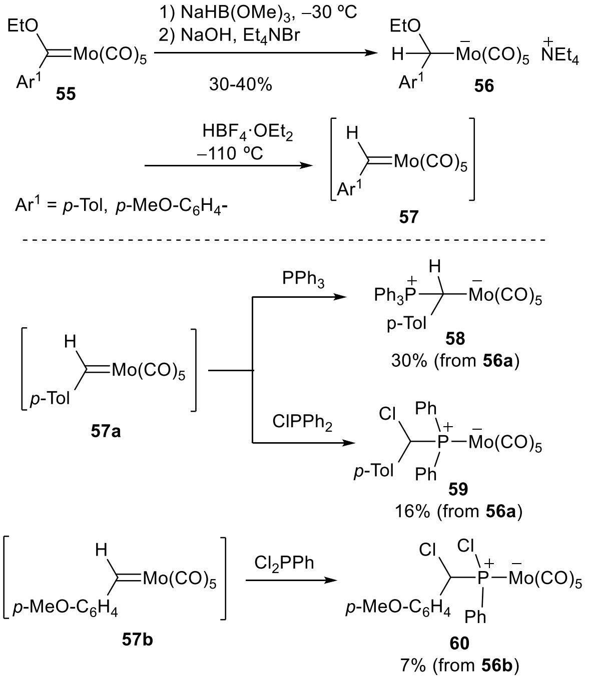
The rapid decomposition of alkyl aryl complexes via β-hydride elimination prompted Casey[24] and Fischer[25] to prepare benzylidene(pentacarbonyl)tungsten(0) and –chromium(0) complexes **50**. The sequential procedure involves hydride reduction of stabilized carbene complexes **16** with KHB(O-*i*-Pr)$_3$ in THF at 0 ºC followed by counter-ion exchange by addition of tetraethylammonium bromide to form tetraethylammonium derivatives **49**, which, although moderately air-sensitive, can be isolated. Then, addition of TFA or $HBF_4{\cdot}OEt_2$ at –78 ºC leads to a deep red coloured solution which suggests the formation of carbene complexes **50** in a quantitative manner. Some carbenes can be purified by column chromatography at –70 ºC, followed by recrystallization to form dark-red, almost black crystals (Scheme 10; *top*).



Scheme 10 Synthesis, characterization and decomposition of chromium and tungsten benzylidene complexes.

Thermal stabilities of complexes **50** are strongly influenced by the nature of substituent R^1 and the metal. Thus, for tungsten carbenes **51**, *p*-anisyl derivative (**51b**, Ar^1 = *p*-MeO-C_6H_4) can be handled at room temperature for short periods of time; for phenyl derivative (**51a**, Ar^1 = Ph), the colour in solution stands for several hours at –78 ºC fading to light orange upon warming to 0 ºC, or decomposes at –56 ºC or 20 ºC in solution with a half-life of *ca.* 24 min (–56 ºC) or 2 min (20 ºC), *trans*-stilbene being the major organic product observed by GC. Therefore, as expected, benzylidene complex **51a** is more stable than methylphenyl carbene tungsten complex **22a**. Besides *cis* and *trans*-stilbenes **53**, other compounds detected in thermolysis of carbene complexes **51** include red-brown μ-benzylidenebis(pentacarbonyl)tungsten complexes **52** and the corresponding *p*-substituted toluene derivatives **54** (Scheme 10; *bottom*).

In a similar manner, benzylidene complexes of molybdenum **57** were prepared by abstraction of the ethoxy group of pentacarbonyl(α-ethoxybenzyl)molybdates **56** with $HBF_4{\cdot}OEt_2$. Carbene complexes **57** are thermally very labile, and react rapidly with nucleophiles even at –100 ºC (Scheme 11). For instance, they can be trapped with phosphines to form zwitterionic adducts such as **58-60**.[26]

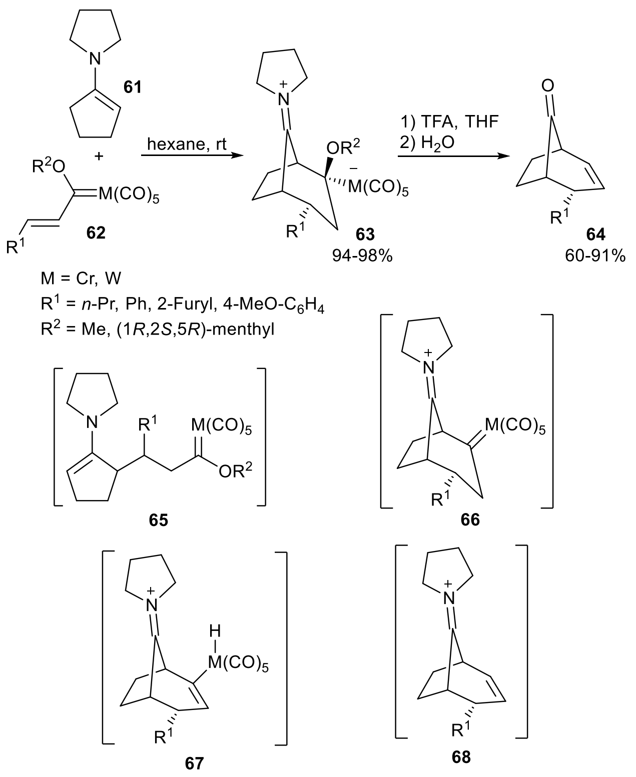


Scheme 11 Synthesis and chemical characterization of molybenum benzylidene complexes **57**.

2.2.3 Initiated by nucleophilic addition of enamines to Fischer alkoxy alkenyl carbene complexes.

Zwitterionic metallate complexes **63** are isolated in excellent yields when Fischer alkenyl carbene complexes **62** and enamines **61** are mixed in hexane at room temperature.[18] Its formation has been rationalized in terms of a 1,4-addition of the Cα-enamine to the electrophilic alkenyl carbene complex to produce Michael adduct **65**, followed by enamine 1,2-addition to the carbene moiety. A sequence involving TFA treatment of **63** at 0 ºC and hydrolysis led to [3+3]-cycloadducts **64** in good to excellent yields via non-heteroatom-stabilized carbene species **66**, generated by R^{2}OH elimination on **63** (Scheme 12). Dry acids (TFA, and HBF_4) were also effective for such transformation.

Compounds **66** are the only examples of group 6 dialkyl carbene complexes reported to date. Although not isolated, tungsten carbene complexes **66a,b** (M = W, R^1 = Ph, 2-Furyl) were generated from the corresponding zwitterionic metallate complexes **63a,b** and characterized by ^{13}C NMR. Complexes **66a,b** are fairly stable at –80 ºC; however, they decompose above –70 ºC to imonium salts **68** in a quantitatively manner, via carbon-to-metal hydrogen shift to species **67** followed by metal elimination. Imonium salts **68** have not been isolated but hydrolysed to 8-bicyclo[3.2.1]octanones **64**.

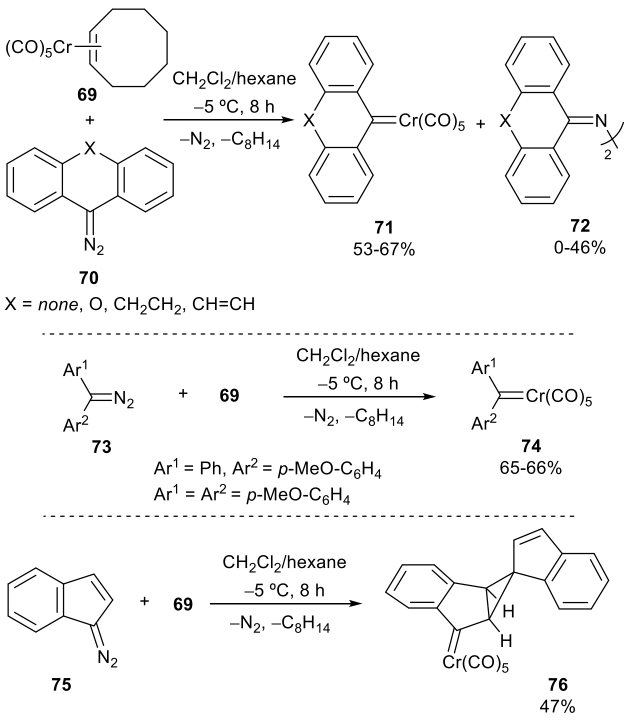


Scheme 12 Non-heteroatom-stabilized metal carbenes by the reaction between alkenyl carbene complexes and enamines.

2.3. Synthesis from diazocompounds with pentacarbonyl(η^2-*cis*-cyclooctene)chromium(0).

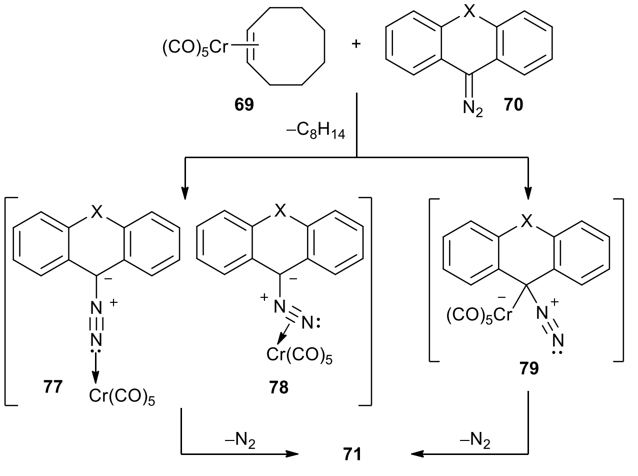
Diaryl carbene complexes of chromium can be synthesized by reaction of diaryl diazo compounds **70** with η^2-*cis*-cyclooctene (pentacarbonyl)chromium(0) **69** in mixtures of dichloromethane/hexane at –5 ºC for 8 h. Crystallization at –78 ºC followed by chromatographic work-up led to the desired carbene complexes **71** in moderate to good yields, along with the corresponding azines **72** (Scheme 13; *top*). Interestingly, carbene complex **71a** (X = O) is stable under inert gas at room temperature due to vinylogous resonance stabilization while other derivatives decompose above –20 ºC.[27]

Unbridged diaryl diazo compounds **73** also provided good yields of non-heteroatom-stabilized diaryl chromium carbene complexes **74** under the optimized reaction conditions (Scheme 13; *middle*). However, the presence of at least a methoxy group seems to be required to provide further carbene stabilization. Additionally, reaction of 1-diazo-1(*1H*)-indene **75** with pentacarbonyl(η^2-cis-cyclooctene)chromium(0) **69** led to a pentacyclic non-heteroatom-stabilized carbene complex **76**, which incorporates two indene moieties; its formation may be explained by the high reactivity of the expected and initially formed carbene complex, which evolves through cyclopropane formation by reaction with the double bond of another molecule of carbene complex (Scheme 13; *bottom*).[28]



Scheme 13 Synthesis of non-stabilized metal carbene complexes from diazo compounds.

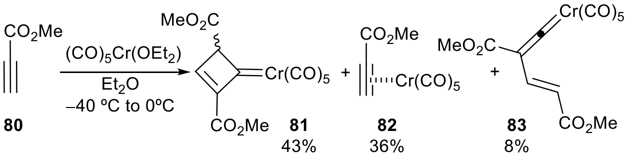
Two possible reaction pathways can be used to rationalize the formation of non-heteroatom-stabilized carbene complexes **71** by this methodology: (i) a direct electrophilic attack of the Lewis acid $Cr(CO)_5$ at the diazo carbon to form **79**, followed by loss of molecular nitrogen, or (ii) an end-on (**77**) or side-on (**78**) coordination of the diazo compound to the $Cr(CO)_5$ fragment (which may behave either as a Lewis acid or as a π-acid) followed by metal migration to the diazo carbon and N_2 elimination (Scheme 14).



Scheme 14 Alternative reaction pathways for the synthesis of non-heteroatom-stabilized metal carbene complexes **71** from diazo compounds.

2.4 Synthesis from $M(CO)_5L$ and alkynes, conjugated dienynes or heterodienynes.

Group 6 metal carbonyl complexes are able to coordinate to C-C triple bonds. The formed π-complex may evolve in different manners depending on the reaction conditions and on the structure of the alkyne. Thus, 2,4-bis(methoxycarbonyl)-cyclobut-2-en-1-yliden-1-pentacarbonylchromium(0) **81** has been obtained as major reaction product by reaction of methyl propiolate with $(CO)_5Cr(OEt_2)$ (Scheme 15).[29] Its synthesis involves the cyclocondensation of two units of methyl propiolate with the chromium carbonyl species.[30] Two other minor reaction products, **82** and **83**, which may be reaction intermediates, have also been isolated.



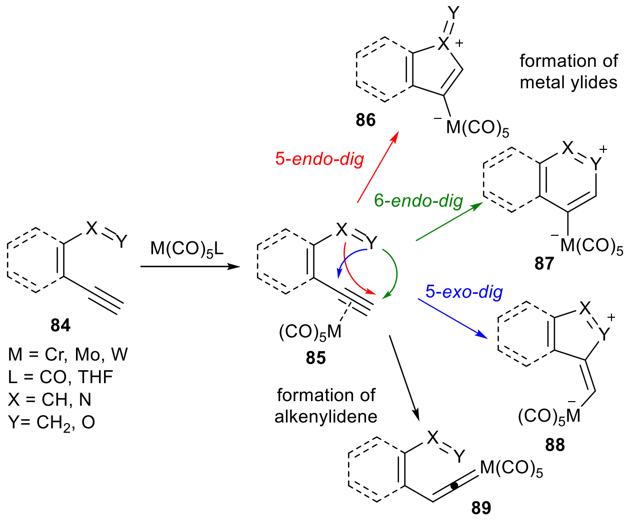
Scheme 15 Synthesis of non-stabilized cyclobutenylidene chromium complex **81.**

Dienynes or heterodienynes of general formulae **84** have shown to be suitable starting materials for the formation of non-heteroatom-stabilized group 6 carbene complexes by reaction with a suitable carbonyl metal complex (Scheme 16). In these transformations the carbonyl metal complex acts as a π-acid activating the triple bond, such as in **85**, for the ulterior cyclization. This cyclization may occur in 5-*endo-dig*, 6-*endo-dig* or 5-*exo-dig* modes depending on the nature of the starting material and the reaction conditions. In some cases, resulting metal-containing ylides (**86-88**) are resonant structures of non-heteroatom-stabilized carbene complexes, which may be isolated (see below), or, in other cases, react with dipolarophiles to provide new non-heteroatom-stabilized carbene complexes, some of them also isolated. At this point, it is worth mentioning that complexes **86-88** could also be considered, depending on the nature of X and Y, as double-vinylogous-stabilized Fischer carbenes.

An additional reaction pathway may take place by formation of an alkenylidene complex **89**, which then may evolve by electrocyclization leading to the reactions products, supposedly through non-heteroatom-stabilized carbene complexes. However, in these cases, these carbene complexes have been proposed as reaction intermediates but have neither been detected nor isolated.

All these situations where non-heteroatom-stabilized carbene complexes have been proposed as reaction intermediates but neither detected nor isolated will not be discussed here but in section 3.10.

Most of these reactions may occur in a catalytic manner although stoichiometric conditions are sometimes required or, in other occasions, have been employed to isolate intermediate carbene complexes, as shown in the following two cases.

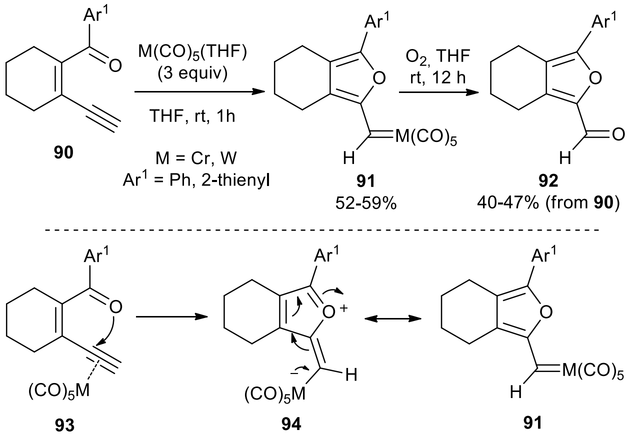


Scheme 16 Alternative reaction patways for metal activated dienynes or heterodienynes.

2.4.1. Synthesis of 2-furyl carbene complexes from β-ethynyl α,β-unsaturated ketones.

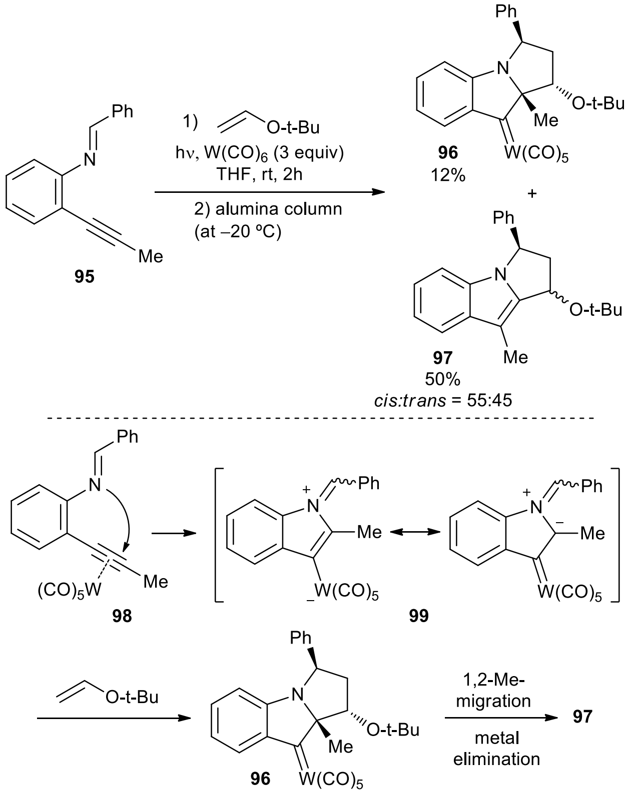
Ohe and Uemura reported that 2-furyl carbene complexes **91** are formed by reaction of β-ethynyl α,β-unsaturated ketones **90** with chromium and tungsten carbonyls. Thus, good yields of blue solid carbene complexes **91** are achieved when three equivalents of $M(CO)_5(THF)$ are employed in THF.[31] Carbenes **91** are relatively stable, as they can be purified by silica gel column chromatography and stored for several days under inert atmosphere. However, they slowly decompose in $CDCl_3$ solutions or under oxygen atmosphere, thus leading to furfural derivatives **92** (Scheme 17; *top*).

The synthesis of carbene complexes **91** is explained by initial coordination of the metal carbonyl to the triple bond followed by 5-*exo-dig* cyclization by nucleophilic attack of the oxygen of the ketone carbonyl to the activated triple bond of **93** (Scheme 17). The formed metal carbonyl ylide **94** is indeed a resonant form of carbene complex **91** (Scheme 17; *bottom*).



Scheme 17 Synthesis of 2-furyl carbene complexes **91**.

2.4.2. Synthesis of an (indolin-3-ylidene)pentacarbonyl tungsten complex from a tungsten-containing azomethine ylide. Iwasawa was able to isolate (indolin-3-ylidene)pentacarbonyltungsten complex **96** by photoirradiation of methyl-substituted *N*-(*o*-alkynylphenyl)imine **95** and *t*-butyl vinyl ether with a stoichiometric amount of $W(CO)_6$ in THF, at room temperature (Scheme 18; *top*). The immediately formed deep blue colour, attributed to carbene complex **96**, remained even after removal of the solvent. A careful chromatographic purification on alumina at –20 ºC allowed the isolation of **96** along with tricyclic indole derivatives **97**.[32]



Scheme 18 Synthesis of an (indolin-3-ylidene)pentacarbonyl tungsten complex from a tungsten-containing azomethine ylide.

After the initial coordination of tungsten carbonyl to the triple bond, a 5-*endo-dig* cyclization would form tungsten azomethine ylide **99** by nucleophilic attack of the nitrogen to the activated triple bond of **96**. Then a [3+2]-cycloaddition should take place leading to non-heteroatom-stabilized carbene complex **96**, which may be isolated. In a later evolution upon standing, compound **96** is transformed into indole derivative **97** through 1,2-methyl migration and metal elimination (Scheme 18; *bottom*).

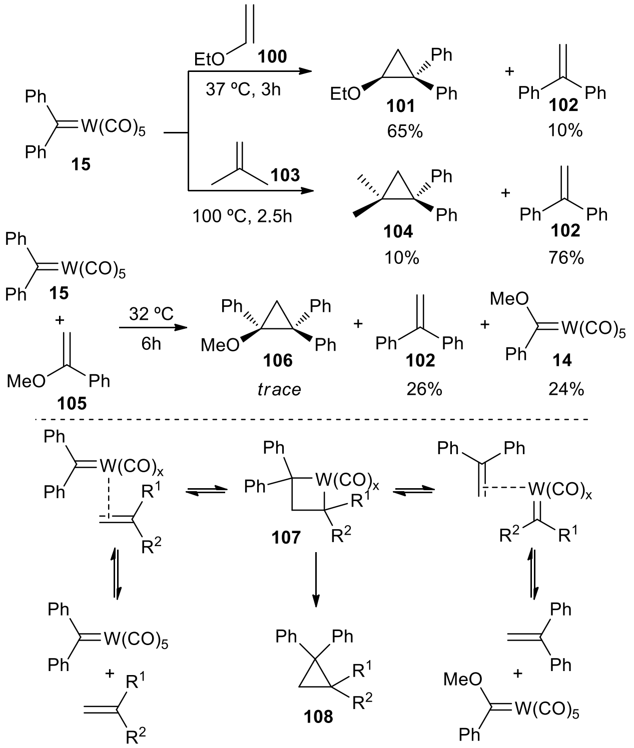
3. Reactivity.

3.1. Cyclopropanation and metathesis.

3.1.1. Olefin metathesis and cyclopropanation.

Non-heteroatom-stabilized group 6 metal carbene complexes have been tested as catalysts for olefin metathesis and cyclopropanation reactions, and they provided support for Chauvin metathesis mechanism.

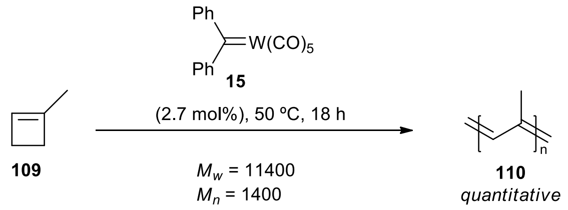
For instance, in the early days of alkene metathesis, prior to the development of Grubbs or Schrock carbene catalysts, Casey and co-workers studied the role of pentacarbonyl(diphenylmethylene) tungsten(0) **15** in reactions with alkenes to synthesize cyclopropanes.[33] They found that both new alkenes coming from metathesis and cyclopropanes were formed in variable amounts depending on the nature of the olefin. Thus, cyclopropane **101** was the mayor product for the reaction with ethyl vinyl ether **100** while 1,1-diphenylethylene **102** was mainly obtained when carbene **15** was reacted with isobutylene **103** (Scheme 19; *top*). Remarkably, only trace amounts of cyclopropane were observed for the reaction with α-methoxystyrene **105**, being 1,1-diphenylethylene and tungsten methoxy carbene complex **14** (both metathesis compounds) the main products.



Scheme 19 Cyclopropanation and metathesis reactions of pentacarbonyl(diphenylmethylene)tungsten(0) **15**.

This result gave a boost to the proposal of Chauvin for the non-pairwise exchange of alkylidene units mechanism;[34] indeed, metallacyclobutane **107** is a key intermediate in all these transformations. It should be generated by a rearrangement of the metal complex containing both an alkene and a carbene ligand, formed by the complexation of the alkene by the metal carbene. Metallacyclobutane **107** can evolve by reductive elimination to form a cyclopropane **108** or by a retro-[2+2]-reaction to give finally 1,1-diphenylacetylene **102** and Fischer carbene complex **14** (Scheme 19; *bottom*).

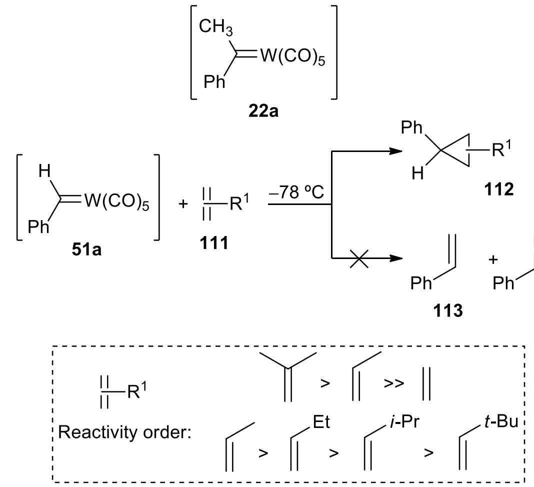
On the other hand, Katz showed that tungsten diphenylcarbene **15** was an effective initiator for cross metathesis of terminal olefins (1-hexene, 1-octene), 1,1-disubstituted olefins (2-methyl-1-heptene and 2-methyl-1-pentene) or 1,2-disubstituted olefins (2-hexene) without requiring a Lewis acid co-catalyst.[35] Carbene complex **15** is also able to catalyse the formation of polyisoprene **110** from 1-methylcyclobutene **109** as expected from a ring-opening metathesis polymerization (ROMP). The polymer obtained had a broad molecular weight distribution, with M_w = 11400 and M_n = 1400. These results also provided evidence of metal carbene complexes as intermediates in olefin metathesis reactions (Scheme 20).[36]



Scheme 20 ROMP of 1-methylcyclobutene **109** catalysed by carbene complex **15**.

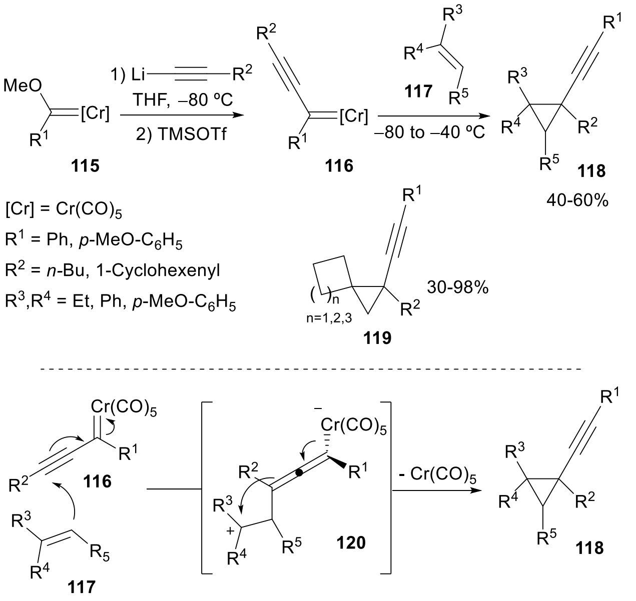
Moreover, in a work by Casey and co-workers, pentacarbonyl[di(*p*-tolyl)methylidene]tungsten(0) **17** ($Ar^1 = Ar^2 = p$-Tol; M = W) was a useful tool to provide information for the metathesis reaction; indeed, research with this carbene complex evidenced: (i) the transfer of the less substituted alkylidene unit on an alkene to the initial carbene ligand and (ii) the higher reactivity of **17** ($Ar^1 = Ar^2 = p$-Tol; M = W) towards less substituted alkenes. Formation of cyclopropanes was observed as a side reaction in these experiments.[13]

Asymmetrically substituted tungsten carbene complexes **22a** and **51a** were also tested as mechanistic probes for cyclopropanation and metathesis reactions (Scheme 21). Most of the research was performed with **51a** due to the rapid decomposition of **22a** via β-hydride elimination from the methyl group. Interestingly, only cyclopropanes were obtained in the reaction of **51a** with alkenes, without formation of metathesis products. This fact emerges as the main difference in reactivity between carbenes **51a** and **15**. Additionally, cyclopropanation of alkenes with **51a** takes place rapidly at –78 ºC while **15** requires 40 ºC for alkene reaction to give cyclopropanes and metathesis products. Phenyl carbene complex **51a** is a more electrophilic reagent and is more reactive to the most substituted alkene while diphenyl carbene complex **15** [and **17** ($Ar^1 = Ar^2 = p$-Tol; M = W)] displays the opposite behaviour.[24] Some conclusions regarding the reactivity of alkenes with tungsten phenyl carbene **51a** were also established: (i) *cis* and *trans*-2-butene form cyclopropanes with retention of the stereochemistry of the alkene precursor; (ii) the number of alkyl groups attached to the more substituted end of the carbon-carbon double bond determines the relative reactivity of alkenes; (iii) the relative reactivity of monosubstituted alkenes is sterically controlled: it decreases as the bulk of substituent increases (Scheme 21). Doyle also concluded that neither differential olefin coordination to a coordinatively unsaturated carbene system nor carbene exchange occur in the reactions of carbene complex **51a** with alkenes.[37]



Scheme 21 Cyclopropanation of alkenes with non-heteroatom-stabilized benzylidene tungsten complex **51a**.

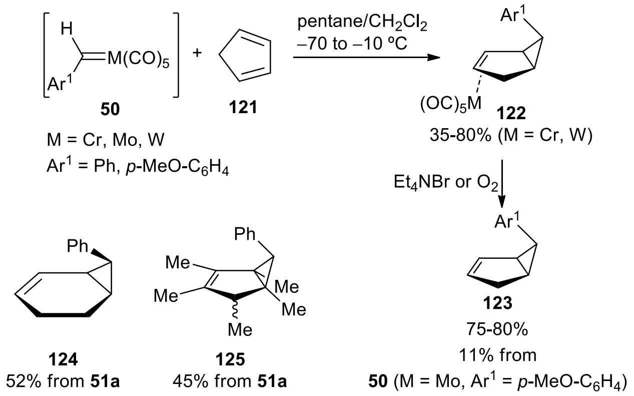
Finally, non-heteroatom-stabilized alkynyl chromium carbene complexes **116**, synthesized in situ by Barluenga and co-workers from the corresponding alkoxycarbenes **115**, are able to undergo cyclopropanation of non-activated olefins **117**.[38] The formation of the corresponding alkynylcyclopropanes **118** takes place in good yields and in an almost totally diastereoselective manner (Scheme 22; *top*). Alkynylspiro[2.3]hexanes, spiro[2.4]heptanes and spiro[2.5]octanes **119** are also accessible, following this methodology. Cyclopropane formation occurs through an initial nucleophilic conjugate attack to the alkynylcarbene **116** to generate a zwitterionic intermediate **120** that evolves to the final product **118** by cyclopropane formation and metal elimination (Scheme 22; *bottom*).



Scheme 22 Synthesis of alkynylcyclopropanes **118** from in situ generated non-heteroatom-stabilized alkynyl carbene complexes **116**.

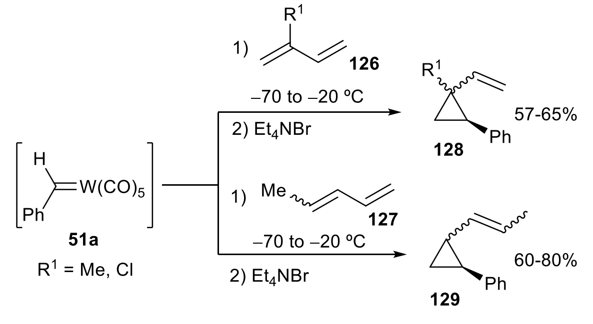
3.1.2. Cyclopropanation of dienes.

Only one of the double bonds undergoes cyclopropanation in the reaction of benzylidene pentacarbonyl complexes **50** with cyclopentadiene.[39] The reaction is stereoselective and metal remains coordinated in *exo*-position to the unreactive double bond, as in **122**. Treatment with Et_4NBr or O_2 liberates the resulting *endo*-6-arylbicyclo[3.1.0]hex-2-ene **123** from the metal (Scheme 23). Chromium carbene complexes provide slightly higher yields than molybdenum or tungsten carbene complexes. Other cyclic dienes such as cyclohexadiene or 1,2,3,4,5-pentamethylcyclopentadiene have undergone cyclopropanation with tungsten carbene complex **51a** and follow a similar trend: only one double bond reacts leading to *endo*-bicyclic products **124** or **125** (Scheme 23).



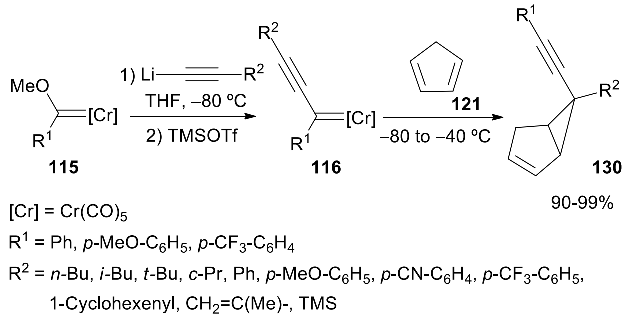
Scheme 23 Cyclopropanation of cyclopentadienes and cyclohexadiene with benzylidene complexes **50**.

In Scheme 24 is described the cyclopropanation of acyclic dienes, such as *cis*- and *trans*-pentadiene, isoprene and chloroprene, with **51a**. This cyclopropanation is also regioselective and provides *E* and *Z* alkenylarylcyclopropanes **128,129** with moderate diastereoselectivities (*E*/Z ratio = 0.22-0.52).



Scheme 24 Cyclopropanation of dienes with non-heteroatom-stabilized benzylidene complexes **51a**.

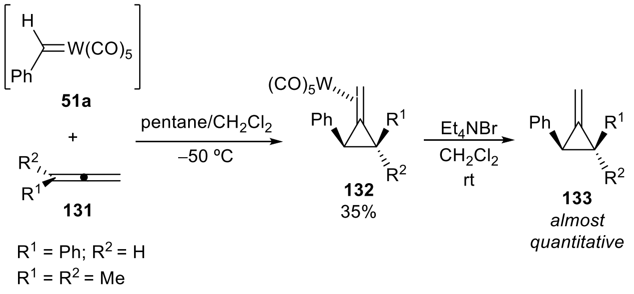
Similarly to what happens with simple non-activated olefins **117**, non-heteroatom-stabilized alkynyl chromium carbene complexes **116** are also able to furnish cyclopentadiene cyclopropanation (Scheme 25). A large family of [3.1.0]bicyclic products **130** are obtained with total regio- and diastereoselectivity in almost quantitative yield.[38] Thus, the *endo*- adducts are formed as single products through a nucleophilic attack of the cyclopentadiene to the conjugate carbon of the *in situ* synthesized non-heteroatom-stabilized chromium carbene complex **116**. The gold catalysed isomerization of the resulting compounds **130** has been recently reported.[40]



Scheme 25 Synthesis of alkynyl[3.1.0]bicyclohexenes **130** from in situ generated non-heteroatom-stabilized and cyclopentadiene.

3.1.3. Cyclopropanation of allenes.

Methylenecyclopropanes **132** are regio- and stereoseletively formed by reaction between benzylidene(pentacarbonyl)tungsten complex **51a** and allenes within several hours in pentane/dichloromethane, even at –50 ºC (Scheme 26). The carbene ligand is exclusively transferred to the substituted double bond of the allene and the resulting methylenecyclopropane remains coordinated to the pentacarbonyl tungsten fragment *via* the exocyclic double bond. Indeed, in complexes **132**, the relative disposition between the phenyl group and the $W(CO)_5$ is *anti*. Decomplexation to **133** is almost quantitatively achieved with Et_4NBr in dichloromethane at room temperature.[41]

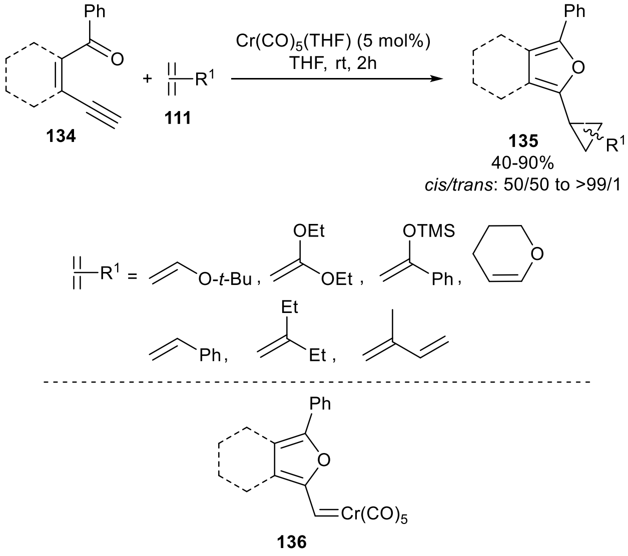


Scheme 26 Cyclopropanation of allenes with non-heteroatom-stabilized tungsten benzylidene complex **47a**.

3.1.4. Catalytic cyclopropanation of electron rich alkenes and dienes.

Cyclopropanation of electron-rich alkenes **111**, such as cyclic and acyclic enol ethers, ketene acetals, silyl enol ethers, styrene, 1,1-dialkylolefins and even dienes (isoprene), has been carried out with ene-yne-ketones **134** to synthesize 2-furylcyclopropanes **135** in a catalytic manner via non-heteroatom-stabilized metal carbene complexes (Scheme 27).[42] The optimized reaction conditions involved catalysis by $Cr(CO)_5(THF)$, although other group 6 metal carbonyl complexes (as well as catalysts of Rh, Ru, Pd and Pt) also promoted the reaction. However, lower yields and stereoselectivities were obtained for metals different than chromium.

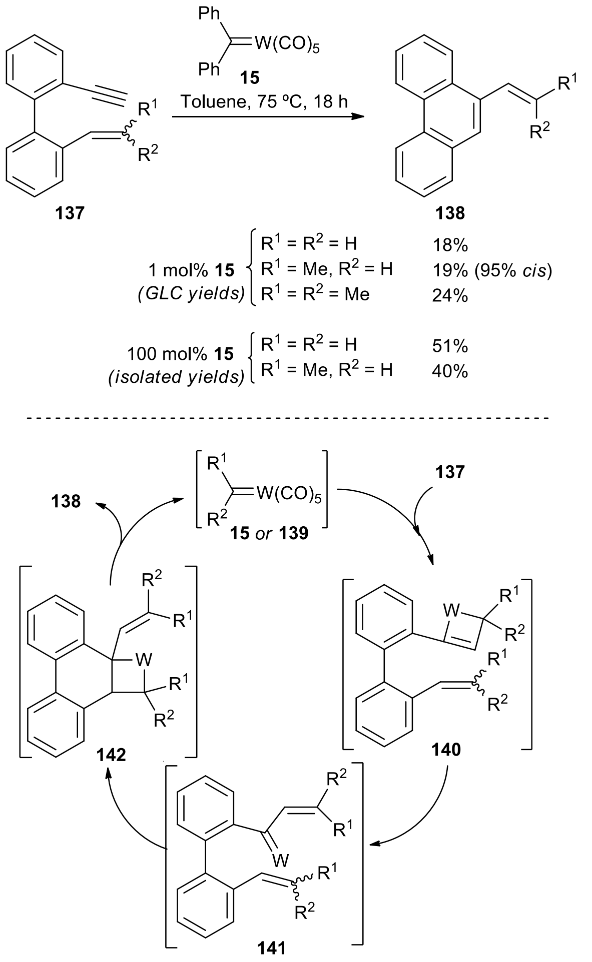
The most plausible reaction pathway should involve a 5-*exo-dig* cyclization of ene-yne-ketone **134** by nucleophilic attack of the carbonyl oxygen to the internal carbon of the π-acid activated triple bond, as depicted in Scheme 17. Furyl carbene complexes **136** are thus generated and are able to undergo the cyclopropanation of the above mentioned double bonds, leading to 2-furylcyclopropanes **135** in moderate to excellent yields.



Scheme 27 Catalytic cyclopropanation involving 2-furyl carbene complexes **136**.

3.1.5. Enyne metathesis.

Katz was also a pioneer on enyne metathesis,[43] which he described as “an hybrid of the metal-catalysed acetylene polimerization and olefin metathesis reactions”. He was the first one to employ metal complexes as catalysts for enyne metathesis and reported that several Fischer carbene complexes were able to promote the synthesis of phenantrene derivatives from enynes by ring-closing metathesis. The reactions were assayed under both stoichiometric and catalytic conditions.[44] Indeed, among tungsten Fischer carbene complexes tested, non-heteroatom-stabilized carbene complex **15** was an active catalyst leading to phenantrenes **138** in moderate yields with remarkable stereoselectivities, and in loadings as low as 1 mol% (Scheme 28).



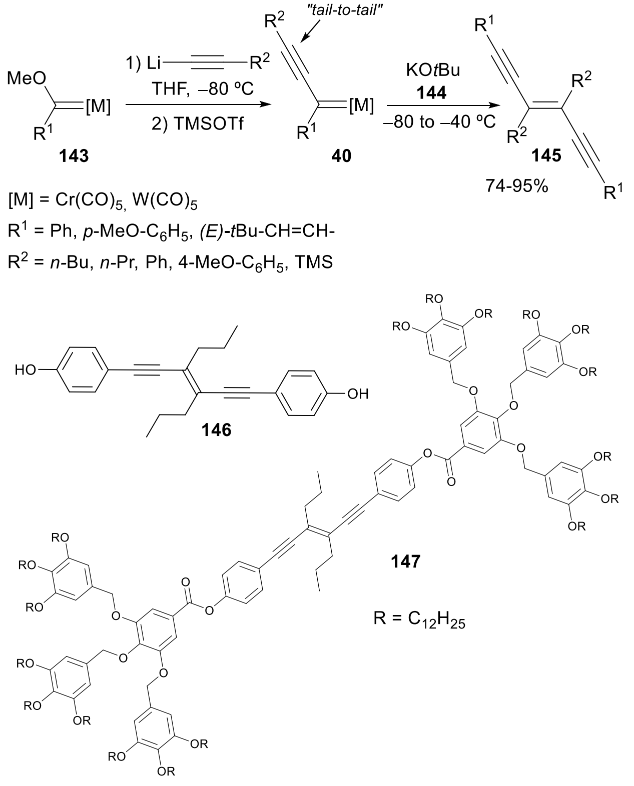
Scheme 28 Non-heteroatom-stabilized carbene complex **15** catalysed ring-closing metathesis of enynes **137**.

The catalytic cycle should follow an yne-then-ene pathway, as it usually happens for Mo and W alkylidene complexes (Schrock type catalysts).[43] Therefore, [2+2]-cycloadddition between the carbene catalyst species **139** and the triple bond should lead to tungstenacyclobutene **140**. Next, a retro-[2+2]-cycloaddition would generate carbene complex **141** which should evolve by an intramolecular [2+2]-cycloaddition with the remaining double bond to form tungstenacyclobutane **142**. A final retro-[2+2]-cycloaddition reaction will liberate 9-alkenylphenanthrenes **138** and regenerate the catalyst species **139**.

It should be noted that non-heteroatom-stabilized carbene complexes are active intermediates in this catalytic cycle. Besides **141**, and regardless of the nature of the initiator (heteroatom stabilized or non-stabilized) carbene complex, the true catalytic species for the enyne metathesis cycle (Scheme 28) is indeed a non-stabilized carbene complex **15** or **139**.

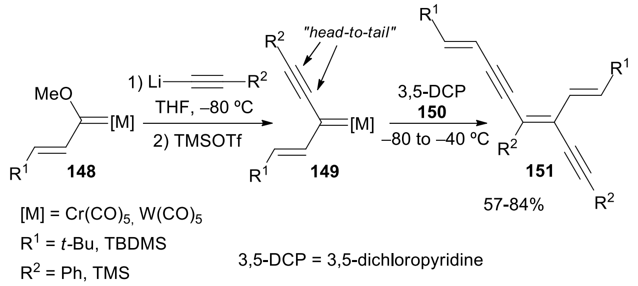
3.2. Dimerization.

A large family of diethynylethenes is accessible through a dimerization reaction of non-heteroatom-stabilized group 6 alkynyl carbenes. Thus, carbene complexes **40** dimerize at low temperature, with complete chemo-, regio-, and steroselectivity in a nucleophile-induced reaction.[22] The selectivity of the process, and consequently the structure of the endiyne adduct obtained, is highly dependent on the nature of the nucleophile used. Thus, the use of potassium *tert*-butoxide **144** as nucleophile results in high yielding tail-to-tail dimerization of carbene complexes **40**. Following this methodology, different types of di-, tri- and tetraynylethenes **145** can be accessed (Scheme 29). This approach has also been applied to the synthesis of molecules such as 1,6-bis(4-hydroxyphenyl)-3-hexen-1,5-diyne **146**, a precursor of compound **147** that self-assembles towards a columnar liquid-crystalline phase and organogels.[45]



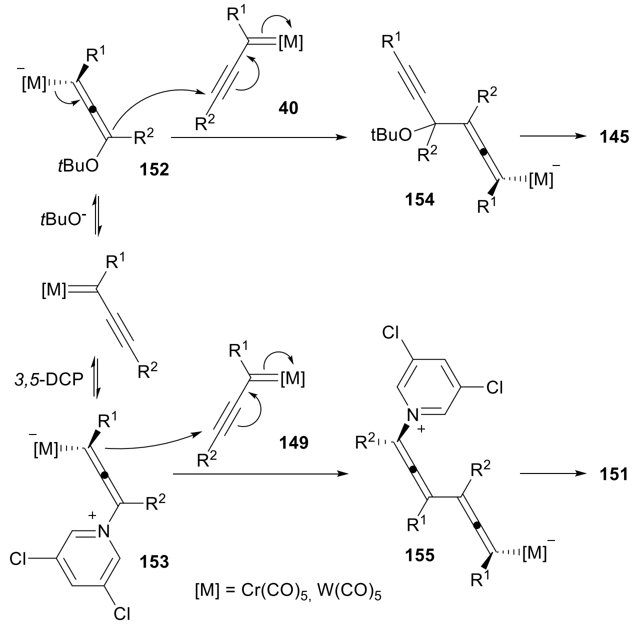
Scheme 29 Tail-to-tail dimerization of non-heteroatom-stabilized alkynylcarbene complexes **40**.

In addition to the tail-to-tail dimerization, several dimers resulting from head-to-tail processes can also been accessed. The synthesis of 3-alkenylocta-3,7-dien-1,5-diynes **151** with excellent selectivity from the corresponding alkenyl-substituted carbene complexes **149** (generated in situ from Fischer carbene complexes **148**) is described in Scheme 30. This reaction has been performed in the presence of 3,5-dichloropyridine (DCP) **150** as nucleophile.[22] Although small amounts of the head-to-head regioisomer have also been observed (head-to-tail/head-to-head ratio: 10/1 to >20/1), the major component can be isolated in pure form after flash chromatography.



Scheme 30 Head-to-tail dimerization of non-heteroatom-stabilized alkynylcarbene complexes **149**.

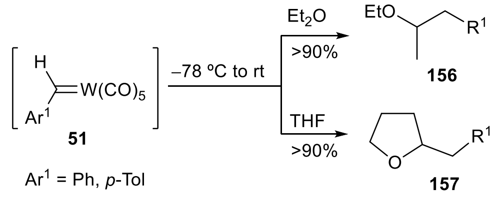
A mechanistic proposal for the formation of the two different families of dimeric structures **145** and **151** is shown in Scheme 31. In both cases, the reaction should begin through a conjugate addition of the nucleophile [t-BuO$^-$ or 3,5-dichloropyridine] to the electrophilic β-carbon of non-heteroatom-stabilized carbene complexes **40,149**, leading to allenylmetallate species **152,153**. At this point, the reaction continues following two different pathways depending on the different nature of these two allenyl intermediates: anionic **152** versus zwitterionic **153**. Thus, intermediate **152** evolves with a conjugate attack –through its propargylmetallate structure– to the second equivalent of non-stabilized carbene complexes **40** to form intermediate **154**. Finally, intermediate **154** would afford tail-to-tail dimer **145** upon elimination of *tert*-butoxide and the metal fragment. On the contrary, zwitterionic intermediate **153** should undergo conjugate addition –through its allenylmetallate structure– to carbene complexes **149** leading to intermediate **155**. Elimination of 3,5-dichloropyridine and the metal fragment from intermediate **155** would lead to head-to-tail dimers **151**.



Scheme 31 Proposed mechanisms for the dimerization of non-heteroatom-stabilized alkynylcarbene complexes.

3.3. C-H insertion.

Tungsten benzylidene complexes **51** are able to regiospecifically insert the benzylidene ligand into the α-C–H bond of diethyl ether or THF in very high yield (>90%) (Scheme 32).[46] The kinetics of the reaction in THF indicated that the insertion follows an associative mechanism initiated by nucleophilic attack of THF to the strongly electrophilic carbene carbon.

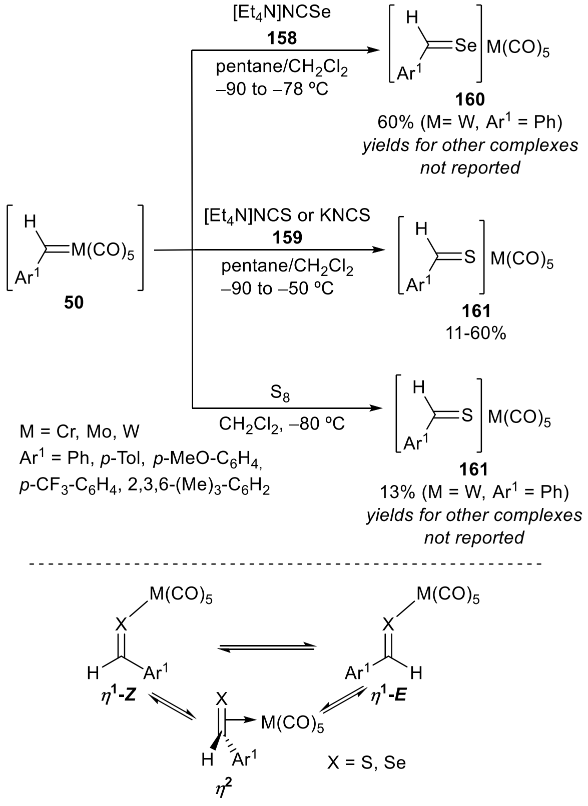


Scheme 32 Regiospecific insertion of benzylidene ligands into the α-C–H bond of ethers.

3.4. Insertion of S or Se.

Insertion of selenium or sulphur into the M=C bond of carbene complex has been observed by reaction of benzylidene(pentacarbonyl) complexes of group 6 metals **50** with selenocyanates **158** [26,47] or thiocyanates **159** at low temperature, to form chalcogenobenzaldehyde ligand complexes **160** and **161,** respectively (Scheme 33). [26,48]

Thiobenzaldehyde complexes **161** may also be formed by reaction of benzylidene(pentacarbonyl) complexes with elemental sulphur (Scheme 33).[48]

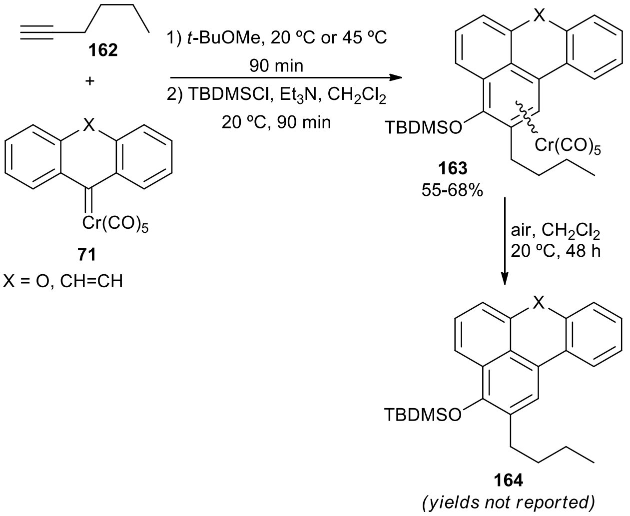


Scheme 33 Insertion of Se or S in the C=M bond.

In solution, the chalcogenobenzaldehyde ligand may be bonded to the metal either in complexes **160** and **161** in a η^1-fashion or in a dynamic equilibrium between two η^1- and one η^2-isomeric forms (Scheme 33; *bottom*).[47,48] The coordination mode depends on the metal, the chalcogen, the aryl group, the solvent and the temperature.

3.5. Dötz reaction.

The Dötz benzannulation reaction is one of the most useful reactions in the chemistry of Fischer carbene complexes.[49] It involves the formation of a benzene ring and the creation of three carbon-carbon bonds by the coupling of an internal or terminal alkyne and two ligands (the carbene and a carbonyl) from a Fischer alkenyl or aryl carbene complex. The alkyne partner is regioselectively inserted into the metal-carbene bond, with the smaller alkyne substituent placed closer to the carbene carbon. The subsequent insertion of a carbonyl ligand allows the synthesis of phenols (from alkenylcarbenes) or naphthols (from arylcarbenes). For non-heteroatom-stabilized carbene complexes, the only case reported to date corresponds to the reaction of symmetric chromium carbene complexes **71** with 1-hexyne.[27] The resulting naphthol derivative is in situ protected with TBDMS chloride in moderate yields. Air oxidation to remove the coordinated chromium fragment of **163** allows the regiochemically controlled synthesis of oxygenated benzo[*k*,*l*]xanthenes (X = O) or cyclohepta[1,2,3-de]naphthalenes (X = CH=CH) **164** (Scheme 34).

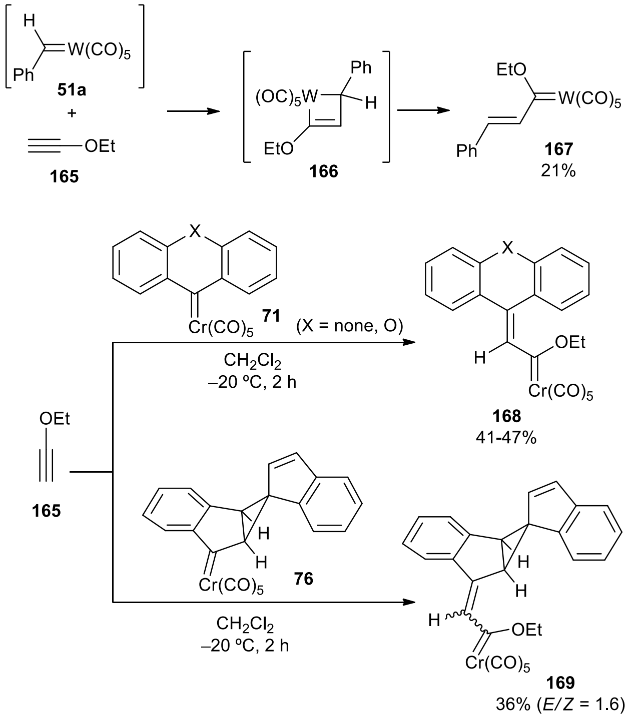


Scheme 34 Dötz benzannulation reaction between non-heteroatom-stabilized chromium carbene complexes **71** and 1-hexyne.

Interestingly, no benzannulation reaction took place from fluorenylidene complex **71** (X = none); instead, carbene dimerization and oxidation was observed. This result was attributed to hampering of the electrocyclic ring closure mechanistic step due to smaller bond angles in the central five-membered ring.[27]

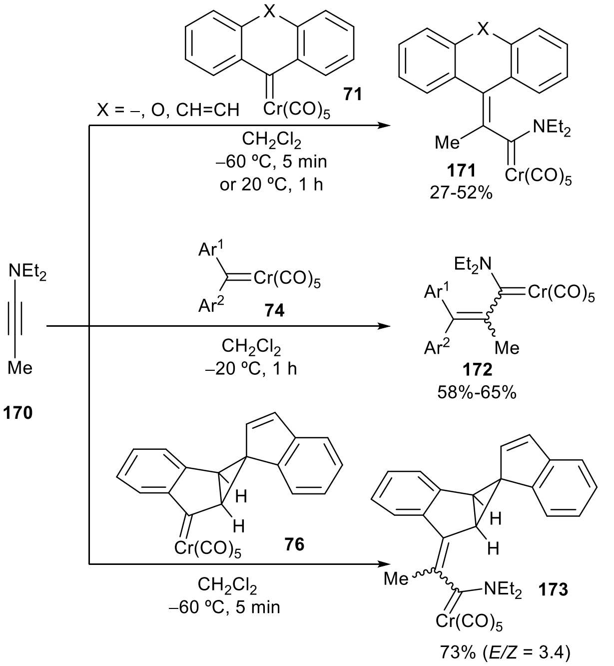
3.6. Reaction with ynol ethers and ynamines.

Electron-rich alkynes, such as ynol ethers or ynamines, undergo insertion into the metal-carbene bond, leading to new stabilized Fischer carbene complexes. The insertion follows a [2+2]-/retro-[2+2] cycloadditions sequence with formation of a metallacyclobutene intermediate **166**. In contrast to the Dötz benzannulation reaction, once the electron-rich alkyne is inserted the reaction does not proceed further due to the high stability of the new carbene complex formed. Alkoxy alkenyl carbene complexes **167-169** have been synthesized by this procedure when ethoxyacetylene **165** was employed as alkyne partner (Scheme 35).[25b,28]



Scheme 35 Regiospecific insertion of ynol ethers **165** in M=C bond.

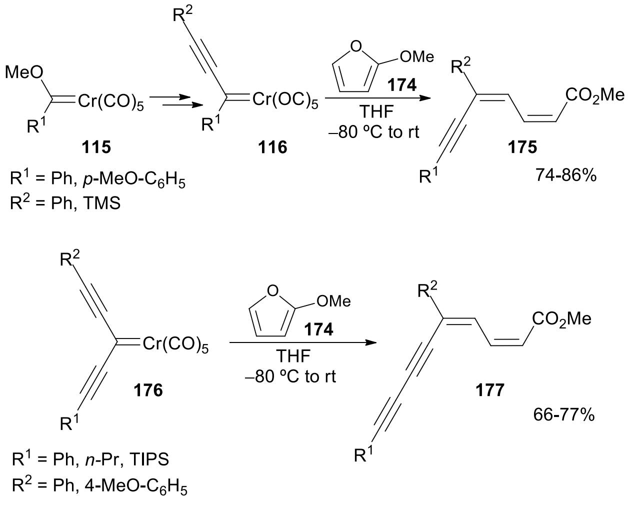
Ynamine **170** displays a similar behaviour and its reactions with non-heteroatom-stabilized carbene complexes **71**, **74** or **76** lead to amino alkenyl carbenes **171-173** in moderate yields and diastereoselectivities (for unsymmetrical starting carbenes **74** or **76**)[28] (Scheme 36).



Scheme 36 Regiospecific insertion of ynamines **170** in Cr=C bond.

3.7. Reaction with 2-methoxyfuran

Non-heteroatom-stabilized alkynyl chromium carbene complexes **116**, in situ synthesized by the previously reported methodology (section 2.2.1.), react with 2-methoxyfuran **174** to form linear dienyne adducts **175**, in good yields (Scheme 37). The reaction occurs upon warming the reaction mixture from low to room temperature.[50] The reaction is initiated by a conjugate attack of the 2-metoxyfuran **175** to the alkynylcarbene **116**, involving formal 1,2-migration of the triple bond and opening of the furan ring. The overall procedure represents a regioselective olefination at C_β of the alkynyl carbene complexes **116**. This approach has been applied to form linear dienediyne adducts **177**, from cross-conjugated diyne carbene complexes **176**.

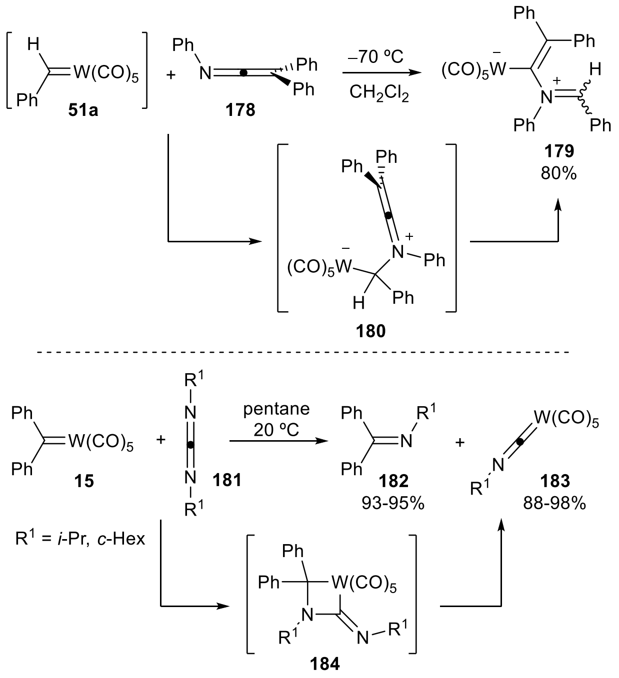


Scheme 37 Synthesis of linear dienynes **175** and diendiynes **177**.

3.8. Reaction with heterocumulenes

Benzylidene tungsten complex **51a** quickly reacts with triphenylketenimine **178** at –70 ºC to form red zwitterionic tungsten complex **179** in 80 % yield (Scheme 38; *top*). A nucleophilic addition of the ketenimine **178** to the carbene **51a** leading to zwitterionic species **180**, followed by 1,3-tungsten migration would account for the observed results.[51]

On the other hand, non-heteroatom-stabilized carbene complex **15** undergoes metathesis at room temperature with symmetric dialkylcarbodimides **181** to form imines **182** and alkylisocyanide(pentacarbonyl)tungsten complexes **183** in excellent yields (Scheme 38; *bottom*). The reaction course can be readily explained through azatungstacyclobutane intermediate **184**.[52]



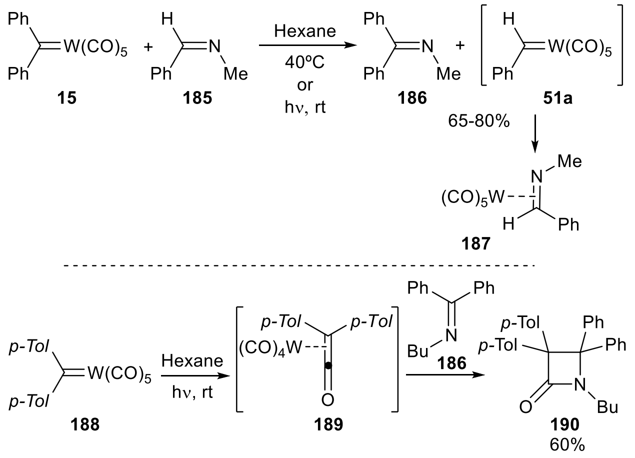
Scheme 38 Reactivity of non-heteroatom-stabilized tungsten carbene complexes against heterocumulenes.

3.9. Reactions with imines.

3.9.1. Methatesis and lactonization.

Non-heteroatom-stabilized tungsten carbene complexes were reacted for the first time with imines by Hoffmann and Weiss.[53] The reaction is very sensitive to both the imine and the carbene substitution. In this sense, aldimine **185** reacts thermally or photochemically to form unstable new carbene complex **51a**, which decomposes yielding the imine-metal complex **187** (Scheme 39; *top*).

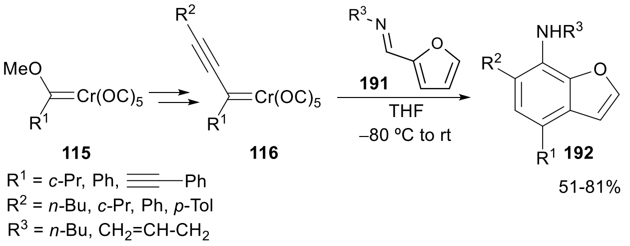
However, a similar reaction performed with keteneimine **186**, progresses only under photochemical conditions and provides β-lactam **190** by a formal [2+2]-cycloaddition of imine **186** with tungsten ketene complex **189** (Scheme 39; *bottom*).



Scheme 39 Methatesis and lactonization of non-heteroatom-stabilized tungsten carbene complexes with imines.

3.9.2. With furfural imines. Synthesis of benzofurans.

Furfural imines **191** react with in situ synthesized non-heteroatom-stabilized alkynylcarbene complexes **116** to afford benzofurans **192** in a regioselective manner (Scheme 40).[54] This procedure represents one of the few methodologies described for the synthesis of benzofurans through construction of the arene ring, instead of more common procedures involving formation of the furan ring onto a preexisting arene nucleous. Additionally, the high regioselectivity of the reaction in combination with an exchange of the carbene substituents (R^1 and R^2) allows for the formation of both regioisomeric benzofurans **192**. A recent theoretical study performed on this synthesis, revealed that the reaction may presumably be initiated by conjugate addition of the imine nitrogen to the carbene complex.[55]

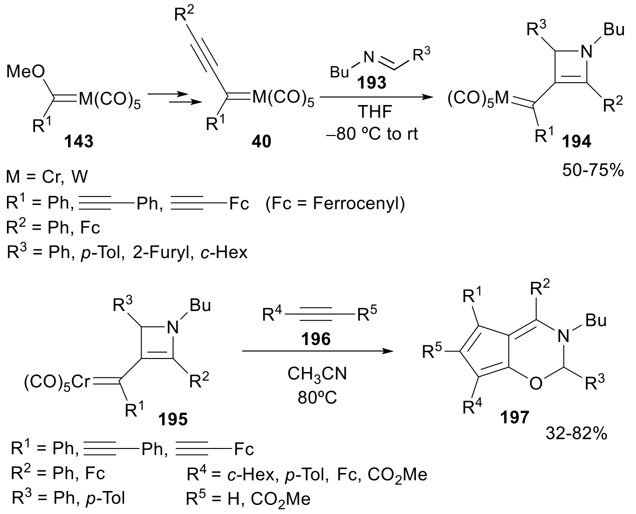


Scheme 40. Synthesis of benzofuran derivatives **192** from non-heteroatom-stabilized alkynylcarbene complexes **116**.

3.9.3. Synthesis of azetinyl carbenes and subsequent transformations.

Examples of synthesis of stable 2-azetine derivatives are scarcely found in the literature as most 2-azetine compounds undergo spontaneous ring opening to afford the corresponding azadienes. In this context, stable 2-azetinyl carbenes **194** are afforded by [2+2] cycloaddition reaction of alkynyl-substituted (pentacarbonyl)chromium or –tungsten carbene complexes **40** with imines **193** (Scheme 41).[56] Subsequent reaction of chromium 2-azetinyl carbenes **195** –that can be considered as vinylogous Fischer aminocarbene complexes or *r*NHCs– with alkynes **196** allows the preparation of 2,3-

dihydrocyclopenta[*e*]oxazines **197** in moderate to good yields.

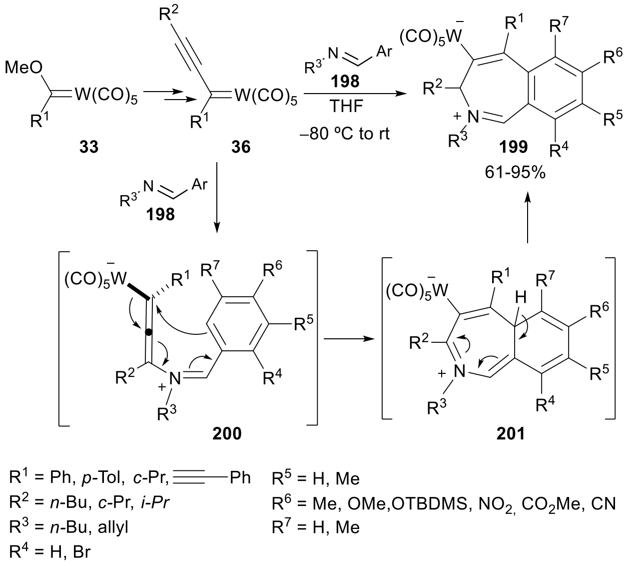


Scheme 41. Synthesis of 2-azetinylcarbenes **194** and 2,3-dihydrocyclopenta[*e*]oxazines **197**.

The formation of azetinyl carbenes **194** is also possible with furfural imines. In this case, the synthesis of the azetinyl derivative **194** competes with the formation of the corresponding benzofuran **192** (*vide supra*). However, the reaction can be driven to one or the other product depending on the electronic nature of the substitution pattern of the non-heteroatom-stabilized carbene complexes **40**.[55]

3.9.4. Synthesis of benzoazepinyl derivatives.

A new family of compounds can be accessed in the reaction of imines with alkynyl carbenes. Thus, alkynyl carbenes **36**, bearing an alkyl group at the conjugate position, react with aryl imines **198** under smooth reaction conditions, yielding benzo[*c*]azepinyl derivatives **199** (Scheme 42). [57] The reaction occurs with total regioselectivity and it is tolerant to a large diversity of functional groups. A theoretical analysis of the reaction mechanism revealed that the presence of an alkyl or aryl group at the conjugate position of the carbene **36** (R^2) plays a determining role in terms of sterical hindrance. Thus, after the initial and regioselective imine attack to the conjugate position of carbene **36** to form zwitterionic allenylmetallate intermediate **200**, the reaction evolves toward a selective formation, through 1,2-pentacarbonylmetal migration, of the benzoazepinyl intermediate **201**, avoiding an early closure of the cycle and formation of the azetinyl carbene **194** *(vide supra)*. Finally, intermediate **201** undergoes a 1,5-hydrogen migration leading to benzoazepinium tungstate **199**.



Scheme 42 Regioselective synthesis of benzo[*c*]azepinyl derivatives **199** from alkynyl carbenes **36** and imines.

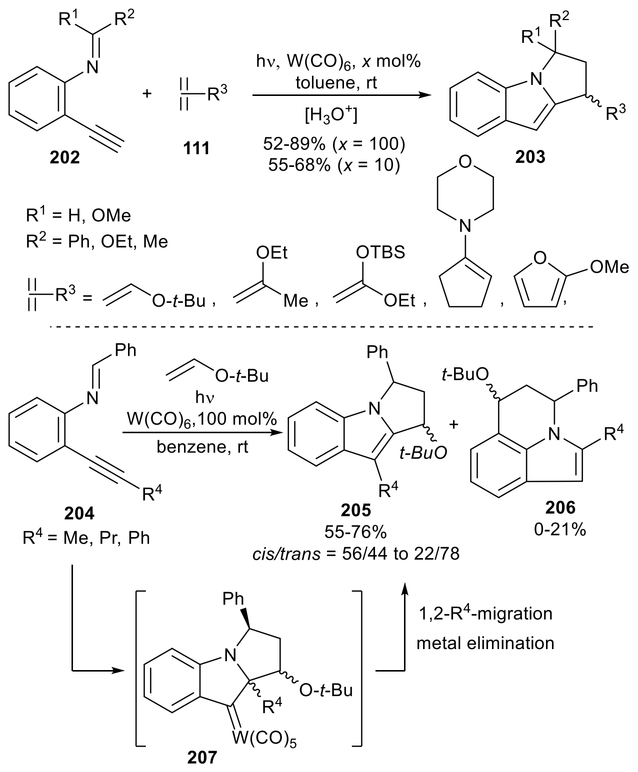
Finally, taking into account the electrophilic and also the nucleophilic nature of the zwitterionic benzoazepinum tungstates **201**, several reactions have been accomplished by this compound, allowing for access to a high number of benzo- and dihydrobenzo[*c*]azepines, with an important degree of substitution.

3.10. Stoichiometric or catalytic transformations involving non-stabilized carbene complexes as intermediates.

In this section several stoichiometric or catalytic transformations involving non-heteroatom-stabilized carbene complexes as presumed intermediates are covered. A general feature to all of them is the employment of group 6 metal carbonyls as π-acids to activate triple bonds, and its further evolution through several reaction pathways depending on the nature of the intramolecular nucleophile (see Scheme 16).

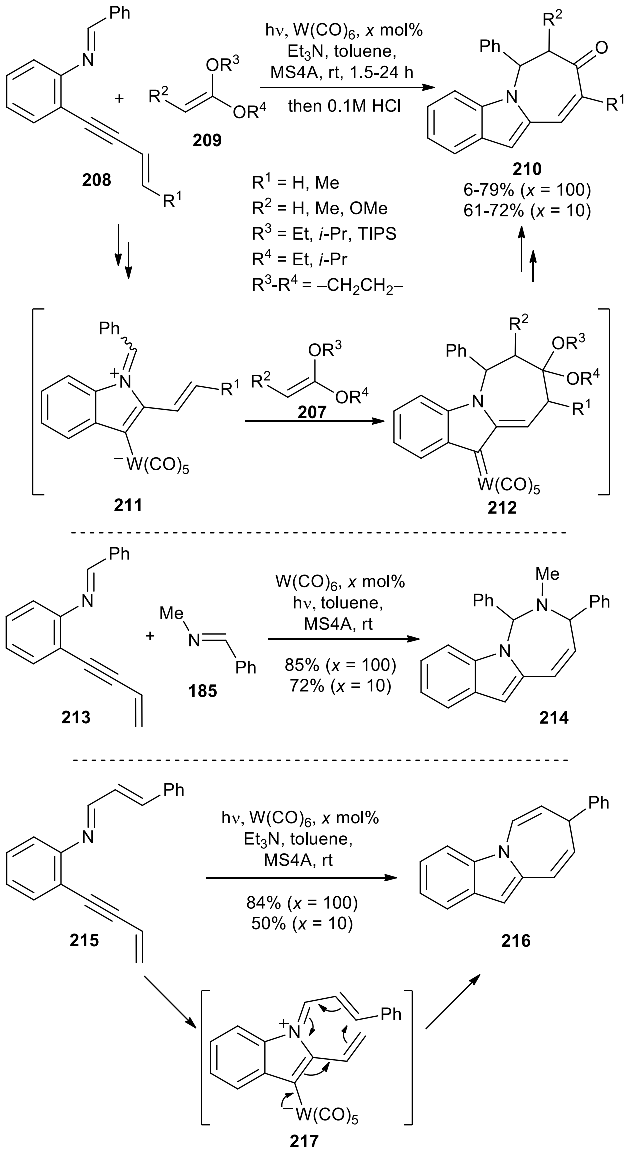
3.10.1. Initiated by 5-endo-dig cyclizations.

For instance, *N*-(*o*-alkynylphenyl)imines **202** have demonstrated to be appropriate starting materials for the synthesis of tricyclic indole derivatives **203** when photoirradiated in the presence of an olefin **111** and $W(CO)_6$ (Scheme 43; *top*).[58] The reaction proceeds with moderate to good yields under stoichiometric conditions or with just a 10 mol% of catalyst. The reaction also works in a satisfactory manner for *N*-(*o*-alkynylphenyl)imines **204**, derived form internal alkynes, to synthesize tricyclic indols **205** (Scheme 43; *bottom*). The mechanism for this transformation has been previously presented (see Scheme 18); a 5-*endo-dig* cyclization followed by a [3+2]-cycloaddition would lead to carbene complexes **207**, which will evolve into the final products. Indeed, intermediate carbene complex **96** (Scheme 18) has been isolated and characterized.[32] Additionally, small amount of adducts **206**, which come from a formal [4+2] cycloaddition between the olefin **111** and the intermediate tungsten-containing azomethine ylide, have been sometimes obtained. More recently, the reaction with internal alkynes has been improved, in terms of time and yield, using $PtCl_2$ or $AuBr_3$ as π-acid catalysts.[59]



Scheme 43 Synthesis of polycyclic indole derivatives by a tungsten carbonyl catalysed reaction.

When the internal alkyne substituent bears a conjugate double bond, as in **208**, seven–membered heterocycles **210** may be formed as a result of a formal [5+2]-dipolar cycloaddition (Scheme 44).[60] The reaction proceeds smoothly even with a 10 mol% of $W(CO)_6$ loading, through tungsten-containing azomethine ylide **211**. Then, a [5+2]-cycloaddition should take place to form non-heteroatom-stabilized tungsten carbene complex intermediate **212**, which evolves into the final azepino[1,2-*a*]indole derivative **210** (Scheme 44; *top*). Tricyclic indoles formed by [3+2]-cycloaddition are sometimes obtained as by-products or even as major products, especially with sterically less demanding acetals and high tungsten hexacarbonyl loadings.



Scheme 44 Synthesis of seven-membered heterocycles by tungsten carbonyl catalysed reactions of *N*-(o-alkynylphenyl)imine derivatives.

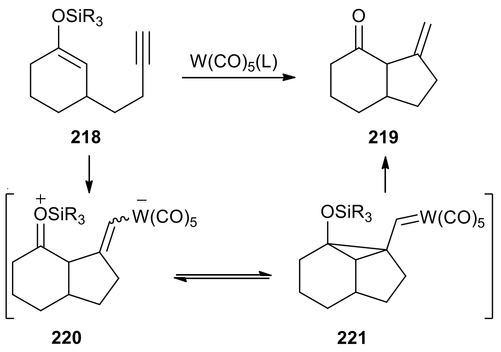
This transformation could be extended to the employment of imines **185** as dipolarophiles, as illustrated by the synthesis of diazepine derivative **214** in good yield, as a mixture of diastereomers (Scheme 44; *middle*).

An intramolecular example has also been reported: good yields of azepino[1,2-*a*]indole derivative **216** were obtained from **215** through [1,7]-electrocyclization of tungsten-containing azomethine ylide **217** (Scheme 44; *bottom*).

More recently, it was found that other metal complexes are able to catalyze this transformation efficiently, particularly $ReBr(CO)_5$, $AuBr_3$ or $PtCl_2$. In this regard, $PtCl_2$ was the catalyst choice for a study toward mitomycin C synthesis from imidate derivatives.[61]

Iwasawa also reported the $W(CO)_5(L)$-catalysed 5-*exo*-cyclization of ω-allenyl or ω-acetylenic silyl enol ethers, such as

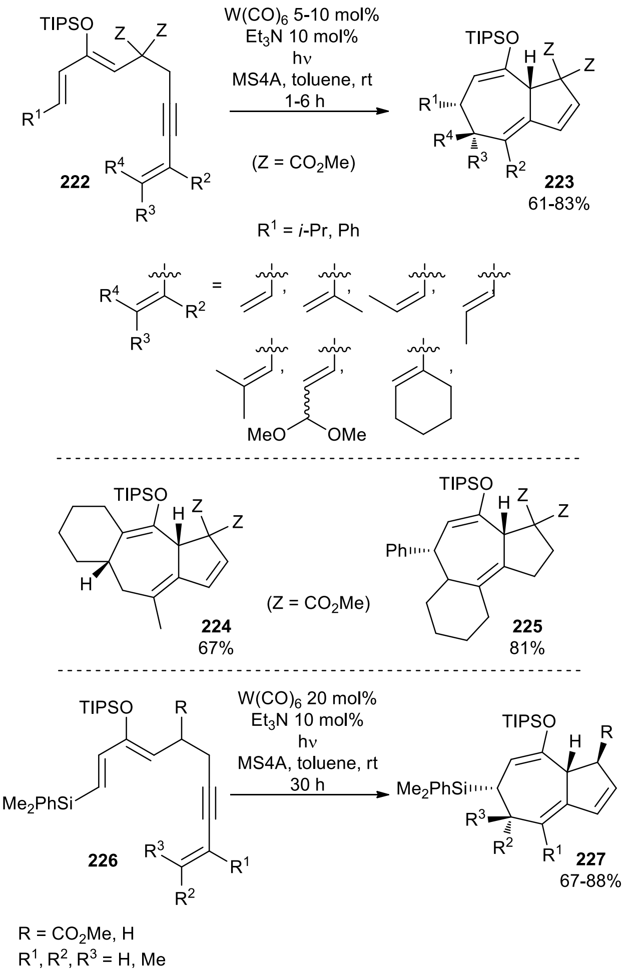
218, to form enones, such as **219**.[62,63] In a similar manner, ω-iodoacetylenic silyl enol ethers undergo cyclization to give *endo*-cyclized products in good yield, although stoichiometric amounts of $W(CO)_5(THF)$ are required.[64] Their mechanistic proposal for the non-iodinated acetylenes **218** suggests the participation of zwitterionic addition species **220** as intermediate for this transformation. However, theoretical studies performed on the reaction found cyclopropyl carbene structure **221** to be the favourable species in the gas phase (Scheme 45).[65]



Scheme 45 Tungsten carbonyl complexes-catalysed cyclization of ω-acetylenic silyl enol ethers **218**.

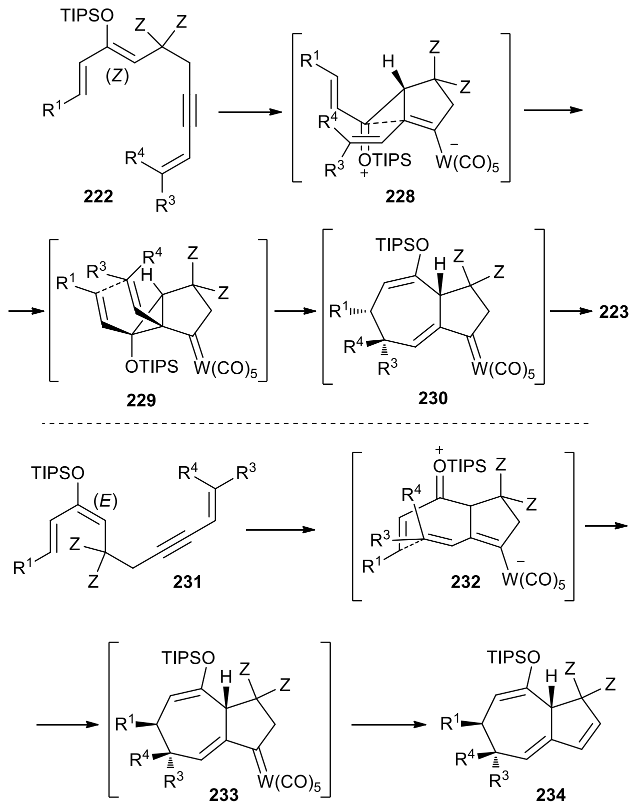
The previous result prompted the search for reactions with low energy activation, which could be feasible through cyclopropyl carbene intermediates, such as **221**.[66] Indeed, according to this approach, bicyclo[5.3.0]decane derivatives **223** can be readily prepared in good yields by intramolecular $W(CO)_5(THF)$ catalysed reaction of substrates **222**, having 2-silyloxydiene and a conjugate enyne moieties in their structure (Scheme 46; *top*). The reaction tolerates a wide range of substituents in the dienol silyl ether skeleton. Indeed, it has been applied to the synthesis of tricyclic compounds such as **224,225** by using the appropriate starting materials: dienol silyl ethers bearing a cyclohexenyl group as part of the diene moiety or at the alkyne terminus (Scheme 46; *middle*).

The synthetic strategy has also been successfully extended to mono-ester substituted substrates (**226**, R = CO_2Me) and to dienynes having no substituent at the 5-position (**226**, R = H) to provide bicyclo[5.3.0]decanes **227** (Scheme 46; *bottom*).[67]



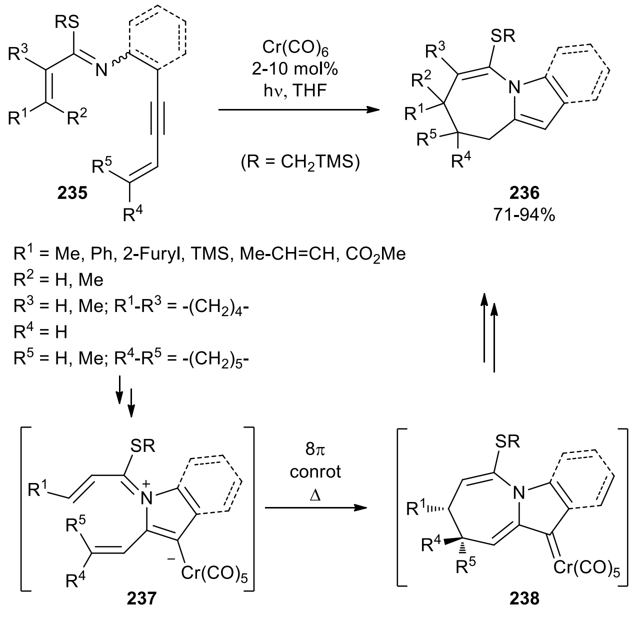
Scheme 46 Tungsten carbonyl complexes-catalysed stereoselective synthesis of bicyclo[5.3.0]decanes **227**.

The overall sequence is stereospecific and highly diastereoselective. Regarding the two contiguous stereocenters generated at the seven-membered ring, all four stereoisomers may be prepared by choosing the appropriate combination of the configurations of the silyl enol ether and enyne double bonds. Indeed, important mechanistic considerations can be inferred from stereochemical analysis. Thus, after the initial 5-*endo-dig* cyclization, two mechanisms seem to be operating depending on the silyl enol ether double bond configuration: a) for (*Z*)-enol silyl ether **222**, a Cope rearrangement of *cis*-divinylcyclopropane carbene complex intermediate **229** would explain the configuration observed in the final product **223** (Scheme 47; *top*); b) for (*E*)-enol silyl ether **231**, nucleophilic addition of the dienyl tungsten moiety to the α,β-unsaturated silyloxonium moiety in the zwitterionic intermediate **232**, would lead to the bicyclo[5.3.0]decane skeleton **234** (Scheme 47; *botton*). This alternative mechanism allows overcoming the limitation caused by the impossibility of a Cope rearrangement in a *trans*-divinylcyclopropane carbene complex.



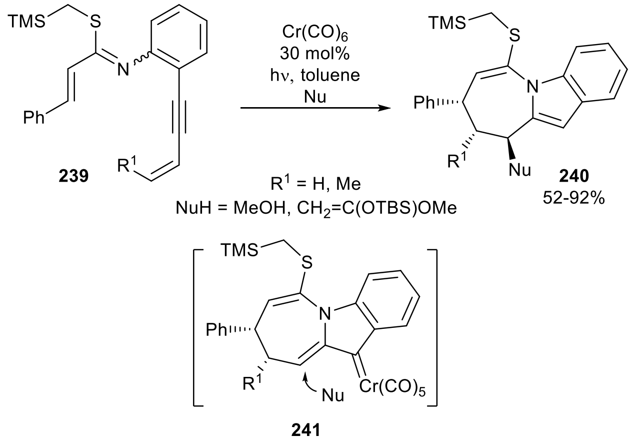
Scheme 47 Proposed mechanisms for tungsten carbonyl complexes-catalysed stereoselective synthesis of bicyclo[5.3.0]decane frameworks.

In a similar manner, 1-azabicyclo[5.3.0]decane derivatives **236** have been formed by treating starting thioimidates **235** with catalytic amounts of chromium hexacarbonyl (as low as 2 mol%).[68] A varied substitution pattern on the starting thioimidates is tolerated for this transformation. Stereochemical results obtained under photochemical or thermal conditions were identical. This fact, together with the relative stereochemistry on the products, suggests that the reaction sequence occurs through conrotatory 1,7-electrocyclization of zwitterionic intermediates **237**, –the opposite way than for carbon analogues– to form non-heteroatom-stabilized chromium carbene complexes **238** which evolve into the final 1-azabicyclo[5.3.0]decane derivatives **236** (Scheme 48).



Scheme 48 Chromium hexacarbonyl-catalysed stereoselective synthesis of 1-azabicyclo[5.3.0]decane frameworks.

Additionally, an external component can be incorporated when the reaction is performed in the presence of a nucleophile, leading to tricyclic indoles **240** bearing up to three consecutive stereocenters (Scheme 49).[68] Methanol or a silyl ketene ketal have been employed as nucleophiles. In most cases, only single isomers are obtained due to stereoselective 1,4-addition of the nucleophile to the less hindered face of the α,β-unsaturated non-heteroatom-stabilized carbene complex intermediate **241**.

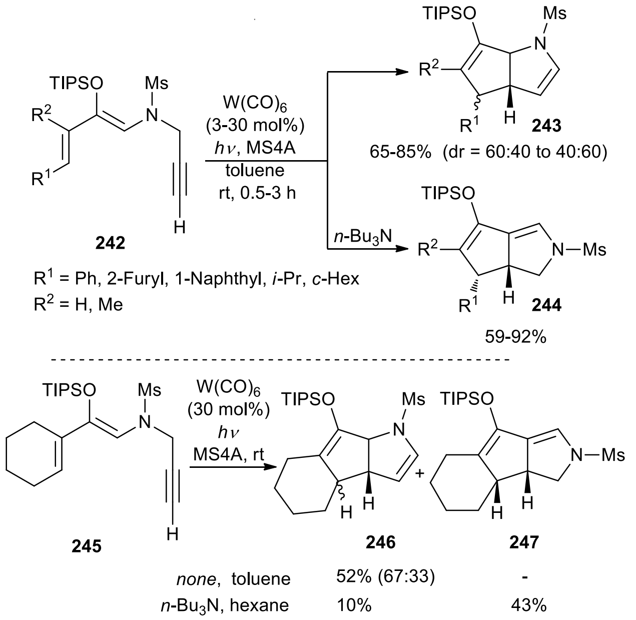


Scheme 49 Chromium hexacarbonyl-catalysed cyclization/1,4-addition of nucleophiles reaction sequence.

Terminal acetylenic dienol silyl enol ethers **242** also undergo $W(CO)_6$ catalysed cyclization to form different types of nitrogen-containing bicyclic compounds.[69] Thus, 2-azabicyclo[3.3.0]octane derivatives **243** are obtained as mixtures of diastereomers when the reaction is carried out in the presence of MS4A under photoirradiation. On the other hand, isomeric 3-

azabicyclo[3.3.0]octanes **244** are formed when the reaction is performed under identical conditions but with tri-*n*-butylamine as an additive (Scheme 50; *top*). Both reactions are completely selective for substrates having an aryl group at the diene terminus, although small amounts of 2-azabicyclo[3.3.0]octanes are formed as by-products in the amine promoted reaction for substrates having an alkyl group at that position.

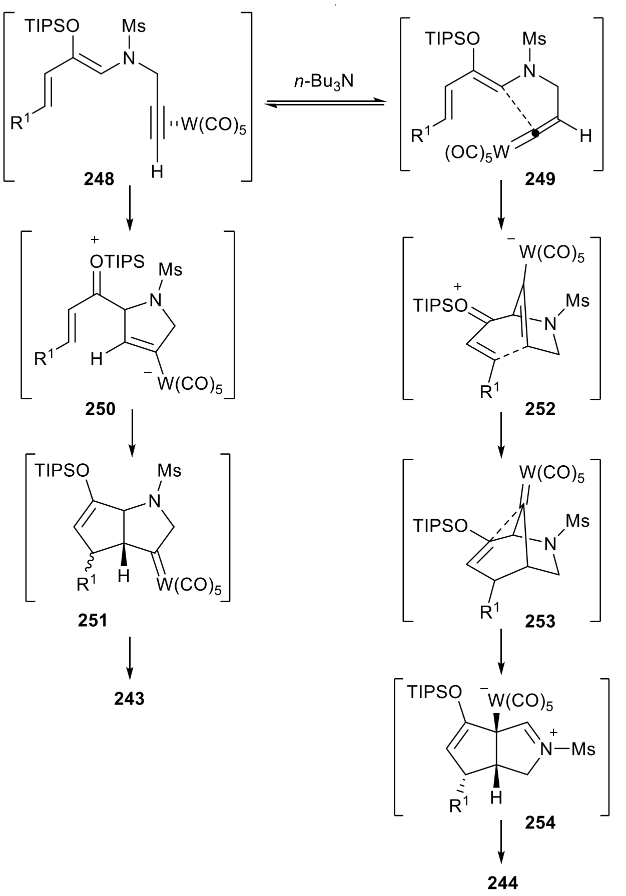
Additionally, tricyclic products **246** and **247** have been obtained in reasonable yields from dienol silyl ether **245**, having a cyclohexenyl group at the diene moiety (Scheme 50; *bottom*).



Scheme 50 Tungsten hexacarbonyl-catalysed synthesis of 2- or 3-azabicyclo[3.3.0]octane frameworks.

These results can be explained considering an equilibrium between π-alkyne complex **248** and alkenylidene complex **249** (Scheme 51). In the absence of tri-*n*-butylamine, the reaction could evolve by an initial 5-*endo-dig* nucleophilic cyclization to form zwitterionic tungstate **250** followed by a Michael-type addition to produce bicyclic non-heteroatom-stabilized carbene complex **251**, which finally should lead to 2-azabicyclo[3.3.0]octane **243**.

On the other hand, the addition of the tertiary amine facilitates the tautomerization to tungsten alkenylidene **249** (for other transformations initiated by formation of an alkenylidene, see section 3.10.3.). Then, nucleophilic attack of the enol silyl ether to the alkenylidene carbon would generate zwitterionic tungstate **252**, and its evolution by Michael-type addition to the α,β-unsaturated silyloxonium moiety would produce non-heteroatom-stabilized bridged-carbene complex **253**. Then, facilitated by electron-donation from the nitrogen atom, a 1,2-alkyl migration should take place to form zwitterionic species **254**. Finally, a metal elimination from intermediate **254** would form 3-azabicyclo[3.3.0]octane **244** (Scheme 51). Deuterium and ^{13}C-labelling experiments support the proposed mechanism.

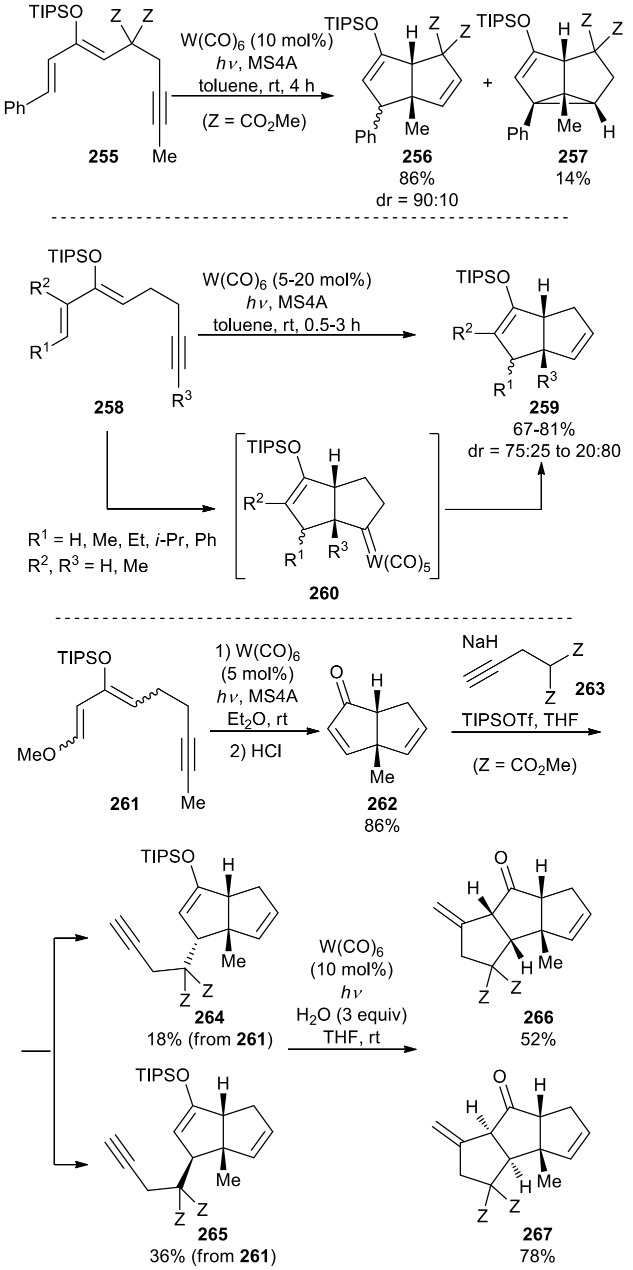


Scheme 51 Proposed mechanism for the tungsten hexacarbonyl-catalysed synthesis of 2- or 3-azabicyclo[3.3.0]octane frameworks.

In a similar manner, bicyclo[3.3.0]octane derivatives **256** are obtained as mixture of isomers when the analogous all-carbon skeleton acetylenic dienol silyl ether **255** is treated with catalytic amount of W(CO)$_6$ (Scheme 52). The isolation of tricyclic compound **257** as a by-product implicates the presence of a carbene complex intermediate (Scheme 52; *top*).[70]

The scope of the reaction indicates that presence of *gem*-diester groups is not necessary for the reaction to proceed. Thus, a variety of bicyclo[3.3.0]octane derivatives **259** are formed with moderate yields and stereoselectivities from acetylenic dienol silyl ether **258**. A mechanism analogous to the one depicted in Scheme 51 would explain the formation of the reaction products through non-heteroatom-stabilized carbene complex intermediate **260** (Scheme 52; *middle*). Rhenium complex, [ReCl(CO)$_5$], also catalyzes this triple-bond geminal carbo-functionalization reaction very efficiently (68-92% yield), with lower catalyst loading.

This tandem cyclization protocol has been applied to a concise synthesis of the basic carbon skeleton of triquinanes (Scheme 52; *bottom*). Thus, tungsten carbonyl (5 mol%) treatment of dienol silyl ether **261**, containing a methoxy group at the diene terminus, followed by hydrolysis, led to bicyclic ketone **262** in very good yield. Conjugate addition of dimethyl propargylmalonate sodium salt **261** in the presence of TIPSOTf provided distereomeric ω-acetylenic silyl enol ethers **264** and **265** in moderate yields. A new photoirradiation, in the presence of catalytic amount of tungsten carbonyl and water, gave tricyclic ketones **266** and **267** bearing a triquinane skeleton.

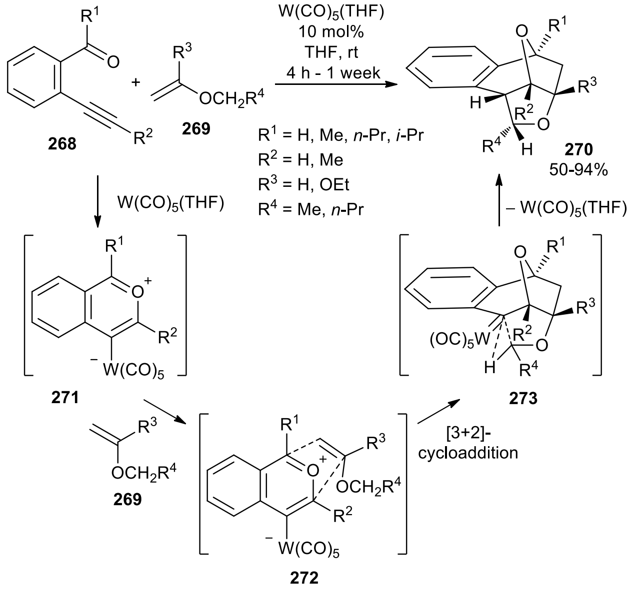


Scheme 52 Tungsten hexacarbonyl-catalysed synthesis of bicyclo[3.3.0]octane frameworks.

3.10.2. Initiated by 6-endo-dig cyclizations.

Several transformations initiated by a 6-*endo-dig* cyclization and involving group 6 metal non-heteroatom-stabilized carbene complexes as reaction intermediates have also been described. Thus, tungsten-containing carbonyl ylides are involved in the $W(CO)_6(THF)$ catalysed reaction between *o*-ethynyl phenyl ketone derivatives **268** and electron-rich alkenes **269** to form polycyclic compounds **270** (Scheme 53). After initial triple bond activation by the tungsten carbonyl π-acid, nucleophilic attack by the oxygen of the carbonyl group causes the previously mentioned 6-*endo-dig* cyclization leading to tungsten-containing carbonyl ylide **271**.[71] A [3+2] cycloaddition should then take place in a concerted manner leading to tungsten non-heteroatom-stabilized carbene complex **273**. This intermediate inserts into a C-H bond of the alkoxy group to give product **270** while the tungsten catalyst species is regenerated.

Interestingly, the absence of the ketene acetal leads to the formation of a benzopyranylidene complex.



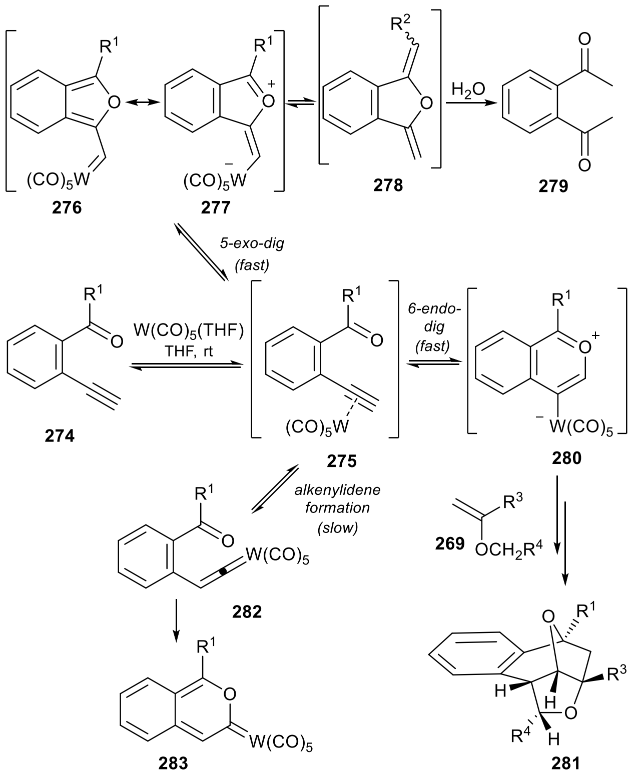
Scheme 53 Synthesis of polycyclic compounds **270** by tungsten carbonyl catalysed rearrangement of *o*-ethynylphenylketones.

Therefore, three different possible reaction pathways have been reported for the tungsten carbonyl mediated cyclization of *o*-ethynylphenylketone derivatives **274**, once generation of activated alkyne complex **275** has been accomplished (Scheme 54):

(a) *5-Exo-dig* cyclization, leading to the formation of tungsten-containing carbonyl ylide **277**, which is a resonance form of furyl carbene complex **276**. As previously mentioned in Schemes 17 and 27, this pathway has been observed also for β-ethynyl α,β-unsaturated ketones. Additionally, an approximately 50% yield of 1,2-bis (acetyl)benzene **279** (R^1 = Me) was isolated when the reaction was performed in the presence of 5 equiv. of H_2O.[71b] Compound **279** is presumably produced by hydrolysis of NMR-observed methyleneisobenzofuran **278**, which comes from **277** by deprotonation from the R^1 group and protonation of tungsten-carbon bond.

(b) *6-Endo-dig* cyclization, to generate tungsten carbonyl ylide **280**, which will explain the synthesis of bicyclic compounds **281** and the results described at Scheme 55 (*vide infra*).

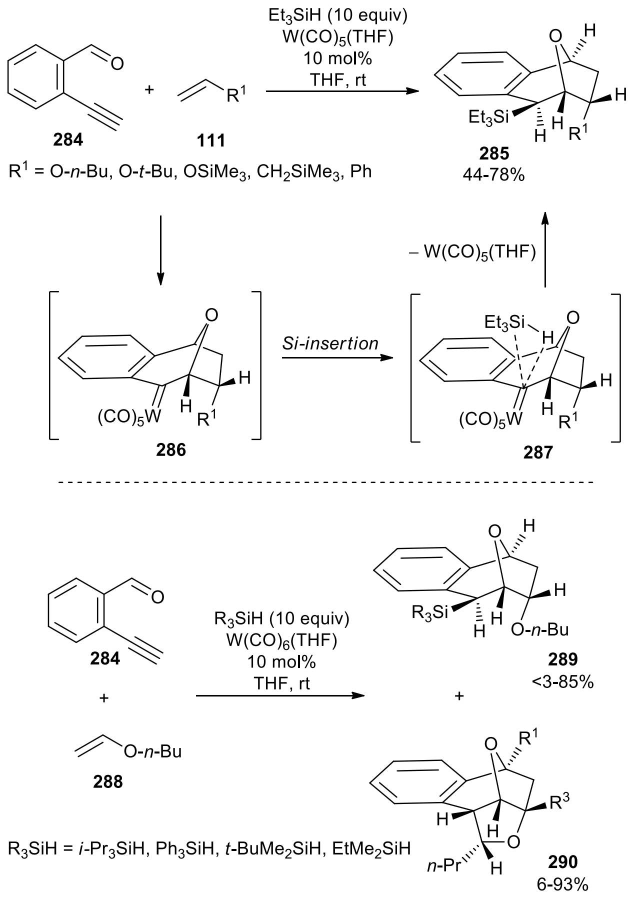
(c) *Formation of alkenylidene* **282**, by 1,2-hydrogen shift, which would lead to benzopyranylidene tungsten Fischer carbene complex **283**.[72]



Scheme 54 Alternative reaction pathways for tungsten hexacarbonyl-catalysed reactions of *o*-ethynylphenylketones.

The reached results pointed out that, presumably, pathways (a) and (b) are faster than (c), which occurs in the absence of the trapping agent (H_2O, alkene). Additionally, (a) and (b) should be reversible and in equilibrium through metal-complexed species **277** while formation of tungsten carbene complex **283** forces pathway (c) to be irreversible.

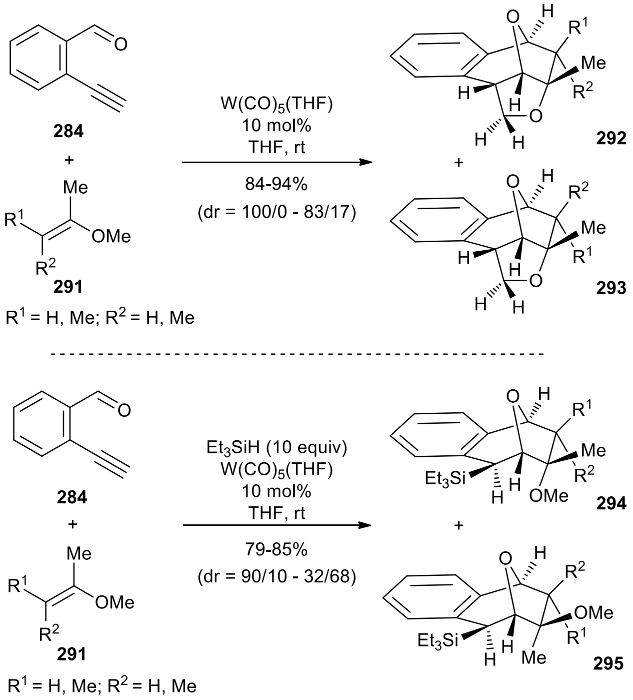
Intermediate polycyclic carbene complexes in these transformations (**273**, Scheme 53; **286**, Scheme 55) could not be isolated. However, their intermolecular trapping was achieved by carrying out the reaction with monosubstituted olefins in the presence of triethylsilane to form polycyclic tetraalkylsilanes **285** in moderate to good yields and with complete regio- and diastereoselectivity (Scheme 55).[71b] Carbene insertion into the silicon-hydrogen bond of silanes, described here for a catalytic multicomponent reaction involving non-heteroatom-stabilized carbene complexes, is a well-stablished reaction of free carbenes or carbene-metal complexes. Its scope was extended also to other trialkylsilanes, although in these cases, besides the corresponding tetraalkylsilane polycyclic products **289**, polycyclic compounds **290** with no insertion in the Si-H bond were also obtained in variable amounts depending on the nature (mainly, bulkyness) of the trialkylsilane (Scheme 55; *bottom*).



Scheme 55 Trapping of non-stabilized carbene complex intermediate **286** with silanes. Synthesis of polycyclic tetralkylsilanes.

The extension of these transformations (in the presence or absence of triethylsilane) to di- and tri-substituted olefins provided useful mechanistic information (Scheme 56).[71b] For instance, the fact that the reaction with 2-methoxypropene **291** (**$R^1 = R^2 = H$**) provides a single isomer **292** in the absence of the trapping agent while a mixture of two diastereomers **294** and **295** were obtained in the presence of triethylsilane, suggests that the facial selectivity of these two reactions strongly depends on the presence of the trapping agent. Therefore, the combination of all these findings suggests a concerted and reversible nature of the [3+2]-cycloaddition reaction step in these catalytic transformations.

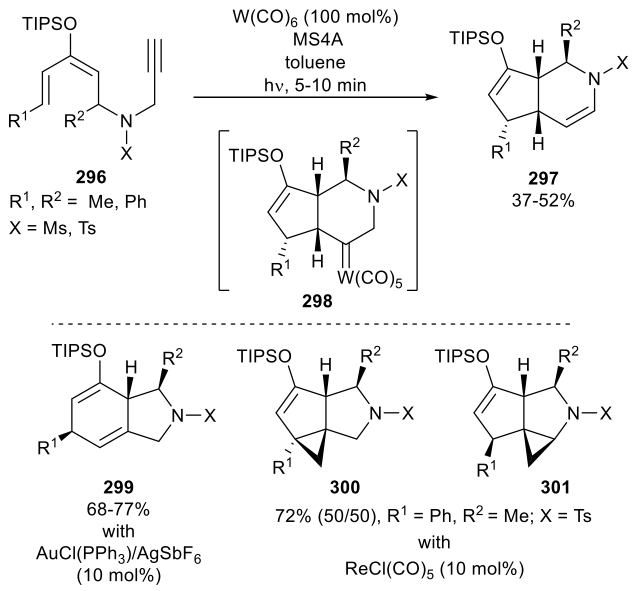
Indeed, a theoretical study of cycloaddition reactions of tungsten-containing carbonyl ylides depicted in Schemes 53, 55 and 56 points out that the [3+2]-cycloaddition proceeds in a reversible and concerted manner, being the *endo*-mode cycloaddition kinetically favoured.[73]



Scheme 56 Mechanistic test: reactions with di- and trisubstituted olefins.

In a similar manner, terminal acetylenic dienol silyl enol ethers **296**, containing N-Ts or N-Ms component in their tethers, undergo geminal carbo-functionalization to produce 3-azabicyclo[4.3.0]nonane derivatives **297** in moderate yields, when photoirradiated in the presence of equimolar amount of $W(CO)_6$ (Scheme 57; *top*). [70,74] A tandem cyclization sequence consisting of an initial 6-*endo-dig* cyclization on the tungsten carbonyl activated triple bond followed by a Michael-type addition would lead to tungsten carbene complex **298**, which should evolve into the final products. The overall sequence takes place in a diastereoselective manner.

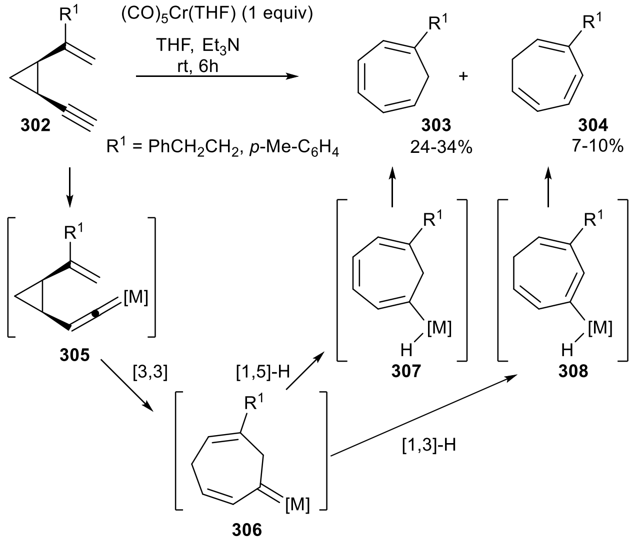
Remarkably, the reaction outcome can be controlled by the selection of the appropriate π-acid catalysts. Thus, 8-azabicyclo[4.3.0]nonane derivatives **299** or tricyclic compounds **300** and **301** are selectively formed by employing either cationic gold or rhenium catalysts (Scheme 57; *bottom*). In a different behaviour than for the tungsten catalyst, all these products come from 5-*exo-dig* cyclizations.



Scheme 57 Catalyst-controlled tandem cyclization reactions.

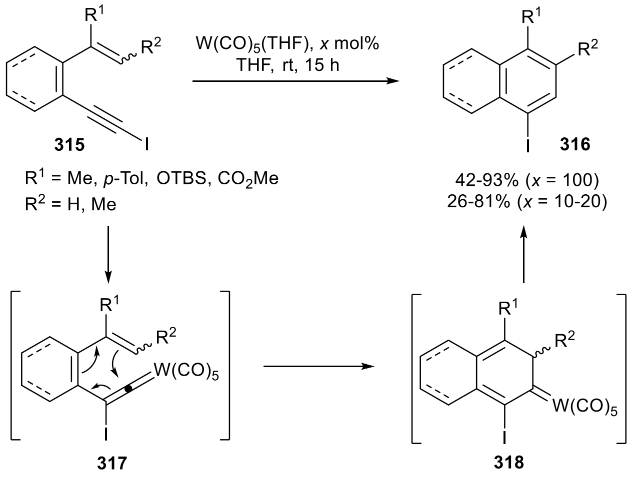
3.10.3. Initiated by alkenylidene formation.

A third type of transformations involving group 6 metal non-stabilized carbene complexes as reaction intermediates include those that are initiated by formation of alkenylidene species. For instance, *cis*-1-alkenyl-2-ethynylcyclopropanes **302** undergo rearrangement in the presence of stoichiometric amounts of $Cr(CO)_5(THF)$ to provide moderate yields of mixtures of isomeric 1,3,5-cycloheptatrienes **303** and **304** (Scheme 58).[75] The reaction should proceed via formation of alkenylidenechromium complex **305**, which should evolve by [3,3]-sigmatropic rearrangement to non-heteroatom-stabilized carbene complex **306**. Subsequent [1,5]- or [1,3]-hydrogen shifts in **306** to generate metallated cycloheptatrienes **307** and **308**, followed by reductive elimination, would readily explain the formation of regioisomeric reaction products.



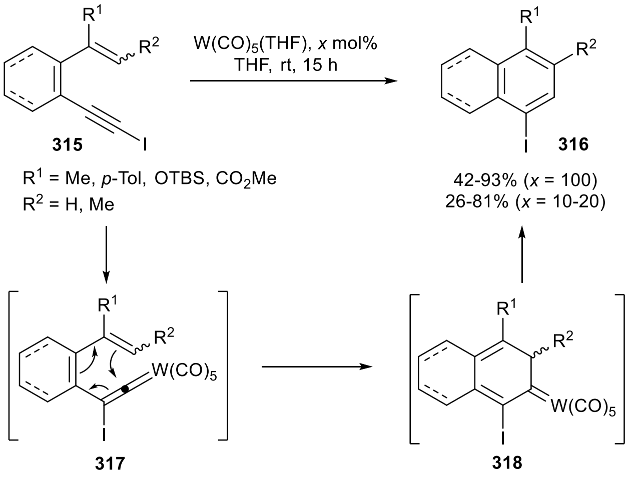
Scheme 58 $Cr(CO)_5(THF)$-catalysed rearrangement of *cis*-1-alkenyl-2-ethynylcyclopropanes to 1,3,5-cycloheptatrienes.

Naphthalene derivatives **310** and heteropolyaromatic compounds **314** have been synthesized from benzenes substituted at the *ortho*-position, with ethynyl and alkenyl (**309**) or heteroaromatic groups (**313**), usually in good to excellent yields (Scheme 59).[76] Catalytic or, in some cases, stoichiometric amounts of $(CO)_5W(THF)$ are required, depending on the nature of the substrate. The reaction seems to proceed via alkenyldiene intermediates **311**, which undergo a 6π electrocyclization to non-heteroatom-stabilized carbene complexes **312**. Isomerization, followed by reductive elimination, should lead to the reaction products. Deuterium-labelling experiments support the proposed mechanism.



Scheme 59 Synthesis of polyaromatic **310** and heteropolyaromatic compounds **314** by tungsten carbonyl catalysed cyclization of aromatic enynes.

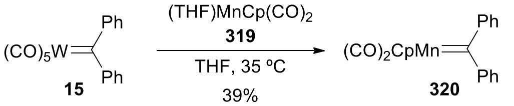
Transformation of 1-iodoalkynes **315** can be also catalysed by tungsten carbonyl complexes to form iodo-substituted benzene or naphthalene derivatives **316** (Scheme 60). The reaction proceeds satisfactorily not only for *o*-(iodoethynyl)styrenes but also for non-aromatic dienyne derivatives. Good yields are usually reached when stoichiometric amount of $W(CO)_5(THF)$ is used, but the yield of the catalytic reaction depends on the structure and the substituents of the substrate.[64,77] Regarding the reaction mechanism, after the initial π-activation of the alkyne (see also Scheme 16), an isomerization via 1,2-migration of iodo group occurs to form tungsten iodoalkenylidene **317**. The evolution of tungsten alkenylidene **317** by a 6π-electron electrocyclization would lead to non-heteroatom-stabilized carbene complex intermediate **318**, which yields the final products by 1,2-hydrogen migration and regeneration of $W(CO)_5(THF)$.



Scheme 60 Synthesis of iodobenzene or -naphthalene derivatives by tungsten carbonyl catalysed rearrangement of 1-iodoalkynes.

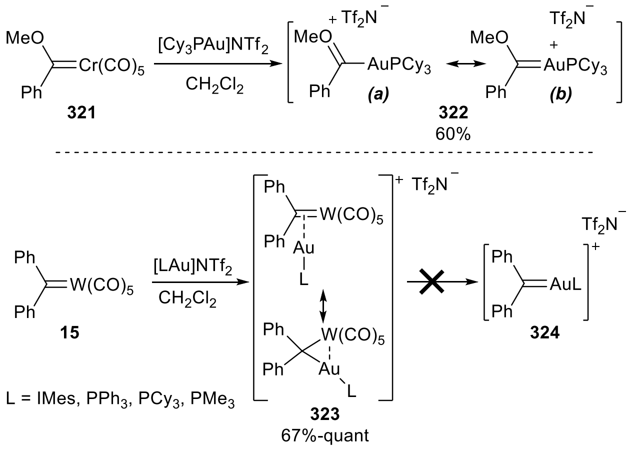
3.14. Transmetallation reactions

Mainly due to the low stability of non-heteroatom-carbene complexes, very few examples can be found in the literature related to their transmetallation reaction.[78] However, diphenyl tungsten carbene complex **15** can be transformed into a manganese carbene complex **320** (Scheme 61).[79] The transmetallation reported here occurs through a thermolysis of the metal carbene in the presence of dicarbonyl(cyclopentadienyl) manganese complex **319**.



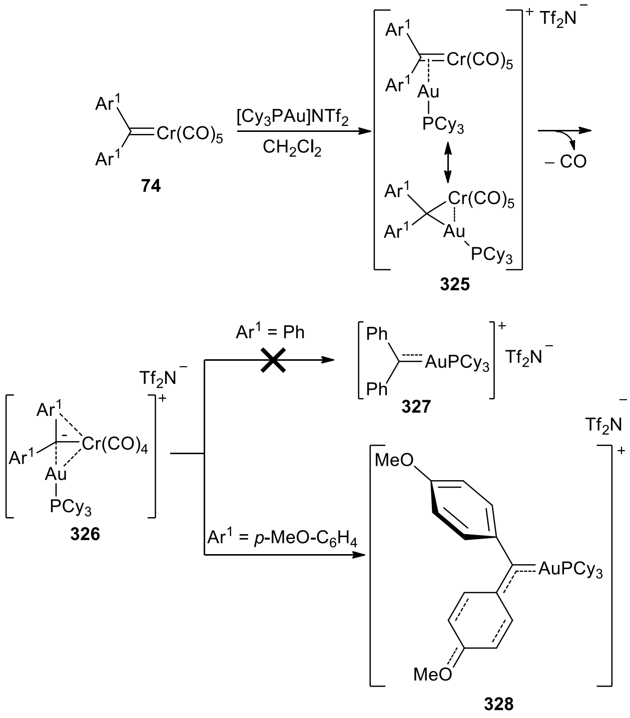
Scheme 61 Transmetallation of a non-heteroatom-stabilized carbene complex from tungsten to manganese.

On the other hand, gold species have bloomed along the last two decades as powerful carbophilic catalysts which are able to activate double and triple C-C bonds (alkenes, allenes, alkynes) toward nucleophilic addition. In many of these transformations gold carbene complexes appear as plausible reaction intermediates.[80] Indeed, gold carbene complexes can be readily prepared by transmetallation from group 6 stabilized Fischer carbene complexes. For instance, Fürstner has described the synthesis of carbene complex **322** by treating chromium carbene complex **321** with $[Cy_3PAu]NTf_2$; in this complex, bond-distances, in X-ray structure, indicate that oxocarbenium resonance form **322-a** is dominant (Scheme 62; *top*).[81] However, the employment of the same transmetallation strategy for the preparation of non-heteroatom-stabilized gold carbene complex **324** was unsuccessful, either from tungsten diphenyl carbene complex **15** or from chromium diphenyl carbene complex **74** (Ar^1 = Ph). Instead, hetero-bimetallic complexes **323** and **325** (Ar^1 = Ph) were obtained in good to excellent yields (Scheme 62; *bottom* and Scheme 63).



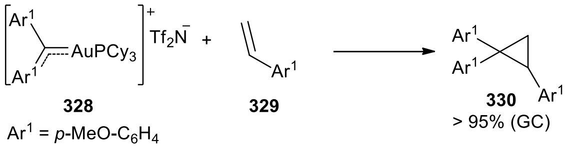
Scheme 62 Gold-complexes by transmetallation reactions.

Some heteroatom stabilizing effect is necessary to achieve an effective gold-for-chromium exchange.[82] Thus, the treatment of chromium carbene complex **74** (Ar^1 = *p*-MeO-C_6H_4) with $[Cy_3PAu]NTf_2$ at low temperature provides heterobimetallic **325** (Ar^1 = *p*-MeO-C_6H_4) species which upon warming to –50 ºC turned into a mixture of hetero-bimetallic compound **326** (ca. 40%) and gold carbene complex **328** (ca. 60%) (Scheme 63).



Scheme 63 Chromium-gold transmetallation.

Addition of *p*-methoxystyrene **329** to an intensely pink-colored solution of carbene complex **328** at –78 ºC followed by warming resulted in full conversion into cyclopropane **330** when room temperature was reached (Scheme 64). This result evidences that gold carbene complex **328** is also a reactive species.



Scheme 64 Cyclopropanation of *p*-methoxystyrene **329** by a gold carbene complex **328**.

4. Conclusions.

The work compiled in this review highlights the significant contribution of non-heteroatom-stabilized group 6 metal carbene complexes to organic synthesis. Thus, diverse strategies for their preparation have been developed, ranging from those limited to the synthesis of specific carbene complexes to others presenting a broader scope.

Regarding their reactivity, early contributions mainly focused in cyclopropanations, olefin and enyne metathesis, and insertion reactions, and highly relevant findings in these fields were achieved by pioneers: E. O Fischer, Casey, Katz, H. Fischer, Dötz…They paved the way for a better understanding of the mechanisms involved in some of those reactions.

Thus, Barluenga pointed out that non-heteroatom-stabilized alkynyl carbene complexes, easily formed by sequential treatment of Fischer carbenes with lithium acetylides and TMSOTf, are highly valuable stoichiometric reagents for the efficient and selective synthesis of diverse conjugate acyclic, carbocyclic and/or heterocyclic products through reactions against unsaturated reagents (alkenes, dienes, imines,…).

On the other hand, seminal approaches for the synthesis of a variety of carbo- and heterocycles have been developed, mainly by Iwasawa, based on the ability of group 6 metal carbonyl complexes to coordinate to C-C triple bonds as π-acids to form π-complexes and on their further evolution involving non-heteroatom-stabilized carbene complexes as stoichiometric or catalytic intermediates. Thus, taking advantage of this behavior, transformations such as high-yielding and atom-economic catalytic cycloisomerizations, cycloadditions with olefins or imines, or even multi-component reactions have provided straightforward access to structurally complex molecules.

Although less explored, transmetallation from non-heteroatom-stabilized carbene complexes has emerged as an attractive option to generate reactive carbene complexes of other metals.

As shown, either as stoichiometric reagents or as catalytic intermediates, non-heteroatom-stabilized group 6 metal carbene complexes offer direct and highly valuable approaches for the synthesis of organic skeletons difficult to access by other routes. Therefore, although the chemistry of non-heteroatom-stabilized carbene complexes is a rather mature area, relevant contributions in the field should be still to come.

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† Dedicated to Professor Dr Barry M. Trost on the occasion of his 75th birthday

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