Conformational Analysis in Heteroaromatic Carbonyl Compounds. Part II.[1] Nuclear Magnetic Resonance Investigation of Thiophen-2,5-dicarbaldehyde in Liquid Crystals

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The 100 MHz n.m.r. spectrum of the title compound partially oriented in the nematic phase has been obtained and interpreted. The values of the direct dipolar couplings have been discussed in terms of models which take into account the possibilities of internal rotation rates either faster or slower than the molecular reorientation in the liquid crystals. It is concluded that the molecule exists in the conformations O-cis–cis (70—80%) and O-cis–trans (20—30%), whilst the proportion of the O-trans-trans rotamer is negligible.

THE n.m.r. spectra of substances partially oriented in the nematic mesophase of liquid-crystal solvents provide valuable information on the geometry of the solute molecules.[2] Investigations carried out by this technique have been mainly concerned with determinations of relative bond lengths, bond angles, and signs of spin–spin coupling constants in rigid molecules; only recently has the method been applied to conformationally flexible compounds.[3,4] In this case the spectral analysis in terms of chemical shifts, indirect couplings, and direct dipolar interactions is straightforward as for rigid compounds. However several problems arise when trying to interpret the dipolar couplings in terms of molecular configurations. These mainly depend on the relative rates of the internal conformational changes and reorientation of the molecules in the nematic solvent.

In thiophen-2,5-dicarbaldehyde, if the internal rotation of the carbonyl groups is the faster process an effective element of symmetry is generated and the orientation may be described by an average ordering matrix having a reduced number of elements; on the other hand, if the reorientation is faster than the internal changes, each isomer requires an individual ordering matrix and the problem will thus become insoluble since only four experimental couplings are available. Even in this case however some reasonable assumptions can be made in order to reduce the number of unknowns and the conformational problem can still be approached.

The aim of the present work is to investigate whether liquid-crystal n.m.r. spectra can be used in assigning rotational isomers less ambiguously than conventional n.m.r. techniques and thiophen-2,5-dicarbaldehyde was employed because of the possibility of a parallel e.s.r. investigation.[1]

Note added in proof: A recent communication (T. N. Huckerby, *Tetrahedron Letters,* 1971, 3497) on the liquid crystal n.m.r. spectrum of thiophen-2,5-dicarbaldehyde gives experimental dipolar couplings in agreement with those of this paper.

EXPERIMENTAL

The 100 MHz spectrum of thiophen-2,5-dicarbaldehyde was recorded at 83 °C with 4,4'-di-n-hexyloxyazoxybenzene as nematogen, the concentration of the aldehyde being 18 mol %. The spectra were run on a JEOL PS 100 spectrometer in the field-sweep mode (external lock) with a sweep time of 5 Hz s⁻¹, and interpreted by means of the programme ATHENA[5] which uses for the iterative procedure the intensities instead of the frequencies. The results were also checked with the programme LAOCOON III modified in order to include the direct dipolar couplings. The experimental and computed spectra are reported in Figure 1.

RESULTS AND DISCUSSION

The Spin Hamiltonian.—In order better to understand the problems we first discuss the spin Hamiltonian for non-rigid molecules oriented in liquid crystalline solvents. The spin Hamiltonian for a given orientation and conformation of the molecule can be written, in the irreducible spherical tensor notation,[6] as expression (1) where the subscript μ denotes the different magnetic

$$\mathscr{H} = \mathscr{H}^\circ + \sum_{\mu, L, p, q} (-1)^P F_\mu^{(L,q)}(i) \mathscr{D}_{q,p}^{(L)}(\Omega) T_\mu^{(L,-p)} \quad (1)$$

interactions of rank L, $F_\mu^{(L,q)}$ is a particular component of the tensor measuring the strength of the coupling in the molecular frame, $T_\mu^{(L,-p)}$ is the appropriate combination of spin operators written in the laboratory axis system, and $\mathscr{D}_{q,p}^{(L)}(\Omega)$ the component of the Wigner rotation matrix connecting the molecular and space-fixed co-ordinate systems.

When both intra- and inter-molecular motions are rapid in the usual sense the static spin Hamiltonian is obtained by taking a time or ensemble average of the equation (1). For rigid molecules in a nematic mesophase the time-dependence is contained entirely in the Wigner rotation matrix whose averaged components, in

[3] A. D. Buckingham, E. E. Burnell, and C. A. de Lange, *Mol. Phys.,* 1970, **33,** 4187; I. J. Gazzard and N. Sheppard, *ibid.,* 1971, **21,** 169; P. Diehl, P. M. Henrichs, and W. Neiderberger, *ibid.,* 1971, **20,** 139; P. Bucci and C. A. Veracini, *J. Chem. Phys.,* 1972, **56,** 1291.
[4] P. Diehl, P. M. Henrichs, and W. Neiderberger, *Org. Magnetic Resonance,* 1971, **3,** 243.
[5] A. M. Serra, to be published.
[6] H. R. Falle and G. R. Luckhurst, *J. Magnetic Resonance,* 1970, **3,** 161.

[1] Part I, L. Lunazzi, G. F. Pedulli, M. Tiecco, C. Vincenzi, and C. A. Veracini, preceding paper.
[2] A. D. Buckingham and K. A. McLauchlan, *Progr. N.M.R. Spectroscopy,* 1967, **2,** 63; A. Saupe, *Angew. Chem., Internat. Edn.,* 1968, **7,** 97; G. R. Luckhurst, *Quart. Rev.,* 1968, **22,** 179; P. Diehl and C. L. Khetrapal, *N.M.R. Basic Principles and Progr.,* 1969, **1,** 1; S. Meiboom and L. C. Snyder, *Account Chem. Res.,* 1971, **4,** 81.

a magnetic resonance experiment, vanish unless p is zero because of the axial symmetry about the magnetic field of the solute alignment.[7] The static Hamiltonian becomes (2). Of course if the molecule is non-rigid

$$\mathscr{H} = \mathscr{H}^\circ + \sum_{\mu, L, q} F_\mu{}^{(L, q)} \overline{\mathscr{D}_{q, 0}{}^{(L)}} T_\mu{}^{(L, 0)} \qquad (2)$$

the interaction tensors $F_\mu{}^{(L, q)}(i)$ are also time-dependent

$$\overline{F_\mu{}^{(L, q)}(i) \mathscr{D}_{q, p}{}^{(L)}(\Omega)} \qquad (3)$$

and we now require the average [8] (3).

For convenience we write this as $\overline{F(i) \mathscr{D}(\Omega)}$ and in terms of the joint probability $P(\Omega), i$ we have equation

equation (4) gives (5), i.e., the parameters in the Hamil-

$$\overline{F(i) \mathscr{D}(\Omega)} = \overline{\mathscr{D}} F \qquad (5)$$

tonian are the averages of the ordering matrix $\overline{\mathscr{D}}$ for the conformer. Such quantities could be fairly difficult to handle in any practical situation.

At the other extreme $\tau_J \ll \tau_R$ and then $P(\Omega, i)$ can still be separated but now $P_i(\Omega)$ is independent of i. In other words the conformation changes many times before reorientation occurs. Substitution into equation (4) then gives equation (6) where $\overline{\mathscr{D}}$ is now the ordering

$$\overline{F(i) \mathscr{D}(\Omega)} = \overline{\mathscr{D}} F \qquad (6)$$
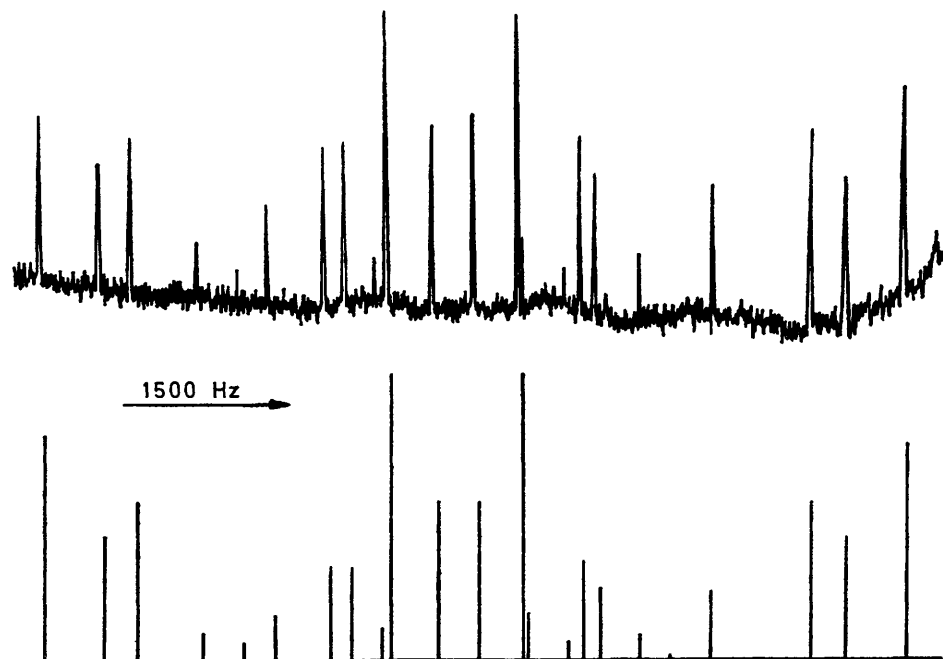

FIGURE 1   Experimental and computed 100 MHz ^{1}H n.m.r. spectrum of thiophen-2,5-dicarbaldehyde in 4,4'-di-n-hexyl-oxyazoxybenzene at 83 °C

(4), where we assume a finite number of conformations

$$\overline{F(i) \mathscr{D}(\Omega)} = \sum_i \int P(\Omega, i) F(i) \mathscr{D}(\Omega) \mathrm{d}\Omega \qquad (4)$$

denoted by i. The probability $P(\Omega, i)$ is the probability that the molecule has an orientation Ω and conformation i. Clearly to proceed further we need to make certain assumptions about the form of $P(\Omega, i)$. For example if the correlation time for the jump between conformations τ_J is long compared with the time for reorientation τ_R, then $P(\Omega, i)$ can be written as $P(\Omega, i) = P_i(\Omega) P(i)$. Here $P_i(\Omega)$ is the orientational probability distribution function and if the conformers have different intermolecular interactions with the meso-phase will depend on i. $P(i)$ is the probability of conformation i. Substitution of this result into

matrix for an average conformation. When τ_J and τ_R have the same magnitude no factorisation of the joint probability is possible and no simple solution of the problem seems attainable.[8]

The spin Hamiltonian expressed in the irreducible tensor notation leads to more compact formulation of the theory, but it is often more convenient for practical purposes to describe the alignment by an ordering matrix S whose elements are related to the average rotation matrices through equations [6] (7)—(11).

$$S_{zz} = \overline{\mathscr{D}_{0.0}{}^{(2)}} \qquad (7)$$

$$S_{xx} - S_{yy} = \sqrt{(3/2)} \left[\overline{\mathscr{D}_{-2.0}{}^{(2)}} + \overline{\mathscr{D}_{2.0}{}^{(2)}} \right] \qquad (8)$$

$$S_{xy} = \sqrt{(3/8)} \left[\overline{\mathscr{D}_{-2.0}{}^{(2)}} - \overline{\mathscr{D}_{2.0}{}^{(2)}} \right] \qquad (9)$$

$$S_{xz} = \sqrt{(3/8)} \left[\overline{\mathscr{D}_{-1.0}{}^{(2)}} - \overline{\mathscr{D}_{1.0}{}^{(2)}} \right] \qquad (10)$$

$$S_{yz} = \sqrt{(3/8)} \left[\overline{\mathscr{D}_{-1.0}{}^{(2)}} + \overline{\mathscr{D}_{1.0}{}^{(2)}} \right] \qquad (11)$$

The diagonal elements lie in the range -0.5 to 1.0

[7] S. H. Glarum and J. H. Marshall, J. Chem. Phys., 1966, 44, 2884.
[8] G. R. Luckhurst, unpublished work.

while the off-diagonal ones lie in the range −0·75 to 0·75. These five parameters are sufficient to define the ordering matrix which is both symmetric and traceless. Often this number can be further reduced by using the symmetry of the molecule to determine the principal axis system. For instance only the two elements S_{zz} and $S_{xx} - S_{yy}$ are needed when the molecule has C_{2v} symmetry while also a third element (S_{xy}) has to be used for a planar asymmetric molecule.[2]

In order to interpret the experimental dipolar couplings D_{ij} (Table 1) three possible models should be

ture was 'built up' by use of bond angles and bond lengths of thiophen[9] and of aromatic carbonyl derivatives;[10-12] the co-ordinates of the hydrogen atoms obtained in this way are reported in Table 2.

In the case of the symmetric structures (cc) and (tt) two ordering parameters are required to describe the orientation because of the C_{2v} symmetry, while in the case of the asymmetric conformations (ct,tc) there might be either two or three depending on whether an effective element of symmetry is created by the fast rotation of the two carbonyl groups.[4] We examined

TABLE 1

Experimental and computed D_{ij}/Hz values obtained by assuming the existence of a single rotational isomer. In the case of the asymmetric rotamer (ct,tc) columns 4 and 5 report the values calculated by using two and three ordering elements respectively (see text)

	Experimental	(cc)	(tt)	(ct,tc)	
δv	178·4 ± 2·3				
D_{12}	−213·0 ± 1·7	−202·2	−414·8	−245·1	− 227·8
D_{13}	−1681·2 ± 2·3	−1680·6	−1657·2	−1680·6	−1682·8
D_{14}	−409·3 ± 2·3	−421·0	−523·7	−408·6	−393·1
D_{34}	−3478·6 ± 0·4	−3478·1	−3448·5	−3476·7	−3478·7
R.m.s. deviation/Hz		8·0	117·6	16·1	11·0
S_{zz}		−0·307	−0·739	−0·484	−0·456
S_{xx}		0·265	0·263	0·265	0·265
S_{yy}		0·042	0·476	0·219	0·191
S_{xy}					0·074

considered: free rotation, the existence of a single conformation, and an equilibrium among the possible rotamers.

Free Rotation.—The possibility of a free rotation of the two carbonyl groups has been considered unrealistic since the e.s.r. experiments clearly indicate the existence of preferred rotational isomers;[1] further, the free rotation model discussed in an analogous case[4] could not explain satisfactorily the experimental D_{ij} values.

Single Conformation.—This model has been tested by comparing the experimental D_{ij} values with those calculated by assuming, respectively, the existence of solely the forms O-cis–cis (cc), O-trans–trans (tt), and the

(cc)

(tt)
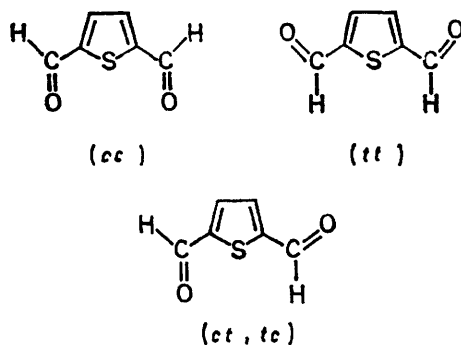
(ct , tc)

asymmetric equivalent structures O-cis–trans and O-trans–cis (ct,tc). In the absence of geometrical parameters for thiophen-2,5-dicarbaldehyde itself its struc-
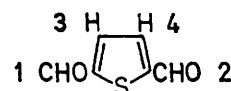
both the possibilities and the results are collected in Table 1. The r.m.s. deviations from the experimental D_{ij} values largely exceed the errors for all the situations

TABLE 2

Co-ordinates (Å) of the hydrogen atoms of the thiophen-2,5-dicarbaldehyde

3 H   H 4

1 CHO   CHO 2
         S

O-cis-cis (cc)			O-trans-trans (tt)	
x	y	Nuclei	x	y
-3.40_2	-1.04_7	1	-2.67_0	-2.90_4
3.40_2	-1.04_7	2	2.67_0	-2.90_4
-1.31_8	0.89_3	3	-1.31_8	0.89_3
1.31_8	0.89_3	4	1.31_8	0.89_3

examined, thus showing that the problem cannot be solved in terms of one single planar conformation. However since the r.m.s. deviation for the rotational isomer O-trans–trans is much larger than for the other two (and its S_{zz} even exceeds the physically allowed limit) it is possible to infer that the weight of this structure will be negligible and that the thiophen-2,5-dicarbaldehyde will exist mainly in the O-cis–cis and O-cis–trans conformations. For the same reason

[9] B. Back, D. Christensen, L. Hansen-Nygaard, and J. Rastrup-Andersen, *J. Mol. Spectroscopy*, 1961, 7, 58.
[10] M. Nardelli, G. Fava, and L. Armellini, *Ricerca sci.*, 1958, 28, 383.
[11] F. Monning, H. Drazler, and H. D. Rudolf, *Z. Naturforsch.*, 1965, 20a, 1323; 1966, 21a, 1633.
[12] R. W. Kilb, C. C. Lin, and E. B. Wilson, jun., *J. Chem. Phys.*, 1957, 26, 1695.

we can also foresee that the symmetric rotamer (cc) will be more stable than the asymmetric one.

Rotamers in Equilibrium.—As we have seen, a different way of handling the experimental data has to be followed depending on the relative values of the correlation time for internal changes τ_J and for reorientation τ_R. Problems of this kind have already been encountered in studying non-rigid molecules [3] and, with few exceptions where both the hypotheses were taken into account, the implicit assumption has been made that internal changes are faster than the reorientation. We too have approached the problem from this point of view and the results will be discussed later.

However to have some idea of the correlation time involved we tried to estimate the magnitude of τ_J and τ_R; in the case of the corresponding radical anion the correlation time for the internal rotation τ_J seems to be longer than 10^{-7} s, as estimated from the separation between the peaks of the rotational isomers.[1] On the other hand, from the data reported for similar neutral molecules such as furan-2-carbaldehyde and 2-acetyl-furan,[13,14] τ_J turns out to be, at 80 °C, *ca.* 10^{-6} to 10^{-7} s; since the rotamers of the analogous thiophen derivatives could not be locked in similar experimental conditions,[15] τ_J in thiophen-2,5-dicarbaldehyde is expected to be shorter at the same temperature.

As concerns the reorientation of molecules in liquid crystals very little is known about the correlation time; from an e.s.r. linewidth investigation of vanadyl acetyl-acetonate dissolved in the nematic phase of 4,4'-di-methoxyazoxybenzene, it has been estimated to be of the order of 10^{-10} s.[16] Even though too much confidence cannot be placed in these values it was nevertheless justified to approach the problem by using also this second approximation, namely $\tau_J \ll \tau_R$.

Fast Rotation.—If the hypothesis $\tau_J \gg \tau_R$ is applied to thiophen-2,5-dicarbaldehyde the magnetic interactions become the weighted average of those of the isomers and can be calculated from a known molecular geometry. The alignment can be described only by the two elements S_{zz} and $S_{xx} - S_{yy}$ since an effective plane of symmetry perpendicular to the heterocyclic ring is generated by the fast rotation of the two carbonyl groups. By calling x and y the amount of the rotamers (cc) and (tt), and $1 - x - y$ that of the asymmetric conformer, we have a total of four unknowns and since four experimental D_{ij} couplings are available the relative weight of the rotamers, as well as the average ordering matrix, can be obtained. The solution gives *O-cis–cis* = 77·5, *O-trans–trans* = 2, and *O-cis–trans* = 21·5% (Table 3).

An alternative way of handling this model is to consider $P(c)$, the probability of having one carbonyl group with the oxygen *cis* to the sulphur atom; then the relative amounts of the rotamers (cc), (tt), and (ct,tc) are

given respectively by $P(c)^2$, $[1 - P(c)]^2$, and $2P(c)[1 - P(c)]$ by assuming the two carbonyl group rotations to be independent. Now only three unknowns have to be determined and the solution will correspond to the

TABLE 3

Elements of the ordering matrix for the models which consider the isomers in equilibrium. The first and second columns refer to the 'fast rotation' model and therefore the average values are reported; the third and fourth columns refer to the slow rotation approximation

(cc) (%)	77·5	77·5	67	72
(tt) (%)	2	1·5	0	0
(ct,tc) (%)	21·5	21	33	28
S_{zz}	−0·345	−0·344	−0·357	−0·343
S_{xx}	0·265	0·265	0·274 *	0·270 *
			0·243 †	0·254 †
S_{yy}	0·080	0·079	0·083 *	0·073 *
			0·113 †	0·089 †

* Ordering elements of the *O-cis–cis* rotamer (cc). † Ordering elements of the *O-cis–trans* rotamer (ct,tc).

minimum r.m.s. deviation, provided it is sufficiently small not greatly to exceed the experimental errors. Figure 2 shows the r.m.s. deviation between experi-
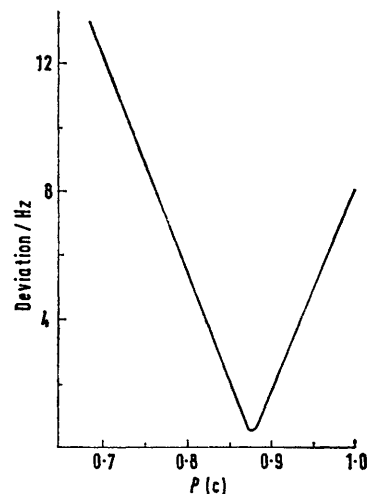

FIGURE 2 Dependence of the r.m.s. deviation on the probability $P(c)$, of having one aldehydic group in the *O-cis*-configuration with respect to the sulphur atom

mental and calculated D_{ij} values as a function of $P(c)$. The best fit is obtained for $P(c) = 0·88$ and accordingly the relative amounts of the rotamers in the thiophen-2,5-dicarbaldehyde should be $(cc) = 77·5$, $(tt) = 1·5$, and $(ct,tc) = 21\%$, in agreement with the previous result (Table 3). This approximation may be useful whenever the number of unknowns exceeds by one the experimental dipolar couplings and also allows us to estimate the sensitivity of the method itself since

[13] K. I. Dahlqvist and S. Forsen, *J. Phys. Chem.*, 1965, **69**, 4062.
[14] L. Arlinger, K. I. Dahlqvist, and S. Forsen, *Acta Chem. Scand.*, 1970, **24**, 662.

[15] L. Arlinger, K. I. Dahlqvist, and S. Forsen, *Acta Chem. Scand.*, 1970, **24**, 672.
[16] S. A. Brooks, G. R. Luckhurst, G. F. Pedulli, and J. Roberts, to be published.

the steeper the curve the lower will be the uncertainty of the results.

The dependence on the geometry has also been tested and variations in the angles of ± 2—$3°$ only affect the result by a few per cent.

Slow Rotation.—In the other possibility previously discussed we have $\tau_J \ll \tau_R$ and an exact solution re-requires in principle a total of seven ordering para-meters; two kinds of approximation however allow a substantial reduction of these elements. Both share the assumption that S_{zz} is equal for all the rotamers, meaning that the degree of orientation of the z-axis normal to the molecular plane is assumed to be inde-pendent of the orientation of the aldehydic groups. In the first model the amount of the *O-trans–trans* isomer has been assumed to be 0 since the e.s.r. spectra do not show the presence of a second symmetric species; [1] its contribution to the neutral molecule is also expected to be negligible, as previously discussed. The ordering matrix elements are now reduced to four, but since the ratio of the rotamers is the fourth unknown we have to take $(S_{xy})_{ct,tc} = 0$ (this term should not be too im-portant). An exact solution is now expected and it was obtained when *O-cis–cis* is 67% (Table 3). In the second model it has been assumed that in each rotamer the axis joining the oxygen atoms is mainly parallel to the optical axis of the solvent. This as-sumption seems reasonable because of the large value of the ordering element along the x direction S_{xx}, compared with S_{yy}, found by use of the previous approxi-mations.

With a given geometry it is thus possible to relate S_{xx}, S_{yy}, and S_{xy} for the asymmetric configuration to S_{xx} and S_{yy} of the symmetric ones as in equations (12)

$$(S_{xx} - S_{yy})_{ct,tc} = (S_{xx} - S_{yy})_{cc} \cos 2\phi \qquad (12)$$

$$(S_{xy})_{ct} = -(S_{xy})_{tc} = (S_{xx} - S_{yy})_{cc}\tfrac{1}{2} \sin 2\phi \qquad (13)$$

and (13) where ϕ is the angle between the axes joining the oxygen atoms in the asymmetric and symmetric rotamers (here 16° 48′). With such an assumption

the number of independent ordering elements becomes 2 and a solution is found for *O-cis–cis* = 73, *O-trans–trans* = 0, and *O-cis–trans* = 27% (Table 3).

Conclusions.—It is gratifying that, irrespectively of the hypotheses and approximations employed, the ratios of the rotational isomers turn out to be sub-stantially the same, and this allows us to conclude that the more stable conformation is the *O-cis–cis* (70—80%) and the less stable the *O-trans–trans* (1—2% or less), the remaining 20—30% being accounted for by the equivalent asymmetric conformers *O-cis–trans* and *O-trans–cis*. Such a conclusion is in agreement with the e.s.r. observations on the corresponding radical anion [1] although the quantitative aspect is not exactly matched by any of the three models discussed. It is noteworthy that the liquid-crystal results agree quantitatively with a dipole-moment assignment of the rotamers in the same molecule [17] the preferred *O-cis–cis* conformation having been explained by the existence of attractive interactions between partially charged sulphur and oxygen atoms.[17,18] Therefore the slight difference observed between the conformer ratio in the neutral molecule and that in the negative radical might be due to the stabilizing effect of the counterion on the *O-cis–cis* rotamer; the lowering of the energy level of this form with respect to that in the neutral molecule might also contribute the negative charge imported by the unpaired electron. For, if the sulphur–oxygen interactions contribute to determine the preferred conformation, they are expected to be even greater in the radical anion owing to the large delocalization of the spin density on the carbonyl oxygen atom. The differences in solvents and tem-peratures employed in the e.s.r. and n.m.r. experiments might also play a role in affecting the populations of the rotamers.

[17] H. Lumbroso and P. Pastour, *Compt. rend.*, 1965, **261**, 1279; H. Lumbroso, D. M. Bertin, M. Robba, and B. Roques, *ibid.*, 1966, **262**, 36.

[18] E. Roques, S. Combrisson, C. Riche, and C. Pascard Billy, *Tetrahedron*, 1979, **26**, 355; B. Roques and M. C. Fournie-Zaluski, *Org. Magnetic Resonance*, 1971, **3**, 305.