Formation and EPR spectra of radical species derived from the oxidation of the spin trap, α-phenyl-*N*-*tert*-butylnitrone (PBN), and some of its derivatives in 1,1,1,3,3,3-hexafluoropropan-2-ol. Formation of isoxazolidine radical cations

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The photolysis of a solution of the spin trap, α-phenyl-*N*-*tert*-butylnitrone† (PBN, 1) with 2,3-dichloro-4,5-dicyano-1,4-benzoquinone (DDQ) in 1,1,1,3,3,3-hexafluoropropan-2-ol (HFP) containing 6% trifluoroacetic acid produces a persistent radical species, the six-line EPR spectrum of which has $a_N = 2.00$ and $a_H = 2.78$ mT. The half-life of this radical was *ca.* 20 min at 22 °C. A similar spectrum was obtained from PBNs substituted by an electron-withdrawing group (NO_2, F) in the 4-position, whereas PBNs with an electron-donating group (4-MeO, 4-Me_2N, 3,4-OCH_2O) upon oxidation gave multi-line spectra which could be assigned to the corresponding radical cations.

The species with the 2.0/2.8 mT spectrum, previously observed in the anodic oxidation of PBN in aqueous solution, was eventually identified as a derivative of the isoxazolidine ring system. The mechanism is believed to involve de-*tert*-butylation of PBN$^{\cdot+}$ with formation of *tert*-butyl cation from which 2-methylpropene is formed by proton abstraction. 1,3-Dipolar addition of PBN to 2-methylpropene gives 2-*tert*-butyl-3-phenyl-5,5-dimethylisoxazolidine, the radical cation of which is formed by DDQ photooxidation and gives rise to the 2.0/2.8 mT spectrum. Support for this mechanism was obtained by adding 2-methylpropene or *tert*-butyl alcohol (as a source of 2-methylpropene under the acidic conditions used) to the photolysis medium, which strongly increased the intensity of the spectrum. The use of other alkenes gave EPR spectra which in their main features were compatible with the isoxazolidine structure.

Introduction

The reactive radical cation of the commonly used spin trap, α-phenyl-*N*-*tert*-butylnitrone (PBN, **1**), was recently characterized by matrix spectroscopy at 77 K and time-resolved spectroscopy at room temperature.[1] The structure of $\mathbf{1}^{\cdot+}$ was suggested to be that of an α-aminoxylcarbenium ion, reactive toward nucleophiles at the α-carbon with formation of spin adducts [eqn. (1)],

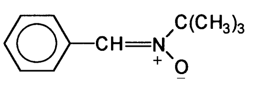
$$\mathbf{1}^{\cdot+} + \mathrm{Nu}^- \longrightarrow \mathrm{Nu{-}}\mathbf{1}^{\cdot} \qquad (1)$$

as shown by reaction with chloride ion generated in the matrix-e$^-$ reaction. The latter reaction was unambiguously established by generating $\mathbf{1}^{\cdot+}$ by γ-irradiation of oxazirane **2** whereby the possibility of spin trapping by **1** was avoided [eqn. (2)].[2] Similarly, it had been demonstrated earlier that another

$$\mathbf{1} + \mathrm{Nu}^{\cdot} \longrightarrow \mathrm{Nu{-}}\mathbf{1}^{\cdot} \qquad (2)$$

spin trap, 5,5-dimethyl-1-pyrroline-*N*-oxide (DMPO), can be oxidized to its radical cation in a low-temperature matrix and be converted into the hydroxyl spin adduct HO–DMPO$^{\cdot}$ by reaction with water.[3]

These results lend support to the idea that the formation of spin trap radical cations, *e.g.* $\mathbf{1}^{\cdot+}$, is a common phenomenon under oxidizing conditions and a possible cause of incorrect interpretation of the spin trapping method. If the nucleophile present (*e.g.* fluoride, acetate, pyridine, water) is more difficult to oxidize than the spin trap, it is likely that the spin trap radical cation–nucleophile reaction is the source of the spin adduct ('inverted spin trapping').[4–8] This is particularly significant in photochemical reactions where excited states can act as strong oxidants.



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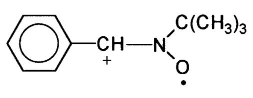
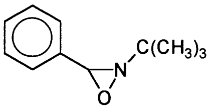


1$^{\bullet+}$



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It has been found recently that 1,1,1,3,3,3-hexafluoropropan-2-ol (HFP) is a superior solvent for radical cations by virtue of its high polarity, low nucleophilicity and exceptionally strong deactivating influence on nucleophile reactivity.[9] This means that radical cations often are 10–100 times more persistent in HFP than in trifluoroacetic acid, giving access to a far broader observation window for EPR spectroscopy.[10] Consequently, it is possible to detect and monitor radical cation intermediates in HFP during conventional aromatic substitution reactions, *e.g.* halogenation by bromine, chlorine or iodine chloride,[11] or nitration by nitrogen dioxide on a min-to-h timescale.[12]

In a study[8] of the possible occurrence of the inverted spin trapping reaction in HFP, initially we found no EPR spectral evidence of a species which could possibly be related to the presence of $\mathbf{1}^{\cdot+}$. However, during studies of the trinitromethyl radical adduct of **1**, it was found that the prolonged photolysis of tetranitromethane and **1** gave a weak EPR spectrum of six lines of equal intensity, $a_N = 1.95$ and $a_H = 2.79$ mT; similar treatment of α-deuteriated **1** (**3**) produced a triplet of triplets: $a_N = 2.03$ and $a_D = 0.428$ mT, the latter corresponding to $a_H = 0.428 \times 6.5 = 2.78$ mT. A small splitting (6–7 visible lines) of 0.053 mT possibly originating from coupling to a *tert*-butyl group was also resolvable. There is a literature report[13] that the anodic oxidation of **1** in aqueous medium produced a species

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† The IUPAC name for PBN is *N*-(α-benzylidene)*tert*-butylamine *N*-oxide.

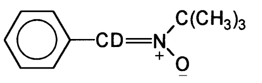
Table 1 Cyclic voltammetry of PBN (**1**), its α-deuteriated isotopomer **3**, various 4-substituted PBNs (**4**–**9**) and a few imine derivatives (**10**–**12**) in HFP–Bu_4NPF_6 (0.15 mol dm^{-3})

Compound	E_{rev}/V *vs.* Ag/AgCl	Sweep rate v/V s^{-1} above which reversibility appears (measured at v =)
PBN (**1**)	1.50	>20 (20)
[α-^{2}H]PBN (**3**)	1.49	>20 (20)
4-NO_2–PBN (**4**)	1.70 (E_{pa})	>50[a] (0.1)
4-F–PBN (**5**)	1.56 (E_{pa})	>50[a] (0.1)
4-CH_3–PBN (**6**)	1.40	>2 (2)
4-CH_3O–PBN (**7**)	1.20	(0.1)
3,4-(OCH_2O)PBN (**8**)	1.15	(0.1)
4-$(CH_3)_2N$–PBN (**9**)	0.68	(0.1)
Ph–CH=N–Bu^t (**10**)	2.95 (E_{pa})[b]	
4-$CH_3OC_6H_4$–CH=N–Bu^t (**11**)	2.08 (E_{pa})[b]	
4-$(CH_3)_2NC_6H_4$–CH=N–Bu^t (**12**)	1.20	>0.05 (0.1)
Ferrocene[c]	0.02	(0.1)
Fe^{III} tris(phenanthroline)[c]	1.00	(0.1)
Tris(4-bromophenyl)amine[c]	0.70	(0.1)

[a] Technical limit of the instrument. [b] Peak potential as determined by differential pulse voltammetry. [c] Included for reference purpose.

with a similar EPR spectrum, $a_N = 2.02$ and $a_H = 2.89$ mT, which was assigned initially to the hydroxyl spin adduct, HO-**1**$^•$, unknown at the time, and later to cyclic aminoxyl radicals of unspecified structure.[14]

With the improved possibilities to observe radical cations offered by HFP in mind, we have extended the EPR spectroscopic study of the unknown species described above to encompass a number of ring-substituted PBNs (**4**–**9**) in order to vary the electron availability in the phenyl ring (4-NO_2, 4-CH_3, 4-F, 4-MeO, 3,4-methylenedioxy, 4-Me_2N). Also the α-deuteriated isotopomer of PBN, **3**, was prepared and investigated. In view of recent evidence[1,15] that deoxidation of PBN to give *N*-*tert*-butyl-α-phenylimine (**10**) can take place under photolytic conditions, **10** and a few derivatives (**11**, **12**) were prepared and their redox and EPR spectroscopic properties examined. The radical cation of compound **10** has been studied by low temperature EPR spectroscopy.[16]



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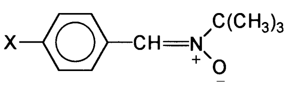
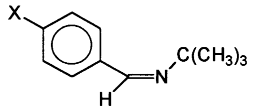


X = NO_2 **4**
X = F **5**
X = CH_3 **6**
X = CH_3O **7**
X = 3,4-OCH_2O **8**
X = $(CH_3)_2N$ **9**



X = H **10**
X = CH_3O **11**
X = $(CH_3)_2N$ **12**

Results

Cyclic voltammetry of PBN (1), its α-deuteriated isotopomer (3) and various 4-substituted PBNs (4–9)

In order to get an idea of the reactivity of the radical cations of PBNs in HFP, cyclic voltammetry (CV) was performed. By varying the sweep rate, the minimum sweep rate for obtaining reversibility was obtained (see Table 1). The PBN$^{•+}$–PBN couple became reversible in HFP at a sweep rate above 20 V s^{-1}, whereas substitution by a 4-methyl group enhanced the stability of the radical cation by a factor of *ca.* 10. With a good donor group in the 4-position (compounds **7**–**9**) reversibility was observed at low scan rates, indicating stability of the corresponding radical cations.

Cyclic voltammetry of imine derivatives 10–12

Cyclic voltammetry of *N*-*tert*-butyl-α-phenylimine **10** in HFP–Bu_4NPF_6 showed an elongated anodic wave merging into the background with E_{pa} around 3 V which was irreversible within the technical limit of the instrument. Differential pulse voltammetry (DPV) gave $E_{pa} = 2.95$ V. The 4-methoxy derivative **11** exhibited an irreversible redox couple with $E_{pa} = 2.08$ V, whereas the 4-dimethylamino derivative **12** showed a reversible couple at scan rates above 0.05 V s^{-1} with $E_{rev} = 1.20$ V.

Thus the imines **10**–**12** are oxidized at much higher potentials than the corresponding nitrones **1**, **7** and **9**. It is therefore unlikely that they could be the origin of EPR spectra detected in the oxidative reactions of nitrones.

EPR spectra from the oxidation of 1 or 3 in HFP

It was found previously[8] that the photolysis of the yellow charge transfer (CT) complex between **1** and tetranitromethane in HFP, using light of $\lambda > 430$ nm to excite solely the CT band, gave a weak signal of the trinitromethyl–**1** spin adduct. Prolonged UV irradiation of this solution destroyed the spin adduct spectrum and gave a new EPR spectrum with $a_N = 1.95$ and $a_H = 2.79$ mT. Further resolution was not possible due to the low intensity, but the line-width, $\Delta H_{pp} = 0.16$–0.18 mT, indicated further splitting. Similar treatment of [α-^{2}H]**1** (**3**) gave a triplet of triplets, $a_N = 2.03$ and $a_D = 0.428$ mT with $\Delta H_{pp} = 0.22$ mT; additionally a coupling constant of 0.052 mT, possibly to the hydrogens of the *tert*-butyl group, was detectable (Table 2).

The same spectrum could be obtained at higher intensity by photolysis of **1** ($\lambda > 430$ nm) with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) in HFP containing 6% of trifluoroacetic acid,[17] as shown in Fig. 1(*a*). The acid was added to suppress the concentration of the radical anion of DDQ (DDQ$^{•-}$), the signal of which otherwise dominated the EPR spectrum, and to drive the electron transfer (ET) reaction to the right. When the light was shut off, the DDQ$^{•-}$ signal disappeared within seconds whereas the 3 × 2 line spectrum persisted with a half-life of *ca.* 20 min. Similar behaviour was exhibited by **3** upon the same treatment [Fig. 1(*b*)].

Also dibenzoyl peroxide (BPO) could be used as an electron acceptor for photolysis (UV) of **1** in HFP–6% trifluoroacetic acid, giving rise to a medium strong signal of the 3 × 2 line spectrum. No signal due to PhCOO–PBN$^•$ appeared.

EPR spectra from the oxidation of 4-6 in HFP

Nitrones **4** and **5** both correspond to reactive radical cations

Table 2 EPR spectroscopy of species formed from PBN (**1**) or its α-deuteriated isotopomer **3** in HFP under oxidizing conditions. All runs were performed at 22 °C, unless otherwise stated

Compound	Method[a]	a_N (1 N)/mT	a_H (1 H)/mT	a_H (x H)/mT[b]
1	DDQ–6% TFA/$h\nu$ (> 430 nm) at 5 °C[c]	2.00	2.80	0.054
1	DDQ–6% TFA/$h\nu$ (> 430 nm)[c]	2.03	2.78	0.060[d]
1	BPO–6% TFA/$h\nu$ (UV)	1.99	2.82	*e*
1	TNM/$h\nu$ (UV)	1.95	2.79	*e*
3	TNM/$h\nu$ (UV)	2.03	0.428[f]	0.052
3	DDQ–6% TFA/$h\nu$ (> 430 nm)[c]	2.03	0.423[f]	*e,g*

[a] DDQ = 2,3-dichloro-5,6-dicyano-1,4-benzoquinone, TFA = trifluoroacetic acid, BPO = dibenzoyl peroxide, TNM = tetranitromethane, Tl^{III} = thallium(III) trifluoroacetate, Hg^{II} = mercury(II) trifluoroacetate. [b] Multiplicity x could not be assigned with certainty, but 5–7 lines were visible. [c] The signal of DDQ was also seen [a_N = 0.055 mT (2 N)]. [d] g value = 2.0051. [e] Not seen due to weak signal. [f] 1:1:1 triplet due to deuterium coupling. [g] g value = 2.0053.

Table 3 EPR spectroscopy of species formed from 4-NO_2– (**4**), 4-F– (**5**) and 4-Me–PBN (**6**) in HFP under oxidizing conditions. All runs were performed at 22 °C

Compound	Method[a]	a_N (1 N)/mT	a_H (1 H)/mT	a_H (x N)/mT	ΔH_{pp}/mT
4	TNM/$h\nu$ (UV)	1.51[a]	0.393	—	0.10
		1.95[b]	2.73	0.067	0.17[c]
4	DDQ–6% TFA/$h\nu$ (> 430 nm)[d]	—	—	—	
5	TNM/$h\nu$ (UV)	1.56	0.475	—	0.13
5	DDQ–6% TFA/$h\nu$ (> 430 nm)	2.01	2.77		0.15[e]
6	TNM/$h\nu$ (UV)	No signal seen			
6	DDQ–6% TFA/$h\nu$ (> 430 nm)	No signal seen			

[a] Initially formed signal, replaced by [b] after a while. [c] See text. [d] g value = 2.0051. [e] g value = 2.0048.

in view of their irreversible electrochemical behaviour (Table 1). UV irradiation of **4**–tetranitromethane in HFP initially produced a medium strong 3 × 2 line spectrum of a typical trinitromethyl spin adduct character (Table 3; in DCM[8] the coupling constants were $a_N = 1.45$, $a_H = 0.37$ mT); prolonged irradiation eventually replaced this spectrum with a 3 × 2 line spectrum of $a_N = 1.95$, $a_H = 2.73$ (1 H) and 0.067 (6–7 visible lines) mT, similar to the spectrum obtained from PBN under these conditions.

Irradiation by light of $\lambda > 430$ nm of **4** with DDQ in the presence of 6% trifluoroacetic acid led to a rapid sequence of events. After 30 s of irradiation a strong 3 × 2 line spectrum ($a_N = 1.39$, $a_H = 0.169$ mT) and an even stronger 3 × 1 line spectrum ($a_N = 0.765$ mT) were detectable; on continued irradiation, the former spectrum disappeared within 1–2 min, whereas the latter decayed over a longer period, *ca.* 30 min. No other spectrum appeared during this period. These spectra must correspond to the so far unknown trifluoroacetoxyl spin adduct of **4**,[18] formed either in an inverted spin trapping mechanism or the nucleophilic addition–oxidation mechanism of Forrester and Hepburn,[19] and the 4-nitrobenzoyl-*tert*-butylaminoxyl radical, formed by decomposition of the former radical.

UV irradiation of **5**–tetranitromethane in HFP produced a medium strong 3 × 2 line spectrum of a typical trinitromethyl spin adduct (Table 3; in DCM[8] the coupling constants were $a_N = 1.46$, $a_H = 0.41$ mT); prolonged irradiation did not give any further spectrum. Irradiation by light of $\lambda > 430$ nm of **5** with DDQ in the presence of 6% trifluoroacetic acid produced a weak spectrum of the same type as from PBN itself, $a_N = 2.01$ and $a_H = 2.77$ mT; the lines were broad (0.15 mT), but no further resolution could be achieved.

For nitrone **6** it would be expected from the CV results that its radical cation would be more stable than that of **1**. Yet, no EPR signal was detectable from oxidation by TNM/$h\nu$ ($\lambda > 430$ nm) or DDQ–6% trifluoroacetic acid/$h\nu$ ($\lambda > 430$ nm).

The results from the oxidation of **4**–**6** are summarized in Table 3.

EPR spectra from the oxidation of 1 and 3–6 in HFP in the presence of 2-methylpropene or a source of 2-methylpropene (*tert*-butyl alcohol)

The common denominator of the behaviour of **1**, **3**–**5** upon oxidation in HFP is the slow formation of a species with a spectrum of $a_N \approx 2.0$ mT and $a_H \approx 2.8$ mT, exemplified in Fig. 1 by oxidation of PBN. An important property of nitrones is their 1,3-dipolar reactivity toward alkenes which has been extensively exploited for the synthesis of isoxazolidines.[20] A source of alkene in the systems studied here could be the *tert*-butyl group which might split off as *tert*-butyl cation from the radical cation of the spin trap, as exemplified by PBN in eqn. (3). Proton abstraction from Bu^{t+} would give 2-methylpropene which upon addition to PBN would give 2-*tert*-butyl-3-phenyl-5,5-dimethylisoxazolidine [**14**, eqn. (4)]. Such a compound should be easily oxidizable and give a persistent radical cation

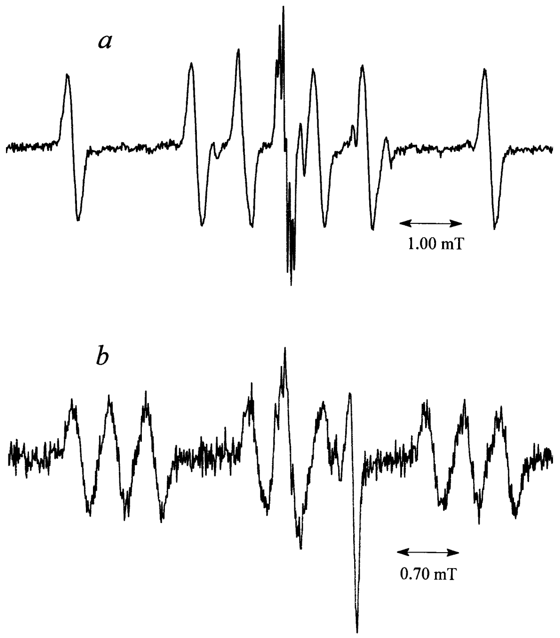


Fig. 1 EPR spectrum recorded from an irradiated solution (~ 20 min, light of $\lambda > 430$ nm) of (*a*) **1** or (*b*) **3** (80 mmol dm^{-3}) and DDQ (40 mmol dm^{-3}) in HFP–6% trifluoroacetic acid at 22 °C. In (*a*) 50 spectra were accumulated during the irradiation period. The central signal is the quintet of $DDQ^{\bullet -}$. In (*b*) 50 spectra were accumulated after the irradiation period to avoid the $DDQ^{\bullet -}$ signal.

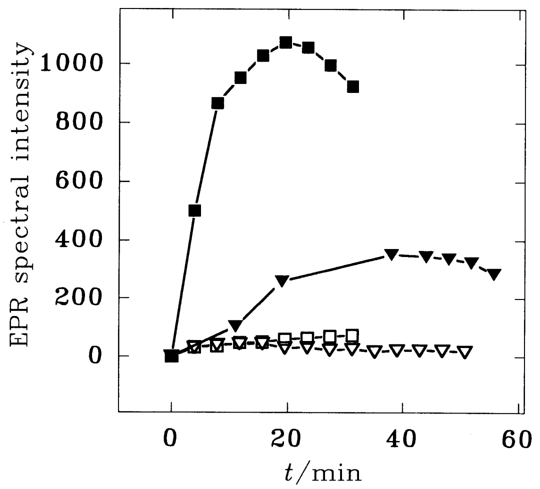
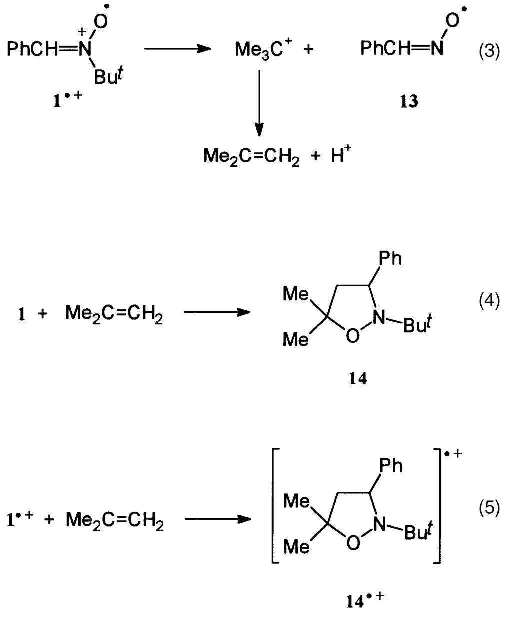


Fig. 2 EPR spectral intensities (leftmost line of 2.0/2.8 mT spectrum) recorded *vs.* time during irradiation (light of $\lambda > 430$ nm) of a solution of **1** (80 mmol dm^{-3}), DDQ (40 mmol dm^{-3}) and acid in HFP at 22 °C with or without Bu^{t}OH present. ▼: trifluoroacetic acid (6%), 0.35 mol dm^{-3}, Bu^{t}OH; ▽: trifluoroacetic acid (6%), no Bu^{t}OH added; ■: methanesulfonic acid (1.5%), 0.35 mol dm^{-3}, Bu^{t}OH; □: methanesulfonic acid (1.5%), no Bu^{t}OH added.

$14^{•+}$ under the prevailing conditions. Another possibility is that the cycloaddition reaction takes place directly between $1^{•+}$ and 2-methylpropene, directly giving $14^{•+}$; radical cation mediated cycloaddition reactions are well known in other systems[21] [eqn. (5)].



In order to provide an additional source of *tert*-butyl cation in the photolysis experiment of Fig. 1(*a*), *tert*-butyl alcohol (0.35 mol dm^{-3}) was added. Photolysis with light of $\lambda > 430$ nm led to the rapid development of the 2.0/2.8 mT spectrum, now considerably more intense than in Fig. 1(*a*). Fig. 2 (triangles) shows the development of the signal intensity in the absence and presence of Bu^{t}OH; in experiments where methanesulfonic acid was used as the acidic component, the effect was even more pronounced (Fig. 2, squares). The improved quality of the spectrum (Fig. 3) made possible the complete resolution of the major lines which in fact showed coupling to six hydrogens in two groups of slightly different coupling constants. This feature agrees well with what is expected from $14^{•+}$ where the 5-methyl groups are non-equivalent. In an experiment with fully deuteriated Bu^{t}OH, the small hydrogen splittings disappeared and ΔH_{pp} decreased from 0.18 to 0.061 mT.

Table 4 EPR spectra of species formed from PBN (**1**), [α-^{2}H]PBN (**3**), 4-NO$_2$- (**4**), 4-F- (**5**) and 4-Me-PBN (**6**) in HFP–6% trifluoroacetic acid upon oxidation with DDQ/*hν* ($\lambda > 430$ nm) in the presence of Bu^{t}OH (0.35 mol dm^{-3}), unless otherwise stated. All runs were performed at 22 °C

Compound	a_N (1 N)/mT	a_H (1 H)/mT	a_H (3 H)/mT	a_H (3 H)/mT
1	2.01	2.76	0.076	0.054
1[a]	2.02	2.77	*b*	*b*
1[c]	1.98	2.74	0.077	0.047
3	2.01	0.419[d]	0.076	0.054
4	1.99	2.66		
5	2.02	2.77	0.076	0.054
6	1.99	2.76		

[a] Run with [^{2}H$_{10}$]Bu^{t}OH. [b] Not resolvable. [c] Run with 2-methylpropene. [d] 1:1:1 triplet due to deuterium coupling.

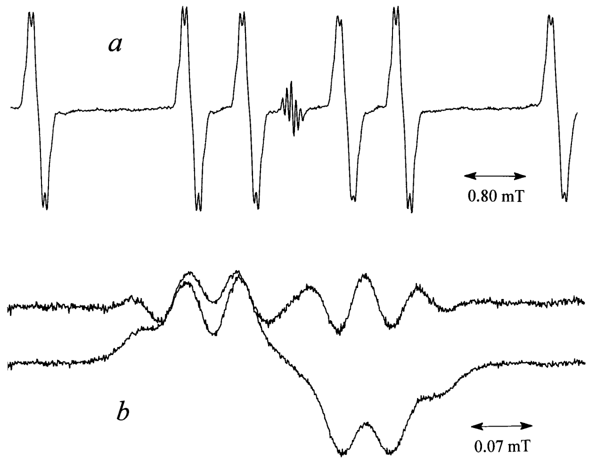


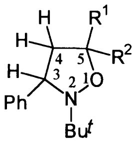
Fig. 3 EPR spectrum recorded from an irradiated solution (*ca.* 4 min, light of $\lambda > 430$ nm) of (*a*) **1** (80 mmol dm^{-3}), DDQ (40 mmol dm^{-3}) and Bu^{t}OH (0.35 mol dm^{-3}) in HFP–1.5% methanesulfonic acid at 22 °C. Ten spectra were accumulated during the irradiation period. The central signal is the quintet of DDQ$^{•-}$. In (*b*) a spectrum of the second line from the left is shown in expanded form, before (lower trace) and after a forward-back Fourier transformation.

Experiments with 2-methylpropene (concentration *ca.* 0.1 or 0.5 mol dm^{-3}) gave a very strong 2.0/2.8 mT spectrum, but with the spectrum of the isoxazolidine of the 2-methylpropene dimer [1-methyl-1-neopentylethylene, $a_N = 1.96$, $a_H = 1.51$ (1 H), $a_H = 0.86$ mT; see below] superimposed. In combination with an acid, HFP should favour the formation of carbocations from alkenes,[22] and thus dimerize 2-methylpropene *via tert*-butyl cation under conditions where 2-methylpropene is present initially in a relatively high concentration. When Bu^{t}OH is the source of 2-methylpropene, the latter is present in a very low equilibrium concentration and thus the second-order dimerization reaction is much slower. We therefore used Bu^{t}OH instead of 2-methylpropene in the experiments described below.

The same reaction applied to **4** and **5** with Bu^{t}OH as the 2-methylpropene source gave much improved 2.0/2.8 mT spectra of similar structure (Table 4). Even **6**, which did not give any such spectrum in the absence of Bu^{t}OH gave rise to a weak spectrum.

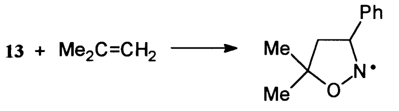
There is also the possibility that the iminoxyl radical **13** might add to 2-methylpropene and give the neutral *N*-centred radical **15** of eqn. (6) and that this species might correspond to the 2.0/2.8 mT spectrum. When *syn*-benzaldoxime was photolysed with Bu^{t}OH, trifluoroacetic acid and DDQ in HFP, conditions which should be favourable for the generation of **15**, no EPR spectrum developed (50 accumulations) during irradiation for 20 min, indicating that the reaction of eqn. (6) is not feasible.

Table 5 EPR spectra of the predominant isomer of isoxazolidine radical cations formed from PBN (**1**) in HFP–6% trifluoroacetic acid upon oxidation with DDQ/$h\nu$ (λ > 430 nm) in the presence of alkenes (0.35 mol dm^{-3}). The small coupling constants (< 0.06 mT) to hydrogens in the 5-alkyl groups have been left out. All runs were performed at 22 °C. The numbering system is as shown:



Alkyl groups in ethylene	a_{N2} (1 N)/mT	a_{H3} (1 H)/mT	a_{H4} (1 H)/mT	a_{H5} (1 H)/mT
1,1-Me$_2$	2.01	2.76	—	—
1-Me-1-CH$_2$OH	2.02	2.68	0.346	—
1-Me-1-Bu^{t}CH$_2$	1.97	1.51	0.85	—
Bu	1.99	1.61	0.33	0.80
Pentyl[a]	1.99	1.58	0.70 (—)[b]	— (0.70)[b]
Pentyl[a]	1.97	1.63	0.32	0.80

[a] Two isomers were discernible in a ratio of *ca.* 2:1. [b] Cannot be assigned presently.



(6)

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Fig. 4 EPR spectrum recorded from an irradiated solution (*ca.* 2 min, light of λ > 430 nm) of **1** (80 mmol dm^{-3}), DDQ (40 mmol dm^{-3}) and hex-1-ene (0.3 mol dm^{-3}) in HFP–6% trifluoroacetic acid at 22 °C. Five spectra were accumulated during the irradiation period.

EPR spectra from the oxidation of 1 in HFP in the presence of some alkenes

The fact that 2-methylpropene, or a source of 2-methylpropene could significantly increase the concentration of the 2.0/2.8 mT species, in combination with its structural assignment as **14**$^{\cdot+}$, suggested that other alkenes might react to give isoxazolidine radical cations as well. Experiments with PBN of the same type as above, in which Bu^{t}OH had been replaced by an alkene, showed this assumption to be correct, although the choice of alkenes was somewhat restricted due to incompatibility with the combination acid–HFP (styrene, limonene; *cf.* also 2-methylpropene above) or limited persistency of the radical cation to be formed (acrylonitrile, hex-1-yne). Table 5 shows EPR spectral data for spectra obtained from those of the alkenes tried where the coupling constants could be assigned with certainty, including the spectrum obtained from the dimer of 2-methylpropene (1-methyl-1-neopentylethylene, see above). Fig. 4 shows the spectrum recorded in the presence of hex-1-ene where one isomer was predominant. The use of [α-^{2}H]PBN gave the spectrum predicted for $a_{^2H_3}$ = 1.61/6.5 = 0.248 mT. It should be recalled that a monosubstituted ethylene can give four isomers (4- or 5-alkyl group, *cis*- or *trans*-isomers); also it is probable that the particular oxidation method used here might not be suited for all types of isoxazolidines.

EPR spectra from the oxidation of 7–9 in HFP

According to CV data (Table 1), the radical cations of nitrones **7**–**9** should be relatively stable species, especially that of **9**, due to the introduction of the electron-donating 4-substituent which will increase the possibility of delocalizing spin density and charge into the aryl group.

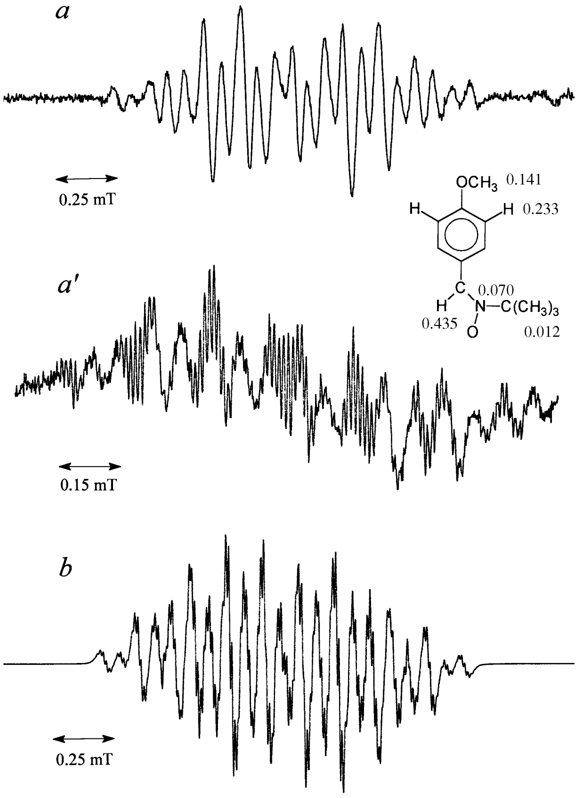


Fig. 5 EPR spectrum recorded from a solution of **7** (50 mmol dm^{-3}) and Tl^{III} trifluoroacetate (15 mmol dm^{-3}) in HFP at 22 °C. (*a*) At a modulation amplitude of 0.03 mT. (*a′*) At a modulation amplitude of 0.005 mT. (*b*) Simulated spectrum (Lorentzian line-shape, 0.020 mT), using the hfs constants shown.

In agreement with this expectation, the 4-methoxy compound **7** upon oxidation by 4-tolyl-Tl^{III} bis(trifluoroacetate) or Tl^{III} tris(trifluoroacetate) in HFP[10] gave a multiline EPR spectrum [Fig. 5(*a*) and 5(*a′*)] with hfs constants as shown. A simulation of the spectrum is shown in Fig. 5(*b*). No spectrum of 2.0/2.8 mT type was obtained upon oxidation by DDQ–6% trifluoroacetic acid/$h\nu$ (> 430 nm); only the signal of DDQ$^{\cdot-}$ was seen.

Compound **8** was included both because of its electron-donating substituent and the property of the methylenedioxy group to have a sizeable hfs constant in radical cations (*ca.* 2.2 mT in unsubstituted methylenedioxybenzene).[23] A disadvantage of this group is its tendency to ring-open readily under oxidizing conditions, presumably at the radical cation level.[10] Oxidation of **8** by Tl^{III} tris(trifluoroacetate) in HFP produced

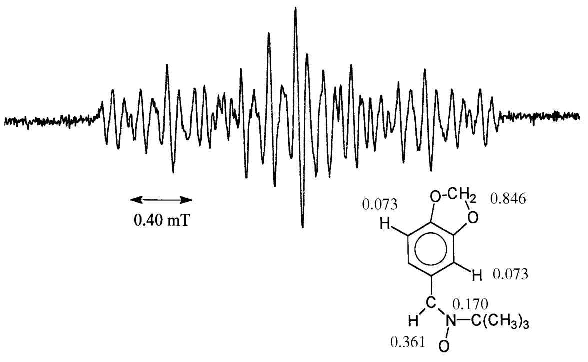


Fig. 6 EPR spectrum recorded from a solution of **8** (50 mmol dm^{-3}) and Tl^{III} trifluoroacetate (15 mmol dm^{-3}) in HFP at 22 °C

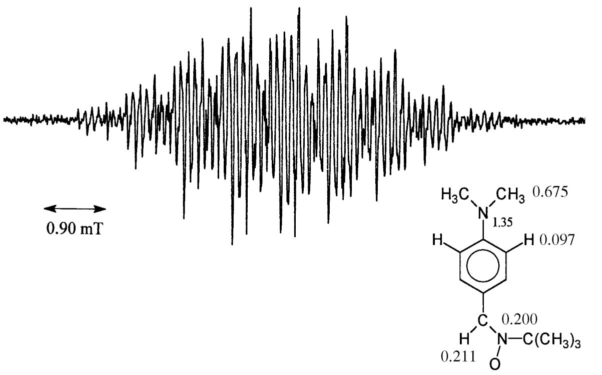


Fig. 7 EPR spectrum recorded from a solution of **9** (10 mmol dm^{-3}) and Fe^{III}(phenanthroline)$_3$(PF$_6$)$_3$ (15 mmol dm^{-3}) in HFP at 22 °C

the EPR spectrum shown in Fig. 6, possessing one large coupling constant to two hydrogens and accordingly assigned to **8**$^{\cdot+}$. No spectrum of 2.0/2.8 mT type was obtained upon oxidation by DDQ–6% trifluoroacetic acid/*hν* (> 430 nm).

The 4-dimethylamino-derivative **9** was easily oxidizable according to the CV results, and hence the persistent EPR spectrum of **9**$^{\cdot+}$ (Fig. 7) could be obtained by treatment with low-potential one-electron oxidants like iron(III) phenanthroline (E_{rev} in HFP = 1.00 V *vs.* Ag/AgCl) (see Table 1) and tris(4-bromophenylaminium) (E_{rev} 0.70 in HFP 0.70 V *vs.* Ag/AgCl). Oxidation by tetranitromethane/*hν* (λ > 430 nm) or DDQ–6% trifluoroacetic acid (thermally) gave the same spectrum as in Fig. 7. In view of the mild conditions used for the generation of this spectrum, it is assigned to **9**$^{\cdot+}$ with coupling constants as given in Fig. 7.

For comparison, the EPR spectrum of 4-dimethylaminobenzaldehyde was recorded in HFP by Tl^{III} oxidation. It has been described earlier,[24] the radical cation being generated by Ce^{IV} oxidation in aqueous medium under flow conditions, $a_N = 1.09$, $a_{CH_3} = 1.27$ (6 H), $a_{H2} = 0.54$ (2 H), $a_{H3} = 0.18$ mT (2 H). The spectrum in HFP was similar: $a_N = 1.09$, $a_{CH_3} = 1.23$ (6 H), $a_{H2} = 0.56$, $a_{H3} = 0.197$ mT. This spectrum thus has similar features to that of **9**$^{\cdot+}$, a large coupling to the ring nitrogen and a small one to the α-CH (actually none). CV of 4-dimethylaminobenzaldehyde in HFP–Bu$_4$NPF$_6$ showed reversible behaviour at low sweep rates, $E_{rev} = 0.94$ V *vs.* Ag/AgCl.

Attempts to record EPR spectra from the oxidation of 10–12

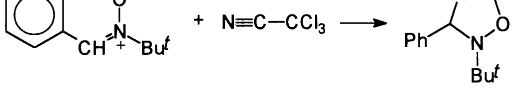
As shown by their electrochemical properties, the imines **10** and **11** are difficult to oxidize and therefore **10**$^{\cdot+}$ or **11**$^{\cdot+}$ should not be credible candidates for the EPR spectra recorded from the oxidation of the corresponding nitrones **1** or **7**. No EPR activity was noticeable from **10** or **11** under any of the conditions used for oxidation of the nitrones. Even for imine **12**, where CV indicated some degree of radical cation stability, no EPR spectrum was obtainable under the conditions used for the oxidation of nitrone **9**.

Discussion

As seen from Fig. 1 and Tables 2 and 3, PBN as well as its 4-nitro- and 4-F-derivatives upon photooxidation give a species with an EPR spectrum with a_H ~ 2.8 and a_N ~ 2.0 mT. The spectrum of [α-^{2}H]PBN (**3**) responds in the expected way to the isotopic substitution, whereas the 4-methyl compound did not give any EPR spectrum. Still more redox active PBNs (**7**–**9**) give radical cations where charge and spin density are delocalized into the ring system.

The reaction exemplified by PBN$^{\cdot+}$ in eqn. (3) provides a consistent explanation for the observations summarized above. The radical cations of PBN and PBNs substituted by electron-withdrawing groups (F, NO$_2$) cannot delocalize charge into the ring and thus undergo de-*tert*-butylation to give *tert*-butyl cation and the aryloximinyl radical [**13** from PBN; eqn. (3)]. In **7**$^{\cdot+}$–**9**$^{\cdot+}$ delocalization into the ring is possible and thus the radical cations are stable with respect to this reaction mode. The 4-methyl-substituted PBN **6** occupies an intermediate position. The fact that photolysis in the presence of a source of 2-methylpropene (Bu^{t}OH–acid) strongly increases the intensity of the 2.0/2.8 mT spectra and the resulting assignment of the 0.05–0.08 mT coupling to two slightly different methyl groups (Table 4) supports the radical cation of a cycloadduct being responsible for the 2.0/2.8 mT spectrum. As exemplified by PBN in eqn. (4), the cycloadduct **14** is suggested to be formed from PBN and 2-methylpropene [eqn. (4)], but we cannot rule out that the reaction occurs between 2-methylpropene and PBN$^{\cdot+}$ [eqn. (5)] to give **14**$^{\cdot+}$ directly, nor that photochemical assistance is necessary. The alternative, formation of radical **15** through eqn. (6), was ruled out by the negative result obtained with *syn*-benzaldoxime as substrate for photooxidation in the presence of Bu^{t}OH. The formation of radical cations with similar characteristics ($a_N \approx 2$ mT, a_{H3} 1.5–2.7 mT) when the oxidation was carried in the presence of other alkenes (Table 5 and Fig. 4) supports further the assumption of isoxazolidine formation.

The finding that isoxazolidines can be converted to relatively persistent radical cations in HFP is of some interest. At least the radical cations of the alkyl-substituted derivatives have life-times long enough in HFP for their EPR spectra to be recorded, but we are convinced that better suited oxidation procedures on purified isomers will give good possibilities for EPR spectroscopy on a range of isoxazolidine radical cations. To the best of our knowledge, the redox properties of this class of compounds has not been studied before, but should offer interesting problems. Also the finding that nitrones can engage in cycloaddition is of some concern in spin trapping chemistry. It was recently[25] shown that PBN reacts with cyanohalocarbons to give cycloaddition products, isoxadiazoles, as exemplified by trichloroacetonitrile [eqn. (7)]. In this



(7)

particular case, no EPR activity was recorded from the radical cation of the cycloaddition product, presumably because it should be much more difficult to oxidize than for example isoxazolidine **14** and besides, the conditions for its generation were not optimal.

Experimental

Materials

PBN (**1**) and 4-NO_2-PBN (**4**) were from Aldrich, whereas its derivatives **3**–**7** were available from an earlier study.[8] Compounds **8**–**12** were prepared according to literature procedures.[26–28] Solvents were of Merck UVASOL quality. Tl^{III} trifluoroacetate and DDQ were from Merck. All other chemicals were of highest commercial quality available.

Instrumental methods

The electrochemical and EPR spectroscopic equipment has been described before.[8] EPR spectra were recorded in 1 mm quartz tubes (100 kHz modulation frequency at an amplitude of 0.005–0.08 mT, microwave effect 0.4–1.6 mW), and irradiation was performed by the 50 W high-pressure Hg lamp from Bruker (ER 202) with a filter with cutoff at 430 nm.

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