Continuous bond rotation models for the conformational analysis of the methoxy groups in 1,2-dimethoxy- and 1,2,3-trimethoxy-benzene using dipolar couplings obtained from the NMR spectra of oriented samples in nematic liquid crystalline solutions

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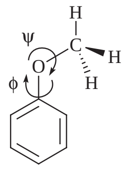
The conformational probabilities generated by rotations about the ring–oxygen bonds in 1,2-dimethoxy- (DMB) and 1,2,3-trimethoxy-benzene (TMB) are determined by comparing observed and calculated ^{1}H–^{1}H dipolar couplings, D_{ij}. The D_{ij} values are obtained by the analysis of the ^{1}H NMR spectra of samples of DMB and TMB dissolved in nematic liquid crystalline solvents. The calculated D_{ij} are obtained by averaging over the conformations which are obtained by taking 5° steps in bond rotational angles, with the severely sterically hindered conformers being eliminated by including a steric term in the bond rotational energies. It is shown that the conformational distributions obtained are strongly dependent on the form adopted for this steric term. The results obtained are compared with conformational distributions obtained by analysing the same data with a rotational isomeric state (RIS) model in which the molecules are assumed to exist in a small number of discrete conformations. It is concluded that the RIS model produces a reasonable approximation to the correct distribution for DMB, but not for the much more sterically hindered TMB.

Introduction

Both experiments and molecular orbital theory concur in concluding that anisole in the gas or liquid state has hindered rotation about the ring–oxygen bond, such that the lowest energy form has the methyl carbon atom in the plane of the benzene ring.[1–3] Thus, the potential for rotation about the ring–O bond through ϕ has a global minimum at $\phi = 0$ or 180°, and there is a secondary, shallow minimum at $\phi = 90°$. Rotation about the O–C bond through ψ is strongly hindered when $\phi = 0$ or 180°, and is almost freely rotating when $\phi = 90°$.



The conformations in the liquid state of di- and tri-methoxybenzenes have been investigated by a number of experimental methods (see refs. 4 and 5 for a review of these data). In all these studies the experimental data have been interpreted by assuming that the conformational distributions can be approximated as being a discrete set of structures, and these have been assumed to be those in which the methoxy groups are either in the ring plane, or orthogonal to it, as shown in Figs. 1 and 2. In 1,2-dimethoxybenzene (DMB) the rotations about the two ring–oxygen bonds is strongly hindered, such that structure **1(1)** has a much lower energy than **1(2)** (see Fig. 1). In 1,2,3-trimethoxybenzene (TMB), **2**, the steric hindrance to rotation is similar to that in **1** for the two outer methoxy groups, but much greater for the inner methoxy group. In the solid state the molecule exists as structure **2(1)** in Fig. 2.

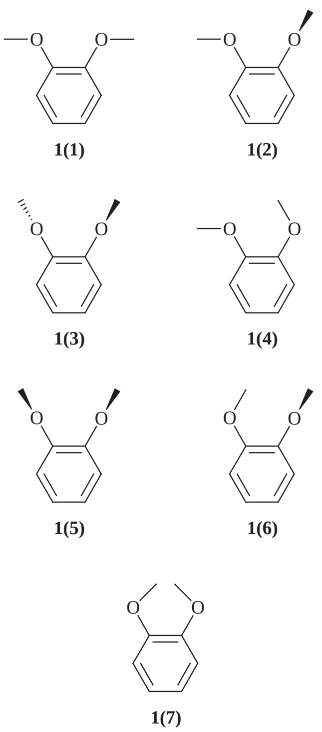

1(1) **1(2)** **1(3)** **1(4)** **1(5)** **1(6)** **1(7)**

Fig. 1 Discrete conformations used in the jump (RIS) model for DMB

This jump (rotational isomeric state, or RIS) model is clearly an approximation to the true conformational distribution, and has been made only in order to simplify the conformational analysis. The simplification is considerable, and is of two kinds. First, the number of conformations is small, which reduced the computational problem to an easily manageable size. Secondly, it is not necessary to identify how the potential energy, $V(\{\phi\})$, varies with the set, $\{\phi\}$, of bond rotation angles. The RIS conformational distribution is determined only by the energy

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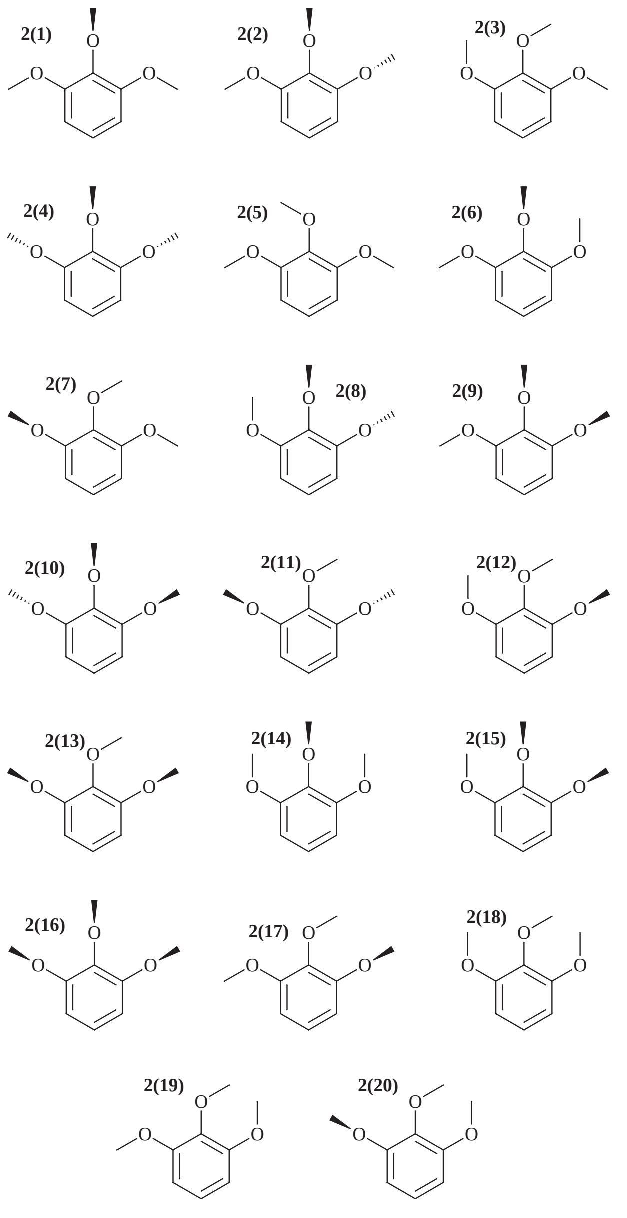


Fig. 2 Discrete conformations used in the jump (RIS) model for TMB

differences between the low energy forms at minima in the potential. Conformations which are sterically hindered have high energies and are excluded from the analysis. The most important defect in the jump model is the neglect of oscillations about minimum energy positions, and it is this aspect which is addressed here by taking into account the form of $V(\{\phi\})$.

One of the methods used previously to study the conformational distributions in both DMB[4] and TMB[5] was to record and analyse their NMR spectra as solutes dissolved in a liquid crystalline solvent. This yields a set of dipolar couplings, D_{ij}, whose values depend on the interproton distances, the degree of orientation of the molecules in the ordered phase and on the intramolecular motions. It has been shown that it is possible to test models for conformational distributions by comparing observed interproton D_{ij} with those calculated by theoretical models which take into account the conformational dependence of orientational order. Only the RIS model was tested for the two compounds and here we compare the results from the RIS model with a treatment of the data using averaging of the dipolar coupling by sampling the full surface generated by rotations about the ring–oxygen bonds. As will be seen, however, this greatly increases the computational task if $V(\{\phi\})$ is to be sampled at small angle intervals. It is also necessary to specify a particular form for $V(\{\phi\})$. The general way of doing this when steric hindrance is not important is to use a truncated Fourier series. For DMB and TMB, in which steric hindrance is very important, we have explored the effectiveness of including a simple Lennard–Jones type of steric term in $V(\{\phi\})$.

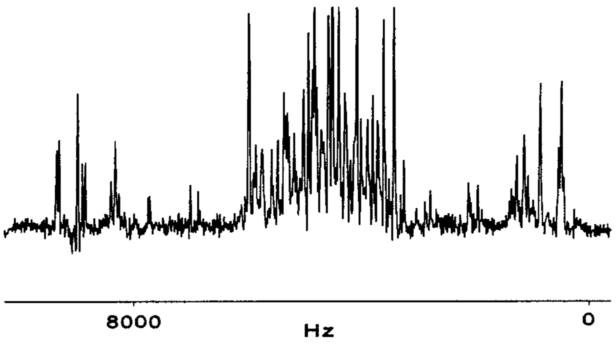
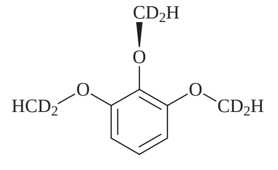


Fig. 3 200 MHz ^1H–{^2H} NMR spectrum of [1,1,2,2,3,3-$^2H_6$]1,2,3-trimethoxybenzene dissolved in the nematic liquid crystalline solvent I35 at 300 K. The free induction decays (400) were accumulated into 4 K data points, and the spectral width was 20 840 Hz. A Lorentzian to Gaussian transformation was applied to diminish the background from the solvent, and to enhance the resolution.

The previous experimental study on DMB obtained the full set of D_{ij} between the protons, and these are used here. In the case of TMB the previous study was of molecules containing two CD_3 groups. This was used to produce a simplified proton spectrum by deuterium decoupling, and enabled dipolar coupling to be obtained between ring and methyl protons, but not between different methyl groups. A complete set of D_{ij} values has now been obtained by recording the deuterium decoupled proton spectrum of TMB containing three CD_2H groups. The conformational distribution may in principle also depend on the chemical structure of the liquid crystal solvent, and this has been investigated by obtaining and analysing dipolar coupling for TMB dissolved in two different solvents.

Experimental

The sample of [$^2H_6$]TMB was synthesized by the method



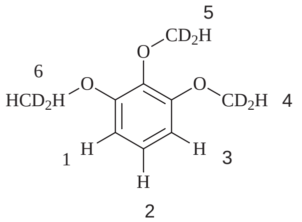
described previously,[5] but using CD_2HI instead of CD_3I. Deuterium-decoupled ^1H NMR spectra were obtained at 300 K on a Bruker MSL 200 spectrometer for samples of [$^2H_6$]TMB (10% by weight) dissolved in the nematic liquid crystalline solvents I35 (Fig. 3) and ZLI 1167 (Fig. 4), both solvents being purchased from Merck Ltd. Iterative analysis of the spectra yielded the data in Table 1, where the errors quoted are those from the least-squares fitting process and are the standard errors based on the standard deviations.

The ^1H NMR spectra of [$^2H_6$]TMB do not yield the intramethyl ^1H–^1H couplings D_{44}, D_{55} and D_{66}. These were obtained by comparing the quadrupolar splittings, $\Delta\nu_4$ and $\Delta\nu_5$ obtained from the deuterium spectra of [$^2H_6$]TMB with the ratios $\Delta\nu_i/D_{ii}$ obtained for the compounds containing CD_3 and CH_3 groups. The quadrupolar splitting in a CD_3 group depends on the order parameter, S_{CD}, for the C–D bond, and q_{CD}, the deuterium quadrupolar coupling constant [eqn. (1)]. The dipolar coupling D_{ii} is given by eqn. (2), where μ_o is the magnetic constant, γ_H is

$$\Delta\nu_i = (3/2)\, q_{CD} S_{CD} \qquad (1)$$

$$D_{ii} = -(\mu_0/4\pi)(\gamma^2_H h/4\pi^2 r_{ii}^3) S_{ii} \qquad (2)$$

Table 1 Dipolar couplings and relative chemical shifts obtained from the analysis of the ^{1}H–{^{2}H} NMR spectrum of [1,1,2,2,3,3-^{2}H$_6$]1,2,3-trimethoxybenzene dissolved in the nematic liquid crystalline solvents I35 and ZLI 1167



i j	D_{ij}/Hz I35	ZLI 1167
1 2	−1611.8 ± 0.5	815.7 ± 1.4
1 3	−409.9 ± 1.6	215.1 ± 3.1
1 4	−109.5 ± 0.7	51.6 ± 1.2
1 5	−20.4 ± 0.7	3.1 ± 1.0
1 6	−605.8 ± 0.6	290.2 ± 1.0
2 4	−145.9 ± 0.4	70.7 ± 1.0
2 5	7.7 ± 1.1	−7.2 ± 1.6
4 6	−64.9 ± 0.9	36.2 ± 0.8
5 6	−141.7 ± 0.6	62.6 ± 0.6
4 4	1686.5 ± 10.8	−983.9 ± 9.4
5 5	−1348.9 ± 10.1	635.9 ± 6.7

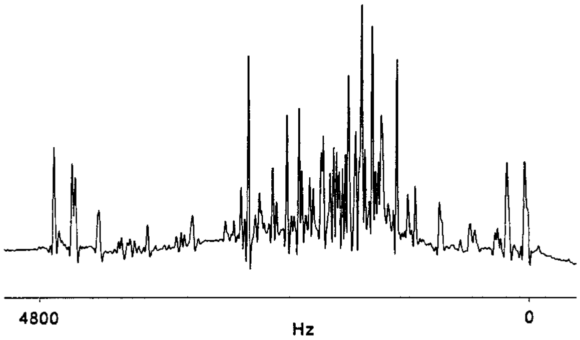


Fig. 4 200 MHz ^{1}H–{^{2}H} NMR spectrum of [1,1,2,2,3,3-^{2}H$_6$]1,2,3-trimethoxybenzene dissolved in the nematic liquid crystalline solvent ZLI 1167 at 300 K. The free induction decays (400) were accumulated into 4 K data points, and the spectral width was 20 840 Hz. A Lorentzian to Gaussian transformation was applied to diminish the background from the solvent, and to enhance the resolution.

the gyromagnetic ratio of the proton, r_{ii} is the separation of the two protons and S_{ii} is an order parameter for the vector $\boldsymbol{r}_{ii}$. The methyl groups rotate about the O–C bonds, and if they are assumed to be rigid with three-fold rotation symmetry, then S_{CD} and S_{ii} are both related to S_{OC}, the order parameter for the O–C bond, by eqns. (3) and (4), where α is the angle between $\boldsymbol{r}_{ii}$

$$S_{ii} = S_{\mathrm{OC}}(3\cos^2\alpha - 1)/2 \qquad (3)$$

$$S_{\mathrm{CD}} = S_{\mathrm{OC}}(3\cos^2\beta - 1)/2 \qquad (4)$$

and the O–C bond, and β is the angle between the O–C and C–D bonds. Combining eqns. (1)–(4) gives eqn. (5), which is

$$\Delta\nu_i/D_{ii} = -[24q_{\mathrm{CD}}\pi^4 r_{ii}{}^3(3\cos^2\beta - 1)]/[\mu_0\gamma_{\mathrm{H}}{}^2 h(3\cos^2\alpha - 1)] \qquad (5)$$

independent of the orientational order, and has a value determined only by the geometry of the methyl group, and the value of q_{CD}, which is expected to be essentially a constant for all methyl groups. The ratio has been measured for the inner and outer methyl groups of TMB, with the results:[5] $\Delta\nu_5/D_{55} = -7.60 \pm 0.06$ and $\Delta\nu_4/D_{44} = -7.25 \pm 0.04$. The values of $\Delta\nu_4$ and $\Delta\nu_5$ obtained from the ^{2}H NMR spectra of the [^{2}H$_6$]TMB samples dissolved in the two liquid crystalline solvents are given in Table 2, and the dipolar couplings derived from them are included in Table 1.

Table 2 Quadrupolar splitting, $|\Delta\nu_i|$, for the deuterium nuclei in [1,1,2,2,3,3-^{2}H$_6$]1,2,3-trimethoxybenzene dissolved in the nematic liquid crystalline solvents I35 and ZLI 1167

Position	$|\Delta\nu_i|$/Hz I35	ZLI 1167
5	10 257.3 ± 1.4	4835.1 ± 15.0
4	12 228.5 ± 4.0	7134.3 ± 25.0

Determination of conformational distributions from dipolar couplings

The dipolar couplings are averages over both the motion of the molecule in the liquid crystalline phase and the conformations adopted by virtue of rotations about bonds. They are related to $D_{ij}(\beta,\gamma,\{\phi\})$, their value at a fixed orientation and conformation, by eqn. (6), where $P_{\mathrm{LC}}(\beta,\gamma,\{\phi\})$ is the probability density that

$$D_{ij} = \int D_{ij}(\beta,\gamma,\{\phi\})P_{\mathrm{LC}}(\beta,\gamma,\{\phi\})\sin\beta\,\mathrm{d}\beta\,\mathrm{d}\gamma\,\mathrm{d}\{\phi\} \qquad (6)$$

the molecule is in a conformation defined by the set of bond rotational angles, $\{\phi\}$, and is at an orientation with the applied magnetic field specified by the polar angles γ and β. The averaging over β and γ leads to conformationally-dependent order parameters $S_{zz}(\{\phi\})$ and $S_{xx}(\{\phi\}) - S_{yy}(\{\phi\})$ to give eqn. (7). Here x,y,z are principal axes for $S(\{\phi\})$, and $D_{ij}(\{\phi\})$

$$D_{ij}(\{\phi\}) = -(\mu_0/4\pi)(h\gamma_i\gamma_j/8\pi^2 r_{ij\{\phi\}}{}^3)[S_{zz}(\{\phi\})(3\cos^2\theta_{ijz\{\phi\}} - 1) + (S_{xx}\{\phi\} - S_{yy}\{\phi\})(\cos^2\theta_{ijx\{\phi\}} - \cos^2\theta_{ijy\{\phi\}})] \qquad (7)$$

is the dipolar coupling in a fixed conformation. The angles $\theta_{ijx\{\phi\}}$, $\theta_{ijy\{\phi\}}$ and $\theta_{ijz\{\phi\}}$ are between $\boldsymbol{r}_{ij\{\phi\}}$ and the x, y and z axes, respectively.

The values of the elements of $S(\{\phi\})$ can be obtained by first defining an average potential for the solute molecule in the liquid crystalline phase as eqn. (8), where Z is defined in eqn. (9).

$$U(\beta,\gamma,\{\phi\}) = -RT\ln[P_{\mathrm{LC}}(\beta,\gamma,\{\phi\})] - RT\ln Z \qquad (8)$$

$$Z = \int\exp[-U(\beta,\gamma,\{\phi\})/RT]\sin\beta\,\mathrm{d}\beta\,\mathrm{d}\gamma\,\mathrm{d}\{\phi\} \qquad (9)$$

The additive potential (AP) method will be used to model the potential, and in this case $U(\beta,\gamma,\{\phi\})$ is written as eqn. (10),[6]

$$U(\beta,\gamma,\{\phi\}) = U_{\mathrm{ext}}(\beta,\gamma,\{\phi\}) + U_{\mathrm{int}}(\{\phi\}) \qquad (10)$$

where $U_{\mathrm{ext}}(\beta,\gamma,\{\phi\})$ is a potential of mean torque and $U_{\mathrm{int}}(\{\phi\})$ is that part of the mean potential which depends only on $\{\phi\}$ and which does not vanish in the isotropic phase. The probability, $P_{\mathrm{iso}}(\{\phi\})$, that the molecule is in a conformation $\{\phi\}$ in an isotropic phase is given by eqn. (11), with Q defined in eqn. (12). In general $P_{\mathrm{iso}}(\{\phi\})$ will differ from $P_{\mathrm{LC}}(\{\phi\})$, which is the

$$P_{\mathrm{iso}}(\{\phi\}) = Q^{-1}\exp[-U_{\mathrm{int}}(\{\phi\})/RT] \qquad (11)$$

$$Q = \int\exp[-U_{\mathrm{int}}(\{\phi\})/RT]\mathrm{d}\{\phi\} \qquad (12)$$

probability of a conformation when the molecule is in the liquid crystalline phase, but which is independent of the orientation. It is given by eqn. (13).

$$P_{\mathrm{LC}}(\{\phi\}) = Z^{-1}\int\exp[-U(\beta,\gamma,\{\phi\})/RT]\sin\beta\,\mathrm{d}\beta\,\mathrm{d}\gamma \qquad (13)$$

The potential of mean torque, $U_{\mathrm{ext}}(\beta,\gamma,\{\phi\})$, is expressed by eqn. (14), where $\varepsilon_{2,0}(\{\phi\})$ are conformationally-dependent

$$U_{\mathrm{ext}}(\beta,\gamma,\{\phi\}) = -\varepsilon_{2,0}(\{\phi\})C_{2,0}(\beta,\gamma) - 2\varepsilon_{2,2}(\{\phi\})C_{2,2}(\beta,\gamma) \quad (14)$$

interaction parameters, and $C_{2,m}(\beta,\gamma)$ are modified spherical harmonics. The conformation dependence of the interaction coefficients is modelled in the AP method by expressing them as sums of contributions, $\varepsilon_{2,p}(j)$, from each of the j rigid sub-units in the molecule, giving eqn. (15), where the Wigner functions,

$$\varepsilon_{2,m}(\{\phi\}) = \Sigma_j\Sigma_p\varepsilon_{2,p}(j)D_{p,m}{}^2(\Omega_j) \quad (15)$$

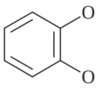
$D_{p,m}{}^2(\Omega_j)$, describe the orientation of j in the molecular reference frame.

The order parameters, such as $S_{zz}(\{\phi\})$, are related to $U_{\mathrm{ext}}(\beta,\gamma,\{\phi\})$ by eqn. (16) with Z' defined by eqn. (17).

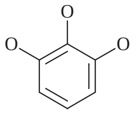
$$S_{zz}(\{\phi\}) = Z'\int\tfrac{1}{2}(3\cos^2\beta - 1)\exp\,[-U_{\mathrm{ext}}(\beta,\gamma,\{\phi\})/RT]\sin\beta\,\mathrm{d}\beta\,\mathrm{d}\gamma \quad (16)$$

$$Z' = \int\exp\,[-U_{\mathrm{ext}}(\beta,\gamma,\{\phi\})/RT]\sin\beta\,\mathrm{d}\beta\,\mathrm{d}\gamma \quad (17)$$

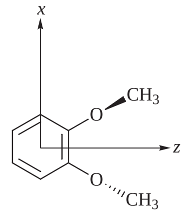
The sub-units, j, for the methoxybenzenes for DMB and TMP (shown below) both require $\varepsilon_{2,0}{}^{\mathrm{R}}$ and $\varepsilon_{2,2}{}^{\mathrm{R}}$, and O–CH$_3$ for



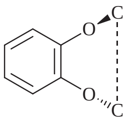
for DMB and



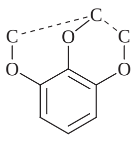
both molecules, which requires just $\varepsilon_{2,0}{}^{\mathrm{OC}}$ since it is cylindrically symmetric. Constructing $U_{\mathrm{ext}}(\beta,\gamma,\{\phi\})$ from these fragments alone does not allow correctly for the changes which occur on rotation about the ring–O bonds. Thus, the conformer below is



predicted to have only $\varepsilon_{2,0}(90°,90°)$ and $\varepsilon_{2,\pm2}(90°,90°)$ non-zero, that is xyz are principal axes for $\varepsilon(90°,90°)$, which is not consistent with the symmetry of this structure, which is such that $\varepsilon_{2,\pm1}(90°,90°)$ should also be non-zero. A similar problem was noted by Photinos *et al.*[7] for *n*-alkanes, and they introduced an additional fragment tensor component, $\varepsilon_{2,0}{}^{\mathrm{chord}}$, for the vector connecting the midpoints of adjacent C–C bonds. The same idea is used here for TMB and DMB, but now the chords are between the methyl C atoms. These elastic chords are assumed



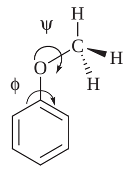
and



to contribute a constant value, $\varepsilon_{2,0}{}^{\mathrm{chord}}$, to the interaction tensor, and thus no allowance is made for the changing length of the chord.

Internal potential $U_{\mathrm{int}}(\{\phi\})$

Even in anisole the motion of the methoxy group is complex.[3] Thus, when ϕ is 0 or 180° there is considerably greater repulsion between the ring and the methoxy group than when ϕ is 90°. This has the consequence of increasing the bond angles, and of increasing the barrier to rotation about the O–C bond through ψ for the in-plane compared with the out-of-plane structure. The geometry distortions and rotational barrier changes will be more important for DMB and TMB, but these have not been taken into account here, since to do so would make the iterative calculations impossibly long. It is also not practicable to average the dipolar coupling over more than three bond rotational motions with currently available computer power, and so the methyl group rotations are simplified to being jumps between three equivalent conformations.



Small amplitude vibrational motion also affects the dipolar couplings, but has been neglected here. For rigid molecules the effect of vibrational motion is typically of the order of a 1% change in the dipolar couplings between protons. A method for computing the vibrational averaging of dipolar couplings between nuclei in flexible molecules has yet to be devised, and would be a formidable task. The neglect of vibrational averaging, however, is probably the least important approximation that is made here for molecules which have large amplitude, sterically-hindered motion.

The potential for rotation about the ring–O bonds will be described by the form given in eqn. (18). The summation in the

$$V(\{\phi\}) = \Sigma_n\Sigma_i\mathrm{V}_{ni}\cos n\phi_i + \Sigma_{j,k}E_{jk}[(A_{jk}/r_{jk})^p - (A_{jk}/r_{jk})^q] \quad (18)$$

second term is over j and k being atoms separated by more than three bonds, and this term will be referred to as the steric term. The values of E_{jk} and A_{jk} are calculated from $E_{jk} = \frac{1}{2}(E_j + E_k)$ and $A_{jk} = (A_jA_k)^{\frac{1}{2}}$, where E_j and A_j are atomic values taken from Spellmeyer *et al.*[2] These values were optimised for $p = 12$ and $q = 6$, but this form of the steric term, which is usually referred to as the Lennard–Jones (LJ) form, is not strictly appropriate for the rotational model in which there is no geometry relaxation. We have therefore explored the effect of changing the values of p and q, whilst retaining the values of E_j and A_j. The different forms of the steric term will be referred to as $(p–q)$. The most important role of the steric term in the calculations with our model is to exclude severely hindered structures. The attractive term, that dependent on q, is not necessary to achieve conformer exclusion, and its role in determining the shape of the potential may perhaps be subsumed into the Fourier coefficients, and so calculations were made in which this term is omitted.

The conformational distributions were obtained by calculating the dipolar couplings for a particular set of values of the fragment interaction tensors, $\varepsilon_{2,m}(j)$, and the potential energy Fourier coefficients, V_{ni}, the model parameters, for a fixed form of the steric term, and comparing these with those observed to form the error function [eqn. (19)], where M is the number of

$$R = \Sigma_{i<j}\,[\Delta D_{ij}{}^2/(M - N)]^{\frac{1}{2}} \quad (19)$$

independent dipolar couplings, N is the number of variable parameters, and $\Delta D_{ij} = D_{ij}(\mathrm{observed}) - D_{ij}(\mathrm{calculated})$.

The best fit parameters were obtained by minimising R with the NAG® (Numerical Algorithm Group Ltd.) routine E04FCF. Note that the errors quoted on the optimised parameters are those obtained in the fitting process, but the values obtained for the V_{in} and the fragment ε values depend strongly on the model chosen for the steric term.

Table 3 Results from fitting calculated to observed dipolar couplings, D_{ij} for DMB by varying the interaction coefficients, $\varepsilon_{2,0}{}^{R}$, $\varepsilon_{2,2}{}^{R}$, $\varepsilon_{2,0}{}^{OC}$ and $\varepsilon_{2,0}{}^{chord}$ together with the Fourier coefficients V_2 and V_4 for fixed forms (p–q) of the steric term

(p–q)	(12–6)	(9–6)	9
R/Hz	0.98	1.14	1.11
V_2/kJ mol^{-1}	−40.5 ± 0.1	−6.3 ± 0.1	−7.50 ± 0.03
V_4/kJ mol^{-1}	−8.4 ± 0.1	−11.5 ± 0.1	−8.8 ± 0.1
$\varepsilon_{2,0}{}^{R}$/kJ mol^{-1}	4.48 ± 0.01	1.69 ± 0.01	1.71 ± 0.01
$\varepsilon_{2,2}{}^{R}$/kJ mol^{-1}	1.24 ± 0.01	0.54 ± 0.01	0.53 ± 0.01
$\varepsilon_{2,0}{}^{OC}$/kJ mol^{-1}	0.88 ± 0.01	0.20 ± 0.01	1.00 ± 0.01
$\varepsilon_{2,0}{}^{chord}$/kJ mol^{-1}	0.92 ± 0.01	0.47 ± 0.01	0.44 ± 0.01

i j	$D_{ij}{}^{obs}$/Hz[4]	ΔD_{ij}/Hz
1 2	−1200.06 ± 0.04	−0.57
1 3	−112.74 ± 0.06	0.09
1 4	−35.69 ± 0.08	0.97
1 5	−34.80 ± 0.03	−0.93
1 6	−865.65 ± 0.03	−0.12
2 3	−277.72 ± 0.08	0.013
2 5	−56.63 ± 0.05	0.55
2 6	−153.21 ± 0.05	2.13
5 5	215.96 ± 0.04	0.02
5 6	−16.92 ± 0.05	0.42

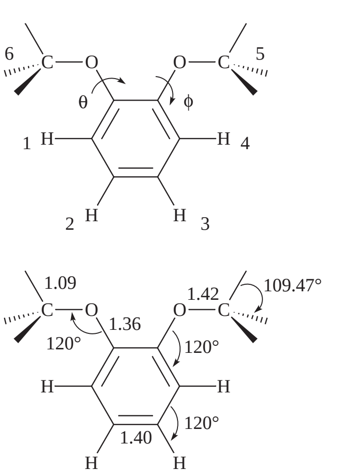


Fig. 5 Atomic labelling, angle definitions and the geometry used for DMB. The aromatic ring has the geometry of a regular hexagon.

Results and discussion

1,2-Dimethoxybenzene

The geometry, which is the same as that used by Emsley *et al.*,[4] atomic labelling and angle definitions for DMB are shown in Fig. 5. The potential energy $V(\theta,\phi)$ is given by eqn. (20).

$$V(\theta,\phi) = V_2(\cos 2\theta + \cos 2\phi) + V_4(\cos 4\theta + \cos 4\phi) + \Sigma_{j,k}\, E_{jk}[(A_{jk}/r_{jk})^p - (A_{jk}/r_{jk})^q] \quad (20)$$

The angles for rotation of each methoxy group were sampled in 5° steps. Terms involving V_2 and V_4 are included because in the absence of a steric term in eqn. (20) both Fourier coefficients are necessary in order to have the possibility of a minimum in $V(\theta,\phi)$ when θ or ϕ are between 0 and 90°, or minima when either θ or ϕ are 0 or 90°. Calculations were carried out in which the form of the steric term was fixed, and V_2, V_4, $\varepsilon_{2,0}{}^{R}$, $\varepsilon_{2,2}{}^{R}$, $\varepsilon_{2,0}{}^{OC}$ and $\varepsilon_{2,0}{}^{chord}$ varied to bring observed and calculated dipolar couplings into best agreement. Three forms for the steric term were used: a 12–6, a 9–6 and a 9, and the optimised parameters are given in Table 3. The lowest R value was obtained with the 12–6 form for the steric term, but the fits to the data with the 9–6 and 9 forms also give an acceptable rms error. The D_{ij} values obtained previously[4] are compared with the individual ΔD_{ij} values obtained with the 12–6 potential in Table 3; all the ΔD_{ij} are <3%, and similar magnitudes of these deviations were obtained with the other two forms for the steric term. The distributions, $P_{LC}(\theta,\phi)$, obtained are shown in Fig. 6. For this molecule $P_{LC}(\theta,\phi)$ and $P_{iso}(\theta,\phi)$ were determined to be essentially identical, which is to be expected for a molecule which is not strongly ordered in the liquid crystalline solvent. The three distributions $P_{LC}(\theta,\phi)$ obtained with different forms for the steric term are very similar, each having a global maximum at $\theta = \phi = 0°$, structure **1(1)** in Fig. 1. The effect of increasing the range of the steric term is to concentrate the probability into being non-zero only close to the two forms **1(1)** and **1(2)** in

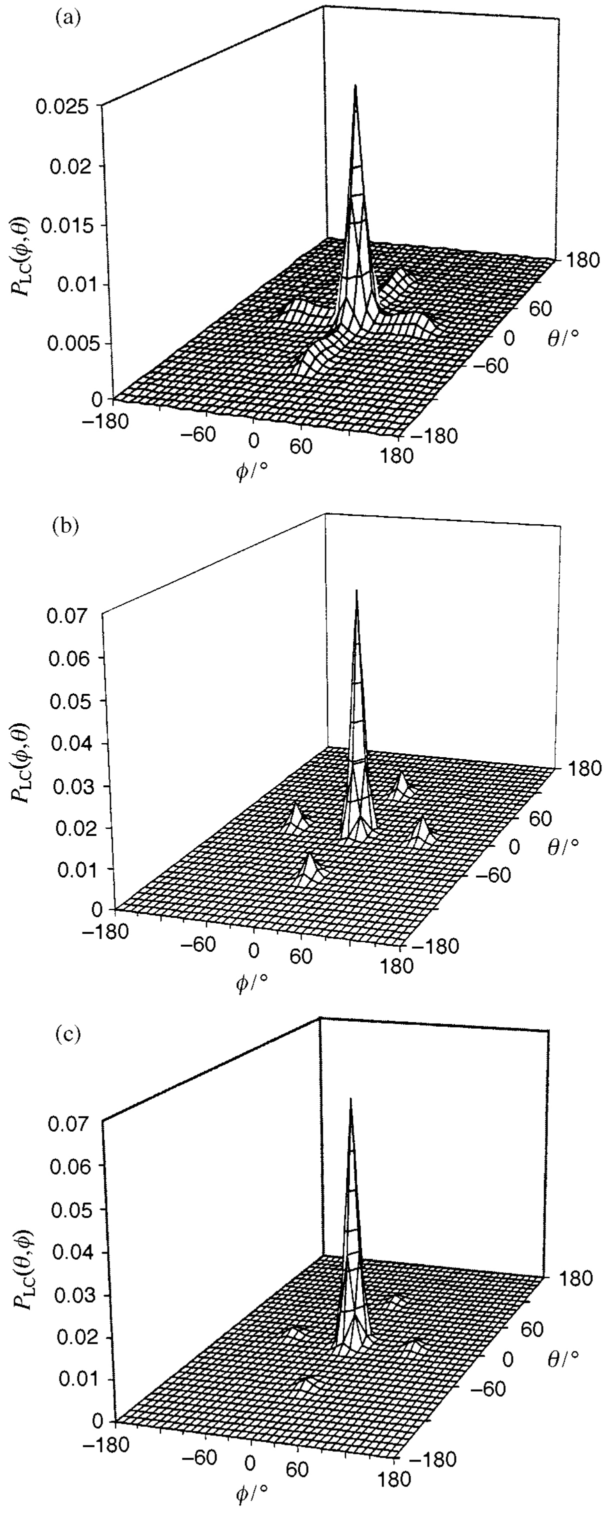


Fig. 6 Probability distributions $P_{LC}(\theta,\phi)$ obtained for DMB as a solute in the nematic liquid crystal ZLI 1132. The three distributions are for (a) the 12–6, (b) the 9–6 and (c) the 9 forms of steric term in the internal energy.

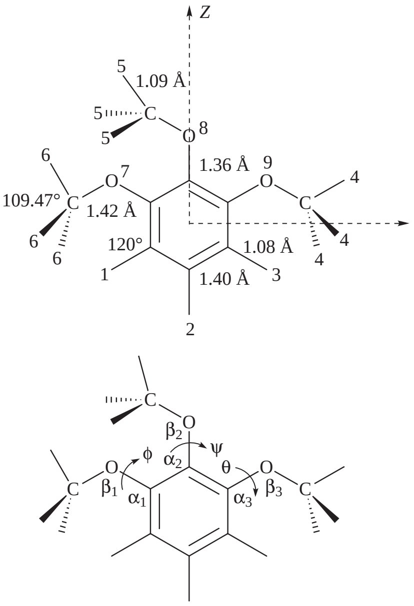


Fig. 7 Atomic labelling, angle definitions and the geometry used for TMB. The aromatic ring has the geometry of a regular hexagon.

Fig. 1, which is the result obtained by the jump model, which gave a ratio of 74% to 25% for these two conformations.[4] The amount of conformer **1(1)** for the continuous rotation model can be estimated by integrating $P_{\mathrm{LC}}(\theta,\phi)$ in the range $\phi = 0 \pm 15°$, $\theta = 0 \pm 15°$, and is determined to be 44% for the 12–6, 67% for the 9–6, and 81% for the nine forms of the steric term, hence the 9–6 form gives a result closest to that obtained by the RIS model.

1,2,3-Trimethoxybenzene

Analysis of the data with a continuous bond rotational model. The geometry, atomic labelling and angle definitions for TMB are shown in Fig. 7. The internal potential $V(\phi,\psi,\theta)$ is given by eqn. (21). Steric hindrance is a much more important effect in

$$V(\phi,\psi,\theta) = V_{21}(\cos 2\phi + \cos 2\theta) + V_{22}\cos 2\psi + V_{41}(\cos 4\phi + \cos 4\theta) + V_{42}\cos 4\psi + \Sigma_{j,k}\, E_{jk}[(A_{jk}/r_{jk})^{p} - (A_{jk}/r_{jk})^{q}] \quad (21)$$

TMB compared to DMB, which means that the choice of the values of p and q in eqn. (18) is more critical. Stressing that the use of a truncated Fourier series plus a steric term is an attempt to model the probability distribution with the smallest number of adjustable parameters, it was found convenient to use $p = 6$ and to omit the attractive term, whose role in determining the shape of the conformer distribution is absorbed into the Fourier coefficients. The motion about the O–CH$_3$ bonds, as with DMB, was assumed to be jumps between three equivalent positions. The angles α_i and β_i (see Fig. 7) were assigned the values $\alpha_1 = \alpha_3 = 124°$, $\alpha_2 = 120°$, $\beta_1 = \beta_2 = \beta_3 = 120°$ for structure **2(1)**. The rotation was about a direction corresponding to these angles being 120°. This has the effect of changing α_1, for example, from 124° when $\phi = 0°$ to 116° when $\phi = 180°$, and is a more realistic path for the methoxy groups than is obtained by rotation with this geometry about the ring–O bond. The O atoms at positions 7 and 9 move out of the ring plane by a maximum of 4° when ϕ or θ is 90°, but this is not directly important in the calculations since these atoms are invisible to NMR. The position of the methyl protons is the important factor, and these will be closest to their expected positions if geometry relaxation were included properly for the most populated forms, and furthest from their expected positions only for the least populated forms. The value used for α_2 is 120°, which ensures that the structures are more correct at the most populated positions.

Table 4 Parameters obtained by fitting the observed D_{ij} (given in Table 1) for TMB dissolved in the nematic liquid crystalline solvents I35 and ZLI 1167 to those calculated with a continuous model for the internal energy containing only V_{2i} Fourier coefficients and the 6 form of the steric term

Parameter	I35	ZLI 1167
R/Hz	3.9	2.5
V_{22}/kJ mol^{-1}	−10.55 ± 0.1	−6.1 ± 0.1
V_{21}/kJ mol^{-1}	−6.55 ± 0.1	−5.4 ± 0.1
$\varepsilon_{2,0}{}^{\mathrm{R}}$/kJ mol^{-1}	1.89 ± 0.02	−0.15 ± 0.02
$\varepsilon_{2,2}{}^{\mathrm{R}}$/kJ mol^{-1}	3.27 ± 0.01	−2.19 ± 0.01
$\varepsilon_{2,0}{}^{\mathrm{OC}}$/kJ mol^{-1}	0.55 ± 0.02	−1.09 ± 0.02
$\varepsilon_{2,0}{}^{\mathrm{chord}}$/kJ mol^{-1}	1.29 ± 0.01	1.10 ± 0.01

i j	ΔD_{ij}/Hz	
1 2	1.76	−1.71
1 3	−10.13	2.12
1 4	−2.01	7.08
1 5	−0.75	0.30
1 6	−1.38	0.53
2 4	8.45	−2.39
2 5	−6.34	1.33
4 6	−4.95	1.70
5 6	0.10	−0.04
4 4	−0.06	0.11
5 5	−0.01	0.11

Calculations were performed with both V_{2i} and V_{4i} terms in eqn. (18), and also with just the V_{2i} terms. The calculations including only V_{2i} terms bring the 11 observed D_{ij} values into agreement with those calculated by varying the 6 parameters $\varepsilon_{2,0}{}^{\mathrm{R}}$, $\varepsilon_{2,2}{}^{\mathrm{R}}$, $\varepsilon_{2,0}{}^{\mathrm{OC}}$, $\varepsilon_{2,0}{}^{\mathrm{chord}}$, V_{21} and V_{22}. The optimised parameters are given in Table 4 for both data sets. The distributions obtained, $P_{\mathrm{LC}}(\phi,\psi,\phi)$, are essentially identical to $P_{\mathrm{iso}}(\phi,\psi,\phi)$, which, as with DMB, is because the orientational order of TMB in the liquid crystalline solvents is small. The $P_{\mathrm{LC}}(\phi,\psi,\phi)$ are four-dimensional, and so are difficult to represent by a single diagram. The main feature of the $P_{\mathrm{LC}}(\phi,\psi,\phi)$ is that there is a single maximum at $\phi = 0°$, $\psi = 90°$ and $\theta = 0°$, conformer **2(1)**, which is the conformation found for TMB derivatives in the solid state, but the methoxy groups oscillate about this structure through a wide angular range. This is illustrated in Fig. 8 where 3D sections are shown for the samples dissolved in I35 and ZLI 1167, where it is seen that the two distributions are very similar. The two outer methoxy groups oscillate about the planar positions by up to ±60°, whereas the middle group oscillates by only ±20°.

Incorporating the V_{4i} terms into the internal potential increases the number of adjustable parameters to eight, and there is a reduction in the rms error of the fit. The optimised parameters are given in Table 5, and the distributions for both samples are shown in Fig. 9. Now the distributions are similar to those of an RIS model, *i.e.* there are narrow peaks in $P_{\mathrm{LC}}(\phi,\psi,\phi)$ at several combinations of the three angles. The most probable conformation is still structure **2(1)** for both the I35 and ZLI 1167 solutions, and with appreciable amounts of **2(5)** and **2(2)** for the I35 sample, and **2(5)**, **2(2)** and **2(17)** for ZLI 1167. An estimate for the relative amounts of these conformers was made from the heights of the peaks in $P_{\mathrm{LC}}(\phi,\psi,\phi)$ at these positions, and these are given in Table 6.

Conformational analysis of TMB with the RIS model. The continuous rotation model for the internal energy is more realistic than a jump model, but its implementation poses problems. Thus, the exclusion of sterically hindered forms requires the use of a repulsion term in the potential, but the correct form for this is uncertain, particularly when used with the assumption of rigid rotors for the methoxy groups. The calculations with the continuous potential for three rotors are also at the limit of what is practicable, and so it is useful to establish whether the much simpler model of jumps between discrete forms gives a

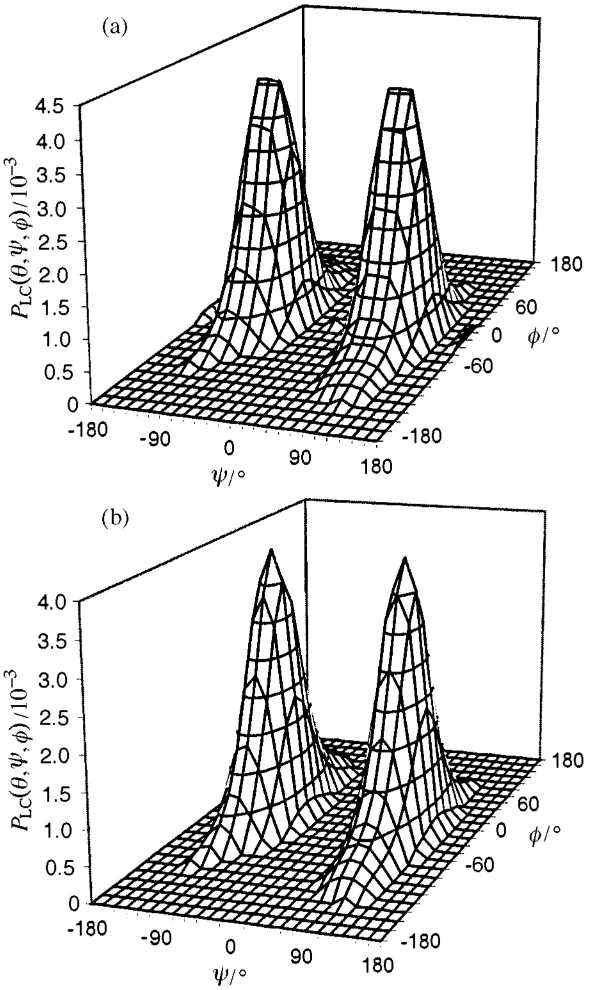


Fig. 8 Sections for $\theta = 0°$ through the distribution $P_{LC}(\theta,\psi,\phi)$ obtained for TMB dissolved in I35 (a) and ZLI 1167 (b) when only the V_{2i} Fourier terms are included in the internal potential. The sections are for $\psi = 90°$ (a), and $\theta = 0°$ (b).

similar result, as is the case for DMB. The jump model obtains $P_{LC}(\phi,\psi,\phi)$ without having to assume a form for the potential, and can easily incorporate different geometries for the conformers. We have therefore analysed the TMB data with the RIS model, and the results are compared with those obtained with the continuous rotation form of the potential.

The new sets of D_{ij} values for the two TMB samples were analysed first by the jump model in the same way, and with the same fixed geometry, following the procedure used for the smaller data set by Emsley *et al.*[5] An acceptable fit to the smaller data set was obtained previously by including only conformers **2(1)** and **2(17)** in the fitting procedure, and so only these two forms were included in attempts to fit the new, larger data sets for the samples dissolved in I35 and ZLI 1167. The fit to the data for the I35 sample is poor, with an R value of 18 Hz, but much better for ZLI 1167, with $R = 3$ Hz. The new data sets allow more conformations to be included in the analysis, and in order to decide which these should be, a semi-empirical molecular orbital calculation was performed on each of the 20 conformations, using the AM1 parametrisation,[8] and in each case optimising the CCO and COC angles, α_i and β_i in Fig. 7. The conformations are ordered in energy, as shown in Fig. 2, and the optimised bond angles are shown in Table 7. On the basis of these results the conformers used in anlysing the dipolar coupling were chosen to be **1**–**6** and **17**, the latter being included for comparison with the results of Emsley *et al.*[5]

Table 6 compares the probabilities P_n(RIS) with those, P_n(CP), obtained from the distribution derived by the continuous potential model and shown in Fig. 9. The main point of note about these results is the large differences between the RIS probabilities for the two solvents compared with the quite similar distributions obtained by the use of a continuous potential.

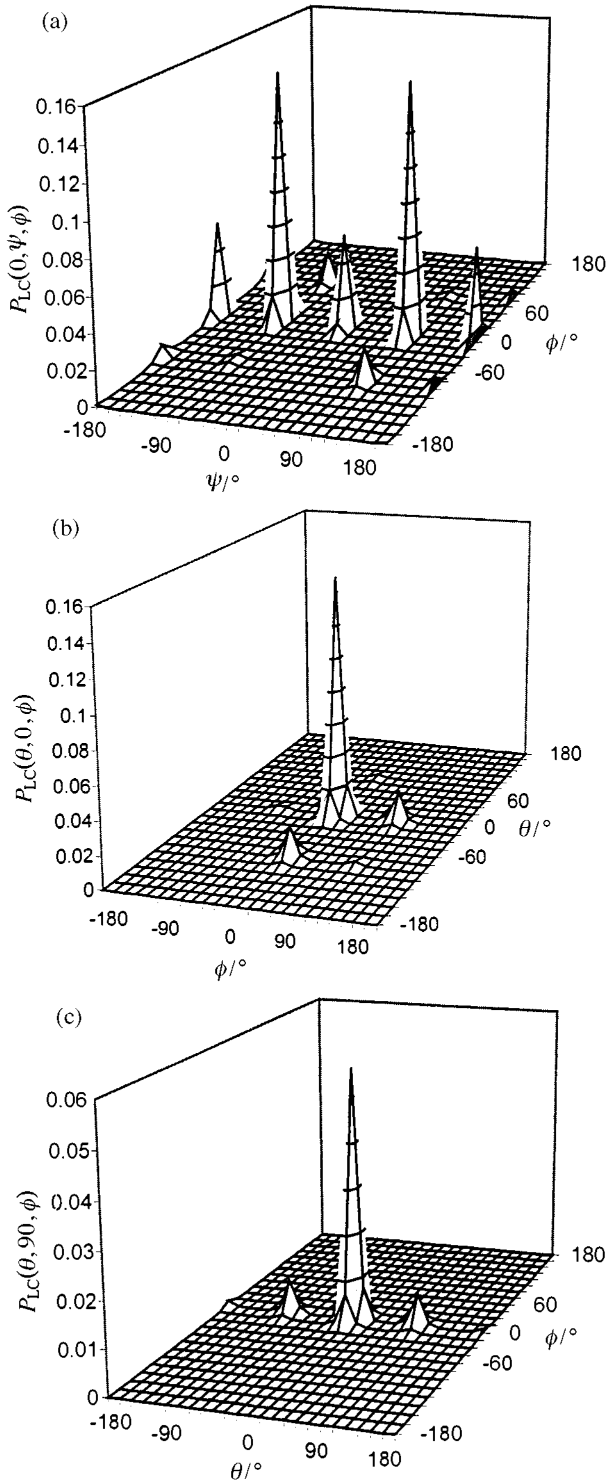


Fig. 9 Sections through the distribution $P_{LC}(\theta,\psi,\phi)$ obtained for TMB dissolved in I35 and ZLI 1167 when both the V_{2i} and V_{4i} Fourier terms are included in the internal potential. The sections are for (a), (b) $\psi = 0°$ and (c) $\psi = 90°$.

Conclusions

The RIS model has the benefit of restricting the rotational distribution to a manageable number of discrete, identifiable, fixed conformations. It is also attractive in giving a distribution of conformers directly, rather than indirectly through the terms in a representation for the potential energy. The RIS model is of course an approximation to the true distribution because it does

Table 5 Parameters obtained by fitting the observed D_{ij} values (given in Table 1) for TMB dissolved in the nematic liquid crystalline solvents I35 and ZLI 1167 to those calculated with a continuous model for the internal energy containing only V_{4i} and V_{2i} Fourier coefficients and the 6 form of the steric term

Parameter	I35	ZLI 1167
R/Hz	1.40	2.1
V_{22}/kJ mol^{-1}	-8.72 ± 0.1	-7.6 ± 0.1
V_{21}/kJ mol^{-1}	-2.77 ± 0.05	-2.6 ± 0.1
V_{42}/kJ mol^{-1}	-52.44 ± 1.0	-38.4 ± 1.0
V_{41}/kJ mol^{-1}	-9.32 ± 0.1	-3.7 ± 0.1
$\varepsilon_{2,0}{}^{R}$/kJ mol^{-1}	0.51 ± 0.02	0.04 ± 0.02
$\varepsilon_{2,2}{}^{R}$/kJ mol^{-1}	1.68 ± 0.01	-0.77 ± 0.01
$\varepsilon_{2,0}{}^{OC}$/kJ mol^{-1}	-0.31 ± 0.02	-0.28 ± 0.02
$\varepsilon_{2,0}{}^{chord}$/kJ mol^{-1}	0.40 ± 0.01	0.20 ± 0.01
i j	ΔD_{ij}/Hz	
1 2	−0.04	−1.1
1 3	−1.76	0.6
1 4	1.42	6.5
1 5	2.02	0.2
1 6	−0.02	−0.2
2 4	0.30	0.7
2 5	−4.89	1.6
4 6	0.11	−0.3
5 6	−0.13	−0.1
4 4	−0.09	0.1
5 5	−0.03	0.1

Table 6 Comparison of the relative conformer populations, P_n, obtained for TMB dissolved in the nematic liquid crystalline solvents I35 and ZLI 1167 when RIS and continuous potential models (CP) are used for the internal energy

	I35		ZLI 1167	
Conformer	P_n(RIS)	P_n(CP)	P_n(RIS)	P_n(CP)
2(1)	38	58	57	67
2(2)	15	17	1	19
2(3)	3	0	11	0
2(4)	0	0	16	0
2(5)	38	21	15	10
2(6)	6	0	0	0
2(17)	0	4	0	4

Table 7 Angles (degrees) α_i and β for TMB derived by the molecular orbital calculations and used in the calculations with the jump model

	$\alpha_1 = \alpha_3$	α_2	$\beta_1 = \beta_3$	β_2
ϕ, ψ or $\theta = \pm 90°$	120	120	113	113
ϕ or $\theta = 180°$	127		119	
$\psi = 0$ or $180°$		128		118
ϕ or $\theta = 0°$	120		116	

not allow for oscillations about probability maxima. The continuous potential model for the conformational distribution, as implemented here, also contains quite major approximations. These are primarily the use of a steric term in the potential, which is necessary in order to eliminate sterically hindered conformations, but which is used without geometry relaxation on rotation.

For DMB the three distributions obtained with different forms of the steric term are very similar to each other in that each shows a global maximum at conformer **1(1)**, and a much weaker secondary maximum at conformer **1(2)**. The distributions differ only in the extent to which conformations close to these maxima are populated. The RIS conformer distribution is qualitatively the same, and, for this molecule, can be judged to give a reasonable approximation to the correct distribution.

For TMB the calculations lead to a less clear cut result. For this very severely hindered molecule the effect of the steric term is much more pronounced, and the approximation of not allowing geometry relaxation to occur is more important. The compromise used of having a weak steric term, which eliminates sterically hindered conformations, but which allows the rest of conformational space to be strongly influenced by the magnitude of the Fourier coefficients, does produce distributions which are reasonable, and which have only a weak dependence, as expected, on the nature of the liquid crystalline solvent. For TMB it is tempting to believe that the model which produces the best fit to the data, that with both V_{2i} and V_{4i} Fourier coefficients, is closer to the truth than that which includes only V_{2i} coefficients. This distribution is similar to a RIS model of discrete conformations, but it is significantly different from the results obtained by analysing the data with the RIS model, not only in allowing oscillations about the minimum energy forms, but also in the relative weights of the conformations. The correct probability distribution will certainly be continuous rather than discrete, and so refinements of the approach adopted here should be sought as computer power makes this possible.

Acknowledgements

We thank EPSRC and the Wellcome Foundation Ltd. (now Glaxo Wellcome) for provision of a CASE award to E. K. F.

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Paper 7/09103F
Received 19*th December* 1997
Accepted 19*th February* 1998