

Metals as surrogates for hydrogen in organic chemistry: anything hydrogen can do, a metal can do better

Alwyn G. Davies

Chemistry Department, University College London, 20 Gordon Street, London, UK WC1H 0AJ. E-mail: a.g.davies@ucl.ac.uk

Received (in Cambridge, UK) 14th December 1999

Published on the Web 2nd June 2000

1	Introduction
2	Autoxidation of hydrocarbons and organometallics
3	Bimolecular homolytic substitution at hydrogen or at metals
3.1	By free radicals
3.2	By photoexcited ketones
4	Photolysis of C–H and C–M bonds, and addition of H· or M· to alkenes
5	Homolytic substitution of vinyl, allyl, and aryl compounds
5.1	Vinyl compounds
5.2	Allyl compounds
5.3	Arenes
6	Nucleophilic substitution by HX or MX
7	Nucleophilic addition by HX or MX
8	Nucleophilic substitution at hydrogen or metals
9	Prototropy and metallotropy
10	Nucleophilic substitution and addition by enols and metal enolates
11	Electrophilic substitution of vinyl, allyl, and aryl compounds
11.1	Vinyl compounds
11.2	Allyl compounds
11.3	Arenes
12	Electrophilic addition of HX or MX to alkenes
13	Elimination of HX or MX
14	Sigmatropic rearrangement of hydrogen and of metals
15	Hydrogen-ene and metallo-ene reactions
16	The Schenck and Smith rearrangements
17	Protection of reactive groups
18	Conclusion
19	Acknowledgements
20	References
Box 1	Steric effects: H versus R ₃ Si
Box 2	Hyperconjugation: C–H versus C–M

1 Introduction

The principle that metals often behave as the equivalent of hydrogen has long been recognised by chemists of all persuasions. In 1869, Graham said “It has often been maintained on chemical grounds that hydrogen gas is the vapour of a highly volatile metal. The idea forces itself upon the mind that palladium with its occluded hydrogen is simply an alloy”.¹ Ramsay, in 1893, proposed that “hydrogen (is) probably a metal as shown by its compounds analogous to those of metals”, and he placed hydrogen together with the alkali metals in Group I of the Periodic Table.²

Amongst organic chemists, the analogy has usually been drawn less explicitly, though it is in organic chemistry, where hydrogen is ubiquitous, that recognition of the principle can be most useful in helping to interpret reaction mechanisms and to invent new experimental procedures and new reactions.^{3–5} Table 1 shows a list, which is by no means exhaustive, of 23 different reaction systems in which the operation of the principle is apparent; in Table 1, the symbol H/M is used to imply that the reaction can involve either hydrogen or a metal. These reactions cover homolytic (Table 1, entries 1, 2, 5–8, 22), heterolytic (entries 9–19, 21), photolytic (entries 3 and 4), and pericyclic (entry 20) mechanisms, and the principle extends not only to the reactants and products, and to the reaction mechanisms, but also frequently to the underlying electronic effects and reaction kinetics.

This principle is important in organic synthesis. If a reaction occurs at or near the hydrogen centre in a molecule HX, there is little that can be done at that (monovalent) hydrogen centre to vary the reactivity of the H–X bond. On the other hand, if the same reaction involves the metal centre in the molecule MX, where M is a metal or organometallic group, a great deal is possible. Metals are usually easy to introduce and to remove. Many different metals are available with various valences, electronegativities, bond strengths, bond lengths, coordination states, steric demands, and solvation characteristics, and these properties can be modulated further by an almost unlimited variety of ligands. By a suitable choice of these parameters, it is often possible to cause the desired reaction, involving a metal rather than hydrogen, to take place at a convenient rate, and to be chemo-, regio-, and stereo-specific.

The M–X bond may be more or less reactive than the H–X bond, depending on the nature of M and of X. Thus a trimethylsilyl group has been referred to as a *super* proton (when it is bonded to C),⁶ as a *feeble* proton (when it is bonded to O),⁶ and as a *bulky* proton in a more general context (see Box 1, at the end of the paper).⁷ Most applications, however, have taken advantage of the controllable enhanced reactivity that replacement of hydrogen by a metal usually confers, and in the present context, the word proton is often not appropriate, because the reaction may not involve electrophilic hydrogen or metal.

Typical disparate systems where recognition of the concept has proved to be useful are the autoxidation of organometallic compounds (Table 1, entry 1), the generation of alkyl radicals for EPR studies (entry 2), the control of substituent effects in aromatic substitution (entry 17), the metal catalysis of the formation of urethanes from alcohols and isocyanates (entry 10), and the ene reaction of allylic hydrocarbons and of allylmetallic compounds (entry 21).

Table 1 Reactions with metals acting as hydrogen surrogates




Entry no.	Reaction involving hydrogen or metal (H/M)	Typical metals
Autoxidation of RH or RM		
1	$\text{RH/M} + \text{O}_2 \longrightarrow \text{ROOH/M}$	B, Mg, Zn, Cd
Bimolecular homolytic substitution at H or M		
2	$\text{X}\cdot + \text{H/MR} \longrightarrow \text{XH/M} + \text{R}\cdot$	B, Sn, Zn
3	$\text{R}'_2\text{C}=\text{O}^\cdot + \text{H/MR} \longrightarrow \text{R}'_2\dot{\text{C}}-\text{OH/M} + \text{R}\cdot$	B, Sn
Photolytic cleavage of C–H or C–M		
4	$\text{Cp}^*\text{H/M} \xrightarrow{h\nu} \text{Cp}^*\cdot + \text{H/M}\cdot$	Sn, Pb, Hg
Addition of H· or M· to alkenes		
5	$\text{H/M}\cdot + \text{CH}_2=\text{CH}_2 \longrightarrow \text{H/MCH}_2\text{CH}_2\cdot$	Si, Ge, Sn
Homolytic displacement of H or M		
6	$\text{X}\cdot + \text{CH}_2=\text{CH}^{\text{H/M}} \longrightarrow \text{CH}_2=\text{CH}^{\text{X}} + \text{H/M}\cdot$	Si, Sn
7	$\text{X}\cdot + \text{CH}_3\text{CH}=\text{CH}^{\text{H/M}} \longrightarrow \text{XCH}_2\text{CH}=\text{CH}_2 + \text{H/M}\cdot$	Sn
8	$\text{X}\cdot + \text{ArH/M} \longrightarrow \text{XAr} + \text{H/M}\cdot$	Hg, Si, Ge, Sn, Pb
Nucleophilic substitution by HX or MX		
9	$\text{H/MX} + \text{R}'\text{Y} \longrightarrow \text{R}'\text{X} + \text{H/MY}$	Li, Na, K, Mg, Sn <i>etc.</i>
Nucleophilic addition by HX or MX		
10	$\text{H/MX} + \text{A}=\text{B} \longrightarrow \text{H/MA}-\text{BX}$	Si, Sn, Pb
Nucleophilic substitution at H or M		
11	$\text{CH}_2=\text{CH}^{\text{H/M}} + \text{BuLi} \longrightarrow \text{CH}_2=\text{CH}^{\text{Li}} + \text{BuH/M}$	Hg, Sn, Pb
Prototropy and metalloprotopy		
12	$\text{H/M}-\text{CH}_2\text{CH}=\text{O} \rightleftharpoons \text{CH}_2=\text{CH}-\text{O}^{\text{H/M}}$	Li, Na, Mg, Zn, B, Al, Si, Sn <i>etc.</i>
Nucleophilic substitution and addition by enols or enolates		
13	$\text{H/M}-\text{O}-\text{CH}=\text{CH}_2 + \text{E}^+ \longrightarrow \text{H/M}^+ + \text{O}=\text{CH}-\text{CH}_2\text{E}$	B, Si, Sn
14	$\text{H/M}-\text{O}-\text{CH}=\text{CH}_2 + \text{R}_2\text{C}=\text{O} \longrightarrow \text{O}=\text{CH}-\text{CH}(\text{CR}_2)-\text{O}^{\text{H/M}}$	Si, Sn, Pb
Electrophilic displacement of H or M		
15	$\text{X}^+ + \text{CH}_2=\text{CH}^{\text{H/M}} \longrightarrow \text{CH}_2=\text{CH}^{\text{X}} + \text{H/M}^+$	Si, Ge, Sn
16	$\text{X}^+ + \text{CH}_3\text{CH}=\text{CH}^{\text{H/M}} \longrightarrow \text{XCH}_2\text{CH}=\text{CH}_2 + \text{H/M}^+$	Si, Ge, Sn, Pb
17	$\text{X}^+ + \text{ArH/M} \longrightarrow \text{XAr} + \text{H/M}^+$	Hg, B, Si, Ge, Sn, Pd <i>etc.</i>
Electrophilic addition by HX or MX		
18	$\text{H/MX} + \text{C}=\text{C} \longrightarrow \text{H/M}-\text{C}-\text{C}-\text{X}$	Hg, Tl
Elimination of HX or MX		
19	$\text{H/M}-\text{C}-\text{C}-\text{X} \longrightarrow \text{H/MX} + \text{C}=\text{C}$	Si
Sigmatropic rearrangement of H or M		
20		Si, Sn, Ge, Pb, Hg

Table 1 (Contd.)

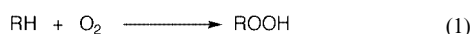
Entry no.	Reaction involving hydrogen or metal (H/M)	Typical metals
Hydrogen-ene and metallo-ene reactions		
21		Ge, Sn, Pb
Schenck and Smith rearrangements		
22		Sn
Protection of functional groups		
23	H/MX + reagent → products	Si

A variety of electronic effects appear to be responsible for the enhanced reactivity which is often observed, including the availability of vacant p- or d-orbitals on the metals, the high σ and σ^* C–M bond energy levels particularly because they result in strong C–M bond hyperconjugation (see Box 2, at the end of paper), the often low C–M bond strength, and the polarity of the $M^{\delta+}-X^{\delta-}$ bond which enhances the nucleophilicity of X and the electrophilicity of M. Steric effects (Box 1) can also be important.

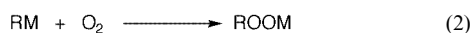
In the sections which follow, this analogy between the behaviour of metals and of hydrogen is surveyed according to the sequence of reactions in Table 1, with an emphasis on those examples which have led to the understanding of reaction mechanisms or the design of new reactions. No attempt has been made to make the coverage comprehensive or to deal in detail with the applications in synthesis; the aim has been rather to emphasise the broad scope of the principle, and to encourage chemists to think in these terms when dealing with reactions involving hydrogen or metals.

2 Autoxidation of hydrocarbons and organometallics (Table 1, entry 1)

Hydrocarbons, RH, react with oxygen to give alkyl hydroperoxides [eqn. (1)], by a reaction (autoxidation) which even



under favourable conditions takes hours or days. The organic derivatives, RM, of many Main Group metals often inflame in the air (e.g. Me_3B , Et_2Zn , Me_2Cd , $PhLi$), but if inflammation is avoided by working with dilute solutions at or below room temperature, and with an excess of oxygen, the corresponding organoperoxy-metallic compounds can be obtained rapidly and in good yield [eqn. (2)], e.g. $Bu_3Bu \longrightarrow BuB(OOBu)_2$,⁸



$Et_2Zn \longrightarrow Zn(OOEt)_2$.⁹ In this context, the metals are therefore behaving as more reactive surrogates of hydrogen.

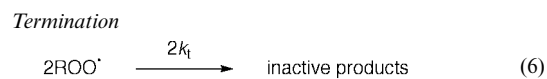
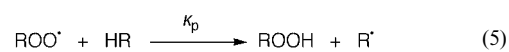
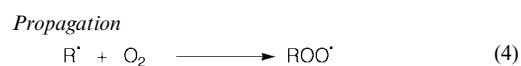
The reactivity of the organometallic compounds can be controlled by varying the ligands about the metal, e.g. $RB(OH)_2 < R_3B$, and simple alkyl hydroperoxides can best be prepared from the reaction of trialkylboranes in THF with oxygen at $-78^\circ C$.¹⁰

The reaction of organometallic compounds can be blocked by making the metal coordinatively saturated; thus the pyridine complex of trimethylborane, $Me_3B \cdot py$, is stable as a solid or in solution, but if the solution is acidified, Me_3B is liberated as a gas, and immediately inflames in the air.

As there is a correspondence between the products of equations (1) and (2), we might look for a correspondence

in the mechanisms of the two reactions, and indeed this does exist.

Hydrocarbon autoxidation is well established to proceed by a radical chain mechanism [eqns. (3)–(6)], and obeys the rate law shown in equation (7).



$$\frac{-d[O_2]}{dt} = k_p[ROO^\cdot][HR] = \frac{k_p[HR] R_i^{1/2}}{(2k_t)^{1/2}} \quad (7)$$

The reactions involve racemisation in optically active compounds R^*H as the radical R^\cdot is planar, and they can be accelerated by initiators which provide a source of the radicals R^\cdot [eqn. (3)], and inhibited by reagents which will trap the radicals ROO^\cdot and/or R^\cdot which are formed in equations (4) and (5).¹¹

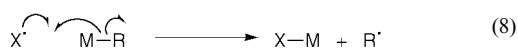
The autoxidation of organoboranes follows the same mechanism [eqns. (3)–(6)] and obeys the same kinetic equation [eqn. (7)] where HR is replaced by MR throughout. Optically active 1-phenylethylboronic acid, $PhMeC^*HB(OH)_2$ is autoxidised to the racemic peroxide $PhMeCHOOB(OH)_2$, and the reactions can be stopped with inhibitors such as galvinoxyl, and accelerated by di-*tert*-butyl hyponitrite as the initiator, with the rate proportional to $[{}^tBuON=NO{}^tBu]^{1/2}$ as required by equation (7).¹²

Similar but more limited studies of the organic derivatives of other metals such as magnesium, zinc, and cadmium show that similar principles apply.¹³ In recent years, this generation of radicals by the R_3B-O_2 or R_2Zn-O_2 system has been widely used for initiating radical chain reactions, particularly hydrostannations, at low temperature.

The correspondence between the autoxidation of hydrocarbons and of these organometallic compounds is therefore complete, covering the nature of the products, the reaction mechanisms, and the reaction kinetics: the first reaction involves bimolecular homolytic substitution (S_H2) by the alkylperoxy radical at hydrogen [eqn. (5)], and the second involves the same process at the metal M. The important practical difference is that, by varying the metal and the ligands

about the metal, the rate of equation (2) can be controlled in a way which is not possible with equation (1).

By measuring the rate of oxidation, the value of k_p , the rate constant for homolytic substitution by the alkylperoxyl radical at boron, can be abstracted.¹² Typical values are Bu_3B 2×10^6 , $\text{Bu}_2\text{BOBBu}_2$ 3×10^5 , and $(\text{BuBO})_3$ $1 \times 10^3 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$ at 30 °C, whereas the equivalent value for substitution at hydrogen in BuH is about $1 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$. This showed for the first time, that $\text{S}_{\text{H}2}$ reactions of electronegative radicals occur at the metal centres in organometallic compounds to displace organic radicals [eqn. (8)] often very much more rapidly than at hydrogen,



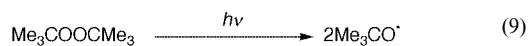
and that the rate constants could be varied widely by suitably selecting the organometallic structure. This was to prove a most useful concept.

3 Bimolecular homolytic substitution at hydrogen or at metals

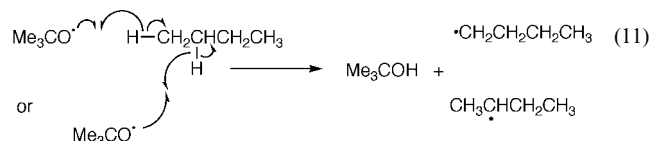
3.1 By free radicals (Table 1, entry 2)

At the time this work on autoxidation was being carried out, EPR studies of persistent organic radical ions were well established, but studies of the relatively short-lived neutral alkyl radicals were in their infancy. Fessenden and Schuler had carried out pioneering studies,¹⁴ but these involved electron irradiation of the samples in the EPR cavity using a van der Graaf generator, which posed formidable experimental difficulties, and there was a need for a simpler general method.

One approach might be to photolyse di-*tert*-butyl peroxide in the presence of a hydrocarbon in the EPR cavity when the *tert*-butoxyl radicals should take part in an $\text{S}_{\text{H}2}$ reaction at hydrogen [eqns. (9) and (10)] similar to the behaviour of the alkylperoxyl

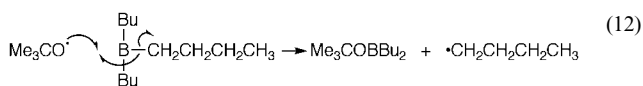


radical [eqns. (4) and (5)]. This method indeed can be used for hydrocarbons such as ethane or cyclohexane where all the hydrogens are equivalent. It is not suitable however for generating, say, the 1-butyl radical because the methyl and methylene hydrogen atoms in butane show a rather similar reactivity towards *tert*-butoxyl radicals [eqn. (11)], and what is observed is



a rather weak spectrum of a mixture of 1-butyl and 2-butyl radicals.

The principle that electronegative radicals can bring about $\text{S}_{\text{H}2}$ reactions at metal centres suggested a solution to the problem, and indeed photolysis of di-*tert*-butyl peroxide in the presence of a trialkylborane [eqn. (12)] gives rise to a strong and



clean spectrum of the corresponding alkyl radical.¹⁵ The fact that the reaction is much faster at the metal than at the hydrogen centres makes it regiospecific, and gives a much higher standing concentration of alkyl radicals: the boron is acting as

a super surrogate for hydrogen. This enabled the EPR characteristics of many alkyl radicals to be studied. Various metals, M, can be used,¹⁶ and the triorganotin chlorides, R_3SnCl , are particularly convenient [e.g. eqn. (13)] as they are stable to air and easier to handle than the boranes.¹⁷



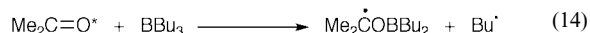
Rate constants for the $\text{S}_{\text{H}2}$ reactions at the metal centres can be measured by EPR spectroscopy, and typical values for the reaction at room temperature of *tert*-butoxyl radicals are Bu_3B 1.5×10^8 , ${}^i\text{Bu}_3\text{B}$ 5.1×10^6 , Ph_3B 1.0×10^8 , $(\text{BuBO})_3$ 1.5×10^6 , and Pr_3SnCl 1×10^6 , compared with cyclopentane $5 \times 10^6 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$.¹⁸

Similar $\text{S}_{\text{H}2}$ mechanisms have been established for the reaction of aminyl (R_2N^\cdot)¹⁹ and thiyl (RS^\cdot) radicals, and for the organic compounds of antimony and bismuth, and the *N*-halogenosuccinimides react with tetraalkyltins in a chain reaction involving an $\text{S}_{\text{H}2}$ process by the succinimidyl radical at the tin centre.²⁰

If the *tert*-butoxyl radicals are generated by laser flash photolysis in the presence of Ph_3B , and the system is monitored by time-resolved optical absorption spectroscopy, a transient spectrum which is ascribed to the radical $\text{Me}_3\text{CO}\dot{\text{B}}\text{Ph}_3$ can be observed. The high reactivity of the organoboranes compared to the hydrocarbons therefore appears to be due to the presence of a vacant low-lying 2p orbital on the borane, and to the relative weakness of the B–C bond, and similar factors probably account for the rapid $\text{S}_{\text{H}2}$ reactions at other metal centres. If the boron is rendered 4-coordinate, as in $\text{Me}_3\text{B}\cdot\text{py}$, this low-lying orbital is no longer available, and the $\text{S}_{\text{H}2}$ reaction at boron is precluded.¹⁸

3.2 By photoexcited ketones (Table 1, entry 3)

Ketones which are excited to their $n \rightarrow \pi^*$ triplet state behave in many ways like alkoxy radicals, and in particular will abstract hydrogen by an $\text{S}_{\text{H}2}$ process from hydrocarbons. They would also be expected therefore to bring about an $\text{S}_{\text{H}2}$ process at the same metal centres at which alkoxy radicals react, to displace an alkyl radical. Such reactions do indeed take place, and, for example, if acetone is photoexcited in the presence of tributylborane, the superimposed EPR spectra of the radicals $\text{Me}_2\dot{\text{C}}\text{OBBu}_2$ and Bu^\cdot [eqn. (14)] can be observed.²¹ Rate constants

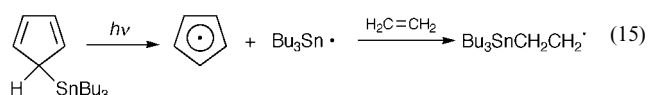


have been measured for some of the reactions at boron and tin centres, and typical figures are, for $\text{Me}_2\text{CO}^\cdot + \text{Bu}_3\text{B}$, 7×10^6 ,²¹ and for $\text{PhMeCO}^\cdot + \text{Bu}_3\text{SnCl}$, $4 \times 10^8 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$.¹⁷ No examples appear yet to have been reported of Norrish II reactions or McClafferty fragmentations of carbonyl compounds with metals in the γ -positions.

4 Photolysis of C–H and C–M bonds, (Table 1, entry 4) and addition of H· or M· to alkenes (Table 1, entry 5)

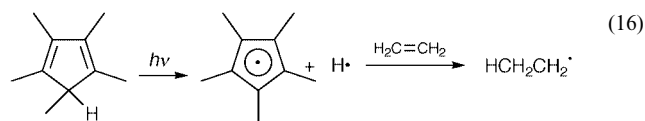
Ready photolytic cleavage of a C–H bond is not a common phenomenon. We found an example of it by being guided by the principle that a C–H bond should react in the same way as the corresponding C–M bond.

If a cyclopentadienyltin compound such as $\text{C}_5\text{H}_5\text{SnBu}_3$ is irradiated in solution with UV light in an EPR cavity, the C–Sn bond is cleaved and the spectrum of the cyclopentadienyl radical can be observed [eqn. (15)]. The metal radical, $\text{Bu}_3\text{Sn}^\cdot$



can be identified by its characteristic reaction with alkyl halides, or in particular, by its addition to ethene to give the stannylethyl radical.²² The cyclopentadienyl derivatives of lead (C₅H₅PbR₃),²³ and of mercury (C₅H₅HgX)²² behave in the same way.

The pentamethylcyclopentadienylmetallic compounds are even more photosensitive, and this system seemed to be the best in which to search for the equivalent cleavage of a C–H bond. Indeed, photolysis of pentamethylcyclopentadiene itself shows the spectrum of the pentamethylcyclopentadienyl radical; in the absence of a radical trap the hydrogen atom which is formed abstracts hydrogen to give dihydrogen, which can be observed to bubble out of the solution, but in the presence of ethene it adds to give the ethyl radical, which shows its characteristic EPR spectrum [eqn. (16)].²⁴ The



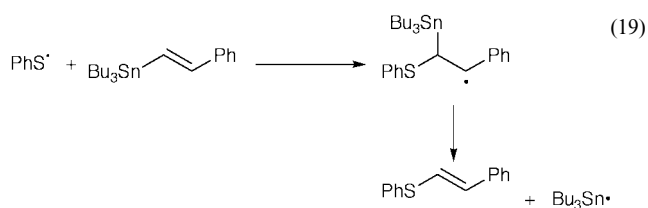
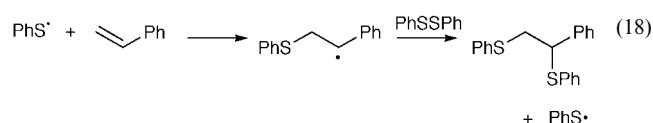
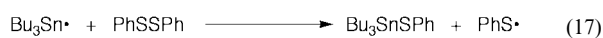
hydrogen/metal analogy is therefore complete in that it covers both the cleavage of the C–H and C–M bonds, and also the reactions of the H· and M· radicals which are formed.

5 Homolytic substitution of vinyl, allyl, and aryl compounds (Table 1, entries 6, 7, and 8)

The reaction of radicals with vinyl, allyl, and aryl compounds, RH or RM, involves addition of the radical to the π-system followed by the possible loss of H or M to complete the substitution reaction. The initial addition is favoured in the organometallic compounds because the carbon-centred radical which is formed in each case is stabilised better by C–M hyperconjugation than by C–H hyperconjugation (see Box 2). Unimolecular cleavage of a β-C–H bond in the radical adduct to give a hydrogen atom does not normally occur because of the strength of the C–H bond, but a carbon–metal bond may be relatively weak (e.g. CH₃CH₂–H 418 kJ mol⁻¹, CH₃CH₂–SnMe₃ 280 kJ mol⁻¹), and homolysis of a C–M bond to give a metal radical is a common occurrence. This makes it possible to carry out homolytic conjugate displacement of a metal in allylmetal compounds, or *ipso* displacement of a metal in vinyl- or aryl-metal compounds, when displacement of hydrogen in the equivalent position would be impossible or would require the intervention of a further reagent to remove the hydrogen.

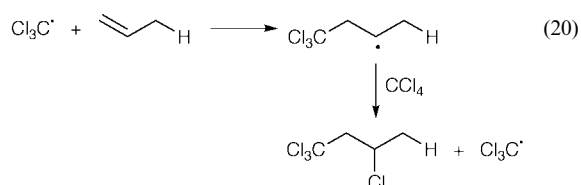
5.1 Vinyl compounds (Table 1, entry 6)

Addition of a radical to a vinylic hydrocarbon is usually completed by abstraction of a further radical to give overall addition, sometimes after telomerisation. The addition of a radical to a vinylmetallic compound usually occurs at the α-carbon atom so that it can take advantage of the C–M hyperconjugation, and is completed by β-scission of the C–M bond to give overall *ipso*-substitution. This is illustrated in equations (17),²⁵ and (18) and (19),²⁶ for the reaction of diphenyl disulfide with styrene and with a β-stannylstyrene.

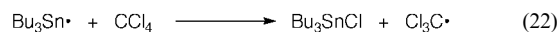
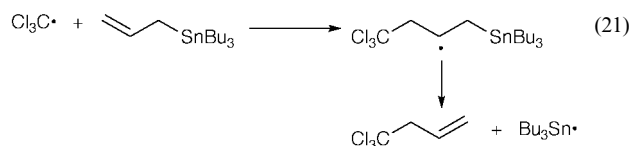


5.2 Allyl compounds (Table 1, entry 7)

The contrasting behaviour of allylic hydrocarbons and allylmetallic compounds is illustrated by the reaction of carbon tetrachloride with propene and with allyltrimethyltin. The reaction with propene is completed by abstraction of chlorine by the carbon-centred radical to give overall addition across the double bond [eqn. (20)],²⁷ whereas the organometallic inter-



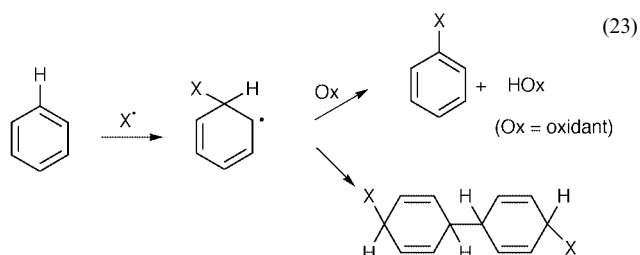
mediate loses the metallic radical, resulting in overall conjugate substitution [eqns. (21) and (22)].²⁸ Other reagents which



react by a similar mechanism include alkyl bromides and iodides, α-bromoketones, sulfinyl chlorides, cyclopropyl ketones, diazoketones, diaryl disulfides, aryl alkyl sulfoxides, and sultams.

5.3 Arenes (Table 1, entry 8)

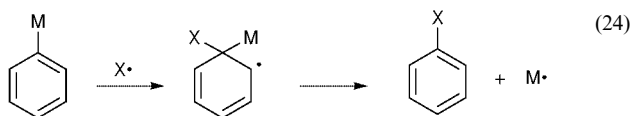
Electrophilic substitution of hydrogen in an aromatic ring involves slow, rate determining, formation of the Wheland intermediate followed by rapid loss of the proton to the solvent. In the corresponding homolytic reaction, loss of the hydrogen atom requires the intervention of a further reagent; the cyclohexadienyl radical intermediate is relatively long lived and can be sometimes detected by EPR spectroscopy. The oxidant to remove the hydrogen can be atmospheric oxygen, or a reducible molecule such as benzoyl peroxide, or a reducible metal ion such as Cu²⁺, but coupling of two cyclohexadienyl radicals to give a tetrahydrobiphenyl frequently detracts from the yield of substitution product [eqn. (23)]. This, and the low regioselectivity of the



reactions, limits the application of these reactions in organic synthesis.

The reaction of the corresponding organometallic compounds does not suffer from these disadvantages. It would be expected to be regioselective for *ipso* substitution because only then can (enhanced) C–M hyperconjugation operate (Box 2), and the metal radical should be rapidly lost without the need for any oxidant [though with some compounds such as triphenylborane, the radical may attack at the metal centre (Section 3)].

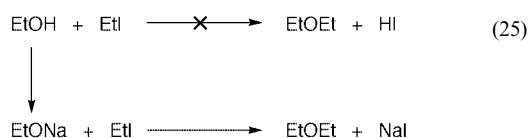
The *ipso* nature of the reaction of silyl radicals with arylsilanes [eqn. (24), X = R₃Si, M = R'₃Si] has been confirmed by



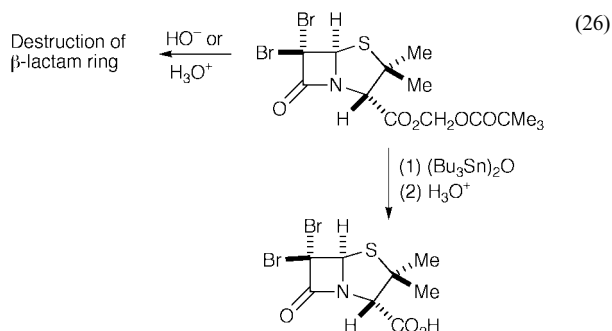
product studies²⁹ and by the identification of the cyclohexadienyl intermediate by EPR spectroscopy,³⁰ but very little work appears to have been done to exploit the preparative potential of homolytic aromatic substitution reactions. The various reagents which are known to bring about conjugate allylic displacement of a metallic group (see above) might be expected also to bring about *ipso* aromatic substitution (Section 11.3), and this would seem to be a promising field for investigation.

6 Nucleophilic substitution by HX or MX (Table 1, entry 9)

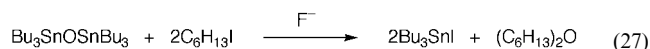
The usual effect of converting an OH group into OM, where M is a metal, is to render the oxygen more nucleophilic because of the electropositive nature of the metal. This enhanced reactivity in M^{δ+}–O^{δ-} where M is sodium was exploited by Williamson in 1852³¹ in his synthesis of ether, and similar behaviour can be quoted for most other metals [eqn. (25)].



Organotin chemistry provides some recent examples. A tributyltin alkoxide will catalyse transesterification between an alcohol and an ester because Bu₃SnOR is a stronger nucleophile than HOR,³² and sensitive esters can be “hydrolysed” under essentially neutral conditions with bis(tributyltin) oxide [eqn. (26)].³³



The nucleophilicity of the oxygen can be enhanced by addition of a good ligand to the tin, such as DMF or MeCN, or particularly F⁻, when reaction with benzyl bromide or an alkyl iodide will give the corresponding ether [eqn. (27)].³⁴ Similarly



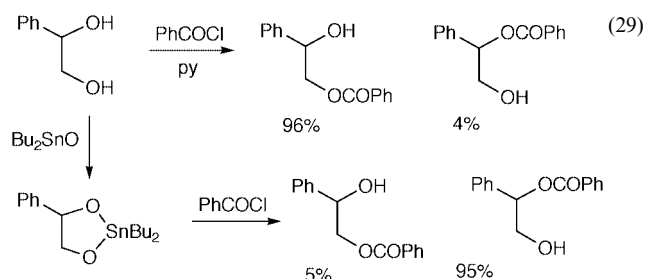
reaction between tributyltin alkoxides and alkyl halides will give mixed ethers.

Organotin sulfides, selenides, and tellurides, (R₃Sn)₂X, similarly act as sources of more nucleophilic X²⁻ than do the corresponding hydrides H₂X, and in the presence of a good ligand will react with alkyl halides to give the corresponding alkyl sulfides, selenides, or tellurides [eqn. (28)].³⁵

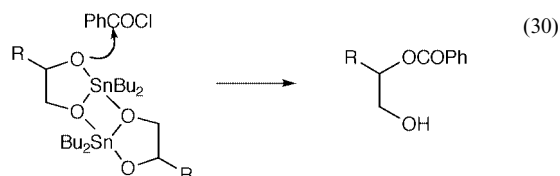


A further example of the superiority of a reagent R₃SiH over HX is provided by the use of Me₃SiI rather than HI for the cleavage of ethers, esters, epoxides, and related compounds.³⁶

In a 1,2-diol, selective activation of one of the two OH groups can be achieved by converting the diol into a dioxastannolane [e.g. eqn. (29)], and this provides a method for the



regioselective reaction of carbohydrates. In solution, these dioxastannolanes are associatively dimerised through their less hindered oxygen atoms rendering the more sterically hindered oxygen the better nucleophile [eqn. (30)].³⁷



This system provides a good illustration of the control over the reaction which is given by varying the metal: the corresponding dioxasilalanes are relatively inert and are used as a protected form of the diol.

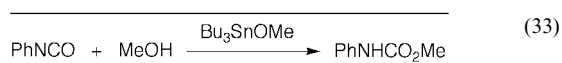
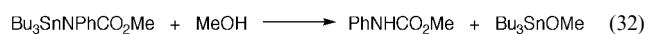
7 Nucleophilic addition by HX or MX (Table 1, entry 10)

Reagents HX will add, usually reversibly, to polar multiply bonded acceptor molecules such as RCH=O, R₂C=O, RN=CO, RN=CS, RNC=NR, OC=O, and OS=O. The corresponding metallic derivatives, MX, particularly MOR, will take part in the same reactions, often more readily because the electropositive character of the metal renders the oxygen more nucleophilic. The major exception to this rule is provided by the alkoxy silanes, R'₃SiOR, where the unshared electrons on oxygen are involved in p_π–d_π or p_π–σ* bonding, but the Si–N bond in aminosilanes does show the same reactions as the H–N bond in amines.

A few examples will show how this enhanced reactivity of the M–O bond can be exploited in organic synthesis.

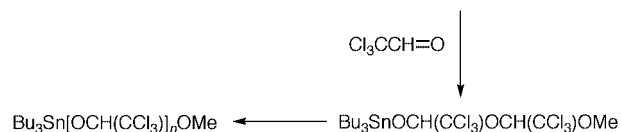
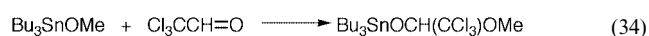
Alcohols (e.g. MeOH) will add to isocyanates (e.g. PhNCO) to give urethanes, but the corresponding reaction of Bu₃Sn–OMe is much faster. The stannylcarbamate which is formed

[eqn. (31)] rapidly reacts with methanol to give the urethane and to regenerate the tin methoxide [eqn. (32)], and thus a small amount of a tin compound will catalyse the addition of alcohols to isocyanates [eqn. (33)].³⁸ The use of organotin or



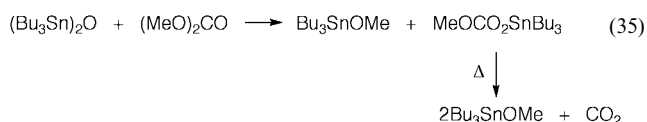
organolead compounds to catalyse the formation of polyurethanes from diols and diisocyanates depends on this principle. If water is incorporated into the reaction mixture, the hydrolysis of the isocyanate to amine and CO_2 is similarly catalysed, and the blowing of the polymer into a foam can be controlled.

Chloral (trichloroacetaldehyde) reacts with tributyltin methoxide to give the acetal which still contains an Sn–O bond, which will in turn add to further chloral, and in the presence of a large excess of chloral will give a polymer [eqn. (34)].³⁹



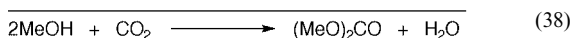
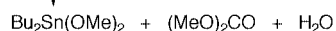
This principle is behind the polymerisation of a variety of polar monomers by metallic catalysts, *e.g.* isocyanates \rightarrow allophanates \rightarrow isocyanurates, and formaldehyde \rightarrow polyformaldehyde.

Bis(tributyltin) oxide reacts with dimethyl carbonate to give tributyltin methoxide and methyl tributyltin carbonate. This latter compound is the adduct of tributyltin methoxide and carbon dioxide, and, on warming, CO_2 is evolved [eqn. (35)].



This reaction provides the most convenient route to tributyltin methoxide, and similar principles provide routes to other organometallic alkoxides.⁴⁰

A potentially useful industrial route to dimethyl carbonate from methanol and carbon dioxide in the presence of catalytic dibutyltin dimethoxide depends on the insertion of CO_2 into the Sn–OMe bond then methanolysis of the methoxytin methyl carbonate to give dimethyl carbonate and regenerate the catalyst.⁴¹ Yields are improved if a desiccant is added to remove the water which is formed [eqns. (36)–(38)].



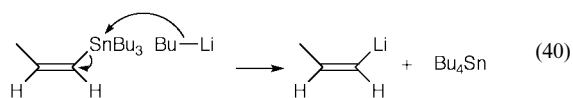
8 Nucleophilic substitution at hydrogen or metals (Table 1, entry 11)

Acidic hydrocarbons such as alkynes or cyclopentadienes can be deprotonated with butyllithium or lithium diisopropylamide as the base. For less acidic hydrocarbons, the nucleophilicity of the base for hydrogen has to be enhanced by ligation of the metal in RLi by, for example, TMEDA or potassium *tert*-butoxide (which gives Schlosser's LIKOR superbases).⁴²

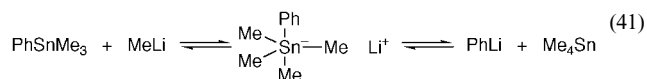
An alternative approach to the lithiation of a less acidic hydrocarbon RH is to exploit the equivalence between hydrogen and a metal, and to carry out the substitution at the metal in RM . M can be chosen so that the reactivity of RM is greater than that of RH , and butyllithium is reactive enough to bring about the transmetalation. Organomercury and organolead compounds have been used [*e.g.* eqn. (39)],⁴³ but the preferred



metal is tin. The reaction is particularly useful for preparing vinyl-, aryl-, and functionally substituted alkylolithiums [*e.g.* eqn. (40)],⁴⁴ and proceeds with retention of configuration at sp^3 or sp^2 hybridised carbon bonded to tin.

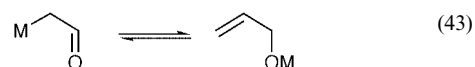
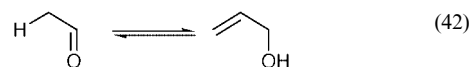


NMR studies of organotin compounds show that the bond-forming and bond-breaking processes are not synchronous, but that a trigonal bipyramidal sp^3d hybridised intermediate is involved [eqn. (41)].⁴⁵



9 Prototropy and metallotropy (Table 1, entry 12)

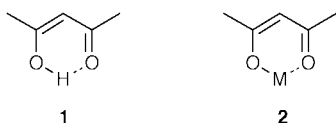
The tautomeric shift of a proton [prototropy; eqn. (42)] has its metallic equivalent in the tautomeric shift of a metal [metallotropy, eqn. (43)]. The most familiar context is that



involving keto–enol [eqn. (42)] or keto–metal enolate [eqn. (43)] equilibria, and enolates of most of the Main Group metals are known.

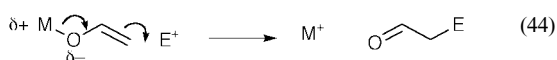
The relative position of the metallotropic equilibrium depends particularly on the C–M and O–M bond dissociation energies, on the steric hindrance which may destabilise the keto form, and on the polarity of the solvent or the presence of other ligands. Simple aldehydes and ketones are more stable in the (protic) keto form, but direct comparison between the protic and metallic systems is difficult because the first are usually studied in aqueous solution, and the second in non-aqueous solution. However, the derivatives of the electropositive metals of Groups 1, 2, and 3 exist predominately in the enol form, but the bromomercury derivative of acetone is in the keto form in the crystal.⁴⁶ Both the keto and enol forms of the silyl enolates can be isolated, but the former convert into the latter on standing. The enol–keto composition of the stannyl enolates depends sensitively on the nature of the substituents in the enol and the ligands about the tin, but the enolate form is the

more reactive towards electrophiles, and as the equilibrium is mobile, the reactions proceed through the enolate form irrespective of the composition of the tautomeric mixture.⁴⁷ The stabilisation of the enol form of a 1,3-dione by intramolecular hydrogen bonding to the carbonyl group has its metallic counterpart in intramolecular coordination (formulae 1 and 2).

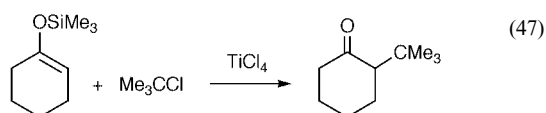
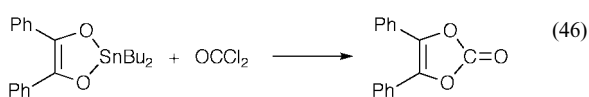
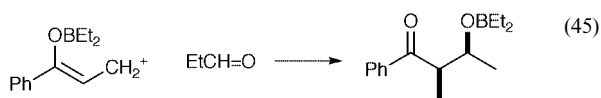


10 Nucleophilic substitution and addition by enols and metal enolates (Table 1, entries 13 and 14)

Most of the applications of the metal enolates in synthesis depend on the fact that the electropositive character of the metal enhances the nucleophilic power of the enolate towards an electrophile, above that of the parent enol [eqn. (44)]. Thus as M is varied, the reactivity follows the sequence Si < Sn < Li.



The metal enolates most commonly used are those of lithium or other alkali metals,⁴⁸ boron,⁴⁹ silicon,⁵⁰ and tin(II)⁵¹ or tin(IV),⁵² and the electrophile is usually an alkyl or acyl halide, the carbonyl group of an aldehyde or ketone (aldol reactions), or carbonyl-activated double bonds (Michael reactions). The stereoselectivity which is often observed in the Lewis-acid catalysed aldol reactions is interpreted in terms of an open (*e.g.* for silyl enolates) or cyclic (*e.g.* for stannyl enolates) transition state.⁵² The following equations (45)–(47)^{53–55} illustrate typical

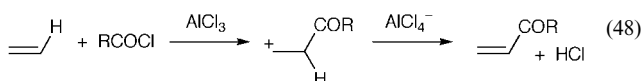


syntheses which can be carried out through the metal enolates rather than through the enols.

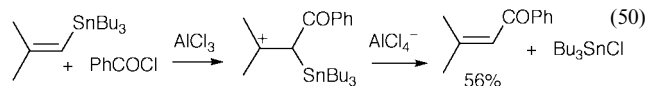
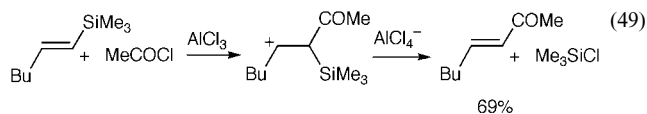
11 Electrophilic substitution of vinyl, allyl, and aryl compounds (Table 1, entries 15, 16, and 17)

11.1 Vinyl compounds (Table 1, entry 15)

Attack of an electrophile on an alkene is usually completed by nucleophilic attack on the carbonium ion centre to give overall addition. The major exception is the aliphatic Diels–Alder reaction in which acyl halides react in the presence of a Lewis acid, and the addition of the acylium ion is followed by loss of a proton to give a vinyl ketone [eqn. (48)].



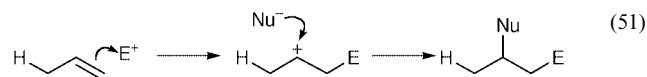
The reaction proceeds more readily with vinylmetallic compounds as attack of the electrophile at the α -carbon atom gives an intermediate carbonium ion which is stabilised by the β -effect of the metal (Box 2), and the C–M bond cleaves more readily. Vinylsilanes and vinylstannanes are commonly used, and the reactions proceed under milder conditions usually with improved yields and high regioselectivity, and side reactions are minimised [*e.g.* eqns. (49) and (50)].^{56,57}



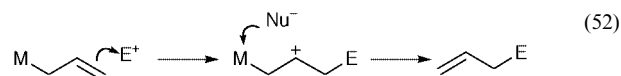
Other electrophilic reagents such as protic (or ²H or ³H) acids which add to alkenes will similarly give substitution reactions with vinyl metallic compounds. Halogens and halogen derivatives react rapidly to give the vinyl halides in good yield, and this is particularly useful for preparing radiohalogen-labelled compounds for radiotracer and therapeutic use where the radionuclide may have a short half-life.⁵⁸

11.2 Allyl compounds (Table 1, entry 16)

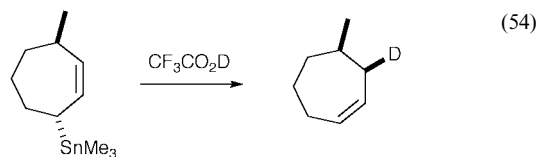
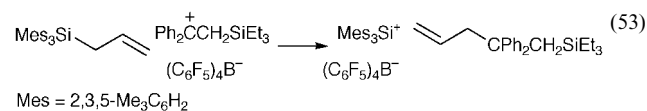
Similarly allylic hydrocarbons usually react with electrophiles by addition to the double bond followed by addition of a nucleophile, rather than by addition followed by loss of an allylic proton [eqn. (51)].⁵⁹ The intermediate carbonium ion



which is formed from allylmetallic compounds is again hyperconjugatively stabilised (see Box 2), and relative reactivities of $\text{MCH}_2\text{CH}=\text{CH}_2$ towards $\text{ArAr}'\text{CH}^+$ for $\text{M} = \text{H}$, Bu_3Si and Bu_3Sn are $1:5 \times 10^5:4 \times 10^9$ respectively.⁶⁰ The reaction is usually completed by attack of the nucleophile at the metal to give overall allylic substitution [eqn. (52)].



Some reactions which exploit this reactivity of the allyl-metal bond include the formation of the free trimesitylsilylium cation,⁶¹ and the regio- and stereo-specific labelling of allylic hydrocarbons⁶² shown in equations (53) and (54). The isolation

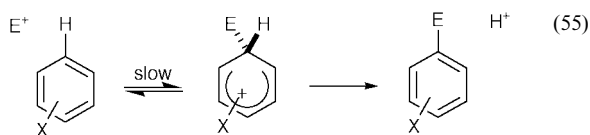


of a free siliconium ion by equation (53) invokes again the hyperconjugative stabilisation of the carbon cation by the Et_3Si group, and illustrates the importance of being able to vary the

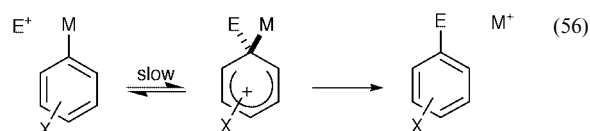
ligands about the multivalent metal: the allyl group allows conjugate displacement of the siliconium ion to occur whereas direct displacement would be sterically prohibited, and the three mesityl groups sterically protect the silicon centre from nucleophilic attack.

11.3 Arenes (Table 1, entry 17)

Electrophilic aromatic substitution of hydrogen occurs by rate-determining addition of the electrophile to give a Wheland intermediate, followed by deprotonation [eqn. (55)].

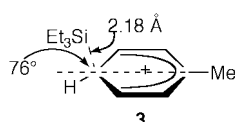


The corresponding arylmetallic compounds react preferentially, and more rapidly, by demetallation [eqn. (56)], the rela-



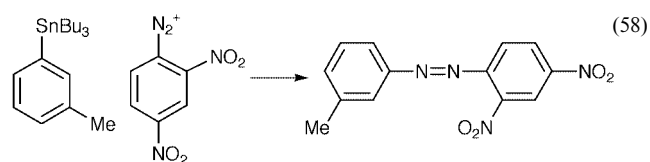
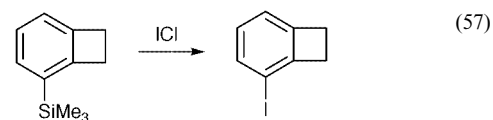
tive rates of protodemetallation in aqueous ethanolic HClO_4 for PhMET_3 being Si 1, Ge 36, Sn 3.5×10^5 , Pb 2×10^8 .^{63,64} After correcting for isotope effects, the relative rates of displacement of H and of Me_3Si (in aqueous H_2SO_4) are 1:ca. 10^4 . This high *ipso* reactivity is ascribed mainly to stabilisation of the Wheland intermediate by (enhanced) hyperconjugation with the M–C bond (Box 2); attack at any other ring position would leave the metal lying in the nodal plane of the π -system, and hyperconjugation with the M–C bond would be zero.

The structure of the Wheland complex $\text{MeC}_6\text{H}_4(\text{H})(\text{SiEt}_3)^+$ has been determined by X-ray crystallography, and can be rationalised on the grounds that hyperconjugation by the C–Si bond is more effective than that by the C–H bond. The C–Si bond is bent towards the ring by 21° to maximise the σ – π^* overlap, and is stretched by ca. 0.30 \AA implying a bond order of ca. 0.28 (formula 3).⁶⁵



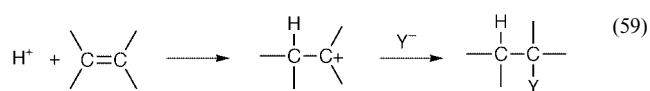
This high *ipso* reactivity makes it possible to determine the substituent effects of the groups X on the electrophilic substitution of M without the need for an analysis of the mixture of products which would be obtained from the protic parents.⁶⁴

It also makes it possible to carry out aromatic substitutions under mild conditions with reagents which would not react with the parent hydrocarbons, and overriding the normal directive effect of substituents.⁶⁴ For example, 3-trimethylsilylbenzocyclobutene reacts with ICl to give the corresponding 3-iodo compound [eqn. (57)] whereas the reaction with the parent hydrocarbon gives mainly the 4-iodo compound with much ring-opening.⁶⁶ Again, 2,4-dinitrobenzenediazonium tetrafluoroborate reacts at room temperature with *m*-tolyltributyltin to give the azo compound [eqn. (58)], whereas toluene, which normally directs substitution to the 2- and 4-positions, is unreactive under these conditions.⁶⁷

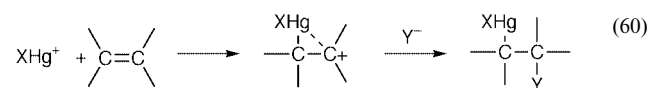


12 Electrophilic addition of HX or MX to alkenes (Table 1, entry 18)

Protic acids such as the hydrogen halides or sulfuric acid, or alcohols or phenols under acid conditions, add to alkenes in the Markovnikoff orientation *via* the hyperconjugatively stabilised carbonium ions (which sometimes undergo rearrangement) [eqn. (59)].

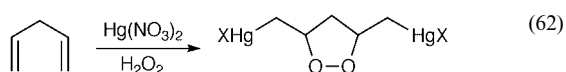
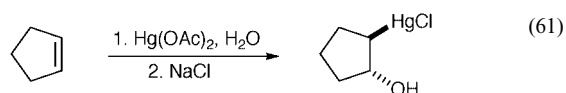


The metallic analogy is best illustrated by solvomercuration [eqn. (60)].⁶⁸

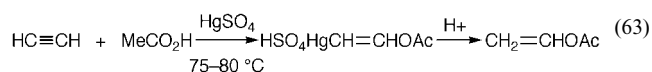


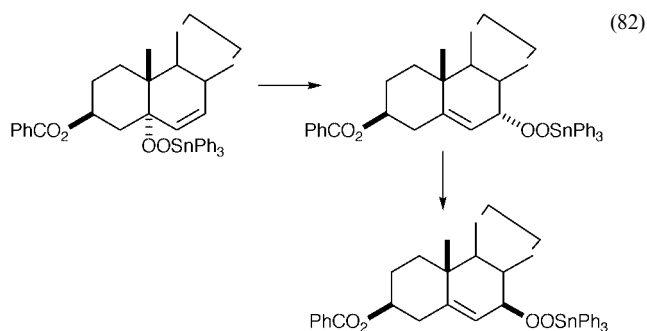
The reagent HgX_2 is commonly the acetate, $\text{Hg}(\text{OCOCH}_3)_2$. The pivalate, $\text{Hg}(\text{OCOCMe}_3)_2$, is more soluble in solvents such as THF, and its steric demands often make its reactions more stereoselective, and the trifluoroacetate, $\text{Hg}(\text{OCOCF}_3)_2$, provides a stronger electrophile: again there is an advantage in being able to vary the ligands. The structure of the intermediate involves at least hyperconjugative interaction (Box 2) between the Hg–C bond and the cationic centre, and, in the limit, a cyclic mercurinium ion. A wide variety of nucleophiles HY can be used, *e.g.* H_2O , HOR, HOOR, HNR_2 , HN_3 , HONO_2 , and HOSO_2R , and there is an example of a reaction involving a metallic nucleophile MY [eqn. (80)].

The reactions usually take place rapidly under mild conditions and tolerate a wide variety of functional groups, and because of the β -effect of the metal, they occur with *anti* orientation and are usually free from the complications of rearrangement which sometimes accompany the reactions of HX. The adducts RHgX can be reduced with NaBH_4 to RH, or converted into the bromides RBr with KBr_3 . Two examples are given in equations (61)⁶⁹ and (62).⁷⁰



Analogous reactions occur with alkynes, and the acetoxymercuration of acetylene [eqn. (63)], and the hydroxymercuration of acetylene [eqn. (64)] provided early industrial routes to

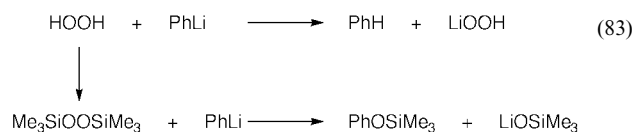




compound HX. Conversely, the reactivity of MX can be chosen to be less than that of HX, and this is exploited in the protection of functional groups. M is usually a triorganosilyl group to exploit the low intrinsic reactivity of the Si–X bond, and the reactivity of R_3SiX can be further controlled sterically by selection of the groups R (Box 2).^{85,86} For example, the OH group in nucleosides, prostaglandins, and carbohydrates, are often protected by silylation, when the R_3SiOR' groups withstand reagents such as $LiAlH_4$, B_2H_6 , RLi , CH_2N_2 , CrO_3 –pyridine, Bu_3SnH , Grignard reagents, or Wittig reagents. Further control of the reactivity can be achieved by varying the groups R, e.g. $Me_3SiOR' > Bu^tMe_2SiOR' > Pr^i_3SiOR' > Bu^i_2MeSiOR'$, when the effect seems to be largely steric in origin. Silylation of an OH group is also used to stop hydrogen bonding

and thereby increase the volatility of hydroxy compounds such as sugars, for gas liquid chromatography and mass spectrometry.

A simple example where the OH group of hydrogen peroxide is protected by silylation, diverting the attack of nucleophilic from H to the peroxide group, is shown in equation (83).⁸⁷



18 Conclusion

Hydrogen is almost as ubiquitous as carbon in organic compounds, and organic reactions, even if they do not take place at the hydrogen centre or at an atom carrying hydrogen, will nevertheless occur with hydrogen as a near-neighbouring group. Whatever the mechanism of the reaction, it is worthwhile considering the effect of replacing hydrogen by a metal: often that can achieve a substantial improvement of the reaction rate or in the chemo-, regio-, or stereo-selectivity.

19 Acknowledgements

I am grateful to Professor Colin Eaborn who read the manuscript and made many useful suggestions.

Box 1

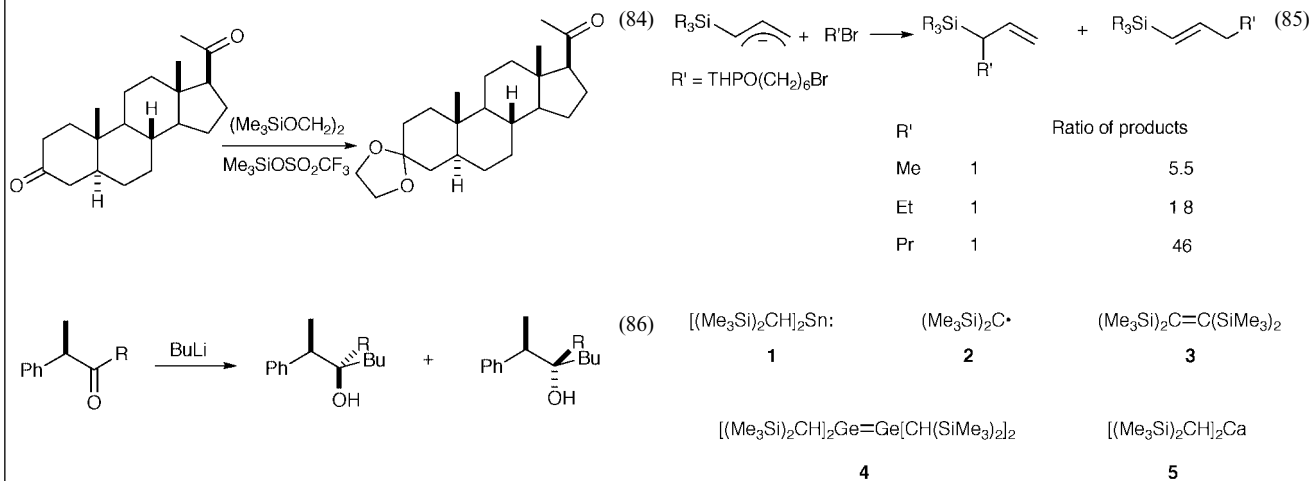
Steric effects: H versus R_3Si

If a hydrogen atom near a reactive centre is replaced by an organosilyl group, the same reactions frequently occur at that centre but at a rate which is now dominated (usually diminished) by the size of the silyl group, and a trimethylsilyl group has been referred to in this context as a bulky proton.⁸⁸ This makes it possible to control the chemo-, regio- and stereo-selectivity of reactions, and the persistence of otherwise transient species, and fine-tuning can be achieved by varying the ligands on the silyl group.

From a correlation of the rates, yields, and regio- and stereo-selectivities of many different reactions, the effective bulk of the R_3Si groups has been placed in a sequence, a selection from which is as follows:⁸⁹ $Me_3Si < PhMe_2Si < Ph_2MeSi < EtMe_2Si < Ph_3Si < Et_3Si < Pr_3Si < BuMe_2Si < Pr_3Si < (cyclohexyl)_3Si$.

Similar effects are observed with other substituents R_3M where M is some other Group 14 metal, but relatively little use of these has been made in synthesis, partly because they are more inclined to divert the reaction into other routes. The steric effect need not always increase with the size of the atom because a larger atom implies a longer bond, which may shift the groups R further away from the other groups with which they interact. Thus the free energy differences (Δ values) in cyclohexyl compounds $C_6H_{11}X$, with the group in the axial or equatorial position respectively, are X = H 0, Me_3Si 10.5, Me_3Ge 8.8, Me_3Sn 4.2, Me_3Pb 2.80 kJ mol^{-1} .

Simple examples of chemo-,⁸⁹ regio-,⁹⁰ and stereo-control of reactions,⁹¹ that can be achieved by using a trimethylsilyl group as a surrogate for a hydrogen atom, are shown in equations (84)–(86), and examples of the stabilisation of reactive species are given in formulae 1,⁹² 2,⁹³ 3,⁹⁴ 4,⁹⁵ and 5.⁹⁶



Box 2
Hyperconjugation: C–H versus C–M⁹⁷

The phenomenon of hyperconjugation provides a further example of the equivalent behaviour of metals and hydrogen.

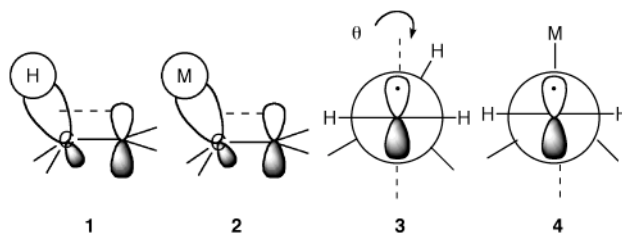
Hyperconjugation in an alkyl cation or radical involves interaction between the unoccupied or singly occupied 2p orbital and the s orbital of a β -C–H bond (1). It is most effective when these orbitals eclipse, and it is zero when they are orthogonal. Hyperconjugation with a β -carbon–metal bond (2) occurs under similar circumstances, and can be much more effective.

The most direct evidence for hyperconjugation comes from the EPR spectra of alkyl radicals, $\text{HR}_2\text{C}^\beta\text{C}^\alpha\text{H}_2\cdot$ where the hyperfine coupling of a β -proton is described by the McConnell equation [eqns. (87) and (88)].⁹⁷

$$a(\text{H}_\beta) = \rho_{\text{C}^\alpha}(A + B \cos^2 \theta) \quad (87)$$

$$\text{or } a(\text{H}_\beta) = c_\alpha^2(A + B \cos^2 \theta) \quad (88)$$

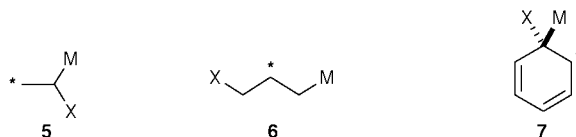
The term ρ_{C^α} represents the electron density at C^α , which is equal to the square of the LCAO coefficient c_α . A is a small (spin polarisation) term arising from transmission of the electron spin through the intervening σ -bonds, and is often neglected. The dominant term, B , arises from hyperconjugation, where θ is the dihedral angle between the two orbitals involved (3).



The spectra of the radicals $\text{Me}_3\text{MCH}_2\text{CH}_2\cdot$, where $\text{M} = \text{Si}, \text{Ge}, \text{Sn}, \text{or Pb}$, show that the most stable conformation is again that where the β -C– MR_3 bond eclipses the 2p orbital (4), and the barriers to rotation about the C^α – C^β are in the sequence $\text{Si} < \text{Ge} < \text{Sn}$.

Similarly hyperconjugation in the β -silyl cations $\text{H}_3\text{SiCH}_2\text{CH}_2^+$, $\text{H}_3\text{SiCH}_2\text{CHR}^+$, and $\text{H}_3\text{SiCH}_2\text{CR}_2^+$ is calculated to confer a stabilisation of 160, 92, and 70 kJ mol^{-1} respectively.

This C–M hyperconjugation confers a high reactivity on organometallic compounds when they react by mechanisms which involve the development of an unpaired electron or a partial or complete positive charge on the β -carbon atom and is often referred to simply as the β -effect of the metallic substituent. This is exploited in the use of organotin and, particularly, organosilicon compounds in synthesis.⁹⁸ For example vinyl-, allyl-, or aryl-metallic compounds react with a radical or an electrophile X^* to give the hyperconjugatively stabilised intermediate 5, 6, or 7 where * represents either an unpaired electron or a positive charge (Sections 5 and 11). The ene reaction (Section 15) provides a further example of the importance of the β -effect in synthesis.



Special conditions govern hyperconjugation in the cyclohexadienyl radicals or cations (7) which are the intermediates in homolytic or heterolytic substitution.⁹⁷ The angle θ is now about 30° rather than zero, which reduces the hyperconjugative interaction by a factor of about 0.75. However, the hyperconjugating C–H or C–M bonds are flanked by two sp^2 carbon centres which form part of a conjugated π system. If the spin polarisation term A is neglected, the EPR coupling is now described by eqn. (89)

$$a(\text{H}_\beta) = (c_\alpha + c_\omega)^2(B \cos^2 \theta) \quad (89)$$

When c_α and c_ω have the same sign and magnitude, as they do in the cyclohexadienyl radical or cation, hyperconjugative coupling is twice as effective (proportional to $c_\alpha^2 + c_\omega^2 + 2c_\alpha c_\omega$) when the two termini operate in concert, as if they operated independently (proportional to $c_\alpha^2 + c_\omega^2$). The enhanced C–M hyperconjugative coupling should be a further factor in favour of *ipso* homolytic or heterolytic substitution of arylmetallic compounds. Conversely, if c_α and c_ω have opposite signs, as they do in the cyclobutadienyl radical or cation, hyperconjugative coupling is negligible.

The stability of $(\text{CH}_3)_3\text{B}$ has been ascribed to C–H hyperconjugation with the vacant B 2p orbital, and C–Si hyperconjugation might be expected to be important in $(\text{Me}_3\text{SiCH}_2)_3\text{B}$ and the many trimethylsilylmethyl, bis(trimethylsilyl)methyl, and tris(trimethylsilyl)methyl derivatives which have been prepared of other metals, particularly in their low oxidation states. No attempt appears to have been made, however, to identify this hyperconjugation, and the properties of these compounds are dominated by the steric effect of the bulky ligands (Box 1).

Hyperconjugation between a C–H σ -bond and a C=C π -system in a neutral, spin-paired molecule such as propene or toluene is usually accepted to be insignificant, but there is good evidence from X-ray crystallography and from photoelectron spectroscopy that σ – π^* conjugation is important in the corresponding allyl- or benzyl-organometallic compounds because of a better match between the energies of the σ and π^* orbitals.^{99,100}

20 References

- 1 T. Graham, *Proc. R. Soc. London*, 1869, **14**, 212.
- 2 W. Ramsay, *Experimental Proofs of Chemical Theory for Beginners*, Macmillan, London, 1893.
- 3 C. Eaborn, *Organosilicon Compounds*, Butterworths, London, 1960.
- 4 A. G. Davies, *J. Organomet. Chem.*, 1982, **239**, 87.
- 5 M. A. Brook, *Silicon in Organic, Organometallic, and Polymer Chemistry*, Wiley-Interscience, New York, 2000.
- 6 I. Fleming, *Chem. Soc. Rev.*, 1981, **10**, 83.
- 7 J. R. Hwu and J. M. Wetzel, *J. Org. Chem.*, 1985, **50**, 3946.
- 8 M. H. Abraham and A. G. Davies, *J. Chem. Soc.*, 1959, 429.
- 9 M. H. Abraham, *J. Chem. Soc.*, 1960, 4130.
- 10 H. C. Brown and M. M. Midland, *Tetrahedron*, 1987, **43**, 4059.
- 11 A. G. Davies and B. P. Roberts, *J. Chem. Soc. B*, 1967, 17.
- 12 A. G. Davies, K. U. Ingold, B. P. Roberts and R. Tudor, *J. Chem. Soc. B*, 1971, 698.
- 13 A. G. Davies and B. P. Roberts, *J. Chem. Soc. B*, 1968, 1074.
- 14 R. W. Fessenden and R. H. Schuler, *J. Chem. Phys.*, 1963, **39**, 2147.
- 15 A. G. Davies and B. P. Roberts, *J. Chem. Soc., Chem. Commun.*, 1969, 699.
- 16 A. G. Davies and B. P. Roberts, in *Free Radicals*, ed. J. K. Kochi, Wiley, New York, 1973.
- 17 A. G. Davies and J. C. Scaiano, *J. Chem. Soc., Perkin Trans. 2*, 1973, 1777.
- 18 D. Griller, K. U. Ingold, L. K. Patterson, J. C. Scaiano and R. D. Small, *J. Am. Chem. Soc.*, 1979, **101**, 3780.
- 19 A. G. Davies, S. C. W. Hook and B. P. Roberts, *J. Organomet. Chem.*, 1970, **22**, C37.
- 20 A. G. Davies, B. P. Roberts and J. M. Smith, *J. Chem. Soc., Perkin Trans. 2*, 1972, 2221.
- 21 A. G. Davies, B. P. Roberts and J. C. Scaiano, *J. Chem. Soc. B*, 1971, 2171.
- 22 P. J. Barker, A. G. Davies and M.-W. Tse, *J. Chem. Soc., Perkin Trans. 2*, 1980, 941.
- 23 A. G. Davies, J. A.-A. Hawari, C. Gaffney and P. G. Harrison, *J. Chem. Soc., Perkin Trans. 2*, 1982, 631.
- 24 A. G. Davies and J. Luszyk, *J. Chem. Soc., Perkin Trans. 2*, 1981, 692.
- 25 R. M. Pierson, A. J. Costanza and A. H. Weinstein, *J. Polym. Sci.*, 1955, **17**, 221.
- 26 G. A. Russell, H. Tashtoushi and P. Ngoviwatthai, *J. Am. Chem. Soc.*, 1984, **106**, 4622.
- 27 F. R. Mayo, *J. Am. Chem. Soc.*, 1943, **65**, 2324.
- 28 J. Grignon, C. Servens and M. Pereyre, *J. Organomet. Chem.*, 1975, **96**, 225.
- 29 C. Eaborn, I. M. T. Davidson and C. J. Wood, *J. Organomet. Chem.*, 1965, **4**, 489.
- 30 H. Sakurai, I. Nozue and A. Hosimi, *Chem. Lett.*, 1976, 129.
- 31 W. A. Williamson, *J. Chem. Soc.*, 1852, **4**, 106.
- 32 K. Steliou, A. Szczygielska-Nowosielska, A. Favre, M. A. Poupart and S. Hanessian, *J. Am. Chem. Soc.*, 1980, **102**, 7578.
- 33 E. G. Mata and O. A. Mascaretti, *Tetrahedron Lett.*, 1988, **29**, 6893.
- 34 D. N. Harpp and M. Gingras, *J. Am. Chem. Soc.*, 1988, **110**, 7737.
- 35 D. N. Harpp and M. Gingras, *Tetrahedron Lett.*, 1987, **28**, 4373.
- 36 T.-L. Ho and G. A. Olah, *Synthesis*, 1977, 417.
- 37 A. Ricci, S. Roelens and A. Vannucchi, *J. Chem. Soc., Chem. Commun.*, 1985, 1457.
- 38 A. J. Bloodworth and A. G. Davies, *J. Chem. Soc.*, 1965, 5238.
- 39 A. G. Davies and W. R. Symes, *J. Chem. Soc. C*, 1967, 1009.
- 40 A. G. Davies, D. C. Kleinschmidt, P. R. Palan and S. C. Vasishtha, *J. Chem. Soc. C*, 1971, 3972.
- 41 J. Kizlink, *Collect. Czech. Chem. Commun.*, 1993, **58**, 1399.
- 42 M. Schlosser, in *Organometallics in synthesis*, ed. M. Schlosser, Wiley, Chichester, 1994.
- 43 A. Maerker and M. Theis, *Angew. Chem., Int. Ed. Engl.*, 1984, **23**, 995.
- 44 D. Seyferth and L. G. Vaughan, *J. Am. Chem. Soc.*, 1964, **86**, 883.
- 45 H. J. Reich and N. H. Phillips, *J. Am. Chem. Soc.*, 1986, **108**, 2102.
- 46 J. A. Potenza, L. Zyontz, J. S. Filippo and R. A. Lalancette, *Acta Crystallogr., Sect. B*, 1978, **34**, 2624.
- 47 M. Yasuda, Y. Katoh, I. Shibata, A. Baba, H. Matsuda and N. Sonoda, *J. Org. Chem.*, 1994, **59**, 4386.
- 48 C. H. Heathcock, in *Comprehensive Organic Synthesis*, vol. 2, ch. 1.6, ed. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991.
- 49 B. M. Kim, S. F. Williams and S. Masamune, in *Comprehensive Organic Synthesis*, vol. 2, ch. 1.7, ed. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991.
- 50 C. Gennari, in *Comprehensive Organic Synthesis*, vol. 2, ch. 2.4, ed. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991.
- 51 T. Mukaiyama and S. Kobayashi, *Org. React. (N.Y.)*, 1994, **46**, 1.
- 52 I. Shibata and A. Baba, *Org. Prep. Proced. Int.*, 1994, **26**, 85.
- 53 S. Masamune, S. Mori, D. Van Horn and D. W. Brooks, *Tetrahedron Lett.*, 1979, 1665.
- 54 A. G. Davies and J. A.-A. Hawari, *J. Chem. Soc., Perkin Trans. 1*, 1983, 875.
- 55 T.-H. Chan, I. Paterson and J. Pinsonnault, *Tetrahedron Lett.*, 1977, 4183.
- 56 I. Fleming, T. W. Newton and F. Roessler, *J. Chem. Soc., Perkin Trans. 1*, 1981, 2527.
- 57 M. L. Saihi and M. Pereyre, *Bull. Soc. Chim. Fr.*, 1977, 1251.
- 58 H. Ali and J. E. van Lier, *Synthesis*, 1996, 423.
- 59 I. Fleming, in *Comprehensive Organic Synthesis*, vol. 2, ch. 2.2, ed. B. M. Trost and I. Fleming, Pergamon, Oxford, 1991.
- 60 H. Mayr and M. Patz, *Angew. Chem., Int. Ed. Engl.*, 1994, **33**, 938.
- 61 J. B. Lambert, Y. Zhao, H. Wu, W. C. Tse and B. Kuhlmann, *J. Am. Chem. Soc.*, 1999, **121**, 5001.
- 62 W. Kitching, B. Laycock, I. Maynard and K. Penman, *J. Chem. Soc., Chem. Commun.*, 1986, 954.
- 63 C. Eaborn and K. C. Pande, *J. Chem. Soc.*, 1960, 1566.
- 64 C. Eaborn, *J. Organomet. Chem.*, 1975, **100**, 43.
- 65 J. B. Lambert, S. Zhang and S. M. Ciro, *Organometallics*, 1994, **13**, 2430.
- 66 C. Eaborn, A. A. Najam and D. R. M. Walton, *J. Chem. Soc., Perkin Trans. 1*, 1972, 2481.
- 67 W. P. Neumann and C. Wicene, *Chem. Ber.*, 1991, **124**, 2297.
- 68 R. C. Larock, *Solvomercuration/demercuration Reactions in Organic Synthesis*, Springer, Berlin, 1986.
- 69 T. G. Traylor and A. W. Baker, *J. Am. Chem. Soc.*, 1963, **85**, 2746.
- 70 A. J. Bloodworth and M. E. Loveitt, *J. Chem. Soc., Chem. Commun.*, 1976, 94.
- 71 D. J. Agar, *Org. React. (N.Y.)*, 1990, **38**, 1.
- 72 P. F. Hudrlik and D. Peterson, *J. Am. Chem. Soc.*, 1975, **97**, 1464.
- 73 P. Jutz, *Chem. Rev.*, 1986, **86**, 983.
- 74 A. Bonny, R. D. Holmes-Smith, G. Hunter and S. R. Stobart, *J. Am. Chem. Soc.*, 1982, **104**, 1855.
- 75 H.-S. Dang and A. G. Davies, *J. Chem. Soc., Perkin Trans. 2*, 1991, 2011.
- 76 J. Cai and A. G. Davies, *J. Chem. Soc., Perkin Trans. 2*, 1992, 1743.
- 77 H.-S. Dang and A. G. Davies, *J. Organomet. Chem.*, 1992, **430**, 287.
- 78 C. W. Jefford and C. G. Rimbault, *Tetrahedron Lett.*, 1977, 2375.
- 79 Y. Yamamoto and N. Asao, *Chem. Rev.*, 1993, **93**, 2207.
- 80 J. Garcia, B. M. Kim and S. Masamune, *J. Org. Chem.*, 1987, **52**, 4831.
- 81 E. J. Thomas, *Main Group Met. Chem.*, 1996, **19**, 307.
- 82 A. Gambaro, D. Marton, V. Peruzzo and G. Tagliavini, *J. Organomet. Chem.*, 1981, **204**, 191.
- 83 J. Cai and A. G. Davies, *J. Chem. Soc., Perkin Trans. 1*, 1992, 3383.
- 84 H.-S. Dang and A. G. Davies, *J. Chem. Soc., Perkin Trans. 2*, 1992, 1095.
- 85 T. W. Greene and P. G. M. Wuts, *Protective Groups in Organic Synthesis*, Wiley, New York, 1991.
- 86 P. J. Kocienski, *Protecting Groups*, Thieme, Stuttgart, 1994.
- 87 M. Taddei and A. Ricci, *Synthesis*, 1986, 633.
- 88 J. R. Hwu and J. M. Wetzel, *J. Org. Chem.*, 1985, **50**, 3946.
- 89 R. J.-R. Hwu, S.-C. Tsay and B.-L. Cheng, in *The Chemistry of Organic Silicon Compounds*, ed. Z. Rappoport and Y. Apeloig, Wiley, Chichester, 1998.
- 90 T. H. Chan and K. Koumaglo, *J. Organomet. Chem.*, 1985, **285**, 109.
- 91 J. Garcia, B. M. Kim and S. Masamune, *J. Org. Chem.*, 1987, **52**, 4831.
- 92 T. Fjeldberg, A. Haaland, B. E. R. Schilling, M. F. Lappert and A. J. Thorne, *J. Chem. Soc., Dalton Trans.*, 1986, 1551.
- 93 G. D. Mendenhall, D. Griller, D. Lindsay, T. T. Tidwell and K. U. Ingold, *J. Am. Chem. Soc.*, 1974, **47**, 4269.
- 94 D. Griller, J. W. Cooper and K. U. Ingold, *J. Am. Chem. Soc.*, 1975, **97**, 4269.
- 95 D. E. Goldberg, P. B. Hitchcock, M. F. Lappert, K. M. Thomas, A. J. Thorne, T. Fjeldberg, A. Haaland and B. E. R. Schilling, *J. Chem. Soc., Dalton Trans.*, 1986, 2387.
- 96 C. Eaborn, S. A. Hawkes, P. B. Hitchcock and J. D. Smith, *Chem. Commun.*, 1997, 1961.
- 97 A. G. Davies, *J. Chem. Soc., Perkin Trans. 2*, 1999, 2461.
- 98 Y. Yamamoto and N. Asao, *Chem. Rev.*, 1993, **93**, 2207.
- 99 T. G. Traylor, W. Hanstein, H. J. Berwin, N. A. Clinton and R. S. Brown, *J. Am. Chem. Soc.*, 1971, **93**, 5715.
- 100 C. G. Pitt, *J. Organomet. Chem.*, 1973, **61**, 49.