Conformation Studies by Nuclear Magnetic Resonance Spectroscopy in Liquid Crystal Solvents. An Investigation of Torsional Angles, Reorientation, and Order Matrices in 3-, 4-, and 5-Phenylisoxazole

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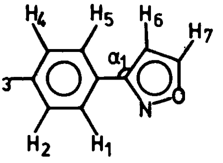
The n.m.r. spectra of 3- (1), 4- (2), and 5-phenylisoxazole (3) partially oriented in the nematic phase of a liquid crystalline solvent have been studied. A twisted conformation around the bond connecting the two rings is preferred, with a twist angle of *ca.* 18° for compounds (1) and (3) and *ca.* 20° for compound (2). Reorientation of these molecules is correlated with the internal rotation, while the direction of the principal order axis, with respect to a reference axis system fixed on the phenyl ring, depends on molecular shape.

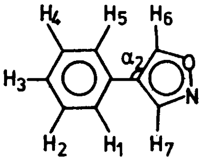
CONFORMATIONAL studies by n.m.r. spectroscopy in liquid crystal solvents involve several problems and limitations.[1,2] It is not always easy to separate the internal motions from the molecular orientational motion. In fact, if the internal motion and reorientation are uncorrelated, as when internal rotation is much faster than reorientation, then a unique ordering matrix can be defined for the molecule, resembling a situation analogous to that of a rigid molecule. If the internal motion and reorientation are correlated it is impossible to describe the orientation of the molecule by a single order matrix.[3-5]

The problem of the coupling of the internal rotation with the reorientation of the whole molecule has recently attracted the attention of many workers. However, as the substituted aromatic derivatives so far investigated [3-7] have substituents coplanar with the aromatic ring, no particular attention has been devoted to the conformational problem.

The purpose of this study is to investigate by n.m.r. spectroscopy both the orientational order and the molecular conformations of 3- (1), 4- (2), and 5-phenylisoxazole (3) partially oriented in a nematic liquid crystalline phase. Such substances, by analogy with molecules having two aromatic rings connected by a single bond,[8-12] are expected to exhibit twisted conformations. The investigations, favoured by a relatively large number of dipolar couplings available from the n.m.r. spectra, were carried out using an appropriate number of order parameters.



(1)



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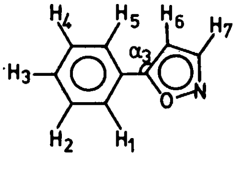
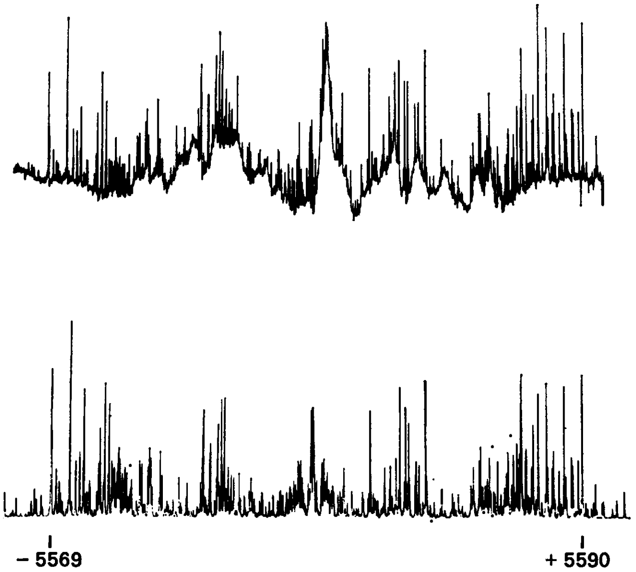


(3)

EXPERIMENTAL

Compounds (1)—(3) were prepared and purified according to literature methods.[13] The 100 MHz n.m.r. spectra were obtained in solution of Nematic Phase IV, at a concentration of *ca.* 15 mole % for compounds (2) and (3) and *ca.* 18 mole % for compound (1). The spectra were recorded on a Varian XL 100 spectrometer in the Fourier transform mode and with an external ^{19}F lock; an average of 100 transients were accumulated for each spectrum at a probe temperature of 30 °C. The line-width was 5—6 Hz. A spectrum of (3), as an example, is displayed in the Figure.



Experimental (upper) and computed 100 MHz n.m.r. spectrum of 5-phenylisoxazole partially oriented in Nematic Phase IV (Merck) at 30 °C. The line width used for the simulated spectrum is 5 Hz

The spectra were analysed using the LAOCOONOR program in terms of chemical shifts ν_i (including anisotropic contributions), isotropic indirect coupling constants J_{ij}, and direct dipolar coupling constants D_{ij}. The J_{ij} couplings were taken from isotropic spectral data for monosubstituted benzenes or measured in isotropic solution. The lines used for the spectral fitting were 188 for (1), 116 for (2), and 156 for (3). Table 1 gives the results of spectral analysis while a simulated spectrum of (3) is displayed in the Figure.

TABLE 1

Spectral parameters used in the simulation of the 100 MHz spectra of compounds (1)—(3) partially oriented in the nematic phase. Indirect coupling constants used are J_{12} 7.8, J_{13} 1.3, J_{14} 0.6, J_{15} 1.8, J_{23} 7.8, J_{24} 1.3, and J_{67} 1.7 Hz for (1) and (3)

	Compound		
Parameter	(1)	(2)	(3)
D_{12}	$-1\,759.5 \pm 0.1$	$-2\,438.7 \pm 0.1$	$-2\,635.5 \pm 0.1$
D_{13}	-226.4 ± 0.1	-306.3 ± 0.1	-334.3 ± 0.1
D_{14}	-5.3 ± 0.1	2.1 ± 0.2	0.2 ± 0.1
D_{15}	101.2 ± 0.3	155.5 ± 0.2	165.9 ± 0.2
D_{16}	-829.5 ± 0.1	-948.2 ± 0.1	$-1\,201.6 \pm 0.2$
D_{17}	-147.6 ± 0.1	$-1\,044.0 \pm 0.3$	-216.0 ± 0.1
D_{23}	-42.4 ± 0.1	5.5 ± 0.4	-1.7 ± 0.1
D_{24}	100.5 ± 0.2	155.3 ± 0.1	166.4 ± 0.2
D_{26}	-135.1 ± 0.2	-178.4 ± 0.5	-196.1 ± 0.1
D_{27}	-54.7 ± 0.1	-185.7 ± 0.5	-81.2 ± 0.1
D_{36}	-84.1 ± 0.2	-116.0 ± 0.2	-123.1 ± 0.1
D_{37}	-42.6 ± 0.1	-123.2 ± 0.3	-63.8 ± 0.1
D_{67}	$-1\,028.7 \pm 0.1$	166.2 ± 0.2	$-1\,441.9 \pm 0.1$
ν_1, ν_5	15.9 ± 0.2	56.1 ± 0.2	56.8 ± 0.2
ν_2, ν_4	43.1 ± 0.1	49.8 ± 0.3	64.2 ± 0.1
ν_3	0	0	0
ν_6	-111.4 ± 0.2	-101.6 ± 0.3	121.1 ± 0.2
ν_7	108.8 ± 0.3	-95.7 ± 0.2	-101.5 ± 0.2

TABLE 2

Relative co-ordinates (Å) and elements of order matrix for the phenyl ring part of molecules (1)—(3) [the distance H(2)—H(3) is fixed at 2.481 Å]

	Compound		
	(1)	(2)	(3)
$x_{H(1)}$	3.712 ± 0.003	3.703 ± 0.001	3.711 ± 0.001
$y_{H(1)}$	2.146 ± 0.004	2.147 ± 0.001	2.153 ± 0.001
$x_{H(2)}$	1.241 ± 0.001	1.2439 ± 0.0003	1.240 ± 0.0003
$y_{H(2)}$	2.1484 ± 0.0008	2.1466 ± 0.0002	2.1489 ± 0.0002
$x_{H(3)} = y_{H(3)}$	0	0	0
$S_{xx} - S_{yy}$	0.2872 ± 0.0003	0.4045 ± 0.0001	0.4415 ± 0.0001
S_{zz}	-0.1543 ± 0.0008	-0.1997 ± 0.0003	-0.2214 ± 0.0003
$(S_{xx} - S_{yy})/S_{zz}$	1.861	2.025	1.994

RESULTS AND DISCUSSION

The direct dipolar couplings depend on the interproton distance r_{ij} and the orientation of the r_{ij} vector with respect to the magnetic field θ_{ij} according to relationship (1) [1] where $S_{ij} = \langle 3\cos^2\theta_{ij} - 1\rangle/2$ is the order parameter.

$$D_{ij} = -\frac{\hbar}{2\pi}\gamma_i\gamma_j\frac{S_{ij}}{\langle r_{ij}{}^3\rangle} \qquad (1)$$

For the determination of the structure of each phenylisoxazole molecule, 13 dipolar couplings are available from spectral analysis. On the basis of symmetry arguments, analogous to those for monosubstituted phenyl derivatives which have planar isomers,[3] it may be concluded that even in the case of twisted conformations the internal motion creates an effective C_{2v} symmetry for the phenyl ring protons. The six D_{ij} couplings of the phenyl ring were therefore used to determine the orientation parameters S_{zz} and $S_{xx} - S_{yy}$ and the interproton distances with the help of the SHAPE program.[14] The results obtained assuming an r_{23} distance of 2.481 Å are given in Table 2. The derived geometry of the fixed part of the molecules shows little deviation from other phenyl derivatives studied so far.

The remaining seven couplings were used to investigate the internal motion on the basis of the following assumptions. (1) The isoxazole ring geometry was obtained from an accurate microwave study.[15] (2) It was assumed that for twisted conformations only isomers with a dihedral twist angle θ between the two rings contribute significantly to the D_{ij} couplings. (3) The vibrational corrections were neglected. (4) The inter-ring distance d and the angle α were considered to be adjustable.

On account of such assumptions, when internal rotation is faster than molecular reorientation, no additional order parameters are required, and the $S_{xx} - S_{yy}$ and S_{zz} elements of the order matrix, derived for the interproton D_{ij} couplings of the phenyl ring, completely define the molecular orientational order. When internal rotation is slower than molecular reorientation one additional order parameter S_{xy}, with opposite sign for different conformers, is needed for planar conformations. In the case of twisted conformers, since the plane of symmetry is lost, three additional order parameters S_{xz}, S_{yz}, and S_{xy} are necessary. Symmetry requires four equivalent conformers with twist angles −θ, θ, 180 − θ, and $180 + \theta$. Each conformer gets a particular combination of sign for the off-diagonal element of S depending on its position in the xyz axis system.

Attempts to fit the D_{ij} couplings in the case of planar conformations were unsuccessful for each of the phenylisoxazoles for internal motion either faster or slower than reorientation. The deviations were too large to rule out this possibility.

The results for twisted conformations are collected in Table 3. In this Table three models are compared for each compound: the model in column I assumes internal motion faster than reorientation, that in column III assumes 'correlated motions', and that in column II simplifies model III for twisted conformations by using only one additional S_{xy} element and assuming that the contributions of S_{zx} and S_{zy} are negligible. The values in parentheses for the α angles in Table 3 refer to the unsubstituted isoxazole molecule for the three positions of substitution.

Inspection of Table 3 establishes that model III has, for the three molecules, the best r.m.s. deviation, the smallest distortion of the angles α, and a realistic value of the inter-ring distance d (this parameter is not known for our molecules; a value of 1.49 Å can be assumed from data for similar compounds). The results of Table 3 also show that the neglect of all the off-diagonal S values (fast internal rotation, model I) gives increased inter-ring distances and distorts the angles. The results further demonstrate that model III works very well for molecules (1) and (3) and all the residuals $\Delta D_{ij} = D_{ij\,\text{exp.}} - D_{ij\,\text{calc.}}$ are comparable with the standard deviations derived from spectral analysis. This is not the case, however for molecule (2); in this case model III, although much better than I, is inadequate. The singular behaviour of (2) can be rationalized by considering that in this molecule non-bonded interactions larger than for isomers (1) or (3) can be expected. Such steric repulsions are probably also responsible for values of the twist angle θ and the inter-ring distance being slightly larger for (2) than for (1) or (3). The inadequacy of model III for the 4-substituted isoxazole reflects the limit of our assumptions. In fact large steric repulsions could invalidate the assumption that the isoxazole ring is a rigid system and produce a flatter potential energy function, and then the rigid rotamer approximation is no longer correct. An averaging of the D_{ij} values with a suitable potential energy function could be made in principle. Moreover this procedure requires Fourier terms for the internal potential and even if the system examined is quite rich in D_{ij} couplings, it is not possible to add parameters beyond those considered. Further, we have to consider that, even in the case of molecules (1) and (2), the non-diagonal elements of the ordering matrix are not fully independent of geometry and a more precise determination of these parameters is not obtainable just from proton spectra. Owing to these uncertainties and to the fact that couplings used do not involve directly bonded atoms, vibrational corrections were not performed.

The data in Table 3 show that the twist angle is not dramatically dependent on the model used. This fact suggests that an estimate of the conformation can still be obtained by neglecting the non-diagonal elements of the order matrix. This procedure cannot, of course, be generalized but it can probably be extended to molecules of similar shape.[11]

Since this study was not aimed principally at investigating the orientational order, experiments were not performed at the same reduced temperature so that no significant comparison can be made among different compounds. According to these considerations we only observe that the ratio $(S_{xx} - S_{yy}) : S_{zz}$ reported in Table 2 has a similar value only for (2) and (3) whose spectra were recorded under similar conditions.

Table 4 reports, for each molecule, the values obtained by diagonalizing the order matrix and the angles bet-

TABLE 3

Non-diagonal elements of order matrix and best fit geometrical parameters of (1)—(3) for three different models for molecular reorientation (see text)

	Compound								
	(1) Model			(2) Model			(3) Model		
	I	II	III	I	II	III	I	II	III
S_{yz}			-0.010 ± 0.008			0.022 ± 0.002			0.004 ± 0.008
S_{xz}			-0.043 ± 0.007			-0.006 ± 0.006			-0.041 ± 0.008
S_{xy}		0.0189	0.012 ± 0.003		-0.002	0.001 ± 0.001		0.0264	0.027 ± 0.003
d/Å	1.59	1.47	1.43	1.53	1.53	1.51	1.59	1.49	1.45
α_1 (°)	123.1	128.1	129.1 (129.1)	127.4	127.4	129.4 (128.47)	127.3	131.3	132.4 (133.3)
θ (°)	20.5	19.5	18.5	20.5	20.5	20.5	19.5	18	18.5
R.m.s. deviation (Hz)	2.47	1.5	0.2	3.2	3.2	1.7	4.7	1.5	0.3

TABLE 4

Elements of diagonalized order matrix and angles of principal order axis with respect to the *para*-axis

	Compound		
	(1)	(2)	(3)
$S_{x'x'} - S_{y'y'}$	0.2714 ± 0.0003	0.4052 ± 0.0001	0.4415 ± 0.0001
$Sz'z'$	-0.1719 ± 0.0008	-0.2011 ± 0.0003	-0.2352 ± 0.0003
θ_z (°)	3.2 ± 0.5	2.5 ± 0.3	3.9 ± 0.5

ween the principal order axis and the *para*-axis. It appears from the Table that the θ_s angles are small, the smallest deviation being shown by molecule (2) which is more symmetrical.

Two main conclusions have been reached: the rate of internal rotation is slower than molecular reorientation and the preferred conformation is a twisted one, with torsional angles of *ca.* 18° for compound (1) and (3), and 20° for compound (2).

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