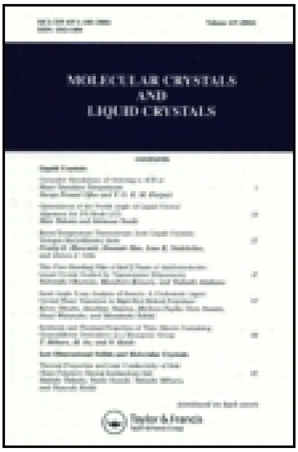

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ELECTROHYDRODYNAMICS IN NEMATICS SUBJECT TO PARALLEL ELECTRIC AND MAGNETIC FIELDS

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Abstract Under parallel electric and magnetic fields, electrohydrodynamic instabilities in nematic liquid crystals having negative dielectric anisotropy are predicted to exhibit a strong dependence of roll spacing on applied magnetic field . We report studies of the parallel magnetic field dependence of the threshold electric field for instabilities and the roll wavelength at threshold. The threshold electric field exhibits fascinating re-entrant behaviour not predicted by theory. We describe qualitatively new mechanisms for the creation and destruction of the convecting state at higher magnetic fields.

INTRODUCTION

Nonequilibrium pattern formation has recently been the subject of intense investigation.[1] In particular, electrohydrodynamic (EHD) motion in nematic liquid crystals having negative dielectric anisotropy is a popular system for experimental investigation, largely because it is readily controllable with a small number of independently accessible parameters. Among these, most researchers have concentrated on the amplitude and frequency of the applied electric field. There are reported experiments where a constant magnetic field is also applied,[2,3,4] but almost exclusively with the magnetic field perpendicular to the electric field. Here we present studies of the initial instabilities when the magnetic field is applied *parallel* to the electric field.

The Carr-Helfrich theory[5,6] is particularly simple to modify for the case where H is perpendicular to the initial director alignment; the magnetic torque has the opposite sign. Thus, following Chandrasekhar,[7] the threshold electric field (E_{th}) for instabilities in the presence of a parallel magnetic field, relative to the threshold in no magnetic field is:

$$\frac{E_{th}^2(H_z)}{E_{th}^2(0)} = \frac{\left(k_{33}q_x^2 - \Delta\chi H_z^2\right)}{k_{33}q_x^2}\ , \qquad (1)$$

where k_{33} is the bend elastic constant, q_x is the wavenumber of the pattern parallel to the initial director alignment and $\Delta\chi$ is the diamagnetic anisotropy. We note that this is the simplest theoretical analysis of EHD and is presented here to foster intuitive understanding. Physically the magnetic field torque enhances the Carr-Helfrich mechanism in tilting the director out of the plane, thus decreasing the threshold.

More sophisticated two-dimensional, treatments[8] give qualitatively the same result when the above quantity is considered. Using Eq. 3.11 in Ref. 8 for our situation gives:

$$\frac{E_{th}^2(H_z)}{E_{th}^2(0)} = \frac{k_{33}q_x^2 + k_{11} - k_{11}(H_z/H_F)^2}{k_{33}q_x^2 + k_{11}}\ . \qquad (2)$$

H_F is the critical field for the splay Freedericksz transition, $H_F = \frac{\pi}{d}\sqrt{\frac{k_{11}}{\Delta\chi}}$, and k_{11} is the splay elastic constant. In this equation and subsequently, q_x is measured in units of π/d, where d is the separation between the glass plates. As in the simple case, this theory predicts a monotonic decrease in the relative threshold voltage with the square of H_z.

EXPERIMENTAL SETUP

Preferential alignment of the liquid crystal in the quiescent state (no convection) is obtained by evaporating about 200Å SiO with an angle of 60^0 between the substrate normal and the line of sight to the evaporation boat.[9] This is known to give uniform homogeneous alignment, with a tilt angle between 15^0 and 25^0.[10] Observation in the polarizing microscope confirmed the uniformity of the alignment and the absence of topological defects. The glass substrates have an indium-tin-oxide conductive coating.

A potential difference between these coatings gives rise to the electric field across the liquid crystal. The substrates are separated and kept parallel by 25μm Mylar spacers. The prepared plates are clamped together in an aluminum press with the spacers in between, and the liquid crystal is introduced between the plates via capillary action. Any alignment effects due to flow that occurs in the filling process are removed by heating the sample at least 10°C above the clearing point. The liquid crystal used for the experiments reported here was methoxybenzylidene-butylaniline (MBBA),[11] and was used as obtained. Thin wires are attached to each plate to make electrical contact.

Once assembled, the sample is mounted between the pole faces of an electromagnet, with the glass plates parallel to the pole faces. The pole faces have 30 cm diameter, and have a 2.5 cm hole through the center for optic access. This configuration gives a very small field inhomogeneity (~0.3%) over the volume that the sample occupies. The sample is viewed with a 4X microscope objective approximately 2 cm from the sample and an eyepiece lens about 75 cm from the sample. A CCD video camera about 20 cm from the eyepiece lens collects the final image. With this configuration the magnification is easily changed so that the height of the video image can be varied from 475 μm to 125 μm. While a real image of the liquid crystal sample can be obtained in this way, convective rolls are seen much better by de-focussing the objective slightly and using the popular shadowgraph technique. An electric field of variable frequency and strength is applied to the sample via the conductive coating, and a dc magnetic field between 0 and 5.5 kG can be applied with the electromagnet. The convective roll pattern is recorded on videotape for later analysis.

Experimental Results

Figure 1 shows the dependence of the threshold voltage for electrohydrodynamic instabilities as a function of applied magnetic field. This is for sinusoidal excitation at frequency 50 Hz. First and most obvious is the decrease in V_{th} with H_z for fields less than 4kG. Overlaid on this graph is a fit to Eq. 2. This functional form clearly fits the data very well; moreover, there is plausible quantitative agreement. The value obtained for the coefficient $\sqrt{k'}H_F$ by fitting to Eq. 2 is 6.04 kG, where we have defined $q_x^2 \frac{k_{33}}{k_{11}} + 1$ to be k' for brevity. Using the measured value $q_x = 1.5$, and published values[12] for the

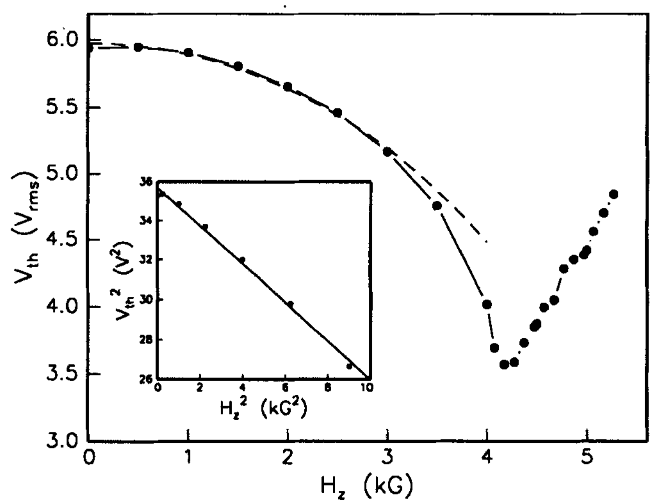

Fig. 1. Threshold electric field for convective rolls as a function of applied magnetic field. The dashed line is a fit to Eq. 2. *Inset:* V_{th}^2 vs H_z^2 fits a straight line demonstrating the validity of the functional form.

elastic constants results in k' being about 4.2. We have measured the critical magnetic field for the splay Freedericksz transition to be just less than 2 kG. It is fairly broad and so difficult to precisely locate. Thus one would expect $\sqrt{k'}H_F \approx 4\text{kG}$. Studies are underway to measure all these quantities on the same sample in order to test more rigorously the applicability of Eq. 2.

Even more interesting than the depression of V_{th} with applied magnetic field is the minimum and subsequent increase in this quantity. We are unaware of any quantitative theoretical explanation for this effect, although it may be understood qualitatively. The initial decrease is caused by the magnetic field applying an out-of-plane torque on the director in its quiescent state, while the increase at higher fields results from the overall stabilizing effect of a magnetic field; however the details of this competition remain to be elucidated. The minimum in V_{th} occurs at 4.25 ± .05kG. After the field exceeds this value, V_{th} tends to increase linearly with applied field. This increase is in direct contradiction to the prediction in Eqs. 1 and 2. The increased uncertainty in determining V_{th} above 4 kG is a result of the very much longer relaxation times required for the roll pattern to attain steady-state in this regime. More is said about this subsequently.

The roll pattern above 4kG is also qualitatively different from that below 4kG. This can be seen in Fig. 2. Furthermore, the spacing between rolls, λ, can be markedly different from the spacing between the plates, d.

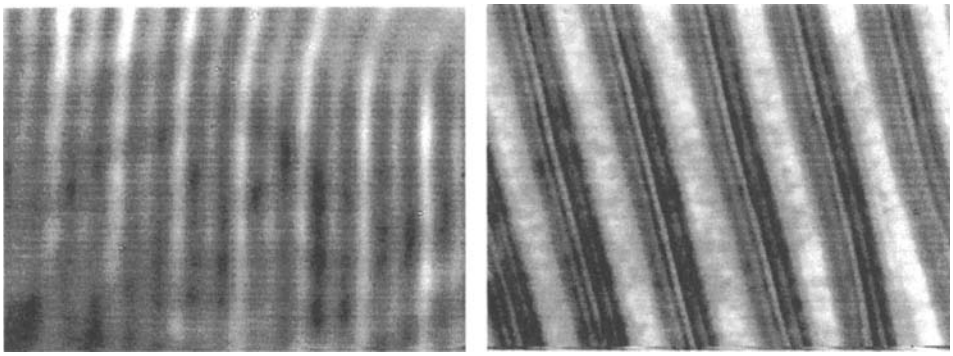

Fig. 2. Comparison of the roll pattern above and below the minimum electric field in Fig. 1. The width of each frames is about 250 μm. Left: 1 kG; 6.12 V_{rms}. Right 4.5 kG; 3.71 V_{rms}.

Figure 3 shows the wavelength of the pattern at the threshold voltage, relative to the zero field wavelength, about 33μm. There is a very steep increase in λ between 4 and 5 kG. The increase in spacing is seen to occur most prominently at larger H_z; this bears out the

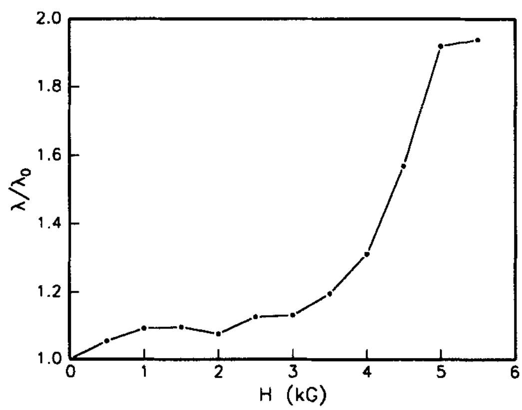

Fig.3. Roll spacing vs magnetic field, relative to roll spacing at H_z=0.

validity of using keeping q constant for the fit in Fig. 1. The graph hints that the behaviour above 5.5 kG might also be interesting, but this unfortunately remains to be determined. What does not show on a graph, but can be seen in Fig. 2 is that the increase in λ arises not from the increasing width of the convective rolls themselves, but a widening of the quiescent (no convection) region between adjacent rolls. This immediately raises the issue of what is the mechanism by which adjacent rolls sense each other, if they are separated by a distance as great as their own width.

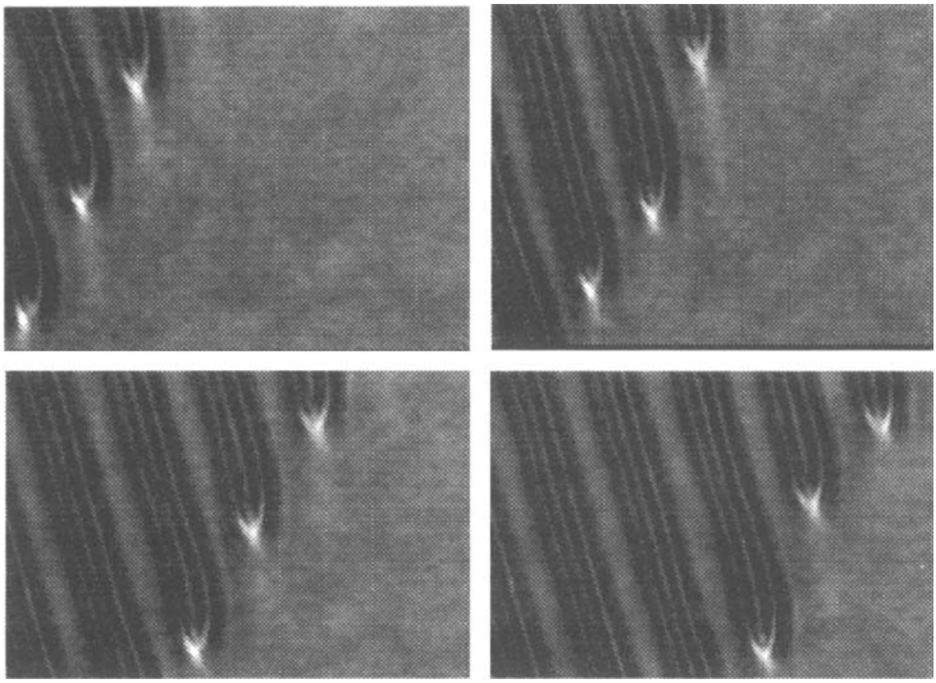

Fig. 4. Time sequence of formation of roll pattern. Time interval between frames is about 200 sec. Note the "blunt" roll ends, indicative of an abrupt front between the convecting and the quiescent state. H_z = 4.67kG; V_{rms} was raised from 4.03V to 4.10V.

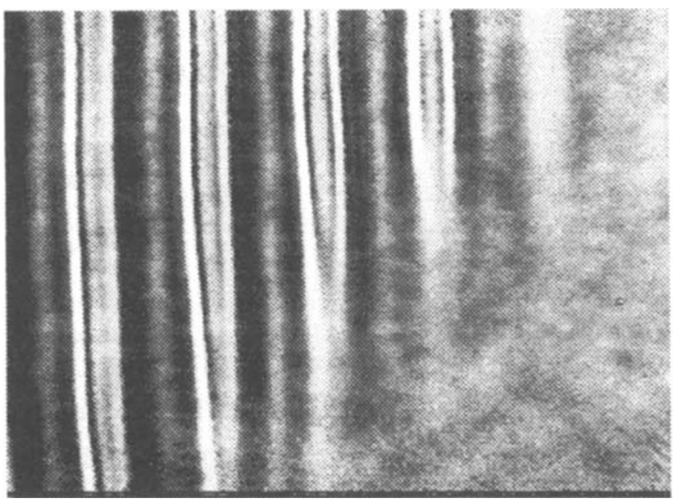

Fig. 5. At lower magnetic field than Fig. 4, the roll ends are distinctly "sharper", indicating a more gradual front between the convecting and the quiescent state. H_z = 4.37kG; V_{rms} = 3.75V.

Also of interest are some remarkable growth morphologies above the magnetic field at which the minimum in V_{th} occurs in Fig. 1. As the electric field is increased from below to slightly above threshold, the rolls grow in sequentially. Figure 4 is a time sequence of this process. Moreover, if the electric field is decreased slightly below threshold, the rolls disappear in a reverse process. This is a form of front propagation;[13] the convective state (a roll) invades the quiescent state at a well-defined speed. The issue of the front profile is also fascinating. Figure 5 shows another roll end front. This is at just slightly lower magnetic field than Fig. 4. Note that the tip of the roll is much "sharper" than the previous case. This indicates a much less abrupt front profile, which should result in a correspondingly larger front velocity; detailed quantitative studies of the front profile and velocity are underway. The existence of observable front propagation is indicative that in this instance the bifurcation from the quiescent state to the convective rolls must be sub-critical. This is qualitatively confirmed by the stable coexistence of rolls with the no-flow state, seen in Fig. 6. While at this moment we cannot be definitively say whether this coexistence is a result of small uniformities in the sample cell, we have not observed any preferential nucleation or destruction of rolls on either the left or the right of Fig. 6. Certainly the presence of the quiescent state on either side of a convective roll indicates that this structure is not caused by inhomogeneities in the sample cell over length scales larger than the plate separation; the straightness of the roll suggest the absence of imperfections over smaller lengths.

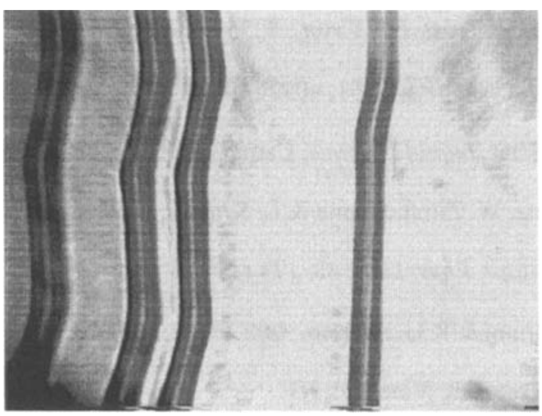

Fig. 6. Coexistence between convective rolls and the quiescent state. This structure was stable for greater than 14 hours. $H_z = 5$kG; $V_{rms} = 4.14$V.

Conclusion

Applying a magnetic field parallel to the electric field in electrohydrodynamic convection in nematic liquid crystals proves to be a very rich source of novel and unexplained behaviour. We have demonstrated a re-entrant quiescent state as the electric field is increased at constant magnetic field (c.f. Fig. 1). Moreover the roll spacing at threshold changes by at least a factor of two as the magnetic field is increased. We shall use this effect to make quantitative, well-controlled studies of the dynamics of changing wavelength. Some effects, such as front propagation, are as yet described only qualitatively, but lend themselves to detailed quantitative studies.

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