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Chromium Vinylidene Carbenoids: Generation, Characterization, and Reactivity. First Evidence for an Internal Proton Return Phenomenon with Vinylidene Carbenoids

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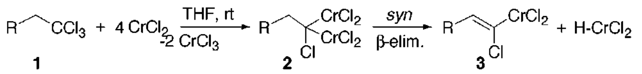
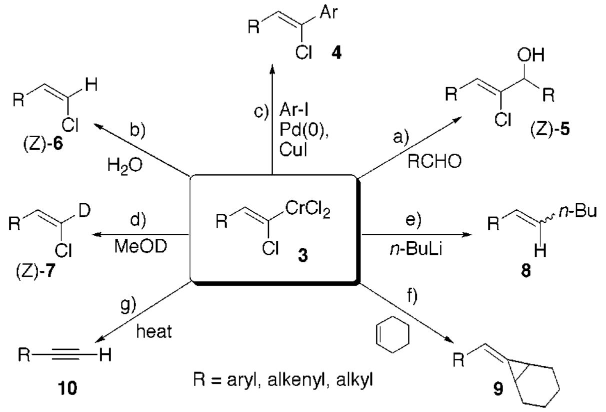
Organometallic chemistry has played an influential role in the development of organic synthesis.[1] Presently, a wide variety of organometallic species are routinely exploited for the creation of new carbon−carbon bonds under mild conditions, often with excellent regio- and stereocontrol.[2] By comparison, organochromium(III) reagents (mostly allylic[3] and vinylic[4]) have been relatively infrequently explored despite their demonstrated superior capabilities for some transformations compared with canonical organometallics.[5] Herein, we describe the formation and reactivity of the first stable halovinylidene chromium(III) carbenoids **3** (Scheme 1).[6] Generally, halovinylidene carbenoids[7] are generated by metal halogen exchanges between organolithium, -sodium, or -potassium reagents and *gem*-dihalovinylidenes[8] or by α-metalation of terminal halovinyldene compounds[9] at −100 to −78 °C. Alternatively, zinc[10] and zirconium[11] halovinylidene carbenoids have been prepared recently by carbometalation of metalated alkynes followed by monohalogenation or by direct carbometalation of haloalkynes below −20 °C. These reactions, however, are plagued by drawbacks, inter alia, multistep procedures at low temperatures, strictly anhydrous conditions, a dependency upon additives (e.g., methylaluminoxane), *β*-elimination, low yields, and poor regioselectivities.

Scheme 1



Scheme 2



In sharp contrast, we have discovered that chlorovinylidene chromium(III) carbenoids **3** can be easily prepared from readily available[12] trichloroalkanes **1** using 4 equiv of $CrCl_2$ in THF at room temperature. The mechanism of formation appears to proceed through highly unstable 1-chloro-1,1-bis-chromium alkane carbenoids **2** generated by the reduction of two C−Cl bonds.[13] Formally, the oxidative addition of Cr(II) into a C−Cl bond involves two consecutive single-electron transfers,[14] thus accounting for the four equiv of $CrCl_2$ needed for the reduction of the two C−Cl bonds. The chlorovinylidene carbenoid is subsequently formed by a *syn β*-elimination of chromium hydride[15] (Scheme 1). As a consequence of the high steric requirements of the terminal bis-chromium intermediate **2**, the stereochemistry of the chlorovinylidene carbenoid **3** is exclusively *trans*. Notably, 1,1-dichloroalkenes do not react with chromium(II) chloride under these reaction conditions, thus excluding them as intermediates in the overall transformation.[16]

The nucleophilic character of **3** is evident by its reaction with aldehydes and water (Scheme 2, reactions a and b, respectively). The reaction of **3** under both Grignard's and Barbier's conditions with a wide variety of aldehydes gave only the (*Z*)-isomer of hydroxy-chloroalkenes **5** in >90% yield. Quenching a THF solution of **3** with water at room temperature afforded (*Z*)-chloroolefins **6** as the sole product. Additionally, chlorovinylidene carbenoids **3** could be induced to cross-couple under mild conditions with aryl iodides (phenyl, furanyl, substituted aryl) in the presence of Pd(0) and Cu(I), furnishing **4** in >85% yield (reaction c). The high yields of these reactions, combined with the ready availability[12] of primary trichloroalkanes **1**, makes this methodology very attractive for the stereoselective synthesis of

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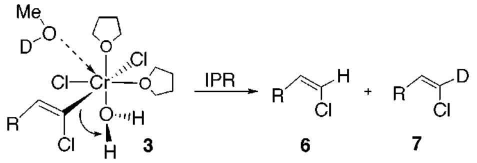
Scheme 3



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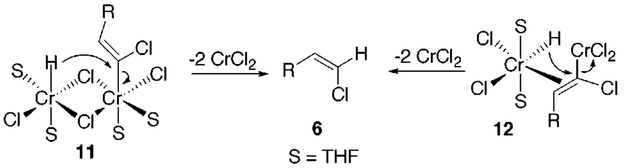
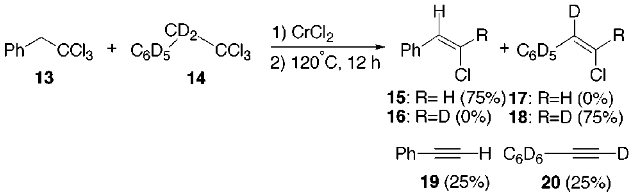
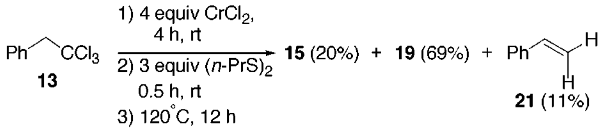


Scheme 5



Scheme 6



(Z)-α-chlorinated olefins.[17] These results are most consistent with a chemically and stereochemically stable (E)-configured chlorovinylidene carbenoid, that is, **3** (Scheme 2). Surprisingly, attempts to intercept **3**, prepared using commercially available chromous chloride, via quenching with MeOD afforded **6** without any incorporation of deuterium. Powder X-ray analysis[18] of commercial chromous chloride revealed a mixture of anhydrous $CrCl_2$ and $CrCl_2{\cdot}2H_2O$ while thermogravimetric analysis[18] (TGA) conducted between 20−800 °C under an argon atmosphere showed a loss of adsorbed water at 150 °C (1−3% w/w) and coordinated water at 430 °C, corresponding to a molar composition of the original reagent as $CrCl_2$:$CrCl_2{\cdot}2H_2O$. Batches of commercial samples from different vendors (inter alia, Acros and Strem Chem. Co.) gave similar results, indicating that the chlorovinylidene carbenoids **3** are remarkably stable at room temperature in the presence of the coordinated water.

The facile addition of carbenoid **3** to aldehydes, despite the presence of water ligated to the hexacoordinated organochromium(III), and the delivery of a proton from the same coordinated water ligand triggered by the addition of MeOD (Scheme 3) are reminiscent of the observations made by Creger[19] and Seebach[20] during the deuteriolysis of lithium enolates. The latter phenomenon was dubbed internal proton return (IPR).

As might be anticipated from this model, stirring commercial $CrCl_2$ twice with an excess of MeOD for 5 h at room temperature and removal of all volatiles in vacuo should result in ligand exchange, that is replace the coordinated water with MeOD. In the event, generation of carbenoid **3** using such pretreated $CrCl_2$ followed by quenching with H_2O gave rise to deuterated chloroolefin (Z)-**7** with 65% of deuterium incorporation in 68% overall yield from **1**. Complete deuterium incorporation was achieved when anhydrous $CrCl_2$ (prepared by the reduction of sublimed $CrCl_3$ and $LiAlH_4$[3a]) was used for the preparation of the chlorovinylidene carbenoid which was then quenched with MeOD (Scheme 2, reaction d). We also observed condensation of chlorovinylidene carbenoid **3** with benzaldehyde gave the expected allyl alcohol (Z)-**5** in good yield, even in the presence of excess (6 equiv) methanol or water.

The electrophilic character of carbenoids **3** was revealed by alkylation with an excess of *n*-BuLi (8 equiv) leading to **8** (87% yield) as an equimolar mixture of (E)- and (Z)-isomers (Scheme 2, reaction e). The requirement for excess *n*-BuLi can be explained by the formation of chromates $Li_2(CrCl_2{}^nBu_2)$[5b] that consumes reagent. Carbene type reactivity was demonstrated by heating **3** in the presence of a large excess of cyclohexene at 160 °C (Scheme 2, reaction f). The cyclopropanation product **9** was formed in 14% yield along with 79% of **6** and 7% of **10**, arising from Fritsch−Buttenberg−Wiechell (FBW) rearrangement.[21] At 120 °C, in the absence of cyclohexene, a 75/25 mixture of **6** and **10** is formed, which did not depend on the hydration state of the $CrCl_2$. The predominant formation of the chloroolefin **6** during the FBW rearrangement can be ascribed to a concerted hydrogen transfer between the chlorovinylidene carbenoid **3** and the H−$CrCl_2$ released during the formation of **3** (Scheme 1). This reductive elimination process[22] is assumed to take place on aggregates such as dinuclear dissymmetric complex **11** or π-complex **12** (Scheme 4).

Moreover when an equimolar mixture of **13** and **14** was subjected to the FBW rearrangement, the expected products **15** and **18** (along with small amounts of **19** and **20**) were obtained, but no crossover products, that is, **16** and **17**, were formed, suggesting the formation of stable aggregates between H−$CrCl_2$ and the vinylidene carbenoids (Scheme 5).

These results were corroborated via in situ scavenging of the H−$CrCl_2$ by reaction with $(nPrS)_2$. Removal of the hydride afforded a highly reactive chlorovinylidene carbenoid or free carbene intermediate which rearranges to the corresponding alkyne **19** (69%) accompanied by styrene **21** (11%) and chloroolefin **15** **(**20%) (Scheme 6).

In conclusion, we have demonstrated that the reaction of a geminal trichloroalkane and $CrCl_2$ affords a thermally stable (E)-chlorovinylidene carbenoid **3**. Also for the first time, we demonstrated IPR utilizing an organochromium(III) intermediate. The chlorovinylidene carbenoid **3** exhibited nucleophilic and electrophilic characteristics. At elevated temperatures, **3** generated a carbene capable of FBW rearrangement and cyclopropanation of an isolated olefin. We anticipate this methodology will prove useful for the stereoselective synthesis of (Z)-chlorinated allylic alcohols and (Z)-1-chloroolefins as well as find utility in the preparation of configurationally defined di- and trisubstituted olefins via transition metal-mediated cross-couplings. Further extensions of these reactions are under intensive investigation, and the results will be reported elsewhere.

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Supporting Information Available: Experimental procedures and TGA graph (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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