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Michael Bender; Peter Holstein; Dieter Geschke

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Nematic reorientation in electric and magnetic fields

MICHAEL BENDER*, PETER HOLSTEIN and DIETER GESCHKE

Universität Leipzig, Fakultät für Physik und Geowissenschaften, Linnéstraße 5,
04103 Leipzig, Germany

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Homogeneous reorientation processes of two nematic liquid crystals in electric and magnetic fields have been observed using proton nuclear magnetic resonance spectroscopy (NMR). Using a recently developed experimental set-up, it is possible to study reorientation processes in liquid crystals by means of NMR experiments in a very flexible way. The time constant τ describing these processes has been determined as a function of the applied electric field. It emerges that the electric field cannot only be used to increase the reorientation time but also to slow the director reorientation by approximately one order of magnitude. Experimental data for 5CB and a fluorinated liquid crystal (BCH-5 FFF) are presented. The reorientation time measured as a function of the electric field can be used to calculate the rotational viscosity γ_1 . By repeating these experiments at different temperatures it was possible to investigate the temperature behaviour of γ_1 .

1. Introduction

The director reorientation of nematic liquid crystals (LCs) in external fields is of great interest for LC applications and also provides information about the fundamental dynamic processes. A number of attempts have been made to investigate the anisotropic and dynamic properties of LCs by means of NMR spectroscopy using electric and magnetic fields [1], reorienting the whole sample [2, 3] or by spinning the sample fast enough to align the director parallel to the spinning axis (VAS) [4–6].

The time constant τ , which describes the homogeneous director reorientation in external fields, is directly related to fundamental material parameters, i.e. $\Delta\chi$, $\Delta\epsilon$, γ_1 . Therefore, the measurements of γ_1 by investigating the director reorientation in the magnetic field of an NMR spectrometer has been established as a standard technique [7–11]. The theoretical description of homogeneous processes is reasonably simple as long as only one external field is present but becomes more complicated if two fields, \mathbf{E} and \mathbf{B} , act on the director at the same time. While a number of experiments using electric fields parallel or perpendicular to the magnetic field have been reported [12–15] little has been published for the more universal case of an arbitrary angle α between the two fields [16–18]. In this case the time constant τ depends on α and shows an interesting dependence on the electric field strength. In the limits of very low and very high electric fields the well known

$1/B_0^2$ and $1/E^2$ behaviour can be found. In the intermediate region the torques arising from the electric and the magnetic fields become comparable and τ increases by up to one order of magnitude compared with the pure magnetic case. The introduction of an additional electric field provides, therefore, not only the possibility to decrease the reorientation time to several microseconds but also to increase it considerably. Slowing down the director reorientation is especially useful for low molar mass LCs with reorientation times in the order of milliseconds. The delayed reorientation often becomes negligible for the duration of the NMR experiment and the electric field can be used instead of additives which increase the viscosity of the LC [19].

We present several time constants measured as a function of the applied electric field, $\tau(\mathbf{E})$, for the low molar mass LCs 5CB and BCH-5 FFF. From these data γ_1 can be estimated provided the diamagnetic and dielectric anisotropies $\Delta\chi$ and $\Delta\epsilon$ are known.

2. Theoretical description

The homogeneous director reorientation of a nematic LC can be described by a simplified form of the Leslie equation [20]

$$\gamma_1 \frac{d\varphi}{dt} = \frac{\Delta\chi}{2\mu_0} \mathbf{B}^2 \sin(2\varphi) - \frac{\epsilon_0}{2} \Delta\epsilon \mathbf{E}^2 \sin(2\alpha - 2\varphi) \quad (1)$$

where φ is the angle between the director \mathbf{n} and the magnetic field \mathbf{B} , γ_1 is the rotational viscosity, $\Delta\chi$ and $\Delta\epsilon$ are the diamagnetic and dielectric anisotropies, \mathbf{B} and \mathbf{E} are the magnetic and electric fields and α is the angle between \mathbf{E} and \mathbf{B} . μ_0 is the permeability of free

* Author for correspondence
e-mail: bender@physik.uni-leipzig.de

space and ε_0 is the permittivity of a vacuum. The solution is given by [17]

$$\varphi(t) = \arctan \left[\tan(\varphi_0 - \varphi_{es}) \exp\left(-\frac{t}{\tau_{re}}\right) \right] + \varphi_{es} \quad (2)$$

where φ_0 is the initial angle between the director and the magnetic field and φ_{es} is the equilibrium state in the external fields, which is given by

$$\varphi_{es} = \begin{cases} \frac{1}{2} \arctan \left[\frac{\sin(2\alpha)}{\frac{\Delta\chi \mathbf{B}^2}{\mu_0 \varepsilon_0 \Delta\varepsilon \mathbf{E}^2} + \cos(2\alpha)} \right] & \text{for } \left| \frac{\Delta\chi}{\mu_0} \mathbf{B}^2 \right| \geq |\varepsilon_0 \Delta\varepsilon \mathbf{E}^2| \\ \alpha - \frac{1}{2} \arctan \left[\frac{\sin(2\alpha)}{\frac{\mu_0 \varepsilon_0 \Delta\varepsilon \mathbf{E}^2}{\Delta\chi \mathbf{B}^2} + \cos(2\alpha)} \right] & \text{for } \left| \frac{\Delta\chi}{\mu_0} \mathbf{B}^2 \right| < |\varepsilon_0 \Delta\varepsilon \mathbf{E}^2| \end{cases} \quad (3)$$

The time constant τ_{re} of the reorientation process is

$$\tau_{re} = \gamma_1 \left[\left(\frac{\Delta\chi}{\mu_0} \mathbf{B}^2 \right)^2 + (\varepsilon_0 \Delta\varepsilon \mathbf{E}^2)^2 + 2 \frac{\Delta\chi}{\mu_0} \mathbf{B}^2 \varepsilon_0 \Delta\varepsilon \mathbf{E}^2 \cos(2\alpha) \right]^{-1/2}. \quad (4)$$

The well known time constants $\tau_{\mathbf{B}} = \mu_0 \gamma_1 / (\Delta\chi \mathbf{B}^2)$ and $\tau_{\mathbf{E}} = \gamma_1 / (\varepsilon_0 \Delta\varepsilon \mathbf{E}^2)$ can be obtained by setting $\mathbf{B} = 0$ and $\mathbf{E} = 0$. While in these simple cases $\tau_{\mathbf{E}}$ and $\tau_{\mathbf{B}}$ decrease with increasing field strength, the behaviour is much more interesting if two fields are applied simultaneously. While for angles $\alpha \leq 45^\circ$ the time constant also decreases with increasing external fields, a maximum appears for $\alpha > 45^\circ$ (figure 1).

For small electric fields the magnetic torque dominates and τ is close to $\tau_{\mathbf{B}}$. On increasing the electric field strength, the electric torque becomes comparable to the magnetic one, and the effective torque acting on the director becomes a minimum resulting in an increased reorientation time. The maximum value of τ is given by

$$\tau_{\max} = \frac{\gamma_1}{\frac{\Delta\chi}{\mu_0} \mathbf{B}^2 [1 - \cos^2(2\alpha)]^{1/2}} = \frac{\tau_{\mathbf{B}}}{[1 - \cos^2(2\alpha)]^{1/2}} \quad (5)$$

where the electric field is

$$\mathbf{E}_{\max}^2 = -\cos(2\alpha) \frac{\Delta\chi \mathbf{B}^2}{\mu_0 \varepsilon_0 \Delta\varepsilon}. \quad (6)$$

For $\alpha = 87^\circ$ this value is about ten times higher than $\tau_{\mathbf{B}}$. It is therefore possible to increase the reorientation time by one order of magnitude. Electric fields above \mathbf{E}_{\max} lead to a decreased reorientation time resulting in a $1/\mathbf{E}^2$ law for high electric fields.

The case $\mathbf{E} \perp \mathbf{B}$ cannot be described using this simplified model of a homogeneous director reorientation. From a formal point of view the torque acting on the director vanishes, corresponding to an unstable equilibrium. The transition to a stable equilibrium cannot be described using this model. In practice the reorientation process becomes inhomogeneous if the initial angle φ_0 exceeds a certain critical angle φ_c , which is near 85° for 5CB [1, 21]. Angles near 90° are therefore impractical if a well defined reorientation process is desirable.

3. Experimental

The director reorientation of some nematic low molar mass LCs in the static magnetic field of an NMR spectrometer and a variable electric field inside a capacitor cell has been measured by means of ^1H NMR

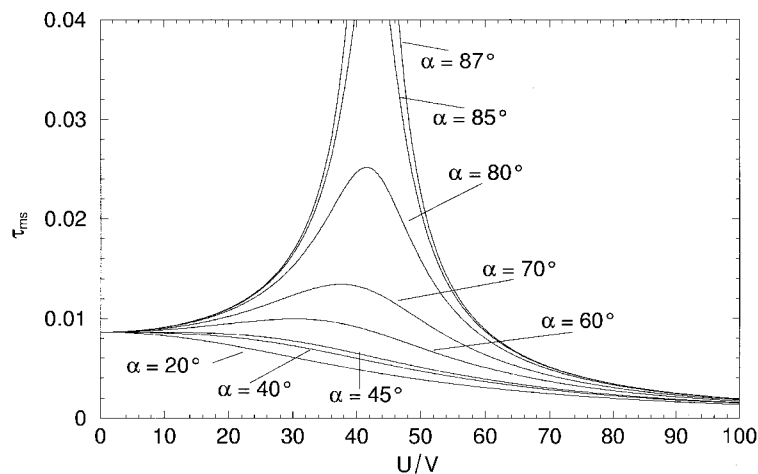


Figure 1. Plot of $\tau_{(U)}$, equation (4), for 5CB at 25°C using the following parameters: $\Delta\chi = 2.136 \times 10^{-6}$, $\Delta\varepsilon = 13$, $\gamma_1 = 0.081 \text{ Pa s}$ [33], $B = 2.35 \text{ T}$ (100 MHz). The voltage has been calculated for a $150 \mu\text{m}$ capacitor cell.

spectroscopy. The experimental set-up has been described elsewhere [17] and will only be shortly reviewed here. The LCs investigated are the well known 4-pentyl-4'-cyanobiphenyl (5CB) and a fluorinated form of a 4,4'-disubstituted biphenylcyclohexane (BCH-5 FFF) (figure 2). Both materials can be supercooled to room temperature.

The capacitor cell consisting of two gold evaporated glass plates, fixed the desired distance apart, was filled with the LC by means of capillary action. No additional treatment was applied to the gold surface providing direct contact between the gold surface and the LC. In the case of thick cells (150 μm for 5CB and 500 μm for BCH-5 FFF) the coupling to the surfaces can be neglected. For the applied fields the coherence length is below 1 μm and less than 1% of the material is influenced by the surfaces. The coupling to gold substrates has been investigated in detail by Gupta *et al.* [22]. The cell thickness was determined by glass spacers and was checked using a microscope equipped with a micrometer scale. The uniformity of the thickness was found to be of the order of 1 μm .

The capacitor was placed in the rf coil of the NMR probe. The experiments were carried out using a 100 MHz NMR spectrometer (Bruker MSL 100) working with a 2.35 T magnetic field and a laboratory built $^1\text{H}/^{19}\text{F}$ NMR probe. The probe is equipped with a goniometer which allows the precise setting of the angle α between

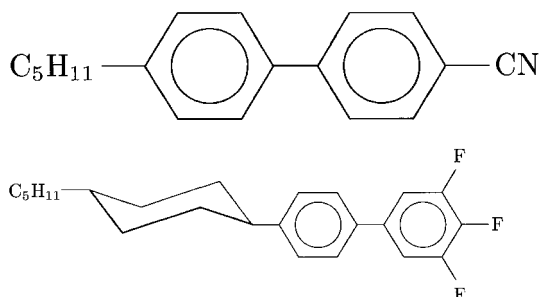


Figure 2. LCs investigated: 5CB (top), $T_m = 24.0^\circ\text{C}$, $T_c = 35.3^\circ\text{C}$; BCH-5 FFF (bottom), $T_m = 30^\circ\text{C}$, $T_c = 55^\circ\text{C}$.

the electric and magnetic fields and has special connections for an external high voltage supply. The goniometer allows very precise changes of the cell orientation with an accuracy of $\sim 0.02^\circ$. The main problem is to adjust the capacitor cell relative to the goniometer axis. Using a special calibration procedure, it is possible to identify the angle between the magnetic field and the cell to an accuracy of better than 0.1° . The wires connecting the LC cell and the amplifier are a major source of noise which is induced in the rf coil of the NMR spectrometer [23, 24]. The new probe has a special design to minimize the length of these wires and to reduce the noise, which is especially important for experiments at 100 MHz.

The high voltage d.c. pulses are triggered by the NMR pulse program in such a way that the rf pulses of the NMR experiment and the electric excitation of the LC sample can be set in any desired combination. The experiments described here were performed using rectangular d.c. pulses of variable voltage and duration (figure 3). Such short electric pulses, with a duration of less than 500 ms and a delay of ~ 1 s between the pulses, do not cause any conduction-induced instabilities inside the LC. The free induction decays (FIDs) were collected after the reorientation in the electric field was finished and the spectrum therefore represents the orientational state at the end of the electric pulse. The reorientation in the 2.35 T magnetic field during the recording of the FID (1–2 ms) can be neglected.

With this experimental set-up, reorientation times down to $\tau = 50 \mu\text{s}$ could be investigated because the orientational state is not changed by the magnetic field for the duration of the FID. The time resolution is given by electronic limitations and is of the order of the rising time of the electric pulse ($\ll 15 \mu\text{s}$).

The director reorientation of nematic LCs is a completely reversible process and it is therefore possible to repeat each experiment until a good signal to noise ratio has been achieved. The 150 μm capacitor cell filled

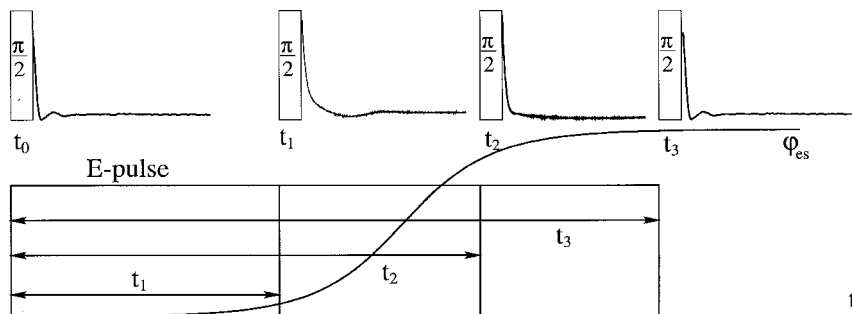


Figure 3. Detection of the director reorientation using d.c. pulses of increasing duration. The spectra are taken after the orientation in the electric field has been stopped. As the reorientation in \mathbf{B} can be neglected for at least 1 ms, each spectrum represents the orientational state at the end of the \mathbf{E} -pulse.

with 5CB typically requires 100–200 accumulations, the 500 μm cell used for BCH-5 FFF needs approximately 50 accumulations.

The NMR experiment results in a number of ^1H NMR spectra for each reorientation experiment. As the angle φ between the director and the magnetic field cannot be measured during the experiment it must be obtained from the NMR spectra. In the case of uniaxial nematic LCs the spectral shape scales with the angle φ and the order parameter S if certain conditions are fulfilled [25]: (1) the line shape is dominated by the dipolar interaction; (2) the molecules of the uniaxial LC undergo fast rotations about their long molecular axis; (3) a monodomain can be assumed. Given these assumptions the effects of the order parameter,

$$S = \frac{1}{2} \langle 3 \cos^2 \vartheta - 1 \rangle \quad (7)$$

and the mean direction of the molecules with respect to the magnetic field

$$S_{\mathbf{B}} = \frac{1}{2} (3 \cos^2 \varphi - 1) \quad (8)$$

can be separated. ϑ is the angle between the long molecular axis and the magnetic field. Any desired spectrum can therefore be obtained by scaling an idealized spectrum, $F_{1,1}$ with $S = 1$ and $S_{\mathbf{B}} = 1$:

$$F_{S,S_{\mathbf{B}}}(\omega) = \frac{1}{S S_{\mathbf{B}}} F_{1,1} \left(\frac{\omega}{S S_{\mathbf{B}}} \right). \quad (9)$$

During the director reorientation, the order parameter S is unchanged and only $S_{\mathbf{B}}$ has to be taken into account:

$$F_{S,S_{\mathbf{B}}}(\omega) = \frac{1}{S_{\mathbf{B}}} F_{S,1} \left(\frac{\omega}{S_{\mathbf{B}}} \right). \quad (10)$$

It is possible therefore to describe the director reorientation by scaling a spectrum $F_{S,1}$ initially collected with $\varphi = 0$. As long as the line shape is unchanged, the linewidth carries the same information as the dipolar splitting and the reorientation process can be described by the angle-dependent line width $\Delta\nu$:

$$\Delta\nu = \Delta\nu_0 \left[\frac{1}{2} (3 \cos^2 \varphi - 1) \right]. \quad (11)$$

The experiments described here meet these conditions. Specifically the strong magnetic field provides a monodomain, and thermal excitation activates rotational molecular states which are fast enough to average the intermolecular dipolar interaction. Due to the fast molecular rotation the dipolar interaction almost vanishes for angles close to the magic angle (54.7°) and the ^1H chemical shift becomes visible. In this region the first condition is violated and the linewidth is overestimated.

The spectra shown in figure 4 compare the result of a scaling procedure according to equation (10) with several spectra taken at different angles φ . The scaled spectra match the measured one very well, neglecting line broadening effects caused by experimental imperfections and incomplete averaging processes. Near the magic angle, line narrowing factors of about 200–300 could be achieved. Therefore, the data for the magic angle passage can be obtained with high precision. As the linewidth decreases near 54.7° to below 10% of its original value, the error due to non-zero width is negligible (see figure 5).

The analysis of the linewidth therefore allows the interpretation of the ^1H NMR spectra even if the dipolar splitting is not well resolved for all values of φ . The linewidth can be taken at any height; we chose to take the full width at half maximum. The ^1H NMR results were compared with ^{19}F NMR data measured for BCH-5 FFF [21]. The ^{19}F NMR spectra consist of three well resolved lines and the angle-dependent chemical shift can be analysed with high accuracy. The ^1H and ^{19}F NMR results agree within the experimental error.

The linewidth can be fitted directly to the experimental data by replacing φ in equation (11) with equation (2). The equilibrium value φ_{es} has to be calculated from the thickness of the capacitor d , the angle between the external fields α , the ratio $\Delta\chi/\Delta\varepsilon$ and the applied voltage. The initial angle φ_0 is always 0° for electric reorientation experiments. With the fitting parameter, the time constant of the reorientation process τ can be obtained. Figure 5 shows an example of the data analysis which has to be made for each reorientation experiment. The spectra have been analysed using special NMR software [26].

4. Results

$\tau_{(U)}$ has been measured for a wide range of voltages, starting with low voltages which lead to $\varphi_{\text{es}} \approx 15^\circ$, and up to high voltages of a few hundred V. The results (figures 6 and 7) are in excellent agreement with equation (4) and verify the theory described. In particular, the maximum value of τ at \mathbf{E}_{max} can be verified experimentally.

The description given in the theoretical section is valid only for homogeneous reorientation processes and not for inhomogeneous processes. In some cases it is not possible to distinguish both processes by investigating the measured time dependent line width. The line shape of the ^1H NMR spectra at the magic angle (54.7°) has therefore been used to identify homogeneous processes. As the spectral width of the ^1H NMR spectra decreases significantly at the magic angle, it is possible to detect line broadening due to the director distribution occurring in inhomogeneous processes. In the case of a homogeneous process a monodomain can be assumed and the ^1H chemical shift becomes visible. This well

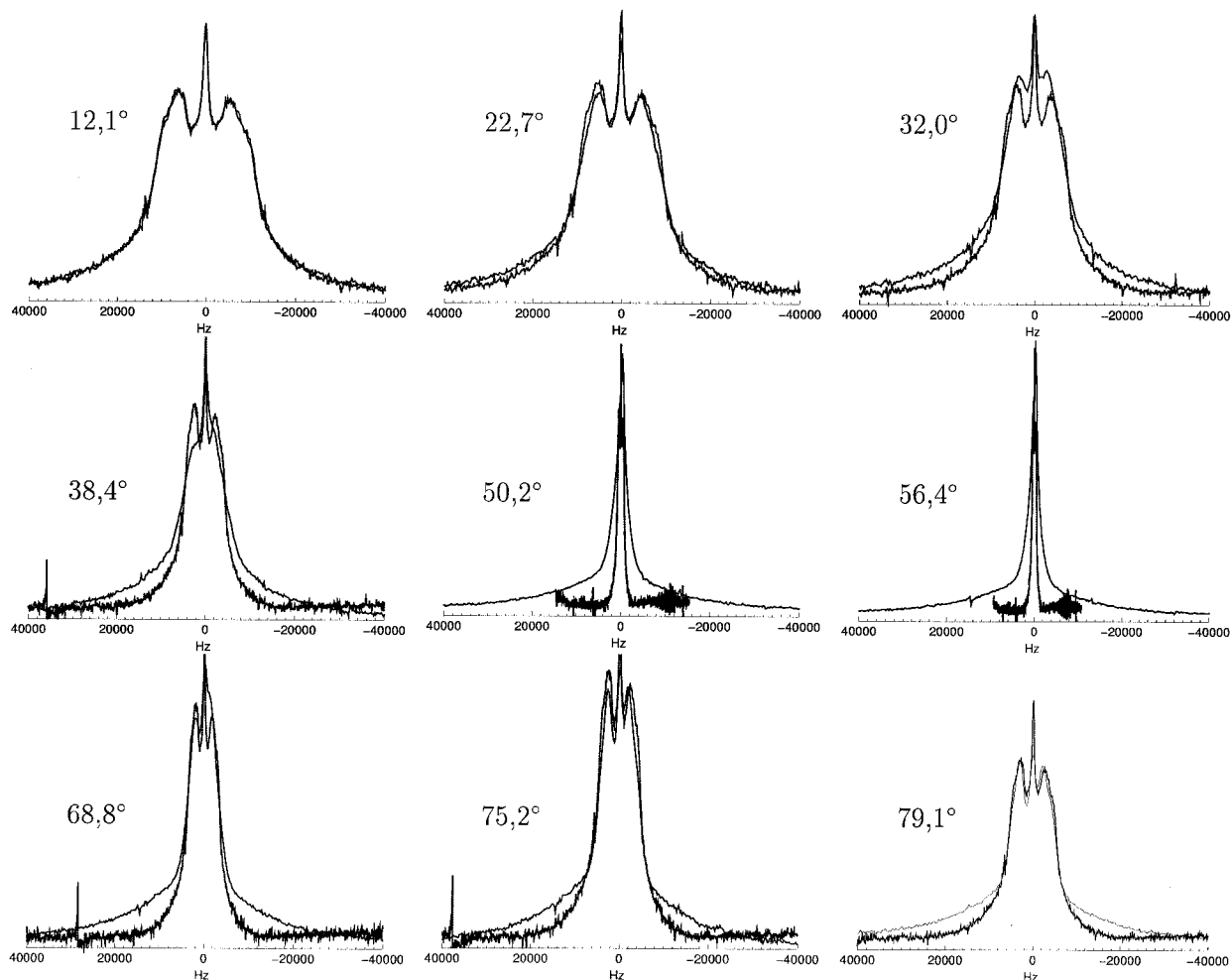


Figure 4. ^1H NMR spectra for 5CB. The spectra collected at different angles with respect to the magnetic field are plotted together with a scaled spectrum (bold line). The spectral shape changes near the magic angle but is otherwise close to the scaled spectrum.

resolved spectrum can be easily distinguished from a spectrum broadened by a director distribution. In figure 5 (left side, insert) two spectra taken at the magic angle are shown. The narrow line observed in a homogeneous process can be easily distinguished from the broadened line which occurs in an inhomogeneous process. All spectra taken in the electric field were identified as homogeneous even for large values of α [21].

The minimum linewidth obtained at the magic angle can be used to gauge the width of the director distribution. As the linewidth scales according to equation (11) it is possible to estimate the variation of the distribution from the ideal monodomain. Experiments with BCH-5 FFF aligned statically at the magic angle yield well resolved spectra which show the ^1H chemical shift. The linewidth of ≤ 500 Hz can be compared with $\Delta\nu_0 = 33.2$ kHz. Such narrow lines cannot be achieved if an

appreciable amount of the LC deviates by more than $\pm 0.5^\circ$ with respect to the magic angle. The minimum linewidth in an inhomogeneous process is about 3.5 kHz and implies a mean deviation of more than $\pm 4.5^\circ$.

While τ can be measured easily at high voltages, it is difficult to obtain reliable τ data at low voltages because φ_{es} decreases with decreasing voltage and the spectra change little during the reorientation process. As can be seen from figures 6 and 7 it was possible to acquire data down to $\varphi_{\text{es}} \approx 15^\circ$ corresponding to a decrease in the linewidth of about 10%. The error in τ increases therefore from approximately 5% for $\varphi_{\text{es}} > 54.7^\circ$ to more than 10% for considerably smaller angles. Below $\varphi_{\text{es}} = 15^\circ$ no reliable data can be obtained.

The measured $\tau_{(U)}$ data are shown in figures 6 and 7 for 5CB and BCH-5 FFF, respectively. Each data point represents a reorientation experiment in a different

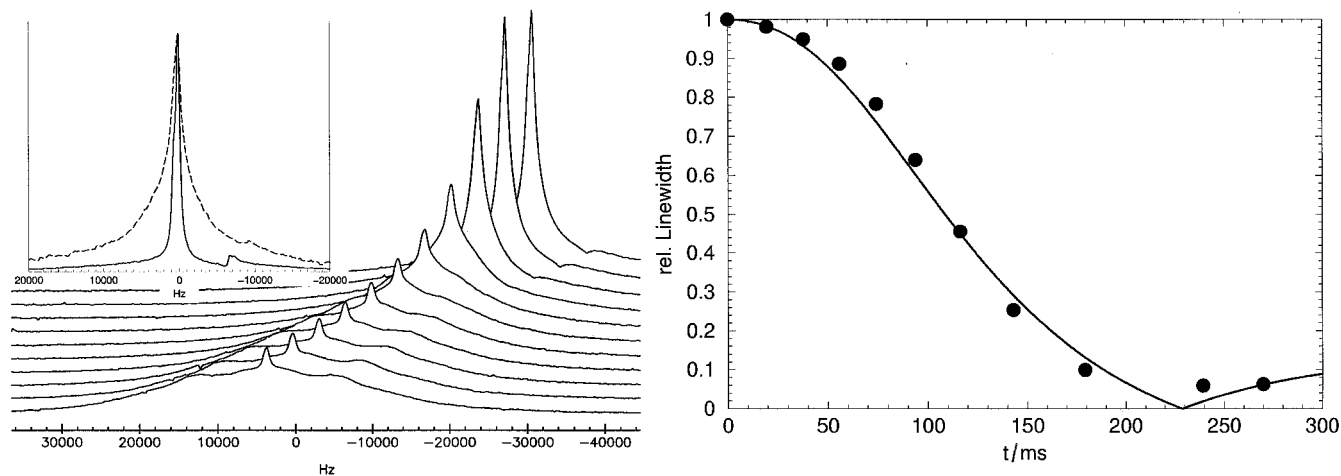


Figure 5. ^1H NMR spectra for BCH-5 FFF (31°C) taken during an electric reorientation process (left), and analysis of the relative linewidth (right). The spectra have been taken after 163 V d.c. pulses of increasing length: 0 ms (bottom), 19.6, 38.0, 55.9, 74.2, 93.8, 116.0, 142.9, 179.2, 239.3, 270.0 ms (top). The insert shows the spectrum taken at the magic angle (solid line) in comparison with a spectrum (dashed line) from an inhomogeneous process. The time dependent line width (left) can be fitted to a combination of equation (2) with equation (11) (solid line) and gives $\tau = 73.9$ ms.

Figure 6. $\tau_{(U)}$ data (left scale) measured for 5CB at 21°C. The solid line has been fitted to the data using equation (4) and $\alpha = 84.0^\circ$, $d = 150 \mu\text{m}$, $\Delta\chi = 2.46 \times 10^{-6}$ and $\Delta\varepsilon = 13.23$; this gives $\gamma_1 = 0.115$ Pa s. The dashed line (right scale) indicates the equilibrium φ_{es} obtained at the given voltage.

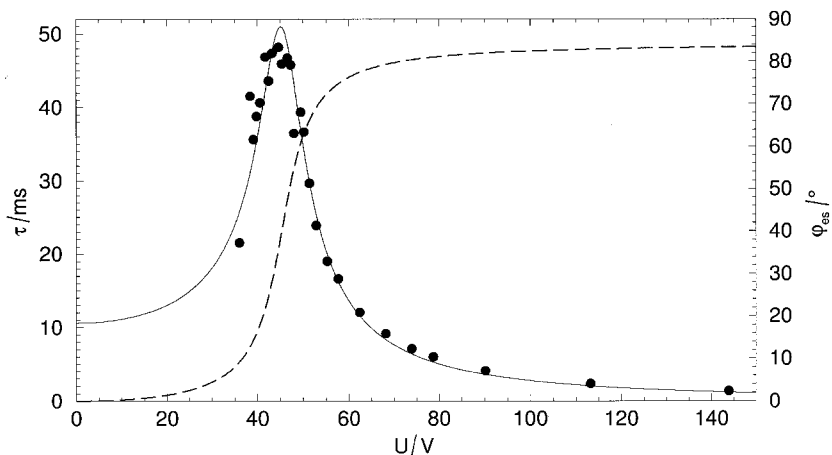
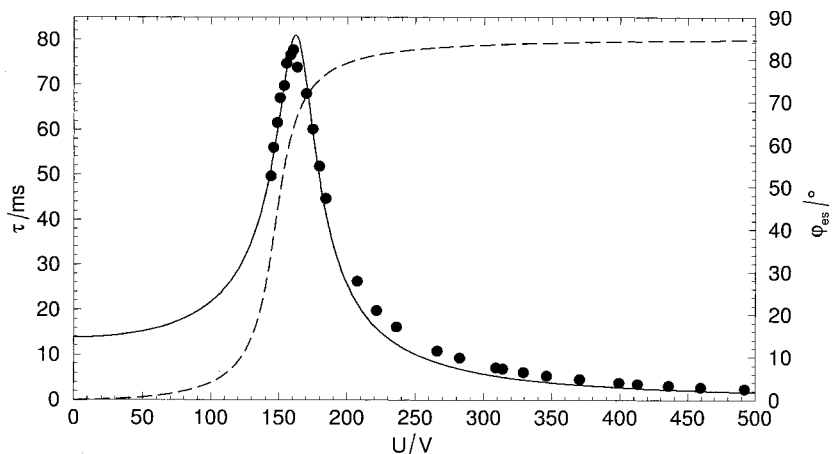


Figure 7. $\tau_{(U)}$ data (left scale) measured for BCH-5 FFF at 31°C. The solid line has been fitted using equation (4) and $\alpha = 85.0^\circ$, $d = 500 \mu\text{m}$, $\Delta\chi = 1.64 \times 10^{-6}$ and $\Delta\varepsilon = 7.6$; this gives $\gamma_1 = 0.0996$ Pa s. The dashed line (right scale) indicates the equilibrium φ_{es} obtained at the given voltage.



electric field which has been analysed as described in the experimental section. The data were fitted to equation (4) using the material parameters given in the figure captions. The rotational viscosity γ_1 has been chosen as the fitting parameter, while the other values were available from independent experiments and, in the case of 5CB, from the literature [27–29]. The same type of experiment could be used to measure $\Delta\chi$ if $\Delta\varepsilon$ and γ_1 were known.

Since the results are in very good agreement with the theoretical predictions, it is possible to use these experiments to obtain some material properties. If the anisotropies $\Delta\chi$ and $\Delta\varepsilon$ are known it is possible to measure the rotational viscosity γ_1 . As in the simple case of the magnetic field, it would be possible to calculate γ_1 from a single τ value. However, much more precise results can be obtained from a series of $\tau_{(U)}$ data. A fit of equation (4) based on a large number of τ data significantly reduces the error in the experiment. While the error in τ and the voltage can be reduced in this way that is not the case for the errors in the anisotropies $\Delta\chi$ and $\Delta\varepsilon$, the cell thickness d and the angle α between \mathbf{E} and \mathbf{B} . Errors in these quantities cause a comparable error in γ_1 ; for example, an error of +5% in $\Delta\chi$ raises γ_1 by about 4.4%. The angle α is the most critical parameter. An error in α of 4° can cause changes in γ_1 of more than 50%. For this reason α has to be adjusted very carefully. As it is difficult to estimate the errors in $\Delta\chi$ and $\Delta\varepsilon$ the error in γ_1 can be up to $\sim 10\%$.

In principle it would also be possible to vary the magnetic field. In most NMR experiments the magnetic field cannot be changed easily and it would be difficult to obtain more than two or three $\tau_{(B)}$ values even if several NMR spectrometers working at different frequencies were available. The introduction of the electric field is therefore a tool with which to increase the accuracy of γ_1 data obtained by NMR.

To compare the behaviour of γ_1 with theoretical models, it has been measured as a function of temperature with particular attention focused on the region near the phase transition to the isotropic phase. γ_1 has been obtained by measuring $\tau_{(U)}$ for 5CB at different temperatures. A fit of equation (4) to these data yields γ_1 . The results are given in figure 8 and table 1 together with some reference data [1, 30–33]. These experiments have not been extended to lower voltages because this would require much more experimental effort without providing more precise γ_1 data.

The rotational viscosity can be described as a function of the order parameter S and an activation energy E_a [34]

$$\gamma_{1(T)} = AS^2 \exp\left(\frac{E_a}{kT}\right) \quad (12)$$

where k is the Boltzmann constant and T is the temperature. T_m is the melting point and T_c is the clearing point of the LC. Together with the usual approximation for

Table. Experimental results for $\Delta\chi$, $\Delta\varepsilon$ and γ_1 . $\Delta\chi$ and $\Delta\varepsilon$ obtained from separate experiments [35]; γ_1 has been fitted to the measured $\tau_{(U)}$ data using equation (4) and the $\Delta\chi$ and $\Delta\varepsilon$ data given in the table.

Temperature/ $^\circ\text{C}$	$\Delta\varepsilon$	$\Delta\chi \times 10^{-6}$	$\gamma_1/\text{Pa s}$
21.0	13.23	2.46	0.115
28.5	9.96	1.85	0.059
29.5	9.85	1.83	0.051
30.5	9.28	1.73	0.047
31.5	9.07	1.69	0.039
32.5	8.32	1.55	0.036
33.0	8.01	1.49	0.032
33.5	7.64	1.42	0.030
34.0	7.14	1.33	0.026
34.5	5.80	1.06	0.021

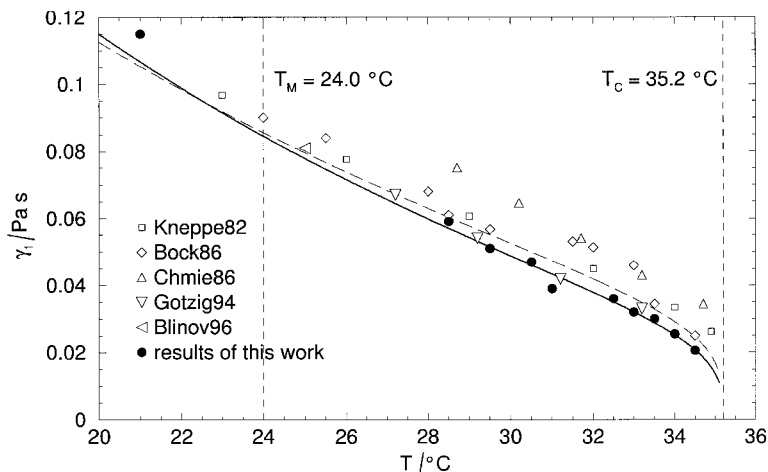


Figure 8. Temperature dependent γ_1 data [1, 30–33] for 5CB. The solid line is fitted to the results of this work (\bullet), the dashed line is plotted using the parameters published by Gotzig *et al.* [1].

the order parameter [20]

$$S_{(T)} = \left(1 - \frac{T}{T_c}\right)^\beta \quad (13)$$

the temperature dependent rotational viscosity γ_1 is available if the pre-exponential factor A , the activation energy E_a and the temperature exponent β are known. A fit of equation (12) and equation (13) to the experimental data yields $A = 4.35 \times 10^{-8}$ Pa s, $E_a = 6.37 \times 10^{-20}$ J and $\beta = 0.158$. These results can be compared with data published by Gotzig *et al.* [1] for 5CB: $A = 2.3 \times 10^{-7}$ Pa s, $E_a = 5.65 \times 10^{-20}$ J and $\beta = 0.141$.

The results are in good agreement with those in the literature and the method described here proves to be a reliable measure of γ_1 . However, it must be noted that considerable experimental effort is necessary to obtain $\gamma_{1(T)}$ using this method, as each τ value is based on approximately 15 spectra and thus, more than 150 spectra have to be acquired to obtain reliable $\tau_{(U)}$ data. If this experiment has to be repeated for ten temperatures, more than 1500 spectra have to be taken and analysed. Such an experiment runs therefore for several days. The data presented in figure 8 are based on 1270 spectra and required nearly one week of data acquisition.

5. Conclusions

The director reorientation of a nematic LC in external electric and magnetic fields has been investigated in detail using ^1H NMR spectroscopy. It was possible to verify the model describing the reorientation of a mono-domain in both fields. In particular, the predicted maximum of the reorientation time was found and it was possible to slow the reorientation process by a factor of 4.5 for 5CB ($\alpha = 84.0^\circ$) and by a factor of 5.6 for BCH-5 FFF ($\alpha = 85.0^\circ$). For higher values of α the reorientation time can be further increased provided that the process remains homogeneous. By application of high voltages, very short reorientation times can be achieved. The only limitations are in the experimental set-up and the breakdown voltage inside the capacitor cell. Experiments with $\tau = 400 \mu\text{s}$ have been successful, demonstrating that it is possible to vary the reorientation time by three orders of magnitude.

The $\tau_{(U)}$ data provide a new possibility to obtain the rotational viscosity, γ_1 ; a fit of the time constant τ as a function of the external fields yields reliable γ_1 data. Experiments with 5CB carried out at different temperatures lead to a temperature dependence of γ_1 which is in good agreement with literature data.

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