

Universality of the nematic mesophase

D. S. Simeão and M. Simões*

Departamento de Física, Universidade Estadual de Londrina, Campus Universitário, 86051-990 Londrina, Paraná, Brazil

(Received 18 July 2012; published 2 October 2012)

This paper presents a detailed comparative study of published order-parameter experimental data of nematic liquid crystals. Throughout a simple linear transformation, it is shown that three distinct nematic mesophases exhibit the same and unique universal behavior for all temperatures below the nematic-isotropic phase transition. This paper generalizes a previous one [M. Simes, D. S. Simeo, S. M. Domiciano, and A. de Campos, *Phys. Lett. A* **372**, 5346 (2008)], in which only the nematic mesophase delimited by the crystalline phase at low temperature was studied. Here we have assembled order-parameter experimental data of 61 different compounds, forming a set with data of 96 experiments, aiming to show that the nematic universal behavior is independent of what is the actual phase or mesophase bordering the nematic phase at low temperatures; our results show that all experimental data of all nematic mesophases coalesce along a common line that extends over the entire range of mesophases.

DOI: [10.1103/PhysRevE.86.042701](https://doi.org/10.1103/PhysRevE.86.042701)

PACS number(s): 64.70.mf, 61.30.Gd

I. INTRODUCTION

Liquid crystals (LCs) are complex fluids that present outstanding properties from both scientific and technological points of view [1–8]. Despite their very good experimental description, which is evident from the diversity of devices developed from it, the theoretical description of the observed phenomena presents many challenges [9–16].

Recently, studies have revealed a universal behavior in the nematic mesophase [17–24]. Namely, it has been shown that the experimental data of Miesowicz’s viscosity coefficients [17–19], elastics constants [20], and order parameter [21–24] can be disposed along universal curves that cover the entire range of the mesophase. Nevertheless, these studies have been restricted to one type of nematic mesophase—that delimited by a crystalline K phase at low temperature and an isotropic I phase at high temperature. Our aim here is to extend these studies to nematic liquid crystals (NLCs) presenting other phase diagrams and show that the global universal behavior of the nematic order parameter does not depend on the nature of the phase transition bordering the nematic mesophase at low temperature.

This paper is organized as follows. First we will present the approach used to observe the universalities. Then we will show the results obtained with the data analysis of different NLCs and different nematic mesophases.

II. NEMATIC TEMPERATURE SCALE

The nematic mesophases’ universalities have been studied by Simões and co-workers over the past eleven years [17–23]. The approach used to capture these universalities consists of a linear rescaling procedure with two steps: First, they defined a different temperature scale, called the nematic temperature scale t_N , and second, they normalized the data at a common temperature point in this alternative scale. The main result obtained is that the nematic mesophase, delimited by the crystalline to nematic KN and nematic to isotropic NI phase transitions, presents a universal behavior that covers its entire temperature domain. To extend this result to other mesophases

we will generalize t_N , assuming that

$$t_N = \frac{T - T_{LT}}{T_{NI} - T_{LT}}, \quad (1)$$

where T_{LT} represents the temperature of the phase transition delimiting N at low temperature, which can be $T_{LT} \equiv T_{KN}$ for KN , $T_{LT} \equiv T_{NS_A}$ for nematic to smectic- A (NS_A), and $T_{LT} \equiv T_{NS_C}$ for nematic to smectic- C (NS_C) phase transitions. All the compounds studied present a NI phase transition at high temperature T_{NI} .

III. EXPERIMENTAL VERIFICATION OF THE UNIVERSALITIES

All the experimental data studied here have been obtained from the LC literature. We have collected data of mass magnetic susceptibility anisotropy $\Delta\chi_M$, volume magnetic susceptibility anisotropy $\Delta\chi_V$, electric permittivity anisotropy $\Delta\epsilon$, and birefringence Δn , which are commonly used as measures of the nematic order parameter. The scientific names and abbreviations of the compounds studied and the references from which these data were collected are organized in Tables I–VII in the Appendix.

Figure 1 shows the result obtained when one considers the data of $\Delta\chi_M$ and $\Delta\epsilon$; Fig. 2 shows the results obtained with the data of Δn and $\Delta\chi_V$. They show the global universal behavior of the order parameter of the nematic mesophase delimited by the KN and NI phase transitions; in them we have a total of 78 data sets: 34 different compounds in Fig. 1 and 35 in Fig. 2. There are 5 data sets presenting some visible deviation from the mean curves. This can be explained by the errors on the experimental measurements and on the values of the parameters used to define t_N . An example is the LC-KN3 compound; in Fig. 1 its data agree very well with the other curves, whereas in Fig. 2 the data do not.

The main message of these figures is already known: The order parameter of that nematic mesophase presents a global universal behavior [17–24]. The difference appears in Figs. 3 and 4: The global universal behavior of the nematic mesophases does not depend on the phase or mesophase bordering them at low temperature, with the resulting universal curve being the same for all. Figure 3 presents the $\Delta\chi_M$ data of 30 NLCs: 22 of them present the K phase delimiting N , 5 present the smectic- A (S_A) mesophase, and 3 present the smectic- C (S_C)

*simoes@uel.br

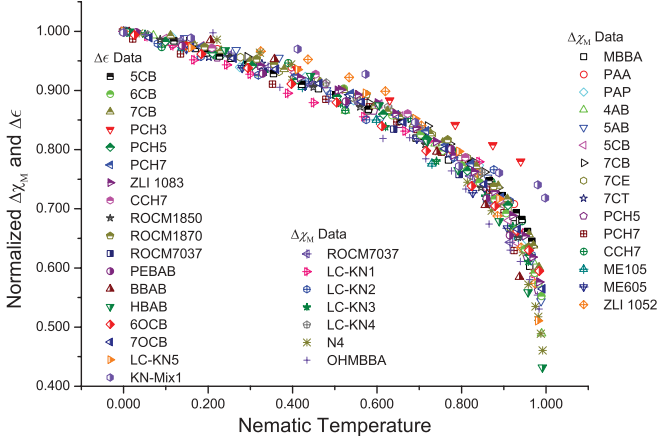


FIG. 1. (Color online) Global universal behavior of the NLCs' order parameters. We have put together 22 data sets of mass magnetic susceptibility anisotropy $\Delta\chi_M$ and 18 data sets of electric permittivity anisotropy $\Delta\epsilon$, all presenting a KN phase transition. Compounds names, phase-transition temperatures, and references are given at Tables I–III.

mesophase, corresponding to NLCs or nematic mesophases of types 1, 2, and 3, respectively. Figure 4 presents the Δn data of 34 NLCs: 24 of type 1, 7 of type 2, and 3 of type 3.

Before ending this section, let us observe that in works Rananavare *et al.* [25], Freed *et al.* [26], and Potukuchi *et al.* [27] obtained results that resemble the ones shown here. They studied the order parameter of several compounds and mixtures of the $n.O.m$ [4- n -(n alkoxy)benzylidene-4'- n -(m alkyl)aniline] homologous series, all being NLCs of type 2. By using a temperature scale similar to t_N (t_N^U), they showed that the electron spin resonance data of 14 mixtures [25] and 12 pure compounds [26] present a global universal behavior. Potukuchi *et al.* [27] obtained the same result with 11 mixtures of 4.O.6 and 6.O.4 using measurements of $\Delta\epsilon$. According to them, the universality observed follows from the fact that the order parameter S of these NLCs has a constant value at the phase transitions bordering the nematic mesophase. To ensure the constancy of S , in the case of a first-order

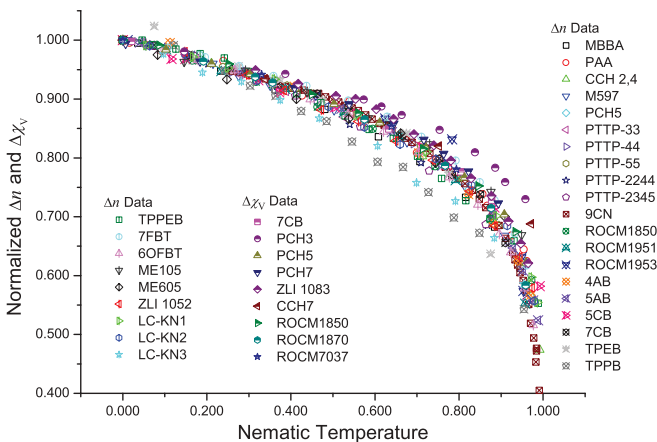


FIG. 2. (Color online) Global universal behavior of the NLCs' order parameters. This result is obtained using 29 birefringence Δn data sets and 9 volume susceptibility anisotropies $\Delta\chi_V$, all presenting a KN phase transition. Compounds names, phase-transition temperatures, and references are given at Tables I, IV, and V.

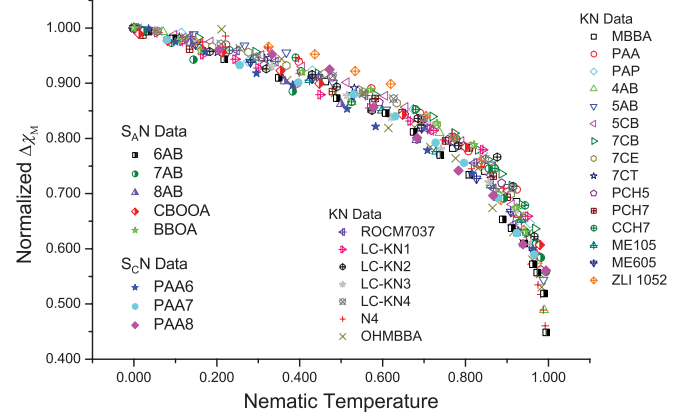


FIG. 3. (Color online) Global universal behavior of the nematic mesophases. Here we put together $\Delta\chi_M$ data sets of 30 distinct compounds pertaining to 3 different nematic mesophases: 22 of them present the KN phase transition at low temperature, 5 present the NS_A phase transition, and 3 present the NS_C phase transition, corresponding to mesophases of types 1, 2, and 3, respectively. Compounds names, phase-transition temperatures, and references are given in Tables I, II, and VI.

NS_A transition, they used an extrapolated temperature $T_{NS_A}^*$ to define t_N^U . The constancy of S should play the role of our normalization of the data at the transition. In this case we note that the relationship between t_N^U and t_N is $t_N^U = 1 - t_N$. Thus, despite their completely different interpretation of the results, the global universalities obtained by these researchers are an independent verification of the ideas discussed here and increase the number of classical nematic mesophases for which the universalities has been verified.

IV. CONCLUSION

In this paper we have assembled a total of 96 experimental data sets of physical quantities from which the nematic order parameter can be measured to show a universal behavior that

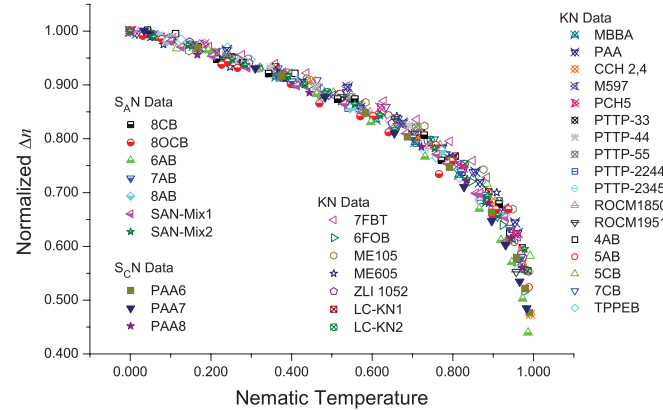


FIG. 4. (Color online) Global universal behavior of the nematic mesophases. This result is obtained by using Δn data of 34 compounds; 24 from the nematic mesophase of type 1, 7 of type 2, and 3 of type 3. Not all Δn data shown in Fig. 2 have been used because the main objective is to show the agreement between the curves of the distinct mesophases. Compounds names, phase-transition temperatures, and references are given at Tables I, IV, and VII.

does not depend on the nematic mesophase. All compounds present a NI phase transition at high temperature; it is the low-temperature phase transition that differentiates them. Among the data sets that we have gathered, 78 present the crystalline-nematic phase transition at low temperature, 12 present the nematic–smectic- A phase transition, and 6 present the nematic–smectic- C phase transition. Figures 3 and 4 present the main result of this paper: The order parameters of these three distinct mesophases have the same global universal behavior.

In a recent paper [10] we studied the order-parameter curve and showed that it presents a power-law behavior characterized

by a single exponent β equal to $1/4$. Of course, all data points considered in this paper are embraced by that analysis and would follow the same laws.

In conclusion, there is strong evidence suggesting the existence of others liquid crystalline phases presenting universalities similar to the ones shown here. For example, Rananavare *et al.* [25] showed that the order parameter of their 14 mixtures presents a unique curve along the entire range of the smectic- A phase: from the nematic–smectic- A phase transition to the smectic- A –smectic- B phase transition. The observation of global universalities in other liquid crystalline phases is stimulating and is a subject for future investigation.

TABLE I. Abbreviation and scientific names of the NLC compounds studied.

Abbreviation	Scientific name
<i>m</i> CB	4- <i>n</i> -(<i>m</i> alkyl)-4'-cyanobiphenyl
<i>m</i> OCB	4- <i>n</i> -(<i>m</i> alkoxy)-4'-cyanobiphenyl
PAA <i>m</i>	4-4'-di-(<i>m</i> alkoxy)azoxybenzene (PAA <i>m</i> = 1, PAP <i>m</i> = 2)
<i>m</i> AB	4-4'-di- <i>n</i> -(<i>m</i> alkyl)azoxybenzene
PCH <i>m</i>	4-cyano-4'- <i>n</i> -(<i>m</i> alkyl)-cyclohexanephenyl
PTTP- <i>mm</i>	4,4'-di- <i>n</i> -(<i>m</i> alkyl)diphenyldiacetylene
MBBA	4-methoxybenzylidene-4'- <i>n</i> -butylaniline
7CT	4- <i>n</i> -heptyl-4'-cyanotolane
CCH7	4'- <i>n</i> -heptyl-bicyclohexyl-4-carbonitrile
ME105	4-methoxy-benzoic acid 4'- <i>n</i> -pentyl-phenyl ester
ME605	4- <i>n</i> -hexyloxy-benzoic acid 4'- <i>n</i> -pentyl-phenyl ester
ZLI 1052	mixture from Merck
ROCM7037	4-(5-heptyl-pyrimidin-2-yl)-benzonitrile
LC-KN1	4-cyano-thiobenzoic acid <i>S</i> -(4'- <i>n</i> -pentyl-phenyl) ester
LC-KN2	4- <i>n</i> -pentyl-thiobenzoic acid <i>S</i> -(4'-cyano-phenyl) ester
LC-KN3	4- <i>n</i> -pentyl-benzoic acid 4'- <i>n</i> -hexyloxy-phenyl ester
LC-KN4	4- <i>n</i> -heptyl-thiobenzoic acid <i>S</i> -(4'-cyano-phenyl) ester
LC-KN5	4-octanoic acid benzylidene-4'-aminobenzonitrile
N4	4-methoxy-4'- <i>n</i> -butylazoxybenzene (mix of two components)
OHMBBA	2-hydroxy-4-methoxybenzylidene-4-butylaniline
7CE	4- <i>n</i> -heptyl-benzoic acid 4'-cyano-phenyl
ZLI 1083	mixture from Merck
ROCM1850	4-pentyl-cyclohexanecarboxylic acid 4'-cyano-phenyl ester
ROCM1870	4-heptyl-cyclohexanecarboxylic acid 4'-cyano-phenyl ester
PEBAB	4- <i>n</i> -ethoxybenzylidene-4'-aminobenzonitrile
BBAB	4- <i>n</i> -butoxybenzylidene 4'-aminobenzonitrile
HBAB	4- <i>n</i> -hexyloxybenzylidene 4'-aminobenzonitrile
KN-Mix1	mixture defined in Ref. [28]
CCH 2,4	mixture defined in Ref. [29]
M597	mixture defined in Ref. [29]
PTTP-2244	mixture defined in Ref. [30]
PTTP-2345	mixture defined in Ref. [30]
9CN	4- <i>n</i> -nonylbenzoate 4'-cyano-phenyl
ROCM1951	4-pentyl-cyclohexanecarboxylic acid 4-methoxy-phenyl ester
ROCM1953	4-pentyl-cyclohexanecarboxylic acid 4-propoxy-phenyl ester
TPEB	trans-4-propyl cyclohexy-4 (trans-4-ethyl cyclohexyl) benzoate
TPPB	trans-4-propyl cyclohexy-4 (trans-4-propyl cyclohexyl) benzoate
TPPEB	trans-4-propyl cyclohexy-4 (trans-4-pentyl cyclohexyl) benzoate
7FBT	4'-heptyl-3-fluoro-4 isothiocyantotolane
6OFBT	4'-hexyloxy-3-fluoro-4 isothiocyantotolane
CBOOA	4- <i>n</i> -cyanobenzylidene-4-octylaniline
BBOA	4- <i>n</i> -butyloxybenzylidene-4'- <i>n</i> -octylaniline
SAN-Mix1	mixture defined in Ref. [31]
SAN-Mix2	mixture defined in Ref. [31]

TABLE II. Phase-transition temperatures and references for the data shown in Figs. 1 and 3.

NLC	T_{KN} (°C)	T_{NI} (°C)	Reference
MBBA	19	45	[32]
PAA	118.2	135.3	[32,33]
PAP	136.8	168.4	[34,35]
4AB	22	31.9	[34,36]
5AB	24	67.5	[34,36]
5CB	24	35.3	[29,37]
7CB	28.5	42	[37,38]
7CE	44	56.5	[37,39]
7CT	58.5	67.5	[37,40]
PCH5	30	55	[37,41]
PCH7	30	59	[37,42]
CCH7	71	83	[37,43]
ME105	29.0	42.7	[44,45]
ME605	50.0	62.1	[44,46]
ZLI 1052	15.0	48.9	[44,47]
ROCM7037	45	51	[37,48]
LC-KN1	66.0	102.0	[44]
LC-KN2	75.5	99	[44]
LC-KN3	40.9	62.5	[44,49]
LC-KN4	82	92.4	[37,50]
N4	17.9	74.9	[34,37]
OHMBBA	44	64.6	[51]

ACKNOWLEDGMENTS

We are grateful to the Brazilian Agencies Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Fundação Araucária (Paraná), Conselho Nacional de Desenvolvimento Científico e Tecnológico (Ministério da Ciência e Tecnologia), Instituto Nacional de Ciência e Tecnologia de Fluidos Complexos for financial support.

TABLE III. Phase-transition temperatures and references for the data shown in Fig. 1.

NLC	T_{KN} (°C)	T_{NI} (°C)	Reference
5CB	22.5	35	[52]
6CB	13.5	29	[52]
7CB	28.5	42	[52]
PCH3	36	46.2	[53,54]
PCH5	30	54.4	[41,53]
PCH7	30	58	[42,55]
ZLI 1083	-3	51.9	[53,56]
CCH7	71	84.1	[43,55]
ROCM1850	47	79	[55,57]
ROCM1870	55.1 ^a	81	[55]
ROCM7037	45	51.3	[48,55]
PEBAB	105.5	128.9	[28]
BBAB	62.9	110.5	[28]
HBAB	54.5	100.9	[28]
6OCB	57	75.8	[58,59]
7OCB	53.5	73.5	[58,59]
LC-KN5	53.7	97.6	[28]
KN-Mix1	18	96.8	[28]

^aLowest temperature in the nematic phase at which the data have been measured.

TABLE IV. Phase-transition temperatures and references for the data shown in Figs. 2 and 4.

NLC	T_{KN} (°C)	T_{NI} (°C)	Reference
MBBA	21	46.25	[60,61]
PAA	110	135	[32,62]
CCH 2,4	34	64	[29]
M597	65	114.4	[29]
PCH5	30	55.2	[29]
PTTP-33	107.5	131.9	[63]
PTTP-44	75.1	101.0	[64]
PTTP-55	86.0	111.3	[63]
PTTP-2244	55.0	98.5	[64]
PTTP-2345	40.0	105.0	[64]
9CN	27.8	59.3	[65]
ROCM1850	47.0	77.7	[66]
ROCM1951	40.7	71.1	[66]
ROCM1953	43.3	71.1	[66]
4AB	15	31.9	[40,62]
5AB	25.8	67.5	[40,62]
5CB	22.4	34.5	[38]
7CB	28.5	41.9	[38]
TPEB	94.0	134.0	[67]
TPPB	92.0	158.0	[67]
TPPEB	67.0	154.0	[67]
7FBT	26.6	43.6	[68]
6OFBT	32.5 ^a	70.7	[68]
ME105	29.0	42.7	[45,69]
ME605	50.0	62.1	[46,69]
ZLI 1052	15.0	48.9	[47,69]
LC-KN1	66.0	102.0	[69]
LC-KN2	75.5	99	[69]
LC-KN3	40.9	62.5	[49,69]

^aLowest temperature in the nematic phase at which the data have been measured.

APPENDIX

In this appendix Tables I–VII give information about the experimental data: the scientific names and abbreviations of the compounds studied and the references from which the data were collected.

TABLE V. Phase-transition temperatures and references for the data shown in Fig. 2.

NLC	T_{KN} (°C)	T_{NI} (°C)	Reference
7CB	29.7	42.6	[40,55]
PCH3	36	46.2	[43,70]
PCH5	30	54.4	[41,53]
PCH7	30	58	[42,55]
ZLI 1083	-3	51.9	[53,56]
CCH7	71	83.3	[43,53]
ROCM1850	47	79	[55,57]
ROCM1870	55.1 ^a	81	[55]
ROCM7037	45	51.3	[48,55]

^aLowest temperature in the nematic phase at which the data have been measured.

TABLE VI. Phase-transition temperatures and references for the data shown in Fig. 3.

NLC	T_{NSA} (°C)	T_{NI} (°C)	Reference
6AB	17	54.2	[34]
7AB	53.9	70.6	[34]
8AB	64.5	66.7	[34]
CBOOA	82.5	108.5	[71]
BBOA	62.7	77.8	[71]
NLC	T_{NSC} (°C)	T_{NI} (°C)	Reference
PAA6	81	129	[34,72]
PAA7	95	124	[34,72]
PAA8	108	126	[34,72]

TABLE VII. Phase-transition temperatures and references for the data shown in Fig. 4.

NLC	T_{NSA} (°C)	T_{NI} (°C)	Reference
8CB	33.5	40.5	[38,73]
8OCB	66.9	79.7	[31]
6AB	17	54.2	[34,62]
7AB	53.9	70.6	[34,62]
8AB	64.5	66.7	[34,62]
SAN-Mix1	45.7	65.3	[31]
SAN-Mix2	29.2	56.5	[31]
NLC	T_{NSC} (°C)	T_{NI} (°C)	Reference
PAA6	81	129	[62,72]
PAA7	95	124	[62,72]
PAA8	108	126	[62,72]

- [1] D. K. Yang and S.-T. Wu, *Fundamentals of Liquid Crystal Devices* (Wiley, New York, 2006).
- [2] G. T. Stewart, *Liq. Cryst.* **30**, 541 (2003); **31**, 443 (2004).
- [3] C. J. Pethick and A. Y. Potekhin, *Phys. Lett. B* **427**, 7 (1998).
- [4] M. Simões and M. Pazetti, *Europhys. Lett.* **92**, 14001 (2010).
- [5] T. Kibble, *Phys. Today* **60** (9), 47 (2007).
- [6] P. Palfy-Muhoray, *Phys. Today* **60** (9), 54 (2007).
- [7] P. G. de Gennes and J. Prost, *The Physics of Liquid Crystals*, 2nd ed. (Clarendon, Oxford, 1993).
- [8] W. Maier and A. Saupe, *Z. Naturforsch. Teil A* **13**, 564 (1958); **14**, 882 (1959); **15**, 287 (1960).
- [9] M. Simões, K. E. Yamaguti, and D. S. Simeão (unpublished).
- [10] M. Simões, D. S. Simeão, and K. E. Yamaguti, *Liq. Cryst.* **38**, 935 (2011).
- [11] I. Chirtoc, M. Chirtoc, C. Glorieux, and J. Thoen, *Liq. Cryst.* **31**, 229 (2004).
- [12] P. K. Mukherjee, *J. Phys.: Condens. Matter* **10**, 9191 (1998).
- [13] P. E. Cladis, in *Handbook of Liquid Crystals*, edited by D. Demus, J. Goodby, G. W. Gray, H.-W. Spiess, and V. Vill (Wiley-VCH, New York, 1998), Vol. 1.
- [14] Z. H. Wang and P. H. Keyes, *Phys. Rev. E* **54**, 5249 (1996).
- [15] C. Rosenblatt, *Phys. Rev. A* **27**, 1234 (1983).
- [16] P. H. Keyes and J. R. Shane, *Phys. Rev. Lett.* **42**, 722 (1979).
- [17] M. Simões and S. M. Domiciano, *Phys. Rev. E* **68**, 011705 (2003).
- [18] M. Simões and S. M. Domiciano, *Phys. Rev. E* **66**, 061703 (2002).
- [19] M. Simões and S. M. Domiciano, *Mol. Cryst. Liq. Cryst.* **367**, 1 (2001).
- [20] M. Simões and D. S. Simeão, *Phys. Rev. E* **73**, 062702 (2006).
- [21] M. Simões, D. S. Simeão, S. M. Domiciano, and A. de Campos, *Phys. Lett. A* **372**, 5346 (2008).
- [22] M. Simões, D. S. Simeão, A. de Campos A, and A. J. Palangana, *Philos. Mag.* **87**, 5237 (2007).
- [23] M. Simões and D. S. Simeão, *Phys. Rev. E* **74**, 051701 (2006).
- [24] I. Zgura, R. Moldovan, T. Beica, and S. Frunza, *Cryst. Res. Technol.* **44**, 883 (2009).
- [25] S. B. Rananvare, V. G. K. M. Pisipati, and J. H. Freed, *Chem. Phys. Lett.* **140**, 255 (1987).
- [26] J. H. Freed, A. Nayeem, and S. B. Rananvare, in *The Molecular Dynamics of Liquid Crystals*, edited by G. R. Luckhurst and C. A. Veracini (Kluwer, Dordrecht, 1989), Chap. 13.
- [27] D. M. Potukuchi, N. V. S. Rao, and V. G. K. M. Pisipati, *J. Mol. Liq.* **50**, 1 (1991).
- [28] M. Schadt, *J. Chem. Phys.* **56**, 1494 (1972).
- [29] S.-T. Wu and C.-S. Wu, *Phys. Rev. A* **42**, 2219 (1990).
- [30] S.-T. Wu, H.-H. B. Meng, and L. R. Dalto, *J. Appl. Phys.* **70**, 3013 (1991).
- [31] P. P. Karat and N. V. Madhusudana, *Mol. Cryst. Liq. Cryst.* **47**, 21 (1978).
- [32] W. H. de Jeu, W. A. P. Claassen, and A. M. J. Spruijt, *Mol. Cryst. Liq. Cryst.* **37**, 269 (1976).
- [33] H. Arnold, *Z. Phys. Chem. (Leipzig)* **226**, 146 (1964).
- [34] W. H. de Jeu and A. P. Claassen, *J. Chem. Phys.* **68**, 102 (1978).
- [35] M. E. Neubert, P. Norton, and D. L. Fishel, *Mol. Cryst. Liq. Cryst.* **31**, 253 (1975).
- [36] J. van der Veen, W. H. de Jeu, M. W. M. Wanninkhof, and C. A. M. Tienhoven, *J. Chem. Phys.* **77**, 2153 (1973).
- [37] A. Buka and W. H. de Jeu, *J. Phys. France* **43**, 361 (1982).
- [38] P. P. Karat and N. V. Madhusudana, *Mol. Cryst. Liq. Cryst.* **36**, 51 (1976).
- [39] L. A. Karamysheva, E. I. Kovshev, and M. I. Barnik, *Mol. Cryst. Liq. Cryst.* **37**, 29 (1976).
- [40] W. W. Beens and W. H. de Jeu, *J. Chem. Phys.* **82**, 3841 (1985).
- [41] T. Szczucinski and R. Dabrowski, *Mol. Cryst. Liq. Cryst.* **88**, 55 (1982).
- [42] L. Pohl, R. Eidenschink, J. Krause, and D. Erdmann, *Phys. Lett.* **60A**, 421 (1977).
- [43] R. Eidenschink, D. Erdmann, J. Krause, and L. Pohl, *Angew. Chem.* **90**, 133 (1978).
- [44] I. H. Ibrahim and W. Haase, *J. Phys. (Paris) Colloq.* **40**, C3-164 (1979).
- [45] J. R. Lalanne, B. Martin, B. Pouligny, and S. Kielich, *Mol. Cryst. Liq. Cryst.* **42**, 153 (1977).
- [46] Merck GmbH (R. Steinsträßer), German Patent No. 2,139,628 (22 February 1973).
- [47] J. M. G. Cowie and D. M. Duncan, *Polym. Adv. Technol.* **12**, 506 (2001).

- [48] A. Boller, M. Cereghetti, M. Schadt, and H. Scherrer, *Mol. Cryst. Liq. Cryst.* **42**, 215 (1977).
- [49] J. D. Margerum, J. E. Jensen, and A. M. Lackner, *Mol. Cryst. Liq. Cryst.* **68**, 137 (1981).
- [50] J. Krause and L. Pohl, German Patent No. 2,603,293 (11 August 1977).
- [51] F. Leenhouts, W. H. de Jeu, and A. J. Dekker, *J. Phys. (Paris)* **40**, 989 (1979).
- [52] B. R. Ratna and R. Shashidhar, *Pramana* **6**, 278 (1976).
- [53] Hp. Schad, G. Baur, and G. Meier, *J. Chem. Phys.* **71**, 3174 (1979).
- [54] R. Eidenschink, D. Erdmann, J. Krause, and L. Pohl, *Angew. Chem.* **89**, 103 (1977).
- [55] Hp. Schad and M. A. Osman, *J. Chem. Phys.* **75**, 880 (1981).
- [56] P. Diot, J. K. Foitzik, and W. Haase, *Rev. Phys. Appl.* **20**, 121 (1985).
- [57] Hoffmann-La Roche, Product Information, 1988 (unpublished).
- [58] S. J. Rzoska, J. Ziolo, W. Sułkowski, J. Jadżyn, and G. Czechowski, *Phys. Rev. E* **64**, 052701 (2001).
- [59] G. W. Gray, K. J. Harrison, and J. A. Nash, *Pramana Suppl.* **1**, 381 (1975).
- [60] S. Jen, N. A. Clark, P. S. Pershan, and E. B. Priestley, *J. Chem. Phys.* **66**, 4635 (1977).
- [61] R. E. Rondeau, M. A. Berwick, R. N. Steppel, and M. P. Serve, *J. Am. Chem. Soc.* **94**, 1096 (1972).
- [62] W. H. de Jeu and P. Bordewijk, *J. Chem. Phys.* **68**, 109 (1978).
- [63] S.-T. Wu, U. Finkenzeller, and V. Reiffenrath, *J. Appl. Phys.* **65**, 4372 (1989).
- [64] S.-T. Wu, H.-H. B. Meng, and L. R. Dalton, *J. Appl. Phys.* **70**, 3013 (1991).
- [65] A. Prasad and M. K. Das, *J. Phys.: Condens. Matter* **22**, 195106 (2010).
- [66] M. Mitra, S. Paul, and R. Paul, *Pramana J. Phys.* **29**, 409 (1987).
- [67] Srinivasa, M. M. M. Abdoh, N. C. Shivaprakash, and J. S. Prasad, *Pramana* **19**, 349 (1982).
- [68] M. S. Zakerhamidi, Z. Ebrahimi, H. Tajalli, A. Ghanadzadeh, M. Moghadam, and A. Ranjkesh, *J. Mol. Liq.* **157**, 119 (2010).
- [69] I. H. Ibrahim and W. Haase, *J. Phys. France* **40**, 191 (1979).
- [70] Hp. Schad, G. Baur, and G. Meier, *J. Chem. Phys.* **70**, 2770 (1979).
- [71] F. Hardouin, H. Gasparoux, and P. Delhaes, *J. Phys. (Paris) Colloq.* **36**, C1-127 (1975).
- [72] W. Urbach, H. Helvet, and F. Rondelez, *J. Chem. Phys.* **78**, 5113 (1983).
- [73] BDH, Product Information, 1986 (unpublished).