A Single Crystal Electron Spin Resonance Study of a Nitroxide Radical exhibiting Hyperfine Coupling with a β-Proton

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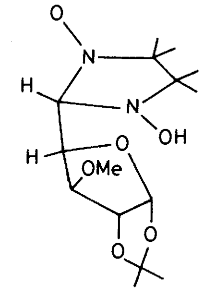
Crystallization of 2-glycosyl-1,3-dihydroxy-4,4,5,5-tetramethylimidazolidine under aerobic conditions gives rise to single crystals which contain a small amount of the 2-glycosyl-3-hydroxyimidazolidin-1-oxyl radical. Hyperfine coupling tensors with the nitroxide nitrogen, a β-proton, and a β-nitrogen are obtained. The anisotropic coupling constants for the β-proton are larger than those calculated for a nitroxide in a planar conformation.

The values of the e.s.r. parameters of a radical in solution provide information about both its electronic structure and its stereochemistry. In particular the value of the isotropic coupling constant, A_H, of a proton to a π-type radical centre is often used as a measure of the dihedral angle, φ, between the two planes which intersect along the CN bond and in which lie, respectively, the nitrogen p orbital containing the unpaired electron, and the CH bond. These quantities are related through the semi-empirical relationship (1) where B_0 and

$$A_H = B_0 + B_1 \cos^2 \varphi \qquad (1)$$

B_1 are constants depending upon the nature of the radical centre. Although this relationship has been widely applied to the nitroxides, where for aliphatic nitroxides the values, in gauss, $B_0 = 0$ and $B_1 = 26$[1] have been commonly employed, as far as we have been able to discover this relationship has not been checked in an oriented system where it should in principle be possible to obtain an independent estimate of the relevant molecular geometry. Thus for an oriented radical the complete coupling tensor for the β-proton can be obtained and since the anisotropic components of this arise from relatively long-range dipole–dipole interactions then the magnitude and orientations of these terms should provide independent evidence of the relative orientation of the methylene and nitroxide fragments. With this in mind we have measured the e.s.r. spectrum of an oriented nitroxide radical containing a β-proton (I) and report the results of this study here.


(I)

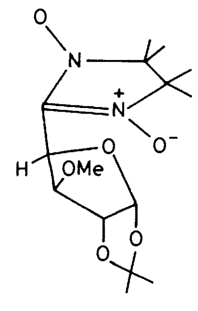

(II)

Table 1. g-values and isotropic hyperfine coupling constants (G) of radicals (I) and (II) in solution in benzene

Radical	g	A_{iso} (N)	A_{iso} (H)	A_{iso} (D)
(I)	2.0060	14.7	20.4	
[^{2}H]-(I)	2.0060	14.6		3.2
(II)	2.0063	N(1) 7.5 N(2) 7.5	1.4 *	

* Coupling with a proton of the sugar moiety.

Experimental

The synthesis of the precursor of the radical in question, the corresponding 2-glycosyl-1,3-dihydroxy-4,4,5,5-tetramethylimidazolidine, has already been described.[2] E.s.r. spectra, both in solution and in the solid state, were obtained on a Varian E-9 X-band spectrometer. The single crystal measurements were obtained using the previously described goniometer.[3] Spectra of solutions were measured after replacement of the dissolved oxygen by argon.

Results

Aerobic oxidation of a benzene solution of 2-glycosyl-1,3-dihydroxy-4,4,5,5-tetramethylimidazolidine yields an e.s.r. spectrum (Figure 1a) consistent with the formation of the expected nitroxide (I). Prolonged oxidation yields a new spectrum (Figure 2) due to a radical containing two identical nitrogen atoms which undoubtedly is the nitronyl nitroxide (II). These identifications were confirmed using a precursor which had been selectively deuteriated in the β-position (Figure 1b). The e.s.r. parameters of all these species are presented in Table 1.

Slow evaporation of a solution of the precursor in benzene gives rise to single crystals which contain an oriented free radical for which a typical e.s.r. spectrum (Figure 3) arises from coupling with two non-equivalent nitrogen atoms, N(1) and N(2), and one proton and these three hyperfine coupling tensors and the g tensor are given in Table 2.

If all three components of the hyperfine coupling tensor of N(1) are of the same sign the isotropic coupling constant is 14.3 G, and with the same hypothesis the proton isotropic coupling is 24.2 G while the average g-value is 2.0048. These values are close to those observed in benzene solution for the nitroxide radical. This radical did not however exhibit any coupling from the second nitrogen. The absence of an observable isotropic coupling would be explained if the three anisotropic components of N(2) were of different signs. Thus for the relative signs +5.7, −5.4, and 4.8 the magnitude of the isotropic coupling would be only 1.5 G. Although a coupling

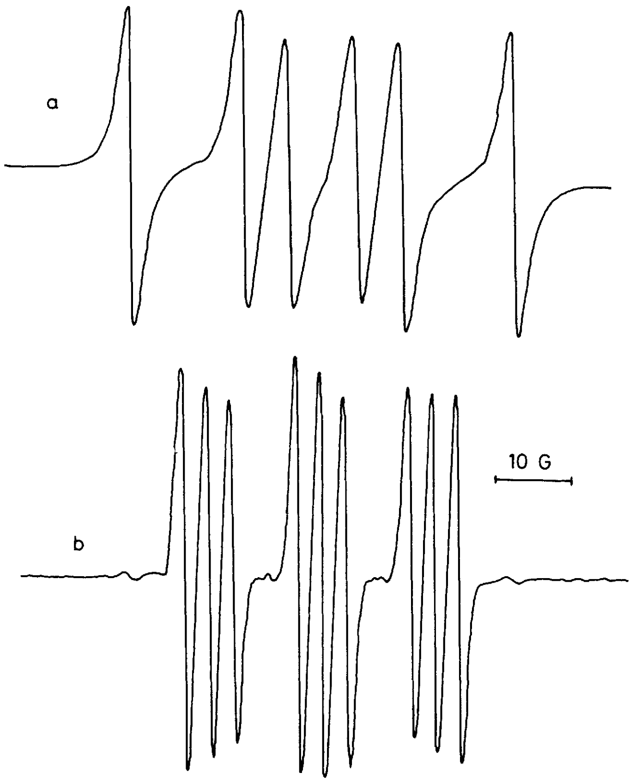


Figure 1. a, E.s.r. spectrum of (I) in benzene solution; b, e.s.r. spectrum of (I) after deuteration in the β-position

Figure 2. E.s.r. spectrum obtained after prolonged aerobic oxidation of (I) in benzene solution

of this magnitude would have been detected in the solution spectrum of (I) where the linewidth is 1.5 G a fairly small change in molecular geometry on going from the solid state to solution could easily result in a reduction of the isotropic coupling constant of N(2) by a factor of two, thus preventing its detection. That the radicals in the solid state and in solution do not have exactly the same geometry is of course already implied by the difference between the proton isotropic coupling constants for these two phases. The identification of the source of both the solution spectrum and the solid state spectrum with the nitroxide radical (I) seems well founded.

Table 2. *g* and hyperfine coupling tensors (G) of radical (I) in a single crystal of 2-glycosyl-1,3-dihydroxy-4,4,5,5-tetramethylimidazolidine

g	2.0092	0.273	0.957	−0.092
	2.0043	−0.957	0.261	−0.122
	2.0012	−0.093	0.122	0.988
		$\bar{g}$ 2.0049		
N(1)	(+) 34.7	0.062	0.116	0.991
	(+) 4.8	−0.993	0.101	0.050
	(+) 3.5	−0.094	−0.987	0.122
		A_{iso} 14.3; *B* 20.3, −9.5, −10.8		
N(2)	(+) 5.7	0.158	0.863	−0.478
	(−) 5.4	−0.942	−0.011	−0.333
	(−) 4.8	−0.293	0.504	0.812
		A_{iso} −1.5; *B* 7.2, −3.9, −3.3		
H	(+) 31.0	0.847	−0.530	0.004
	(+) 22.5	0.528	0.843	−0.091
	(+) 19.0	0.044	0.079	0.995
		A_{iso} 24.2; *B* 6.9, −1.7, −5.2		

Table 3. Theoretical anisotropic coupling tensor *B* (G) of the β-proton as a function of dihedral angle according to the parameters given in the text

ϕ (°)		*B*	
90	2.726	−1.312	−1.414
60	2.731	−0.689	−2.041
30	2.913	−0.7024	−2.2109
0	3.222	−1.043	−2.179
−30	3.343	−0.828	−2.514
−60	3.274	−0.954	−2.320
−90	3.203	−1.569	−1.635

In order to obtain an estimate of the anisotropic coupling of the β-proton we have calculated the dipole coupling tensor as a function of dihedral angle from a model derived from that which we have previously used for the ethyl radical.[4] Figure 4 illustrates the model and the axis system. Thus the atoms ONC lie in the *xy* plane and the *x*-axis lies along the NC bond. The origin is at the nitrogen atom, the carbon atom has a positive *x* co-ordinate, while the oxygen atom has a negative *y* co-ordinate. The assumed dimensions of the nitroxide fragment are shown in Figure 4. They are based on the dimensions found for the five-membered ring nitroxide, 3-carboxy-2,2,5,5-tetramethylpyrolidin-1-oxyl.[5] The unpaired electron is assumed to be localised in a N–O π orbital with densities ρ^O and ρ^N in the two atomic orbitals of oxygen and nitrogen, respectively. As for our calculations on the ethyl radical, hyperconjugation was allowed for byplacing a constant spin density ρ_z^C in the $2p_z$ orbital of the carbon atom and ρ^H in the appropriate π combination of the three $1s$ orbitals of the methyl group. Although the total spin density on the three hydrogen atoms remains constant its distribution among them varies with the dihedral angle. Finally, account was taken of the spin density ρ_σ^C induced in the orbitals of the N–C σ bond by the positive spin density in the nitrogen $2p\pi$ orbital. To facilitate reference to our work on the ethyl radical[4] we have used as far as possible the same symbols for the various spin densities. Finally the various valence orbitals of carbon, nitrogen, and oxygen are assumed to be Slater orbitals with effective charges of 3.18, 3.80, and 4.50, respectively. Using exactly the methods described previously we have calculated the β-proton dipole–dipole coupling tensor as a function of the dihedral angle φ for various values of these spin densities. In Table 3 we show the results of such a calculation for a particular set of spin densities which we may justify as follows.

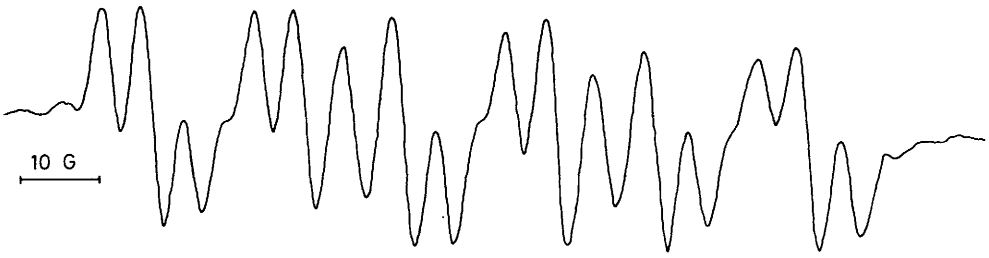


Figure 3. E.s.r. spectrum obtained with a single crystal of 2-glycosyl-1,3-dihydroxy-4,4,5,5-tetramethylimidazolidine doped with (I)

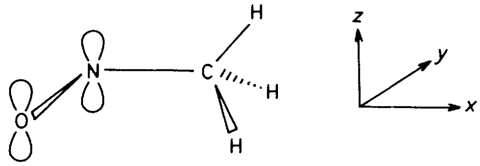


Figure 4. Reference system for the nitroxide fragment. The following dimensions have been assumed: N–C 1.479 Å, C–H 1.09 Å, N–O 1.27 Å, $\widehat{ONC}$ 122°

Table 4. Theoretical and experimental angles between the principal directions of the β-proton tensor and the maximum component of the N(1) tensor

Theoretical		Experimental	
Principal value	Angle (°)	Principal value	Angle (°)
3.22	79.5	6.9	90.3
−1.04	87.4	−1.7	87.5
−2.18	10.9	−5.2	3.7

The relative spin densities ρ^N and ρ^O have been the subject of much discussion with values for ρ^N ranging from 0.75 to 0.4.[6] We have chosen values within this range (ρ^N 0.6 and ρ^O 0.4), our bias towards the higher value for ρ^N being due to the fact that, as will be seen below, our theoretical values for the β-proton anisotropic coupling constants are much too small and reducing ρ^N would make things even worse. The density ρ^H follows from the measured isotropic coupling constant of a freely rotating methyl group adjacent to a nitroxide group as well as from the value of $B_1 = 26$ G. The values of ρ_z^C and $\rho\sigma^C$ are essentially those used in our work on the ethyl radical scaled down by an amount corresponding to the lower spin density on the nitrogen atom and the methyl group. The results are not too sensitive to these parameters.

The most striking thing about the results of Table 3 is the fact that the magnitudes of the theoretical dipole coupling tensors are smaller than the experimental values of Table 2 by a factor of two. No reasonable values of the various spin densities can overcome this difficulty and simple calculations based on a point dipole will soon convince one that to achieve such relatively high anisotropies the spin density must be placed closer to the β-proton.

According to equation (1) with values of B_0 and B_1 for aliphatic nitroxides quoted above and the experimental value of the isotropic proton coupling constant the dihedral angle φ is in the neighbourhood of 0°. For this orientation we show in Table 4 the angles between the z axis, which for this model defines the direction of the maximum component of the ^{14}N coupling tensor, and the three components of the β-proton tensor and compare them with the experimental directions. There is thus qualitative agreement between theory and experiment for the principal directions of the proton coupling tensor but to a considerable extent these directions are determined as much by the approximate local symmetry as anything else. Too much weight must not, therefore, be placed on this agreement in view of the very considerable difference between the magnitudes of the theoretical and experimental tensor components.

In our view the most probable reason for the above differences is that the present nitroxide is not planar. This would certainly not be surprising for a nitroxide group forming part of a five-membered ring and indeed X-ray crystal structure determinations have shown that some nitroxides, both forming part of five-membered [7] and six-membered [8–13] rings, are non-planar. The result of the non-planarity would be to create positive spin density in the p_x orbital of the nitrogen atom. This non-planarity would likewise explain the large positive spin density on N(2) (*ca.* 20%) which is deduced from the anisotropic components of Table 2 with the choice of signs discussed in the text.

An estimate of the effect of non-planarity can be obtained by changing the spin density in the nitrogen–carbon σ orbital. With all other spin densities as before, changing the spin density ρ_σ^C from −0.035 to +0.1 yields the β-proton principal components of 13.2, −5.6, and −7.6 MHz, respectively. It is clear that quite small changes in the spin densities close to the β-proton, ρ_σ^C, and ρ_z^C, can produce large changes in the dipolar coupling tensor. In the absence of more extensive experimental data, for other nitroxides and for systems where the structure of the host crystal is known, detailed manipulation of the basic model would be premature.

Acknowledgement

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