Organometallic Chemistry sans Organometallic Reagents: Modulated Electron-Transfer Reactions of Subvalent Early Transition Metal Salts

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The potential of low-valent, early transition-metal reagents as selective reductants in organic chemistry has been foreshadowed by intensive research on the ill-defined and heterogeneous subvalent titanium intermediates generated in the McMurry reaction and its numerous variants. As part of a long-term research effort to develop soluble, well-defined transition-metal reductants of modulated and selective activity toward organic substrates, the THF-soluble reductant, titanium dichloride, has been thoroughly examined, as well as the analogous $ZrCl_2$ and $HfCl_2$ reagents, all of which are readily obtainable by the alkylative reduction of the Group 4 tetrachloride by butyllithium in THF. Noteworthy is that such interactions of MCl_4 with butyllithium in hydrocarbon media lead, in contrast, to M(III) or M(IV) halide hydrides. Analogous alkylative reductions in THF applied to VCl_4, $CrCl_3$, and $MoCl_5$ have yielded reducing agents similar to those obtained from MCl_4 but gradated in their reactivity. Such reductants have proved capable of coupling carbonyl derivatives, benzylic halides, acetylenes and certain olefins in a manner consistent with an oxidative addition involving a two-electron transfer (TET). Such a reaction pathway is consistent with the observed stereochemistry for pinacol formation from ketones and for the reductive dimerization of alkynes. In contrast to the reaction of $CrCl_3$ with two equivalents of butyllithium, which leads to a CrCl intermediate, the interaction of $CrCl_3$ in THF with four equivalents of butyllithium at −78°C yields a reagent of the empirical formulation, $LiCrH_4 \cdot 2\,LiCl \cdot 2\,THF$, as supported by elemental and gasometric analysis of its protolysis. This hydridic reductant cleaves a wide gamut of σ carbon−heteroatom bonds (C−X, C−O, C−S and C−N), towards which the CrCl reductant is unreactive. The type of cleavage and/or coupled products resulting from the action of "$LiCrH_4$" on these substrates is best understood as arising from single-electron transfer (SET). In light of the aforementioned findings, the gradated reducing action noted among $TiCl_2$, $ZrCl_2$, $HfCl_2$ and CrCl, as well as the contrasting reducing behavior between CrCl and $LiCrH_4$, there is no doubt that future research with early transition metals will continue to yield novel reductants of modulated and site-selective reactivity.

The search for selective carbon−carbon coupling reactions has commanded the attention of organic chemists from the very origins of the science and recent advances in this field continue to be greeted with unabated interest. From Fittig's pinacol coupling discovered in 1859[1] to low-valent titanium reagents introduced in 1973[2] and finally to the modified transition-metal metallocene[3] and nonmetallocene salts[4,5] currently under study, the scope and versatility of such reductive couplings have greatly increased. Transition-metal-mediated carbon−carbon bond formation has now grown to be an indispensable part of modern organic synthesis.

Historical Background

The transition-metal-promoted transformation of unsaturated hydrocarbons, now a topic of such pervasive importance in modern chemistry, originated from mid-19th century studies of hydrocarbon pyrolysis conducted over red-hot surfaces of iron or iron-containing glass. Illustrative are the achievements of Marcellin Berthelot who first observed the conversion of acetylene into benzene, naphthalene and other aromatics, as well as the smooth dehydrogenative coupling of benzene to biphenyl[6a]. The active role of iron in such processes was explicitly proved almost a century later by the finding that iron carbonyl derivatives catalyze the cyclotrimerization of acetylenes below 300°C[6b]. It should also be recalled that the unexpected reaction between cyclopentadiene and heated iron powder in 1952 led to the generation and discovery of ferrocene, the harbinger of revolutionary change in both organometallic chemistry and industrial catalysis[7]. Moreover, the researches of Roelen on hydroformylation catalyzed by cobalt[8], of Reppe with nickel-catalyzed acetylene reactions[9] and finally of Wilke on olefin and diene oligomerization by soluble, well-defined nickel complexes[10] served to demonstrate the great industrial importance of the late transition metal trio of iron, cobalt and nickel.

MICROREVIEWS: This feature introduces Berichte's readers to the authors' research through a concise overview of the selected topic. Reference to important work from others in the field is included.

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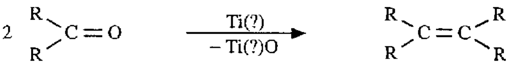
Contemporaneous with these astonishing discoveries with late transition metals were the pioneering and revolutionary studies of Karl Ziegler and co-workers with early transition metals, whose salts ($TiCl_4$, $ZrCl_4$ and VCl_4) in combination with aluminium alkyls were found to be highly active catalysts for the oligomerization and/or polymerization of olefins and diolefins[11–13]. Contrasting with the long-standing reputation of late transition metals as superior reactants and catalysts in organic chemistry, the possible value of early transition metals for organic chemistry was completely unappreciated prior to Ziegler's remarkable findings in the period of 1952–1956. Thereafter, early transition metals were intensively studied as reagents for organic transformations, with the result that in 1973 three research groups reported independently on the novel reductive dimerization of carbonyl derivatives to olefins by various subvalent titanium reagents[14–16] (eq. 1).


(1)

The transformation depicted in eq. 1, which has come to be termed the McMurry reaction after one of its discoverers, is a most impressive and versatile method for the construction of a wide variety of open-chain and ring carbon skeletons in gratifying yields[2,17]. Unfortunately, the various subvalent titanium reductants used for the McMurry reaction have largely remained shrouded in alchemy: in almost all applications, neither the exact oxidation state(s) of the titanium reductants in solution nor their mechanism(s) of reaction can be confidently specified, even after almost 25 years[18]. Problems in formulating a molecular interpretation of this reaction are not difficult to find: (1) the titanium reductant is often generated in a heterogeneous phase; (2) the presence of more than one subvalent state [Ti(0) and Ti(II)] often cannot be ruled out; (3) residual reductant used to generate subvalent titanium ($LiAlH_4$, Mg, Al, Zn) may play a role: and (4) the Lewis acid generated from generating subvalent titanium (LiCl, $MgCl_2$, $AlCl_3$, $ZnCl_2$) can and almost surely does influence the reducing character of the titanium reagent.

Therefore, if greater mechanistic insight into the course of the McMurry reaction is to be achieved and if superior reagents are to be found for carrying out such reductive couplings on a wider variety of C=O, C=N, C=S and C≡N derivatives, subvalent transition metal complexes of Ti and other early transition metals must be sought that have the following attributes: (1) a soluble metal reagent; (2) the metal present in one well-defined oxidation state; (3) the absence of any residual, secondary reductant (main group metal or metal hydride); and (4) absence of any possibly disturbing Lewis acid (main group metal halide).

What we wish to report in the following account are the results we have obtained over the last five years from research designed to uncover soluble, well-defined reductants of early transition metals and to determine their scope of action toward organic substrates. In light of the foregoing discussion, it is understandable why we initiated our studies with titanium reagents.

Subvalent Transition Metal Complexes via Alkylative Reduction

The thermal lability of σ carbon–transition metal bonds toward homolysis and thus to organic free-radical formation had become so well-established prior to 1950 that

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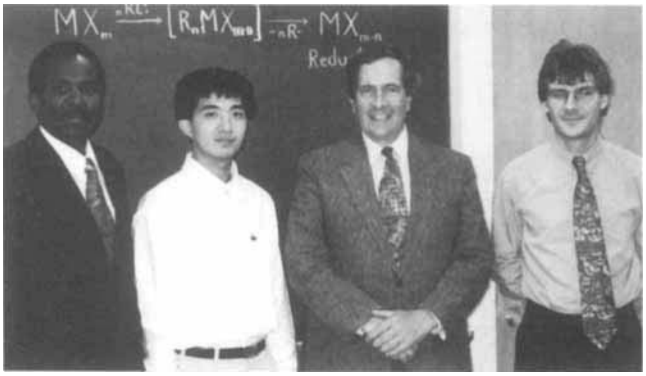
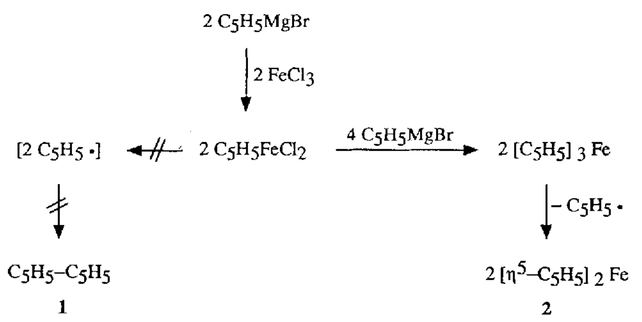
John Joseph Eisch (second from right) was born in Milwaukee, Wisconsin, in 1930 where he was graduated from Marquette University with a B.S. degree in chemistry, summa cum laude, in 1952. Thereupon he studied chemistry at Iowa State University and earned the Ph.D. degree in March 1956 for research in organic chemistry under the supervision of Henry Gilman. Under a Union Carbide fellowship he was a postdoctoral associate with Karl Ziegler at the Max-Planck Institut für Kohlenforschung, Mülheim, Germany, for the next 12 months and then a research fellow at Union Carbide's European Research Associates Center in Brussels, Belgium, for the following six months. Beginning his academic career with junior appointments at St. Louis University (1957–1959) and the University of Michigan (1959–1963), he moved to the Catholic University of America where he was Professor of Chemistry and Department Head. Finally, in 1972 he became Chairman of Chemistry of the State University of New York at Binghamton until 1978. In 1983 he was promoted to the SUNY-wide rank of Distinguished Professor of Chemistry. Over the years he has held visiting professorial appointments at Kyoto University, Max-Planck-Institut für Kohlenforschung, the University of Munich and the Technical University of Munich, the Polytechnic University of Warsaw, the California Institute of Technology and Cornell University. He was appointed Fellow of the Japan Society for the Promotion of Science in 1979 and has received the Alexander von Humboldt Senior Scientist Award in 1993. Professor Eisch's scholarly work has focused on developing novel reagents for organic transformations and elucidating their mode of action on a molecular level. His principal efforts in these areas have been devoted to the stoichiometric and catalytic reactions of organometallic compounds of both main-group and transition metals. The results of such investigations have been reported in over 300 scientific publications, in some 150 invited lectures worldwide, in the monograph,



Scheme 1



Kealy and Pauson sought to apply this homolysis reaction to the coupling of cyclopentadienyl groups to form the desired bicyclopentadienyl (**1**) (Scheme 1)[19]. The starting and unprecedented formation of ferrocene (**2**) instead surely makes this one of the most successful "abortive" reactions in modern chemistry.

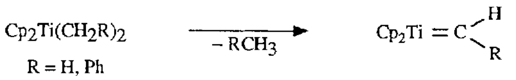
Despite this surprising result with πC–Fe bonds, Group 4 alkyls readily undergo homolyses to produce subvalent metal salts (eqs. 2–3)[20,21a]:

$$\underset{\mathbf{3}}{\mathrm{CH_3TiBr_3}} \xrightarrow[-\,[\mathrm{CH_3}\bullet]]{} \mathrm{TiBr_3} \qquad (2)$$

$$\underset{\mathbf{4}}{\mathrm{(CH_3CH_2)_2TiCl_2}} \xrightarrow[-\,[\mathrm{C_2H_5}\bullet]]{} \mathrm{TiCl_2} \qquad (3)$$

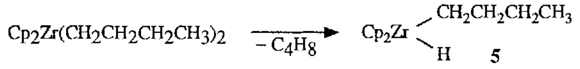
Since **3** and **4** can in turn be generated from TiX_4 and one or two equivalents of RMgX or RLi, the formation of $TiBr_3$ or $TiCl_2$ represents an alkylative reduction of TiX_4. Such a process has been applied in our studies initially to the trio of titanium, zirconium and hafnium tetrahalides and thereafter to the higher valent halides of chromium, vanadium and molybdenum. Although such alkylative reduction of Group 4 transition metals has been clearly shown to produce the divalent state, the subvalent state formed by the alkylative reduction of Group 5 and 6 metal salts remains to be ascertained beyond doubt.

Depending upon the detailed environment of the σ carbon–transition metal bond, decomposition pathways other than simple carbon–metal bond homolysis can be followed[21b]. First, dialkyl derivatives where the alkyl groups lack a labile β-hydrogen, such as dimethyl- or dibenzyl–titanocene, can undergo hydrocarbon elimination to produce a methylene derivative with no change in the metal's oxidation state (eq. 4)[22,23].


(4)

$$\underset{\mathrm{R\,=\,H,\,Ph}}{\mathrm{Cp_2Ti(CH_2R)_2}} \xrightarrow[-\,\mathrm{RCH_3}]{} \mathrm{Cp_2Ti=C}\begin{smallmatrix}\mathrm{H}\\ \mathrm{R}\end{smallmatrix} \qquad (4)$$

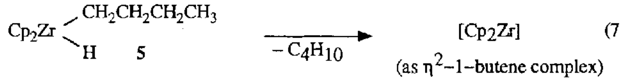
Secondly, for alkyl derivatives with a labile β-hydrogen, the formation of a metal–hydrogen bond can result from olefin elimination (eq. 5–6)[24,25].


(5)

$$\mathrm{Cp_2Zr(CH_2CH_2CH_2CH_3)_2} \xrightarrow[-\,\mathrm{C_4H_8}]{} \underset{\mathbf{5}}{\mathrm{Cp_2Zr}\begin{smallmatrix}\mathrm{CH_2CH_2CH_2CH_3}\\ \mathrm{H}\end{smallmatrix}} \qquad (5)$$

$$\mathrm{Cl_2Zr(CH_2CH_2CH_2CH_3)_2} \xrightarrow[-\,\mathrm{C_4H_8}]{} \mathrm{Cl_2ZrH_2} \qquad (6)$$

Finally, the reductive elimination of an alkane from alkylmetal hydrides like **5** can also lead to subvalent derivatives (eq. 7)[26].


(7)

$$\underset{\mathbf{5}}{\mathrm{Cp_2Zr}\begin{smallmatrix}\mathrm{CH_2CH_2CH_2CH_3}\\ \mathrm{H}\end{smallmatrix}} \xrightarrow[-\,\mathrm{C_4H_{10}}]{} \underset{\text{(as }\eta^2\text{–1–butene complex)}}{[\mathrm{Cp_2Zr}]} \qquad (7)$$

"The Chemistry of Organometallic Compounds", Macmillan, 1967, in the edited series, "Organometallic Syntheses", J. J. Eisch and R. B. King, editors, 4 volumes, and in many invited reviews appearing as chapters in monographs. He has been an editorial board member of the Journal of Organometallic Chemistry almost from its inception and has been a consultant to the chemical industry in the United States, Europe and Japan on organometallic chemistry and Ziegler-Natta polymerization catalysis.

Xian Shi (second from left) was born in Nanjing, The People's Republic of China in 1963. He was graduated from Nanjing University with a B.S. degree in chemistry in 1985 and obtained the M.S. degree in organic chemistry at the Institute of Chemistry, Academia Sinica, in Beijing. After serving as a research associate in the Department of Chemistry, The Chinese University of Hong Kong, he began his doctoral studies in Professor Eisch's research group at the State University of New York at Binghamton and has received the Ph.D. degree in 1996 with the dissertation, "The Use of Group 4 Metal Dichlorides in Organic Synthesis". His research interests lie in synthesis methodology, in which area he has already published 10 contributions. Currently he is active as a synthetic organic chemist in the pharmaceutical industry.

Joseph Ramogi Alila (far left) was born in the Homa Bay District in Kenya in 1956. He began his university education at the University of Nairobi where he received the B.A. degree with a major in chemistry in 1981. After a period as high school chemistry teacher, he earned the master's degree in education from Kenyatta University in 1987. After serving as a teacher-trainer at Moi Diploma College of Education, he assumed his present position as lecturer in Egerton University in 1989. On leave of absence, he began graduate studies in chemistry at the State University of New York at Binghamton in 1994. He is currently completing his doctoral dissertation with Professor Eisch on the theme, "Novel Low-Valent Chromium Reductants in Organic Synthesis".

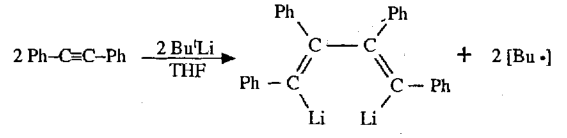
Sven Karl-Heinz Thiele (far right) was born in Magdeburg in the then German Democratic Republic in 1966. He began the university study of chemistry at Halle and completed his work for the diploma degree in Münster in 1991. Under the direction of Professor Gerhard Erker he then undertook doctoral research at Münster and was awarded the Ph.D. degree in 1994. He joined Professor Eisch's research group in 1995 as a Fellow of the Deutsche Forschungsgemeinschaft. His research interests and publications are currently focused on the design of novel Ziegler-Natta catalysts and their oligomerizing or polymerizing action on unsaturated organic substrates.

Despite the accessibility of these other modes of decomposition for transition metal alkyls, we have found that alkylative reduction leading to subvalent metal reductants can be brought about by a judicious selection of ligands on the metal and the solvent (eq. 8).

$$M_tE_n + 2\,RM \xrightarrow[-2\,MX]{} [R_2M_tE_{n-2}] \xrightarrow[-2\,R\cdot]{} M_tE_{n-2} \qquad (8)$$

$E = X, OR, NR_2$ $\quad M = Li, MgX, AlR_2$

The great potential of such early transition metal reductants lies in their variegated and modulated electron-transfer properties. The starting main-group organometallics used in alkylative reduction (eq. 8) can sometimes themselves be employed for single-electron transfer (SET) reductions (eqs. 9–10)[27,28], but generally competing nucleophilic attack by R^- and/or by H^- formed by β-elimination often leads to undesired side products. Transforming organometallics to subvalent transition metal salts (eq. 8) preserves the reducing character of the original carbanion while minimizing any alkylating or hydridic side reactions.



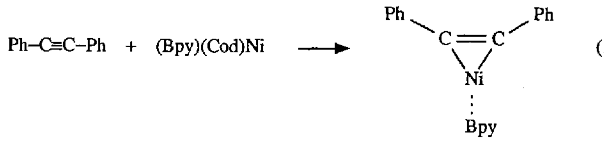
(9)

$$Ph{-}SO_2{-}Ph \xrightarrow{PhCH_2K} Ph{-}CH_2{-}Ph + PhSO_2K \qquad (10)$$

Overview of Electron-Transfer Reductions with Subvalent Early Transition Metal Salts

(a) *Preliminary Mechanistic Considerations.* Depending on the specific subvalent transition metal complex, electron transfer to unsaturated substrates can occur either singly (eq. 11) (SET)[29] or doubly (eq. 12) (TET)[30].

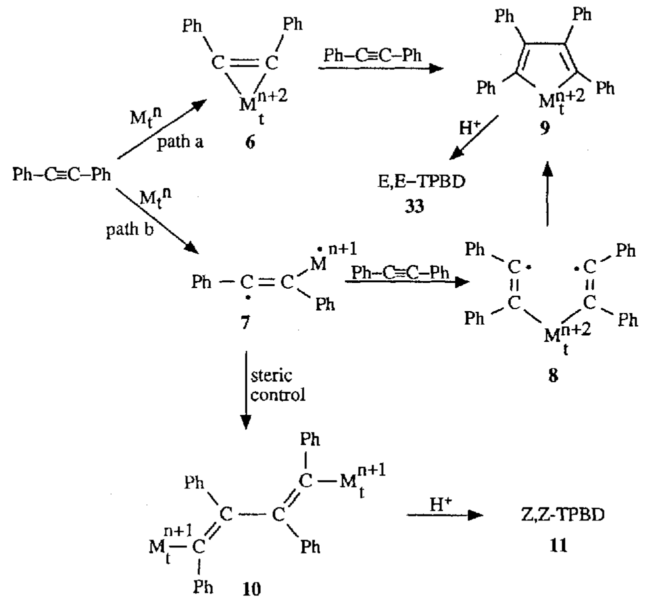
$$Ph_2C{=}O + (Cod)_2Ni \rightleftharpoons \underset{\text{ESR-signal}}{Ph_2\dot{C}{-}O{-}Ni(Cod)_2} \qquad (11)$$



(12)

Furthermore, a net two-electron transfer (TET) may occur in a concerted manner (path a), leading directly to **6** and then to **9** by further reaction or via two distinct single-electron transfers, leading to **7** and then to **8** and finally to **9** (path b). The importance of path b may sometimes be revealed by detecting dimerization of **7** to **10**, whose hydrolysis would furnish a different isomer of tetraphenylbutadiene (**11**, the *Z,Z*-isomer) than would the hydrolysis of **9** (giving **33** the *E,E*-isomer) (Scheme 2).

Scheme 2



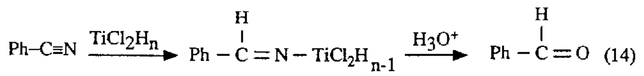
Thus, by a combination of observed stoichiometric ratios of reactants and the resulting stereochemical nature of the products, one may be able to distinguish between concerted TET pathways and consecutive SET processes[31].

(b) *Alkylative Reduction of Early Transition Metal Salts*[31,32]. The efficiency of alkylative reduction of the salts of the Group 4 metal trio, titanium, zirconium and hafnium, was found to depend on the metal (decreasing ease, Ti > Zr > Hf), the anionic salt ligand and the solvent employed for the reaction of M_tE_4. The reaction of $TiCl_4$ with two equivalents of *n*-butyllithium in THF proceeded smoothly to produce *black*, analytically pure $TiCl_2$, which could be separated from the LiCl by-product and was obtained as a bis(tetrahydrofuran) complex (**13**) in toluene (eq. 13).

$$TiCl_4 \xrightarrow[-2\,LiCl]{2\,Bu^nLi} \underset{\mathbf{12}}{Bu_2^nTiCl_2} \xrightarrow[-2\,Bu^\cdot]{THF} \underset{\mathbf{13}}{TiCl_2\cdot 2\,THF} \qquad (13)$$

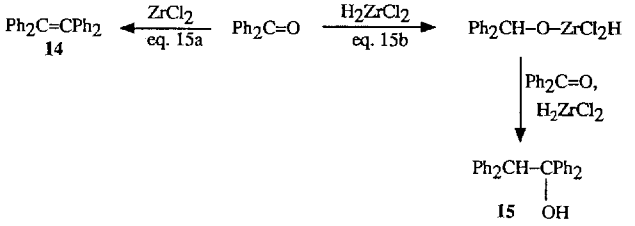
However, when the reaction was conducted completely in toluene, the resulting black suspension with LiCl gave chemical evidence for the presence of Ti–H bonds. Thus, benzonitrile, which reacts very slowly with pure **13**, reacted with "$TiCl_2H_n$" to produce benzaldehyde upon hydrolysis (eq. 14)[33]. Evidently, in toluene **12** undergoes, to some extent, both alkylative reduction and some olefin elimination to produce **13** and either $TiCl_2H_2$ or $TiCl_2H$.

The coformation of divalent M_tCl_2 and tetravalent $M_tCl_2H_2$ becomes especially significant with zirconium and with hafnium[25]. The apparently greater kinetic stability of the Zr–C and Hf–C bonds towards homolysis retards the rate of alkylative reduction and favors olefin elimination (eq. 5) and the formation of the Zr–H or Hf–H bond. As evidence for this alternative course are the attempted preparations of $ZrCl_2$ and $HfCl_2$ in THF according to the



$$Ph{-}C{\equiv}N \xrightarrow{TiCl_2H_n} Ph-\overset{H}{\overset{|}{C}}=N-TiCl_2H_{n-1} \xrightarrow{H_3O^+} Ph-\overset{H}{\overset{|}{C}}=O \quad (14)$$

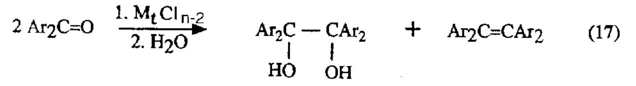
method given in eq. 13 and applied to the M_tCl_4. The resulting zirconium reagent contained almost 60% of H_2CrCl_2 and the hafnium reagent greater than 90% of H_2HfCl_2, as evidenced by the products obtained from benzophenone: although pure $ZrCl_2$ clearly converts the ketone into the McMurry coupling product **14** (eq. 15a), the H_2ZrCl_2 side product gives cross-coupling product **15** (eq. 15b), resulting from coupling of the ketone with benzhydrol (**16**). With the "$HfCl_2$ reagent, the reaction with $Ph_2C{=}O$ leads to a 90% yield of benzhydrol (eq. 16), showing that attempted alkylative reduction of $HfCl_4$ had produced instead predominantly H_2HfCl_2.



$$Ph_2C{=}O \xrightarrow[2.\ H_2O]{1.\ H_2HfCl_2} \underset{\mathbf{16}}{Ph_2CH{-}OH} \quad (16)$$

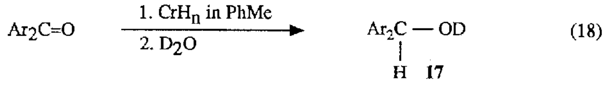
Subsequent studies have shown that practically pure $TiCl_2$ and $ZrCl_2$, free of significant $M_t{-}H$ bonds, can be obtained by conducting the alkylative reductions in THF[25]. On the other hand, conducting the reaction in hydrocarbon media tends to favor the preparation of the mixed hydride chlorides, $H_nM_tCl_2$. Our observations on this reaction may help explain an apparent discrepancy in the literature: in a professed attempt to produce our $TiCl_2$ reagent, which we prepared from $TiCl_4$ and Bu^nLi in THF (eq. 13), Bogdanovic and Bolte[34] treated instead a $TiCl_3$ suspension in pentane with one equivalent of *n*-butyllithium. Thereupon, they isolated and analyzed a *green* solid, whose composition was said to agree with its being the complex, $TiCl_2\cdot LiCl$. However, to our knowledge authentic samples of uncomplexed or complexed $TiCl_2$ have uniformly been reported to be *black* solids. Accordingly, we suggest that the green, putative "$TiCl_2\cdot LiCl$" is actually $TiCl_2H\cdot LiCl$, a composition that would better accord with the green color of Ti(III) and which would still correspond closely with the observed elemental analyses[34].

Compared to our extensive studies on the alkylative reduction of Group 14 metal salts, work with salts of Groups 15 and 16 are still in a preliminary stage. Treatment of VCl_3, $CrCl_3$ or $MoCl_5$ in THF with 2 or more equivalent of *n*-butyllithium leads to subvalent metal centers, which are capable of the reductive dimerization of aromatic ketones, such as 9-fluorenone, to a mixture of olefins and pinacols (eq. 17)[32,35].



$$2\,Ar_2C{=}O \xrightarrow[2.\ H_2O]{1.\ M_tCl_{n-2}} \underset{HO\quad OH}{Ar_2C-CAr_2} + Ar_2C{=}CAr_2 \quad (17)$$

However, here again such alkylative reductions can be accompanied by metal hydride formation, depending both on the reaction medium and the number of Bu^nLi equivalents. For example, treating $CrCl_3$ with 2 equiv. of Bu^nLi in THF solution apparently yields some form of black CrCl (**63**), since the reagent reductively couples ketones with >90% conversion (eq. 17). However, when the interaction of $CrCl_3$ with 2 equiv. of Bu^nLi is conducted in toluene suspension, the reduced chromium reagent transforms an aryl ketone into its corresponding secondary alcohol (**17**) with >90% conversion (eq. 18). Since deuteriolytic work-up gave no C−D bond in the alcohol, the H−C−O bond was formed before hydrolysis (eq. 18)[32]. Thus, some kind of chromium hydride must have been formed from $CrCl_3$ and Bu^nLi in toluene.



$$Ar_2C{=}O \xrightarrow[2.\ D_2O]{1.\ CrH_n\text{ in PhMe}} \underset{H\ \ \mathbf{17}}{Ar_2C-OD} \quad (18)$$

A totally unexpected result was observed when $CrCl_3$ in THF was treated with 4 equiv. of Bu^nLi at −78 °C: instead of the formation of a black solution or suspension, the reagents interacted to form a deep red solution. Removal of the THF and extraction of the residue with toluene left the insoluble LiCl. From the toluene extract a gray solid was obtained with an apparent empirical composition of $LiCrH_4\cdot 2\ LiCl\cdot 2\ THF$ (**64**), as shown by elemental and gasometric analysis (eq. 19)[32]. Since only 3 moles of dihydrogen was evolved upon hydrolysis and since **64** in THF displayed an ESR signal consistent with the presence of paramagnetic chromium(I), we suggest that **64** has the structure of $Li^+CrH_2^-$ with an η^2-dihydrogen on the chromium center.

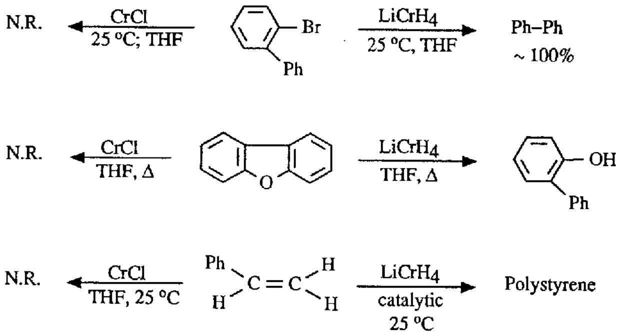
$$\text{"}LiCrH_4\text{"} + 4\,HOAc \longrightarrow LiOAc + Cr(OAc)_3 + 3\,H_2\uparrow \quad (19)$$

or

$LiCrH_2\cdot H_2$
64

Consistent with its composition, the interaction of a 1 : 1 ratio of **64** and 9-fluorenone in THF yielded 96% of 9-fluorenol and only 2% of the corresponding pinacol upon hydrolysis. Despite the indisputable hydridic character of **64**, there are a number of other reactions where **64** appears to function as an efficient electron-transfer agent. By contrast, CrCl (**63**) displays little or no electron-transfer activity (Scheme 3).

Scheme 3



These studies on the alkylative reduction of Groups 14–16 metal salts have shown that a variety of subvalent reducing agents can thereby arise: (1) monovalent or divalent metal salts that can effect the reductive coupling of various organic substrates, such as acetylenes, carbonyl derivatives and benzylic halides by apparent two-electron transfers ($TiCl_2$, $ZrCl_2$, CrCl and VCl_2); (2) covalent, metal hyydrides that reduce unsaturated linkages by hydrometallation (such as $TiCl_2H$, $Zr_2Cl_2H_2$ and $LiCrH_4$); (3) metal hydrides or subvalent metal salts that can also react with organic substrates by single-electron transfer, such as perhaps $LiCrH_4$ and its titanium and vanadium analogs[35].

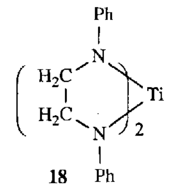
Scope of Electron-Transfer Reductions by Group 4 Metal Divalent Salts

(a) *Generation of Divalent Titanium Salts of the Type TiL_2.* An instructive comparison of the ligand effect (L) on the reducing action of divalent titanium emerged by treating successively $TiCl_4$, TiF_4, $Ti(OBu^n)_4$ and $Ti(NEt_2)_4$ each with 2 equivalents of Bu^nLi in toluene, first at −78°C and finally at reflux. The dark brown or black suspensions were then treated with benzophenone (TiL_2: Ph_2CO = 2:1) at 110°C to give the results given in Table 1[36]. In addition, complexes **18** and **19** were also alkylatively reduced, presumably with the removal of one $(PhNCH_2CH_2CH_2NPh)^{2-}$ ligand or two Cl^- ligands, respectively.

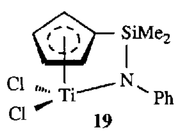
Table 1. Reduction of Ph_2CO by TiL_2 in toluene at 110°C

TiL_2 (presumed)	$Ph_2C=CPh_2$	$(PhCOH)_2$	Ph_2CHOH	Ph_2Bu^nCOH
$TiCl_2$	only	–	–	–
TiF_2[a]	–	–	39	61
$Ti(OBu^n)_2$	27	21	52	–
$Ti(NEt_2)_2$	–	–	76	24
18 red.	27	15	58	–
19 red.	24	7		(6, other)

[a] When the generation of TiF_2 was undertaken in a toluene-THF mixture, the resulting reagent gave 66% yield of $Ph_2C=CPh_2$ from Ph_2CO.

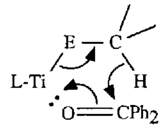


18



19

From the formation of the butyldiphenylcarbinol with the presumed "TiF_2" and "$Ti(NEt_2)_2$" reagent, it is clear that the reductive alkylation had not gone to completion in pure toluene and that most likely a titanium(III) intermediate, Bu^nTiF_2 and $Bu^nTi(NEt_2)_2$ persisted, so as to add to the benzophenone. The same intermediates could also effect reduction by β-hydride transfer to the ketone to produce benzhydrol. However, the formation of benzhydrol and the absence of the butyl carbinol with $Ti(OBu^n)_2$ and $Ti(NPhCH_2)_2$ (**18** red.) suggests that such divalent titanium alkoxides and amides reduce by hydride transfer and not by electron transfer (**20**). Consistent with this interpretation is the absence of benzhydrol from the reaction of benzophenone with the Ti(II) reagent formed from **19**, which lacks the β-hydrogen necessary for transfer. Thus, the most suitable ligand on Ti(II) for electron-transfer reductions are the chloride or the N-phenylamidodimethylsilylcyclopentadienyl ligand incorporated in **19**.



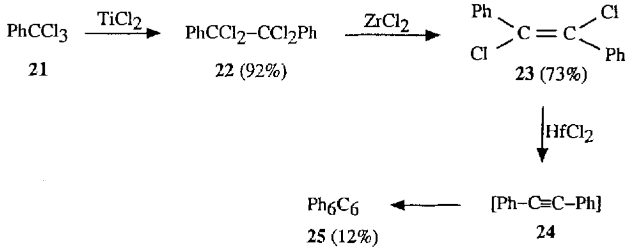
20 : E=O, NPh

(b) *Comparison of the Reducing Actions of Divalent Titanium, Zirconium and Hafnium Reagents*[25]. To prepare the chlorides of Ti(II), Zr(II) and Hf(II), it is best to conduct the reaction with *n*-butyllithium in THF and then, to assure thermolysis of any residual $C-M_t$ or $H-M_t$ bonds, to remove the THF and heat at elevated temperatures. A test on whether the reductive alkylation has gone to completion can be performed with benzophenone. The exclusive reductive coupling of the ketone and the absence of benzhydrol rules out the presence of $M_tH_nCl_2$ (eq. 20).

$$M_tCl_4 \xrightarrow[-2\,LiCl]{2\,Bu^nLi,\,THF} M_tH_xCl_2 \xrightarrow{\Delta} M_tCl_2 \qquad (20)$$

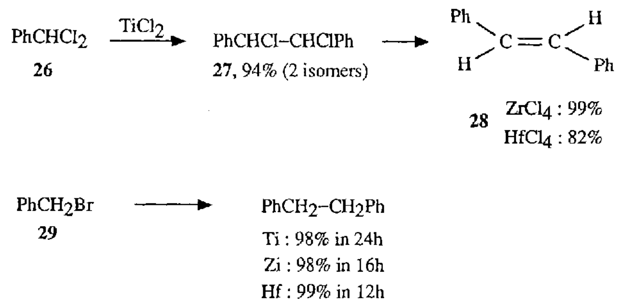
The gradated reducing action of these metal dichlorides is nicely exhibited toward benzotrichloride **21** (Scheme 4): $TiCl_2$ in refluxing THF forms only **22**; $ZrCl_2$ in refluxing THF yields no **22** but rather principally **23**; and $HfCl_2$ under the same conditions slowly converts **21** into hexaphenylbenzene (**25**), presumably via **24**. The behaviors of benzal chloride (**26**) and benzyl bromide (**29**) in such reductions illustrates further the greater and more rapid reducing action of $ZrCl_2$ and $HfCl_2$ in refluxing THF over $TiCl_2$ (Scheme 5). Moreover, the reductive coupling of 9-bromofluorene (**30**) was most selectively achieved with $HfCl_2$, which gave almost no fluorene (**32**) (eq. 21). Finally, in refluxing THF after 60 h the action of $TiCl_2$ on **24** consumed only 14% to yield upon hydrolysis solely **33**; under comparable conditions, $ZrCl_2$ produced solely 30% of **25** (70% of **24** recovered) and $HfCl_2$ gave 20% of **25** and 18% of (E)−1,2,3′,4-tetraphenyl-1-butene (**34**) (eq. 22).

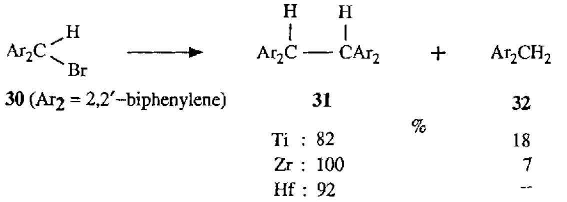
Scheme 4



The greater reactivity of $ZrCl_2$ and $HfCl_2$ over $TiCl_2$ and possibly the greater kinetic stability of C−Zr and C−Hf bonds over C−Ti bonds in key reaction intermediates undoubtedly account for the differences in reaction and in reactivity among these Group 4 dichlorides. The lower reactivity of $TiCl_2$ in THF partly stems from the presence of

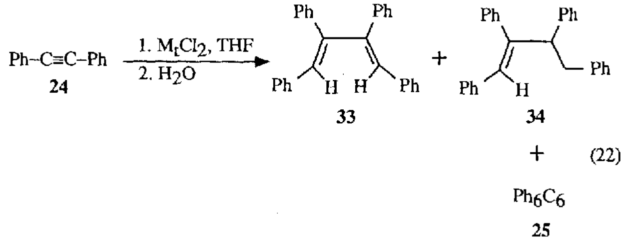
Scheme 5

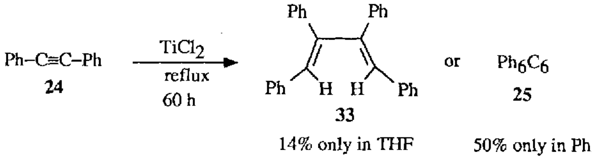




(21)

the Lewis bases, THF and chloride ion. Use of a more active reagent, $TiCl_2 \cdot 2$ THF in toluene, or the direct generation of $TiCl_2$ in toluene suspension yields not only a more active reductant but permits a higher reaction temperature (eq. 23)[31].

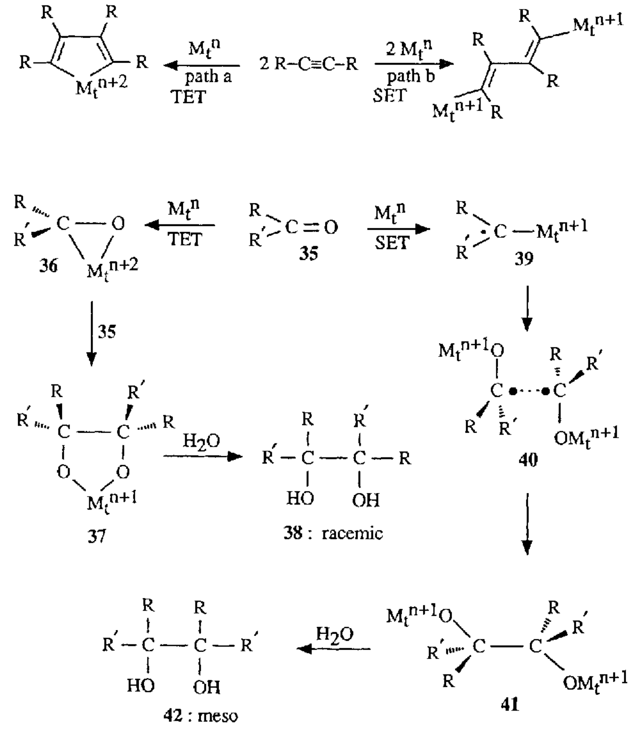




(23)

(c) *Stereochemical Selectivities in Reductive Coupling With Titanium Dichloride*[25,31]. As already depicted in Scheme 2, the stereochemical course observed for the reductive coupling of alkynes presents the opportunity for distinguishing between a concerted two-electron transfer (TET, path a) and a consecutive, discrete single-electron transfer (SET, path b) (Scheme 6). A similar possibility exists with prochiral carbonyl derivatives, RR'C=O (**35**). A TET-process on **35** would form the titanaoxacyclopropane **36**; the insertion of a second unit of **35** into the C–Ti bond of **36** with a minimization of the steric repulsions between the R and R' groups should generate **37** preferentially; and finally hydrolysis of **37** would lead to racemic glycol **38**.

Scheme 6

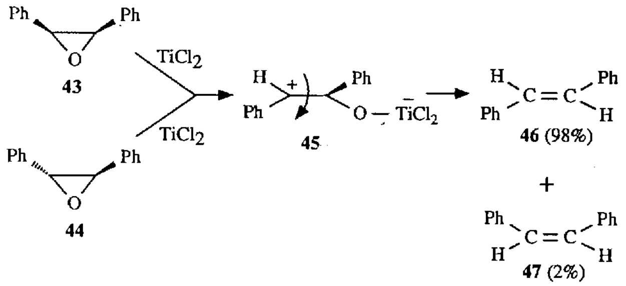


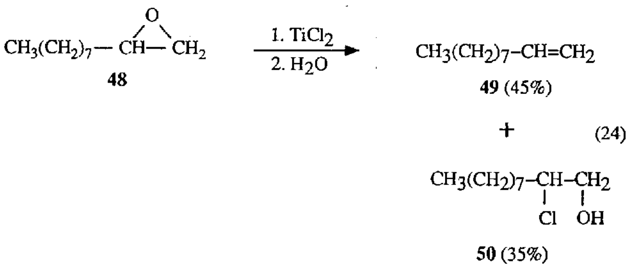
On the other hand, an SET-process on **35** would generate radicals **39**, whose radical coupling would be controlled by steric front-strain in the staggered transition state **40** and would lead preferentially to **41** and thus to meso glycol **42**, upon hydrolysis.

A third system that might supply some stereochemical insight into such ET-processes is the deoxygenation of *cis*- and *trans*-epoxides (**43** and **44**) to olefins. However, when applied to the stilbene oxides, no kinetic selectivity but rather thermodynamic selectivity resulted (Scheme 7), forming in both reactions a 98:2 mixture of *E*- and *Z*-isomers. A polar (**45**), rather than a radical-Ti(III) intermediate is proposed, since **45** would explain the formation of large proportions of **50** in the deoxygenation of 1,2-epoxydecane (**48**) (eq. 24).

That $TiCl_2$ in THF slowly converts diphenylacetylene (**24**), after hydrolysis, into only **33** and that it efficiently couples acetophenone (**51**) into only the racemic glycol **55** support the proposal that both processes proceed by way of TET pathways via intermediates **52**, **53** and **54**, respectively (Scheme 8).

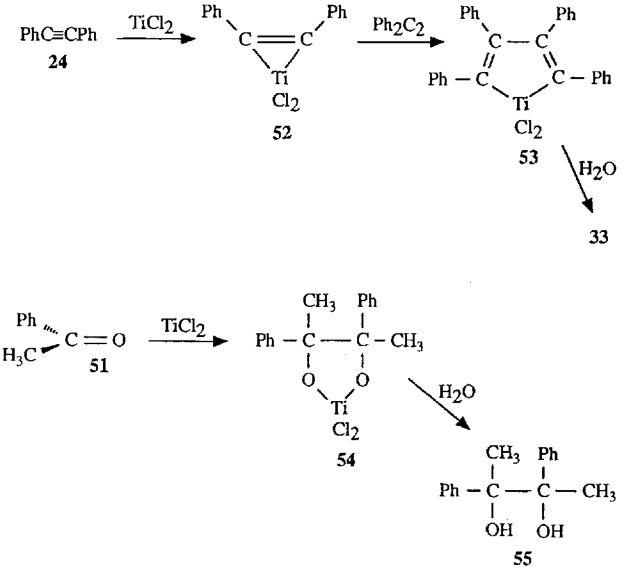
Scheme 7



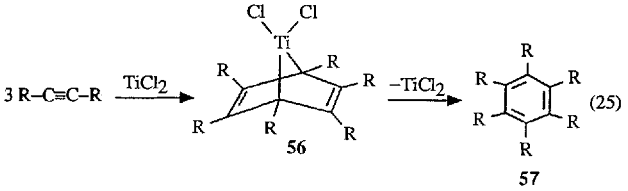


(24)

Scheme 8



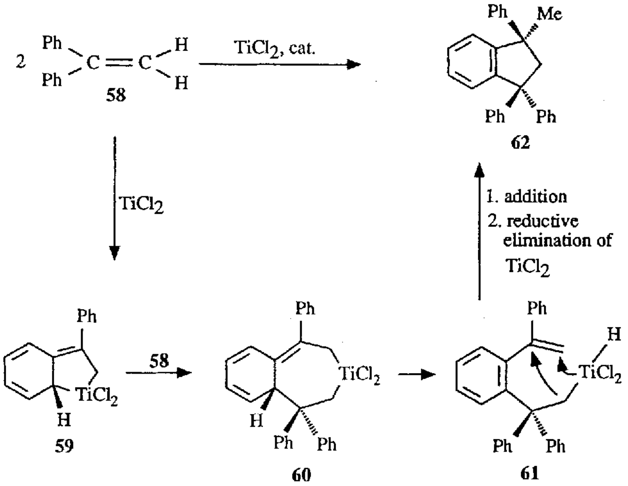
Metallocycles like **52**, having the Cp_2Ti or Cp_2Zr groupings in place of Cl_2Ti, have been prepared from Cp_2MCl_2 and Mg in the presence of the alkyne[37]. Also a titanole like **53**, but having Cp_2Ti in place of Cl_2Ti, has been prepared in good yield by the photolysis[38] or thermolysis[39] of η^3-allyltitanocene in the presence of **24**, presumably by way of divalent titanocene. Accordingly, titanirenes and titanoles like **52** and **53** are most probably the reactive intermediates in the catalytic cyclotrimerization of 4-octyne, 5-decyne, and phenylethylene with $TiCl_2$ in refluxing THF (eq. 25). In this view, the titanole would form a Diels-Alder adduct (**56**), which would decompose to the final cyclotrimer **57**. With phenylethyne **57** consists of about a 1:1 mixture of 1,2,4- and 1,3,5-substituted isomers.



(25)

Further support for such couplings proceeding by way of a TET-process comes from the slow dimerization of 1,1-diphenylethene (**58**) to indan derivative **62** (Scheme 9). The conversion can be viewed as a TET-1,4-addition of $TiCl_2$ to form **59**, carbotitanation of **58** by **59** to yield **60**, dehydrotitanation of **60** to **61**, intramolecular carbotitanation and subsequent reductive elimination of $TiCl_2$ to produce **62**.

Scheme 9

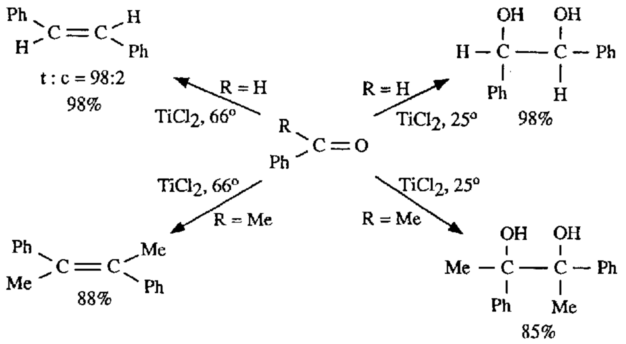


(d) *Scope and Limitations of Group 4 Divalent Metal Reductions.* The reducing actions of these metal dichlorides in THF generally decrease in the series, Hf > Zr > Ti, as is discussed in section b. However, the reactivity of $TiCl_2$ in such reductions can be increased markedly by removing the LiCl or by operating in toluene suspension. Nevertheless, there remain reductions for which $TiCl_2$ in THF is much more effective than $ZrCl_2$ or $HfCl_2$. The coupling of benzyl alcohol to biphenyl gives a 65% yield with $TiCl_2$ (eq. 26) but barely traces with the other dichlorides. In many other instances, namely the reductions of carbonyl derivatives, the reaction proceeds well with each of the dichlorides and thus there is no advantage to employing the zirconium or hafnium reagent.

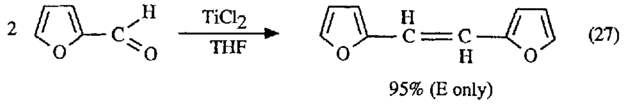
$$2\,PhCH_2OH \xrightarrow[THF,\,\Delta]{TiCl_2,\ excess} Ph\text{–}CH_2\text{–}CH_2\text{–}Ph + 2\,[OH] \qquad (26)$$

A wide variety of carbonyl derivatives have been found to undergo a smooth and sometimes *complex* reductive coupling with $TiCl_2$: aldehydes, ketones, acids (in the form of nitrile), acid chlorides, esters and amides as well as 1,5-diketones which undergo cyclic coupling. By conducting the reaction at 25°C, with low ratios of $TiCl_2$: carbonyl = 2:1, aldehydes and even many ketones yield principally the glycol, whose configuration is principally, if not exclusively, racemic (cf. section c) (Scheme 10).

Scheme 10



With higher ratios of $TiCl_2$: carbonyl and at reflux, only or preponderantly the *E*-isomer of the olefin becomes the dominant product. The structures of the glycols and the ensuing olefins are consistent with the concerted *syn*-elimination of the two glycolic oxygens from the putative intermediate **54** (Scheme 8). Some preparatively useful reductive couplings follow in eqs. 27–29. The stereochemistry of the glycol formed in eq. 29 is noteworth, for it implies that the carbonyl oxygens were oriented *cis* to each other as the ring was being closed. Such positioning of the carbonyls would ensue if the second carbonyl would have to insert into the C–Ti bond of a titanaoxacyclopropane (cf. **36** in Scheme 6) formed at the first carbonyl (**62**) and the stereochemistry is consistent with the TET path suggested in Scheme 6 for the *rac* stereoselectivitiy of coupling for prochiral carbonyl derivatives.

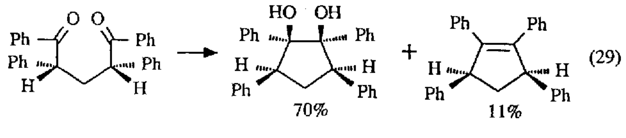


(27)

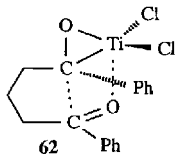
$$2\,Ar_2C{=}O + 4\,TiCl_2 \longrightarrow AR_2C{=}CAr_2 + 2\,Cl_2Ti{-}O{-}TiCl_2 \quad (28)$$

benzophenone,
9-fluorenone

90%

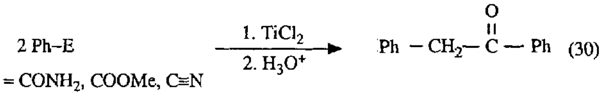


(29)



62

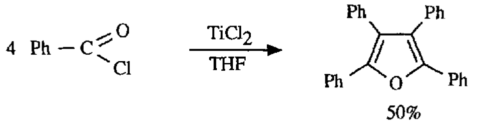
The reductive coupling of nitriles, esters or amides by $TiCl_2$ proceeds very slowly in THF and even in refluxing toluene gives only about 40% conversion after 48 h. The product from the phenyl-substituted acid derivatives is most interesting (eq. 30). Obviously reductive coupling has occurred, followed by partial deoxygenation (or deamination), but the reaction pathway remains to be determined.



$$2\,Ph{-}E \xrightarrow[2.\ H_3O^+]{1.\ TiCl_2} Ph-CH_2-\overset{\overset{O}{\|}}{C}-Ph \quad (30)$$

$E = CONH_2, COOMe, C{\equiv}N$

In closing this section on the applications of $TiCl_2$ in organic synthesis, it is fitting to report the observation of a reductive coupling of a carbonyl derivative by $TiCl_2$, of defined oxidation state, that results in the net formation of *three* C–C bonds and a heterocyclic ring in a surprising, non-optimized yield of almost 50% (eq. 31)[40]. Attempts to achieve analogous cyclization to pyrroles and to thiophenes are currently under way.



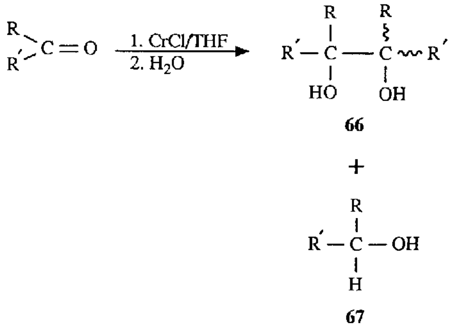
(31)

This arresting result, taken together with the foregoing reductive couplings and reductive cyclization depicted in Scheme 5 and in eqs. 27–30, shows that $TiCl_2$ represents a valuable, well-defined reagent that is capable of achieving a wide variety of intermolecular and intramolecular C–C couplings to produce a wide range of olefins, *racemic* glycols, carbocycles and heterocyclic systems[25,31].

Electron-Transfer Reductions by Subvalent Chromium Reagents

(a) *Generation of Useful and Distinctive Subvalent Chromium Reductants*[32]. Treatment of $CrCl_3$ in THF with *n*-butyllithium at −78 °C and then warming to room temperature gives a visually different outcome depending on the number of equivalents of the lithium reagent employed: (1) with 2 equivalents the result is a black suspension of presumably $CrCl \cdot n$ THF (**63**); and (2) with 4 equivalents a deep red solution is obtained. From the latter solution, after THF evaporation and toluene extraction, a chloride-free composition of $LiCrH_4 \cdot 2\,LiCl \cdot 2$ THF (**64**) was isolated as a gray powder. TGA measurements of the solid gave a weight loss at 200 °C consistent with the loss of 2 equivalents of both THF and dihydrogen. The composition of **64** also accords with the amount of H_2 evolved upon acetolysis. Since the chemical reactivity of the supposed CrCl generated in toluene differs from that of **63**, we suggest that the bistoluene complex of CrCl (**65**) may be formed in toluene, analogous to the formation of such complexes in the Fischer– Hafner synthesis[41].

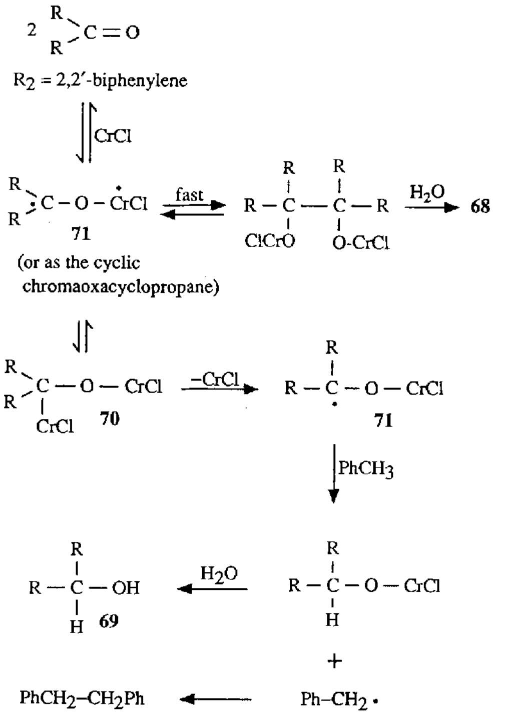
(b) *Reactivity of Formally Considered Chromium(I) Chloride* (**63** *and* **65**). The behavior of CrCl generated in THF (**63**) precludes the presence of significant proportions of Cr–H bonds in such reagents. For example, the treatment of carbonyl derivatives RR′C=O (benzaldehyde, acetophenone, benzophenone or 9-fluorenone) with CrCl in THF yields, upon hydrolysis, 85–90% of the pinacol (**66**) and only 1–2% of the carbinol (**67**) (eq. 32). The stereochemistry of the pinacol **66** resulting from benzaldehyde or from acetophenone again reveals a preferential formation of the *rac*-pinacol over the *meso*-isomer (6:1 to 10:1). This selectivity of reductive coupling is in accord with the TET-process, analogous to that outlined in Scheme 6.



(32)

Even in toluene suspension, reagent **65** reacted more like an SET-reagent than a Cr−H source. Thus, a 1:1 mixture of 9-fluorenone and **65** at 25°C gave principally 9,9′-bifluorenol (**68**) for short reaction times (70% conversion) but almost only 9-fluorenol (**69**) (≈ 45% conversion) at longer reaction times. In the latter situation, small amounts of bibenzyl were detected. These findings support the following SET-reaction pattern (Scheme 11). It is noteworthy that treatment of such reaction mixtures with D_2O produces *no* 9-deuterio-9-fluorenol, which demonstrates that no **70** survives to the hydrolysis step. The bibenzyl detected is consistent with H-abstraction by **70** or **71** from the toluene. In none of these reactions with ratios of carbonyl: CrCl of 3:1 or 1:1 were any significant amounts of olefin of the type, $R_2C{=}CR_2$, detected. Only with high ratios of CrCl: R_2CO was olefin formation prominent.

Scheme 11



In addition to smooth reductive coupling of carbonyl derivatives, CrCl in THF (**63**) is able to achieve the interesting dehalogenative couplings shown in Table 2. Significant are at the following observations: (1) the coupling of (1-bromoethyl)benzene yields a 1:1 mixture of *meso*- and *rac* dimers, which is in agreement with a random rather than a sterically controlled C−C bond formation; (2) benzotrichloride is quantitatively dehalogenated to the acetylene, without any of the subsequent cyclotrimerization to hexaphenylbenzene, as encountered with Group 4 dichloride reductants (eq. 25); (3) a single or a dual dehalogenative coupling can be favored by varying the proportion of CrCl used (entries 5 and 6); and (4) although aromatic halides are only slowly cleaved by CrCl alone, catalysis by nickel(0) markedly accelerates the process (entries 8a and 8b). Overall, therefore, CrCl in THF (**63**) is less reactive than either $TiCl_2$ or $ZrCl_2$ but therefore it offers greater selectivity in such coupling reactions, producing pinacols from carbonyl substrates without olefin formation and acetylenes from 1,1,1-trichlorides without subsequent cyclotrimerization. As to prevailing reaction mechanism(s) for such processes, a credible case can be made for oxidative additions via TET-processes with carbonyl derivatives and at least with benzylic halides (Scheme 12).

Table 2. Coupling of organic halides by CrCl in THF (**63**)[32]

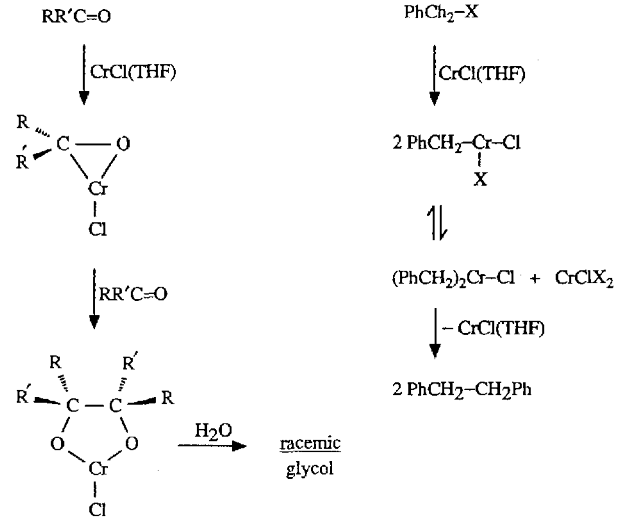
Entry	Substrates[a]	Products	Yield[b]
1.	$C_6H_5CH(CH_3)Br$	$C_6H_5CH(CH_3)CH(CH_3)C_6H_5$[c]	81
2.	Benzyl chloride	1,2-Diphenylethane	79
		Toluene	1
3.	9-Bromofluorene	9,9′-Bifluorenyl	96
		Fluorene	4
4.	Benzotrichloride[d]	Diphenylacetylene	100
5.	$(C_6H_5)_2CCl_2$[e]	$(C_6H_5)_2C{=}C(C_6H_5)_2$	52
		$(C_6H_5)_2CCl-CCl(C_6H_5)_2$	48
6.	$(C_6H_5)_2CCl_2$[f]	$(C_6H_5)_2C{=}C(C_6H_5)_2$	98
7.	2-Bromobiphenyl[g]	Biphenyl	20
8a.	4-Bromotoluene[h]	Toluene	1
8b.	4-Bromotoluene[h]	Toluene	84

[a] The reactions were conducted for up to 12 h at 25°C with a reagent ratio of 2:1 for **63**:substrate. – [b] The yields are not yet optimized. – [c] A 1:1 ratio of *meso*:*rac* coupling product was found. – [d] No hexaphenylbenzene was formed. – [e] A ratio of 2:1 of **63**:substrate at 25°C was employed. – [f] A ratio of 3:1 of **63**:substrate at reflux was employed. – [g] Hydrolysis with D_2O yielded no deuteriated biphenyl. – [h] These experiments differ in that entry 8b involved the use of 5% of nickel(II) acetylacetonate as a catalyst.

(c) *Reactivity of Formally Considered Lithium Chromium Hydride* (**64**)[32]. As suggested earlier, this reagent readily effects a variety of transformations, of which CrCl is barely capable or not at all, such as olefin polymerization and the cleavage of carbon−heteroatom bonds (Table 3). By contrast with CrCl either in THF or in toluene medium, this reagent gives every indication of reacting by SET-processes. Perhaps this will become evident by examining its scope of reaction with a variety of substrates (Table 3).

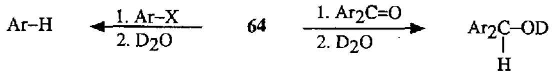
The first generalization concerning the reactivity of **64** versus that of **63** in THF is that **64** tends to favor monomolecular reduction of aldehydes and ketones to the alcohols (entries 1, 2, 3, 4b, 5, 6 and 7 in Table 3) while **63** yields the bimolecular pinacol products (eq. 32). Secondly, reagent **64** readily attacks not only benzylic halides, as does reagent **63**

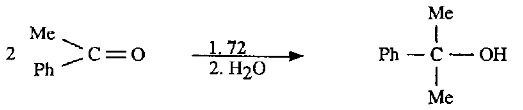
Scheme 12



(Table 2), but also aryl, vinyl and alkyl halides as well. In so doing, **64** tends to yield less of the dimer and more of the simple hydrodehalogenation product. Thus, 9-bromofluorene with **63** gives a 96:4 ratio of 9,9′-bifluorenyl to fluorene, while **64** yields a 70:30 ratio. Further, although **63** only slowly converts aryl halides to arenes (entries 7 and 8a in Table 2), **64** responds rapidly towards bromides and iodides (entries 20, 21 and 23 in Table 3) and even hydrodechlorinates at a moderate rate (entry 22). Both in the monomolecular reduction of carbonyl derivatives and hydrodehalogenation of aryl halides, the C−H bond is formed in the reaction mixture and not upon hydrolysis, as confirmed by workup with D_2O (Scheme 13).

Scheme 13





(33)

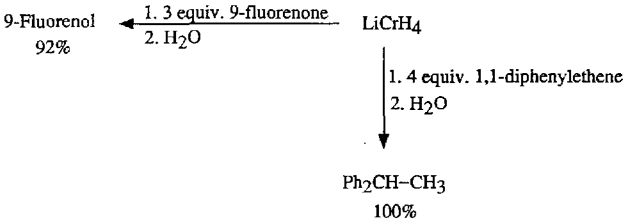
Thirdly, **64** reacts readily not only with aryl C−X, but also aryl C−N=N, C−O and C−S, as well as some alkyl C−O (epoxide), C−N and C−S bonds. Indeed, what puts a natural limit on what bonds can be cleaved by **64** in THF is the slow cleavage of the solvent. For example, triphenylamine is not cleaved by **64** in THF at 25 °C and when the attempted reaction is conducted at 70 °C, the amine remains unattacked but hydrolysis now yields *n*-butyl alcohol.

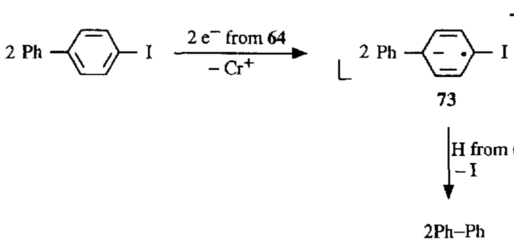
Fourthly, some of the reactions attainable with **64**, but not with **63**, took a complex, unexpected course. In this category are the following: (1) the polymerizations of styrene and methyl methacrylate, but not ethylene; (2) the oligomerizations, albeit in low efficiency, of diphenylacetylene to hexaphenylacetylene and of benzonitrile to 2,4,6-triphenyl-1,3,5-triazine; (3) the coupling and C−N bond cleavage of benzonitrile to 2,4,6-triphenylimidazole and of benzylamine to principally 1,2-diphenylethene and (4) the quantitative isomerization of 1-decene to internal decenes with less than 1% of decane.

The mechanisms of the formation and the reactions of **64** are evidently complicated and hence cannot be specified at the present. However, some pertinent findings can form the basis of preliminary proposals. As to the formation of **64**, it is noteworthy that the treatment of $CrCl_3$ in THF with 4 equivalents of methyllithium yields reagent **72**, which when admixed with acetophenone (2 equiv.) leads to about 95% of carbinol **73** upon hydrolysis (eq. 33). From this reaction it follows that reagent **72** is most likely $LiCrMe_4$, which was formed instead of **64** because of the inability of **72** to undergo elimination of olefin by β-Cr−H bond elimination.

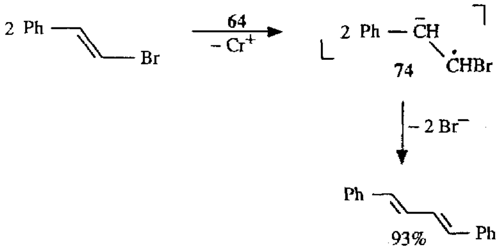
The reaction pathways for the interaction of **64** with the wide variety of substrates presented in Table 3 appear to range from evident hydrochromations with unsaturated centers (C=O, C=N, C=C and C≡C linkages) to electron-transfers of the SET or TET type, which seem operative in the cleavage of C−X, C−O, C−N and C−S bonds. The reduction of 3 equivalents of 9-fluorenone or 4 equivalents of 1,1-diphenylethene by 1 equivalent of **64** reveals that 3 or 4 of the Cr−H bonds are available for hydrochromation (Scheme 14). On the other hand, in the ET cleavage of σ C−X bonds **64** appears to be a two-electron source, since one equivalent of **64** can hydrodehalogenate up to two equivalents of aryl halide (eq. 34). The intermediacy of radical-anion **73** is supported by the efficient reductive coupling observed with certain vinylic halides (eq. 35).

Scheme 14





(34)



(35)

Consonant with the generation of such radical-anions in these reactions is the observed polymerizations of styrene and of methyl methacrylate by **64**. Both monomers are

Table 3. Reduction with „$LiCrH_4$" (**64**) in THF[32]

Entry	Substrates (S:Cr)[a]	Products	Yield[b]
1.	Acetophenone (2:1)	2,3-Diphenyl-2,3-butanediol	33
		1-Phenylethanol	67
2.	Benzophenone (1:1)	1,1,2,2-Tetraphenyl-1,2-ethanediol	2
		Diphenylmethanol	98
3.	9-Fluorenone (1:1)	9,9′-Bifluorenol	2
		9-Fluorenol	96
4a.	Benzaldehyde (1:1)	1,2-Diphenyl-1,2-ethanediol	51
		Benzyl alcohol	21
4b.	Benzaldehyde (3:1)	(*E*)-1,2-Diphenylethene	10
		Benzyl alcohol	96
5.	2-Adamantanone (1:1)	2-Adamantanol	97
6.	2-Benzoylpyridine (1:1)	2-(1-Hydroxybenzyl)pyridine	95
7.	Benzil (1:2)	Benzoin	95
8.	Cyclohexene oxide (1:1)	Cyclohexanol	100
9.	Dibenzofuran (2:1)	2-Hydroxybiphenyl[c]	84
10.	Dibenzothiophene (1:2)	Biphenyl[c]	24
11.	1,1-Diphenylethene (2:1)	1,1-Diphenylethane	92
12.	(*E*)-1,2-Diphenylethene (2:1)	Bibenzyl	43
13.	Styrene[d]	Poly(styrene)	100
14.	Methyl methacrylate[d]	Poly(methylmethacrylate)	100
15.	Diphenylacetylene (2:1)	1,2-Diphenylethane	40
		1,2-Diphenylethene[e]	45
		Hexaphenylbenzene	15
16.	1-Decene (1:1)	Decenes(2-, 3, 4- and 5-)	100
17.	Benzalaniline (1:1)	N-Benzylaniline	96
18.	Azobenzene (1:1)	Aniline	64
		4,4′-Diaminobiphenyl[f]	31
19.	2,2′-Dinitrobiphenyl (1:4)	2,2′-Diaminobiphenyl	88
20.	3-Bromo-1-phenylpropane (1:1)	1-Phenylpropane	99
21.	α-Bromostyrene (2:1)	(E,E)-1,4-Diphenyl-1,3-butadiene	93
22.	4-Bromoanisole	Anisole	98
23.	2-Bromobiphenyl (2:1)	Biphenyl[g]	98
24.	4-Iodobiphenyl (2:1)	Biphenyl	100
25.	4-Chloroanisole	Anisole[h]	50
26.	2,2′-Diiodobiphenyl (1:1)	Biphenyl	98
27.	Benzonitrile (3:1)	2,4,6-Triphenyl-1,3,5-triazine	20
		2,4,5-Triphenylimidazole[i]	30
28.	Benzylamine (1:1)	Bibenzyl	5
		1,2-Diphenylethene[e]	60
		Benzaldehyde	30
29.	Diphenylaminomethylphenyl sulfide (1:1)	Diphenyl(methyl)amine	34
		Diphenylamine	19
		Methyl phenyl sulfide	3
		Thiophenol	50

[a] The reactions were conducted for 12 h at 25 °C, sometimes with subsequent reflux; the occurrence of THF cleavage was detected by finding 1-butanol upon hydrolysis. – [b] The yields are not yet optimized. – [c] Starting material was recovered: 16% for entry 9 and 76% for entry 10. – [d] Polymerizations proceeded catalytically. – [e] A *cis,trans*-mixture of 2:98 was obtained. – [f] The benzidine most likely arose from acid-catalyzed rearrangement of the primary product, hydrazobenzene, during workup. – [g] Hydrolysis of such a reaction mixture with D_2O gave *undeuteriated* biphenyl. – [h] The remainder of the 4-chloroanisole was recovered. – [i] Significant amounts of polymeric(?) material, which was insoluble in $CHCl_3$ or in Et_2O, was formed, as well as small amounts of benzaldehyde and benzil.

known to be polymerizable by ET-initiation[42]. Further study will be required to corroborate both the hydrochromation and the electron-transfer pathways for the reducing action of **64** on organic compounds. Indeed, some of the reductive transformations may well involve a combination of the two processes, such as the reaction of **64** with benzylamine (entry 28, Table 3). Despite these persisting mechanistic uncertainties, it is clear that $LiCrH_4$ has already proved its value as an efficient reductant for a variety carbon-heteroatom π- and σ-bonds and that it has earned its rightful place alongside $CrCl_2$ as a most versatile reagent for selective organic synthesis[32d].

Vistas of Novel Selective Reductants for Organic Synthesis

Our research results have shown that an array of soluble, selective reductants towards organic substrates can be generated from early transition metals and that their reactivity can be modulated by: (1) choice of the specific transition metal and its formal oxidation state; (2) control of its ET- or hydridic character; (3) the type of anionic ligands on the metal, whether of hydride, halide, alkoxide or amide character; and (4) the presence of retarding or adjuvant Lewis bases or Lewis acids, arising from the solvent (THF or toluene) or from the byproduct of subvalent transition metal salt generation (LiCl, $MgCl_2$, $ZnCl_2$). The latter effect is illustrated by the inertness of $TiCl_2 \cdot 2$ THF toward ethylene; however, the addition of Me_2AlCl (6–8 equiv.) generates an active catalyst for the production of polyethylene[39].

The useful differences in the reducing activity among the trio of Group 4 dihalides, TiX_2, ZrX_2 and HfX_2, and among the neutral and anionic hydrides, such as $HTiCl_2$, H_2ZrCl_2 and $LiCrH_4$, encourage us to explore the character of reductants obtainable from Group 5 (V, Nb, Ta) and the higher members of Group 6 (Mo, W). This current work has indeed offered promising vistas of new selective reductants for organic synthesis.

This research had its origin in a materials science project generously funded by *Akzo Corporate Research Inc.* during the period of 1988–1991 and was continued mainly with the support of a grant from the *U.S. National Science Foundation* and the *Alexander von Humboldt* Senior Scientist Award to the principal investigator. Former postdoctoral associates, Drs. *Marek Boleslawski, Jacek Lasota* and *Sofya I. Pombrik,* contributed greatly in the initial exploratory phase of this research. Dr. *Sven Thiele*'s participation in this research was supported by a postdoctoral fellowship from the *Deutsche Forschungsgemeinschaft.*

Although the experimental details for the generation and reactions of the subvalent zirconium, hafnium, chromium and vanadium reductants have not yet been published, the chemist interested in employing any of these reagents can readily implement them by employing the stated reaction ratios of the transition metal salt and *n*-butyllithium in the specified solvent medium and following the published procedure for preparing $TiCl_2$, given in ref.[31] Hydrolytic work-up on any reaction of such a transition-metal reductant with any organic substrate is straightforward and unexceptional.

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