This article was downloaded by: [University of California, Berkeley] On: 22 April 2013, At: 13:12 Publisher: Taylor & Francis Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



# Molecular Physics: An International Journal at the Interface Between Chemistry and Physics

Publication details, including instructions for authors and subscription information:

http://www.tandfonline.com/loi/tmph20

Two-dimensional N.M.R. studies of flexible molecules in liquid crystals: orientational order and conformational probabilities of nhexane

M. Gochin  $^{a\ b\ c}$  , A. Pines  $^{a\ b}$  , M.E. Rosen  $^{a\ b}$  , S.P. Rucker  $^{a\ b}$  & C. Schmidt  $^{a\ b\ d}$ 

<sup>a</sup> Materials and Chemical Sciences Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California, 94720, U.S.A.

<sup>b</sup> Department of Chemistry, University of California, Berkeley, California, 94720, U.S.A.

<sup>c</sup> Department of Pharmaceutical Chemistry, University of California, San Francisco, California, 94143, U.S.A.

<sup>d</sup> Institut für Makromolekulare Chemie, Universität Freiburg, Stefan-Meier-Strasse 31, D-7800, Freiburg, F.R. Germany Version of record first published: 23 Aug 2006.

To cite this article: M. Gochin , A. Pines , M.E. Rosen , S.P. Rucker & C. Schmidt (1990): Twodimensional N.M.R. studies of flexible molecules in liquid crystals: orientational order and conformational probabilities of n-hexane, Molecular Physics: An International Journal at the Interface Between Chemistry and Physics, 69:4, 671-695

To link to this article: http://dx.doi.org/10.1080/00268979000100501

# PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <u>http://www.tandfonline.com/page/terms-and-conditions</u>

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

# Two-dimensional N.M.R. studies of flexible molecules in liquid crystals: orientational order and conformational probabilities of *n*-hexane

by M. GOCHIN<sup>†</sup>, A. PINES, M. E. ROSEN, S. P. RUCKER and C. SCHMIDT<sup>‡</sup>

Materials and Chemical Sciences Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720, U.S.A., and Department of Chemistry, University of California, Berkeley, California 94720, U.S.A.

(Received 13 October 1989; accepted 7 November 1989)

By means of two-dimensional N.M.R. spectroscopy, the sixteen timeaveraged magnetic dipolar couplings between proton spins of partially (nonselectively) deuterated *n*-hexane oriented in a liquid crystal are determined. Using multiple-quantum N.M.R. together with simple models of the solute energy in the liquid crystalline environment, the dipole couplings are assigned to specific pairs of protons on the hexane molecule. One of the parameters of the models is the trans-gauche energy difference, for which the value consistent with the N.M.R. observations is about  $3.5 \text{ kJ mol}^{-1}$ , higher than the usually assumed values of about  $2.0 \text{ kJ mol}^{-1}$ . The order tensors and conformational probabilities derived from the data and models are presented and the possibility of extending these experiments to larger molecules is discussed briefly.

#### 1. Introduction

Since the first narrow line N.M.R. spectrum of a solute dissolved in a liquid crystal [1], various studies have been undertaken towards using N.M.R. in liquid crystals for molecular structure determination [2]. In some cases, the spectrum of the fully protonated molecule was analysed, while in others selective or random deuteration was used to simplify the spectra. It was quickly realized that conventional one-dimensional proton N.M.R. spectra rapidly become intractable with increasing molecular size and number of protons, and also uninterpretable for any-thing other than small rigid or highly symmetrical molecules.

One solution for somewhat larger molecules is to study the deuteron quadrupole coupling of the corresponding isotopically labelled molecules. However, the spectral simplicity thus achieved has a price—the quadrupole couplings are smaller in number than the dipole couplings and they provide little information about internuclear distances. An alternative is to use the proton N.M.R. of randomly deuterated molecules to determine the proton dipole–dipole couplings [3]. The determination of dipole couplings has proved particularly convenient when random deuteration is combined with two-dimensional and multiple-quantum N.M.R. techniques [4].

<sup>‡</sup> Present address: Institut für Makromolekulare Chemie, Universität Freiburg, Stefan-Meier-Strasse 31, D-7800 Freiburg, F.R. Germany.

<sup>&</sup>lt;sup>†</sup> Present address: Department of Pharmaceutical Chemistry, University of California, San Francisco, California 94143, U.S.A.

#### M. Gochin et al.

For flexible molecules the observed dipole couplings between proton pairs i-j,  $\langle D_{ij} \rangle$ , are averages over complex molecular motions and cannot be interpreted directly in terms of molecular structure and orientation. The averaging (indicated by angular brackets  $\langle \rangle$ ) involves both the interproton distance  $r_{ij}$  and the angle  $\theta_{ij}$  between the vector  $\mathbf{r}_{ij}$  and the external magnetic field

$$\left\langle \mathbf{D}_{ij} \right\rangle = -\frac{h\gamma^2}{4\pi^2} \left\langle \frac{1}{r_{ij}^3} \frac{1}{2} \left( 3 \cos^2 \theta_{ij} - 1 \right) \right\rangle. \tag{1}$$

Generally, a separation of the coordinates  $r_{ij}$  and  $\theta_{ij}$  is not possible, and models are required in order to analyse the molecular structures and orientations. In our first approach to the interpretation of the dipole couplings of *n*-hexane we made the assumption that the orientational order is the same (the average) for all conformations of the molecule [5]. Here we present the results of two models [6, 7] which account for the more realistic situation that the order depends on conformation. Both models have been used before in combination with deuterium quadrupole couplings in alkyl chains [6, 8]. We anticipate that the full set of experimental dipole couplings presented in this work provides a more rigorous test of such models.

In this paper we present a detailed description of the N.M.R. techniques and the information obtained by means of the simple statistical mechanical models, using n-hexane dissolved in a nematic liquid crystal as an example. The most probable conformers of this molecule are depicted in figure 1, which also shows the labelling of the different sites and the numbering of the protons referred to throughout the text. Section 2 summarizes the experimental approach taken to obtain the sixteen average dipole couplings between the protons of n-hexane. Section 3 describes the experimental results and outlines the method of assigning each of the dipole couplings to a specific pair of protons on the molecule. Section 4 contains the results from model calculations, which provide information about the conformations and orientations assumed by n-hexane in the liquid crystal solvent. This last section is concluded with a brief discussion of the possible applicability of these techniques to larger molecules.

# 2. Extracting proton dipole couplings from partially deuterated molecules

One of the difficulties with high resolution N.M.R. spectra in liquid crystals is the exponential rise in the number of transitions with the number (n) of coupled proton spins. Yet such complexity represents a vast redundancy since the unknowns in the spin hamiltonian

$$\mathscr{H} = \sum_{i} \langle \delta_i \rangle I_{zi} + \frac{1}{2} \sum_{i < j} \langle D_{ij} \rangle (3I_{zi} I_{zj} - \mathbf{I}_i \cdot \mathbf{I}_j), \tag{2}$$

are at most *n* averaged chemical shifts  $\langle \delta_i \rangle$  and n(n-1)/2 dipole couplings  $\langle D_{ij} \rangle$ . For example, for the fourteen protons in *n*-hexane there are only three distinct chemical shifts and sixteen dipole couplings, but there are about 60 000 onequantum transitions. Figure 2 shows the one-quantum spectrum of *n*-hexane in a nematic liquid crystal; the chemical shifts and dipole couplings cannot easily be determined from such a spectrum.

A solution to this problem is provided by a series of synthetic and spectroscopic steps, the first three of which are represented in the scheme of figure 3. The idea is to



Figure 1. Primary rotational isomeric state conformations of hexane. The methyl and methylene groups are labelled as M and  $E_1$ ,  $E_2$ , and the protons are numbered as 1-14.

replace the intractable spectrum of a many-spin system by a superposition of several simple spectra from two-spin systems: Non-selective (random) deuteration reduces the number of protons on the solute molecules from fourteen to primarily one, two, or three; multiple-quantum spectroscopic filtering then essentially eliminates the signal from all but the two-proton molecules. Together with this filtering, twodimensional correlation spectroscopy facilitates the determination of the dipole couplings between the proton pairs. In a fourth step, multiple-quantum spectroscopy helps in the assignment of the couplings to specific protons on the molecule.

# Step 1: Random deuteration

The first step, non-selective deuteration of the hexane molecule, yields a statistical mixture of partially protonated molecules. Non-selective deuteration is far



Figure 2. One-quantum proton N.M.R. spectrum of *n*-hexane in the liquid crystal EK 11650; taken with the echo sequence  $\pi/2 - \tau/2 - \pi - \tau/2$ ,  $\tau = 2$  ms. 500 scans were recorded at a recycle time of 7.5 s.

less synthetically demanding than specific deuteration. The success of the N.M.R. experiment described here depends only on having all pairs of protons represented. The probability of finding m protons on a statistically deuterated molecule is

$$P(m) = d^{n-m}(1-d)^m \binom{n}{m},$$
(3)

where d is the degree of deuteration  $(0 \le d \le 1)$ , n the total number of hydrogen sites, and m the number of unsubstituted protons. The degree of deuteration (d) is chosen so that the maximum of P(m) occurs near m = 2. Figure 4 illustrates the protonation profile for a hexane sample used in our studies (d = 0.81). Two- and three-proton species are the most abundant.

#### Step 2: Multiple-quantum filtration

A one-quantum proton N.M.R. spectrum of the non-selectively deuterated n-hexane yields a superposition of subspectra from the different isotopically labelled species in the mixture, with relative intensities determined by the symmetry-dictated isomer distribution [9]. Table 1 gives some statistical information for n-hexane at the optimum deuteration level (the one with the highest two-proton probability) of

Table 1. Probabilities of *m*-proton molecules, P(m), number of different *m*-proton isomers, Z(m), and probabilities of *m*-proton isomers, P(m)/Z(m), for *n*-hexane at a deuteration level of 0.86.

m	1	2	3	4	5
P(m) $Z(m)$ $P(m)/Z(m)$	0·276	0·292	0·190	0·085	0·028
	3	16	38	86	133
	0·0920	0·0182	0·0050	0·0010	0·0002



Figure 3. Schematic description of the correlated random label spectroscopy experiment (CRASY). A large molecule gives a complex single quantum spectrum. Random labelling (step 1) produces a mixture of molecules each containing a small number of protons yielding a many-line superposition of simple spectra. Multiple-quantum filtered (step 2) two-dimensional correlated spectroscopy (step 3) leads to spectroscopic separation of the individual components of the mixture, each with a simple few-line spectrum.

d = 0.86. Since the dipole coupling is a two-spin interaction, we are interested primarily in the two-proton isomers and seek to exclusively measure their N.M.R. signals. Two-quantum filtered spectroscopy [10] by phase-cycling provides a way to achieve this goal, by selecting only coherences of order two or higher for detection. This removes signal from one-proton isomers. Still greater selectivity in multiplequantum filtration can be achieved by averaging spectra with different multiplequantum evolution times. In molecules with more than two protons, two-quantum coherence will be modulated by couplings to other protons, and signals from molecules with an odd number of protons will be averaged away. Signals from higher even-order coherences (m = 4, 6, 8, ...) still remain, but their intensity will be low because of the low concentration of molecules giving rise to such signals (molecules

Downloaded by [University of California, Berkeley] at 13:12 22 April 2013



Figure 4. Mass spectral data for *n*-hexane after 80 hours exchange with  $D_2$ ; shown are the measured relative intensities ( $\odot$ ) at masses 100 (no protons) through 91 (9 protons) and the statistical fraction calculated from equation (3) in the text (---) assuming a deuteration level of 0.81.

with four or more protons, cf. table 1) and because the intensity is distributed over many transitions.

#### Step 3: Correlation spectroscopy

The combination of random deuteration and multiple-quantum filtration reduces signals from all but two-proton molecules. Two-dimensional spectroscopy [11] is then used to separate the subspectra from different isomers by correlating peaks from the same subspectrum. Experimentally, steps 2 and 3 are achieved simultaneously in a single two-dimensional spectrum. We used both one-quantum versus one-quantum correlation spectroscopy (COSY) [12] and two-quantum versus one-quantum correlation spectroscopy (INADEQUATE) [13]. Two peaks, one from each of the spectra (projections) along the frequency axes ( $v_1$  and  $v_2$ ) of the two-dimensional spectrum, are correlated only if they arise from a coupled spin system, that is, when they belong to protons on the same molecule. Correlations are identified by the crosspeaks in the two-dimensional spectrum.

The two-dimensional patterns expected for two-spin systems are depicted in figure 5. Figures 5(a)-(c) show the two-dimensional COSY patterns expected for  $A_2$  and AB spin systems, assuming that J couplings can be neglected. With the COSY experiment, an  $A_2$  system results in a square with sides of length

$$s = \frac{3}{2} \langle D_{ij} \rangle. \tag{4}$$

For a coupled AB system, the COSY patterns are more complex: the length of a side on the outermost square of the AB pattern is given by

$$s = \langle D_{ij} \rangle + \sqrt{[\langle D_{ij} \rangle^2 / 4 + (\langle \delta_i \rangle - \langle \delta_j \rangle)^2]}.$$
 (5)

The INADEQUATE experiment, which correlates two-quantum frequencies along the  $v_1$  axis and one-quantum frequencies along the  $v_2$  axis, results in patterns of peaks lined up in rows parallel to the one-quantum axis. There are two peaks and four peaks for the  $A_2$  and AB spin systems, respectively, as shown in figures 5(d)



Figure 5. Schematic  $A_2$  and AB two-dimensional spectra (relevant to molecules containing two protons) calculated for various pulse sequences. (a) and (b) are two-quantum filtered COSY spectra of an  $A_2$  and AB system, calculated from pulse sequence (A) in the text; (c) is a two-quantum filtered refocused COSY AB spectrum, calculated from pulse sequence (A) with an additional  $\pi$  pulse in  $t_1$ ; (d) and (e) are INADEQUATE  $A_2$ and AB spectra calculated from pulse sequence (B) in the text. Open circles indicate negative and closed circles positive signals. The relative intensities of the signals are: (a) equal intensity for all lines, (b)  $(1 - \sin 2\theta)^2$ ,  $(1 - \sin^2 2\theta)$ ,  $(1 - \sin^2 2\theta)$ , and  $(1 + \sin 2\theta)^2$  for the numbered peaks; (c)  $-(1 - \sin 2\theta)^2 \sin 2\theta$ ,  $2 \cos^2 2\theta (1 - \sin 2\theta)$ ,  $\cos^2 2\theta \sin 2\theta$ ,  $-\cos^2 2\theta \sin 2\theta$ ,  $2\cos^2 2\theta(1 + \sin 2\theta)$ , and  $(1 + \sin 2\theta)^2 \sin 2\theta$  for the six numbered peaks, (d) equal intensity for both lines, (e)  $(1 - \sin 2\theta) K$  and  $(1 + \sin 2\theta)K$  for the two numbered peaks, where K is a phase factor depending on the dipole coupling. The chemical shift frequency of the spins for an  $A_2$  pair is v, the average chemical shift frequency of spins A and B is  $\bar{v}$ , and the chemical shift difference is  $\Delta v$ . D is the dipole coupling,  $v_+ = D/2 + C/2$ , and  $v_- = D/2 - C/2$ , with  $C = (\Delta v^2 + (D/2)^2)^{1/2}$ ; tan  $2\theta = -D/(2\Delta v)$ .

and (e). With both types of correlation spectra (COSY and INADEQUATE), the average chemical shift of the two protons of a coupled pair can be read off from the position of the centre of the peak pattern, and the dipole coupling can be determined from the magnitude of the splitting.

#### Step 4: Multiple-quantum spectroscopy

The synthetic and spectroscopic methods described thus far result in a list of absolute values of dipole couplings and average chemical shifts of the coupling partners. In the next step, multiple-quantum spectroscopy [11,14] of 1, 1, 1, 6, 6,  $6-d_6$ -n-hexane (an eight-spin system) [15] is used to help in determining the relative signs of the couplings and in assigning the couplings to specific pairs of protons. A solution to the assignment problem is obtained from a faithful simulation of the experimental six- and seven-quantum spectra. The assignment based on multiple-quantum spectroscopy is unique down to permutations which leave the spin-hamiltonian invariant [16]—i.e. permutations between spins which have the same chemical shift and coupling partners.

#### 3. Experimental results

Randomly deuterated *n*-hexane was synthesized by exchange of *n*-hexane in the gas phase with  $D_2$  over Pd on charcoal at 190°C. The reaction was stopped after 80 hours when a deuteration level of 0.81 was reached. As shown in figure 4, the mass spectrum of the sample agrees well with the statistical distribution of molecules with different numbers of protons for an 0.81 deuteration level calculated from equation (3). This agreement implies that the deuteration is essentially random, and therefore the sample can be expected to contain a selection of all possible two-proton-containing isomers. We refer to this sample as *n*-hexane- $d_{0.81}$ . The nematic liquid crystal used for all measurements was Eastman Kodak 11650 (EK 11650, *p*-pentylphenyl-2-chloro-(4-*p*-pentylbenzoyloxy)benzoate). Solutions containing about 20 mole % of *n*-hexane- $d_{0.81}$  were prepared for the N.M.R. work.

The N.M.R. experiments were carried out at 362 MHz on a home-built spectrometer. Two-dimensional data sets, up to  $8192 \times 1024$  points, were recorded directly on a VAX 11-730 computer for ease of storage and data processing. Proton spectra were observed, with continuous two-quantum deuterium decoupling [17] over a 15 kHz bandwidth, and Hahn spin-echo detection in order to suppress the signal from the liquid crystal. The irradiation caused considerable heating, despite air flow temperature regulation, raising the temperature of the sample by about 20°C. Sample heating caused by deuterium decoupling was calibrated in a separate test spectrum, using a capillary of ethylene glycol centred in a tube of EK 11650/CCl<sub>4</sub>. The line splitting in the ethylene glycol spectrum served as a measure of the temperature.

# 3.1. Two-proton filtering

The result of multiple-quantum filtering is demonstrated in figure 6 for *n*-hexane- $d_{0.81}$ . Figure 6(a) shows the unfiltered spectrum displaying three prominent lines



Figure 6. Effect of random deuteration and spectroscopic filtering. (a) One-quantum spectrum of *n*-hexane- $d_{0.81}$  in the liquid crystal *EK* 11650; taken with the echo sequence  $\pi/2 - \tau/2 - \pi - \tau/2$ ,  $\tau = 2 \text{ ms}$ ,  $\tau = 1.0 \text{ ms}$ . 1000 scans were recorded at a recycle time of 7.5 s. (b) Two-quantum filtered echo spectrum of *n*-hexane- $d_{0.81}$  taken with pulse sequence (A) in the text,  $\tau_1 = 2 \mu s$ ,  $t_1 = 500 \mu s$ ,  $\tau_2 = 4 \text{ ms}$ . 6600 scans were acquired, with a recycle time of 7.5 s. (c) Two-proton filtered echo spectrum of *n*-hexane- $d_{0.81}$  taken with pulse sequence (A) in the text,  $t_1 = 500 \mu s$ ,  $\tau_2 = 4 \text{ ms}$ , and with  $\tau_1$  varied from 0 to 9.8 ms in 20  $\mu s$  increments. 4000 scans were acquired, with a recycle time of 7.5 s. Spectra are presented in absolute value mode.

from the one-proton molecules. These lines provide the chemical shifts of the three sites M,  $E_1$  and  $E_2$  (cf. figure 1). The two-quantum filtered spectrum of figure 6(b) and the two-spin filtered spectrum of figure 6(c) were both measured with the pulse sequence

$$\left(\frac{\pi}{2}\right)_{\phi} - t_1 - \left(\frac{\pi}{2}\right)_{\phi} - \frac{\tau_1}{2} - \pi_x - \frac{\tau_1}{2} - \left(\frac{\pi}{2}\right)_x - \frac{\tau_2}{2} - \pi - \frac{\tau_2}{2} - t_2, \quad (A)$$

using a fixed  $t_1$  value. The phase  $\phi$  was incremented in 90° steps, and the receiver phase alternated between 0° and 180°. For the spectrum with the high pass twoquantum filter (figure 6(b))  $\tau_1$  was kept constant and four scans completed the cycle, whereas the two-spin filtered spectrum (figure 6(c)) was obtained by incrementing  $\tau_1$ after every 4th scan. Figure 6(c) is therefore a superposition of the eight  $A_2$  and eight AB spectra arising from the sixteen isomers of C<sub>6</sub>H<sub>2</sub>D<sub>12</sub>. In order to separate these two-proton subspectra and to find the peak correlations, two-dimensional two-spin filtered COSY and INADEQUATE spectra were recorded.

# 3.2. COSY spectra

The two-spin filtered COSY spectra were acquired with pulse sequence (A), both without and with a refocusing  $\pi$  pulse in  $t_1$ , and with varying two-quantum evolution time  $(\tau_1)$  for two-proton filtration. Examples of COSY spectra are shown in figures 7 and 8. Figure 7 shows stacked plots of both types of COSY spectra (simple and refocused) illustrating the high signal-to-noise ratio and spectrum quality.

The  $A_2$  and AB patterns expected for the two types of COSY experiments were shown in figures 5(a)-(c). In the experimental refocused COSY spectra, typically no more than eight of the 24 peaks predicted for the AB patterns had sufficient intensity to be observed. The refocused COSY experiment was easier to analyse because of its slightly narrower lines. For many observed AB patterns, the ratio of coupling constant to chemical shift difference is greater than two, so that the inner peaks are very small. These subspectra resemble  $A_2$  patterns, but from their chemical shift position they were recognized as AB patterns and interpreted according to equation (5). J couplings are ignored because they are small (less than 10 Hz) relative to the  $\langle D_{ij} \rangle$ . Figure 8 shows all sixteen of the expected dipolar square patterns in a set of three consecutive contour plots of the refocused spectrum.

Without a  $\pi$  pulse in  $t_1$ , the hamiltonians in  $t_1$  and  $t_2$  are identical, leading to AB patterns that are centred about the average chemical shift positions  $\langle \delta_{AB} \rangle =$ 



Figure 7. Two-quantum filtered COSY spectra of *n*-hexane- $d_{0.81}$  taken with pulse sequence (A) (see text) both without (a) and with (b) a  $\pi$  pulse in  $t_1$ . The size of the measured data matrices was 128  $(t_1) \times 1024$   $(t_2)$ . For each  $t_1$  value 200 scans were acquired, varying the double-quantum mixing time; the recycle delay was 5s. In (b) only the centre part of the spectrum is shown.



Figure 8. Refocused two-quantum filtered COSY spectra, taken with pulse sequence (A) in the text, but with a  $\pi$  pulse in  $t_1$ . (a), (b) and (c) show successively expanded regions of the spectrum. The 16 dipole coupling square patterns of *n*-hexane are shown. 512  $(t_1) \times 1024 (t_2)$  points were recorded with 80 scans per  $t_1$  value at a recycle delay of 6s.

 $\frac{1}{2}(\langle \delta_A \rangle + \langle \delta_B \rangle)$  along the main diagonal. In the refocused COSY experiment, the *AB* patterns are concentric about the points ( $v_1 = 0$ ,  $v_2 = \langle \delta_{AB} \rangle$ ). The shift of peaks from one experiment relative to the other allows for accidental overlap of peaks to be resolved. Since each of the sites *M*,  $E_1$  and  $E_2$  has a different chemical shift, the six averaged chemical shift positions  $\langle \delta_{MM} \rangle$ ,  $\langle \delta_{ME_1} \rangle$ ,  $\langle \delta_{E_1E_1} \rangle$ ,  $\langle \delta_{E_2E_2} \rangle$ , and

 $\langle \delta_{E_1E_2} \rangle$  can be used to group the proton pairs into six categories. This narrows down the search for the exact assignment considerably.

# 3.3. INADEQUATE spectra

Figure 9 shows a two-dimensional INADEQUATE spectrum, acquired with sequence

$$\left(\frac{\pi}{2}\right)_{\phi} - \frac{\tau_1}{2} - \pi_{\phi} - \frac{\tau_1}{2} - \left(\frac{\pi}{2}\right)_{\phi} - t_1 - \left(\frac{\pi}{2}\right)_x - \frac{\tau_1}{2} - \pi_x - \frac{\tau_2}{2} - t_2, \quad (B)$$

where  $\phi$  was incremented by 90° and the receiver phase alternated between 0° and 180°. The experiment was repeated for different values of the two-quantum preparation time  $\tau_1$ , in order to vary the relative intensities of the different subspectra. For higher values of  $\tau_1$ , the more weakly coupled pairs appear with greater intensity. For two-proton molecules, signals along the two-quantum axis  $(v_1)$  lie in one of six possible chemical shift positions,  $2\langle \delta_M \rangle$ ,  $\langle \delta_M \rangle + \langle \delta_{E_1} \rangle$ ,  $\langle \delta_M \rangle + \langle \delta_{E_2} \rangle$ ,  $2\langle \delta_{E_1} \rangle$ ,  $2\langle \delta_{E_2} \rangle$ , and  $\langle \delta_{E_1} \rangle + \langle \delta_{E_2} \rangle$ . The six slices parallel to the one-quantum axis  $(v_2)$  are drawn in figure 9. Within each slice, one-quantum  $A_2$  and AB patterns could be easily identified due to their symmetric disposition around the appropriate chemical



Figure 9. Part of an INADEQUATE (double-quantum versus single-quantum) spectrum of *n*-hexane- $d_{0.81}$  dissolved in the liquid crystal EK 11650, obtained with pulse sequence (B) in the text,  $\tau_2 = 4$  ms. The signals for two preparation times,  $\tau_1 = 250 \,\mu s$  and 2.5 ms, were added. 128  $(t_1) \times 1024 (t_2)$  points were recorded with quadrature phase detection in both dimensions. Vertical lines parallel to the one-quantum axis illustrate the six double-quantum frequencies of molecules with two protons. Along these lines the  $A_2$  and AB spectra can be identified.

shift position in  $v_2$ . There are 2 MM, 2 ME<sub>1</sub>, 2 ME<sub>2</sub>, 3  $E_1E_1$  (2 shown), 3  $E_2E_2$  (1 shown), and 4  $E_1E_2$  (3 shown) subspectra. Figure 9 is an expansion of the central region of the spectrum, so the three resonances with the largest splittings lie outside the range of  $v_2$  shown. Three-proton spin systems tend not to interfere in the INADEQUATE experiment. Their signals in  $v_1$  are modulated by the large dipole coupling term and tend to lie outside the small chemical shift range of two-proton signals. Signals lying within this region are unlikely except by accident to be aligned symmetrically about the correct chemical shift position. While the INADEQUATE experiment provides simpler spectra, the more complex patterns of the COSY experiment were found to be more useful for assignment purposes.

Table 2 is a compiled list of the dipole couplings of hexane. The third and fourth columns contain the experimental couplings obtained from the COSY and the INADEQUATE spectra, and the fifth column lists the errors estimated from the widths of the N.M.R. peaks. The values of  $\langle D_{ij} \rangle$  from the two experiments agree well within the errors, which originate mainly from the temperature gradients caused by continuous deuterium decoupling. The site assignments (first column of table 2) were deduced from the positions of the two-spin patterns in the two-dimensional spectra. The second column of table 2 gives the assignments to the proton pairs on the molecule (see discussion at the end of this section), and columns 6 and 7 contain couplings calculated from models discussed in §4.

## 3.4. Multiple-quantum N.M.R. of the methylene chain

To find the relative signs of the dipole couplings and the assignments of the dipole coupling to specific pairs of protons, six- and seven-quantum spectra of 1, 1,

		Experimental $\langle D_{ij} \rangle$ /Hz			Calculated	$\langle D_{ij} \rangle / \text{Hz}$
Sites	Assignment	COSY	INAD	error	Model A	Model B
MM MM	1-2 1-12	1876 206	1862 - 203	$\pm 28$ $\pm 13$	1792 	1837 201
$ME_1 ME_1$	14 110	- 386† - 322†	- 382† - 314†	$\pm 15 \pm 14$	- 366 - 289	-350 -316
$\frac{ME_2}{ME_2}$	$1-6 \\ 1-8$	-1034 -598	1041 591	$\pm 25$ $\pm 15$	1025 591	$-1091 \\ -645$
$E_1E_1\\E_1E_1\\E_1E_1$	4-5 4-10 5-10	3974 609† 713†	3986 612† 706†	$\pm 34 \\ \pm 14 \\ \pm 18$	3980 543 789	3743 612 860
$\begin{array}{c} E_2 E_2 \\ E_2 E_2 \\ E_2 E_2 \end{array}$	6-7 6-8 7-8	4487 43† 190	4482 48† 	$\pm 34 \\ \pm 12 \\ \pm 12$	4515 119 106	4329 136 11
$E_1E_2\\E_1E_2\\E_1E_2\\E_1E_2\\E_1E_2$	46 56 48 58	186† 81† 1616 1086	183† 81† 1626 1106	$\pm 14 \\ \pm 12 \\ \pm 25 \\ \pm 27$	184 28 1719 1019	216 165 1827 1104

Table 2. Dipole couplings of hexane.

<sup>†</sup> For these couplings alternative assignments are possible as discussed in the text and in table 8.

1, 6, 6,  $6 \cdot d_6 \cdot n$ -hexane (hexane- $d_6$ ) were measured. The spectra were recorded using time-proportional phase incrementation (TPPI) [18]. The pulse sequence was

$$\left(\frac{\pi}{2}\right)_{\phi} - \frac{\tau}{2} - \pi_{\phi} - \frac{\tau}{2} - \left(\frac{\pi}{2}\right)_{\phi} - \frac{t_1}{2} - \pi_{\chi} - \frac{t_1}{2} - \left(\frac{\pi}{2}\right)_{\chi} - \frac{\tau}{2} - \pi - \frac{\tau}{2} - t_2. \quad (C)$$

The phase  $\phi$  was incremented proportionately with  $t_1$  in 22.5° increments, allowing 16 phase separated intervals for the 0 to  $\pm 8$  quantum spectra ( $\pm 8$  quantum at the edge). The phase  $\chi$  was cycled through 0°, 90°, 180°, 270° for each  $t_1$  point, with the receiver held constant to observe even-quantum transitions and alternated between 0° and 180° to observe odd-quantum transitions.

Figure 10 shows the experimental six- and seven-quantum spectra of hexane- $d_6$ , obtained by adding the even- and odd-order spectra. The seven-quantum spectrum has two pairs of lines, which correspond to the number of distinct ways of selecting seven out of eight protons from a spin system with  $C_{2h}$  symmetry such as *n*-hexane rapidly exchanging between different conformers. For the six-quantum spectrum nine of the fourteen possible pairs of lines are observed.

#### 3.5. Assignment of the dipole couplings

To begin the simulations of the six- and seven-quantum spectra of hexane- $d_6$  the following assumptions were made:

(1) The strongest dipole couplings arise from geminal protons (those on the same carbon), and the inner methylene groups  $(E_2)$  have stronger couplings than the outer methylene groups  $(E_1)$ .



Figure 10. Experimental 6- and 7-quantum spectra of *n*-hexane- $d_6$  (deuterated at the methyl positions) taken with pulse sequence (C) in the text,  $\tau = 11.706$  ms for even quanta and 12.000 ms for odd quanta. The two absolute value spectra were added. 8192 points were recorded in  $t_1$  and 1024 points in  $t_2$ . Different multiple-quantum orders were separated by phase increments  $\Delta \phi = 22.5^{\circ}$ . Six scans were averaged for each  $t_1$  value with a recycle time of 4.5 s.



Figure 11. Comparison of the experimental 6- and 7-quantum spectra with spectra calculated for various assignments and signs of the dipole coupling constants. All spectra have a digital resolution of 30.5 Hz/point. (a) is the projection onto the multiplequantum axis of the spectra in figure 10. (b)-(e) are calculated according to the assignments of table 2 with the exceptions specified on the left side of the figure.

(2) The hexane molecules are predominantly oriented with their long axes parallel to the nematic director, which, for our sample, is parallel to the external magnetic field. Therefore (cf. equation (1)), dipole couplings between geminal protons are positive, and couplings between protons which are separated by at least three carbon atoms are negative.

With these assumed signs and assignments of some of the couplings as a starting point, the six- and seven-quantum spectra of hexane- $d_6$  were simulated in order to determine the signs and assignments of the remaining  $E_1$  and  $E_2$  couplings. As shown in figure 11, the best agreement with the experimental multiple-quantum spectra was obtained with the assignment of table 2 and an alternative assignment of the vicinal  $E_1E_2$  couplings 4–6 and 5–6. The six- and seven-quantum spectra for these two assignments are compared in figure 11(b) and (c). The six-quantum spectra differ in only two of the frequencies. In figure 11(b) these two frequencies are only 24 Hz apart and not resolved within the experimental resolution of 30 Hz. In figure 11(c) they are 97 Hz apart. At the present level of precision the assignment of figure 11(b) is more likely. The positive signs of both these couplings are unequivocal: changing any of their signs gives completely different multiple-quantum spectra, as shown in figure 11(d). Figure 11(e) shows that switching a geminal and a vicinal coupling in the group  $E_2 E_2$  ( $\langle D_{6,7} \rangle$  and  $\langle D_{7,8} \rangle$ ) results also in completely different spectra.

At this point in the analysis, assignments of the dipole couplings from the multiple-quantum spectra are determined only down to permutations which leave the spin hamiltonian invariant. In addition, we do not know the assignment of the methyl-methylene couplings, in particular the two  $ME_1$  couplings ( $\langle D_{1,4} \rangle$  and  $\langle D_{1,10} \rangle$ ) which are the same magnitude. We will show in the following section, that simple model calculations can help to resolve most of the remaining ambiguities.

# 4. Model calculations

Given the experimental average dipole couplings,  $\langle D_{ij} \rangle$ , models are used in which these couplings serve as constraints for the determination of the model parameters. From such model calculations order parameters and conformational probabilities are obtained.

As a first simplifying step, a fixed number of conformational states is assumed (rotational isomeric state (RIS) approximation. [19]). Thus the dipole couplings can be calculated from a finite sum over conformers [20],

$$\langle D_{ij} \rangle = \frac{2}{3} \sum_{n} \sum_{\alpha,\beta} P^n S^n_{\alpha\beta} D^n_{ij,\alpha\beta}.$$
(6)

 $P^n$  is the probability of conformer *n* and  $S^n_{\alpha\beta}$  its order tensor in a molecule-fixed coordinate frame. The order tensor is defined as

$$S_{\alpha\beta}^{n} = \frac{1}{2} \langle 3 \cos \theta_{\alpha} \cos \theta_{\beta} - \delta_{\alpha\beta} \rangle, \tag{7}$$

where  $\theta_{\chi} (\chi = x, y, z)$  is the angle between the director and the molecular  $\chi$  axis.

The dipole coupling tensor components of conformer n for spin pair i - j in the molecular frame are

$$D_{ij,\alpha\beta}^{n} = -\frac{\gamma^{2}h}{4\pi^{2}} \frac{1}{r_{ij}^{3}} (3\cos\theta_{\alpha}^{ij}\cos\theta_{\beta}^{ij} - \delta_{\alpha\beta}), \tag{8}$$

with  $\theta_{\chi}^{ij}$  the angle between the internuclear vector  $\mathbf{r}_{ij}$  and the molecular  $\chi$  axis.

In general, the product  $P^n S^n_{\alpha\beta}$  is inseparable because of the complex conformational and reorientational averaging. Therefore, the determination of the structure of a flexible molecule requires the development of a parameterized model to describe the orientations and energies of the various conformers, and optimization of the parameters by least-squares minimization with respect to the experimental data. While to date only deuterium quadrupole couplings have been available for any sizeable alkane chain, the present work has resulted in a full set of dipole couplings. In the following we will use two models [6, 7] to analyse our experimental data.

# 4.1. Parameterization of the models

Following the treatment by Emsley and Luckhurst [21], the total energy of a solute conformer n in the liquid crystal is separated into an isotropic part describing the internal energy of the conformer and an orientation-dependent part describing the solute—solvent interaction

$$U_{\rm tot}^n = U_{\rm int}^n + U_{\rm ext}^n(\theta, \phi). \tag{9}$$

The internal energy is calculated using the RIS approximation

$$U_{\rm int}^n = n_g E_g + n_{g^+g^-} E_{g^+g^-}, \qquad (10)$$

where  $n_g$  is the number of gauche bonds in the given conformer,  $E_g$  is the difference in energy between a trans and a gauche bond, and the second term accounts for the pentane effect [19] by penalizing adjacent  $g^+g^-$  bonds. The gauche energy,  $E_g$ , is used as an adjustable parameter, while the  $g^+g^-$  energy,  $E_{g^+g^-}$ , whose variation has only a minor effect on the results is taken as a constant of  $12.55 \text{ kJ mol}^{-1}$  [19] in our calculations. An alternative for the second term of equation (10) is to use a Lennard-Jones interaction between pairs of united atoms (treating the methyl and methylene groups as single atoms) which are three or more bonds apart. This form of  $U_{int}^n$  was used, for example, by Samulski and co-workers [6].

For the external part of the energy,  $U_{ext}^n$  several models have been described in the literature, for example [6, 7, 22]. In some models each solute conformer is treated as an entity whose interaction with the liquid crystal mean field is based primarily on its size and shape. In other models, the interaction is assumed to be the sum of contributions from the various segments of the conformer. In the following, two realizations of the former approach are described.

Samulski and co-workers [6] used a model in which each conformer is approximated by a rectangular parallelepiped with length L, breadth B, and width W. They used this model to simulate quadrupole couplings of several *n*-alkanes ranging in size from pentane up to hexadecane [6]. The values of L, B, and W are chosen equal to twice the semiaxes of the inertia ellipsoid [22(a)] of the conformer. The solute– liquid crystal interaction is described by the excluded volume interaction of the parallelepipeds [23]. This interaction is parameterized as

$$U_{\text{ext}}(\theta, \phi) = \varepsilon [u_{20} d_{00}^2(\theta) + 2u_{22} d_{02}^2(\theta) \cos(2\phi)], \qquad (11)$$

with the coefficients

$$u_{20} = \frac{1}{3} [6LBW + L(W^2 + B^2) - 2W(L^2 + B^2) - 2B(W^2 + L^2)], \qquad (12)$$

$$u_{22} = \frac{1}{\sqrt{6}} \left( L^2 - BW \right) (B - W), \tag{13}$$

the reduced Wigner matrix elements, which describe the orientation dependence,

$$d_{00}^{2}(\beta) = \frac{1}{4} [1 + 3\cos(2\beta)], \tag{14}$$

$$d_{02}^2(\beta) = \frac{\sqrt{6}}{8} \left[ 1 - \cos\left(2\beta\right) \right],\tag{15}$$

and the adjustable interaction energy parameter  $\varepsilon$  [6].

#### M. Gochin et al.

Burnell and co-workers [7, 8, 24] modelled the liquid crystalline matrix as an elastic continuum which exerts an orienting force on the solute. This model was originally used for small solutes [7, 24] to simulate dipole and quadrupole couplings. More recently, it was used for flexible molecules such as the liquid crystal 4-*n*-pentyl-4'-cyanobiphenyl [8] to model deuterium quadrupole couplings. In this model the interaction energy is given by

$$U_{\text{ext}}(\theta, \phi) = \frac{k}{2} c^2(\theta, \phi), \qquad (16)$$

where c is the circumference of the projection of the molecular shape, approximated by a group of van der Waals spheres, onto a plane perpendicular to the director of the liquid crystal. The circumference shown in figure 12 is the 'minimum circumference,' which gives slightly better results than the 'maximum circumference' [7]. The force constant k is an adjustable parameter in this model.

For our calculations we used both Samulski's model (with equation (10)) and Burnell's model. In the following these models are referred to as model A and model B, respectively.

With the parameterizations of the energy given above for the two models, we can proceed by standard statistical mechanical methods in order to calculate the conformer probabilities and order matrices. The conformer probability is given by

$$P^{n} = \exp\left(-\frac{U_{\text{int}}^{n}}{kT}\right) \frac{Z_{\text{ext}}^{n}}{Z_{\text{tot}}},$$
(17)

with the total partition function

$$Z_{\text{tot}} = \sum_{n} \exp\left(-\frac{U_{\text{int}}^{n}}{kT}\right) Z_{\text{ext}}^{n}$$
(18)



Figure 12. Projection of a *n*-hexane conformer along the director (z axis) of the liquid crystal into the x, y-plane. The minimum circumference c (obtained for the van der Waals radii given in [25]) is used to calculate the interaction between the conformer and the liquid crystal according to equation (16) in the text.

Length of C-H bond	1∙09 Å
Length of C-C bond	1∙53 Å
Bond angle HCH of methylene group	109·0°
Bond angle HCH of methyl group	109·47°
Bond angle CCC	112·0°
Dihedral angles for gauche conformations	$\pm 112.5^{\circ}$
van der Waals radius of H	1·2 Å
van der Waals radius of C	1·7 Å

Table 3. Molecular constants used in the model calculations.

and the orientational partition function

$$Z_{\text{ext}}^{n} = \int_{0}^{2\pi} \int_{0}^{\pi} \exp\left(-\frac{U_{\text{ext}}^{n}(\theta, \phi)}{kT}\right) \sin \theta \ d\theta \ d\phi.$$
(19)

The order matrix is obtained according to equation (7) by

$$S_{\alpha\beta}^{n} = \frac{1}{2Z_{\text{ext}}^{n}} \int_{0}^{2\pi} \int_{0}^{\pi} (3 \cos \theta_{\alpha} \cos \theta_{\beta} - \delta_{\alpha\beta}) \exp\left(-\frac{U_{\text{ext}}^{n}(\theta, \phi)}{kT}\right) \sin \theta \, d\theta \, d\phi.$$
(20)

With the geometric parameters of the hexane molecule given in table 3, the average dipolar couplings can be calculated from equations (6) and (8), (17) and (20).

# 4.2. Results and discussion of the model calculations

Both models, each with only two adjustable parameters ( $E_g$  and  $\varepsilon$  for model A and  $E_g$  and k for model B), were fitted to the experimental couplings from the COSY experiment by minimizing

$$R = \sqrt{\left[\sum_{(ij)} \left[ \left( \langle D_{ij} \rangle^{\exp} - \langle D_{ij} \rangle^{\operatorname{calc}} \right)^2 / \sigma_{ij} \right]} \right]}.$$
 (21)

The sum runs over all sixteen distinct dipole couplings;  $\sigma_{ij}$  is the experimental error of coupling  $\langle D_{ij} \rangle^{exp}$ . Both models could be best fitted with the assignment of table 2. The calculated dipole coupling constants,  $\langle D_{ij} \rangle^{eale}$ , for the best fits are listed in columns 6 and 7 of table 2. In table 4 we summarize the values of the adjustable parameters  $E_a$ ,  $\varepsilon$  and k and of the deviation R.

Deuterium quadrupole couplings, which were not included in the fitting procedure, provide an additional test of the models. Table 5 compares the quadrupole splittings measured at 50°C, the approximate temperature of the COSY and INADEQUATE experiments, with the quadrupole splittings calculated for both models.

Table 4. Results of the least-squares fits for n-hexane.

Model	$E_g/kJ \mathrm{mol}^{-1}$	$10^7 \mathrm{Jm^{-3}}$	$\frac{k}{10^{-3}}$ N m <sup>-1</sup>	R/ Hz
A B	$3.34 \pm 0.09$ $3.65 \pm 0.07$	$2.59\pm0.03$	$4.30 \pm 0.04$	13·9 23·8

Sites	Experiment	Model A†	Model B†
Ме	7.0	7.1	7.2
$E_1$	21.8	20.9	21.3
$E_2$	25.1	24.0	24.8

Table 5. Quadrupole splittings vo (kHz).

† Assuming a quadrupole coupling constant of 168 kHz.

The probabilities of the different conformers obtained for the best fits shown in table 6 are similar for both models. Conformers with adjacent  $g^+g^-$  bonds have negligibly low ( $\leq 0.0002$ ) probabilities and are not listed in the tables. Table 6 also compares the conformer probabilities from the best fits of models A and B with the values obtained for  $E_{q}$  from each fit, but assuming  $U_{ext} = 0$ . This comparison shows that the orientation-dependent part of the potential (shown in figure 13 for two different conformers) has a minor influence on the conformer probability. Although the influence is small, it is significant that the sign of the effect differs for the two models. This difference in sign is compensated by the difference in the values obtained for the adjustable parameter  $E_q$ . The trans-gauche energy of the models is obviously not a purely intramolecular parameter, but contains a contribution from the solute-liquid crystal interaction. For the simple models used here, the magnitude of this contribution to  $U_{\rm int}$  depends on the parameterization of the second term,  $U_{\text{ext}}$ . Our values of  $E_g$  (3.34 kJ mol<sup>-1</sup> for model A and 3.65 kJ mol<sup>-1</sup> for model B) are at the upper end of the widely varying range of  $E_q$  values previously measured for liquid alkanes (between ca. 2.0 and 3.8 kJ mol<sup>-1</sup>, see for example [26]). (Recently, Photinos et al. [22(d)] have given a parametrization of  $U_{ext}$  with which good fits of experimental couplings can be obtained for the nominal  $E_g$  value of  $2.09 \text{ kJ mol}^{-1}$ .)

Table 7 lists the order matrices S in the principal axis systems of the inertia tensors of each molecule. While the matrices S are diagonal in those frames for model A, they have non-vanishing but small components  $S_{xy}$ ,  $S_{xz}$  and  $S_{yz}$  for model B, reflecting the different symmetries of the potentials. The order parameters of models A and B differ slightly, but both follow the same trends for the different conformers. As expected, the most elongated conformers, ttt and ttg, have the

	Model A ( $E_g =$	$3.34 \text{ kJ mol}^{-1}$ )	Model $B (E_g = 3.65 \text{ kJ mol}^{-1})$			
(frequency)	Best fit	$\varepsilon = 0$	Best fit	k = 0		
ttt (1)	0.304	0.291	0.303	0.322		
ttg (4)	0.083	0.084	0.083	0.083		
tgt (2)	0.083	0.084	0.083	0.083		
tgg (4)	0.023	0.024	0.023	0.021		
$g^{+}tg^{+}$ (2)	0.023	0.024	0.023	0.021		
$g^{+}tg^{-}(2)$	0.023	0.024	0.023	0.021		
ggg (2)	0.006	0.007	0.006	0.002		

Table 6. Probabilities of different conformers<sup>†</sup>.

† Errors are approximately 5 per cent.



Figure 13. Energy (E) of the interaction between the solute and the liquid crystal, calculated for the two different models described in the text. The orientation dependence ( $\theta$  and  $\phi$ are the polar angles of the director in the inertia frame of the conformer) is shown for two selected conformers: for the elongated all-trans conformer and for the more globular all-gauche conformer.

highest order parameters. The averages of the two dominant order parameters ( $S_{zz}$  and  $S_{xx-yy}$ ) from models A and B agree with the results of assuming a single (average) order tensor [5],  $S_{zz} = 0.21$ ,  $S_{xx-yy} = -0.06$ ,  $S_{xy} = -0.003$ ,  $S_{xz} = 0.009$ , and  $S_{yz} = -0.016$ .

Table 7. Order parameters (given in the principal axis system of the inertia tensor, the z axiscorresponding to the long axis of the molecule).

	Model A		Model B						
Conformer	Szz	$S_{xx-yy}$	Szz	$S_{xx-yy}$	S <sub>xy</sub>	S <sub>xz</sub>	$S_{yz}$		
ttt	0.25	-0.062	0.27	-0.011	0.0000	0.0000	-0.0068		
ttg	0.20	-0.074	0.21	-0.023	-0.0025	-0.0018	0.0032		
tgt	0.20	-0.062	0.22	-0.050	0.0000	-0.0021	0.0000		
tgg	0.14	-0.046	0.16	-0.032	-0.0032	0.0033	0.0019		
g <sup>+</sup> tg <sup>+</sup>	0.15	-0.035	0.17	-0.023	0.0000	0.0055	0.0000		
g <sup>+</sup> tg <sup>-</sup>	0.18	-0.010	0.20	-0.022	-0.0054	-0.0010	0.0085		
ggg	0.12	-0.011	0.16	-0.004	0.0000	0.0000	0.0068		
Average	0.20	-0.063	0.22	-0·019	-0.0014	-0.0005	-0.0003		

	E /		<b>D</b> /
Difference from assignment of table 2	$kJ \mod^{L_g/1}$	ε or k	K/ Hz
Model A:		$\varepsilon 10^7 \mathrm{J}\mathrm{m}^{-3}$	
$\langle D_{6,8} \rangle = -43 \mathrm{Hz}$	$3.35 \pm 0.09$	$2.59 \pm 0.03$	18.3
$\langle D_{1,4} \rangle = -322 \mathrm{Hz}, \langle D_{1,10} \rangle = -386 \mathrm{Hz}$	$3.26 \pm 0.09$	$2.62 \pm 0.03$	15.3
$\langle D_{4,10} \rangle = -713 \mathrm{Hz}, \langle D_{5,10} \rangle = -609 \mathrm{Hz}$	3·53 ± 0·09	$2.52 \pm 0.03$	19.8
$\langle D_{4,6} \rangle = 81 \mathrm{Hz}, \langle D_{5,6} \rangle = 186 \mathrm{Hz}$	$3.32 \pm 0.09$	$2.60 \pm 0.03$	19.3
$\langle D_{4,8} \rangle = -1086 \mathrm{Hz}, \langle D_{5,8} \rangle = -1616 \mathrm{Hz}$	$2.84 \pm 0.08$	$2.73 \pm 0.03$	34.5
Model B:		$k  10^{-3}  \mathrm{N  m^{-1}}$	
$\langle D_{6,8} \rangle = -43 \mathrm{Hz}$	3·65 <u>+</u> 0·07	$4.29 \pm 0.04$	26.9
$\langle D_{1,4} \rangle = -322 \mathrm{Hz}, \langle D_{1,10} \rangle = -386 \mathrm{Hz}$	$3.58 \pm 0.07$	$4.32 \pm 0.04$	24.1
$\langle D_{4,10} \rangle = -713 \mathrm{Hz}, \langle D_{5,10} \rangle = -609 \mathrm{Hz}$	$3.77 \pm 0.08$	$4.20 \pm 0.04$	29.0
$\langle D_{4,6} \rangle = 81 \mathrm{Hz}, \langle D_{5,6} \rangle = 186 \mathrm{Hz}$	$3.70 \pm 0.07$	$4.21 \pm 0.04$	25.3
$\langle D_{4,8} \rangle = -1086 \mathrm{Hz}, \langle D_{5,8} \rangle = -1616 \mathrm{Hz}$	$3.27 \pm 0.07$	$4.44 \pm 0.04$	39.9

 Table 8. Results of the least-squares fits for hexane with different assignments of the dipole couplings.

The model calculations demonstrate that both model A and model B together with the N.M.R. data describe the main features of the orientation of a flexible molecule in a nematic liquid crystal and give reasonable estimates of the probabilities of the different conformers. Table 8 shows how R (equation (21)) changes when assignments of the dipole couplings different from those in table 2 are used. The difference in R is small when two couplings of similar size, such as  $\langle D_{1,4} \rangle$  and  $\langle D_{1,10} \rangle$  or  $\langle D_{4,6} \rangle$  and  $\langle D_{5,6} \rangle$  (which could not be assigned from the multiplequantum spectrum), are exchanged. Hence the possibility cannot be excluded that the assignments of these two pairs of couplings are different from table 2, although this would not significantly change the calculated order parameters and conformer probabilities, and therefore would not affect the interpretation of our results. However, an exchange of couplings of different magnitude, like  $\langle D_{4,8} \rangle$  and  $\langle D_{5,8} \rangle$ , increases R significantly and can therefore safely be excluded. This demonstrates how the model calculations can resolve the significant ambiguities of assignment which arise from the remaining solutions to the multiple-quantum spectrum.

An interesting question is whether the method for determining dipole couplings which has been presented here can be applied to larger molecules. With increasing size of the solute molecule, two problems arise: more lines appear in the spectrum, and the intensities of the individual lines decrease. The first problem is illustrated in table 9. As the length of the alkane chain increases from six to twenty carbon atoms, the number of square patterns in the COSY spectrum increases rapidly; hence spectra will be more crowded and more difficult to interpret. The second problem is illustrated in figure 14 showing the probability of two-proton isomers as a function

Table 9. Number of unique 2-proton isomers (number of unique dipole couplings), Z(2), as a function of chain length for *n*-alkanes.

Number of carbon atoms	6	8	10	12	14	16	18	20
Z(2)	16	29	46	67	92	121	154	191



Figure 14. Isomer statistics for higher *n*-alkanes (N = number of carbon atoms). (a) Probability of each 2-proton isomer, i.e., probability of 2-proton molecules divided by the number of different 2-proton isomers, as a function of deuteration level. The arrow indicates the level of deuteration of the sample used for our experiments. (b) Probability of each *m*-proton isomer evaluated at the maxima of the curves in (a) as a function of the number of carbon atoms.

of deuteration for various *n*-alkanes. The maxima in the curves decrease rapidly as the length of the alkane chain increases. The maxima are a measure of the relative intensities of the peaks in the spectrum for different chain lengths. For example, for *n*-decane one expects about three times as many lines as for *n*-hexane, each line at about one third the intensity, and for *n*-octadecane one expects a tenfold increase in complexity and a tenfold reduction in signal intensity. We expect that it is feasible with this method to analyse spectra for alkanes with up to twelve carbon atoms.

Since the spectra for larger molecules will be more crowded, higher experimental resolution is required. This can be achieved by implementing a recently developed new decoupling technique [27]. High resolution spectra will also allow consideration of J couplings, resulting in more accurate values for the dipole couplings. Then, with better experimental data, more elaborate models for the solute-liquid crystal interaction can be considered.

The models play a more important role in solving the assignment problem for larger molecules with more dipole couplings, and in cases where multiple-quantum spectra are not available or do not provide sufficient information. An example is n-octane with 29 dipole couplings, which is currently under study in our laboratory. For this solute the similar chemical shifts of the inner methylene groups render the

assignment difficult. Preliminary results obtained with the aid of models A and B show a striking similarity between the dipole couplings of hexane and the corresponding couplings of octane dissolved in the same liquid crystal [28].

We thank Herbert Zimmermann for the preparation of the deuterated *n*-hexane sample. M. E. R. was supported by a National Science Foundation Graduate Fellowship. C. S. acknowledges the Alexander von Humboldt Foundation for a Feodor-Lynen-Fellowship. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

#### References

- [1] SAUPE, A., and ENGLERT, G., 1963, Phys. Rev. Lett., 11, 462.
- [2] See for example: (a) DIEHL, P., and KHETRAPAL, C. L., 1969, NMR—Basic Principles Prog., 1, 1. (b) EMSLEY, J. W., and LINDON, J. C., 1975, NMR Spectroscopy Using Liquid Crystal Solvents (Pergamon Press). (c) KHETRAPAL, C. L., and KUNWAR, A. C., 1983, Adv. liq. Crystals, 6, 173. (d) EMSLEY, J. W. (editor), 1985, Nuclear Magnetic Resonance of Liquid Crystals (Reidel Publishing Company). (e) DIEHL, P., and JOKISAARI, J., 1986, NMR in Stereochemical Analysis, Vol. 6, edited by Y. TAKEUCHI and A. P. MARCHAND (VCH Publishers Inc.). (f) KHETRAPAL, C. L., KUMAR, B. S., and RAGHOTHAMA, S., 1988, Nucl. magn. Reson., 17, 359. (g) KHAN, A., 1989, Nucl. magn. Reson., 18, 408.
- [3] (a) HEWITT, R. C., MEIBOOM, S., and SNYDER, L. C., 1973, J. chem. Phys., 58, 5089. (b) LUZ, Z., and MEIBOOM, S., 1973, J. chem. Phys., 59, 1077. (c) MEIBOOM, S., HEWITT, R. C., and LUZ, Z., 1977, J. chem. Phys., 66, 4041.
- [4] (a) GOCHIN, M., SCHENKER, K. V., ZIMMERMANN, H., and PINES, A., 1986, J. Am. chem. Soc., 108, 6813. (b) GOCHIN, M., HUGI-CLEARY, D., ZIMMERMANN, H., and PINES, A., 1987, Molec. Phys., 60, 205.
- [5] GOCHIN, M., ZIMMERMANN, H., and PINES, A., 1987, Chem. Phys. Lett., 137, 51.
- [6] JANIK, B., SAMULSKI, E. T., and TORIUMI, H., 1987, J. phys. Chem., 91, 1842.
- [7] VAN DER EST, A. J., KOK, M. Y., and BURNELL, E. E., 1987, Molec. Phys., 60, 397.
- [8] HOATSON, G. L., BAILEY, A. L., VAN DER EST, A. J., BATES, G. S., and BURNELL, E. E., 1988, Liq. Crystals, 3, 683.
- [9] (a) BALASUBRAMANIAN, K., 1979, Theor. Chim. Acta (Berlin), 51, 37. (b)
   BALASUBRAMANIAN, K., 1980, J. chem. Phys., 73, 3321.
- [10] (a) PIANTINI, U., SØRENSEN, O. W., and ERNST, R. R., 1982, J. Am. chem. Soc., 104, 6800.
   (b) SHAKA, A. J., and FREEMAN, R., 1983, J. magn. Reson., 51, 169. (c) SØRENSEN, O. W., LEVITT, M. H., and ERNST, R. R., 1983, J. magn. Reson., 55, 104.
- [11] ERNST, R. R., BODENHAUSEN, G., and WOKAUN, A., 1987, Principles of Nuclear Magnetic Resonance in One and Two Dimensions (Clarendon Press).
- [12] AUE, W. P., BARTHOLDI, E., and ERNST, R. R., 1976, J. chem. Phys., 64, 2229.
- [13] BAX, A., FREEMAN, R., and FRENKIEL, T. A., 1981, J. Am. chem. Soc., 103, 2102.
- [14] WEITEKAMP, D. P., 1983, Adv. magn. Reson., 11, 111.
- [15] DROBNY, G., WEITEKAMP, D. P., and PINES, A., 1986, Chem. Phys., 108, 179.
- [16] DIEZ, E., SANTORO, J., and ESTEBAN, A. L., 1982, J. magan. Reson., 46, 440.
- [17] PINES, A., VEGA, S., and MEHRING, M., 1978, Phys. Rev. B, 18, 112.
- [18] DROBNY, G., PINES, A., SINTON, S., WEITEKAMP, D. P., and WEMMER, D., 1979, Faraday Div. Chem. Soc. Sympos., 13, 49.
- [19] FLORY, P. J., 1969, Statistical Mechanics of Chain Molecules (Wiley).
- [20] EMSLEY, J. W., LUCKHURST, G. R., and STOCKLEY, C. P., 1982, Proc. R. Soc. Lond. A, 381, 117.
- [21] EMSLEY, J. W., and LUCKHURST, G. R., 1980, Molec. Phys., 41, 19.
- [22] (a) SAMULSKI, E. T., and DONG, R. Y., 1982, J. chem. Phys., 77, 5090. (b) EMSLEY, J. W., HEATON, N. J., LUCKHURST, G. R., and SHILSTONE, G. N., 1988, Molec. Phys., 64, 377.
  (c) DELIKATNY, E. J., and BURNELL, E. E., 1989, Molec. Phys., 67, 775. (d) PHOTINOS, D. J., SAMULSKI, E. T., and TORIUMI, H., J. phys. Chem. (submitted).

- [23] STRALEY, J. P., 1974, Phys. Rev. A, 10, 1881.
- [24] (a) WEAVER, A., VAN DER EST, A. J., RENDELL, J. C. T., HOATSON, G. L., BATES, G. S., and BURNELL, E. E., 1987, *Liq. Crystals*, 2, 633. (b) KOK, M. Y., VAN DER EST, A. J., and BURNELL, E. E., 1988, *Liq. Crystals*, 3, 485. (c) BURNELL, E. E., VAN DER EST, A. J., PATEY, G. N., DE LANGE, C. A., and SNIJDERS, J. G., 1987, *Bull. magn. Reson.*, 9, 4.
- [25] BONDI, A., 1964, J. phys. Chem., 68, 441.
- [26] (a) MIZUSHIMA, S., and OKAZAKI, H., 1949, J. Am. chem. Soc., 71, 3411. (b) SHEPPARD, N., and SZASZ, G. J., 1949, J. chem. Phys., 17, 86. (c) ABE, A., JERNIGAN, R. J., and FLORY, P. J., 1966, J. Am. chem. Soc., 88, 631. (d) DEVAURE, J., and LASCOMBE, J., 1979, Nouv. J. Chim., 3, 579. (e) COLOMBO, L., and ZERBI, G., 1980, J. chem. Phys., 73, 2013. (f) KINT, S., SCHERER, J. R., and SNYDER, R. S., 1980, J. chem. Phys., 73, 2599. (g) ROSENTHAL, L., RABOLT, J. F., and HUMMEL, J., 1982, J. chem. Phys., 76, 817. (h) WONG, P. T. T., MANTSCH, H. H., and SYNDER, R. G., 1983, J. chem. Phys., 79, 2369. (i) KANESAKA, I., SNYDER, R. G., and STRAUSS, H. L., 1986, J. chem. Phys., 84, 395. (j) MENGER, F. M., and D'ANGELO, L. L., 1988, J. Am. chem. Soc., 110, 8241.
- [27] (a) SUTER, D., SCHENKER, K. V., and PINES, A., 1987, J. magn. Reson., 73, 90. (b) SCHENKER, K. V., SUTER, D., and PINES, A., 1987, J. magn. Reson., 73, 99.
- [28] SCHMIDT, C., ROSEN, M. E., RUCKER, S. P., NEIDIG, P., and PINES, A. (in preparation).