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Cholesteric–nematic transition induced by a rotating magnetic field

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ABSTRACT

We study theoretically the unwinding of helical orientational structure of a cholesteric liquid crystal under rotating magnetic field action. We analyze the non-stationary rotation regime of the orientational structure at the initial stages of the cholesteric helix unwinding in weak magnetic fields. For small deformations of the orientational structure we analytically obtain the dependence of the pitch of the cholesteric helix on the strength and rotation velocity of a magnetic field. For the stationary rotation regime in a magnetic field, the orientational phase diagram of the cholesteric–nematic transition is constructed. We study numerically and analytically the dependences of the cholesteric helical pitch on the strength and rotation velocity of the magnetic field. We reveal that in the narrow range of rotating magnetic field strength, the reentrant cholesteric–nematic–cholesteric orientational transitions take place. We show that in the stationary rotation regime, an increase in the rotation velocity of the field leads to a decrease in the cholesteric–nematic transition field. In the absence of rotation, our results are reduced to the well-known for static magnetic fields.

1. Introduction

Cholesteric liquid crystals (CLC), or cholesterics, are characterized by spontaneous helicity of the orientational structure [1]. This property is due to mirror-like asymmetric (chiral) molecules that form the cholesteric phase. In the absence of external fields, the direction of preferential orientation of anisometric molecules of a cholesteric, characterized by a unit vector (director **n**), continuously rotates around an orthogonal axis called the cholesteric helix axis, and forms a helicoidal structure. The distance over which the director makes 2π turn is called the helical pitch. The combination of large optical activity of such media with strong pitch sensitivity of their spiral structure to external influences leads to the practical applications of CLC in optical devices, sensors, tunable color filters, etc. [2]. The controlled change in the pitch of cholesteric helix makes it possible to operate the light flux passing through it, and is one of the actual problems in the physics of liquid crystals explaining the permanent interest in the study of these optically active chiral media.

It is known [3-5] that, when cholesteric is placed in a magnetic field H orthogonal to the helix axis, the helix pitch increases. With increasing magnetic field strength, when the critical value $H_{c0} = (\pi q_0/2)\sqrt{K_{22}/\chi_a}$ is reached, the cholesteric helix is completely untwisted, i.e., the helix pitch goes to infinity. Here q_0 is the intrinsic wave-number of CLC helical structure, K_{22} is twist elastic constant. When a cholesteric is in a layer of finite thickness, the deformation of the helix by an external magnetic field is not smooth, but shows stepwise behavior [6]. Such stepwise behavior of the pitch of the cholesteric helix for different types of potentials of the director coupling to the boundaries of the layer, depending on the layer thickness and the magnetic field strength, has been theoretically studied in Ref. [7].

The dynamic properties of cholesterics are of particular interest. The unwinding of the cholesteric helix by a shear flow has been theoretically studied for an infinite sample [8] and for a planar layer [9]. The experimental and theoretical results concerning the dynamics of disclinations in the CLC layer in a weak magnetic field are presented in Refs. [10, 11]. The effect of a shear flow and a magnetic field on the helical structure of a cholesteric was investigated in Ref. [12]. The transverse drift of various types of cholesteric fingers, which form rotating spirals in thin layers of a CLC in an ac or dc field, has been studied in Ref. [13]. As shown in Ref. [14], the combined action of the oscillating shear flow and the electric field makes it possible to form a defect-free uniform lying helix, which has a fast electro-optical response independent of the cell thickness [15]. In Ref. [16] the optical methods were used to study the unwinding of the chiral nematic phase of a cellulose microfibril suspension with a negative anisotropy of the diamagnetic susceptibility in a rotating magnetic field. The effect of the magnetic field applied orthogonally to the helical axis on the scattering of light is discussed in Ref. [17]. In Ref. [18] two modes of the helix response to a pulsed magnetic field, i.e. a fast

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regime characterized by local rotations of the director field, and a slow mode associated with a change in the angle of rotation between the surfaces bounding the CLC sample, have been investigated. The oscillations of the helical structure of a cholesteric in a weak oscillating magnetic field have been studied in Ref. [19], and the dynamics of unwinding of its helix by a pulsed electric field has been examined in Ref. [20]. In Ref. [21] the effect of a magnetic field randomly changing its direction on the cholesteric was investigated.

We also note the studies of dynamics of chiral nanoparticles of various shapes in rotating magnetic fields [22-25], which help to control the motion of particles by transporting them into the required area of the sample [26, 27]. While the behavior of nematic LC in a rotating magnetic field is sufficiently well studied [28], much less work is devoted to the dynamics of cholesterics. In particular, the problem of the CLC helical structure unwinding by a rotating magnetic field remains unstudied. In the present paper we show the possibility of cholesteric–nematic transition in rotating magnetic field.

2. Equations of cholesteric dynamics

To describe the dynamics of the orientational structure of a cholesteric liquid crystal placed in a rotating magnetic field, we use the continuum theory of Eriksen and Leslie [1], in which the equation of motion and the incompressibility condition are as follows

$$\rho\frac{dv_i}{dt} = \nabla_k\sigma_{ki}, \tag{1}$$

$$\nabla_i v_i = 0, \tag{2}$$

where ρ, $\mathbf{v}$ and $\sigma_{ki} = \sigma'_{ki} + \sigma^{(e)}_{ki}$ are density, velocity, and stress tensor of a liquid crystal; $d/dt = \partial/\partial t + \mathbf{v}\cdot\nabla$ is the total time derivative. Here and below we assume summation over repeated tensor indices.

The viscous stress tensor σ'_{ki}, included in σ_{ki}, has the form

$$\sigma'_{ki} = \alpha_1 n_k n_i n_l n_m A_{lm} + \alpha_2 n_k N_i + \alpha_3 n_i N_k + \alpha_4 A_{ki} + \alpha_5 n_k n_l A_{li} + \alpha_6 n_i n_l A_{lk}, \tag{3}$$

where α_s are the Leslie viscosity coefficients [1], connected by Parodi's relation $\alpha_2 + \alpha_3 = \alpha_6 - \alpha_5$; $\mathbf{n}$ is the director of the liquid crystal. The vector $N_i = dn_i/dt - \Omega_{ik}n_k$ determines the rate of change of the director $\mathbf{n}$ relative to the moving medium. The tensors $A_{ik} = (\nabla_k v_i + \nabla_i v_k)/2$ and $\Omega_{ik} = (\nabla_k v_i - \nabla_i v_k)/2$ represent the symmetric and antisymmetric parts of the velocity gradient tensor.

The Ericksen stress tensor $\sigma^{(e)}_{ki}$, included in σ_{ki}, is determined by the expression

$$\sigma^{(e)}_{ki} = -P\delta_{ki} - \frac{\partial F}{\partial(\nabla_k n_l)}\nabla_i n_l, \tag{4}$$

where P is the pressure, δ_{ki} is the Kronecker symbol, F is the bulk density of free energy of a cholesteric in a magnetic field, which has the form [1]

$$\begin{aligned} F &= F_1 + F_2,\\ F_1 &= \frac{1}{2}\left[K_{11}(\nabla\cdot\mathbf{n})^2 + K_{22}(\mathbf{n}\cdot\nabla\times\mathbf{n} + q_0)^2 + K_{33}(\mathbf{n}\times\nabla\times\mathbf{n})^2\right],\\ F_2 &= -\frac{1}{2}\chi_a(\mathbf{n}\cdot\mathbf{H})^2. \end{aligned} \tag{5}$$

Here K_{11}, K_{22}, and K_{33} are the Frank elastic constants, q_0 is the wave number of an unperturbed spiral structure of a CLC with the pitch $2\pi/q_0$ (for definiteness, we assume that q_0 is positive). The contribution F_1 in the free energy density (5) corresponds to the Oseen-Frank energy of orientational elastic deformations of the director, F_2 is the bulk density of the interaction energy of the magnetic field $\mathbf{H}$ with the CLC.

The equation of the director motion has the form [1]

$$h_i = \gamma_1 N_i + \gamma_2 n_k A_{ki}, \tag{6}$$

where $\gamma_1 = \alpha_3 - \alpha_2$ and $\gamma_2 = \alpha_3 + \alpha_2$ are the coefficients of the rotational viscosity of a liquid crystal. The molecular field $\mathbf{h}$, acting on the director, is determined by the expression

$$h_i = -\frac{\partial F}{\partial n_i} + \nabla_k\frac{\partial F}{\partial(\nabla_k n_i)}. \tag{7}$$

Variation of the free energy when calculating the molecular field $\mathbf{h}$ is carried out under the condition $\mathbf{n}^2 = 1$.

3. Cholesteric in a rotating magnetic field

Let us consider a CLC in a rotating magnetic field, which is perpendicular to the axis of the helix. We introduce a rectangular coordinate system with the z-axis directed along the axis of the cholesteric helix (see Fig. 1).

Let the external uniform magnetic field $\mathbf{H}(t) = H(\cos\omega t,\ \sin\omega t,\ 0)$ rotates around the z-axis with the angular velocity ω. In this case the director $\mathbf{n}$ can be written as

$$\mathbf{n} = [\cos\varphi(z,t), \sin\varphi(z,t), 0], \tag{8}$$

where $\varphi(z,t)$ is the rotation angle of the director, measured from the x-axis, t is the time. By substituting Eq. (8) in the density of free energy (5), we obtain

$$F = \frac{K_{22}}{2}\left(\frac{d\varphi}{dz} - q_0\right)^2 - \frac{\chi_a H^2}{2}\cos^2(\varphi - \omega t). \tag{9}$$

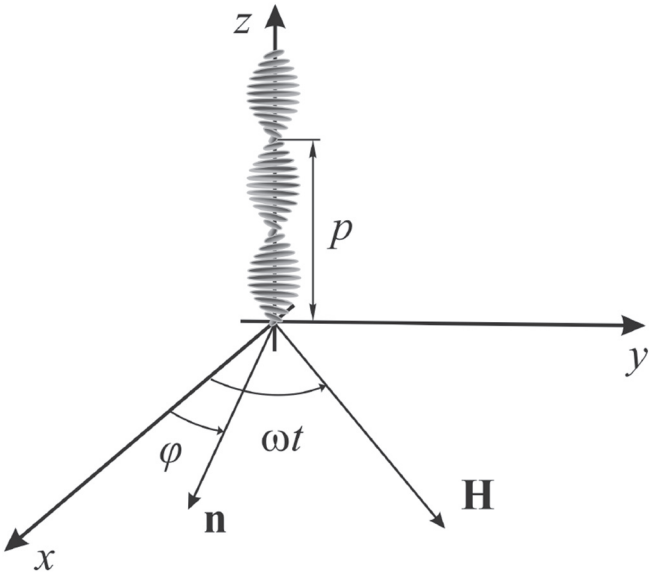

Fig. 1. Cholesteric in a rotating magnetic field.