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Electron paramagnetic resonance studies on the generation and solvation of n-heptafluoropropyl t-butyl nitroxide

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Abstract

n-Heptafluoropropyl t-butyl nitroxide (**3**) has been generated by the use of the electron-transfer reaction of *O*-benzoyl-N-t-butylhydroxylamine (**1**) and heptafluorobutyryl peroxide (**2**) in $CFCl_2CF_2Cl$ solution. Electron paramagnetic resonance (EPR) measurements of a_N and a_F^β values for **3** in 25 solvents have been carried out at 25 ± 2 °C. The a_N values for **3** in 16 aprotic solvents (but not in t-BuOH and acetone) show a linear correlation with the cybotactic solvent parameters E_T and Z (Kosower constant) i.e. $a_N = 3.60 \times 10^{-2} E_T + 10.25$ and $a_N = 1.56 \times 10^{-2} Z + 10.66$. The physical significance for the slope, (slope $\times E_T$) or (slope $\times Z$), and the extrapolated intercept on the a_N axis is linked to the sensitivity of the nitroxide toward solvation, the magnitude of the overall solvation effect on the a_N values and the intrinsic a_N value of **3** in the ideal gaseous state, respectively. It is believed that the virtually constant value of a_N (11.56–11.61 G) for **3** in alcohols and carboxylic acids is caused by H-bond formation between **3** and the solvents.

Introduction

The solvent dependencies of a_N values, g factors and line widths are well-established for some bulky and stable di-t-alkyl nitroxides such as di-t-butyl nitroxide and TEMPO [1]. However, the unhindered, rather unstable di-n-alkyl and di-s-alkyl nitroxides have never been subjected to solvation studies.

In the last few years, a large number of fluorinated nitroxides with a wide variety of structures have been generated and subjected to extensive studies [2] in our laboratories. Of the fluorinated nitroxides, $R_fN(O\cdot)Bu^t$ are much less hindered, with no β-H atoms and being subject to extrastabilization by a capto-dative effect [3]. They have been found to be sufficiently stable to enable EPR determination in various solvents.

Following our EPR study on the nitroxide $CF_3N(O\cdot)Bu^t$ in 16 solvents [4], we now report our results for the higher homolog n-$C_3F_7N(O\cdot)Bu^t$ (**3**) in 25 solvents.

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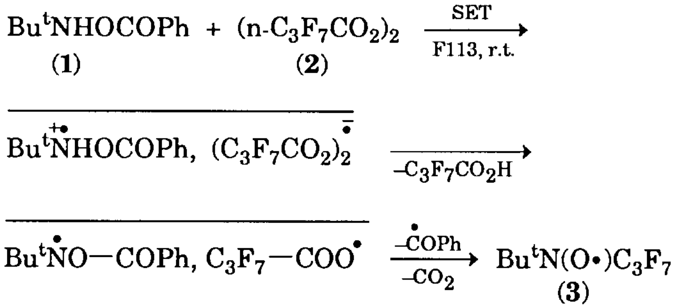
Results and discussion

Heptafluoropropyl t-butyl nitroxide (**3**) was generated via the electron-transfer reaction between *O*-benzoyl-*N*-t-butylhydroxylamine (**1**) and heptafluorobutyryl peroxide (**2**) in F113 ($CFCl_2CF_2Cl$) solution at room temperature. We have suggested the mechanism to be as follows [5]:



$$\underset{(\mathbf{1})}{\mathrm{Bu^tNHOCOPh}} + \underset{(\mathbf{2})}{(\mathrm{n\text{-}C_3F_7CO_2})_2} \xrightarrow[\text{F113, r.t.}]{\text{SET}}$$

$$\overline{\overset{+\bullet}{\mathrm{Bu^tNHOCOPh}}, (\mathrm{C_3F_7CO_2})_2^{\bullet-}} \xrightarrow[-\mathrm{C_3F_7CO_2H}]{}$$

$$\overline{\mathrm{Bu^t\dot{N}O{-}COPh, C_3F_7{-}COO^{\bullet}}} \xrightarrow[-\mathrm{CO_2}]{-\mathrm{\dot{C}OPh}} \underset{(\mathbf{3})}{\mathrm{Bu^tN(O\bullet)C_3F_7}}$$

Scheme 1.

The nitroxide **3** prepared in this way was found to be sufficiently pure and stable for EPR determination in selected solvents at room temperature. The EPR spectra of **3** in some of these solvents are shown in Fig. 1. EPR parameters determined in all the solvents are listed in Table 1.

The table shows an increase in the a_N values with an increase in the polarity of the 15 aprotic solvents plus Bu^tOH and acetone. Among the many sets of solvent polarity parameters, some cybotactic parameters such as E_T values (Dimroth [6]) and Z constants (Kosower [7]) have been found to be linearly correlated with the a_N values (Figs. 2 and 3). The a_N versus E_T and a_N versus Z correlation equations are well established as:

$$a_N = 3.60 \times 10^{-2} E_T + 10.25 \ (r = 0.987)$$

$$a_N = 1.56 \times 10^{-2} Z + 10.66 \ (r = 0.995)$$

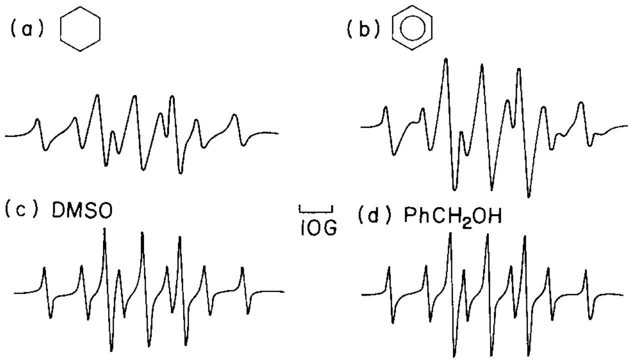


Fig. 1. EPR spectra of nitroxide **3** in some representative solvents. (a) Cyclohexane; (b) benzene; (c) DMSO; (d) benzyl alcohol.

TABLE 1

EPR parameters of nitroxide **3** in various solvents at 25±2 °C (±0.02 G)

Solvent	E_T (kcal mol^{-1})	Z (kcal mol^{-1})	a_N (G)	a_F^β (G)	ρ_N
n-hexane	30.9		11.34	19.68	0.343
c-hexane	31.2		11.36	19.18	0.343
tetrachloroethylene	31.9		11.37	19.06	0.344
carbon tetrachloride	32.5		11.41	19.04	0.345
n-butyl ether	33.4	60.1	11.47	19.32	0.347
benzene	34.5	54.0	11.51	19.18	0.348
ether	34.6		11.52	18.97	0.348
trichloroethylene	35.9		11.58	18.75	0.350
dioxan	36.0		11.58	19.06	0.350
tetrahydrofuran	37.4	58.8	11.52	19.40	0.348
chlorobenzene	37.5	58.0	11.60	19.02	0.350
chloroform	39.1	63.2	11.69	18.60	0.353
dichloromethane	41.1	64.7	11.70	18.50	0.353
acetone	42.2	65.5	11.74	19.25	0.355
t-butyl alcohol	43.9	71.3	11.66	19.04	0.352
dimethyl sulfoxide	45.0	71.1	11.64	19.14	0.352
i-butyl alcohol	47.1	78.05	11.57	19.06	0.350
i-propyl alcohol	48.6	76.3	11.56	19.04	0.349
n-butyl alcohol	50.2	77.7			
benzylic alcohol	50.8		11.56	19.00	0.349
acetic acid	51.2	78.6	11.59	18.99	0.350
ethanol	51.9	79.6	11.61	19.24	0.351
glycol	53.8		11.61	18.96	0.352
methanol	55.5	83.6	11.59	19.02	0.350

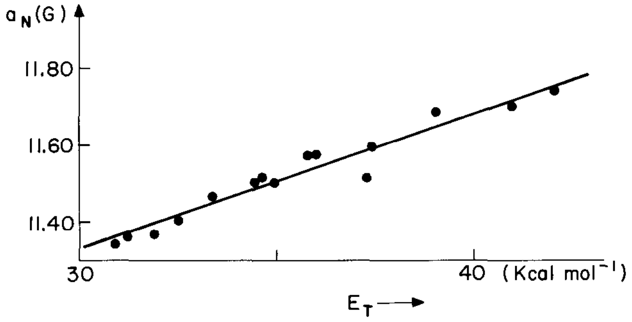


Fig. 2. Linear correlation between a_N (G) for **3** and solvent polarity parameter E_T (kcal mol^{-1}).

However, no correlation has been found between a_N values and the constants characterizing the non-cybotactic properties of solvents, such as dipole moment and dielectric constant (see Figs. 4 and 5).

The solvation of nitroxides must involve dispersion forces as well as dipole–dipole interactions. However, electron-pair donor–electron-pair acceptor interactions (EPD–EPA) between nitroxide and solvent molecules

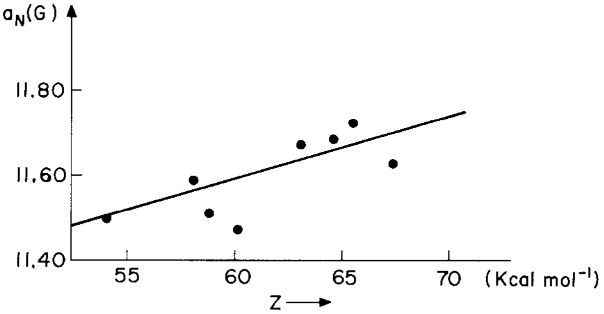


Fig. 3. Linear correlation between a_N (G) for **3** and solvent polarity parameter Z (kcal mol^{-1}).

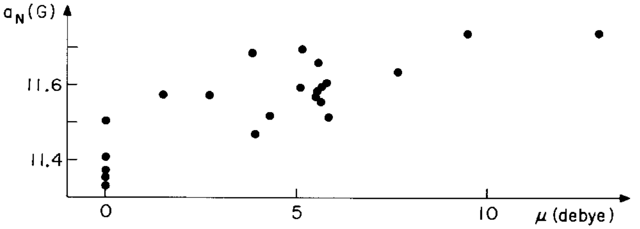


Fig. 4. Plot of a_N values for **3** versus solvent dipole moment μ.

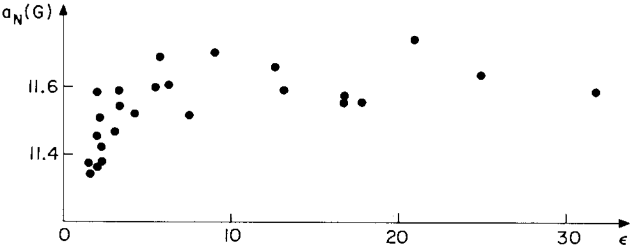
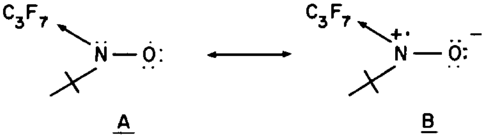


Fig. 5. Plot of a_N values for **3** versus solvent dielectric constant ϵ.

have usually proved to be the predominant factors [8]. We may use the canonical structures **A** and **B** to show schematically the spin delocalization on to the nitroxyl N and O atoms in nitroxide **3** [9] (Scheme 2):



Scheme 2.

The strongly electron-withdrawing n-C_3F_7 group attracts the lone pair of electrons from the N atom, reducing significantly the resonance interaction between the lone pair and the spin, and hence decreasing the spin density on the N atom (for example, $\rho_N = 0.37$ in F113) and thus causing a remarkable smaller a_N value (12.1 G in F113) compared to the a_N value for di-t-butyl nitroxide (15.1 G in the same solvent). Hence, for the fluorinated nitroxide **3** the contribution of structure **A** becomes much important than that of structure **B**, and the spin is largely localized on the O atom ($\rho_O \sim 0.63$). As a result, nitroxide **3** functions mainly as an oxygen radical and has been found to be reactive in H-abstraction and oxidation reactions [10]. If $A \leftarrow D$ depicts a molecule of all the solvents studied, the interaction of $A \leftarrow D$ with nitroxide **3** may be illustrated as follows:

Scheme 3.

As shown in Scheme 3, the solvent dipole $A \leftarrow D$ may orient in opposite directions towards the canonical structures **A** and **B**. The electronically dative end D bearing a partial positive charge would be capable of a close approach to the N atom of the nitroxide bearing a lone pair of electrons [$A \leftarrow D \leftarrow - - -$ **A**] and thus reduce the spin delocalization onto the N atom resulting in a decrease in the a_N values. In contrast, the capto end A bearing a $\delta -$ charge would preferably attract the positively charged N atom in structure **B** as depicted by $D \rightarrow A - - - \rightarrow$ **B** and cause an increase in the spin density on the N atom (increase of a_N value).

Highly polar aprotic solvents may favor the contribution of **B** and cause an increase in a_N. The net increase in the a_N values is proportional to the E_T value and Z (Kosower) constant of the solvent:

$$a_N = bE_T(\text{or } Z) + C$$

The slope b indicates the susceptibility of the nitroxide towards solvation. It is characteristic of a specific nitroxide dissolved in certain kinds of solvents. The term bE_T (or bZ) measures the net increase of the a_N value due to solvation in a specific solvent. For example, in DMSO ($E_T = 45.0$, $Z = 71.1$), the highest polar solvent among those listed in Table 1, the net increase in the a_N value is $\Delta a_N = 3.60 \times 10^{-2} \times 45.0 = 1.62$ G or $\Delta a_N = 1.56 \times 10^{-2} \times 71.1 = 1.11$ G.

The extrapolated interception C on the a_N axis ($E_T \rightarrow 0$, $Z \rightarrow 0$) may indicate the coherent a_N value of a specific nitroxide in the gas phase under standard conditions. The constant C (with unit G value) should be a function of the coherent electronic and geometrical structures of a specific nitroxide in the absence of solvation perturbation.

By comparison of the C constants of $RN(O\cdot)Bu^t$ homologs ($R_f = CF_3$, C_2F_5, C_3F_7, etc.), we have found the order of the coherent electronegativity values of the perfluoroalkyl groups to be: $CF_3 < C_2F_5 < C_3F_7 \sim n\text{-}C_7F_{15}$ [11].

We believe that this newly established electronegativity order will be theoretically important to physical organic chemists.

Finally, it is worth pointing out that nitroxide **3** exhibits almost constant a_N values (11.56–11.61 G) in simple alcohols (MeOH, EtOH, Pr^iOH, Bu^nOH, Bu^iOH, $PhCH_2OH$; Bu^tOH is an exception), diols (such as $HOCH_2CH_2OH$) and carboxylic acids (such as CH_3CO_2H) under the same conditions. The significant change in E_T values for these protic solvents (from 47.1 for Bu^iOH to 55.5 for MeOH) does not affect the solvation state of nitroxide **3**. The constancy of this a_N value is believed to be caused by H-bond formation between the nitroxyl oxygen and the OH group of the alcohol and carboxylic acid, since H-bonding interaction is usually much stronger than EPD–EPA which is not exhibited by the systems.

Further experimental and theoretical studies on solvation of fluorinated nitroxides are being conducted.

Experimental

Preparation of $Bu^tNHOCOPh$ (1)

In a typical procedure, 6.05 g (25 mmol) of recrystallized benzoyl peroxide was dissolved in 35 ml dry benzene in a N_2-flushed 100 ml flask equipped with a dropping funnel containing 10 ml of a solution of 3.05 g (50 mmol) Bu^tNH_2 in benzene. With magnetic stirring and cooling in an ice-water bath, the amine solution was added over a period of 30 min, the mixture was warmed up to 40 °C and maintained there for 30 min. After adding 20 ml ether, the mixture was filtered and the pale-blue solution washed with $FeSO_4$ (aq.) solution, acidified with H_2SO_4 several times, then washed with distilled water twice. The solvent was removed under vacuum to give an oily yellow liquid. After chromatographic purification on a silica gel column with petroleum ether/ether (4:1) as eluent, 3.7 g (yield 77%) of **1** as a colorless liquid was obtained. The pure liquid was dissolved in dry ether and kept in a cool place under N_2 in the dark.

Characterization of **1**: MS *m/e*: 194 (M + 1, 100%); 105 (86%); 77 (10%). IR(l) (liquid) (cm^{-1}): 3300 (s) (N–H); 2980 (m) (C–H); 1720 (s) (C–O); 1270 (s); 710 (phenyl). ^1H NMR δ: 7.9–8.2 (m, 3H); 7.75 (s, 1H, D_2O-exchangeable); 7.3–7.6 (m, 3H); and 1.20 (s, 9H) ppm. UV (MeOH) λ_{max} (nm): 230.5 ($\epsilon = 8.30 \times 10^3$); 202.0 ($\epsilon = 4.83 \times 10^3$).

Preparation of nitroxide 3

$Bu^tNHOCOPh$ (**1**) (0.303 g, 1.57 mmol) was dropped into **2** (0.669 g, 1.57 mmol) in F113 (6.0 ml) (molar ratio 1:1) with stirring at room temperature under N_2, filtered, and washed twice with distilled water, concentrated to F113 (3 ml) and dried over anhydrous Na_2SO_4. It was kept under nitrogen in a refrigerator for use within 2 d. The EPR spectra showed good purity as required for further studies.

EPR determination

About 0.01 ml of a concentrated F113 solution of **2** was transferred through a stainless-steel syringe into each of the N_2-flushed EPR tubes containing about 0.30 ml of solvent. After shaking, the tube was inserted into the cavity and the spectra at 25 ± 2 °C were recorded by a JEOL JEX-FEIXG EPR spectrometer. The conditions employed were: field, 3270 G; modulation frequency, 100 kHz; modulation amplitude, 0.1–1.0 G; frequency, 9.17 GHz (X band); power, 0.5–30 mW; time constant, 0.128–0.5 s; scan range, 100–200 G; scan time, 2–32 min. Correlation analysis was achieved by using standard linear regression covering 16 data points.

Acknowledgement

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