

# EFFECTS OF FLEXOELECTRICITY IN LIQUID CRYSTAL BLUE PHASES

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Blue phases are mesophases that emerge in chiral nematic liquid crystals. The main goal of this article is to emphasize that crystalline unit cells of the molecular orientational order can emerge in these mesophases (blue phases I and II), and are stable over a wide temperature range as a result of flexo- and order electricity. After a brief review of liquid crystal basics, and the order parameter, the total free energy is introduced. The structure of blue phases is discussed, as well as compared to the results obtained with numerical simulations. Flexo- and order electricity in blue phases and their contribution to their stability is examined. At last, a possible application of making microscopic channels for ion transport in such materials, is described.

## VPLIV FLEKSOELEKTRIČNOSTI V TEKOČEKRISTALNIH MODRIH FAZAH

Modre faze so mezofaze, ki se pojavijo v kiralnih nematilnih tekočih kristalih. Glavni cilj članka je poudarek, da lahko v modrih fazah najdemo kristalinične osnovne celice molekularnega reda. Takšne strukture so stabilne tekom širokega temperaturnega območja kot posledica vpliva fleksoelektričnosti, ter električnosti reda. Po kratkem uvodu s ponovitvijo osnov tekočih kristalov, je vpeljan parameter reda, ter celotna prosta energija. Prav tako je komentirana struktura modrih faz, ter primerjana z rezultati numeričnih simulacij. Še posebej se članek osredotoči na vpliv fleksoelektričnosti, ter električnosti reda. Za konec je opisana še možna uporaba omenjenih vplivov za izdelavo mikroskopskih kanalov za transport ionov v takšnih materialih.

### 1. Introduction

Crystalline unit cells of the molecular orientational order can emerge in certain liquid crystal mesophases, called the blue phases. Recently, advancements in extending the temperature range in which blue phases are stable have been made. The goal of this article is to provide insights in the theory behind this novel topic as well as further explore yet another effect that turns out to affect the stability criteria.

In 1959, Richard Feynman stated that there's still plenty of room at the bottom, motivating scientists around the globe to build a microscopic engine. This was the figurative beginning of so-called Micro-Electro-Mechanical systems, or MEMS for short. On the verge of the 21st century, nanotechnology started gaining more mainstream attention, and MEMS with it. We can now build sensors and other devices at the micrometer scale with countless possible applications, for example an intra-ocular pressure sensor that provides information to doctor of patients dealing with glaucoma. However, when it comes to the transport of ions, the manufacturing process of nanowires is technologically demanding and therefore expensive. The reaching idea of the seminar is to show how flexoelectric nature of blue phases could be used and designed to offer an alternative to nanowires.

Liquid crystals flow like simple liquids, while also exhibiting crystal-like optical properties of molecular ordering. Nematic liquid crystals consist of anisotropic molecules that align to acquire orientational order, while their position remains disordered. Because of this, liquid crystals are apolar. Sure enough, highly symmetric molecules, that lack net polarity, form liquid crystals. Polar molecules can, however, also form liquid crystals, which leads to flexoelectricity and order electricity, further discussed later on [1].

Molecular alignment is described by a headless vector  $\mathbf{n}$ , called the director; with states  $\mathbf{n}$  and  $-\mathbf{n}$  being equivalent. We can further divide the nematic phase based on the presence of chiral molecules into non-chiral nematics and chiral nematics, often labeled as cholesterics. The former contain achiral molecules resulting in an inversion symmetry of the fluid, whereas in the latter, the left- and right-handed versions of the same molecule (or the dopant) are not equally represented. Alternatively, chiral dopant molecules can be added into a system of achiral nematic molecules [1].

Flexoelectricity is a second-order piezoelectricity involving certain second-order strains of the liquid crystal structure, that is, curvatures rather than the first-order shear strains of piezoelectric crystals. If the liquid crystal undergoes an elastic deformation, or an electric field is applied, the polar molecules align themselves to induce macroscopic polarization. The effect itself is negligible in most materials; it plays a greater role, however, in highly bent materials such as blue phases. In recent years, more and more research has been focused on observing the effects flexoelectricity and order electricity bring to the table [2].

This article is organized as follows: In section 2 we delve into the effects that contribute to the extended Landau-de Gennes free energy. Electric field effect is also discussed and regimes with either fixed charge or fixed voltage are considered. In section 3 we introduce flexo- and order electricity and the consequential rise of macroscopic polarization, as well as constructing the corresponding free energy density. At last, we introduce special blue phase structures that appear in liquid crystals and study the flexoelectricity. We also touch upon how ions can further stabilize the blue phase and present a possible application for ion transport.

## 2. Landau-de Gennes free energy

The main theoretical concept that we use to describe macroscopic properties of confined liquid crystal samples, is that of the free energy  $F$ . The optimal configuration of the tensor order parameter can be calculated with minimizing the functional.

The extended Landau-de Gennes free energy functional can be written in the following form

$$F = \int (f_e + f_D + f_{ion} + f_G) dV + \int f_W dS, \quad (1)$$

where  $f_e$  is the distortion free energy density,  $f_W$  is the contribution from anchoring of the liquid crystal on the boundary,  $f_D$  describes coupling with external electric field  $\mathbf{D}$ ,  $f_{ion}$  accounts for the screening effect of free ions, and lastly  $f_G$  is the corresponding flexoelectric and order electric term.

### 2.1 Nematic order parameters

The nematic liquid crystal orientational order can be described by either a vector or by tensor order field. The director field  $\mathbf{n} = \mathbf{n}(\mathbf{r})$  represents the average orientation of molecules. Orientational fluctuations of the molecules around the director, as a result of thermal fluctuations, can be quantified by introducing the nematic degree of order  $S$ . It is defined as an

ensemble average of the second Legendre polynomial

$$S = \langle P_2(\cos \theta) \rangle = \frac{1}{2} \langle 3 \cos^2 \theta - 1 \rangle, \quad (2)$$

where  $\theta$  represents the angle between the molecular long axis and the director. We see that if all molecules point along the director such that  $\theta = 0$  for all molecules, then the order parameter equals  $S = 1$ . This state corresponds to perfect nematic order. If the molecules are oriented isotropically,  $\langle \cos^2 \theta \rangle = 1/3$  and  $S = 0$ , this is the isotropic phase. A special kind of nematic orientational order is that with all molecules perpendicular to the director ( $\theta = \pi/2$ ). In this case,  $S = -1/2$ .

Order parameter  $Q$  of an uniaxial liquid crystal is defined as

$$Q_{ij} = \frac{S}{2} (3n_i n_j - \delta_{ij}). \quad (3)$$

It is a traceless, symmetric, second rank tensor based on the anisotropic part of the dielectric tensor. Using a tensor allows both the magnitude and the direction of the order to be recorded. With this normalization, the largest eigenvalue describes the nematic degree of order  $S$  and the corresponding eigenvector characterizes the director  $\mathbf{n}$ . The eigenvalues corresponding to the directions perpendicular to  $\mathbf{n}$  are identical and equal to  $S = -1/2$ . In case of biaxial order, the eigenvalues corresponding to the perpendicular directions to  $\mathbf{n}$  are not identical, therefore the degree of biaxiality  $P$  is introduced. In this case, the order parameter is written as

$$Q_{ij} = \frac{S}{2} (3n_i n_j - \delta_{ij}) + \frac{P}{2} (e_i^{(1)} e_j^{(1)} - e_i^{(2)} e_j^{(2)}), \quad (4)$$

which besides the scalar order parameter  $S$  and the director  $\mathbf{n}$  includes also the biaxial ordering around second director  $e^{(1)}$  with the degree of biaxiality  $P = \frac{1}{2} \langle \sin^2 \theta \cos 2\phi \rangle$ , with  $\phi$  representing the azimuthal angle of the molecular long axis.

Another interesting fact is that a nematic liquid crystal molecule has 5 degrees of freedom. A second rank tensor has 9 degrees of freedom, but the symmetric nature of the order parameter tensor reduces the number to 6. The fact that  $Q_{ij}$  is traceless drops the number of degrees of freedom to 5. This parametrization then consists of two angles determining the orientation of the director, the scalar order parameter, and the angle specifying the orientation of the secondary director as well as the parameter of biaxiality.

## 2.2 Distortion

To describe the spatially distortion of the director  $\mathbf{n}(\mathbf{r})$ , Frank theory is used. For chiral nematics the Frank free energy reads

$$f_d = \frac{K_{11}}{2} (\nabla \cdot \mathbf{n})^2 + \frac{K_{22}}{2} (\mathbf{n} \cdot \nabla \times \mathbf{n} - q_0)^2 + \frac{K_{33}}{2} (\mathbf{n} \times \nabla \times \mathbf{n})^2 - \frac{K_{24}}{2} \nabla \cdot (\mathbf{n} (\nabla \cdot \mathbf{n}) + \mathbf{n} \times \nabla \times \mathbf{n}), \quad (5)$$

where the three terms represent the splay, twist, bend, and saddle-splay deformations, whereas  $K_{11}$ ,  $K_{22}$ ,  $K_{33}$ , and  $K_{24}$  are the corresponding elastic constants.  $q_0$  is the parameter of chirality, related to the pitch of the helical phase by  $p = 2\pi/q_0$ . The last term can

sometimes be omitted, because it can be transformed to a surface integral via Gauss theorem.

Since the elastic constants are typically not very different from one another, they are sometimes assumed to be equal. This leads to the one-constant approximation, where the distortion free energy is expanded in powers of order parameter tensor  $Q_{ij}$  and its first derivatives

$$f_e = \left( \frac{A}{2} Q_{ij} Q_{ij} - \frac{B}{3} Q_{ij} Q_{jk} Q_{ki} + \frac{C}{4} (Q_{ij} Q_{ij})^2 \right) \quad (6)$$

$$+ \left( \frac{L}{2} \frac{\partial Q_{ij}}{\partial x_k} \frac{\partial Q_{ij}}{\partial x_k} + 2q_0 L \epsilon_{ikl} Q_{ij} \frac{\partial Q_{lj}}{\partial x_k} \right), \quad (7)$$

where  $A$ ,  $B$ , and  $C$  are nematic material constants,  $L$  is the single elastic constant,  $q_0$  is the parameter of chirality, and  $\epsilon_{ijk}$  is the Levi-Civita tensor [2].

### 2.3 Electric field effects

To characterize the effect of internal or external electric field on chiral or achiral nematic liquid crystal, an additional free energy term is needed.

Liquid crystals are anisotropic materials, meaning that the electric permittivity tensor  $\epsilon_{ij}$  is anisotropic and is related to the order tensor parameter by

$$\epsilon_{ij} = \bar{\epsilon} \delta_{ij} + \frac{2}{3} (\epsilon_{\parallel}^m - \epsilon_{\perp}^m) Q_{ij}, \quad (8)$$

where  $\bar{\epsilon} = \text{Tr}(\epsilon/3)$  is the macroscopic permittivity and  $\epsilon_i^m$  are the molecular dielectric permittivities parallel and perpendicular to the nematic director, respectively.

On the molecular scale, electric field couples with nematic through the dielectric interaction with induced dipoles of the nematic molecules. The thermodynamic potential for dielectric coupling distinguishes between the regimes with either fixed charge or fixed voltage. The work done on electrically insulated body in the fixed charge regime induces an electric field in dielectric media, which attributes to the change of the total free energy as

$$f_D^{\text{charge}} = \frac{1}{2} \int \mathbf{E} \, d\mathbf{D}, \quad (9)$$

where  $\mathbf{E}$  is the electric field and  $\mathbf{D}$  electric displacement field. In the case of the fixed voltage regime, where the electric field  $\mathbf{E}$  is independent, it is beneficial to introduce a new thermodynamic potential instead of  $\mathbf{D}$  as

$$f_D^{\text{volt}} = -\frac{1}{2} \int \mathbf{D} \, d\mathbf{E} \quad (10)$$

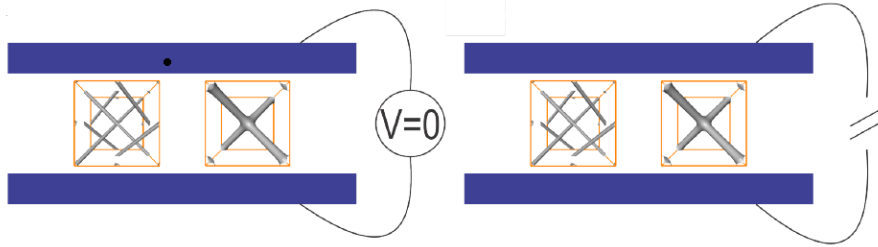
Assuming linear relations  $\mathbf{D} = \epsilon \mathbf{E}$  above equations differ only by sign. Free ions are neglected and will be added later.

Combining the equations above, the dielectric coupling within the LdG framework is introduced as

$$f_D = \pm \frac{1}{2} \epsilon_0 \epsilon_{ij} E_i E_j, \quad (11)$$

where  $\epsilon_0$  is the dielectric vacuum permittivity constant and  $\epsilon_{ij}$  is the electric permittivity tensor [2].

The dielectric interaction provides a coupling between the nematic distortion field and electric potential. The sign  $\pm$  distinguishes between fixed charge and fixed voltage regime. Most commonly electrodes on cell boundaries are connected and material exchanges charge with its surroundings and the system is at a fixed voltage regime. On the contrary, if there is no external field and the electrodes and material do not exchange charge with the surroundings, the system has fixed charged regime [3].



**Figure 1.** The setup on the left is a representation of the fixed voltage regime, where two electrodes are physically connected. Ions can therefore travel from one plate to another. On the right side, a case of fixed charge regime is presented where electrodes are separated and ions are separated. Between the electrodes, disclination unit cells of blue phase I and blue phase II are shown [2].

Effectively, the dielectric potentials for fixed charge or fixed voltage are different only by a sign, but this makes for a crucial difference on the overall energetics of liquid crystals. As the field couples directly to the orientational order parameter. This field is also quadratic in the field strength and the molecules tend to align parallel or perpendicular to the field, depending on the sign of the dielectric anisotropy. The dielectric coupling free energy density can be written as

$$f_D = \frac{1}{2} \epsilon_0 \epsilon_{ij} \left( \frac{\partial \Phi}{\partial x_i} \right) \left( \frac{\partial \Phi}{\partial x_j} \right), \quad (12)$$

where  $\epsilon_0$  is dielectric vacuum permittivity constant, and  $\Phi$  is the dielectric potential  $\mathbf{E} = -\nabla \Phi$  [2].

## 2.4 Free ions

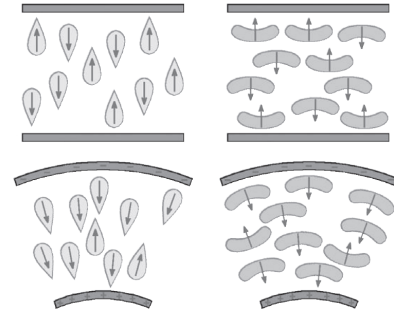
Soft materials also generally have free ions that are screening the electric potential. In liquid crystals their concentration is relatively low, however can become important in regions with high electric field. Monovalent liquid crystals are assumed, which possess equal number of positive and negative ions  $e_0 = e_+ = e_-$  in equilibrium. As we will see, liquid crystal blue phases induce highly nonuniform electric potential. The free ion term in LdG free energy density can be approximately written as [2]

$$f_{ion} = \pm 2k_B T c_0 \left( \cosh \left( \frac{e_0 \Phi}{k_B T} \right) - 1 \right). \quad (13)$$

### 3. Flexo- and order electricity

Flexoelectricity occurs as a result of elastic distortions in liquid crystals, which cause the emergence of flexoelectric polarization. If the liquid crystal is, for example, as shown in Figure 2, composed of asymmetric molecules, an elastic distortion can lead to a spontaneous polarization. Order electricity on the other hand, is a similar mechanism that also results in spontaneous polarization, except that it is now a result of variation in the nematic degree of order. If a polarization is induced by an external electric field then an elastic distortion is a result of the torque  $\mathbf{P} \times \mathbf{E}$ .

Focusing solely on flexoelectricity, if the liquid crystal consists of cone-shaped molecules, such molecule must possess an electrical dipole moment oriented either parallel or antiparallel to the axis of the cone. A splay distortion would tend to orient the cone molecules preferentially, which results in net macroscopic polarization. If molecules are instead banana-shaped, each must possess a transverse dipole moment oriented either toward or away from the center of curvature of the banana. In this case a bend curvature would preferentially orient the bananas, also resulting in polarization [4].



**Figure 2.** Induced polarization as a result of splay and bend deformations in liquid crystals with cone-shaped molecules (left) and banana-shaped molecules (right)[4].

#### 3.1 Induced flexo- and order electric polarization

Polarization induced by flexoelectricity and order electricity arises from distortion in the nematic profile and is therefore proportional to gradients of the tensor order parameter

$$P_{Gi} = G_{ijkl} \frac{\partial Q_{jk}}{\partial x_l}, \quad (14)$$

where  $G_{ijkl}$  is in general a fourth rank coupling tensor.

A more common expression for the induced polarization is instead described by gradients of the director field  $\mathbf{n}$  and nematic degree of order  $S$ . In an uniaxial case the induced polarization reads

$$\mathbf{P}_G = e_1 \mathbf{n}(\nabla \cdot \mathbf{n}) - e_3 (\mathbf{n} \times (\nabla \times \mathbf{n})) + e_2 \mathbf{n}(\mathbf{n} \cdot \nabla S) - e_0 \nabla S, \quad (15)$$

where  $e_1$  and  $e_3$  are flexoelectric coefficients corresponding to splay and bent distortions, respectively, and  $e_2$  and  $e_0$  determine order electricity [14]. Often, single flexoelectric constant approximation  $G_{ijkl} = \frac{1}{2}G(\delta_{ik}\delta_{jl} + \delta_{ij}\delta_{kl})$ , is used, which determines the coefficients as  $e_1 = e_3 = \frac{3}{2}SG$ ,  $e_0 = \frac{1}{2}G$ , and  $e_2 = \frac{3}{2}G$ . We also introduce effective single flexoelectric coefficient  $e = \frac{3}{2}SG$ .

The flexoelectric and order electric polarization in nematic induces a non-uniform electric potential  $\Phi$ , that reflects the underlying profile of the nematic. The corresponding flexoelectric and order electric free energy density can be constructed as

$$f_G = G \left( \frac{\partial Q_{ij}}{\partial x_i} \right) \left( - \frac{\partial \Phi}{\partial x_j} \right). \quad (16)$$

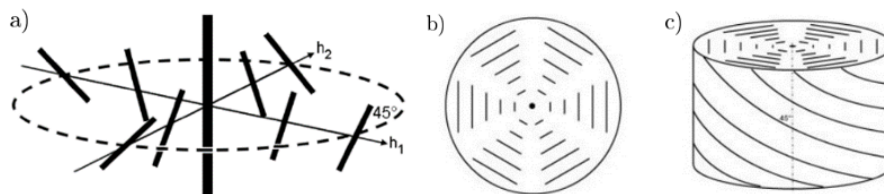
As we will see, this non-uniform electric potential plays a vital role in stabilizing blue phases. Such structures are periodically highly deformed and exhibit aforementioned electric potential, which is induced by flexo- and order electricity.

Flexoelectricity is linear in the applied electric field and as such fundamentally different from effects due to the anisotropy of the susceptibility in liquid crystals, which are quadratic in the field strength. In a fixed geometry, the sign of the applied field matters, so positive and negative fields can produce different responses, either linear or non-linear in nature, depending on the geometry of the particular sample and electrodes. One must also consider the interaction of the field with the anisotropy of the polarizability of the medium, which tends to align the director either parallel or perpendicular to the applied field. This can suppress the flexoelectrically induced curvature in many geometries [4].

Flexoelectricity will produce space charges at the electrodes, but these can be screened by free ionic charges in the material. Any fields produced by flexo-induced space charges would only propagate a distance of the order of the Debye screening length.

#### 4. Blue phases

When nematics are doped with chiral molecules they can show stable phases with a natural twist known as cholesterics. In general cholesteric phases form a one-dimensional helix structure characterized by the helical vector field  $\mathbf{n}(z) = (\cos q_0 z, \sin q_0 z, 0)$ , where  $q_0$  is the parameter of chirality, related to the pitch of the helical phase by  $p = 2\pi/q_0$ . This is indeed the favorable ordering without introducing defects or disclination lines into the structure. The helical structure twists only in one direction perpendicular to the director, which is different as in blue phases, where effectively, twisting emerges in three spatial directions. Local regions of double twist cylinders in the director field are possible. In this immediate region of the cylinder axis, the double twist structure has a lower free energy than the helical phase [5].



**Figure 3.** a) double twist [5]; b) and c) show different projections of a double twist cylinder. Both a) and b) are taken from [6].

The double twist cylinders can be considered as the essential building blocks of the blue phases. They can be arranged in ways that minimize the unfavorably aligned regions in the space between them. A local energy minimum cannot be extended throughout the whole volume, hence blue phases represent a frustrated system. As one could expect, the formed blue phases are inhomogeneous – the order parameter is spatially dependent. They are, however optically isotropic, which means, that they show no net birefringence at the scales of multiple unit cell lengths.

When three double twist cylinders are stacked together, a defect in the director field is formed at their effective junction region (see Fig. 4 and 5). To relieve the consequent elastic strain energy in the right-handed corners,  $-\frac{1}{2}$  topological line defects or disclinations appear in the regions where the cylinder directors form singularities. Every stable cylinder structure is therefore always accompanied with a distinct arrangement of disclinations.

There are two distinct ways of packing the double twist cylinders, which are known as BPI and BP II. In BP II, double twist cylinders are arranged into a periodic array with simple cubic translational symmetry constructing a so-called  $O^2(P4_232)$  space group (figure 4a) [5]. This layout succeeds to fill around 60% of space with double twist cylinders, areas where the free energy is lower than that of the helical phase (figure 4b) [5]. The layout also comes with a corresponding defect unit cell arrangement as shown in figure 4c. [5] In BPI, double twist cylinders are arranged into BCC formations, which fall into the  $O^8$  space group (figure 5a) [5]. This layout succeeds to fill around 68% of space with double twist cylinders, areas where the free energy is lower than that of the helical phase (figure 5b) [5]. The layout also comes with a corresponding defect unit cell arrangement as shown in figure 5c. These sketches are a rough approximation of an actual blue phase. If one is to acquire the order parameter tensor  $Q_{ij}$  after minimizing the free energy, one can then present the defect arrangement in detail, while also showcasing the highly bent and highly splayed regions [8].

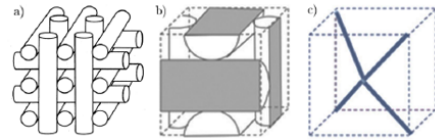


Figure 4: a) Structure [5], b) unit cell [7], and c) defect arrangement of simple cubic BP II [7].

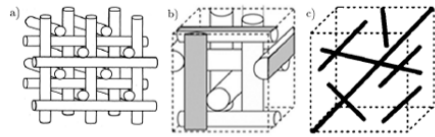
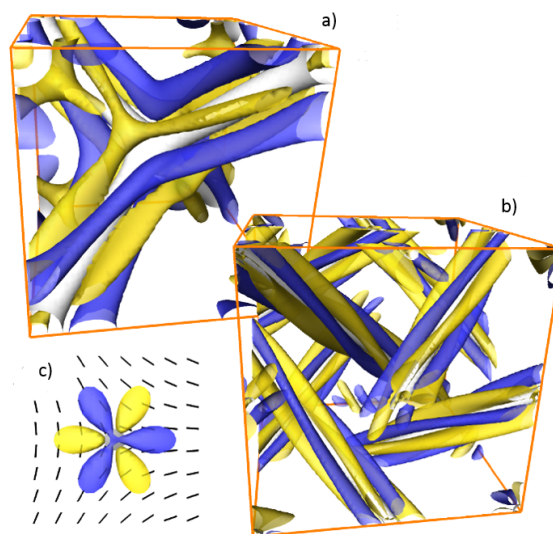


Figure 5: a) Structure [5], b) unit cell [7], and c) defect arrangement of body centered cubic BPI [7].



**Figure 4.** Blue phase unit cells. a) Blue phase II. b) Blue phase I. Defect lines are drawn as white isosurfaces. c) Splay and bend deformations are drawn with Splay-Bend parameter with highly bent regions drawn with yellow and highly splayed regions drawn in blue [2].



#### 4.1 Stabilization using flexo- and order electricity

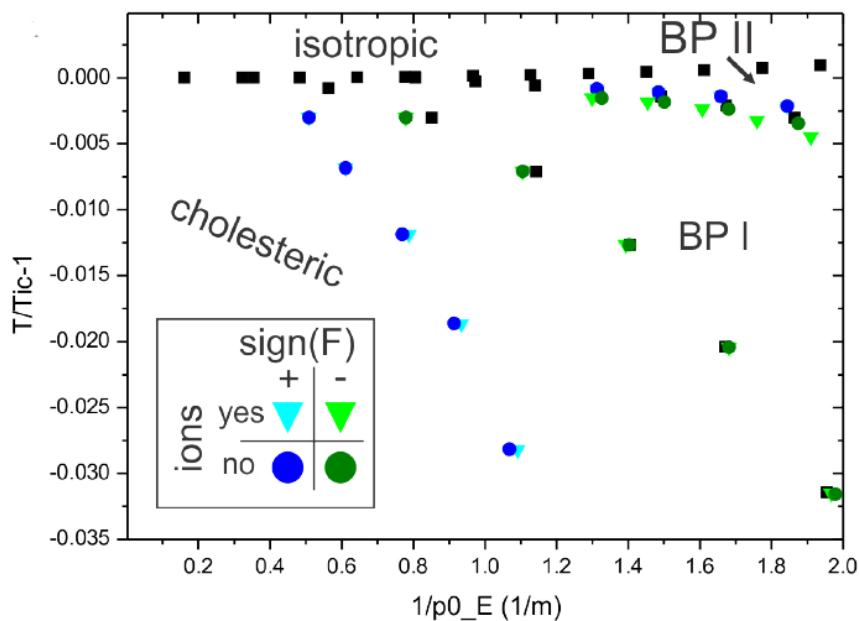
The energy of blue phases has two contributions: the elastic energy of a nematic which is prevalent in double twist cylinders, and the energy of internal ordered structure, which is a result of the presence of defect lines. Packing double twist cylinders in a finite confined space results in singularities in the director field, which is why every stable blue phase structure comes along with its defect line lattice. Even with defect lines that are not efficient energy-wise, and locally less favorable than the helical phase, the global free energy density still remains lower compared to the helical phase.

Effects of the flexo- and order electricity on stability are typically negligible, but become important in highly distorted regions, since the electric potential and changes in local free energy are the largest there. It is interesting to consider possible effects of the flexoelectric polarization in blue phases.

Flexoelectric polarization is induced by splay and bend elastic deformation on nematic around defect lines and is given by the gradients of director field. In general, flexoelectricity only plays a role when curvature distortions are involved or when there are inhomogeneous applied fields.

Coles and Castles [10], as well as Yeomans and Alexander [11] have numerically shown that flexoelectricity indeed stabilizes the blue phase while having little effect on the field-induced birefringence. This is especially the case in new bimesogenic and bent-core materials with large flexoelectric coefficients.

The following phase diagram is from a paper by Porenta, Ravnik, et al. [2] and shows the stabilization in both constant charge and constant potential regime, also accounting for free ions.



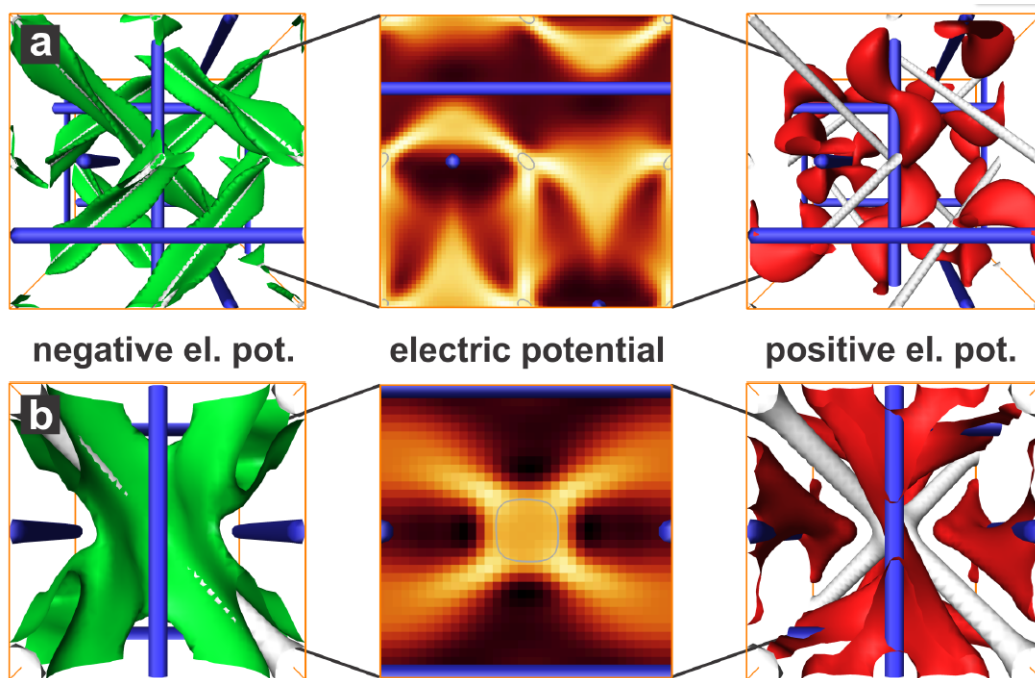
**Figure 5.** In constant charge regime (dark blue) BPI is strongly stabilized and phase region expands over cholesteric and BPII region. In constant potential regime (dark green), no significant effect is observed. Accounting free ions, phase diagram shows that free ions increases flexo- and order electric effect (light blue – constant charge regime, light green – constant potential regime) [2].

As we see, the BPI region of the phase diagram extends over cholesteric region as well as over BPII region. The opposite is observed in constant potential regime where BPI is destabilized while stability of BPII expands. Free ion effects must also be included in Blue Phases. Free ions are screening the potential and further amplify the flexo- and order electric stabilization of the structure.

#### 4.2 Flexoelectric micro-channels in blue phase fluids for ion transport

Apart from further stabilizing the blue phase structure of chiral liquid crystals, the flexoelectric effect could also be used in making microscopic channels for ion transport. Such application is based on the effect of internal rise of electric potential due to deformation.

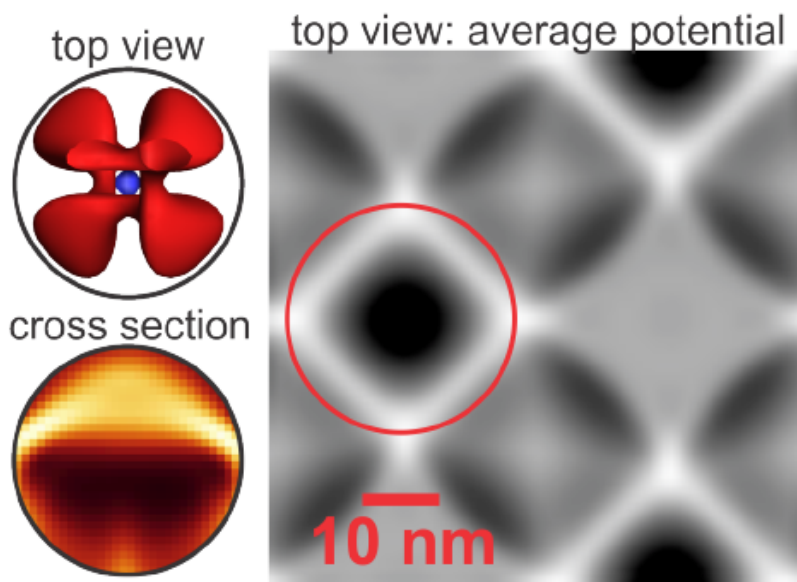
Porenta, Ravnik, et al. [2] used a numerical relaxation method to calculate effects of flexoelectricity, order electricity and free ions in nematic liquid crystal. Total free energy we discussed in chapter 2 is minimized using Euler-Lagrange formalism. Equations for both order parameter tensor  $Q_{ij}$  as well as electric potential  $\Phi$  are obtained. Electric potential and nematic order parameter tensor are alternatively computed, until converged to stable or metastable solution. Mesh resolution is varied to satisfy minimum free energy per volume. An absolute minimum in the free energy per volume corresponds to the equilibrium state. The set of coupled material differential equations is solved numerically by using an explicit Euler finite difference algorithm on a cubic mesh.



**Figure 6.** Electric potential in blue phases induced by flexo- and order electric effect. a) Blue phase; b) blue phase II; In the middle electric potential in blue phases (high - black, low - yellow) is represented. Negative electric potential is induced in regions around defect lines defects (green isosurfaces) and positive around double twist cylinders (red isosurfaces). Cores of cylinders are drawn in blue, while defect lines are drawn as white isosurfaces. High flexoelectric constant of 50 pC and free charge density of  $c = 10^{30}$  ions  $\text{m}^{-3}$  are taken [2].

Since blue phases possess a crystal like property of unit cell periodicity, the electric potential is also periodic. Negative electric potential wraps around nematic disclinations. Using

flexoelectric material could help gather charged particles inside defect lines. Positive electric potential, on the other hand, wraps around double twist cylinders and forms long thick regions of high electric potential. Assuming high enough mobility of electrons or ions blue phases could form ordered structure of nanowires.



**Figure 7.** Top view and cross section of a nanowire (minimum of electric potential) on the left and average of electric potential when going from top to bottom of basic cube [2].

## 5. Conclusion

Blue phases have matured, with recent advances in their construction, from exotic to regular stable phases in a chiral liquid crystal. Their structure can be understood by combining specific tools used in physics, from the Landau-de Gennes theory, to the theory of defects. Flexoelectricity and order electricity must also be taken into account when describing blue phases. In some cases said effects further stabilize/destabilize the structure with the help of free ions. There is more insight yet to be gained in further focusing on the effect of free ions that amplifies the effect of flexoelectricity.

Blue phases have also been proven of being applicative, especially because of their optical properties. These properties can further be controlled via external electric field, and taken advantage of to innovate liquid crystal displays. Apart from that, the new insight of possible application of blue phases for micro transport as a consequence of flexoelectric micro-channels should be further examined theoretically as well as experimentally. Having a conducting wire analog in a liquid sure sounds interesting.

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