Chiral hedgehog textures in two-dimensional XY-like ordered domains

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The textures associated with a point defect centered in a circular domain of a thin film with XY-like ordering have been analyzed. The family of equilibrium textures, both stable and metastable, can be classified by a new radial topological number in addition to the winding number of the defect. Chiral textures are supported in an achiral system as a result of spontaneously broken chiral symmetry. Among these chiral textures, our theoretical analysis accurately describes two categories of recently discovered “reversing spiral” textures, ones that are energetically stable and metastable.

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Thin films of elongated molecules with tilt ordering, including smectic-C liquid crystals and dense fluid phases of amphiphiles deposited on water, very often possess fascinating distributions of the tilt azimuth. The organization of the tilt azimuth is referred to as the texture and can be observed by polarized light microscopy or Brewster angle microscopy. Many classes of these textures have been found experimentally, like stripes [1], stars [2], boojums [3], and hedgehogs [4]. These examples are observed in Langmuir monolayers composed of molecules that are symmetric under in-plane reflection, or achiral. Recently, more attention has been paid to the hedgehog patterns, obtained in a circular domain with a central point defect. The reversing spiral is one of the spectacular hedgehog textures discovered in a chiral tilted smectic-C liquid-crystal film on water [5]. Let us emphasize that both systems described above are polar, they are not symmetric under 180° rotation about an in-plane axis. The tilt azimuth can be represented by a two-dimensional vector \( \vec{c} \), the projection onto the film of the elongated molecules, analogous to the order parameter of an XY model. Textures in two-dimensional XY-like systems have attracted a good deal of attention. A brief theoretical account based on a perturbative approach of hedgehogs in achiral monolayers can be found in Ref. [6]. The stability of the hedgehog configuration in an isotropic and achiral system has also been investigated [7]. Spiral textures in an achiral system have been studied in the small distortion regime [8]. Although a theoretical approach to solutions for hedgehog textures is given in Ref. [5], to the best of our knowledge, a systematic discussion of hedgehog textures in a chiral system has not been presented.

In this paper, we study a generic model [9] for the texture in a circular domain of a two-dimensional XY-like system. We have found a family of equilibrium configurations that can be classified by a new topological number analogous to the winding number that classifies a two-dimensional point defect [10]. When a system is achiral, these metastable configurations can be chiral as a result of spontaneously broken chiral symmetry. When chirality is explicitly introduced, more complex equilibrium textures result. The crossed polarizer images generated from the theoretical textures are in excellent agreement with the pictures taken experimentally. The starting point of our investigation is the following elastic energy of a chiral polar film with tilt ordering:

\[
H[\vec{c}] = \frac{1}{2} \int_{\Omega} dA \left( K_s |\nabla \cdot \vec{c}|^2 + K_{sb} (\nabla \times \vec{c}) \cdot (\nabla \times \vec{c}) \right) + K_b |\nabla \times \vec{c}||^2 + \int_{\Gamma} \sigma(\theta - \Theta) \ ds, \tag{1}
\]

It is computed for a circular area \( \Omega \) containing the ordered medium enclosed by the boundary \( \Gamma \). The unit vector \( \hat{z} \) points normal to the film. The quantities \( K_s \) and \( K_b \) are, respectively, the bend and splay elastic moduli, \( \hat{c} = \hat{x} \cos \Theta + \hat{y} \sin \Theta \) is the order parameter of the system, \( \Theta \) is the angle between \( \hat{c} \) and the \( x \) axis, and \( \theta \) is the angle between the outward normal to \( \Gamma \) and the \( x \) axis. The anisotropic line tension \( \sigma(\phi) \) can formally be expanded as \( \sigma_0 + \Sigma_0(a_n \cos n\phi + c_n \sin n\phi) \). We will consider only the first few coefficients in the expansion. The first-order terms are \( a_1 \) for polar films and \( c_1 \) for chiral systems. When the system is nonpolar, \( a_1 \) vanishes and \( a_2 \) must be considered. The coefficient \( c_2 \) is relevant when the system is both polar and chiral, but it will be neglected because \( a_1 \) and \( c_1 \) are nonzero for such a system. The cross term \( (\nabla \times \vec{c}) \cdot (\nabla \times \vec{c}) \) has to be included when the film is both chiral and polar. It is required that the coefficient \( |K_{sb}| < 2\sqrt{K_s K_b} \) so that the elastic energy density remains positive for arbitrary splay and bend distortions.

We will restrict ourselves to the hedgehog textures, each containing a central point defect of winding number \( +1 \) with core radius \( \xi \). The defect core corresponds to the region in
which \( \hat{c} \) is not defined. We assume that its presence does not affect the elastic energy only through the inner boundary condition at \( r = \xi \) and we neglect its energetic contribution when \( r < \xi \) where \( r \) is the radial distance. The boundary condition is taken to be \( \Theta |_{r=\xi} = \varphi + \varphi_d \), where \( \varphi \) is the polar angle in plane-polar coordinates, and \( \varphi_d \) is a constant. This is indeed justifiable for \( \pm 1 \) defects with the structure discussed in Ref. [12]. We further assume that the defect is stable when it is located at the center of \( \Omega \) and that the system is cylindrically symmetric, i.e., \( \Theta = \varphi + f(\ln r) \), where \( f(\ln r) \) is the radial distribution of \( \hat{c} \). These assumptions can be shown to be valid for all the textures to be discussed. We shall compute the possible expressions for \( f(\ln r) \) that minimize the elastic energy and give the equilibrium textures. In terms of \( k = \ln r \), the elastic energy reduces to

\[
H[f,f'] = \pi \kappa \int_{\ln \xi}^{\ln R_0} dk \frac{1}{2} \left[ 1 + f'^2 - \mu \left( (1 - f'^2) \cos(2f - 2s_+) \right. \right. \\
\left. \left. - 2f' \sin(2f - 2s_+) \right) \right] + 2\pi R_0 \sigma (-f)|_{\ln R_0}.
\]

where \( 2\mu = K_b + K_b \), \( 2\kappa = K_a - K_b \), \( 2\kappa = K_a + K_b \), \( \mu = \sqrt{\beta^2 + \tau^2} \), \( 2s_+ = \tan^{-1} \beta/\pi \), where \( R_0 \) is the radius of the boundary \( \Gamma \). The equilibrium condition for \( f(k) \) is

\[
f'' - \mu [f'' \cos(2f - 2s_+) - (f'' - 1) \sin(2f - 2s_+)] = 0
\]

and the boundary condition at \( k = \ln R_0 \) is

\[
\kappa [f' + \mu (f' \cos(2f - 2s_+) + \sin(2f - 2s_+))] = -R_0 \sigma' (-f) = 0.
\]

Depending on the choice of the parameters, \( f \) may possess more than one or, at times, numerous solutions. We use linear stability analysis to determine if these solutions are local minima. The elastic energy is expanded to second order in small variations \( \psi = f - f_0 \) about an equilibrium configuration \( f_0 \) as \( \delta H = fdk \mathcal{L} \chi + \psi^T \mathbf{B} \psi \), where

\[
\mathcal{L} = -\pi \kappa \left[ 1 + \mu \cos(2f - 2s_+) \right] \frac{d^2}{dk^2} \\
- \mu \left( f''_0 \sin(2f_0 - 2s_+) + 2 \cos(2f_0 - 2s_+) \right)
\]

\[
\mathbf{B}_{\chi'\chi'} = 0,
\]

\[
\mathbf{B}_{\chi\chi'} = \frac{\pi \kappa}{2} \left[ 1 + \mu \cos(2f_0 - 2s_+) \right] |_{\ln R_0},
\]

\[
\mathbf{B}_{\chi\chi} = \pi [ -\kappa \mu (f''_0 \sin(2f_0 - 2s_+) - 2 \cos(2f_0 - 2s_+)) \right. \\
+ R_0 \sigma'' (-f_0) |_{\ln R_0},
\]

and \( \psi^T = (\chi', \chi) |_{\ln R_0} \). The deviation of the elastic energy \( \delta H \) from its equilibrium value can be examined in terms of the eigenvalue \( \lambda \) and associated eigenfunction \( \phi_\lambda \) satisfying \( \mathcal{L} \phi_\lambda = \lambda \phi_\lambda \). The eigenfunctions \( \phi_\lambda \) are normalized so that \( fdk \phi_\lambda^2 = 1 \) and \( \phi_\lambda |_{\ln \xi} = 0 \) for infinitely strong anchoring at the inner boundary. It is typical in linear stability analysis that there is another boundary condition on \( \phi_\lambda \) that isolates a set of eigenvalues \( \lambda \) in which the sign of the lowest one is to be tested. For our particular case, there is no other restriction on \( \phi_\lambda \) that can be imposed and all \( \lambda \)'s are allowed. The deviation of energy associated with the fluctuational mode \( \phi_\lambda \) is no longer \( \lambda \) but

\[
\delta H_\lambda = \lambda + \psi^T \mathbf{B} \psi_\lambda,
\]

where \( \psi^T = (\lambda', \chi) |_{\ln R_0} \). Instability is signified by \( \delta H_\lambda \) becoming negative. The asymptotic behavior of \( \delta H_\lambda \) can be shown to be \( \delta H_\lambda \sim -[\lambda + R_0 (1 + 2|\xi|)] \) when \( \lambda \rightarrow -\infty \), and

\[
\delta H_\lambda \sim (1 - \mathbf{B}_{\chi'\chi'} / 2k^2) \lambda \quad \text{when} \quad \lambda \rightarrow \infty
\]

for \( R_0 \sqrt{|a_1^2 + c_1^2|} \gg \kappa \) and \( \sigma'' (-f_0) |_{k = \ln R_0} \gg \sqrt{a_1^2 + c_1^2} \). We see that \( \delta H_\lambda \) is positive in both limits and can only change sign for small \( \lambda \).

We have outlined the procedures to obtain the equilibrium textures and to examine their stability against infinitesimal fluctuations. To understand these equilibrium textures, we first look at the simplest case \( \beta = \tau = c_1 = a_2 = \varphi_d = 0 \) and \( a_1 < 0 \). It corresponds to a polar film made of achiral molecules, with isotropic elastic constants and having fixed anchoring at the inner boundary such that \( \hat{c} \) points normal into the bulk. The condition \( a_1 < 0 \) indicates that \( \hat{c} \) favors the outward normal direction at the outer boundary, without being locked. In this case, there are analytic solutions. It is obvious that \( f_0(k) = 0 \) is the lowest-energy configuration: all \( \hat{c} \) vectors point along the radial direction. The general solution to \( f_0(k) \) is

\[
f_0(k) = \frac{\varphi_b}{\ln R_0 - \ln \xi} (k - \ln \xi)
\]

and \( \varphi_b \) satisfies

\[
\varphi_b = \frac{R_0 a_1 (\ln R_0 - \ln \xi)}{\kappa} \sin \varphi_b.
\]

The quantity \( \varphi_b \) is the anchoring angle of \( \hat{c} \) measured with respect to \( \varphi \) at \( k = \ln R_0 \). It is easy to see that the system supports numerous equilibrium solutions when the amplitude \( |R_0 a_1 (\ln R_0 - \ln \xi)| \gg 1 \). Figure 1 shows the plots of \( \varphi_b \) and \( R_0 a_1 (\ln R_0 - \ln \xi) \sin \varphi_b / \kappa \). We denote the solutions of Eq. (11) by \( \varphi_b^{(i)} \) with an index \( i \). Not all the solutions are stable. The stable ones are indicated by open circles in Fig. 1. When \( \varphi_b^{(i)} \neq 0 \), we have spirals in which \( \hat{c} \) points in the radial di-

![Fig. 1. Plots of \( y = \varphi_b \) and \( y = R_0 a_1 (\ln R_0 - \ln \xi) \sin \varphi_b / \kappa \) vs \( \varphi_b \). The intersections, \( \varphi_b^{(i)} \), give the equilibrium configurations \( f_0^{(i)}(k) \). Those marked with open circles are stable. The parameters used are \( \kappa = 1, R_0 = 5, \xi = 0.1, \) and \( a_1 = -1.1 \).](image)
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swings nearly $\pi$ to a value close to $\Theta_+$ and finally returns rapidly to $\varphi + \varphi_0$ (which has been set to be around $\Theta_-$) near the outer boundary. The function $f_0^{(2)}(k)$ and its texture are depicted in Fig. 3. There is strong resemblance between the density plot of $\cos 2\Theta$, simulating the images obtained with slightly uncrossed polarizers, and the experimental picture of the DRS.

Remarkably, the DRS is only a metastable texture! It is easy to see that $f_0^{(2)}(k)$ is not the lowest-energy solution. The configuration, in which $Q$ sets smoothly near $Q_2$ without going through the rapid changes to $Q_1$ and then back to $Q_2$, has the lowest-elastic energy. Since $f_0^{(2)}(k)$ is not the global minimum of the elastic energy $\delta H_{2\lambda}$, the deviation in energy associated with the reversing spiral solution, in a wide range of $\lambda$, and conclude that the DRS is a metastable configuration for the present choice of the parameters. In general, the DRS texture is not even metastable for an arbitrary set of parameters. As noted in Ref. [5], the DRS texture is rare, which is consistent with these findings.

In conclusion, we have analyzed a generic model for textures associated with a $+1$ defect in domains with $XY$-like ordering. Restricting our analysis to the class of textures with the defect fixed at the center, we find the equilibrium configurations and examine the stability of these configurations against infinitesimal fluctuations. Many metastable configurations are supported at some suitable choice of parameters. These can be classified by a new radial topological number analogous to the winding number classifying the point defect. It is also found that metastable configurations are chiral, including the stable lowest-energy texture when $a_1 > 0$, even if the system possesses in-plane reflection symmetry. When elastic anisotropy, chirality, and polarity are introduced explicitly, more equilibrium solutions exist. Among the equilibrium textures, we have found two kinds of reversing spirals, simple ones that are absolutely stable textures, and metastable ones of a more dramatic appearance, that resemble closely the reversing spiral reported in Ref. [5].

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