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Mini Review

Early transition metal carbenoid reagents in epimetallation and metallative dimerization of unsaturated organic substrates[☆]

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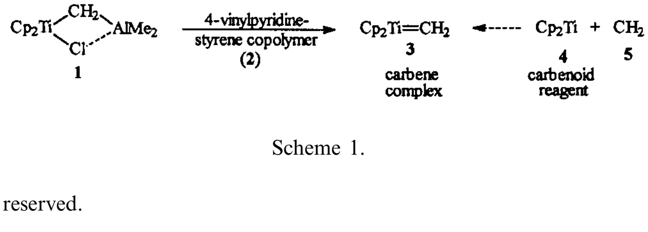
Abstract

The focus of this review is transition metal carbenoid reagents, which are considered to be subvalent transition metal compounds having at least one unshared electron pair on the metal center and are thus able to undergo oxidative addition to either σ- or π-bonds of substrate reactants. Illustrative carbenoids are Cp^*_2Ti and Bpy·Ni, which are contrasted with related carbene complexes, such as $Cp^*_2Ti{=}CH_2$ and Bpy·Ni=CPh–CPh=CHPh. The XRD and IR data for the carbenoid-like adducts of Cp^*_2Ti with $H_2C{=}CH_2$ and of Bpy·Ni with PhC≡CPh have been analyzed to assess the electron-transfer bonding from the metal to the complexed hydrocarbon. Such considerations lead to the conclusion that such adducts have significant σ-bonding of a typical three-membered metallocycle. The impact of two other characteristics of these metal carbenoids, namely their singlet or triplet state and their electrophilic or nucleophilic reactivity towards π-bonded substrates, is also assessed in exploring their possible modes of reaction. The succeeding discussion of recent research then focuses on non-metallocene early transition metal carbenoids of the type, M_tX_2, $M_t(OR)_2$ and $M_tH_2^-$. The utility of alkylative reduction of transition metal salts, M_tX_m, by RMgX or RLi is shown to be widely applicable and the resulting neutral (M_tX_{m-n}) or anionic (CrH_2^-) carbenoids are shown to insert into or add to a diverse array of linkages, such as C–X, C=O, C=N, C=C and C≡C bonds leading to C–C bond formation and thus to coupling, oligomerization and/or polymerization. Especially with C=E bonds (E = C, N, O) and M_tX_{m-n} the initial three-membered metallocycle formed plays a demonstrable role in the organic products generated. Utilization of this metallocycle in selective organic synthesis has already been highly successful in the research groups of Kulinkovich, Sato and Eisch.

1. Introduction

1.1. *Transition metal carbenoids*

Although our research group is pursuing investigations in the area of transition metal complexes of carbenes, the main theme of this volume, with the encouragement of the editor we have decided instead to present our most recent, rewarding findings on the complementary topic of transition metal carbenoid reagents. To illustrate the distinction to be made here between these two classes of intermediates, let us consider the Tebbe reagent [1] (**1**, Scheme 1). If the complexed Me_2AlCl is removed by Lewis base **2**, the reactive carbene complex **3** results [2]. In a *Gedankenexperiment* **3** can be viewed as resulting from the union of titanocene **4** with methylene **5**. Titanocene can thus be considered as a carbene equivalent or carbenoid reagent. As with all transition metal carbenoid reagents, the transition metal fragment will formally be in a subvalent oxidation state. Extended Hückel calculations have been carried out for the bent $(\pi\text{-}C_5H_5)_2Ti$ molecule in support of the reactive singlet carbenoid nature of such an intermediate [3]. In fact, the pyrolysis



Scheme 1.

[☆] Part 21 of the series, "Organic Chemistry of Subvalent Transition Metal Complexes"; for the previous Part 20, see Eur. J. Inorg. Chem. (2000) in press.

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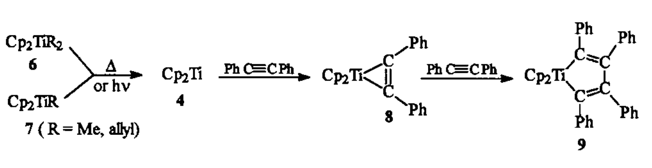
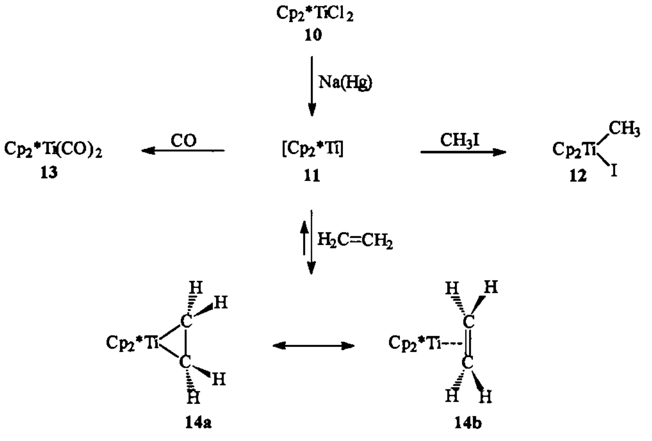
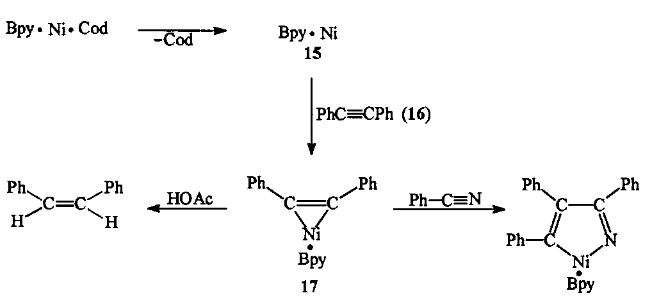


Scheme 2.



Scheme 3.



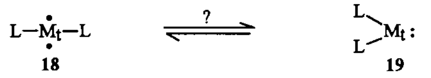
Scheme 4.

or photolysis of various titanocene derivatives, such as Cp_2TiR_2 [4], Cp_2TiMe [5] and $Cp_2Ti(\pi\text{-allyl})$ [6], in the presence of diphenylacetylene, has led to moderate or good yields of titanole **9**, which is consistent with the carbene-like addition of Cp_2Ti to the alkyne to form intermediate **8** (Scheme 2). A further insertion of the alkyne to the strained titanacyclopropene **8** provides **9**.

The carbenoid character of such titanocenes can be most clearly delineated with bis(pentamethylcyclopentadienyl) derivative **11** (Cp_2^*Ti), readily generated in situ by the dehalogenation of **10** (Scheme 3). The reactions of **11** with a wide variety of σ- and π-bonded substrates nicely parallel the insertions and additions of singlet and triplet carbenes in synthetic organic chemistry [7]. The individual significance of the three types of reactions depicted in Scheme 3 deserves some brief comment. The reaction of **11** with CO is the actual realization of the Gedankenexperiment of Cp_2Ti with a carbene, except that an additional CO becomes bonded. With CH_3I it is evident that a two-electron transfer or oxidative addition to produce **12** has resulted in complete cleavage of the C–I bond. However, the bonding involved in the formation of **14** is not immediately deducible. Whether **14** should be viewed as a titanacyclopropane (**14a**) and hence the product of oxidative addition or whether **14** would rather resemble a π-complex of carbenoid Cp_2^*Ti with a moderately perturbed C=C bond must be decided on the basis of the specific crystallographic and spectroscopic data of **14**. The observed Ti–C(ethylene) separation of 2.160 Å is very close to that of σ Ti–C bonds where the carbon is sp^2 hybridized, as in **9** (2.15 Å), but the C–C separation in the ethylene unit of 1.438 Å is intermediate between that of a free ethylene unit (1.337 Å) and that of a cyclopropane C–C bond (1.510 Å). No infrared band higher than 1490 cm^{-1} is reported, so the expected C=C band in **14** is shifted significantly to lower frequency. Therefore, all such structural data for **14** can be better reconciled by concluding that the bonding is much more closely represented by resonance structure **14a**, in which significant electron transfer from titanium to the ethylene's antibonding MO has occurred.

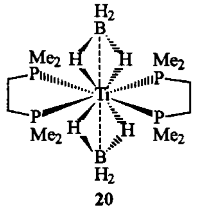
A similar structural analysis has most recently been applied to the adduct of the late transition metal carbene, Bpy·Ni (**15**), with diphenylacetylene (**16**). The spectroscopic and crystallographic data observed with **17**, as well as its chemical reactions, are in excellent accord with the bonding expected of a nickelacyclopropene having a nickel(II) oxidation state [8a] (Scheme 4). Noteworthy are the Ni–C separations of 1.86 Å (compared with typical Ni–C(sp^2) separation of 1.89 Å) and the acetylenic carbon–carbon separation of 1.30 Å (compared with the C=C separation in cyclopropene of 1.30 Å). Finally, the C–C infrared stretch at 1770 cm^{-1} in **17** is lowered by 330 cm^{-1} from the acetylenic stretch in phenylacetylene and is much closer to the stretching vibration in disubstituted *cis*-alkenes (1660 cm^{-1}). Furthermore, the chemical reactions undergone by **17**, namely protodenickelation by acetic acid and the insertion of benzonitrile, are typical reactions expected of a nickelacyclopropene (Scheme 4). It should be noted that **15** interacts with 1,2,3-triphenylcyclopropene apparently to form the corresponding carbene complex, Bpy·Ni=CPh–CPh=CPhH [8b].

A further consideration in such a carbenoid analogy for subvalent transition metal reagents, experimentally most evident for divalent Group 4 analogs, M_tL_2:, is whether such carbenoids can exist either as linear, triplet structures (**18**) or as bent, singlet structures (**19**) (Eq. (1)).



(1)

The previously cited Hückel MO calculations on titanocene [3] show a minimum in the total energy, not when the Cp rings are parallel (as in **18**), but when the interring angle is 30–40° (as in **19**). The carbenoid reactions of titanocenes **4** and **11** (Schemes 3 and 4) further support a bent, singlet ground state for such carbenoids. In complexes where the ligands are *trans* to each other, as in **20**, it is not surprising that the resulting linear array of BH_4–Ti–BH_4 should be found to be paramagnetic, as implied by **18** [9]. But what is not readily understandable is why the closely analogous structure **21** (both determined by combined XRD and neutron diffraction data) is diamagnetic, both in solution and in the solid state. Special π-interactions of the C–H bonding orbitals have to be invoked to explain such unexpected diamagnetism.



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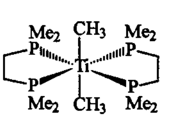

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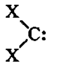
A final feature of such transition metal carbenoids would be to consider the electron-withdrawing (EW) or electron-donating (ED) effect of the ligands on the reactivity of such oxidative additions to σ- or π-bonds in the substrates. These effects parallel the distinctions made in carbene chemistry between electrophilic carbenes, such as dihalocarbenes (X_2C: **22**), which add readily to electron-rich olefins because the electron-withdrawing (EW) halo groups on the carbon makes it a better π-electron acceptor, and nucleophilic carbenes, such as the Wanzlick carbene (**23a** and **23b**) which adds various acidic H–C bonds by virtue of the electron-donating N-centers adjacent to the carbene site (**23b**) [10a]. For further information on such carbenes a most recent review should be consulted [10b].



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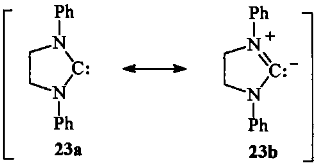
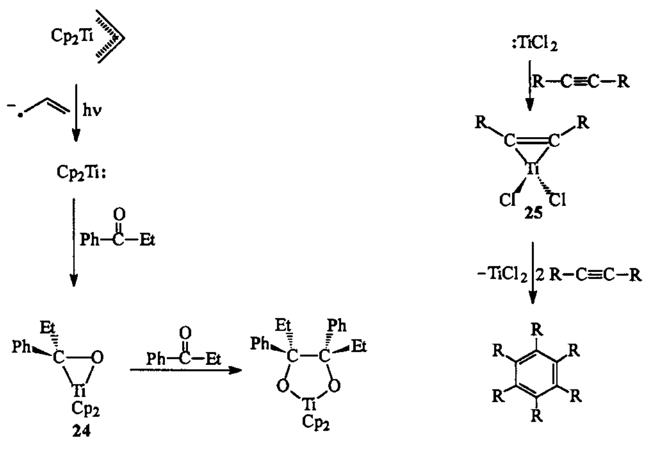


23a **23b**



Scheme 5.

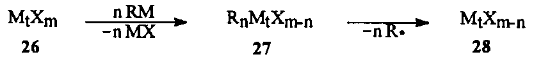
With reference to titanocene carbenoids **4** and **11**, the cyclopentadienyl and especially the pentamethylcyclopentadienyl rings would be expected to function as electron-donating (ED) ligands and thus to make **4** and **11** nucleophilic carbenoids towards carbonyl substrates. Analogously, in titanium(II) halides, the electron-withdrawing (EW) halogens should make such reagents behave as electrophilic carbenoids towards alkenes and alkynes. As is depicted in Scheme 5, both expectations have been realized experimentally [11,12].

As will be seen later, in both reactions there is persuasive evidence that the stoichiometric and stereoselective dimerization of propiophenone and the catalytic cyclotrimerization of the alkyne occur by way of three-membered ring adducts **24** and **25**, respectively.The fruitfulness of the carbene analogy for both early and late subvalent transition metal compounds is reflected in the diverse oxidative additions and most valuable couplings, cyclizations and oligomerizations that have been observed with both titanocene(II) and zirconocene(II) intermediates [13,14] and with nickel(0) complexes [15,16]. The significant advances made in these areas over the last 30 years have been reviewed insightfully elsewhere [13–16] and do not require further comment here.

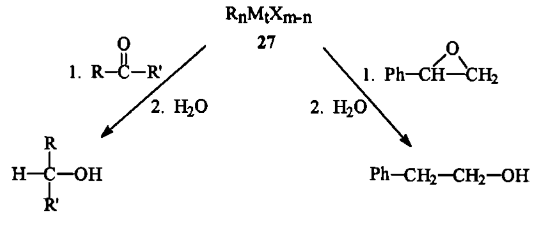
1.2. Non-metallocene, early transition metal carbenoids

Over the last decade the generation of transition metal carbenoids of the early transition metals that do not contain cyclopentadienyl ligands has attracted the keen attention of not only our research group, but also those of the Kulinkovich group in Russia and the Sato group in Japan. The advantages of forgoing the cyclopentadienyl groups on the transition metal lie in the lower expense of generating the carbenoid reagents as well as in avoiding the electron-donating and the steric effects of such rings. The attractive prospects of generating electrophilic, sterically undemanding transition metal carbenoids from commercially available salts and main-group organometallics clearly has motivated the burgeoning research in this area. Such non-metallocene, early transition metal carbenoids will be the focus of the present discussion.

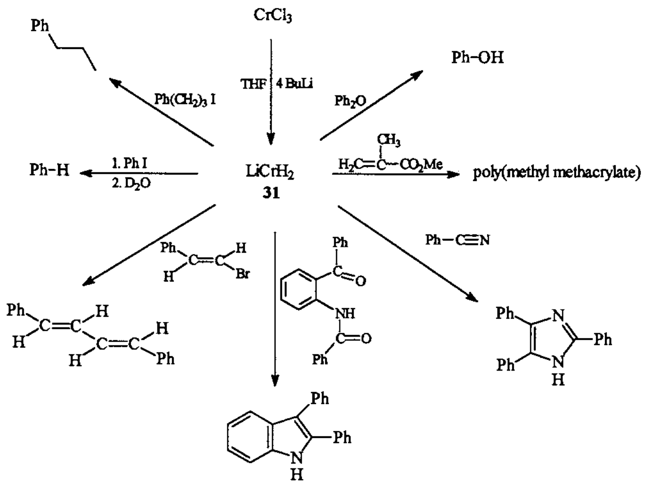
Our group's contributions to such subvalent transition metal carbenoids stemmed from a materials science project underway during 1990, in which we required a convenient route to Group 4 metal dihalides, which were to serve as precursors to metal borides [17]. Our observation that such dihalides were most useful reducing agents in organic chemistry and possibly were the active agents in so-called McMurry reducing agents caused us to launch a systematic study of generating subvalent early transition metal salts by a process we have come to term *alkylative reduction* [18].



Scheme 6.



Scheme 7.



Scheme 8.

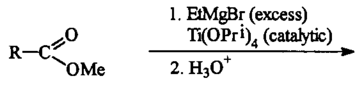
1.3. Alkylative reduction of early transition metal salts

By such studies we have shown that the interaction of transition metal salts (**26**) with main group metal alkyls (RM, most notably *n*-butyllithium) can lead, via transition metal alkyl intermediates (**27**), especially in donor solvents [18], to subvalent metal complexes (**28**) [18,19], which have proved to be selective reducing agents for a wide array of organic substrates (Scheme 6) [18–22]. By this process termed alkylative reduction [18], reducing agents of the empirical compositions $TiCl_2$ [18–20], $HfCl_2$ [18,20], CrCl [21], and MoCl [18,23] can readily be obtained in THF media. By the simple variant of conducting the alkylations of **26** in hydrocarbon media the intermediate transition metal alkyls (**27**) possess sufficient kinetic stability to function instead as hydrometallating agents, via olefin elimination, toward organic substrates as exemplified in Scheme 7 (M = Ti, Zr, Hf, Cr) for ketone substrates or epoxide substrates [24].

In our continuing search for transition metal reductants of greater scope and versatility, we then sought to overcome the limited solubility and hence lower reactivity of the aforementioned neutral salts, M_tX_{m-n} (**28**) in organic media by converting them into *ate*-complexes of the type MN_tR_{m-n+1} (**29**). We were gratified to find that the alkylative reduction of $CrCl_3$ in THF with four equivalents of *n*-butyllithium indeed resulted in the efficient production not of an *ate*-complex like (**30**) but of a dark red, THF-soluble complex hydride of empirical formula $LiCrH_2$ (**31**). This lithium chromium(I) dihydride is a powerful reductant that far surpasses the reactivity of previously examined neutral salts, M_tX_{m-n} (**28**), in the range of σ- and π-bonds reductively cleaved and in the scope of C–C bonds formed by the cyclization, oligomerization, or polymerization of π-bonded substrates. An overview of the bond cleavage and bond coupling reactions effected by $LiCrH_2$ is presented in Scheme 8 (products obtained after hydrolytic workup) [22].

In most of the foregoing cases the subvalent transition salts, M_tX_{m-n} (X = Cl, **28**), and the $LiCrH_2$ could be obtained free of the LiCl by-product and hence in an analytically pure state corresponding to their empirical formulae. However, the states of aggregation of their solvates, such as those with THF, remain to be determined. Nevertheless, the availability of such stoichiometrically defined transition metal carbenoids has permitted us to study the scope and mechanism of their reducing action on a diverse array of organic substrates [18,19,21,22].

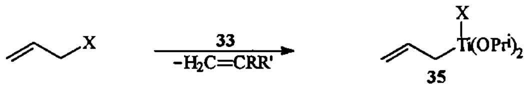
A remarkable reaction reported in 1989 by Kulinkovich and co-workers served to reveal the great potential importance of subvalent titanium compounds in organic synthesis [25]. Ethylmagnesium bromide in the presence of catalytic amounts of titanium(IV) isopropoxide reacted with carboxylic esters to provide high yields of cyclopropanols in a one-pot operation (Eq. (2)).



(2)

Subsequent research on extending the scope of the reaction has furnished support for the assumption that the Grignard reagent reduces the titanium(IV) isopropoxide to titanium(II)isoproxide (**32**), which adds to the olefin generated by such reduction to form the eponymous Kulinkovich reagent **33** [26,27]. The action of **33** on the carboxylic ester leads to the cyclopropanol **34**, after hydrolysis [28] (Scheme 9).

Intermediate **33** has been employed by Sato and coworkers to generate both allylic titanium(IV) reagents **35** [29] (Eq. (3)) and titanacyclopropene intermediates **36** [30] (Eq. (4)) and such proposed Kulinkovich reagents have already found many applications in organic synthesis [31]. To our knowledge, however, neither intermediate **32** or **33** has yet been isolated or been separated from the the $MgX(OPr^i)$ by-product.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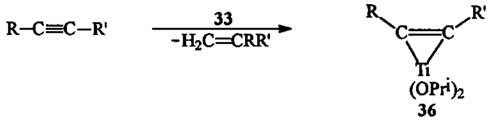
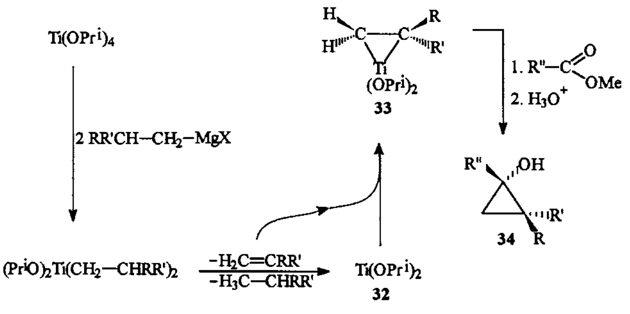
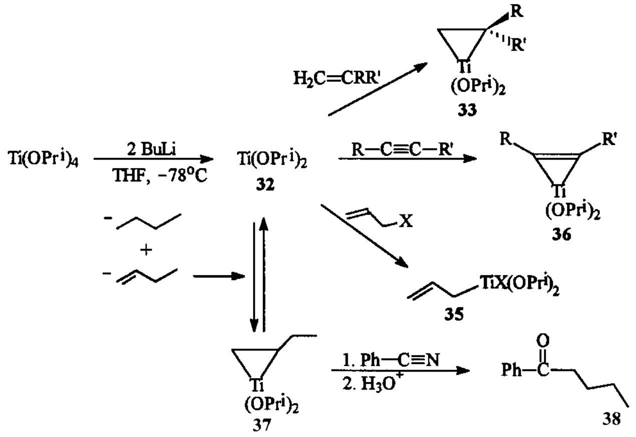

(4)

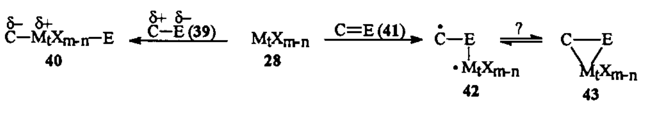
Recently, we have discovered a more general and convenient route to titanium(II) isoproxide (**32**) and to such Kulinkovich reagents derived from appropriate alkenes or alkynes. Simply treating $Ti(OPr^i)_4$ in THF at −78°C with two equivalents of *n*-butyllithium generates **32** in equilibrium with its complex (**37**) with 1-butene. Complex **37** reacts with benzonitrile to yield ketone **38** upon hydrolysis. In order to obtain **32** free of **37**, the THF need only be removed with warming under reduced pressure. Subsequent addition of the desired alkene, alkyne [27] or the allylic halide provides titanium reagents of types **33**, **36** or **35**, respectfully [32] (Scheme 10).



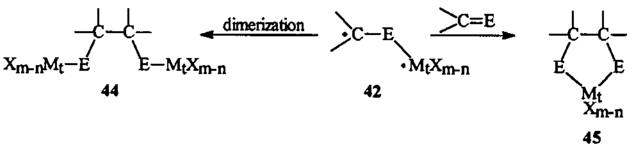
Scheme 9.



Scheme 10.



Scheme 11.

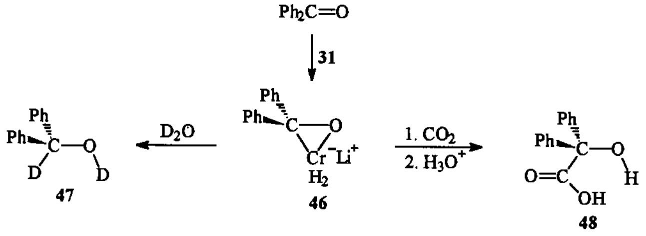


Scheme 12.

2. Reactions of early transition metal carbenoids with organic substrates

2.1. Primary reaction processes

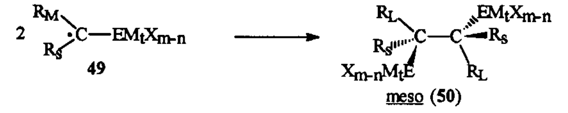
In such oxidative addition reactions of these metal carbenoids (M_tX_{m-n}, **28**) to either σ- or π-bonds in organic reactants, it is evident that electron transfer from the metal to the antibonding orbitals of the organic substrate has occurred to some extent. Such reactions with carbon–non-metal σ-bonds (C–E) leading to reductive cleavage are two-electron transfer processes (TET) and effect the *Umpolung* of the carbon from plus in C–E bonds (**39**) to minus in $C-M_tX_{m-n}-E$ (**40**) (Scheme 11). Addition of M_tX_{m-n} to π-bonds of the type C=E (**41**, E = C, N, O) can involve either a single electron transfer (SET) to form **42** or a TET process yielding a metallocyclopropane ring (**43**). By analogy with the term, epoxidation, for the adding of oxygen to a π-bond, the formation of **42** or **43** could usefully be termed epimetallation. An experimental distinction between the two intermediates may be possible based on the paramagnetic and hence ESR-active character of **42** or through the expected reactivity of **42** toward facile dimerization (**44**) or toward the incorporation of a further unit of C=E to yield a metallocyclopentane (**45**) (Scheme 12). However, such testing for the presence of **42** or **43** would be futile if facile equilibration between **42** and **43** can occur. On the other hand, positive evidence for structure **43** may be possible if the presence of the C–M bond can be established. This is the case in the interaction of the carbenoid $LiCrH_2$ (**31**) with benzophenone in a 1:1 ratio. The generation of adduct **46** (or its dimer) in THF at −78°C is made most likely by two chemical trapping experiments: (1) the isolation of **47** in 90% yield by the addition of D_2O [22]; and (2) the formation of **48** in over 65% yield by addition of CO_2 and hydrolysis [33] (Scheme 13). These results support the conclusion that metallocycles like **43** can be sufficiently more stable than biradicals (**42**) and hence can be important intermediates in subsequent reactions. This is compellingly evident in the carbon–carbon coupling reactions of carbonyl derivatives and acetylenic substrates, which are discussed next.



Scheme 13.

2.2. Coupling reactions of carbonyl derivatives and of unsaturated hydrocarbons

The stereoselectivity of carbon–carbon bond formation effected by diverse transition metal carbenoids ($TiCl_2$, $ZrCl_2$, CrCl and $LiCrH_2$) has proved to be most pertinent and valuable in distinguishing between the intermediates of types **42** and **43**. Were biradicals of type **42** involved in such carbon–carbon coupling reactions, steric effects of the substituents on the carbon radical (**49**) should cause C–C bond coupling to favor the *meso*-dimer (**50**) for the carbonyl derivatives (Eq. (5)) and the stereoisomer **51** for the alkyne (Eq. (6)).



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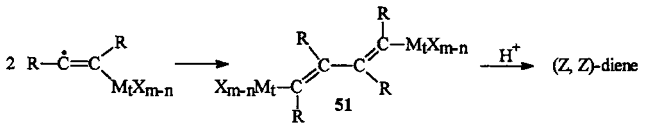
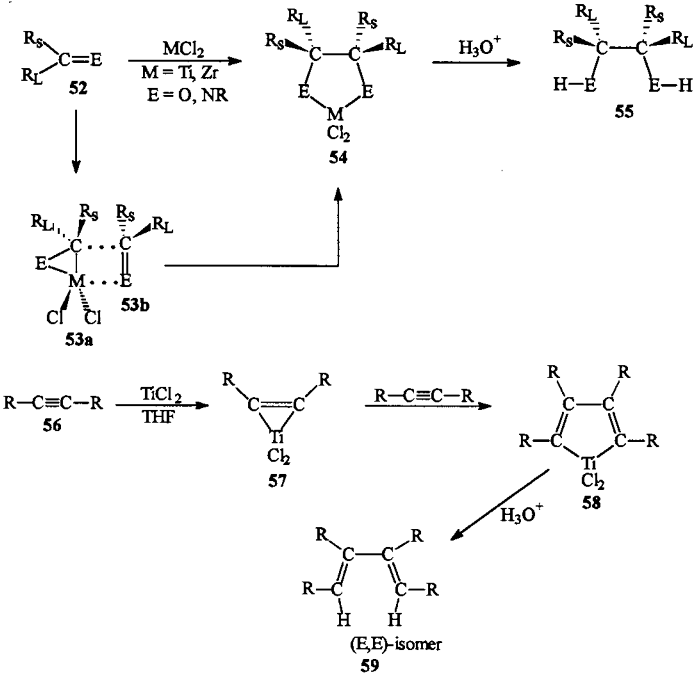


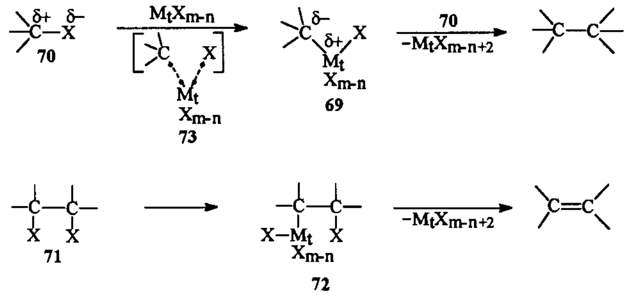
(6)

However, the experimental observations are just the reverse of these expectations: carbonyl derivatives (**52**, C=E as C=O, C=NR) give mainly or exclusively the racemic isomers (**55**) and alkynes (**56**) give adduct **58,** which on protolysis yields the (*E*,*E*)-diene (**59**) [18]. This observed stereochemistry is consistent with the formation of metallocyclopropanes **53a** and **57** and the insertion of another substrate unit into the C–E bond. For **53a** such insertion would occur preferentially so that the larger substituents R_L remain farther apart in the transition state (**53a** + **53b**) (Scheme 14). At higher temperatures **58** reacts with further alkyne in a Diels–Alder manner to give the substituted benzene and eliminate $TiCl_2$, which can thus cyclotrimerize the alkyne catalytically. Were the alkyne to dimerize to **51**, as depicted in Eq. (6), no such cyclotrimerization of the alkyne could ensue. This marked stereoselectivity in carbon–carbon bond coupling processes is a strong argument for the great potential of such metal carbenoids in organic synthesis.

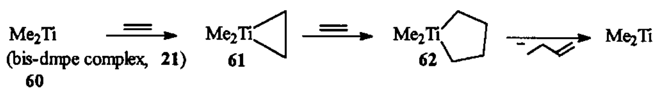
Although ordinary olefins do form detectable but weaker complexes with certain transition metal complexes (cf. supra Schemes 9 and 10), the oligomerization or the polymerization of olefins can be realized catalytically by certain metal carbenoids. The dimethyltitanium(II) complex **60** has been found to catalyze the rapid dimerization of ethylene to 1-butene at −20°C, presumably by way of metallocycles **61** and **62** (Eq. (7)) [34]. Polar alkenes, such as styrene and methyl methacrylate, are readily polymerized by $LiCrH_2$, possibly by way of a biradical intermediate like **42** but the reaction requires further study [22].



Scheme 14.

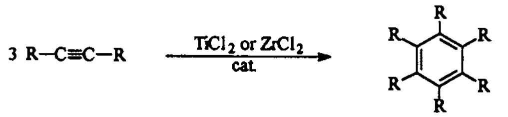


Scheme 15.

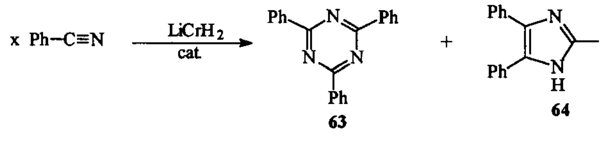


(7)

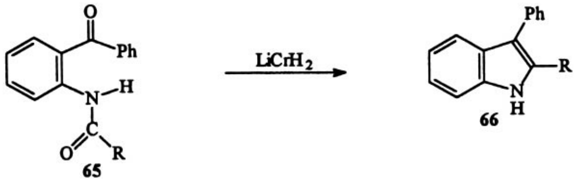
Further carbon–carbon coupling reactions of unusual interest for organic synthesis are the extremely rapid cyclotrimerization of alkynes by TiCl$_2$ or ZrCl$_2$ (*free* of THF, cf. Scheme 14) (Eq. (8)), the oligomerization of benzonitrile into mainly triazine **63** or mainly imidazole **64**, depending upon the benzonitrile: LiCrH$_2$ ratio (Eq. (9)) and the efficient intramolecular cyclization of **65** into indole **66** [22] (Eq. (10)).



(8)

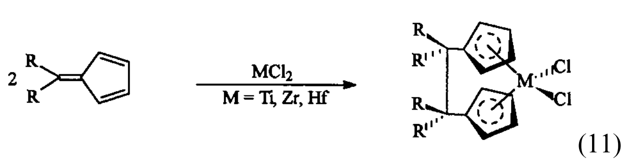


(9)

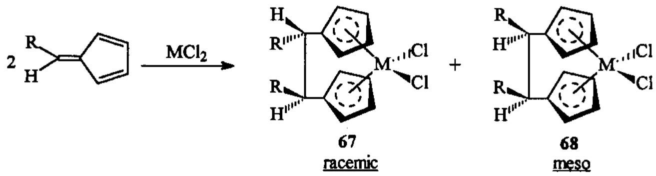


(10)

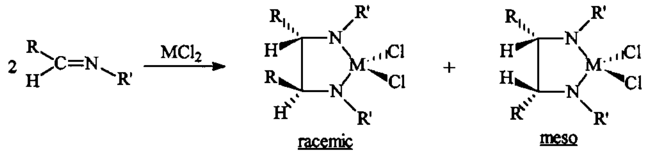
Finally, metallative dimerizations of great importance to olefin polymerization are the direct syntheses of *ansa*-metallocene and *ansa*-non-metallocene polymerization catalysts from Group 4 metal dichlorides and fulvenes or imines, respectively. 6,6-Disubstituted fulvenes yield symmetrical metallocenes (Eq. (11)) [20] but 6-substituted fulvenes provide varying proportions of the *racemic* (**67**) and *meso* (**68**) isomeric metallocenes [20] (Eq. (12)) and *meso ansa*-non-metallocenes as well [35] (Eq. (13)). In Eqs. (12) and (13), the *racemic* isomer will be favored significantly because of steric hindrance of the substituents on the ethylene bridge.



(11)



(12)



(13)

2.3. Carbon–carbon coupling and reductive cleavage with organic halides

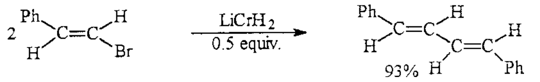
Although the entire gamut of carbon–non-metal bonds, C–E, where E = N, O, P, S, X, etc., are prone to cleavage by transition metal carbenoids, the most useful C–E bond cleavages in organic synthesis involve the halogens, except fluorine. The oxidative addition product obtained, **69** (cf. Scheme 11), has become through *Umpolung* the negative carbon with which to couple with the positive carbon of **70** to yield a new carbon–carbon bond (Scheme 15). A similar oxidative addition in a vicinal dihalide (**60**) sets the stage for π-bond formation via **72**. The ease with which such dehalogenations occur has been found to depend upon the strength of the C–X bond and thus their reactivity decreases as $I > Br > Cl \gg F$. Correspondingly, the ease of cleavage of the C–X bond increases with the increase in the relative stability of the carbon radical in the putative intermediate **73**. This suggested model of an SET process in oxidative addition would account for the facile dehalogenative dimerization of all allylic or benzylic halides by M_tX_{m-n}. That such carbon radicals can also escape from intermediate **73** is indicated by the small but significant proportion of monomeric reduction obtained.

The coupling of 9-bromofluorene (**74**) by the trio of carbenoids, TiCl$_2$, ZrCl$_2$ and HfCl$_2$, is instructive: the titanium reagent gives about 20% of monomeric reduction, ZrCl$_2$ only 7% and HfCl$_2$ none at all [18]. This outcome is consistent with escape of radicals from intermediate **73**. The C–Ti(IV) bond is kinetically weaker than corresponding bonds with zirconium and notably with hafnium and hence is especially prone to homolysis (Scheme 16).

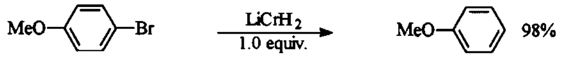
A further revealing comparison of these Group 4 metal dichlorides is their individual reaction in THF with benzotrichloride (**75**). While $TiCl_2$ stops at simple dimerization (**76**), $ZrCl_2$ continues the dehalogenation to yield principally **77** and $HfCl_2$ is even a more potent reductant in producing **77** and a 12% yield of **79**. In a separate experiment, **78** was shown to yield **79** by the action of $HfCl_2$. Thus **78** must have been formed by $HfCl_2$ from **75** as an intermediate on the way to **79** [18] (Scheme 17).

It should be noted that the carbenoid, CrCl (**80**), in threefold excess, converts **75** quantitatively only into **78**.

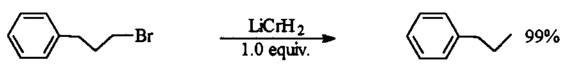
Reactions of such M_tCl_2 reagents in THF with aromatic or aliphatic halides are impractically slow, which is consistent with the foregoing consideration of radical stability in suggested intermediate **73**. However, the anionic carbenoid, $LiCrH_2$ (**31**) has been found to be an effective dehalogenating reductant for allylic, benzylic, vinylic, aryl and even aliphatic halides, leading to monomeric or dimeric reduction (Eqs. (14)–(17)).



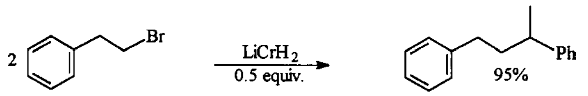
(14)



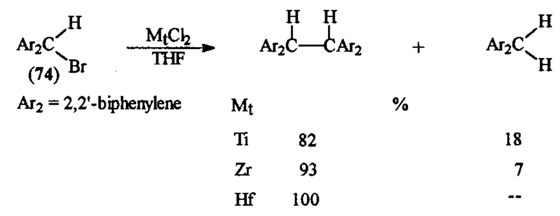
(15)



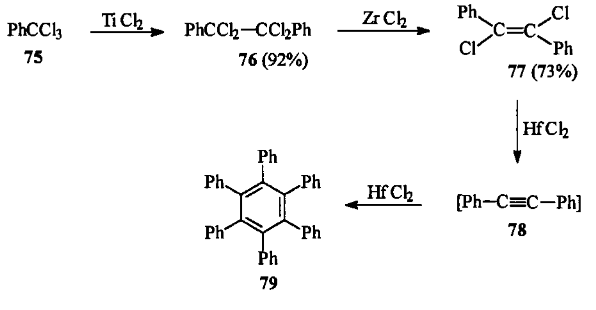
(16)



(17)

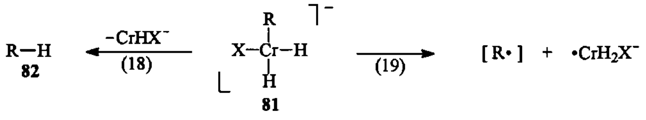


Scheme 16.



Scheme 17.

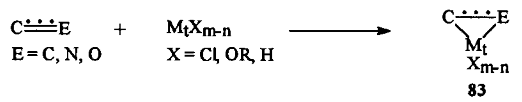
The monomeric reductions involve the transfer of H from the $LiCrH_2$ reagent, as work-up with D_2O served to prove. Such reactions undoubtedly pass through oxidative addition adducts such as **81**, which can decompose either by reductive elimination to **82** (Eq. (18)) or homolytically to produce radicals capable of coupling or rearrangement (Eq. (19)). By controlling the courses of decomposition for intermediate **81** an array of C–C and C–H bond-forming reactions should be achievable and should enhance the value of such metal carbenoids in selective organic synthesis.



(18,19)

3. Future prospects for transition metal carbenoids

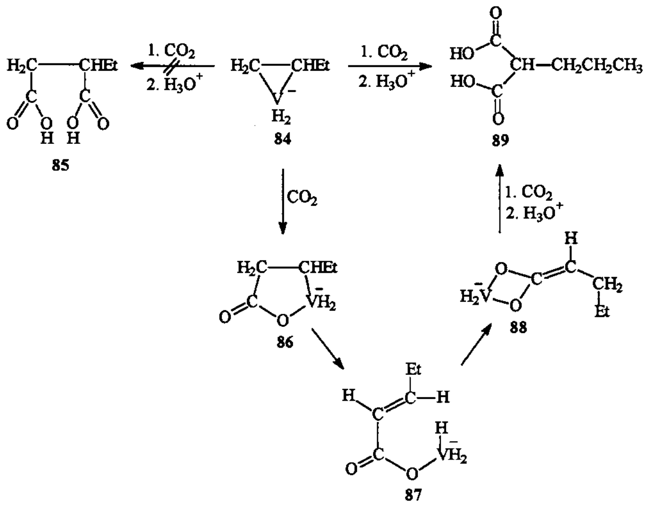
Since the epimetallation of C=C, C=N, C=O and C≡C linkages by metal carbenoids, such as $TiCl_2$, $Ti(OPr^i)_2$, CrH_2^- and VH_2^- [18,22,25,32,36] can be readily achieved even at −78°C, an array of three-membered metallocycles (**83**) having one or two C–M bonds are easily accessible for organic synthesis (Eq. (20)).



(20)

Treatment of **83** with protons yields syn-reduction of C=E bonds (**47**, Scheme 13); with alkyne or alkene units, dimeric or trimeric products are formed via metallative dimer intermediates (Scheme 14); and with carbonyl derivatives insertion of such substrates can occur into the C–M bond of **83** (**38**, Scheme 10; **48**, Scheme 13). Most recently, such insertions have been shown to be most efficient in the expedient construction of multiple stereogenic centers in acyclic organic compounds [37]. Current developments in the applications of such transition metal carbenoids for organic synthesis have been discussed in recent reviews by the Kulinkovich group [36] and the Sato group [38].

In generating metallacyclopropanes from C=E in high yield, it is likely that two characteristics of metal carbenoids will play decisive roles, namely their singlet or triplet character (**18** versus **19**, Eq. (1)) and their electrophilic or nucleophilic reactivity (**22** versus **23**). As to the singlet or triplet carbene character of M_tX_{m-n}, it is proposed that triplet metal carbenoids may promote olefin polymerization rather than epimetallation (**42** in Scheme 12). Preliminarily, one might further suggest that electrophilic $TiCl_2$ and $Ti(OPr^i)_2$ might prove more suitable for epimetallation of olefins and acetylenes while nucleophilic CrH_2^- and VH_2^- would be particu-



Scheme 18.

larly responsive to electron-deficient C=O and C=N bonds.

It might further be noted that the electrophilic character of M_tX_{m-n} reagents can be enhanced by employing their 1:1 complexes with Lewis acids, as exemplified by $TiCl_2 \cdot Me_2AlCl$, which polymerizes ethylene and cyclotrimerizes alkynes [39]. In a complementary sense, complexes of M_tX_{m-n} with Lewis bases react more readily in a nucleophilic manner with carbonyl substrates. The bimolecular reducing action of $TiCl_2 \cdot 2THF$ on aldehydes and ketones is illustrative [19].

Moreover, since the adduct of M_tX_{m-n} with olefins has two vicinal C–M bonds (cf. the Kulinkovich intermediate **33** in Scheme 9), one might expect that treating the adduct of 1-butene and $LiVH_2$ or $LiCrH_2$ (**84**) with CO_2 and then hydrolyzing the resultant adduct would yield α-ethylsuccinic acid (**85**). Thus it was astonishing to discover that the actual product is α-propylmalonic acid (**89**)! (Scheme 18). The observed product can be accounted for through a dehydrometallation–rehydrometallation sequence (**86** → **88**) and carbonation of **88** to **89**, but the actual nature of such an unexpected rearrangement remains to be established [40].

In conclusion, therefore, the foregoing adumbration of particularly advantageous expected and unexpected reactions of three-membered metallocycles of generic type **83** should serve to recommend their further applications in modern organic synthesis.

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