

ORIENTATION OF BENZOTHIOPHENE BY A MAGNETIC FIELD IN THE ISOTROPIC LIQUID PHASE

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The 1H NMR spectra of benzothiophene (a 2 M solution in acetone), recorded on spectrometers with magnetic field intensities of 4.7, 9.39, and 11.74 T, were analyzed with high accuracy. By the use of the method of "many spectrometers" the spin–spin and dipole–dipole coupling constants were obtained for all the pairs of protons, and the orientation parameters for the investigated molecule $\Delta\chi$ and $\delta\chi$, characterizing the anisotropy and asymmetry of the magnetic susceptibility, were obtained.

At the present time one of the main sources of information on molecular structure is the NMR spectrum. Modern NMR spectroscopy is characterized by the use of strong and ultrastrong magnetic fields. Earlier it was shown that a molecule having anisotropy of magnetic susceptibility is capable of being oriented in the constant magnetic field of the spectrometer [1]. In isotropic media the thermal motion of the molecules prevents their ordering, and the resultant orientation is small. The partial orientation of the molecules in liquids and gases due to the anisotropic interactions of the nuclear spins is clearly seen in the NMR spectra. This is the nonaveraged to zero direct dipole–dipole interaction between the nuclei and the interaction between the quadrupole moment of the nucleus and the gradient of the local electric field caused by its environment.

At present the chief tool for the calculation of these small effects and determination of the orientation parameters is measurement of the quadrupole splittings in the 2H NMR spectra for compounds selectively labelled with deuterium. Information on the orientation effects can also be obtained from precise analysis of the PMR spectra in the case where small (in value) dipole–dipole coupling constants (DDCC) lead to strong coupling in the NMR spectra of highly symmetrical molecules with chemical equivalence (benzene [2], naphthalene [3, 4], *ortho*-dichlorobenzene [5], see the discussion in [6]). For molecules of relatively low symmetry, such as benzofuran and benzothiophene, it is almost impossible to give a separate assessment of the spin–spin and dipole–dipole coupling constants from analysis of the NMR spectra recorded at one working frequency. For spectrometers with a high working frequency the PMR spectra of these compounds are of first order. Here, the observed splittings correspond to the sum of the indirect and direct coupling constants. For the reliable identification of these parameters it is necessary to use the spectra recorded on spectrometers with greatly differing working frequencies.

To study the orientation effects systematically in the present work we studied benzothiophene. The PMR spectra of this compound, recorded on spectrometers with magnetic field intensities of 4.7, 9.39, and 11.74 T (200, 400, and 500 MHz respectively for protons), were analyzed. For accurate determination of the orientation parameters we used our previously developed method of "many spectrometers," which is a development of the method of "two spectrometers" (see [1, 7]). This method requires that the spectra obtained for a series of spectrometers with greatly differing working frequencies are used to assess the orientation parameters — the dipole–dipole coupling constants and the anisotropy and asymmetry of magnetic susceptibility. This requires that all other experimental conditions remain unchanged.

The obtained spectra of benzothiophene were first analyzed by means of the LAOCOON5 software [8, 9], described in detail in our previous paper [7]. Preliminary values for the parameters $\Delta\nu_{ij}$ were obtained. In a first-order approximation the $\Delta\nu_{ij}$ values for pairs of protons i and j of oriented molecules represent the algebraic sum of the true spin–spin coupling constants J_{ij} , not dependent on the magnitude of the constant magnetic field B_0 , and twice the values of the dipole–dipole coupling constants D_{ij} , directly proportional to B_0^2 [4, 10]:

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$$\Delta\nu_{ij} = J_{ij} + 2D_{ij} \quad (1)$$

It is clear that for each of the spectra, recorded on instruments with different working frequencies, the quantities

$$\Delta\nu_{ij} (\Delta\nu_{ij}^{200}, \Delta\nu_{ij}^{400}, \Delta\nu_{ij}^{500}) \text{ and } D_{ij} (D_{ij}^{200}, D_{ij}^{400}, D_{ij}^{500})$$

are different, while the J_{ij} values for one and the same pair of nuclei i and j are identical, and (as already mentioned above) only the $\Delta\nu_{ij}$ values are known.

The traditional approach to analysis of the spectrum in order to determine the dipole-dipole coupling constants was based on the use of the full Hamiltonian of the spin system with allowance for the possible anisotropic interactions in terms of the UEA iteration procedure [10]. Here it is necessary to know the true values of the spin-spin coupling constants. The spin-spin coupling constants J_{ij} are fixed during calculation by the UEA program, while the dipole-dipole coupling constants D_{ij} vary. It is clear that it is impossible to do this for one spectrum. However, if there are at least two spectra recorded on instruments with greatly differing working frequencies (e.g., 200 and 400 MHz for ^1H nuclei), the problem can be solved.

For this in order to determine the true values of the spin-spin and dipole-dipole coupling constants, the next stage in the analysis of the spectra is undertaken by means of our previously developed ALIGN iteration procedure, on the algorithm of which the Eq. (1) is based. At the initial stage of the calculation it is assumed that the D_{ij}^{200} values for the downfield spectrum ($B_0 = 4.7$ T; 200 MHz for ^1H nuclei) are negligibly small within the experimental error limits. Then, the initial values of the spin-spin coupling constants J_{ij} for the upfield spectra ($B_0 = 9.39$ T, 400 MHz and $B_0 = 11.74$ T, 500 MHz) are $\Delta\nu_{ij}^{200}$. Starting from this premise, the initial D_{ij}^{400} and D_{ij}^{500} values for the upfield spectra are calculated in terms of the UEA iteration procedure in the form of a subprogram, included in the ALIGN program. Then, in view of the fact that

$$D_{ij}^{400} / D_{ij}^{200} = 3.99 \quad (2)$$

[see Eqs. (3) and (5) below] we obtain values for D_{ij}^{200} , which are used for analysis of the upfield spectra and to obtain J_{ij} . Such a sequence of calculations is repeated in the iteration cycle until the mean-square deviation (MSD) of the frequencies of the lines of the whole series of experimental and theoretical spectra reaches a minimum. The final values of the interproton spin-spin and dipole-dipole coupling constants for the investigated series of spectra of benzothiophene are presented in Table 1.

Theoretical examination of the question of the anisotropic interactions of the nuclear spins [11, 12] gives an expression for the dipole-dipole coupling constant of nuclei i and j :

$$D_{ij} = - \frac{\mu_0 \gamma_i \gamma_j h}{4 \pi 2 \pi^2 r^3} \left[\left\langle \frac{3}{2} \cos^2 \theta - \frac{1}{2} \right\rangle_B \left(\frac{3}{2} \cos^2 \theta_{zz''} - \frac{1}{2} \right) + \right. \\ \left. + \frac{3}{4} (\sin^2 \theta \cos 2\varphi)_B (\cos^2 \theta_{xz''} - \cos^2 \theta_{yz''}) \right], \quad (3)$$

where μ_0 is the magnetic permeability of vacuum, γ is the gyromagnetic ratio of the nucleus, h is Planck's constant, r is the vector linking the interacting nuclei, $\theta_{az''}$ represents the angles between the vector r and the axes of the molecular system of coordinates ($\alpha \in x, y, z$), and the axis z'' of the local coordinate system is directed parallel to the vector r . In the case where the molecule is oriented under the influence of an external magnetic field, the molecular reference system is selected in such a way that the magnetic susceptibility tensor χ in it is diagonal ($\chi_{xy} = \chi_{xz} = \chi_{yz} = 0$) [13], it is sufficient to have two independent orientation parameters averaged with respect to the molecular motion, i.e., the anisotropy ($\Delta\chi$) and asymmetry ($\delta\chi$) of the magnetic susceptibility of the molecule:

$$\Delta\chi = \chi_{zz} - \frac{1}{2} (\chi_{xx} + \chi_{yy}) \\ \delta\chi = \chi_{xx} - \chi_{yy}, \quad (4)$$

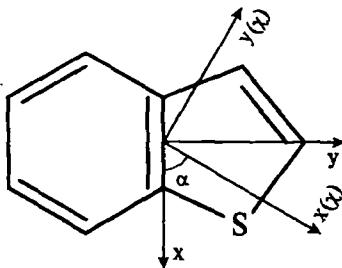


Fig. 1. Diagram of the arrangement of the axes of the molecular coordinate system (x , y , z) and the axes of the magnetic susceptibility tensor $\{x(x), y(x), z(x)\}$ for benzothiophene. The direction of the z and $z(x)$ axes is orthogonal to the plane of the molecule.

which are related unequivocally to the measured dipole-dipole coupling constants D_{ij} [or more accurately to the first and second terms in Eq. (3)]:

$$\begin{aligned} \left\langle \frac{3}{2} \cos^2 \theta - \frac{1}{2} \right\rangle_B &= \frac{1}{15} \frac{\Delta \chi B_0^2}{\mu_0 kT} \\ \left(\sin^2 \theta \cos 2\varphi \right)_B &= \frac{1}{15} \frac{\delta \chi B_0^2}{\mu_0 kT} \end{aligned} \quad (5)$$

where k is the Boltzmann constant, T is absolute temperature, and θ and φ are the polar angles between the direction of the vector of the external magnetic field B_0 and the axes of the molecular coordinate system.

In aromatic compounds the z axis gets to be perpendicular to the plane of the molecule so that $|\Delta \chi| > |\delta \chi|$. In highly symmetrical molecules, such as naphthalene [3], for example, the axes of the molecular coordinate system (x , y , z) coincide with the axes of the magnetic susceptibility tensor $\{x(x), y(x), z(x)\}$. For molecules with low symmetry, such as benzothiophene, for example, it will probably be reasonable to suppose that the z and $z(x)$ axes coincide (the molecule is planar), and there is a certain angle α between the x and $x(x)$ axes [3]. The value of the parameter $\delta \chi$ clearly depends on the size of this angle (Fig. 1).

The orientation parameters were determined by the method of least squares in the iteration regime using the expressions (3)-(5) in terms of the ALIGN program. In order to obtain the values of the angles θ_{az} it is necessary to know the position of the interacting nuclei i and j in the molecular coordinate system. For their determination, a full optimization of the geometry was undertaken with the use of the semiempirical quantum-chemical PM3 method, which gives good results for the calculation of aromatic heterocycles [14]. Here, the geometric parameters of benzothiophene [15] with the natural correction for the nearest environment of the heteroatom were used as starting values. The final values of the orientation parameters of benzothiophene were as follows:

$$\Delta \chi = -8.71 \pm 0.70 \times 10^{-34} \text{ m}^3,$$

$$\delta \chi = -1.26 \pm 0.64 \times 10^{-34} \text{ m}^3,$$

$$\alpha = 58^\circ.$$

As expected, the main anisotropic factor is the presence of the ring current of the 10π -electron system of the conjugated rings in the benzothiophene molecule, which is responsible for the appearance of an induced magnetic moment along the z axis of the molecular coordinate system. The "minus" sign of the parameter $\Delta \chi$ signifies that the direction of the induced magnetic moment is opposite to the external magnetic field. Here, an orientation of the molecule in the external magnetic field where the z axis of the molecular coordinate system becomes orthogonal to the direction of the field is preferred [16]. The values of $\Delta \chi$ obtained in the present work agree with data for naphthalene [4] and benzothiophene [7]. It should be pointed out that our

TABLE 1. Spin-Spin Coupling Constants J_{ij} and Dipole-Dipole Coupling Constants D_{ij} (Hz) in Benzothiophene (306.6 K, 2M Solution in Acetone-d₆) for a Series of Spectra Recorded on NMR Spectrometers at 200, 400, and 500 MHz for Protons (the standard deviations of the parameters in parentheses)

Protons	J_{ij}	D_{ij}^{200}	D_{ij}^{400}	D_{ij}^{500}
2-H, 3-H	5.4742 (0.0020)	-0.0013 (0.0004)	-0.0059 (0.0011)	-0.0074 (0.0012)
2-H, 4-H	0.1985 (0.0017)	-0.0005 (0.0004)	-0.0011 (0.0009)	-0.0047 (0.0011)
2-H, 5-H	0.0104 (0.0027)	*	*	*
2-H, 6-H	0.5135 (0.0023)	0.0000 (0.0004)	-0.0005 (0.0011)	0.0011 (0.0011)
2-H, 7-H	0.0272 (0.0019)	*	*	*
3-H, 4-H	-0.2935 (0.0018)	-0.0018 (0.0004)	-0.0073 (0.0009)	-0.0105 (0.0010)
3-H, 5-H	0.0165 (0.0035)	*	*	*
3-H, 6-H	-0.1222 (0.0021)	0.0003 (0.0006)	0.0025 (0.0010)	0.0003 (0.0010)
3-H, 7-H	0.8478 (0.0020)	-0.0003 (0.0004)	-0.0003 (0.0010)	-0.0039 (0.0010)
4-H, 5-H	8.0387 (0.0022)	-0.0017 (0.0006)	-0.0063 (0.0012)	-0.0115 (0.0012)
4-H, 6-H	1.1969 (0.0017)	-0.0006 (0.0004)	-0.0023 (0.0008)	-0.0044 (0.0008)
4-H, 7-H	0.7637 (0.0017)	-0.0004 (0.0003)	-0.0017 (0.0009)	-0.0024 (0.0009)
5-H, 6-H	7.1155 (0.0034)	-0.0023 (0.0004)	-0.0080 (0.0009)	-0.0137 (0.0009)
5-H, 7-H	1.0486 (0.0022)	0.0001 (0.0006)	0.0021 (0.0011)	-0.0026 (0.0013)
6-H, 7-H	8.1599 (0.0021)	-0.0013 (0.0004)	-0.0051 (0.0010)	-0.0083 (0.0010)

*Not determined.

value for $\Delta\chi$ is approximately two times lower in absolute value than the value of this parameter for the related naphthalene molecule [3, 11, 12]. Further study will be necessary to determine the reasons for this discrepancy.

EXPERIMENTAL

The ¹H NMR spectra of benzothiophene were recorded on Bruker AC-200, Varian VXR-400, and Varian Unity-500 spectrometers for 2 M solutions in acetone-d₆ at 306.6 K. The data acquisition times were between 24 and 30 sec. To increase the resolution, the Lorentzian line shape was transformed to Gaussian. The line widths in the transformed spectra were 0.03-0.04 Hz with a digital resolution of 1-2 mHz. The spectra were analyzed by the LAOCOON5 [8,9] and UEA [10] iteration programs, modified for calculation on an IBM PC. The accuracy of agreement of the experimental peaks and the theoretical frequencies of the transitions (MSD) amounted to 0.0026, 0.0057, and 0.0056 Hz for the spectra at 200, 400, and 500 MHz respectively. The geometry of benzothiophene was optimized by the PM3 method on an IBM PC [14].

The work was carried out with financial support from the Russian Fundamental Research Fund (project code 95-03-09639).

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