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Inertial effects in rotating lyotropic liquid crystals

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The orientation of the director of a lyotropic liquid crystal with negative anisotropy of the diamagnetic susceptibility is studied when the sample is spun at various speeds and angles from the magnetic field. Different behaviours is observed at low and high spinning speeds where the orientation is governed by the magnetic and the inertial torques, respectively. At intermediate frequencies it is possible to reach an equilibrium between these two torques. The evolution of this equilibrium with the average magnetic torque allows one to form a conclusion on the inertial nature of this effect.

1. Introduction

The effect of rotation, at an angular velocity w, on a nematic liquid crystal of negative anisotropy of the diamagnetic suscpetibility ($\Delta\chi$) is quite well understood [1]. If the spinning frequency is faster than the director reorientation rate, typically 10 Hz for a magnetic field of 1·5 T, the director n of the liquid crystal reaches a state where it is distributed in the plane perpendicular to the spinning axis R if the angle β between the rotation axis and the magnetic field H_0 is smaller than the magic angle, and it aligns parallel to the rotation axis when β is greater than the magic angle (figure 1). When the spinning speed is very high we have shown that another torque appears which tilts the nematic director in a plane perpendicular to the rotation axis [2].

In the present study, we analyse the director behaviour of a lyotropic nematic phase spinning at various speeds and angles to the magnetic field. For a low spinning frequency this kind of liquid crystal behaves as a $\Delta\chi < 0$ thermotropic phase. For high values of w the director lies, for all angles β, in the plane perpendicular to the rotation axis following what we think to be the effect of the inertial torque. At an intermediate spinning speed we are going to show that for a given angle β_0 an equilibrium is reached which allows a precise analysis of the inertial nature of the phenomenon.

2. Experimental

1, 2, 2, 2-tetrachloro 1, 1-difluoro ethane was dissolved in the quaternary lyotropic nematic phase (3)

	SDS	Decanol-*d*	D_2O	Na_2SO_4
percentage by weight	40	5	50	5

The ^{19}F N.M.R. spectra of this A_2 spin system were recorded on a modified WP 60 Bruker spectrometer. The field was locked on an external D_2O sample. The rotor-stator assembly has already been described [3]. It allows the rotation of liquids around

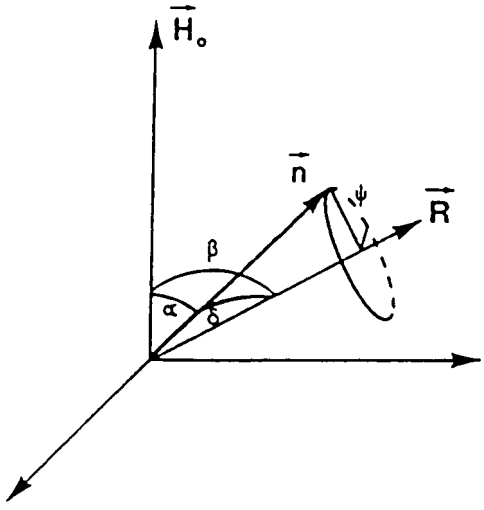
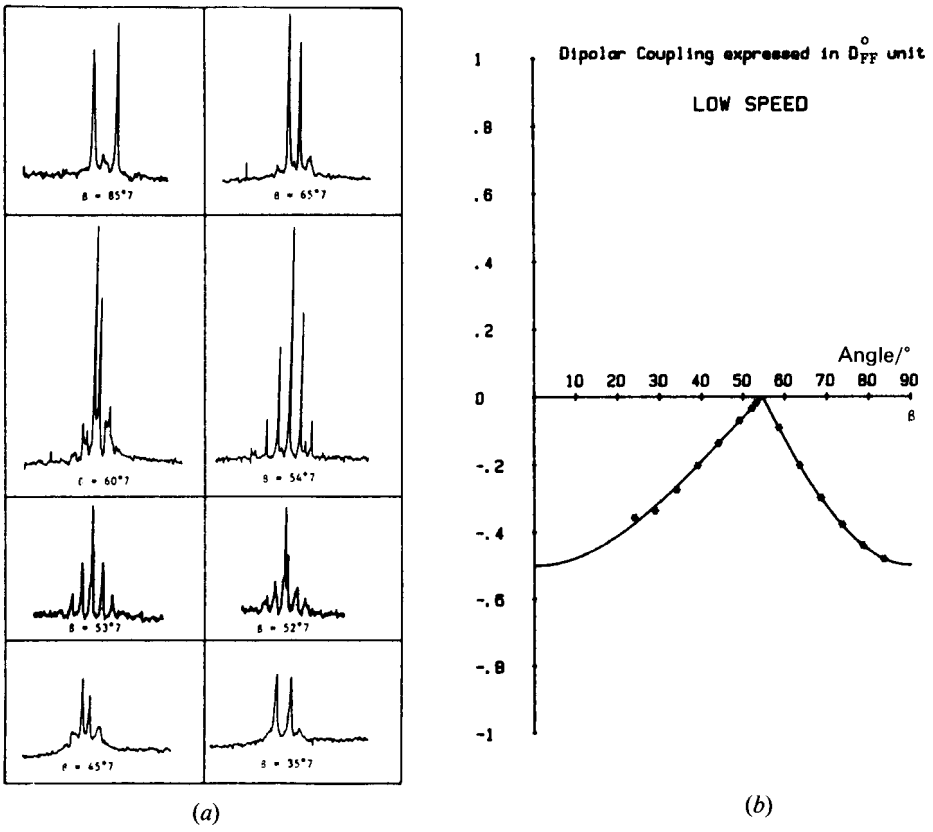


Figure 1. Definition of the axis and the angles used in the text: H_0, n and R are the magnetic field, the director and the rotation axis respectively; α, β and δ are the angles between H_0 and n, H_0 and R and n and R respectively.



(*a*) (*b*)

Figure 2. (*a*) ^{19}F N.M.R. spectra of our A_2 spin system for various angles β. The spinning frequency was equal to 101 Hz. n appears parallel to R when β is greater than the magic angle. (*b*) Plot of the fluorine dipolar coupling as a function of β. D_{FF}° is defined as the dipolar coupling whenever n is parallel to H_0 ($\alpha = 0$).

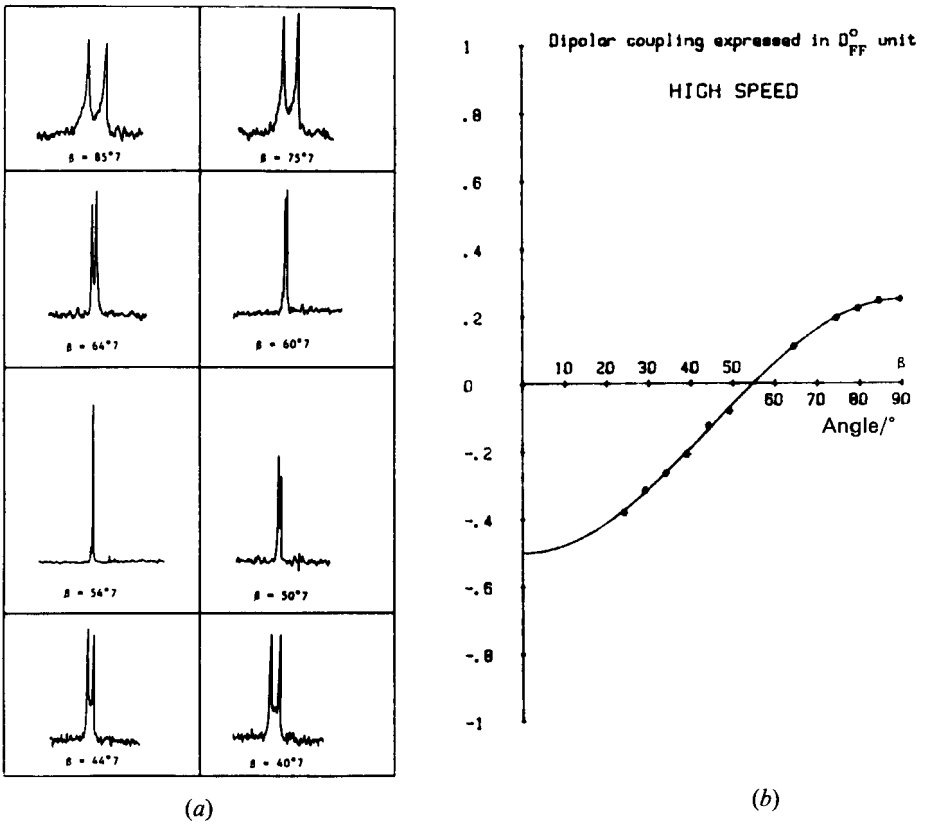


Figure 3. (*a*) ^{19}F N.M.R. spectra of the same sample for various angles β and a spinning frequency equal to 1280 Hz. (*b*) Plot of the fluorine dipolar coupling as a function of β. Compare with figure 2 (*b*). It indicates that n is perpendicular to R whatever β is.

an axis tilted at any angle from the magnetic field and variable temperature experiments. The samples were filled in an N.M.R. tube 15 mm long and 5 mm in diameter. This tube was inserted in a 10 mm cylindrical rotor which allows a rotation speed adjustable between 20 Hz and 2000 Hz. A goniometer is mounted at one end of the spinner holder which gives an angle accuracy of 0·1°. The temperature of the sample can be adjusted within an accuracy of $\pm$ 1°C by controlling the temperature of the flow gas.

3. Results and discussion

3.1. *Slow spinning speeds*

Figure 2 (*a*) shows the ^{19}F N.M.R. spectra of 1, 2, 2, 2-tetrachloro 1, 1-difluoro ethane obtained for different angles β at a 101 Hz spinning frequency. Figure 2 (*b*) gives, for the same value of w, the F–F residual dipolar coupling versus β. The dipolar coupling behaves with β as follows:

$$\text{if} \quad 0° < \beta < 54{\cdot}7° \quad \text{then} \quad D_{FF} = -D_{FF}^{\circ}(3\cos^2\beta - 1)/4,$$

$$\text{if} \quad 54{\cdot}7° < \beta < 90° \quad \text{then} \quad D_{FF} = +D_{FF}^{\circ}(3\cos^2\beta - 1)/2,$$

where D_{FF}° is the dipolar coupling that would be obtained if the director was parallel to H_0. This is the typical behaviour of a negative $\Delta\chi$ liquid crystal. The director is

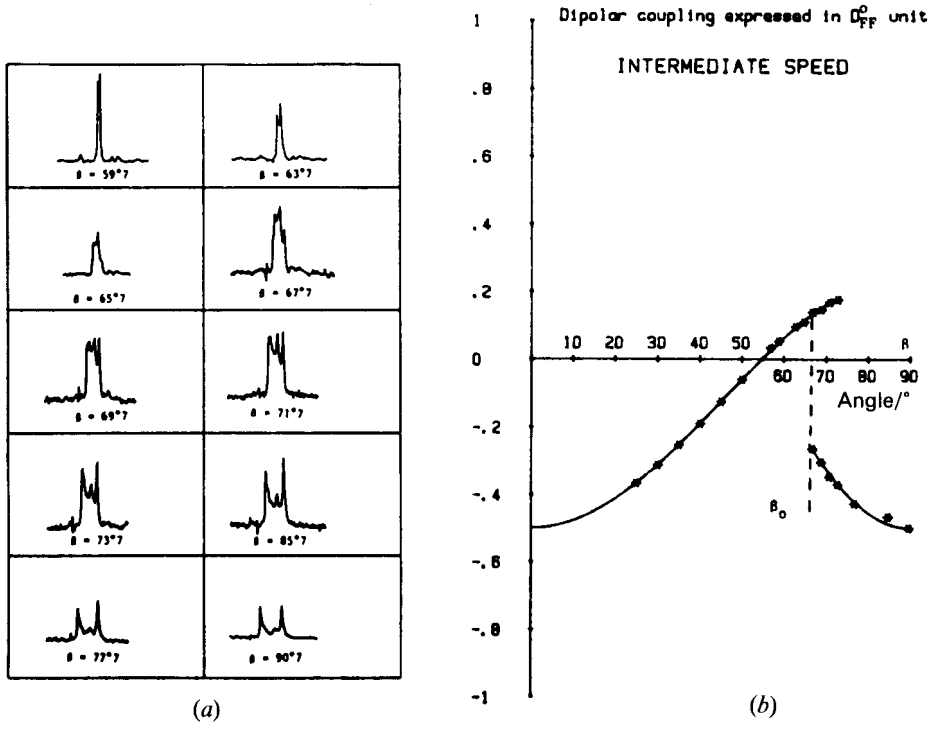


Figure 4. (*a*) ^{19}F N.M.R. spectra of the same sample for different angles β and a spinning frequency equal to 224 Hz. Note the four peaks powder patterns which shows that the director is switching between parallel and perpendicular orientations to R. (*b*) Plot of the fluorine dipolar coupling versus β. Compare with figures 2 (*b*) and 3 (*b*). Obviously at this spinning frequency the director switches from a perpendicular to a parallel orientation to R at an angle $\beta_0 = 66°$.

perpendicular to the rotation axis for $0° < \beta < 54{\cdot}7°$ and parallel to the rotation axis for $54{\cdot}7° < \beta < 90°$.

3.2. *High spinning speeds*

Figure 3 (*a*) shows the ^{19}F N.M.R. spectra of 1, 2, 2, 2-tetrachloro 1, 1-difluoro ethane obtained for different angles β at a 1280 Hz rotation frequency. Figure 3 (*b*) gives for the same value of w the F–F dipolar coupling versus β. At any angle β the residual dipolar coupling can be expressed as

$$D_{FF} = -D_{FF}^{\circ}(3\cos^2\beta - 1)/4.$$

A new torque, which is stronger than the magnetic one, does align the director perpendicular to the rotation axis irrespective of the angle β.

3.3. *Intermediate spinning speeds*

The spectra presented in figure 4 (*a*) have been obtained at a spinning frequency of 224 Hz for different angles β and figure 4 (*b*) gives the corresponding plot of the residual dipolar coupling as a function of β. It is obvious that the director switches from a perpendicular to a parallel position versus R for an angle $\beta_0 = 66°$

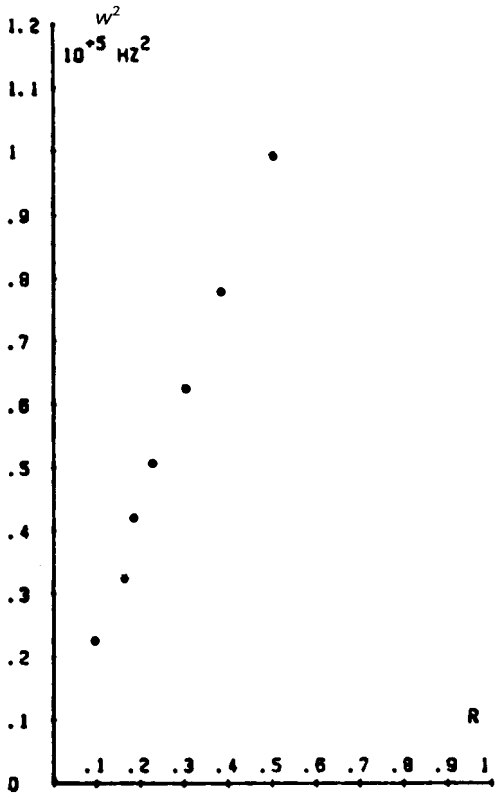


Figure 5. Plot of the reduction factor $R_0 = -(3\cos^2\beta_0 - 1)/2$ versus the square of the angular velocity w^2. Note the linear relationship between these two parameters which are proportional to the magnetic and inertial torques respectively.

as

$$\text{if} \quad 0° < \beta < \beta_0 \quad \text{then} \quad D_{FF} = -D_{FF}°(3\cos^2\beta - 1)/4,$$

$$\text{if} \quad \beta_0 < \beta < 90° \quad \text{then} \quad D_{FF} = +D_{FF}°(3\cos^2\beta - 1)/2,$$

It must be concluded that for $\beta > \beta_0$ the magnetic torque governs the orientation, but if $\beta < \beta_0$ then another torque is stronger than the magnetic one. The value of the switch has been found to depend strongly on the rotation frequency as can be seen in figure 5. This point is of interest because at this particular angle the different torques are in equilibrium. This evolution of β_0 with w is analysed below.

3.4. *Equilibrium between the magnetic and the inertial torques*

At an intermediate spinning frequency it is possible to realise an equilibrium between the rotationally averaged magnetic torque $\bar{\tau}_m$, which can be written from the average potential theory [1] as

$$\bar{\tau} = \Delta\chi \, H_0^2 \sin\delta\cos\delta\,(3\cos^2\beta - 1)/2,$$

and the inertial torque τ_1. We are not yet able to give a detailed description of τ_1. But it should be clear that if the described effect is to be analysed in terms of the anisotropic inertial properties of liquid crystal media, τ_1 must be proportional to the

square of the angular velocity w, because the radial component of the body force per unit mass due to the effective centrifugal force can be written as $F = w^2 r$ in a fluid rotating at a constant angular velocity [4]. Then we can conclude that the torque equality at equilibrium must give a linear relationship between the reduction factor $R_0 = -(3\cos^2\beta_0 - 1)/2$ which is proportional to $\bar{\tau}_m$, and w^2 which is proportional to τ_I. In this sense the straight line obtained in the plot of the reduction factor R_0 versus w^2 (Figure 5) must be taken as the first experimental evidence of the inertial origin of this effect.

4. Conclusions

It has been shown that for a high spinning frequency the director of a lyotropic nematic liquid crystal switches from a parallel to a perpendicular orientation to the rotation axis. The inertial origin of the phenomenon may be seen from the linear relationship between the reduction factor at the switch and the square of the angular velocity, as they are proportional to the magnetic and inertial torques respectively. The slope of that curve should contain some information on the inertial anisotropy of these phases. This problem is now under study.

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