Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

Liquid Crystalline State of DNA Molecules Complexed with Biologically Active Compounds

Yu. Yevdokimov [a] , V. Salyanov [a] & M. Palumbo [a b]
[a] Institute of Molecular Biology, USSR Academy of Sciences, UI. Vavilova 32, Moscow, 117334, USSR
[b] Institute of Organic Chemistry of Padova University, Via Marzolo 1, 35131, Padova, Italy
Version of record first published: 19 Oct 2010.

To cite this article: Yu. Yevdokimov , V. Salyanov & M. Palumbo (1985): Liquid Crystalline State of DNA Molecules Complexed with Biologically Active Compounds, Molecular Crystals and Liquid Crystals, 131:3-4, 285-297

To link to this article: http://dx.doi.org/10.1080/00268948508085050

Mol. Cryst. Liq. Cryst., 1985, Vol. 131, pp. 285–297
0026-8941/85/1314–0285/$20.00/0

Printed in the United States of America

Liquid Crystalline State of DNA Molecules Complexed with Biologically Active Compounds

YU. YEVDOKIMOV, V. SALYANOV, and M. PALUMBO†

Institute of Molecular Biology, USSR Academy of Sciences, Ul. Vavilova 32, Moscow 117334, USSR

(*Received December 7, 1984; in final form April 9, 1985*)

Liquid crystalline microphases (LCMs) formed as a result of condensation of rigid double-stranded right-handed DNA molecules complexed with different antibiotics and dyes (external chromophores) are shown to be characterized by two bands in circular dichroism (CD) spectra; one of them is located in the region of absorption of DNA chromophores (nitrogen bases) at $\lambda \sim 270$ nm, the other—in the region of absorption of external chromophores at $\lambda \sim 500$ nm. The appearance of these two bands in the CD spectrum demonstrates that LCMs formed from DNA molecules of low-molecular-weight are helically twisted. Correlation between signs of bands in the CD spectrum of LCMs and orientation of molecules of external chromophores about the helical axis of DNA molecules has been established. The data obtained allow to draw a conclusion that the selective reflection band connected with the pitch (P) of the twisted structure formed from adjacent DNA molecules is located at $\lambda > 600$ nm.

INTRODUCTION

The rigid right-handed double-stranded molecules of DNA of low-molecular-weight ($< 1 \times 10^6$), when condensing at definite conditions in water-salt solutions containing poly(ethyleneglycol) (PEG), form a dispersed phase scattering light.[1,2] Basing on measurements of the dependence of "apparent" optical density (i.e. the optical density in the region of the spectra where molecules of DNA or PEG do not absorb, $\lambda > 320$ nm) on wavelength estimations of the size of particles of the dispersed phase built of adjacent double-stranded DNA mol-

†Institute of Organic Chemistry of Padova University, Via Marzolo 1, 35131, Padova, Italy.

ecules show that an "effective" mean diameter of particles is equal to ~ 3,000 Å.[2] Determination of the diameter of particles as of the dispersed phase using the diffusion coefficient of the particles confirms the above-estimated value.[3] These data demonstrate that the size of particles of the dispersed phase built of DNA molecules is "microscopic" (therefore "microphases of DNA"). The study of X-ray scattering by particles of the DNA dispersed phase formed at a concentration of PEG in the range from 120 to 300 mg/ml demonstrates that the X-ray diagram contains a small-angle reflexion at any concentration of PEG, its value (40–25 Å) depending on the concentration of PEG in solution.[4,5] Appearance of a small-angle reflexion indicates that there is a local order in the arrangement of the neighbouring DNA molecules forming the particles of the dispersed phase, i.e. the molecular structure of particles is similar to that of liquid crystals. Taking into account these properties of the dispersed phase built of adjacent low-molecular-weight double-stranded DNA molecules, a term "liquid crystalline microphases" (LCMs) is used to denote them.[2]

Formation of LCMs from low-molecular-weight DNA molecules at definite conditions[6] is accompanied by the appearance of an intense band in the CD spectrum. One of the reasons to explain the appearance of the intense band in the CD spectrum of the LCMs is based on the supposition that the intense band in the CD spectrum is a selective reflection band.[7] However this explanation is not unequivocal for the case of DNA microphases since the intense band in the CD spectrum of LCMs ($\lambda \sim 270$ nm) is located in the region of strong absorption ($\lambda \sim 260$ nm) of nitrogen bases (chromophores) of DNA. Appearance of the intense band in the CD spectra in the UV-region where light-scattering strongly affects both the shape of the CD spectra and the amplitude of the band is the subject of discussion (see reference 8). The intense band in the CD spectrum in the absorption region of chromophores can point out to a helical twist of microphases,[9–11] but the presence of the band may not be connected with location of the selective reflection band in the given area of the spectrum. The small size and very small concentration of particles of the DNA dispersed phase in PEG-containing solutions ($C_{DNA} \sim 20$ mkg/ml) prevents the using of the polarization microscopy method for determination of the position of the selective reflection band in the case of LCMs of DNA. In order to evaluate the region of the spectrum where the selective reflection band for LCMs of DNA is located one can use a method of external chromophores.[12] The main idea of the widely adopted method of external chromophores is relatively simple: appearance of optical activity in the absorption region

of some dyes, introduced into preformed liquid crystals is the proof of its helical twist. Application of some empirical rules[12] permits to estimate the relative location of the selective reflection band in this case. For DNA LCMs external chromophores can be biologically active molecules. The use of these compounds offers definite advantages: firstly, they absorb in the visible region of the spectrum, therefore the light scattering does not distort greatly the shape of the CD spectrum of DNA molecules; secondly, they form strong complexes with DNA molecules, the orientation of external chromophores about the axis of the DNA double-stranded helix being known.

In the present paper the CD spectra of LCMs formed from double-stranded right-handed DNA molecules of low-molecular-weight that were complexed with external chromophores prior to LCM formation were studied. (When using the standard method, dyes are added to preformed LCMs). Our modification of the standard method of external chromophores is based on the fact that the parameters characterizing the binding of external chromophores to DNA molecules were estimated for free (i.e. not LCM) DNA molecules. Hence, in PEG-containing solution LCMs were formed not only from free DNA molecules but also from DNA molecules complexed with different dyes (external chromophores). The optical properties of external chromophores and the geometry of their binding to molecules of DNA differ strongly.[13]

EXPERIMENTAL

The preparation of salmon sperm DNA was purified.[14] The molecular weight of DNA molecules after ultrasonic depolymerization (0.3 M NaCl, 4°C) of the initial high-molecular-weight preparation of DNA (10×10^6), estimated by electrophoresis in the 3.3% poly(acrylamide) gel, was $(5-7) \times 10^5$. Preparations of distamycin A ("Serva," FRG) Hoechst-33258 ("Hoechst," FRG), propidiumiodide ("Calbiochem," USA), carminomycin, 3-propyl derivative of distamycin A, netropsin (Moscow), 1-(ω-diethylaminopropylamido)-2-methoxy-4-hydroxy-9, 10-anthracenedione hydrochloride, 1-(ω-diethylaminopropylamido)-4-hydroxy-9, 10-anthracenedione hydrochloride (Institute of Organic Chemistry, Padova, Italy), steffimycin, violamycin, adriamycin, daunomycin and iremycin (Central Institute of Microbiology and Experimental Therapy, Jena, GDR) were used without purification.

LCMs from low-molecular-weight DNA molecules were prepared by mixing the equal volumes of water-salt (0.3 M NaCl) solution of DNA molecules (the concentration of DNA was two times greater

in comparison with the required concentration) and water-salt (0.3 M NaCl) solution of PEG (concentration of PEG was 340 mg/ml). LCMs from complexes of low-molecular-weight DNA molecules with different antibiotics were prepared according to the following two-stage scheme:

Step 1: water-salt (0.3 M NaCl) DNA solution + antibiotic →
($C_{DNA} \sim 20$ mkg/ml) ($C_{ant} \sim 10^{-6} \div 10^{-5}$ moles/l)
→ complex (DNA-antibiotic) in water-salt solution.

Every complex was characterized by "r" value. (The "r" value is expressed as relation of the molar concentration of antibiotic bound in a complex to a molar concentration of DNA nitrogen bases;[15] "r" value was within the range from 0.01 to 0.2). The binding constants of antibiotics to the DNA in water-salt solution were evaluated as described earlier.[16]

Step 2: water-salt solution of complex (DNA-antibiotic) was mixed with water-salt solution of PEG (D_{PEG} = 340 mg/ml). As a result of mixing, LCMs of complex (DNA-antibiotic) were formed.

The water-salt solutions (0.3 M NaCl, phosphate buffer, pH 6.7) containing PEG (mol. weight of PEG 4,000, "Loba Chemie," Austria) were filtered through membrane filters ("Synpor," Czechoslovakia; diameter of pores—1.5 μm) in order to remove possible mechanical impurities.

The concentration of antibiotics and DNA in solutions were derived from the optical density of solutions of these compounds using known extinction coefficients.[17-19]

Spectrophotometric measurements were taken on the "Specord M 40" spectrophotometer (GDR), the CD spectra—on the "Jobin-Yvon (Mark III) dichrograph (France). CD and absorption spectra were taken in a 1 cm cells at room temperature. All CD spectra are presented[20-21] as $\Delta\epsilon_{(\lambda)} = \epsilon_L - \epsilon_R$, i.e. the difference between the molar extinction coefficients for left- and right-handed circularly polarized light. The data were calculated from experimentally taken on the dichrograph CD spectra and expressed as circular dichroism ($\Delta\epsilon_{(\lambda)}$) according to following equation:[20,21]

$$\Delta\epsilon_{(\lambda)} = \Delta A_{(\lambda)}/C \cdot 1 \qquad (1)$$

where: $\Delta A_{(\lambda)} = A_L - A_R$ ($\Delta A_{(\lambda)}$ in optical units); C—concentration of the substances used (moles per liter); 1 = 1 cm. In the case of absorption of DNA nitrogen bases ($\lambda \sim 260$ nm) the $\Delta\epsilon_{(\lambda)}$ value is expressed as before,[8] per mole of DNA nucleotides in solution (in

units: 1/mole of nitrogen bases, cm). In the case of absorption of antibiotics and dyes the $\Delta\epsilon_{(\lambda)}$ values are given per mole of antibiotics bound in a complex (in units: 1/mole of bound antibiotics, cm).

RESULTS AND DISCUSSION

A. Appearance of two bands in CD spectra of LCMs formed from complexes (DNA-antibiotic)

Figure 1 exemplifies the CD spectra of the LCMs formed from DNA molecules complexed with compounds that are found to be "intercalators," i.e. they are located between adjacent nitrogen bases of DNA (curves II_1, I_3, III_1; structural formula, see Table I). Formation of LCMs from DNA molecules complexed with intercalators was accompanied by the appearance of the intense band in a CD spectrum in the absorption region of DNA chromophores ($\lambda \sim 270$ nm) as well as chromophores of intercalators ($\lambda \sim 500$ nm).

Curve IY_1 illustrates the CD spectrum of the LCM formed from DNA molecules complexed with the compound IY_1 (see Table I) that is not located between nitrogen bases but in the minor groove on the surface of the DNA molecule. In this case the negative band ($\lambda \sim 270$ nm) is still present in a CD spectrum in the region of absorption of chromophores of DNA. At the same time in the absorption region ($\lambda \sim 320$ nm) of external chromophore IY_1 there occurred a positive band in a CD spectrum.

In the case of LCMs formed from DNA molecules complexed with compound "Hoechst-33258" an intense band in CD spectrum was not induced in the region of absorption of this compound ($\lambda \sim 340$ nm) in spite of existence of the intense negative band in the region of absorption of DNA nitrogen bases ($\lambda \sim 270$ nm).

Comparison of results (Figure 1, Table I) allows a conclusion to be made. One can see that at a small level of complexing of DNA molecules with antibiotics or dyes (small "r" values) formation of LCMs from complexes of DNA molecules with external chromophores leads to the appearance (irrespective of the chemical structure of chromophores) of the intense band in the CD spectrum in the absorption region of DNA chromophores (nitrogen bases). In some instances, intense bands appear also in the region of absorption of external chromophores, i.e. antibiotics and dyes. Taking into account the results of theoretical calculations,[9-11] one can say that this result proves the helical twist of a LCM formed at condensation of rigid double-stranded right-handed DNA molecules in PEG-containing solution.

TABLE I

Some optical characteristics of LCMs formed from

Group of ompounds	N	Biologically active compounds (External chromophores)	Maximum of absorption of biologically active compounds, λ, nm	Angle between the plane of chromophore of biologically active compounds and long axis of the DNA molecule, degrees. (Data from literature)
I	1	Aclacinomycin A	434	90
	2	Iremycin	495	--"--
	3	Daunomycin	487	--"--
	4	Carminomycin	492	--"--
	5	Adriamycin	500	--"--
II	1	1-(ω-Diethylamino-propylamido)-4-hydroxy-9, 10-anthracenedione hydrochloride	455	--"--
	2	1-(ω-Diethylamino-propylamido)-2-methoxy-4-hydroxy-9, 10-anthracenedione hydrochloride	416	Does not form
III	1	Propidiumiodide	495	--"--
IV	1	Distamycin A	300	45 ± 2
	2	3-propyl derivative of distamycin A	303	----
	3	Netropsin	297	41 ± 2
V	1	Hoechst-33258	338	49 ± 2

B. Correlation between the angle of orientation of antibiotics or dyes about the long axis of the DNA molecule and the sign of the band in CD spectra of LCMs

At small "r" values there is a correlation between the sign of the band in the CD spectrum and the angle (α) which is formed by the

the DNA molecules complexed with different biologically active compounds

"r" values	Maximum of band in the CD spectra of LCMs formed from DNA molecules complexed with biologically active compounds, nm.	Amplitude ($\Delta\epsilon_{270}$), of band in CD spectra in region of absorption of DNA nitrogen bases	Amplitude ($\Delta\epsilon$) of bands in CD spectra in regions of absorption (see column 7 in this Table) of external chromophores
0.02	445–450	−55	−60
0.13		−50	−50
0.02	500	−50	−80
0.15		−50	−60
0.04	505	−50	−40
0.14		+50	+40
0.04	500	−50	−60
0.20		+50	+30
0.02	507	−50	−60
0.14		+55	+60
0.01	475–480	−55	−40
0.09		−55	−40

a complex with the DNA molecules under experimental conditions

0.02	520–525	−110	−65
0.11		−80	−55
0.01	325–330	−110	+800
0.04		+100	−750
0.01	315–320	−60	+210
0.09		+55	−100
0.01	305–310	−55	+300
0.04		−50	+200
	---	−110	---

plane of the chromophore and the long axis of the DNA molecule (Table I). This fact is in agreement with the theory.[12] According to the theoretical considerations, the major reason for the appearance of the intense band to be induced in the CD spectrum of LCMs is linear dichroism of chromophores located in helically twisted microphases. The amplitude of the band in this case is expressed as fol-

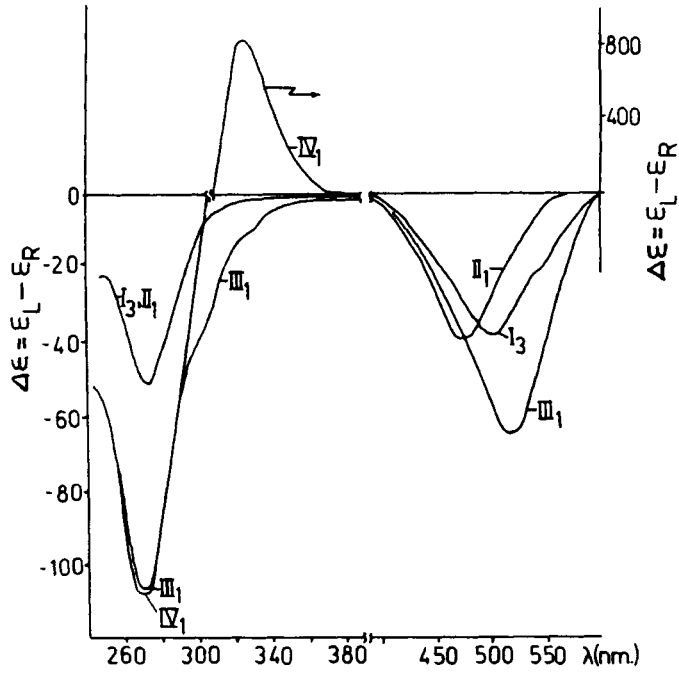

FIGURE 1 The CD spectra of LCMs formed from low-molecular-weight DNA molecules complexed with different antibiotics and dyes at small "r" values (0.3 M NaCl, C_{PEG} = 170 mg/ml). "r" value in the case of DNA molecules complexed with I_3 was 0.04; with II_1—0.01; with III_1—0.02; with IY—0.01. "r" is relation of molar concentration of bound antibiotic to molar concentration of DNA nitrogen bases. Numbers correspond to antibiotics listed in Table I. LCMs from DNA molecules complexed with compounds I_3 and II_1 were prepared by direct mixing of PEG-containing water-salt solutions (C_{PEG} = 340 mg/ml) with water-salt solutions of the DNA molecules complexed with indicated compounds. The method,[3] which avoids a direct mixing PEG-containing solution and water-salt solution of DNA molecules complexed with compounds III_1 and IY_1 was used for preparation of LCMs of DNA molecules with indicated compounds. $\Delta\epsilon$ values in the region of absorption of DNA nitrogen bases were calculated per mole of nitrogen bases (see "Experimental"), $\Delta\epsilon$ values in the regions of absorption of antibiotics and dyes were calculated per mole of antibiotics bound in a complex (see "Experimental").

lows:[22]

$$\Delta\epsilon = \epsilon_L - \epsilon_R = K_1 \times \frac{\Delta n}{\lambda^*} \times \tanh K_2 \times (\epsilon_{\parallel} - \epsilon_{\perp}) \qquad (2)$$

where: K_1 and K_2—constants, $\Delta n = (n_{\parallel} - n_{\perp})/(n_{\parallel} + n_{\perp})$, $\epsilon_{\perp}$ and $\epsilon_{\parallel}$—coefficients of absorption for the light propagated perpendicular and parallel to the director of the layer formed from neighbouring mol-

ecules (in the discussed case, parallel and perpendicular to the axes of DNA molecules forming the neighbouring layers).

Anisotropy of the chromophore is connected with the angle:[8]

$$\frac{\epsilon_{\parallel} - \epsilon_{\perp}}{\epsilon_o} = K_3 \times (3\,\mathrm{Cos}^2\alpha - 1) \qquad (3)$$

where: α—angle between the plane of the chromophore and the long axis of DNA molecule; K_3—constant.

From Equations 2 and 3 it is clear that at a definite orientation of the chromophore ($3\,\mathrm{Cos}^2\alpha - 1 = 0$; the "magic" angle) the band in the CD spectrum may not appear in spite of the helical twist of LCMs. In addition, at constant direction of the helical twist of LCMs and small "r" values, the band in the CD spectrum for chromophores oriented by $\alpha > 54°$ differs in its sign for the case of chromophores with $\alpha < 54°$. It means, that the sign of the band in the CD spectrum is determined not only by the direction of the helical twist of LCMs of DNA molecules but also by the angle (α) at which the chromophore oriented about the DNA helix.

C. Reverse of signs of bands in CD spectra of LCMs

The CD spectra (see Figure 2) and the data of Table I show that in some instances at high "r" values one can observe simultaneous reverse of signs of the bands located in the regions of the absorption both for the DNA chromophores and the external ones. When passing to the analysis of reasons that induce a reverse of the signs of the band in the CD spectra of LCMs formed from DNA molecules complexed with some antibiotics, it is necessary to take into account the following. Firstly, upon interaction with antibiotics the right-handed structure of DNA is preserved,[23] the DNA base pairs and the intercalated antibiotic molecules are oriented nearly perpendicular to the long axis of the DNA molecule. Secondly, the local order of the DNA molecules complexed with antibiotics and forming LCMs that are characterized by intense positive bands in the CD spectra is similar[23] to the local order of the free DNA molecules forming LCMs with intense negative bands in the CD spectrum.

These two observations and the fact that the signs of the bands in different regions of the CD spectrum are reversed "simultaneously" allow to use the theory[24] for explanation such reverse. Following the theory the ϕ_{min} angle between two polymer molecules that are con-

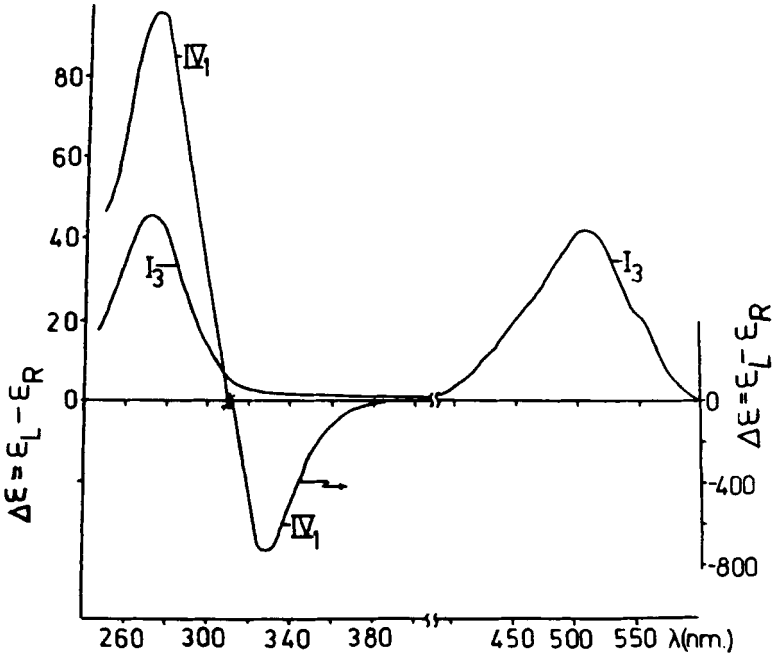

FIGURE 2 The CD spectra of LCMs formed from DNA molecules complexed with different antibiotics and dyes at high "r" values (0.3 M NaCl, C_{PEG} = 170 mg/ml). For details see Table I and Legends to Figure 1.

sidered as rigid dielectric rods immersed in dielectric medium is described by equation:[24]

$$\phi_{min} = 1/2 \tan^{-1} \{\epsilon_m \times (J_{11} - J_{22}) \times C\} \quad (4)$$

where: C—adjustment constant, ϵ_m—dielectric constant of solution.

$$(J_{11} - J_{22}) = \left[\frac{(\epsilon_y - \epsilon_x) \cdot \epsilon_m \cdot (\epsilon_m^2 - \epsilon_x \cdot \epsilon_y)}{\{[\epsilon_m + 1/2 \cdot (\epsilon_x - \epsilon_m)] \cdot [\epsilon_m + 1/2 \cdot (\epsilon_y - \epsilon_m)]\}^2}\right] \quad (5)$$

ϵ_x, ϵ_y—dielectric constants of the polymer measured in the directions perpendicular to the long axis of the polymeric molecule. $(J_{11} - J_{22}) = 0$, and therefore $\phi_{min} = 0$ (this implies that the twist of a polymer's LCM is absent, a compensated structure arises and a high optical activity disappears) if one of two conditions is observed:

1. $\epsilon_m = \epsilon_m^* = \sqrt{\epsilon_x \times \epsilon_y}$; this implies that the value of the dielectric constant of solution (ϵ_m) reaches a "critical" value (ϵ_m^*). In the so-

lutions whose dielectric constants higher or lower than the "critical," the values of the ϕ_{min} differ, and therefore, the direction of the helical twist of the polymer's LCMs also differ.

2. $\epsilon_x = \epsilon_y$; this indicates that the values of dielectric constants measured in the directions perpendicular to the long axis of a polymeric molecule are equalized, i.e. the polymeric molecules "lose" their dielectric "helicity."

Equation (4) shows that the direction of the helical twist of polymer molecules predetermining the sign of the band in the CD spectrum in absorption region of chromophores depends on the ϕ_{min} sign.

The first factor to induce a "simultaneous" reverse of the sign of the bands that are located in different regions of the CD spectrum may be the change of the direction of the helical twist of the whole LCM. Such alteration of the direction of the spacial twist can result from the change of the interaction energy between DNA molecules complexed with antibiotics. At a fixed temperature and ϵ_m value the direction of the LCMs twist (i.e. ϕ_{min} value) arises at the "moment of approaching" of DNA molecules and remains constant.[3]

The second possible reason is the simultaneous change of dielectric properties (ϵ_x, ϵ_y values) both for DNA base pairs and antibiotic molecules at complex formation. The direction of the helical twist of LCMs formed from DNA molecules complexed with antibiotics may remain constant within this interpretation. It should be noted that a similar reason was used to explain the reverse of the signs of the bands in the CD spectra of liquid crystals of low-molecular-weight compounds.[25]

The above-presented considerations are experimentally verified.[23] To the PEG-containing solution with LCMs formed from DNA-antibiotic complexes that were characterized by two positive bands in the CD spectra (see Figure 2), sodiumdodecylsulfate (SDS) was added, i.e. the substance capable of inducing a dissociation of the DNA-antibiotic complexes. The addition of SDS was found to result in a disappearance of the positive band in the CD spectrum in the region of absorption of antibiotics ($\lambda \sim 500$ nm) whereas the positive band in the region of absorption of DNA nitrogen bases remained constant in spite of dissociation of the DNA-antibiotic complex. If the second reason suggested were true, then not only the positive band in the absorption region of antibiotic would have disappeared but the sign of the band in the region of absorption of DNA nitrogen bases would have changed from positive to negative. This must be the consequence of the preservation of the direction of helical twist of the DNA mol-

ecules forming LCMs according to the second supposition. The experiment made[23] allows to reject the second supposition.

Thus, the reverse of signs of the bands located in different regions of the CD spectrum is, in the discussed case, the change of the direction of the helical twist of DNA molecules forming LCMs.

D. A region of possible location of the selective reflection band of LCMs.

The intense bands in CD spectra of LCMs formed from DNA molecules complexed with external chromophores are interpreted as due to linear dichroism of the chromophores stacked in the helical structure. Similarly, the CD around 270 nm can be interpreted as due to linear dichroism of DNA molecules. This allows one to make a suggestion that the selective reflection band is located away from the absorption band of the DNA molecule, which is also true of the absorption band of external chromophores, i.e. at $\lambda > 600$ nm or at $\lambda < 250$ nm. We expect that the selective reflection band exists at $\lambda > 600$ nm. The appearance of the selective reflection band at $\lambda < 250$ nm is less probable because in this case the angle between the DNA layers forming the LCM should be great. Recent measurements showed that the half-pitch of LCMs of free DNA molecules in vitro can reach 1,000 nm.[26] In addition, right-handed double-stranded molecules of synthetic polymer—poly(A)·poly(U) (mol. weight 3.9×10^5) at high concentration form a liquid crystalline structure. The neighbouring rods of poly(A)·poly(U) show a nearly parallel orientation, but a slight twist seems to exist, which leads to a twisted structure having a pitch of the order 1,000 nm.[27]

References

1. S. Cheng and S. C. Mohr, *Biopolymers*, **14**, 663 (1975).
2. Yu. M. Yevdokimov, S. G. Skuridin and N. M. Akimenko, *Vysokomolekuljarnye sojedynenya A* (Moscow), **26**, 2403 (1984).
3. S. G. Skuridin, E. W. Schtikova and Yu. M. Yevdokimov, *Biophysica* (Moscow), **29**, 337 (1984).
4. T. Maniatis, J. H. Venable and L. S. Lerman, *J. Mol. Biol.*, **84**, 37 (1974).
5. Yu. M. Yevdokimov, S. G. Skuridin, A. T. Dembo, E. W. Schtikova, V. A. Kadykov and Ya. M. Varshavsky, *Molecular Biology* (Moscow), **13**, 1110 (1979).
6. S. G. Skuridin, W. S. Shashkov, Yu. M. Yevdokimov and Ya. M. Varshavsky, *Molecular Biology* (Moscow), **13**, 804 (1979).
7. M. F. Maestre and Ch. Reich, *Biochemistry*, **19**, 5214 (1980).
8. I. Tinoco, C. Bustamante and M. F. Maestre, *Ann. Rev. Biophys. Bioeng.*, **9**, 107 (1980).
9. G. Holzwath and N. A. W. Holzwarth, *J. Opt. Soc. America*, **63**, 324 (1973).

10. G. S. Ranganath, S. Chandrasekhar, U. D. Kini, K. A. Suresh and S. Ramaseshan, *Chem. Phys. Letters*, **19**, 556 (1973).
11. E. Sackman and J. Voss, *Chem. Phys. Letters*, **14**, 528 (1972).
12. F. D. Saeva, "Liquid Crystals," F. D. Saeva, Ed., Marcel Dekker, Inc., New York, 1979, p. 249.
13. V. L. Makarov, A. I. Poletaev and P. G. Sveshnikov, *Molecular Biology* (Moscow), **13**, 450 (1979).
14. J. Marmur, *J. Mol. Biol.*, **3**, 208 (1961).
15. V. A. Bloomfield, D. M. Crothers and I. Tinoco, "Physical Chemistry of Nucleic Acids," Harper and Row Publishers, New York, London, 1974, p. 408.
16. Yu. M. Yevdokimov, V. I. Salyanov and H. Berg, *Nucl. Acids Res.*, **9**, 743 (1981).
17. V. I. Salyanov and Yu. M. Yevdokimov, *Antibiotiki* (Moscow), **2**, 114 (1979).
18. A. Walter, H. Schütz and E. Stutter, *Internatl. J. Biol. Macromol.*, **5**, 351 (1983).
19. M. Palumbo and S. M. Magno, *Internatl. J. Biol. Macromol.*, **5**, 301 (1983).
20. D. E. Metzler, "Biochemistry," Academic Press, New York, London, vol. 3, p. 23 (1977).
21. U. V. Dunina, E. G. Ruchadze and V. M. Potapov, "Poluchenie i Issledovanie Opticheski Aktivnich Veschestv," MGU, 1979, p. 38.
22. B. Norden, *Appl. Spectroscopy Rev.*, **14**, 157 (1978).
23. Yu. M. Yevdokimov, V. I. Salyanov, A. T. Dembo and H. Berg, *Biomed. Biochim. Acta*, **42**, 855 (1983).
24. T. V. Samulski and E. T. Samulski, *J. Chem. Phys.*, **67**, 824 (1977).
25. B. W. Van der Meer and G. Vertogen, "Molecular Physics of Liquid Crystals," G. R. Luckhurst and G. W. Gray, Ed., Academic Press, London, New York, 1979, p. 149.
26. F. Livolant, *European J. Cell Biol.*, **33**, 300 (1984).
27. E. Senechal, G. Maret and K. Dransfeld, *Internatl. J. Biol. Macromol.*, **2**, 256 (1980).