Novel Cholesteric Phase in Dispersions of Nucleic Acids due to Polymeric Chelate Bridges

V.L. GOLO¹, E.I. KATS^{2†}, YU.S. VOLKOV¹, V.I. SALYANOV³ and
YU.M. YEVDOKIMOV³

¹*Department of Mechanics and Mathematics, Moscow University, Moscow 119899, Russia*

²*Institute Laue – Langevin, BP – 156, Grenoble, Cedex – 9, France*

³*Institute of Molecular Biology, Russian Academy of Sciences, Moscow, Russia*

Abstract. We consider cholesteric liquid-crystalline DNA dispersions, and show that polymeric (Dau-Cu) complexes, the so-called bridges, between pairs of DNA molecules may generate a super liquid-crystalline structure (BR-phase), characterized by a soliton lattice of the spatial distribution of the order parameter. The BR-phase could have a layered spatial structure and an abnormal optical activity that could have a bearing upon the intense CD-band observed in DNA-dispersions.

Key words: dichroism, DNA, liquid crystal

1. Introduction

The liquid crystalline order of DNA dispersions is an important phenomenon to a wide range of relevant biological processes. Besides it has an fundamental physical interest (see e.g. the review article [1] and references herein). The existence of the liquid-crystalline (LC)-phases of DNA molecules complexed with antibiotics of the anthracycline family opened a new avenue to studying both DNA and solvents. In this respect the circular dichroism (CD)-experiments [2–4] using daunomycin (Dau) are very interesting, owing to the (dau-DNA) complexes having very specific structural properties and optical activity. It is alleged [5–6], that Dau-molecules may intercalate between base pairs of the double-stranded DNA fixed in liquid-crystalline dispersion, forming the so-called intercalation complex (I), and generate an additional set of chromophores contained in a DNA-molecule, that is besides the original ones due to nitrogen bases absorbing in the UV region of 270 nm, there emerge chromophores, belonging to Dau-molecules, that absorb in the region of 500 nm (see [5, 7–8], for the detailed analysis of optical phenomenon involved). As the concentration of daunomycin increases, the intensity of the CD-band at 500 nm rises, until it reaches a saturation point. According to [6] the saturation of the CD-intensity corresponds to the ratio of one Dau molecule per five base pairs, see Figure 1. Further adding the daunomycin results only in a larger number of

[†]Also Landau Institute for Theoretical Physics, Moscow, Russia

Figure 1. Schematical structure of DAU-DNA complexes with intercalated and free DAU molecules.

Dau molecules that are not attached to DNA molecules. These free Dau molecules do not produce a coherent effect as regards the CD absorption, and therefore do not have a bearing upon the CD intensity, in agreement with the saturation effect mentioned above. It is worth noting that one can change the sign of both CD bands [10], at 270 nm and 500 nm by increasing the concentration of Dau above a certain point. Since the sign of CD band corresponds to the sense of the helical twist, i.e. the left/right one for the negative/positive band, respectively, one may conclude that Dau molecules generate a structural transition of the cholesteric DNA phase.

The conformation of (DNA-Dau) complex is substantially modified, if the dispersion is treated with CuCl_2 , and therefore copper ions, Cu^{2+} , are added in the system. Then according to the X-ray analysis [6], the Dau-saturation discussed above having been reached, there appear Dau-molecules, *adsorbed* at the surfaces of the DNA-double helices fixed in the cholesteric phase, the so-called external complex II, see Figure 2. If the concentration of Cu^{2+} is large enough, they result in the formation of chelate complexes. In the case the chelate complexes are properly located with respect to the double helices of adjacent DNA molecules, there arise certain planar structures, or bridges, that cross-link pairs of adjacent DNA-molecules [6], see Figures 1–3 [9–12]. It is generally accepted that the bridges have the form of polymeric chelate complexes.

Figure 2. Schematic view of external complexes and chelate bridge formation.

Figure 3. A bridge cross-linking adjacent DNA molecules.

The amplitude of CD-bands increases tens times after the Dau- and the copper concentrations having reached threshold values [3], see Figure 4. Here it should be noted that for one thing isolated Dau-molecules, as well as other isotropic aggregates, are not sufficient to produce an abnormal optical activity, and for another there are relatively few Dau-molecules that are properly oriented so as to form chelate bridges. Thus, even though according to the arguments given above, the thresholds could correspond to the formation of the chelate bridges, the total effect due to Dau-molecules and their chelate complexes considered separately could be too small.

Figure 4. CD intensity (in arbitrary units) as a function of DAU (axis 1) and Cu^{2+} ions (axis 2) concentrations.

Therefore, it is reasonable to suggest that the observed increase in the CD-bands be due to a cooperative effect related to chelate bridges, and one should look for it in their spatial organization. Even though the anisotropy of the chelate bridges is small, they could acquire an orientational ordering while serving as a kind of linker between DNA-molecules. Thus, we may suggest that cholesteric dispersions of DNA doped with Cu^{2+} could be visualized as two LC systems in interaction; the DNA molecules forming the dominant part of them.

2. Double Cholesterical Phase

In what follows we shall not take into account the influence of ambient solvent on DNA molecules and polymeric chelate bridges. We may cast the arguments given in the Introduction in a more quantitative form by employing the familiar macroscopic formalism of the order parameter and assign a unit vector $\mathbf{n}$ to the cholesteric phase formed by the DNA-molecules, and a unit vector $\mathbf{v}$ to the bridges. From a general macroscopic point of view as the order parameter for the system as a whole one can use a 2-rank symmetric tensor, describing spontaneous breaking of $O(3)$ rotational symmetry. In our case we have two specific directions ($\mathbf{n}$ and $\mathbf{v}$) and therefore the order parameter has biaxial symmetry, and such a tensor is actually defined by five quantities: two scalar order parameters and three independent angles characterizing mutual orientations of $\mathbf{n}$ and $\mathbf{v}$. In this paper we will not discuss phase transitions and critical phenomena, assuming that the system under consideration is far from any phase transition point. In this case only part of degrees of freedom associated with the order parameter, so-called the degeneracy parameter (in our case $\mathbf{n}$, $\mathbf{v}$) has to be taken into account at macroscopic consideration.

Initially, we do not make any assumption about their forming a nematic or cholesteric phase; their orientational ordering is to a large extent determined by the molecules of DNA. Therefore, we assume that the free energy of the compound system formed by DNA and bridges, should contain an interaction term given by the following equation

$$F_I = \int d^3\mathbf{r} \lambda (\mathbf{v} \cdot \text{rot } \mathbf{n})^2 \quad (2)$$

in which the real unit vectors $\mathbf{n}$, $\mathbf{v}$ are the order parameters for the DNA and the bridges, respectively. It is important that the expression given above is the simplest one for the interaction energy that takes into account the cholesteric twist of the phase due to DNA-molecules, and its possible interaction with bridges.^{††} Next, we may write down the part of the free energy related to the DNA-molecules considered as a separate system, and since we aim at deriving only a qualitative model, we may employ one dimensional approximation and write

$$F_{DNA} = \int_0^L \frac{k_{22}}{2} (\mathbf{n} \cdot \text{rot } \mathbf{n} - \mathbf{q}_0)^2 dz, \quad (3)$$

That is the usual form accommodating the cholesteric twist [13–14]. Here k_{22} is the so-called twist modulus of a liquid crystal, and L is the sample size in the direction of the cholesteric axis z (we assume the system being homogeneous in the orthogonal plane $x - y$).

In the expression for the energy given by Eq. (3) we have kept only the term corresponding to the twist deformation of cholesterics, and neglected the two other types of deformation, generally considered in liquid crystals, that is the splay and the bend described by the expressions

$$k_{11}(\text{div } \mathbf{n})^2, k_{33}[(\mathbf{n} \nabla) \mathbf{n}]^2$$

Our choice relies on the fact [13–14] that there is the relation between elastic moduli that read

$$k_{11} > k_{33} > k_{22}$$

in case the length of molecules L_f constituting the liquid crystal, is large enough. It is worth noting the DNA-dispersion verifies the requirement of large L_f , and according to the paper [15] the module k_{11} diverges as $L_f \rightarrow \infty$. Therefore, the splay and bend deformations are to a large extent suppressed, if the constituent molecules are long enough, so that we may confine ourselves only to the twist energy as regards Eq. (3).

Again employing the most simple terms, we assume that the bridges have only the orientational energy, proper, the cholesteric effects being due to their interaction with the DNA-molecules, and write

^{††} For the ideal cholesteric structure for $\mathbf{n}$ (2) is equivalent to the standard (see e.g. [13–14]) contribution into liquid crystal energy in an external field.

Figure 5. Geometrical illustration that for fixed l (the length of the bridges) and d (the distance between two DNA planes Π_1 and Π_2) the angle θ (see (7)) should be also fixed.

$$F_{Br} = \int_0^L \frac{\mu}{2} \left(\frac{d}{dz} \mathbf{v} \right)^2 dz \quad (4)$$

i.e. we use one constant approximation for Frank elastic moduli related to bridge orientational order e.e. $\mu_{11} = \mu_{22} = \mu_{33} \equiv \mu$, for the length of the bridges l much smaller than the length of a DNA molecule L_f (see [13–14]). On combining equations (2), (3), and (4), we obtain the equation for the free energy of the whole system

$$F = \int_0^L \left[\frac{k_{22}}{2} (\mathbf{n} \cdot \text{rot} \mathbf{n} - q_0)^2 + \frac{\mu}{2} \left(\frac{d}{dz} \mathbf{v} \right)^2 + \lambda (\mathbf{v} \cdot \text{rot} \mathbf{n})^2 \right] dz \quad (5)$$

in which the z -axis is assumed to be the helical one of the DNA-cholesteric, so that the vector $\mathbf{n}$ can be cast in the form

$$\mathbf{n} = (\cos \phi, \sin \phi, 0) \quad (6)$$

in which the polar angle ϕ is a function of z and

$$\frac{d\phi}{dz}$$

describes cholesteric twist. The vector $\mathbf{v}$ reads

$$\mathbf{v} = (\sin \theta \cos \psi, \sin \theta \sin \psi, \cos \theta) \quad (7)$$

The angle θ is, to a certain extent, a common characteristic of the position of adjacent DNA-molecules and chelate bridges linking them. In fact, let us consider two molecules of DNA which we may visualize as two skew straight lines, Λ_1 and Λ_2 , at a distance d from each other, d being equal to the distance between two parallel planes, $\Pi_{1,2}$, that contain the lines $\nabla_{1,2}$, respectively, see Figure 5. If the length of a bridge, l , and the distance d are fixed, the angle θ is fixed as well. In real

life, there are fluctuations of the positions of the planes $\Pi_{1,2}$ that produce a change in d . Also, the length of bridges may vary, for the structural form given by Eq. (1) may correspond to different values of the number of Cu-units, n . According to X-ray analysis [3], in the absence of the bridges, the change in d amounts to 1%. Because of a crude and qualitative nature of our model we shall consider only sufficiently small fluctuations of d , and assume the angle θ fixed.

Thus, let us assume that $\theta = \theta_0 = \text{const}$. Then the equation for the free energy (5) acquires the form

$$F = \int_0^L \left[\frac{k_{22}}{2} (\dot{\phi} - q_0)^2 + \frac{\mu}{2} \sin^2 \theta_0 \dot{\psi}^2 + \lambda \sin^2 \theta_0 \cos^2(\phi - \psi) \dot{\phi}^2 \right] dz \quad (8)$$

in which the dot means the differentiation with respect to z .

It is worthwhile to note that we should not have confined ourselves only to orientational deformations as regards the energy given by Eq. (5), because of the presence of the bridges linked with the molecules of DNA fixed into a liquid crystalline dispersion. In case the bridges being present, an orientational deformation that involves the vectors $\mathbf{n}$ and $\mathbf{v}$, must cause a deformation of the network of linkers in the system of the DNA molecules and the bridges. To describe the properties of the system we need certain characteristics that describe the deformation of the linker network, as is done in the theory of anisotropic elastomers [17]. In the present case, for one thing we may assume the elastic moduli of the linker network to be small enough, so that we may neglect the constraints imposed by the linker network, and for another we shall take into account, in contrast to the conventional theory of elastomers, the orientational order of the bridges itself and its interaction with the ordering of the DNA cholesterics. Hence we aim at describing our system by the two orientational order parameters (unlike classical strong elastomers with the orientational and the rubber-like order parameters).

The minimization of equations for the free energy given by Eq. (8) reads

$$\ddot{\phi} = \frac{\lambda \sin^2 \theta_0 \sin[2(\phi - \psi)]}{k_{22} + 2\lambda \sin^2 \theta_0 \cos^2(\phi - \psi)} (2\dot{\phi}\dot{\psi} - \dot{\phi}^2) \quad (9)$$

$$\ddot{\psi} = \frac{\lambda}{\mu} \sin[2(\phi - \psi)] \dot{\phi}^2$$

We are looking for the solution of the equations (9) satisfying boundary conditions at $z = 0$ (i.e. the functions θ and ψ and their first derivatives $\dot{\phi}$ and $\dot{\psi}$ should be given at $z = 0$). It turns out that all general features of the behaviour is fairly universal. In particular for the size of the system, L , much larger than characteristic space scale of the solutions, they are always periodic in space and do not depend on L (see Figure 8 and descriptions below).

If there are no bridges, i.e. $\mu = \lambda = 0$, we have the usual solution $\dot{\phi} = q_0$ corresponding to the minimum of F and giving the cholesteric structure. We assume that the terms related to the bridges are small in comparison with the main cholesteric term

Figure 6. Ellipse shows the locus of the points for the middle of the bridge with a given length l .

Figure 7. Schematical illustration of the bridge motion round the supporting ellipse.

$$\frac{k_{22}}{2}(\dot{\phi} - q_0)^2,$$

and measure the constants μ and λ in units of k_{22} ; the latter being of order 10^{-6} dyn. There is no experimental information about the values of μ and λ ; we suggest that for one thing μ is much smaller than k_{22} , $\mu \ll k_{22}$, owing to a small concentration with those of DNA, and for another the magnitude of λ approaches that of k_{22} , even though being smaller, for the interaction term should be strong enough to drive the bridges along the orientational twist of DNA molecules. In fact, one can visualize a chelate bridge as a planar rectangle with the ratio of the sides about 3 by $10\text{\AA}$, so that its anisotropy is much smaller than that of DNA-molecules. Therefore, we shall take $k_{22} = 1$ and μ of the order of 0.01 and λ of 0.1, in the units given above. It is worth to mention that the qualitative behaviour of the solutions does not change at the variations of the elastic moduli μ and λ in the limits of several 0.001 and several 0.01 correspondingly.

As regards functional (8), we do not have the ambition to look for its minimum, but even studying the necessary condition for the latter, provides valuable information about the structure of the system. In fact, there is an exact solution to the minimization equations for (8), but its formulas are not particularly tractable, and

it is more practical to employ computer, from the very beginning. For our purpose we need to consider the behaviour of the twist angles, that is $\dot{\phi}$ for the DNA-molecules, and $\dot{\psi}$ for the bridges. To understand their possible configuration, let us visualize two adjacent molecules of DNA as two skew straight lines, see Figure 5. It is easy to convince oneself that the locus of points for the middle of the segment AB of a given length l is a rather elongated ellipse ε , see Figures 6 and 7.

It is worth noting that the ellipse is 'flat' proportionally to the smallness of the twist angle Φ between the skew lines $\Lambda_{1,2}$. The z-axis being the rotation axis of the helical structure for the DNA-cholesteric, the straight lines $\nabla_{1,2}$ rotate about Oz at the angular velocity $\dot{\phi}$, while an observer moves along Oz . In the meantime the segment AB, corresponding to a bridge, participates in two motions; that of the straight lines, and a motion of its own along the ellipse ξ . The latter has its own structure as to the sign of the motion along ξ and characteristic time, or period. Of course, we do not mean the motion in time, our problem is the statical one, and there is no time, but only a change in the characteristic of the system as we move along the helical axis, Oz , which is the rotation axis of the cholesterical structure. It is important that the spatial conformation of the bridges and the DNA-molecules is determined by equilibrium conditions imposed on the system, and is of the thermodynamical nature.

Thus, our hypothesis is that the orientational ordering of the bridges could substantially differ from that of the DNA-molecules. The numerical simulation of Eqs. (9) supports the claim.

The behaviour of the twist angles $\dot{\phi}$ and $\dot{\psi}$ is illustrated in Figure 8. We see that they can differ in magnitude several times, and in sign as well. We can visualize the phenomenon with the help of Figures 6 and 7 for the motion of the segment AB, or bridge, round the supporting ellipse ξ . In fact, the comparison of the numerical simulation given in Figure 8 and Figures 4, 5 indicates that the periods during which the twists $\dot{\phi}$ and $\dot{\psi}$ are almost identical correspond to the location of the segment AB, or bridge, at the aphelion and the perihelion of the ellipse ξ . On the contrary, the flat regions of the ellipse correspond to the motion of the bridge at its own angular velocity, which is several times larger than that of the twist $\dot{\phi}$. It should be noted that we do not mean an actual motion in time, but only the change in variables as we move along the Oz -axis.

However a number of remarks are in order. First note that the solutions of the equations (9) depend strongly on boundary conditions, i.e. $\phi(0)$, $\psi(0)$, $\dot{\phi}(0)$, $\dot{\psi}(0)$. Second, for the large enough L solutions we have found are periodic ones and form a soliton lattice of the spatial distribution of the function $\dot{\psi}$. We may indicate three qualitatively different kinds of the behaviour (shown schematically on Figure 8):

- a) bridges rotate faster than DNA, making more turns than DNA helix (therefore the second pitch describing the bridge structure is smaller than the initial DNA cholesteric one);
- b) bridges rotate slower than DNA, making less turns than DNA helix (i.e. the second pitch is larger than the cholesteric one);

Figure 8. DNA $\dot{\phi}$ (horizontal straight line) line and bridge $\dot{\psi}$ twists:
(a): $\mu = 0.05$, $\lambda = 0.025$, $\theta_0 = 0.10$, $\phi(0) = 0.00$, $\psi(0) = 1.57$, $\dot{\phi}(0) = \dot{\psi}(0) = 0.03$.
(b): $\phi(0)$, $\psi(0)$, $\dot{\phi}(0)$, $\dot{\psi}(0)$, μ , λ as in (a), but $\theta_0 = 0.15$.
(c): μ , λ , θ_0 , $\phi(0)$, $\dot{\phi}(0)$, $\dot{\psi}(0)$ as in (b), but $\psi(0) = 1.00$.

- c) bridges rotate faster or slower than DNA but make the same number of turns as DNA helix (i.e. both pitches are equal).

Though it might seem that the case where DNA and bridges rotate with the same average speed should never arise, or at least the boundary conditions leading to such a behaviour should be very rare, it is not so. There is a rather large area (in the phase space) of boundary conditions resulting in the case (c).

Second, as it is well known [13] cholesterics are internally frustrated systems. Frustrations arise for example from the competition between chirality, which favours a twist in the molecular orientation and the applied field which favours alignment of the molecules along the field. The system balances these opposing influences by introducing domain walls (2π solitons). In our case (when the competition is associated to the specific twist interaction (2) between bridges and DNA cholesteric director), and for our choice of parameters, this balance is achieved by introducing the second pitch. The mechanism we found to relieve the frustrations in a certain sense is intermediate between the standard soliton formation in cholesterics in an external field and double twist blue phases where frustrations are relieved by disclination defect lines formation.

Figure 9. Superhelical structure of bridges in the cholesteric DNA dispersion.

Thus, we may expect that in a dispersion of DNA cross-linked by chelate bridges there is a super helical structure due to the bridges, which is in a way superimposed on the cholesteric one of DNA molecules, see Figure 9. In fact, the numerical simulation shows that there is a layered orientational structure of bridges that has the property of a cholesteric with a variable twist angle. It admits of the abnormal CD-band discussed in the Introduction. In fact, it is alleged to be known that the absorption strongly depends on the twist angle of the cholesteric structure, and therefore, the cholesteric twist for bridges being several times larger than that for DNA, one may expect that the CD-band could be stronger than for the cholesteric phase of DNA in the absence of them.

3. Conclusion: Cholesterical BR-Phase

We suggest that in dispersions of DNA containing chelate bridges there could exist, besides the cholesterical phase of DNA molecules, another cholesterical phase generated by the bridges, which we call the BR-phase, see Figure 9. The latter could be the cause for the abnormal optical activity observed in CD-spectra in the region of 500 nm, and should have a layered structure.

It should be noted that, as follows from our crude model, the cholesteric pitch of the DNA dispersion does not change under the influence of the bridges, at least for the values of parameters considered in this paper. So the cholesteric structure of a DNA dispersion sustains the influence of the bridges for the set of parameters we have used corresponding to the current experiments. The circumstance has an important bearing upon the optical properties of DNA dispersions. One could expect that the intensity of the CD band at 270 nm, which corresponds to DNA

chromophores, should have remained unaltered in the presence of the bridges, but it increased. Therefore, we shall conclude that the intensity of the CD bands depends also on certain factors besides the orientational ordering of the bridges. Perhaps, the chelate bridges could change the coupling of oscillating dipole moments of adjacent DNA molecules so that collective excitation modes should emerge and result in the observed large intensity of the CD bands [10]. It is also important that the presence of the bridges may increase the average size of liquid crystalline domains that constitute the DNA dispersion. In the paper [16], it is reported that the intensity of CD bands increases with the size of the mono-crystalline domains, and therefore one could suggest that the bridges might make for the CD intensity by increasing the size of the domains.

Finally it is worth noting that the use of ions of different transition metals, e.g. cadmium or nickel, instead of copper, results in different properties of the BR-phase, as regards, at least, its optical activity [11–12]. The phenomenon could serve as a kind of probe into the physics of DNA and solvents. For example, it would be extremely interesting to find compounds capable of changing the sign of CD-absorption band; the picture given above of a chelate bridge ‘moving’ along the supporting ellipse in the opposite direction with respect to the cholesteric twist of DNA, suggests that it could be possible.

Acknowledgements

The research described in this publication was made possible in part by RFFR Grant 00-02-17785. One of the authors (V.L.G.) is thankful to ENS – Lyon for the hospitality.

References

1. Livolant, F. and Leforestier, A.: Condensed Phases of DNA: Structures and Phase Transitions, *Progr. Polym.* **21** (1996), 1115–1164.
2. Yevdokimov, Yu.M., Salyanov, V.I., Spener, F. and Palumbo, M.: Adjustable Cross-Linking of Neighbouring DNA Molecules in Liquid-Crystalline Dispersions Through Daunomycin-Copper Polymeric Chelate Complexes, *Int. J. Biol. Macromolecules* **19** (1996), 247–255.
3. Yevdokimov, Yu.M., Salyanov, V.I., Buligin, L.V., Dembo, A.T., Gedig, E., Spener, F. and Palumbo, M.: Liquid-Crystalline Structure of Nucleic Acids: Effect of Anthracycline Drugs and Copper Ions, *J. Biomol. Struct. Dynamics* **15** (1998), 97–105.
4. Yevdokimov, Yu.M., Salyanov, V.I., Mchedlishvili, B.V., Bykov, V.A., Spener, F. and Palumbo, M.: Molecular Construction based on Double-Stranded Nucleic Acids and Synthetic Polynucleotides for Use in an Integral Bioprobe, *Sens. Syst.* **13** (1999), 81–89.
5. Barthelemy-Clavey, V., Maurizot, J.C. and Sicard, P.J.: Etude Spectro-Scopique du Complexe ADN-Daunomycin, *Biochimie* **55** (1973), 859–868.
6. Fritsche, H. and Berg, H.: An Analysis of Equilibrium Kinetic and Structural Data of Anthracycline-DNA Interaction, *Gazetta Chimica Italiana* **117** (1987), 331–351.
7. Bell, M.J., Buchanan, G.W., Hollebone, B.R. and Jones, E.D.: Antitumor Activity at the Molecular Level: Binding Modes in Anthracycline – Dinucleotide Complexes as Determined by Optical Titration and Magnetic Circular Dichroism, *Can. J. Chem.* **60** (1982), 291–298.

8. Pigram, W.J., Fuller, W. and Hamilton, L.D.: Stereochemistry of Intercalation: Interaction of Daunomycin with DNA, *Nature New Biol* **235** (1972), 17–18.
9. Greenaway, F.T. and Dabrowiak, J.C.: The Binding of Copper Ions to Daunomycin and Adriamycin, *J. Inorg. Biochem.* **16** (1982), 91–107.
10. Bustamante, C., Samori, B. and Builes, E.: Daunomycin Inverts the Long-Range Chirality of DNA Condensed States, *Biochemistry* **39** (1991), 5661–5666.
11. Philips, D.R. and Carlyle, G.: The Effects of Physiological Levels of Divalent Metal Ions on the Interaction of Daunomycin with DNA: Evidence of a Ternary Daunomycin-Cu²⁺-DNA Complex, *Biochem. Pharmacol.* **30** (1981), 2021–2023.
12. Mikelson, P. and Levinson, W.: Metal Ion Participation in Binding of Daunomycin, Daunomicinone, and Adriamycin to Nucleic Acids, *Bioinorg. Chem.* **9** (1978), 441–452.
13. de Gennes, P.G. and Prost, J.: *The Physics of Liquid Crystals*, Clarendon Press, Oxford, 1993.
14. Chandrasekhar, S.: *Liquid Crystals*, Cambridge University Press, New York, 1977.
15. de Gennes, P.G.: Nematic Liquid Crystalline Polymers, In: A. Ciferri, W.R. Krigbaum and R.B. Meyer (eds.), *Polymer Liquid Crystals*, Academic Press, New York, 1982, pp. 115–121.
16. Belyakov, V.A., Orlov, V.P., Semenov, S.V., Skuridin, S.G., Lordkipanitze, G.B., Chernukha, B.A. and Yevdokimov, Yu.M.: Some Features of Circular Dichroism Spectra of Liquid-Crystalline Dispersions of Double-Stranded DNA Molecules with Stained Compounds, *Biophysics* **41** (1996), 1044–1055.
17. Terentjev, E.M. and Warner, M.: *Linear Hydrodynamics and Viscoelasticity of Nematic Elastomers*, cond-mat/0101042, 4 Jan. 2001.