liquids

MDPI

Article

On the Question of a Twist-Bend (TB) Phase and the Associated Length Scales

Harald Pleiner [1,*] and Helmut R. Brand [2]

[1] Max Planck Institute for Polymer Research, 55021 Mainz, Germany
[2] Department of Physics, University of Bayreuth, 95440 Bayreuth, Germany; brand@uni-bayreuth.de
* Correspondence: pleiner@mailbox.org

Abstract

We first present an introduction on the issue of macroscopic versus microscopic characteristic length scales and a characterization of the ingredients of a continuum description as well as of a hydrodynamic approach. This is followed by an overview on the macroscopic twist-bend nematic phase, the continuum approach of Bob Meyer. After that, we elucidate the macroscopic description of ferromagnetic and ferroelectric/polar nematic phases. The emphasis is here on the role played by symmetry properties and the choice of hydrodynamic variables. Using this description we compare the continuum approach of Bob Meyer with the macroscopic description of usual nematic phases as well as polar/ferroelectric nematics. This is followed by a brief description of truly ferroelectric and antiferroelectric phases in smectics thus highlighting some recent developments The lessons learned from antiferroelectricity in smectic phases are then used to discuss the issues of polar-twisted (PT) nematic and of twist-bend (TB) nematic phases with characteristic length scales of ∼10 nm In addition, we present a perspective for future synthesis related to the question of whether it is possible to synthesize PTN and TBN phases on larger length scales for the characteristic repeat distance.

Keywords: liquid crystals; macroscopic description; microscopic description; nematics; smectics; twist bend

1. Introduction: Macroscopic Versus Microscopic Characteristic Length Scales

Throughout the present paper the distinction between microscopic and macroscopic length scales plays a crucial role. In a continuum-type theory one is looking at length scales for which microscopic scales such as lattice constants in a solid or molecular lengths in a liquid-crystalline phase play no role. This means that in a continuum theory one is confined to length scales that are very large compared to any microscopic length. A typical example from the field of liquid crystals for such an approach is Frank's free energy for the director deformations of a uniaxial nematic liquid crystal [1,2]. To derive Frank's free energy, a uniaxial nematic ground state is assumed and deviations from this ground state are analyzed.

When the continuum approach is extended to include dynamic processes, which are slow on sufficiently long time scales, one is talking about hydrodynamics. For the application of this approach to uniaxial nematic liquid crystals, we refer to refs. [3–6]. For the hydrodynamic approach, the restrictions can be summarized succinctly as follows. The focus is on length scales $kl_c << 1$ and on the frequency regime $\omega\tau_c << 1$, where τ_c is a typical microscopic collision time, l_c a microscopic length scale, and where ω and k

Check for updates

Academic Editor: Enrico Bodo

Received: 2 October 2026
Revised: 20 November 2026
Accepted: 23 November 2026
Published: 27 November 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

are the frequency and wavevector for the spatio-temporal variations of the hydrodynamic variables considered.

In a simple fluid, the hydrodynamic variables are [6,7] the density, the density of momentum and the energy density. In a uniaxial nematic liquid crystal, one has in addition the director variations, δn_i, as hydrodynamic variables characterizing the spatio-temporal variations in the averaged preferred direction, the director n_i (with $n_i^2 = 1$), for sufficiently large length scales and sufficiently small frequencies [4,6]. In technical terms, the director variations, δn_i, are associated with the spontaneously broken continuous rotational symmetry in a uniaxial nematic liquid crystal.

In liquid crystals, nematic liquid crystals that carry a helical structure (including cholesteric liquid crystals) are sometimes described by a mapping to smectic structures using the helical pitch as a fictitious layer thickness. Certainly, this is a reasonable approximation only if the "in-plane" details are considered as unimportant. A continuous return to the original nematic picture is not possible.

From the analysis just summarized, it is clear that phenomena that have a characteristic length scale of one or two molecular lengths (~10 nm) cannot be possibly described by a continuum or hydrodynamic approach. Or, to summarize graphically the condition for the length scales of interest in a continuum description,

$$l_c << \lambda < L$$

where l_c is a molecular length scale on the order of nanometers, L is a typical sample dimension and λ the wavelength of a hydrodynamic excitation.

On molecular length scales, one must therefore use microscopic considerations and/or simulations of various different types including Monte Carlo and MD (molecular dynamics) simulations.

2. On the Macroscopic Twist-Bend Nematic Phase—The Continuum Approach of Bob Meyer

In the following, we give a somewhat compressed version of the original work of Meyer [8], which was presented over 50 years ago. At that time, usual uniaxial nematic phases were the only nonchiral liquid-crystalline phases with fluidity in three dimensions known to exist in the bulk. Over the last decade or so this situation has changed qualitatively by the reports of uniaxial ferromagnetic nematic phases [9] and of uniaxial ferroelectric nematic phases [10,11]. As we show in the following sections these developments also strongly influence our perception of the pioneering work of Bob Meyer. This applies all the more since during the same period of time, several types of fluid smectic phases with various types of long-range electric order including truly ferroelectric order (smectic A_F [12–14] and smectic C_F [15,16]) and antiferroelectric order [17–21] have been found. Naturally, all these developments were not anticipated 50 years ago.

In section IIC.2 of ref. [8] Meyer combines Frank's free energy derived for a nonpolar uniaxial nematic with the macroscopic polarization $\mathbf{P}$ and a finite polarization $\mathbf{P^0}$ due to intermolecular interactions to obtain the free energy

$$\begin{aligned} g &= \frac{1}{2}K_{11}^0 S^2 + \frac{1}{2}K_{22}t^2 + \frac{1}{2}K_{33}^0 B^2 + \frac{1}{2}\alpha_1(P_\parallel - P_\parallel^0)^2 \\ &\quad + \frac{1}{2}\alpha_3(\mathbf{P}_\perp - \mathbf{P}_\perp^\mathbf{0})^2 - a_1 P_\parallel S - a_3 \mathbf{P}_\perp \cdot \mathbf{B} \end{aligned} \quad (1)$$

where S is splay, and $\mathbf{B}$ denotes bend.

Then, **P** is eliminated to give

$$P_{\parallel} = P_{\parallel}^{0} + \frac{a_1}{\alpha_1} S$$
$$\mathbf{P}_{\perp} = \mathbf{P}_{\perp}^{\mathbf{0}} + \frac{a_3}{\alpha_3} \mathbf{B}. \quad (2)$$

and

$$g = \frac{1}{2}[K_{11}^{0} - \frac{a_1^2}{\alpha_1}]S^2 + \frac{1}{2}K_{22}t^2 + \frac{1}{2}[K_{33}^{0} - \frac{a_3^2}{\alpha_3}]B^2$$
$$-a_1 P_{\parallel}^{0} S - a_3 \mathbf{P}_{\perp}^{\mathbf{0}} \cdot \mathbf{B} \quad (3)$$

From the terms linear in S and **B** it is concluded in [8] that the ground state contains finite splay or bend or both. And it is pointed out that "this effect is similar in principle to that found for chiral asymmetry in the case of a chiral nematic phase." After that it is concluded that "a state of finite torsion and bend is possible. The latter is a modified helix in which the director has a component parallel to the helix axis. In laboratory coordinates

$$n_z = cos\varphi$$
$$n_x = sin\varphi\ cos(t_0 z)$$
$$n_y = sin\varphi\ sin(t_0 z) \quad (4)$$

with the helical wavenumber t_0."

This is the phase frequently referred to as the twist-bend nematic phase N_{TB} for an apolar nematic director $\hat{n}$ [22]. It has been derived in the framework of a macroscopic description, and it is concluded in [8] and in [22] that such a phase with a macroscopic twist bend has never been observed experimentally until the present day. Or to quote from [22], "the spontaneous formation of a heliconical trajectory of the **apolar** nematic director **n**, the so-called twist bend nematic N_{TB} lay dormant for a quarter of a century."

We would like to point that without a polarization **P**, Equation (1) reduces to the expression for a usual nonpolar nematic phase without spontaneous bend and/or twist, thus removing the possibility of a twist-bend nematic phase.

In Section 5 below, we discuss nematic-like phases with a microscopic characteristic length of about ~8 nm observed experimentally [23,24], as well as the approaches to model such phases using simulations [25–30].

3. On Ferromagnetic and Ferroelectric/Polar Nematic Phases

In this section we summarize selected macroscopic properties of ferromagnetic nematic liquid crystals and of ferroelectric liquid crystals that have been obtained experimentally up to now.

So far, ferromagnetic nematics exist with a spontaneous magnetization $\mathbf{M_0} \neq 0$, which is an axial vector, even under parity and odd under time reversal. They show a coexistence of quadrupolar order as in a usual nematic and of ferromagnetic order with $\mathbf{M_0} \parallel \hat{\mathbf{n}}_\mathbf{0}$. Their macroscopic properties have been investigated already in quite some detail, experimentally [9,31–33] and theoretically [34–38]. In particular, quantitative comparisons of their macroscopic dynamics with experiments have been performed [36,37]. We emphasize that so far, the majority of ferromagnetic nematics are based on the dispersion of magnetic platelets in a low-molecular-weight nematic. Importantly, the easy magnetic axis of the platelets is parallel to the nematic director and thus perpendicular to the plane of the platelets [9,31,33,36].

Ferroelectric order is characterized by a nonvanishing macroscopic electric polarization $\mathbf{P_0} \neq 0$. It is a well-established phenomenon in solid-state physics [39,40] that has been

studied for decades in detail. The macroscopic electric polarization has completely different symmetry properties from the macroscopic magnetization. $\mathbf{P_0}$ is a polar vector, odd under parity and even under time reversal. Therefore, the macroscopic polarization has completely different symmetry properties from those of the usual director field in a nonpolar nematic.

In particular, spontaneous splay $\nabla \cdot \mathbf{P_0}$ can arise for fluid systems such as a polar nematic. As shown in ref. [41], an infinite system of $\nabla \cdot \mathbf{P_0} = \mathbf{const.}$, called a splay phase, necessarily leads to the formation of defects for space-filling reasons. Therefore, homogeneous structures cannot be the ground state with the lowest free energy.

The macroscopic dynamic equations for defect-free polar or ferroelectric nematics with $\mathbf{P_0} = \mathbf{const.}$ have been investigated in 2006 [42] (compare also [43].) The macroscopic polarization as well as the deviation from its equilibrium value, $\delta\mathbf{P}$, break parity symmetry, meaning there is no head-to-tail symmetry. As a result, the number of macroscopic material parameters is larger compared to the usual nonpolar uniaxial nematics with exclusively quadrupolar order. But there are no linear bend or twist contributions in the ferroelectric phases, even if one considers mixtures of polar and apolar nematics. The reason is the existence of the homogeneous coupling $(\mathbf{P} \cdot \mathbf{n})^2$ that leads to either $\mathbf{P} \parallel \mathbf{n}$ or $\mathbf{P} \perp \mathbf{n}$. This contribution is lacking in Equation (1) and is incompatible with it. A mixing of the two different descriptions is not possible. We also note that no macroscopic twist-bend phase has been found experimentally as of yet for ferroelectric nematics.

The first unequivocal experimental observations of a truly ferroelectric nematic phase have been reported by two groups in 2017 [10,11]. After their discovery, ferroelectric nematics have been investigated experimentally [44–57] and theoretically [58–60] by a number of groups, and the field is still growing. As a qualitative difference to the macroscopic behavior of nonpolar nematics, we just mention the observation of a ferroelectric hysteresis loop as well as of a strong second-harmonic generation [11] not possible in usual nonpolar nematics.

In this section, we have presented a short summary about the differences in symmetry and in macroscopic behavior between usual nonpolar nematics on the one hand and ferroelectric nematics as well as ferromagnetic nematics on the other.

It emerges that the twist-bend phase discussed by Bob Meyer does not belong to nonpolar nematics or to ferroelectric nematics (nor to splay phases). Given the combination of a director description and a polarization he inspected, it is not clear which symmetry for the ground state he had in mind. Therefore, it appears not too surprising that the macroscopic twist-bend nematic N_{TB}) phase has never been observed experimentally.

We close this section with a final remark concerning biaxial nematic phases. While a uniaxial phase with the polarization $\mathbf{P}$ along the director $\hat{\mathbf{n}}$ is the simplest possibility and the only one that appears to have been realized so far, we note that polar biaxial nematic phases might also exist, even if one focuses on orthogonal phases. For early work on this question, we refer to ref. [61].

4. On Truly Ferroelectric and Antiferroelectric Phases in Smectics—Some Recent Developments

For comparison, we discuss what kind of macroscopically ordered polar phases in *smectic* phases have been discussed over the last four years or so. The advantage of smectic phases is the increased possibility of different spatial structures. These developments started with ferroelectric smectic A phases, A_F [12–14]. In the A_F phase, there is a macroscopic polarization parallel to the layer normal of smectic layers and complete fluidity within the layering. Smectic A_F shows a ferroelectric hysteresis loop, and the resulting macroscopic dynamics is heavily influenced by the presence of a polar direction [62].

In this connection, we note that a macroscopic description for layered smectic phases works well for sufficiently thick samples [2,4]. This is due to the fact that there is a clear-

cut separation of scales, namely, the microscopic length scale associated with the layer spacing (frequently ~3 nm in thermotropic smectics) and the macroscopic sample thickness (typically ~ 3 μm ... 100 μm). Therefore, a continuum description has been successfully applied to smectic phases for over five decades [2,4].

About two years ago, there were two important developments in this field. One is the smectic C_F phase, the first truly ferroelectric smectic *C* phase in the bulk [15,16]. It has C_{1h} symmetry. The associated macroscopic dynamics [63] strongly reflects the presence of polar directions of the anisotropic in-plane fluidity as well as of the direction parallel to the layer normal. We emphasize that smectic A_F and C_F are the first truly ferroelectric smectic phases in the bulk with in-plane fluidity.

Second, a rather intriguing fluid smectic phase with long-range order of macroscopic polarization is the antiferroelectric Z_A phase [17–21] with an in-plane polarization that changes its sign from one layer to the next. This leads to an overall double-layer structure with a repeat distance of the order of the smectic layer thickness. Although this is a "microscopic" length scale, it leads to a macroscopic order, since the antiferroelectric order in Z_A is long range. For a description of its macroscopic dynamics we refer to ref. [64].

From a symmetry point of view, it turns out that for sample thicknesses that are large compared to the repeat distance of the bilayers, the symmetry of Z_A (without external electric fields) is D_{2h} and thus the same as that of smectic C_M studied theoretically [2,65–67] and experimentally [68] several decades ago. C_M is an orthogonal biaxial fluid smectic phase with an in-plane director which does not distinguish between head and tail and thus allows for defects of the in-plane director of half-integer strength as predicted in [67] and demonstrated experimentally [68]. External electric fields applied on Z_A lead, as a function of the external field strength, to the characteristic double hysteresis loop of antiferroelectric order, well known from solid antiferroelectrics [69].

5. On Twist-Bend (TB) Nematic Phases and on Polar-Twisted (PT) Nematic Phases with Typical Microscopic Characteristic Length Scales

In this section we comment briefly on nematic phases obtained experimentally with a characteristic length scale of ~10 nm. These phases cannot possibly be related to the twist-bend phase (TB nematic phase) suggested by Bob Meyer [8]. First of all, a continuum or macroscopic description cannot be applied to length scales of about two molecular lengths. Clearly, a different, more microscopic approach is needed for the description of such features. And surely, ref. [8] is using a continuum description. Secondly, if there is a spontaneous non-vanishing value of the macroscopic polarization, the phase investigated can no longer be a usual nonpolar nematic phase with director variations as macroscopic variables. And for ferroelectric/polar nematics, as they have been found in 2017, the macroscopic description is different (compare [41,42] for early work in this field.)

In refs. [23,24] a nematic-like phase with a characteristic length scale of ~8 nm was identified in addition to a usual nonpolar nematic phase. The authors of both references associated this nematic-like phase with the twist-bend phase of ref. [8]. However, refs. [23,24] use an apolar description and lack a macroscopic polarization. These two papers followed ref. [70], where it was suggested that a number of phases formed by dimers can be classified as twist-bend nematics (TBNs). But naturally, a more microscopic approach is called for to identify the origin of a characteristic distance and the correlation length of this nanoscale modulation.

Using simulations, there appear to be two types of microscopic models on the market today to account for such a modulation. One is based on the work of Memmer [25] making use of director modulations. Ref. [25] was followed by a number of papers describing simulations of various models on the nano scale, including refs. [26–28]. In this connection, we note that in the microscopic picture, the N_{TB} phase acquires chirality involving a local

flexoelectric polarization and not an intrinsic polar axis. We refer to ref. [29] for a detailed exposition and discussion of the various director-based models used for simulations as well as for an elucidation of their numerous shortcomings. This situation is in contrast to the polar-twisted phase N_{PT} discussed next. The N_{PT} model uses a polar direction in the plane perpendicular to the helical axis of the helix with a pitch of ~10 nm [30]. In ref. [22] it was already discussed in detail why there cannot be any overlap with a macroscopic model, in particular emphasizing the important difference between macroscopic and microscopic length scales. Ref. [29] also presents details of the polar-twisted nematic (PTN) model exhibiting a mirror symmetry breaking helicoidal supramolecular structure with nanoscale modulation and a polar axis. That reference also includes a detailed analysis of why the TBN model does not apply for the description of the modified nematic phases on a length scale of about two molecular lengths. In particular, the authors of ref. [29] emphasized the importance of entropic considerations and of form chirality.

For a recent Landau phenomenological interpretation in which a short-range orientational order parameter condenses at a finite wave vector, we refer to the work of Kats [71] in the present volume. In that paper, the emergence of a nanoscale modulation in liquid crystals is discussed, and it is pointed out that the N_{PT} phase is compatible with the model suggested.

From a macroscopic perspective, an interesting observation was reported in ref. [72]. It was demonstrated that for certain chiral materials, a heliconical deformation of the cholesteric helix, which is in the micrometer range, could be achieved by the application of an electric field. We note, however, that this not a case of a spontaneously broken symmetry.

6. Perspective: Is It Possible to Synthesize PTN and TBN Phases on Larger Length Scales for the Characteristic Repeat Distance?

In the introduction we briefly summarized the spirit of continuum theories and of hydrodynamics. We already clarified in that section that nematic liquid-crystalline phases with an additional characteristic length scale of two molecular lengths could not possibly be amenable to a macroscopic approach for features on a scale of ~10 nm.

Section 2 was dedicated to a review of the continuum model of Bob Meyer for the twist-bend nematic (TBN) phase dating back more than five decades, at a time when ferroelectric/polar nematic phases as well as ferromagnetic nematic phases did not exist.

In Section 3 we presented selected recent developments on the macroscopic behavior of ferromagnetic nematics as well as of ferroelectric/polar nematics. We pointed out that it was completely unclear which ground state formed the basis for the twist-bend nematic phase postulated in the continuum approach of Bob Meyer. In addition, in his model, the homogeneous lowest-order coupling term $(P_i n_i)^2$ is missing from the generalized energy. As discussed in detail in refs. [31,33,36,37], the magnetic analog of this coupling plays a crucial role in describing the static and dynamic properties of ferromagnetic nematics.

In Section 4 we briefly touched on recent developments on the question of ferroelectricity and antiferroelectricity in various types of smectic phases, thus putting the question of ferroelectricity in liquid crystals into a broader context.

In Section 5 we succinctly summarized the microscopic modeling situation for nematic phases with an additional characteristic length scale of two molecular lengths:

(a) The older, microscopic twist-bend nematic (TBN) phase without an electric polarization;
(b) The more recent polar-twisted nematic (PTN) model with a polar axis perpendicular to the helical axis [22,29,30].

It will be most interesting to see whether one can scale up either of these two models to predict a new type of liquid-crystalline phase with a macroscopic length scale of interest. Perhaps even more exciting will be the synthesis of such a novel phase.

In this connection it seems worthwhile to mention that there have been interesting developments in the context of spontaneous chiral symmetry breaking in systems showing ferroelectric nematics over the last couple of years [73–77]. In these systems, the pitch of the resulting helices is comparable to 1 μm and thus very large compared to the molecular length. It has also been shown that an electric field can be used to tune the pitch [76,77]. Helical structures observed include conical helices for which the polarization encloses an angle different from 90 degrees with the helix axis, as well as helices for which the enclosed angle is 90 degrees.

We close with a rather simple observation. While spontaneous symmetry breaking in ferroelectric nematics can lead quite frequently to C_1 symmetry on length scales smaller than the pitch, but large compared to molecular lengths, such a low symmetry—or actually no symmetry—can also be achieved by different means. Candidates that immediately come to mind are truly ferroelectric smectic *C* phases, C_F, briefly mentioned in Section 4, which have C_{1h} symmetry in their ground state. By adding a chiral agent, the horizontal mirror plane is removed, and a phase with C_1 symmetry is obtained [78]. This reduction in symmetry leads to numerous consequences for the macroscopic dynamic behavior [78].

Author Contributions: Conceptualization, H.P. and H.R.B.; Methodology, H.P. and H.R.B.; Formal analysis, H.P. and H.R.B.; Investigation, H.P. and H.R.B.; Writing—original draft, H.P. and H.R.B.; Writing—review & editing, H.P. and H.R.B. Both authors contributed equally to all parts of the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Frank, F.C. On the theory of liquid crystals. *Discuss. Faraday Soc.* **1958**, *25*, 19–28. [CrossRef]
2. De Gennes, P.G. *The Physics of Liquid Crystals*; Clarendon Press: Oxford, UK, 1975.
3. Forster, D.; Lubensky, T.C.; Martin, P.C.; Swift, J.; Pershan, P.S. Hydrodynamics of liquid crystals. *Phys. Rev. Lett.* **1971**, *26*, 1016–1019. [CrossRef]
4. Martin, P.C.; Parodi, O.; Pershan, P.S. Unified hydrodynamic theory for crystals, liquid crystals and normal fluids. *Phys. Rev. A* **1972**, *6*, 2401–2420. [CrossRef]
5. Pleiner, H.; Brand, H.R. Hydrodynamics and Electrohydrodynamics of Nematic Liquid Crystals. In *Pattern Formation in Liquid Crystals*; Buka, A., Kramer, L., Eds.; Springer: New York, NY, USA, 1996; pp. 15–67.
6. Forster, D. *Hydrodynamic Fluctuations, Broken Symmetry, and Correlation Functions*; W.A. Benjamin: Reading, MA, USA, 1975.
7. Landau, L.D.; Lifshitz, E.M. *Fluid Mechanics*; Pergamon: London, UK, 1959; Volume 6.
8. Meyer, R.B. Structural problems in liquid crystal physics. In *Molecular Fluids, Les Houches Summer School in Theoretical Physics, Lectures of 1973*; Balian, R., Weill, G., Eds.; Gordon and Breach: New York, NY, USA, 1976; pp. 271–343.
9. Mertelj, A.; Lisjak, D.; Drofenik, M.; Čopič, M. Ferromagnetism in suspensions of magnetic platelets in liquid crystal. *Nature* **2013**, *504*, 237–241. [CrossRef] [PubMed]
10. Mandle, R.J.; Cowling, S.J.; Goodby, J.W. Rational design of rod-like liquid crystals exhibiting two nematic phases. *Chem. Eur. J.* **2017**, *23*, 14554–14562. [CrossRef] [PubMed]
11. Nishikawa, H.; Shiroshita, K.; Higuchi, H.; Okumura, Y.; Hasebo, Y.; Yamamoto, S.; Sago, K.; Kikuchi, H. A fluid liquid-crystal material with highly polar order. *Adv. Mater.* **2017**, *29*, 1702354. [CrossRef] [PubMed]
12. Kikuchi, H.; Matsukizono, H.; Iwamatsu, K.; Anam, S.; Okumura, Y. Fluid layered ferroelectrics with global $C_{\infty v}$ symmetry. *Adv. Sci.* **2022**, *9*, 2202048. [CrossRef] [PubMed]
13. Song, Y.; Deng, M.; Wang, Z.; Li, J.; Lei, H.; Wan, Z.; Xia, R.; Aya, S.; Huang, M. Emerging ferroelectric uniaxial lamellar (smectic S_F) fluids for bistable in-plane polarization memory. *J. Phys. Chem. Lett.* **2022**, *13*, 9983–9990. [CrossRef] [PubMed]

14. Chen, X.; Martinez, V.; Nacke, P.; Körblova, E.; Manabe, A.; Klasen-Memmer, M.; Freychet, G.; Zhernenkov, N.; Glaser, M.A.; Radzihovsky, L.; et al. Observation of a uniaxial ferroelectric smectic *A* phase. *Proc. Natl. Acad. Sci. USA* **2022**, *119*, e2210062119. [CrossRef] [PubMed]
15. Kikuchi, H.; Nishikawa, H.; Matsukizono, H.; Iino, S.; Sugiyama, T.; Ishioka, T.; Okumura, Y. Ferroelectric smectic *C* liquid crystal phase with spontaneous polarization in the direction of the director. *Adv. Sci.* **2024**, *2024*, 2409827. [CrossRef] [PubMed]
16. Hobbs, J., Gibb, C.J., Pociecha, D.; Sydlowska, J.; Gorecka, E.; Mandle, R.J. Polar order in a fluid like ferroelectric with a tilted lamellar phase—observation of a polar smectic C (SmCP) phase. *Angew. Chem. Int. Ed.* **2024**, *63*, e202416545. [CrossRef] [PubMed]
17. Chen, X.; Martinez, V.; Körblova, E.; Freychet, G.; Zhernenkov, N.; Glaser, M.A.; Wang, C.; Zhu, C.; Radzihovsky, L.; McLennan, J.E.; et al. The smectic Z_A phase: Antiferroelectric order as a prelude to the ferroelectric nematic. *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2217150120. [CrossRef] [PubMed]
18. Nacke, P.; Manabe, A.; Klasen-Memmer, M.; Chen, X.; Martinez, V.; Freychet, G.; Zhernenkov, N.; McLennan, J.E.; Bremer, M.; Giesselmann, F.; et al. New examples of ferroelectric nematic materials showing evidence for the antiferroelectric smectic-Z phase. *Sci. Rep.* **2024**, *14*, 4473. [CrossRef] [PubMed]
19. Nacke, P.; Tuffin, R.; Klasen-Memmer, M.; Rudquist, P.; Giesselmann, F. Revealing the antipolar order in the antiferroelectric SmZ_A phase by means of circular dichroism. *Sci. Rep.* **2024**, *14*, 15018. [CrossRef] [PubMed]
20. Hobbs, J.; Gibb, C.J.; Mandle, R.J. Emergent antiferroelectric ordering and the coupling of liquid crystalline and polar order. *Small Sci.* **2024**, *4*, 2400189. [CrossRef] [PubMed]
21. Gibb, C.J.; Hobbs, J.; Nikolova, D.I.; Raistrick, T.; Berrow, S.R.; Mertelj, A.; Osterman, N.; Sebastian, N.; Glesson, H.F.; Mandle, R.J. Spontaneous symmetry breaking in polar fluids. *Nat. Commun.* **2024**, *15*, 58454. [CrossRef] [PubMed]
22. Samulski, E.T.; Vanakaras, A.K.; Photinos, D.J. The twist bend nematic phase: A case of mistaken identity. *Liq. Cryst.* **2020**, *47*, 2092–2097. [CrossRef]
23. Chen, D. ; Porada, J.H.; Hooper, J.B.; Klittnick, A.; Shen, Y.; Tuchband, M.R.; Korblova, E.; Bedrov, D.; Walba, D.M.; Glaser, M.A.; et al., Chiral heliconical ground state of nanoscale pitch in a nematic liquid crystal of chiral molecular dimers. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 15931–15936. [CrossRef] [PubMed]
24. Borshch, V.; Kim, Y.-K.; Xiang, J.; Gao, M.; Jákli, A.; Panov, V.P.; Vij, J.K.; Imrie, C.T.; Tamba, M.G.; Mehl, G.H.; et al. Nematic twist-bend phase with nanoscale modulation of molecular orientation. *Nat. Commun.* **2013**, *4*, 2635. [CrossRef] [PubMed]
25. Memmer, R. Liquid crystal phases of a chiral banana-shaped molecules: a computer simulation study. *Liq. Cryst.* **2002**, *29*, 483–496. [CrossRef]
26. Greco, C.; Ferrarini, A. Entropy-driven chiral order in a system of achiral bent particles. *Phys. Rev. Lett.* **2015**, *115*, 147801. [CrossRef] [PubMed]
27. Chiappini, M.; Dijkstra, M.j A generalized density-modulated twist-splay-bend phase of banana-shaped particles. *Nat. Commun.* **2021**, *12*, 2157. [CrossRef] [PubMed]
28. Kubala, P.; Tomczyk, W.; Cieśla, M. *In silico* study of liquid crystalline phases formed by bent-shaped molecules with excluded volume type interactions. *J. Mol. Liq.* **2022**, *366*, 1201256. [CrossRef]
29. Vanakaras, A.G.; Samulski, E.T.; Photinos, D.J. Entropy stabilized form chirality in curved rod nematics: structure and symmetries. *Soft Matter* **2025**, *21*, 1341–1352. [CrossRef] [PubMed]
30. Vanakaras, A.G.; Photinos, D.J. A molecular theory of nematic-nematic phase transitions in mesogenic dimers. *Soft Matter* **2016**, *12*, 2208–2220. [CrossRef] [PubMed]
31. Mertelj, A.; Osterman, N.; Lisjak, D.; Čopič, M. Magneto-optic and converse magnetoelectric effects in a ferromagnetic liquid crystal. *Soft Matter* **2014**, *10*, 9065–9072. [CrossRef] [PubMed]
32. Sahoo, R.; Rasna, M.V.; Lisjak, D.; Mertelj, A,; Dahra, S. Magnetodielectric and magnetoviscosity response of a ferromagnetic liquid crystal at low magnetic fields. *Appl. Phys. Lett.* **2015**, *106*, 161905. [CrossRef]
33. Mertelj, A.; Lisjak, D. Ferromagnetic nematic liquid crystals. *Liq. Cryst. Rev.* **2017**, *5*, 1–33. [CrossRef]
34. Jarkova, E.; Pleiner, H.; Müller, H.-W.; Fink, A.; Brand, H.R. Hydrodynamics of nematic ferrofluids. *Eur. Phys. J. E* **2001**, *5*, 583–588. [CrossRef]
35. Jarkova, E.; Pleiner, H.; Müller, H.-W.; Brand, H.R. Macroscopic dynamics of ferronematics. *J. Chem. Phys.* **2003**, *118*, 2422–2430. [CrossRef]
36. Potisk, T.; Svenšek, D.; Brand, H.R.; Pleiner, H.; Lisjak, D.; Osterman, N.; Mertelj, A. Dynamic magneto-optic coupling in a ferromagnetic nematic liquid crystal. *Phys. Rev. Lett.* **2017**, *119*, 097802. [CrossRef] [PubMed]
37. Potisk, T.; Mertelj, A.; Sebastián, N.; Osterman, N.; Lisjak, D.; Brand, H.R.; Pleiner, H.; Svenšek, D. Magneto-optic dynamics in a ferromagnetic nematic liquid crystal. *Phys. Rev. E* **2018**, *97*, 012701. [CrossRef] [PubMed]
38. Potisk, T.; Pleiner, H.; Svenšek, D.; Brand, H.R. Effects of flow on the dynamics of a ferromagnetic nematic liquid crystal. *Phys. Rev. E* **2018**, *97*, 042705. [CrossRef] [PubMed]
39. Kittel, C. *Introduction to Solid State Physics*, 4th ed.; Addison Wesley: New York, NY, USA, 1971.

40. Mason, W.P. *Physical Acoustics and the Properties of Solids*; D. Van Nostrand: New York, NY, USA, 1958.
41. Pleiner H.; Brand, H.R. Spontaneous splay phases in polar nematic liquid crystals. *EPL* **1989**, *9*, 243–249. [CrossRef]
42. Brand, H.R.; Pleiner, H.; Ziebert, F. Macroscopic dynamics of polar nematic liquid crystals. *Phys. Rev. E* **2006**, *74*, 021713. [CrossRef] [PubMed]
43. Brand, H.R.; Cladis, P.E.; Pleiner, H. Reversible macroscopic dynamics of polar nematic liquid crystals: Reversible currents and their experimental consequences. *Phys. Rev. E* **2009**, *79*, 032701. [CrossRef] [PubMed]
44. Mertelj, A.; Cmok, L.; Sebastian, N.; Mandle, R.J.; Parker, R.R.; Whitwood, A.C.; Goodby, J.W.; Copic, M. Splay nematic phase. *Phys. Rev. X* **2018**, *8*, 041025. [CrossRef]
45. Mandle R.J.; Mertelj, A. Orientational order in the splay nematic ground state. *Phys. Chem. Chem. Phys.* **2019**, *21*, 18769–18772. [CrossRef] [PubMed]
46. Chen, X.; Korblova, E.; Dong, D.; Wei, X.; Shao, R.; Radzihovsky, L.; Glaser, M.A.; Mclennan, J.E.: Bedrov, D.; Walba, D.M.; Clark, N.A. First principles experimental demonstration of ferroelectricity in a thermotropic nematic liquid crystal: Polar domains and striking electro-optics. *Proc. Natl. Acad. Sci. USA* **2020**, *117*, 14021–14031. [CrossRef] [PubMed]
47. Connor, P.L.M.; Mandle, R.J. Chemically induced splay nematic phase with micronscale periodicity. *Soft Matter* **2020**, *16*, 324–329. [CrossRef] [PubMed]
48. Sebastian, N.; Cmok, L.; Mandle, R.J.; de la Fuente, M.R.; Olenik, I.D.; Copic, M.; Mertelj, A. Ferroelectric-ferroelastic phase transition in a nematic liquid crystal. *Phys. Rev. Lett.* **2020**, *124*, 037801. [CrossRef] [PubMed]
49. Mandle, R.J.; Sebastian, N.; Martinez-Perdiguero, J.; Mertelj, A. On the molecular origins of the ferroelectric splay nematic phase. *Nat. Commun.* **2021**, *12*, 4962. [CrossRef] [PubMed]
50. Manabe, A.; Bremer, M.; Kraska, M. Ferroelectric nematic phase at and below room temperature. *Liq. Cryst.* **2021**, *48*, 1079–1086. [CrossRef]
51. Mandle, R.J.; Cowling, S.J.; Goodby, J.W. Structural variants of RM734 in the design of splay nematic materials. *Liq. Cryst.* **2021**, *48*, 1780–1790. [CrossRef]
52. Sebastian, N.; Mandle, R.J.; Petelin, A.; Eremin, A.; Mertelj, A. Electrooptics of mm-scale polar domains in the ferroelectric nematic phase. *Liq. Cryst.* **2021**, *48*, 2055–2071. [CrossRef]
53. Nishikawa, H.; Sano, K.; Kunihara, S.; Watanabe, G.; Nishonyanagi, A.; Dahra, B.; Araoka, F. Nano clustering mediates phase transitions in a diasteriomerically-stabilized ferroelectric nematic system. *Commun. Mater.* **2022**, *3*, 89. [CrossRef]
54. Mandle, R.J. A new order of liquids: Polar order in nematic liquid crystals. *Soft Matter* **2022**, *18*, 5014–5020. [CrossRef] [PubMed]
55. Ferroelectric nematic liquid crystalline phases. Sebastian, N.; Copic, M.; Mertelj, A. *Phys. Rev. E* **2022**, *106*, 021001. [CrossRef] [PubMed]
56. Zavvou, E.; Klasen-Memmer, M.; Manabe, A.; Bremer, M.; Eremin, A. Polarization-driven magneto-optical and nonlinear optical behavior of a room-temperature ferroelectric nematic phase. *Soft Matter* **2022**, *18*, 8804–8812. [CrossRef] [PubMed]
57. Matsukizono, H.; Iwamatsu, K.; Endo, S.; Okumura, Y.; Anan, S.; Kikuchi, H. Synthesis of liquid crystals bearing 1,3-dioxane structures and characterization of their ferroelectricity in the nematic phase. *J. Mat. Chem. C* **2023**, *11*, 6183–6190. [CrossRef]
58. Rosseto, M.P.; Selinger, J.V. Theory of the splay-nematic phase: Single versus double splay. *Phys. Rev. E* **2020** *101*, 052707. [CrossRef] [PubMed]
59. Kats, E.I. Stability of the uniform ferroelectric nematic phase. *Phys. Rev. E* **2021**, *103*, 012704. [CrossRef] [PubMed]
60. Brand, H.R.; Pleiner, H. A two-fluid model for the macroscopic behavior of polar nematic fluids and gels in a nonchiral or a chiral solvent. *Eur. Phys. J. E* **2022**, *45*, 17. [CrossRef] [PubMed]
61. Brand, H.R.; Cladis, P.E.; Pleiner, H. Polar biaxial liquid crystalline phases with fluidity in two and three spatial dimensions. *Int. J. Eng. Sci.* **2000**, *38*, 1099–1112. [CrossRef]
62. Brand, H.R.; Pleiner, H. Macroscopic dynamics of the ferroelectric smectic A_F phase with $C_{\infty v}$ symmetry. *Eur. Phys. J. E* **2024**, *47*, 10. [CrossRef] [PubMed]
63. Pleiner, H.; Brand, H.R. Macroscopic dynamics of the ferroelectric smectic C_F phase with C_{1h} symmetry. *Phys. Rev. E* **2025**, *112*, 055426. [CrossRef] [PubMed]
64. Brand, H.R.; Pleiner, H. Macroscopic dynamics of the antiferroelectric smectic Z_A phase and its magnetic analog Z_M. *Eur. Phys. J. E* **2025**, *48*, 11. [CrossRef] [PubMed]
65. Brand, H.R.; Pleiner, H. The biaxial nematic—Smectic C_M transition in polymeric liquid crystals. *Macromol. Rapid Commun.* **1991**, *12*, 539.
66. Brand, H.R.; Pleiner, H. Hydrodynamic and electrohydrodynamic properties of the smectic C_M phase in liquid crystals. *J. Phys. II France* **1991**, *1*, 1455–1464. [CrossRef]
67. Brand, H.R.; Cladis, P.E.; Pleiner, H. Symmetry and defects in the C_M phase of polymeric liquid crystals. *Macromolecules* **1992**, *25*, 7223–7226. [CrossRef]
68. Hegmann, T.; Kain, J.; Diele, S.; Pelzl, G.; Tschierske, C. Evidence for the existence of the McMillan phase in a binary system of a metallomesogen and 2,4,7-trinitrofluorenone. *Angew. Chem. Int. Edit.* **2001**, *40*, 887–890. [CrossRef]

69. Randall, C.A.; Fan, Z.; Reaney, I.; Chen, Lo.; Trolier-McKinstry, S. Antiferroelectrics: History, fundamentals, crystal chemistry, crystal structures, size effects, and applications. *J. Am. Ceram. Soc.* **2021**, *104*, 3775–3810. [CrossRef]
70. Cestari, M.; Diez-Berart, S.; Dunmur, D.A.; Ferrarini, A.; Fuente, M.R.d.; Jackson, D.J.B.; Lopez, D.O.; Luckhurst, G.R.; Perez-Jubindo, M.A. Phase behavior and properties of the liquid crystal dimer 1″, 7″-bis (4-cyanobiphenyl-4′-yl) heptane: A twist bend nematic liquid crystal. *Phys. Rev. E* **2011**, *84*, 031704. [CrossRef] [PubMed]
71. Kats, E.I. Emergence of nanoscale modulation in liquid crystals from short-range order parameter condensation. *Liquids* **2026**, *6*, 34. [CrossRef]
72. Xiang, J.; Shiyanovskii, S.V.; Imrie, C.; Lavrentovich, O.D. Electrooptic response of chiral nematic liquid crystals with oblique helicoidal director. *Phys. Rev. Lett.* **2014**, *112*, 217801. [CrossRef]
73. Kumari, P.; Basnet, B.; Lavrentovich, M.O.; Lavrentovich, O.D. Chiral ground state of ferroelectric liquid crystals. *Science* **2024**, *383*, 1364–1368. [CrossRef] [PubMed]
74. Karcz, J. ; Herman, J.; Rychłowicz, N.; Kula, P.; Górecka, E.; Szydlowska, J.; Majewski, P.W.; Pociecha, D. Spontaneous chiral symmetry breaking in polar fluid-heliconical ferroelectric nematic phase. *Science* **2024**, *384*, 1096–1099. [CrossRef] [PubMed]
75. Nishikawa, H.; Okada, D.; Kwaria, D.; Nihonyanagi, A.; Kuwayama, M.; Hoshino, M.; Araoka, F. Emergent ferroelectric nematic and heliconical ferroelectric nematic states in an achiral 'straight' polar rod mesogen. *Adv. Sci.* **2024**, *11*, 2404718. [CrossRef] [PubMed]
76. Nishikawa, H.; Kwaria, D.; Nihonyanagi, A.; Sano, K.; Yoshida, H.; Araoka, F. Electrically tunable heliconical smectic superstructure in polar fluids. *Adv. Mater.* **2026**, *38*, e74025. [CrossRef] [PubMed]
77. Himel, M.S.H.; Dharmarathna, R.; Gleeson, J.T.; Twieg, R.J.; Sprunt, S.; Jákli, A. Selective reflection of chiral ferroelectric nematic liquid crystals tuned by electric field along the helix axis. *Adv. Opt. Mater.* **2026**, *14*, e71279. [CrossRef]
78. Brand, H.R.; Pleiner, H. The influence of chirality on the macroscopic behavior of multiferroic smectic phases. *J. Chem. Phys.* **2026**, *164*, 244902. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.