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On the Actual EPR Detection of Thioacyl Radicals

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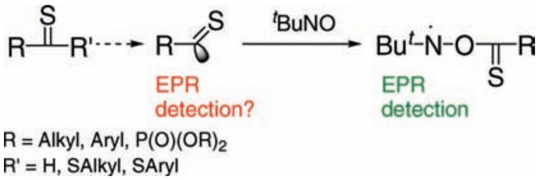
ABSTRACT



The direct EPR detection of thioacyl radicals has been reported only once, while thioacyl nitroxides remain an elusive species. We failed to detect the thioacyl radicals from two thioaldehydes and from phosphoryldithioformates but have obtained EPR evidence that thioacyl radicals react with 2-methyl-2-nitrosopropane to give thiocarbonyloxyaminyls rather than thioacyl nitroxides. The results of DFT calculations support this unexpected reactivity of thioacyls, while making questionable their previous EPR identification.

Phosphoryldithioformates (RO)$_2$P(O)C(S)SR′ are valuable compounds that find a variety of applications, ranging from pesticides to chain transfer agents in controlled radical polymerization. These compounds are readily synthesized through a simple two-step one-pot process[1] whereby the appropriate dialkylphosphite is initially reacted with sodium, then with an excess of CS$_2$ (>2 equiv), and eventually with an alkyl bromide. In contrast, when reacting sodium dialkylphosphites with a deficit of CS$_2$ (<1 equiv), methylene diphosphonates **1** are obtained as main products (50−60% yield).[2] To explain the origin of the hydrogen atoms of the methylenic group, a tentative mechanism has been proposed (see Scheme 1) that involves phosphorylthioacyl radicals **2**.

With the aim to prove the actual intermediacy of thioacyl radicals **2**, we reacted sodium diethylphosphite with a deficit of carbon disulfide inside the cavity of an EPR spectrometer. This led to the detection of the spectrum shown on the left-hand side of Figure 1. Although in principle the observed doublet splitting (a_{31P} = 2.80 mT) might have been in line with thioacyl radical **2**, we felt that the g-factor value (g = 2.0119) was much too high for a species which, by analogy with acyl radicals,[3,4] was expected to have a σ configuration.

We have therefore undertaken a computational approach, and indeed DFT calculations at the B3LYP/6-31+G* level predicted for **2** (R = Me) a σ configuration.

The calculations also predicted a phoshorus splitting twice as large (a_{31P} = 5.94 mT) than experimentally found, while the very low computed g-factor value (g = 1.9880) reflects the σ nature of the radical. In light of available literature data,[5] we tentatively assign the observed spectrum to the dianionic species **3**. The assignment is also supported by DFT

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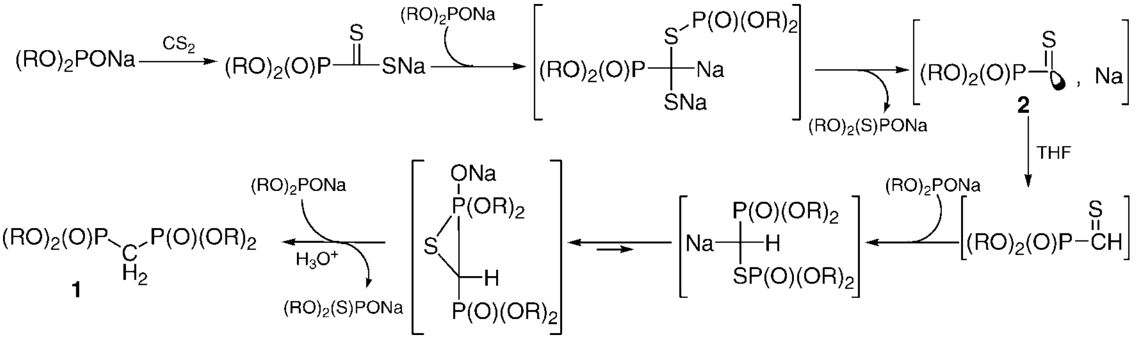
Scheme 1



calculations that predict for this species spectral parameters ($a_{31P} = 2.10$ mT, $g = 2.0104$) in fairly good agreement with experiment.

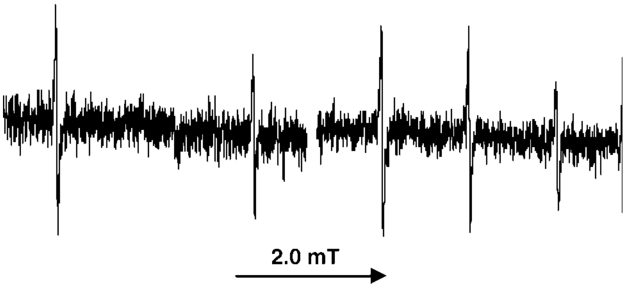


Figure 1. EPR spectra observed at 343 K by reacting sodium diethylphosphite with defect CS_2 in the absence (left) and in the presence (right) of MNP.

Having failed to observe thioacyl radical **2**, we repeated the reaction in the presence of the spin trap 2-methyl-2-nitrosopropane, MNP, in an attempt to observe its spin adduct **4**. A spectrum characteristic of a nitroxide was indeed detected (right-hand side of Figure 1), but its spectral parameters ($a_N = 1.24$ mT, $g = 2.0063$) were far from those exhibited by structurally similar acylnitroxides.[6,7]

Also, DFT calculations predict for radical **4** spectral parameters ($a_N = 0.40$ mT, $g = 2.0167$) that differ drastically from those measured. While it seems clear that the detected species should not be identified as a thioacyl nitroxide, its actual identity remains a puzzle. The spectral parameters are in line with a dialkyl nitroxide, although the nitrogen splitting is on the lower side of expectation, and we propose that the observed spectrum is due to nitroxide **5**, resulting from the trapping of radical **3** by MNP (Figure 2). DFT calculations carried out on **5** (a_N = 1.31 mT, g = 2.0055) may be considered to lend support to this identification.

At this point, we decided to focus our attention on thioacyl radicals in general, but a search in the literature showed that not much is known about these species. (Arylsulfanyl)thiocarbonyl radicals, obtained by addition of aryl radicals to carbon disulfide, rapidly react with either disulfides or azido groups but may also quickly lose CS.[8] The reaction of stannyl radicals with xanthic anhydrides conveniently produces alkoxythiocarbonyl radicals[9,10] that however undergo rapid β-fragmentation to give alkyl radicals, and the factors affecting this fragmentation process have been computationally investigated.[11,12] B3LYP/6-311G** calculations predicted[13,14] a σ structure for HC(•)=S and for the muoniated species Mu(^{t}Bu)NC(•)=S. The latter species was also detected by μSR spectroscopy whereas the only available report of the EPR detection of thioacyl radicals concerns a few ROC(•)=S species observed in a revisitation[15] of the Barton−McCombie deoxygenation of secondary alcohols.[16]

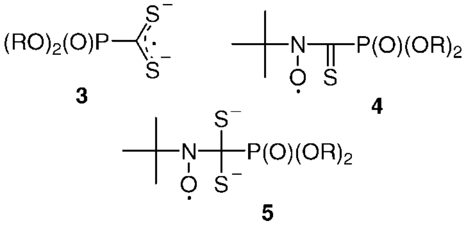


Figure 2. Radicals possibly accounting for the EPR spectra shown in Figure 1.

It should however be noticed that the g-factor values (ca. 2.0019) reported for these alkoxythiocarbonyls are fairly high considering that they are expected to be significantly lower

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than those of the corresponding acyl radicals (ca. 2.0012) since the spin−orbit coupling constant of the S atom is about twice as large as that of the O atom. DFT calculations were therefore carried out on two thioacyl radicals and, to check the reliability of the computed *g*-factors, on a number of structurally related acyl radicals. The results collected in Table 1 show an excellent agreement for acyl radicals, while the *g*-values calculated for thioacyl radicals are, as expected, much lower than those previously reported.

Table 1. Experimental and DFT Computed *g*-Values for Some Thioacyl and Acyl Radicals

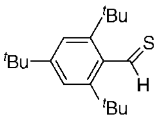
radical	g_{exptl}	g_{DFT}
Me−C(·)=S		1.9913
MeO−C(·)=S	2.0020[15]	1.9985
^{n}HexylO−C(·)=S	2.0019[15]	
^{n}OctylO−C(·)=S	2.0020[15]	
2-OctylO−C(·)=S	2.0019[15]	
Me−C(·)=O	2.0005[17]	2.0005
F_3C−C(·)=O	2.0010[18]	2.0012
H_2N−C(·)=O	2.0017[19]	2.0017
MeO−C(·)=O	2.0013[20]	2.0013
^{t}BuO−C(·)=O	2.0011[21]	2.0011
MeS−C(·)=O		2.0009

Actually, the values collected in Table 1 suggest that the identification of the alkoxythioacyl radicals may be questionable. Particular attention should be drawn to methoxythioacyl and methylthiylacyl radicals that are structural isomers.

It would appear that the measured *g*-values are more appropriate for alkylthiylacyl rather than for alkoxythioacyl radicals, and it should be noted that DFT calculations predict the former species to be more stable than the latter by 19.5 kcal/mol.

To remove any possible ambiguity regarding acyl and thioacyl radicals, we tried to generate the authentic thioacyl radicals from different sources and to determine their EPR spectral parameters as well as those of their possible spin adducts with MNP.

First, we photolyzed at different temperatures a *tert*-butylbenzene solution of compound **6** and hexabutylditin inside the cavity of the EPR spectrometer. Although according to previous studies the reaction might have led to the ethoxythioacyl radical,[10,15] in our hands it led to the observation of EPR spectra that proved reversibly dependent on temperature (see Figure 3) and that were attributed to radical **7**, either slowly exchanging between two different conformations (a_{2H} = 0.267 mT, $g = 2.0036_7$, and a_{2H} = 0.326 mT, $g = 2.0037_7$) at lower temperature or as their average at higher temperature. No signal related to a possible thioacyl radical was instead detected.



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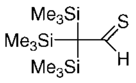

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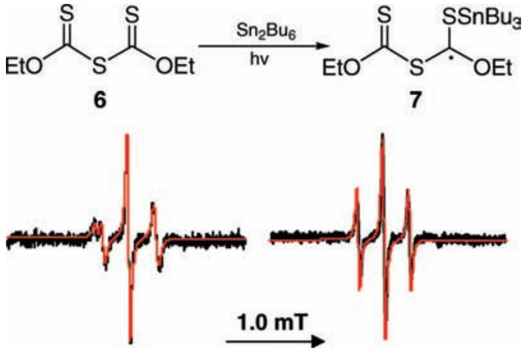

Figure 3. Experimental (black) and simulated (red) EPR spectra of radical **7** observed upon UV irradiation of a solution of **6** and Sn_2Bu_6 at 268 K (left) and 313 K (right).

By adding MNP to the reaction system, di-*tert*-butyl nitroxide, a species always present when photolyzing MNP, and *n*-butyl *tert*-butyl nitroxide, deriving from the loss of butyl radicals from hexabutylditin, were the only observed species.

We also tried to generate thioacyl radicals from one of the two stable thioaldehydes **8** and **9** but could not find an efficient way to abstract the thioaldehyde hydrogen atoms.

Actually, ^{t}butoxy radicals are known to readily add to the thiocarbonyl function,[22] and indeed photolysis of either **8** or **9** in the presence of di-*tert*-butyl peroxide led to the observation of the spin adducts resulting from the thiophilic addition of the ^{t}butoxy radicals to the C=S double bonds. Also, the use of DPPH or galvinoxyl radicals as hydrogen abstractors proved unsuccessful leading to the detection of the EPR spectra of DPPH and galvinoxyl themselves.

The failure to observe the thioacyl radicals from **8** or **9** does not necessarily mean that these species are not formed, since it is possible that they do not reach a steady state concentration large enough to be detected. The photoreactions between the two thioaldehydes and di-*tert*-butyl peroxide were therefore repeated in the presence of MNP. As shown in Figure 4 for **8**, complex spectra were obtained, indicating the presence of several nitroxides.

In particular, besides the signal from ^{t}butoxy ^{t}butyl nitroxide (yellow circle, a_N = 2.72 mT, g = 2.0054) and that from di^{t}butyl nitroxide (green circle, a_N = 1.54 mT, g = 2.0059), the signals from two other adducts were observed (blue circle, a_N = 0.74 mT, g = 2.0068 and red circle, a_N = 1.41 mT, g = 2.0049). While the spectral parameters of the

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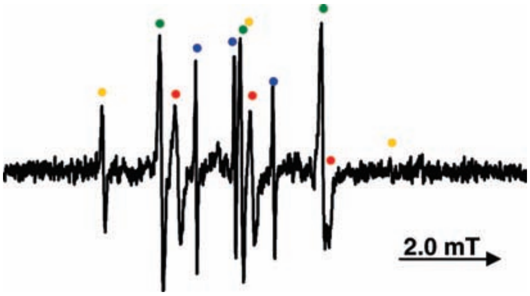
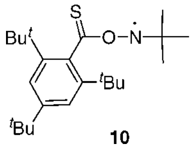


Figure 4. EPR spectrum observed upon short UV irradiation of a solution of **8**, di-*tert*-butylperoxide and MNP at 298 K.

former radical are typical of an acyl nitroxide that is identified as ArC(O)N(O•)^{t}Bu, the latter has a *g*-factor too low for a nitroxide, and we identify it as the thiocarbonyloxyaminyl **10**.

A species with almost identical spectral parameters (a_N = 1.42 mT, g = 2.0048) and identified as thiocarbonyloxyaminyl **11** was detected in the case of **9**. It should be noticed that the spectral parameters of **10** and **11** agree well with those reported for two structurally related carbonyloxyaminyl radicals.[23]

DFT predicted that spectral parameters (a_N = 1.39 mT, g = 2.0058) for radical **10** are in reasonable agreement with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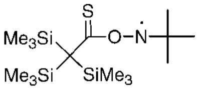
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experiment thus lending support to the above assignment. Addition to the oxygen atom of hindered nitroso derivatives by relatively large radicals is known to be favored over addition to nitrogen.[24] We believe that unexpected formation of oxyaminyls **10** and **11** can be ascribed to the large dimensions of thioacyls from **8** and **9** that make these species sterically demanding.

Overall, the above results indicate that thioacyl radicals have never been really detected by EPR spectroscopy and that their reaction with MNP does not lead to thioacyl nitroxides. Finally, it should be noted that the spectra shown in Figure 1 do not directly establish the involvement of thioacyl radical **2** in the formation of methylene diphosphonate **1**, yet in the light of the present results, the failure to detect **2** does not necessarily invalidate the mechanism shown in Scheme 1.

Supporting Information Available: Experimental details. This material is available free of charge via the Internet at http://pubs.acs.org.

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