EPR studies on phosphoryldithioformates. Part 2[1]

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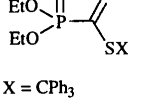
The addition of a variety of radicals to triphenylmethyl 1, allyl 2, benzyl 3 and but-3-enyl (diethoxyphosphoryl)dithioformate 4 has been investigated by EPR spectroscopy. Reactions with the first substrate always led to displacement of the triphenylmethyl radical; release of the allylic or benzylic moieties from 2 and 3 was observed above 243 K under photolytic conditions, while at lower temperatures or in the dark the adducts resulting from thiophilic addition of the radicals were detected. The weak EPR spectra detected when reacting dithioformates 1–4 and methyl(diethoxyphosphono)dithioformate 5 with Grignard reagents are attributed to the radical anions of the starting compounds and to their ion pairs with magnesium cations.

The importance of free radicals in many organic reactions is well established and, despite earlier statements that free radical processes would be of little use in organic synthesis because of their lack of selectivity and tendency to form a variety of undesired side-products, free radical chemistry has developed rapidly in the last two decades and several radical-based synthetically useful processes have been devised. Typical examples are the reduction of haloalkanes with tributyltin hydride[2,3] or tris(trimethylsilyl)silane,[4] the formation of C–C bonds[3] and radical cyclization reactions.[5]

On the other hand, radicals, owing to their high reactivity, are in most cases short-lived species which very rarely reach a steady-state concentration high enough to allow direct detection by EPR in a reaction medium unless they are intercepted by an appropriate substrate to form persistent or longer-lived spin adducts. This so-called 'spin trapping' technique[6] requires efficient scavengers which are inert to the other species present in the reaction system and produce paramagnetic adducts 'informative' of the nature of the trapped radical.

In the continuing search for new and efficient scavengers it has been shown that thiocarbonyl derivatives can easily trap a wide variety of radicals[7] and are particularly effective at intercepting oxygen- or sulfur-centred species; in the first part of this study[1] the trapping ability of methyl phosphoryldithioformates was examined.

The investigation has now been extended to four additional compounds of this family, triphenylmethyl (diethoxyphosphoryl)dithioformate **1**, allyl (diethoxyphosphoryl)dithioformate **2**, benzyl (diethoxyphosphoryl)dithioformate **3** and but-3-enyl (diethoxyphosphoryl)dithioformate **4**; the reactions of Grignard reagents with **1**–**4**, as well as with methyl (diethoxyphosphoryl)dithioformate **5** have also been studied.



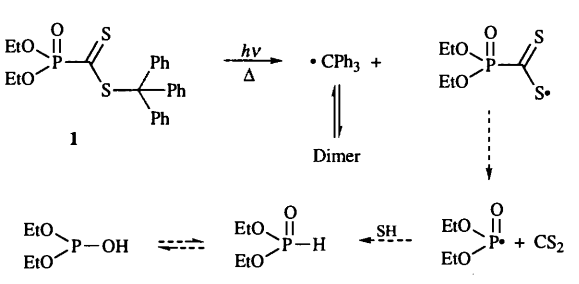
1 X = CPh_3
2 X = CH_2-CH=CH_2
3 X = CH_2Ph
4 X = CH_2-CH_2-CH=CH_2
5 X = CH_3

Results and discussion

Radical addition reactions

When a quartz tube containing a nitrogen-purged benzene solution of compound **1** was put inside the cavity of the EPR spectrometer, no immediate signal was observed. However, a signal started developing as the sample was warmed ($T \geq$ 323 K); its intensity increased with temperature, but became vanishingly small on allowing the system to cool down. The spectrum was well resolved, did not show any coupling attributable to a phosphorus atom and on the basis of its spectral parameters (a_{6H} = 1.14, a_{6H} = 2.59, a_{3H} = 2.82 G† and g = 2.0026_1) could be assigned to the triphenylmethyl radical. A strong signal from the triphenylmethyl radical was observed at or below room temperature after briefly exposing the sample to UV light (1–5 s flash).

These results indicate that the fragmentation of **1** can be photo- or thermal-induced to produce triphenylmethyl radicals, whose tendency to dimerize is reflected in the reversible variations in spectral intensity observed with changes in temperature (Scheme 1). The other radical species resulting from fragmentation of **1** possibly undergoes loss of CS_2 with subsequent formation of diethylphosphite, but product studies are required to confirm this suggestion. The possibility that the diethoxyphosphoryl radicals are trapped by **1** is also to be considered, although no EPR signals from such an adduct could ever be detected.



Scheme 1

When a small amount of dibenzylmercury was added to the benzene solution of **1** at room temperature, a weak but

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† 1 G = 0.1 mT.

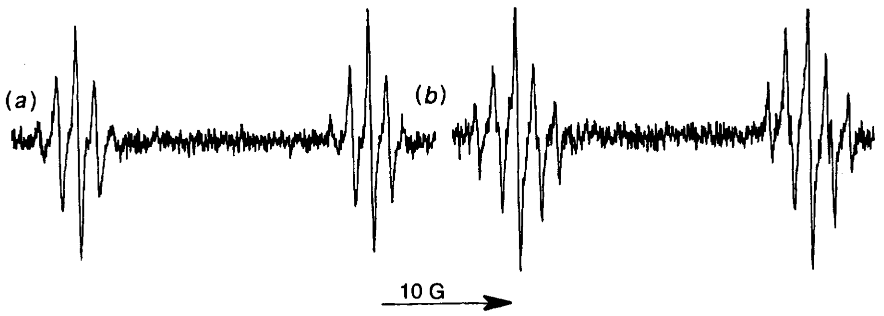
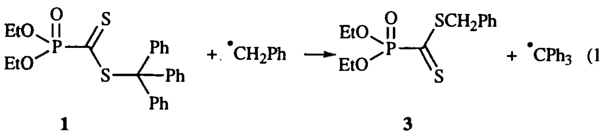


Fig. 1 Experimental EPR spectra of (*a*) the self-adduct **2c** at room temperature and (*b*) of the benzyl adduct **2f** at −30 °C

unambiguous EPR signal of the triphenylmethyl radical was detected. It is known that organomercury compounds can be convenient sources of organic radicals *via* thermal- or photo-induced[8] homolysis of the relatively weak Hg–C bond. On the other hand, organomercury compounds may undergo slow decomposition even at room temperature,[9] and it is therefore possible that a small amount of benzyl radicals may be trapped by the thioformate; however, the additional fact that under these conditions the spectrum of the triphenylmethyl radical is observed instead of that of the benzyl adduct, indicates that the process taking place is not a simple addition, but rather a displacement reaction [reaction (1)]. Analogous behaviour is observed on replacing dibenzylmercury with diphenylmercury.

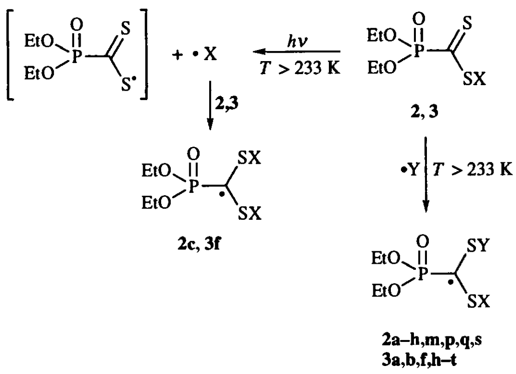


(1)

A similar displacement reaction is likely to take place when a benzene solution of **1** reacts with potassium superoxide, KO_2, and 18-crown-6 ether, a convenient method for the production of the superoxide radical anion.[10] Once again, the spectrum of the triphenylmethyl radical is observed instead of that of the adduct $(EtO)_2P(O)\dot{C}(SO_2^-)SCPh_3$.

Allyl, benzyl and but-3-enyl (diethoxyphosphoryl)dithioformate **2–4** proved thermally more stable than the triphenylmethyl derivative **1** and no EPR signals were observed when heating deoxygenated benzene solutions of these compounds up to the solvent boiling point (348 K). Also, no signals were detected upon photolysis of **4** over the investigated temperature range, while photolysis of solutions of **2** and **3** at room temperature afforded similar EPR spectra consisting of a doublet of quintets. These can be safely attributed to the self-adducts **2c** [see Fig. 1(*a*)] and **3f** whose formation can be explained by the fragmentation of **2** or **3** and the trapping of the resulting allyl or benzyl radicals by another molecule of dithioformate. The fragmentation process becomes less and less important as the temperature is lowered and practically no signal is observed when photolysing a *tert*-butylbenzene solution of **2** and **3** at $T \leqslant 233$ K.

The formation of the self-adducts indicates that radical addition to dithioformates **2** and **3**, as already established in the case of **5**,[1] proceeds through a thiophilic attack as outlined in Scheme 2.



Scheme 2

The fragmentation process may interfere with the trapping of other radicals when the addition is carried out at temperatures higher than −40 °C. Thus when **2** reacts with benzyl radicals generated by thermal decomposition of dibenzylmercury, a spectrum is observed consisting of the overlapping of two signals: those of the benzyl adduct **2f** and of the self-adduct **2c**. The same signal is observed when dibenzylmercury is photolysed in the presence of **2** at similar temperatures, but in this case the amount of the self-adduct decreases as the temperature is lowered and a clean spectrum of **2f** [see Fig. 1 (*b*)], characterized by the non-equivalence of the two pairs of β-protons, can be observed at $T = 230$ K.

The spectra of the *tert*-butyl adducts **2d–4d** are observed on photolysing a *tert*-butylbenzene solution of **2–4** containing di-*tert*-butyl ketone at 233 K. At this temperature the appearance of the spectra is only slightly asymmetric, but the asymmetry becomes more pronounced as the temperature is lowered further. Indeed photolysis of di-*tert*-butyl ketone results in the formation of *tert*-butyl and pivaloyl‡ radicals, but only the addition of the former to the dithioformates is observed at −30 °C. This is an indication that at this temperature the fragmentation of pivaloyl into a *tert*-butyl radical and carbon monoxide ($k_f^{233} \approx 3.4 \times 10^3\ s^{-1}$)[11] prevails over its addition to the dithioformates, which seems, at least at this temperature, a rather slow process when compared with addition to thiobenzoyltriphenylsilane, a very efficient thiocarbonylic scavenger that under similar conditions traps both the *tert*-butyl and the pivaloyl radicals.[7b] As the temperature is lowered, addition becomes competitive with fragmentation, but the simultaneous presence of the *tert*-butyl adducts prevents the determination of the spectral parameters of the pivaloyl adducts.

Unexpectedly the photolysis of **2–4** in the presence of diphenylmercury failed to afford the phenyl adducts **2g–4g**. Only in the case of the allylic derivative could a spectrum of the phenyl adduct **2g** be observed upon photolysis in the presence of hexaphenyldilead.

The signal of **2g** was however very weak; on the other hand, when **3** and **4** similarly photoreacted with Ph_6Pb_2 the spectra of the triphenylplumbyl adducts **3t** and **4t** with the characteristic low *g*-factor[1] were observed. While the failure to detect the adduct **2t** is unexpected, the observation of a weak spectrum of **2g** is not: indeed, during photolysis of organodilead compounds $R_3Pb–PbR_3$, the formation of plumbyl radicals, $R_3Pb^•$, is often accompanied by that of the $R^•$ radicals; the ease of formation of the latter species varies with the nature of the group R, the

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‡ Pivaloyl = 2,2-dimethylpropanoyl.

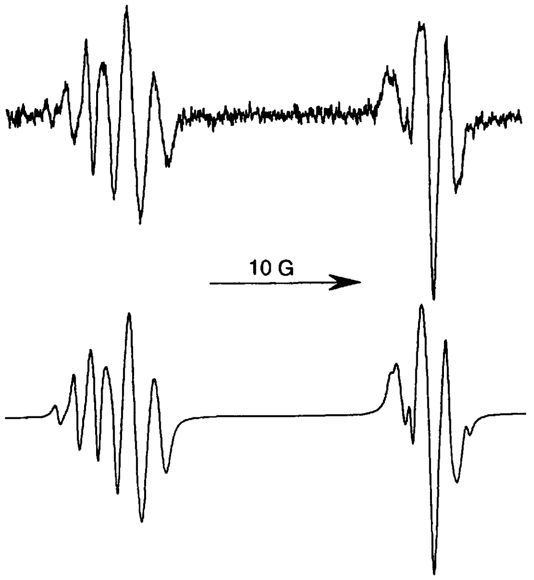


Fig. 2 Experimental (top) and simulated EPR spectrum observed upon photolysis of a deoxygenated di-*tert*-butyl peroxide solution of **2** at room temperature and resulting from the superposition of the signals from **2c** and **2h**

cleavage of a C–Pb bond having little relevance with respect to that of the Pb–Pb bond when R is an aromatic ring and being more important when R is an aliphatic group. Actually, photolysis at a low temperature of solutions of **2**–**4** containing some hexacyclohexyldilead led in all cases to the detection of only the cyclohexyl adducts **2e**–**4e**, characterized on the basis of the small extra splitting due to a single hydrogen atom observed in their spectra in addition to the doublet of triplets from the phosphorus atom and two methylenic protons.

The low temperature ($T = 223$ K) reaction between dithioformates **2** and **3** and *tert*-butoxyl radicals, generated by photolysis of either di-*tert*-butyl peroxide or *tert*-butylhyponitrite, resulted in the observation of clean spectra of the adducts **2h** and **3h**, but as the temperature was raised above 243 K additional signals due to the self-adducts **2c** and **3f**, whose intensity increased with temperature, were simultaneously observed. The presence of two radicals is clearly evident in the spectrum shown in Fig. 2, observed by irradiation of a deoxygenated di-*tert*-butylperoxide solution of **2** at room temperature. At variance with the allylic and benzylic derivatives, photolysis of solutions of compound **4** containing the peroxide only led to the adduct **4h** at all temperatures.

The addition of $\mathrm{Bu^tO^\bullet}$ radicals to **2** and **3** takes place very readily and seems to be easier than addition to the methylderivative **5**, as indicated by experiments carried out in the presence of triphenylsilane. Irradiation of a *tert*-butylbenzene solution of **5** and $\mathrm{Ph_3SiH}$ containing a small amount of $\mathrm{Bu^tOOBu^t}$ at a low temperature led to the EPR detection[1] of both the adducts of $\mathrm{Ph_3Si^\bullet}$ and of $\mathrm{Bu^tO^\bullet}$, while with **2** and **3** only the spectra of **2h** and **3h** are observed at low temperature, the signals due to the self adducts being also evident at room temperature (see Fig. 2).

Thus it would appear that hydrogen abstraction from triphenylsilane by *tert*-butoxyl radicals, ($k_{\mathrm{abs}}^{300} = 1.1 \times 10^7$ dm^3 mol^{-1} s^{-1}),[12] can compete with their addition to **5**, but not to **2** and **3**. On the other hand, when $\mathrm{Ph_3SiH}$ is replaced by $\mathrm{(Me_3Si)_3SiH}$, a silane characterized by a much weaker Si–H bond ($k_{\mathrm{abs}}^{296} = 1.0 \times 10^8$ dm^3 mol^{-1} s^{-1}),[13] hydrogen abstraction becomes easier and only the spectra of the silyl adducts **2p**–**4p** are detected.

The rate of hydrogen abstraction by *tert*-butoxyl radicals from triphenylgermanium hydride, ($k_{\mathrm{abs}}^{300} = 9.2 \times 10^7$ dm^3 mol^{-1} s^{-1}),[12] is close to that from tris(trimethylsilyl)silane and, not surprisingly, on substituting $\mathrm{Ph_3GeH}$ for the silane the spectra of the adducts **2q**–**4q** are observed, along with only small traces of those of the butoxyl adducts **2h**–**4h**. Another Group 14 organometallic hydride with a very weak metal–hydrogen bond is $\mathrm{(Me_3Si)_3GeH}$,§ and indeed the adducts **2r**–**4r** could be readily observed at $T \leqslant 263$ K. On the other hand, adducts **2r** and **3r** under photolytic conditions were extremely short-lived and their spectra were soon replaced by the very intense and persistent doublet shown in Fig. 3, exhibiting several satellite lines. The spectrum was attributed to radical **6**, originating from adducts **2r** and **3r** as outlined in Scheme 3,

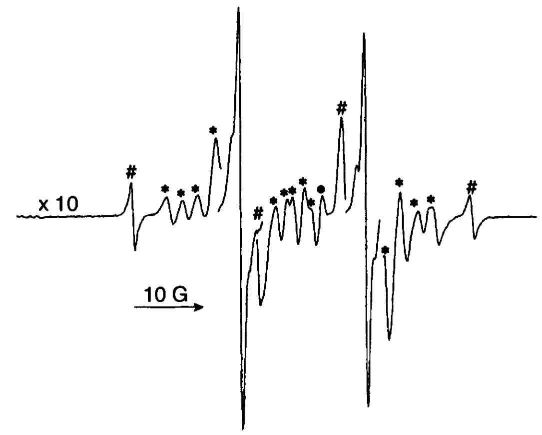
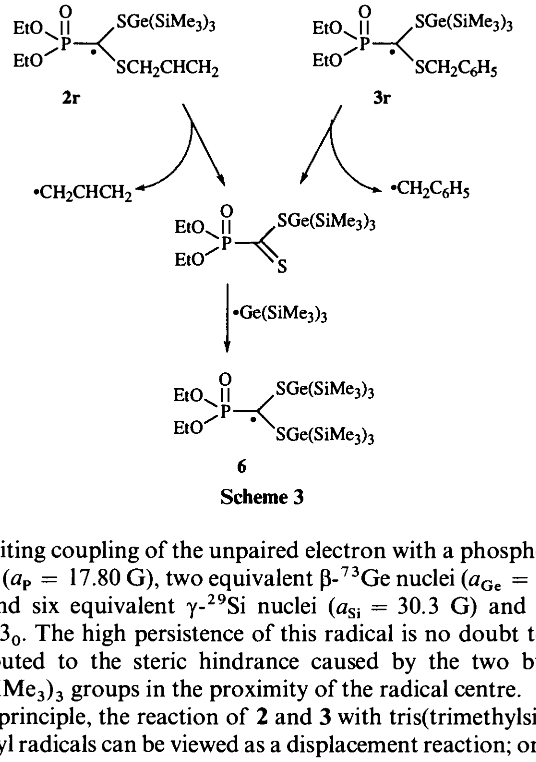


Fig. 3 Room temperature EPR spectrum of radical **6**. The two sides of the spectrum have been amplified to show germanium [*] (^{73}Ge, $I = \frac{9}{2}$, na 7.61%) and silicon [#] satellites (^{29}Si, $I = \frac{1}{2}$, na 4.70%).



Scheme 3

exhibiting coupling of the unpaired electron with a phosphorus atom ($a_{\mathrm{P}} = 17.80$ G), two equivalent β-^{73}Ge nuclei ($a_{\mathrm{Ge}} = 2.21$ G) and six equivalent γ-^{29}Si nuclei ($a_{\mathrm{Si}} = 30.3$ G) and $g = 2.0083_0$. The high persistence of this radical is no doubt to be attributed to the steric hindrance caused by the two bulky $\mathrm{Ge(SiMe_3)_3}$ groups in the proximity of the radical centre.

In principle, the reaction of **2** and **3** with tris(trimethylsilyl)germyl radicals can be viewed as a displacement reaction; on the other hand, the observation of the adducts **2r** and **3r** indicates that, at least at low temperature, the attack of the germyl radicals and the departure of the allyl or benzyl radicals are not simultaneous. At room temperature only the doublet spectrum due to radical **6** could be observed, independent of the starting compound.

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§ The BDE of $\mathrm{(Me_3Si)_3SiH}$ is 79 kcal mol^{-1},[14] while the actual value of that of $\mathrm{(Me_3Si)_3GeH}$ is not known. Recent results[15] indicate however that the metal–hydrogen bond in the latter compound might be even weaker than that in tributyltin hydride.

Table 1 Hyperfine spectral parameters for radical adducts $(EtO)_2P(O)\dot{C}(SX)SCH_2CHCH_2$ in *tert*-butylbenzene at 233 K

Radical	X	a_P/G	a_{2H}(β-CH_2)/G	a_X/G	g
2a	CH_3	22.70	3.50	nr	2.0061_7
2b	CH_2CH_3	22.70	1.80	0.93(2H)	2.0060_5
2c[a]	$CH_2CH{=}CH_2$	22.40	1.41	1.41(2H)	2.0059_0
2d	$C(CH_3)_3$	24.26	2.79	0.49(9H)	2.0058_9
2e	cC_6H_{11}	22.56	1.76	0.68(1H)	2.0060_6
2f	$CH_2–C_6H_5$	22.80	1.69	1.33(2H)	2.0059_4
2g	C_6H_5	22.17	1.23		2.0062_9
2h	$O–C(CH_3)_3$	19.69	1.79		2.0051_2
2m	SC_6H_5	21.98	3.13		2.0058_8
2p	$Si[Si(CH_3)_3]_3$	20.99	1.93		2.0064_4
2q	$Ge(C_6H_5)_3$	23.86	2.65		2.0061_9
2r	$Ge[Si(CH_3)_3]_3$	22.77	1.31		2.0060_5
2s	$Sn(CH_3)_3$	22.75	0.93		2.0067_3

[a] T = 298 K.

Table 2 Hyperfine spectral parameters for radical adducts $(EtO)_2P(O)\dot{C}(SX)SCH_2C_6H_5$ in *tert*-butylbenzene at 233 K

Radical	X	a_P/G	a_{2H}(β-CH_2)/G	a_X/G	*g*
3a	CH_3	23.19	0.63	3.51(3H)	2.0061_5
3b	CH_2CH_3	22.68	1.85	1.19(2H)	2.0060_3
3c	$CH_2CH{=}CH_2$	22.80	1.69	1.33(2H)	2.0059_0
3d	$C(CH_3)_3$	23.84	3.24	0.49(9H)	2.0061_0
3e	cC_6H_{11}	22.77	1.21	0.83(1H)	2.0060_2
3f[a]	$CH_2–C_6H_5$	22.75	1.76	1.76(2H)	2.0058_9
3h	$O–C(CH_3)_3$	19.66	2.10	0.23(9H)	2.0050_5
3i	SCH_3	22.40	3.54	1.07(3H)	2.0061_4
3j	$SCH(CH_3)_2$	22.61	3.34		2.0065_5
3k	$SC(CH_3)_3$	22.91	2.79		2.0059_6
3m	SC_6H_5	21.99	3.97		2.0057_6
3p	$Si[Si(CH_3)_3]_3$	20.72	2.41		2.0063_4
3q	$Ge(C_6H_5)_3$	23.45	3.14		2.0060_7
3r	$Ge[Si(CH_3)_3]_3$	20.66	2.30		2.0072_9
3s	$Sn(CH_3)_3$	22.84	1.04		2.0066_6
3t	$Pb(C_6H_5)_3$	22.32	1.41		2.0032_1

[a] *T* = 298 K.

Table 3 Hyperfine spectral parameters for radical adducts $(EtO)_2P(O)\dot{C}(SX)SCH_2CH_2CHCH_2$ in *tert*-butylbenzene at 298 K

Radical	X	a_P/G	a_{2H}(β-CH_2)/G	a_X/G	*g*
4a	CH_3	22.60	0.96	3.02(3H)	2.0062_9
4b	CH_2CH_3	22.69	1.45	0.21(2H)	2.0061_5
4d	$C(CH_3)_3$	24.40	2.89	0.52(9H)	2.0061_6
4e	cC_6H_{11}	22.70	1.72	0.57(1H)	2.0061_5
4f	$CH_2–C_6H_5$	22.55	1.05	1.84(2H)	2.0060_3
4h	$O–C(CH_3)_3$	19.32	2.28		2.0057_2
4i	SCH_3	22.72	3.25	1.08(3H)	2.0062_6
4j	$SCH(CH_3)_2$	23.12	3.29		2.0061_4
4m	SC_6H_5	22.07	3.43		2.0059_2
4n	$Si(C_6H_5)_3$	22.29	1.40		$2.0061_{=}$
4p	$Si[Si(CH_3)_3]_3$	21.70	2.09		2.0065_2
4q	$Ge(C_6H_5)_3$	24.15	2.69		2.0063_4
4r	$Ge[Si(CH_3)_3]_3$	21.59	1.89		2.0074_4
4s	$Sn(CH_3)_3$	22.56	1.22		2.0060_9
4t	$Pb(C_6H_5)_3$	22.05	1.51		2.0029_3

The value of the rate constant for hydrogen abstraction by *tert*-butoxyl radicals from tributyl or triphenyl tin hydrides (k_{abs}^{300} = 2–4 × 10^8 dm^3 mol^{-1} s^{-1})[12] suggests that the formation of tin adducts should prevail over that of the *tert*-butoxyl adduct; on the other hand, stannyl radicals may be easily generated by photolysis of the appropriate distannane, $R_3Sn–SnR_3$, and indeed low temperature photolysis of *tert*-butylbenzene solution of **2**–**4** containing hexamethyldistannane resulted in the detection of the spectra of the trimethylstannyl adducts **2s**–**4s**.

Although the addition of alkoxyl radicals to dithioformates **2**–**4** takes place very readily, the analogous reaction with alkylthiyl radicals is less efficient and only weak spectra are obtained from **3i**,**j** and **4i**,**j** by addition of such radicals as $H_3CS^•$, $(H_3C)_2CHS^•$, obtained by photolysis of the corresponding disulfides, to **3** and **4**, while with **2** the reactions only resulted in very weak and uninterpretable EPR signals. This may be the result of the C–S bond photocleavage taking place simultaneously to the cleavage of the S–S bond,[16] the competition being increasingly important with increasing stability of the alkyl radical. Indeed, upon photolysis of Bu^tSSBu^t in the presence of the dithioformates, no adducts were observed with **2**, the *tert*-butyl adduct **4d** was observed with **4**, and only **3** led to a very weak spectrum assignable to the *tert* butylthiyl adduct **4k**. Strong spectra of the phenylsulfanyl adducts **2m**–**4m** were instead observed when photolysing at low temperature solutions of **2**–**4** containing some diphenyldisulfide. Also in this case, lines due to the self-adducts **2c** and **3f** began to appear when working at $T \geqslant 243$ K.

An examination of the data collected in Tables 1–3 indicates that the spectral parameters of the adducts of **2**–**4** seem to be rather insensitive to the nature of the attacking radical X$^•$. A notable exception is provided by the *tert*-butoxyl adduct **2h**–**4h** whose values for the ^{31}P hyperfine splitting and of the *g*-factor are smaller than those found for all the other adducts, behaviour that parallels that exhibited by the Bu^{t}O$^•$ adduct of the methyl dithioformate **5**;[1] a relatively low *g*-factor value is also a typical feature of the alkoxyl adducts with thiocarbonyl compounds.[7a]

The above results rule out the possibility that triphenylmethyl (diethoxyphosphoryl)dithioformate **1** may be successfully used as radical scavenger in spin trapping experiments. It readily undergoes thermolysis or photolysis and additionally the stability of the triphenylmethyl radical makes displacement reactions important thus precluding the utilization of **1** even when working at low temperatures and in the absence of UV irradiation. Allyl (diethoxyphosphoryl)dithioformate **2** and benzyl (diethoxyphosphoryl)dithioformate **3** seem to undergo significant photoinduced fragmentation only above 233 K, while being thermally stable up to *ca.* 350 K. Compounds **2** and **3** can therefore be used over a relatively wide temperature range in spin trapping experiments carried out in the absence of UV irradiation, or at a low temperature in photolytic studies, being particularly suitable for the scavenging of alkoxyl radicals. The behaviour of but-3-enyl (diethoxyphosphoryl)dithioformate **4** is instead analogous to that of the methyl-derivative **5**, and, since it does not undergo significant photo- or thermal-degradation, it can be safely used for trapping experiments in organic media.

The importance of oxygen-centred radicals (HO$^•$, HOO$^•$, $O_2^{•-}$ and RO$^•$) as well as of sulfur-centred species in biological systems is well established, and the introduction of new and efficient traps for these species would be very welcome to the community studying radical processes of biological interest. Unfortunately dithioformates **2**–**5**[1] are insoluble in aqueous media and would therefore be of no use in such studies. In the search for a water soluble dithioformate, the dipyridinium salt **7** was synthesized which proved totally insoluble in such organic solvents as benzene or *tert*-butylbenzene, but was indeed extremely soluble in water.

It was frustrating to find that when **7** was added to a DMSO solution of potassium superoxide–18-crown-6 ether, a system containing $O_2^{•-}$,[10] no EPR signal was observed; the failure to trap the superoxide radical might be attributed to the very low solubility of the salt in this solvent, but when the dipyridinium salt **7** was added to a water solution of hypoxanthine–xanthine oxidase, a system also capable of producing the oxygen superoxide radical anion,[17] the results were equally negative, *i.e.* no EPR signals were observed; on the other hand, when 5,5-dimethylpyrroline *N*-oxide (DMPO) was substituted for **7** an unmistakable signal of the DMPO–$O_2^{•-}$ radical adduct was detected.

The Fenton reaction is a well known source of hydroxyl radicals, but no EPR signals were observed on addition of iron(II) sulfate to an aqueous solution of **7** and hydrogen peroxide. However, when **7** was again replaced by DMPO in a parallel experiment, the 1:2:2:1 quartet typical of the DMPO–OH adduct was immediately detected.

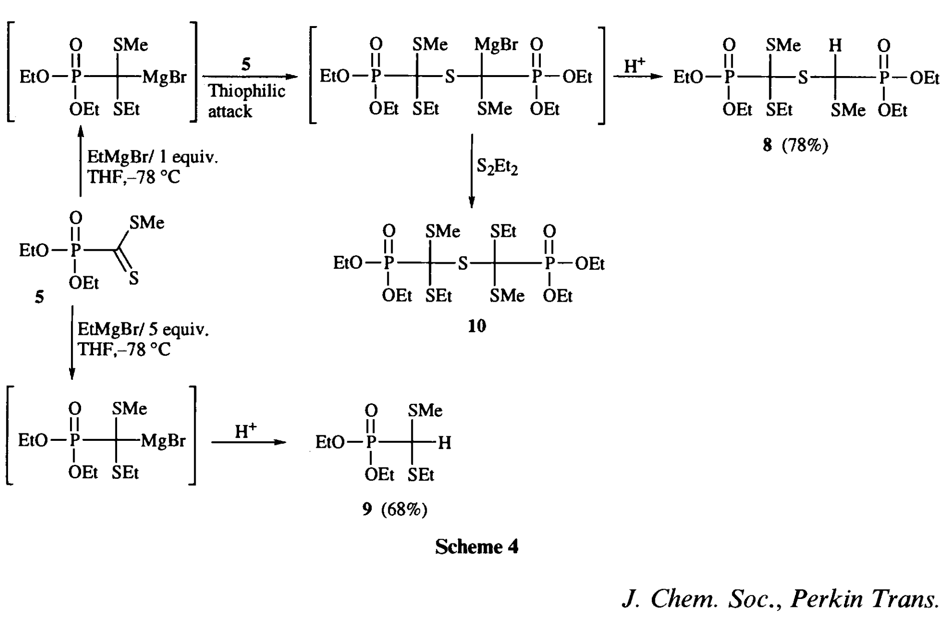
These negative results suggest that care must be taken when predicting spin trapping activity for a given compound on the basis of its structural similarity with other derivatives proven to be active under different experimental conditions.

Reactions with Grignard reagents

Every textbook of organic chemistry indicates that secondary and tertiary alcohols can be easily synthesized by reaction of a suitable Grignard reagent with an aldehyde or a ketone, respectively, followed by hydrolysis of the intermediate complex. In the early eighties it was recognized[18] that benzophenone reacts with RMgX according to a mechanism involving the formation of a radical anion–radical cation pair that may either collapse to products (1,2-addition) or fragment to a radical ion pair and to a neutral radical; these may either recombine to 1,2- and 1,6-addition products or exit the cage leading to such derivatives as pinacols and alkanes.

The analogous reactions between Grignard reagents and thioketones have also received much attention. These reactions do not lead to the corresponding thiols, but give products which depend very much on the nature of the thiocarbonylic substrate. In particular, aromatic thioketones lead to the corresponding sulfides,[19] while with aliphatic thioketones reduction takes place quantitatively.[20] Despite several indications suggesting that these reactions should proceed through thiophilic attack of the carbanion from the Grignard reagent rather than from a mechanism similar to that of the reactions with ketones, in a preliminary study of the reactions between thiobenzoyltriphenylsilane and phenyl- or methyl-magnesium bromide we obtained EPR evidence for the formation of the radical ion pair between the radical anion of the thiocarbonylic compounds and the magnesium cation.[21]

In a previous investigation of the reaction between phosphoryldithioformates and Grignard reagents carried out by some of us it was found[22] that the nature of the products is strongly dependent on the ratio of the organometallic reagent to



5

8 (78%)

10

9 (68%)

Scheme 4

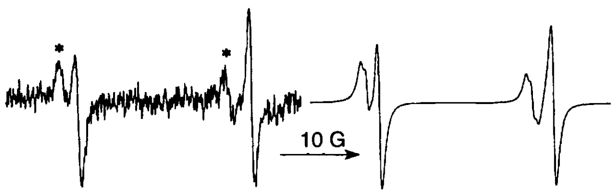


Fig. 4 Experimental (left) and simulated EPR spectrum observed when adding PhMgBr to a deoxygenated THF solution of **2** at −10 °C. In the simulation, a 40% decay during recording has been assumed for the radical responsible for the starred doublet.

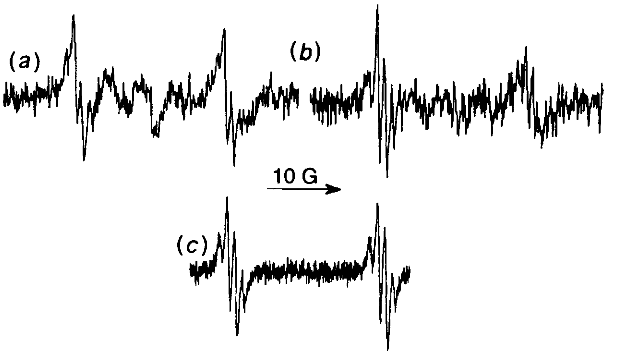
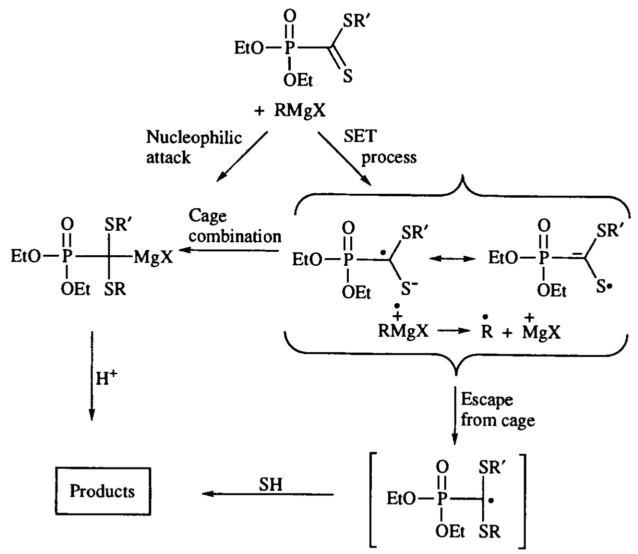


Fig. 5 EPR spectra observed immediately after addition of PhMgBr to deoxygenated THF solutions of dithioformate **5** at 273 K (*a*) and at 298 K (*b*). The spectrum (*c*) is observed by electrochemical reduction of **5** in ACN at 298 K.



Scheme 5

the substrate, as well as on the work-up. As shown in Scheme 4 for the reaction of methyl (diethoxyphosphoryl)dithioformate **5** with EtMgBr the polysulfide **8** was formed in *ca.* 80% yield with 1 equiv. Grignard after acidic hydrolysis, while with 5 equiv. EtMgBr the phosphoryldithioacetal **9** was the main product.

Following the preliminary experiments on the reaction of thiobenzoyltriphenylsilane with MeMgBr, we repeated the reactions of **2**–**5** with Grignard reagents inside the cavity of the EPR spectrometer. Thus, when PhMgBr was added to a deoxygenated THF solution of **2** at −10 °C, the spectrum shown in Fig. 4 was observed. It results from the superposition of a weak and ill-resolved doublet of triplets ($a_P = 20.98$, $a_{2H} = 0.40$ G and $g = 2.0088_7$) and a stronger doublet ($a_P = 21.91$ G and $g = 2.0075_0$). The broader doublet signal decreased with time and after a while only one doublet was observed; both signals disappeared on raising the temperature above 0 °C. Only very weak signals were obtained when **2** reacted with MeMgBr over a wide temperature range.

An unambiguous identification of the species responsible for the observed spectra is certainly difficult, but the very high values of the *g*-factors exclude the fact that they originate from neutral radical adducts akin to those observed when adding alkyl radicals to **2** (see previous section). Actually the high *g* values suggest that in this case we are dealing with ionic species: in particular, the broad doublet ($g = 2.0088_7$) might be due to the dissociated radical anion $\mathbf{2}^{\bullet-}$, while the somewhat longer lived doublet ($g = 2.0075_0$) might be attributed to an ion pair $[\mathbf{2}^{\bullet-}, {}^{+}\mathrm{MgX}]$ between the dithioformate radical anion and a magnesium cation. Indeed higher *g*-factor values are expected for the free anions than for the ion pairs, delocalization of the unpaired electron on the sulfur atom being more important for the former species.

The reacting of **3** with PhMgBr in THF at −10 °C led to a very short-lived species whose EPR spectrum was characterized by parameters ($a_P = 22.90$, $a_{2H} = 1.40$ G and $g = 2.0060_5$) more in line with a spin adduct rather than with a radical anion. This transient adduct might be tentatively identified as the phenyl adduct **3g**, but comparison with the 'authentic' phenyl adduct cannot be made, as this species could not be otherwise generated. Raising the temperature led to the observation of several weak signals, none of which could be associated with a definite chemical species.

While the reaction of PhMgBr with but-3-enyl (diethoxyphosphoryl)dithioformate **4** also resulted in weak and uninformative spectra, a signal attributable to the corresponding radical anion was observed when reacting dithioformate **5** with PhMgBr at *ca.* 0 °C: despite the rather messy spectral pattern (Fig. 5), one can easily recognize, superimposed on other signals, a doublet of quartets ($a_P = 20.21$, $a_{3H} = 0.98$ G and $g = 2.0095_4$) centred at a rather low field with a phosphorus splitting similar to that attributed to the free anion $\mathbf{2}^{\bullet-}$. The spectrum, assigned to $\mathbf{5}^{\bullet-}$, was soon replaced by a number of new signals which could not be rationalized, indicating rapid evolution of the initially formed anionic species, and in no case was it possible to identify the alkyl radical adduct to **5**. Although a much better resolution could be obtained by carrying out the reaction at room temperature (see Fig. 5), the signal decayed so rapidly that the high field group of lines could hardly be distinguished from the noise. As in the case of the allyl derivative the reaction with methylmagnesium bromide led to similar though weaker signals.

As it is clearly shown by Figs. 4 and 5(*a*) and (*b*), the quality of the EPR spectra observed in the reaction of phosphoryldithioformates with Grignard reagents was rather poor; indeed the signals were in all cases very weak, ill-resolved and could be observed for a very short time. Although the measured EPR parameters all pointed towards the identification of the species responsible for the observed spectra as the radical anions of the starting compounds, it was felt necessary to compare them with the spectral parameters of an authentic radical anion from a phosphoryldithioformate. For this purpose, the electrochemical reduction of methyl (diethoxyphosphoryl)dithioformate **5** in acetonitrile solution was carried out at room temperature inside the cavity of the EPR spectrometer: this led to the detection of the EPR spectrum shown in Fig. 5(*c*), whose spectral parameters ($a_P = 20.63$, $a_{3H} = 0.98$ G and $g = 2.0100_4$) were nearly identical to those of the spectra observed when reacting **5** with Grignard reagents. This finding further substantiates the attribution of the latter spectra to the radical anion $\mathbf{5}^{\bullet-}$, and, by analogy, the identification of the species responsible for the spectra observed when reacting **2** or **3** with Grignard reagents as the radical anions $\mathbf{2}^{\bullet-}$ and $\mathbf{3}^{\bullet-}$. A detailed study of the electrochemical reduction of a variety of phosphoryl- and thiophosphoryl-dithioformates is currently being carried out and will be reported elsewhere.

The present results are at odds with previous reports[19] of the detection of the alkyl radical adduct resulting from thiophilic addition in the reaction of alkyl Grignard reagents with thiocarbonyl compounds such as thiobenzophenone, and, together with our preliminary results on the reactions of Grignard reagents with thiobenzoyltriphenylsilane and other thiocarbonyl compounds[21] provide the first direct EPR evidence that radical anions are involved in these reactions.

A possible rationalization of the overall process is outlined in Scheme 5: the formation of the radical anions can be accounted for by accepting that a single electron transfer process from the Grignard to the dithioformate takes place, if not instead of, at least alongside nucleophilic attack at sulfur by the carbanion from the Grignard. The radical anions from the phosphoryldithioformates can only be observed while the reaction with the Grignard has not yet reached completion. Besides, in-cage recombination is most likely to be a very fast process, which might also explain why the alkyl radical adducts of the dithioformates are not observed, a failure that should not be exclusively ascribed to fast hydrogen abstraction from the solvent.

Experimental

Materials

Compounds **1–5** were easily prepared from the sodium salt of diethylphosphite and excess carbon disulfide,[23] and alkylation of the intermediate sodium phosphoryldithioformate. The salt **7** was synthesized by reacting **5** and trimethylsilyl bromide, and by treating the resulting product with pyridine in methanol.[24] Organomercury compounds and all other reagents were commercially available.

EPR studies

EPR spectra were recorded on a Bruker ER200D X-band spectrometer, equipped with a dedicated ESP 300 data system, a standard variable temperature device, an NMR gaussmeter for field calibration and a frequency counter for the determination of *g*-factors that were corrected against that of the perylene radical cation in conc. sulfuric acid (2.0025$_8$). When required the samples were irradiated by focussing the UV light from a Hanovia 1 kW high pressure mercury lamp onto the EPR cavity.

In a typical radical-trapping experiment, a Suprasil® tube (id 3.9 mm) containing a nitrogen-purged benzene or *tert*-butylbenzene solution of the selected dithioformate and the radical precursors was put inside the cavity of the spectrometer. Alkoxyl and sulfonyl radicals were generated by photolysis of the appropriate peroxide or disulfide, alkyl radicals by photodecomposition of organomercury compounds, and Group 14 radicals either through hydrogen abstraction from the silicon and germanium hydrides or by photocleavage of the metal–metal bond in ditin compounds.

The reactions with the Grignard reagents were performed by placing the sample tube containing the dithioformate, inside the spectrometer cavity, letting it reach the appropriate temperature and adding the THF or ethereal PhMgBr or MeMgBr solution by injecting it through a soft rubber stopper.

In situ electrochemical EPR studies were carried out at room temperature using an Amel potentiostat and a flat quartz electrolytic cell with a platinum gauze and a mercury pool as electrodes. Experiments were carried out using 5 mM solutions of phosphoryldithioformate **5** in anhydrous acetonitrile containing tetrabutylammonium perchlorate (0.1 M) as supporting electrolyte.

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References

1 J. Levillain, S. Masson, A. Hudson and A. Alberti, *J. Am. Chem. Soc.*, 1993, **115**, 8444.
2 B. Giese and J. A. González-Gómez, *Angew. Chem., Int. Ed. Engl.*, 1984, **23**, 69.
3 B. Giese, *Radicals in organic synthesis: formation of carbon carbon bonds*, Pergamon Press, New York, 1986.
4 (*a*) C. Chatgilialoglu, D. Griller and M. Lesage, *J. Org. Chem.*, 1988, **53**, 3641; (*b*) M. Lesage, C. Chatgilialoglu and D. Griller, *Tetrahedron Lett.*, 1989, **30**, 2733.
5 (*a*) M. Julia, *Acc. Chem. Res.*, 1971, **4**, 386; (*b*) A. L. Beckwith and K. U. Ingold, in *Rearrangements in ground and excited states*, ed. P. de Mayo, Academic Press, New York, 1980; (*c*) D. Curran, *Synthesis*, 1988, 417; (*d*) D. Curran, *Synthesis*, 1988, 489; (*e*) T. V. RajanBabu, *Acc. Chem Res.*, 1991, **24**, 139 and refs. therein.
6 E. G. Janzen and B. J. Blackburn, *J. Am. Chem. Soc.*, 1969, **91**, 4481.
7 (*a*) A. Alberti, B. F. Bonini and G. F. Pedulli, *Tetrahedron Lett.*, 1987, **28**, 3737; (*b*) A. Alberti, M. Benaglia, B. F. Bonini and G. F. Pedulli, *J. Chem. Soc., Faraday Trans. 1*, 1988, **84**, 3347; (*c*) A. Alberti and M. Benaglia, *J. Organomet. Chem.*, 1992, **434**, 151.
8 (*a*) J. L. Wardell, in *Comprehensive Organometallic Chemistry*, eds. G. Wilkinson, F. Gordon, A. Stone and E. W. Abel, Pergamon Press, Oxford, 1982; (*b*) A. Alberti, F. P. Colonna, M. C. Depew and X. Li, *J. Organomet. Chem.*, 1985, **292**, 335.
9 A. J. Canty and G. B. Deacon, *Aust. J. Chem.*, 1974, **24**, 489.
10 J. S. Valentine and A. B. Curtis, *J. Am. Chem. Soc.*, 1975, **97**, 224.
11 H. Schuh, E. J. Hamilton, Jr., H. Paul and H. Fischer, *Helv. Chim. Acta*, 1974, **57**, 2011.
12 C. Chatgilialoglu, K. U. Ingold, J. Lusztyk, A. S. Nazran and J. C. Scaiano, *Organometallics*, 1983, **2**, 1332.
13 C. Chatgilialoglu and S. Rossini, *Bull. Chem. Soc. Fr.*, 1988, 298.
14 J. M. Kanabus-Kaminska, J. A. Hawari, D. Griller and C. Chatgilialoglu, *J. Am. Chem. Soc.*, 1987, **109**, 5267.
15 C. Chatgilialoglu and M. Ballestri, *Organometallics*, 1995, **14**, 5017.
16 T. J. Burkey, J. A. Hawari, F. P. Lossing, J. Lusztyk, R. Sutcliffe and D. Griller, *J. Org. Chem.*, 1985, **50**, 4966.
17 M. C. Krishna, D. A. Grahame, A. Samuni, J. B. Mitchell and A. Russo, *Proc. Natl. Acad. Sci. USA*, 1992, **89**, 5537.
18 E. C. Ashby and J. R. Bowers, Jr., *J. Am. Chem. Soc.*, 1981, **103**, 2242.
19 M. Dagonneau and J. Vialle, *Tetrahedron*, 1974, **30**, 3119.
20 D. Paquer and M. Vazeux, *J. Organomet. Chem.*, 1977, **140**, 257.
21 A. Alberti, M. Benaglia and G. F. Pedulli, unpublished results.
22 A. Bulpin, S. Masson and A. Sene, *Tetrahedron Lett.*, 1989, **30**, 3415.
23 D. W. Grisley, *J. Org. Chem.*, 1961, **26**, 2544.
24 A. Bulpin, *Thèse de Docteur en Sciences*, Université de Caen, France, 1991, p. 142.

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