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Optical activity of the guest azobenzene molecule generated by inclusion complexation with steroidal bile acids

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Abstract—The crystalline inclusion complexes of azobenzene **1** with cholic **CA** and deoxycholic **DCA** acid were prepared and their solid state CD spectra measured. The positive Cotton effect sign, corresponding to the lowest energy n–π* transition, was correlated with the *M*,*M* helicity of the twisted guest molecule. The absolute sense of twist of the enclathrated guest molecule **1** was deduced from the X-ray structure of the **1**·**CA** complex. In addition, the solid state CD spectrum of the enantiomorphous crystals of methyl yellow **2** was measured. The source of the optical activity is a slight twisting of the constituent molecules and their helical arrangement in the crystal.

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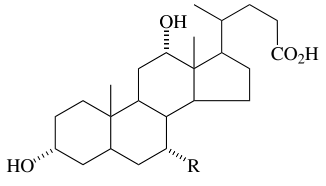
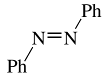
1. Introduction

Circular dichroism (CD) spectroscopy is a powerful tool in the determination of the molecular configuration and conformation in solution.[1] Unfortunately, its application is restricted to chiral compounds and the CD spectra cannot be measured for achiral molecules. However, optical activity can be induced into such systems by placing them in a dissymmetric environment.[2] Interaction of achiral molecules with chiral species in solution usually gives rise to an asymmetric perturbation of the chromophore or causes an excess population of rapidly interconverting enantiomers that leads to a measurable CD. In recent years, increasing attention has been given to inclusion complexation of achiral guests with optically active hosts, like cyclodextrins or crown ethers.[2,3] The CD spectra of crystalline inclusion complexes appeared to be useful in the elucidation of the mechanisms of induction of optical activity particularly in combination with X-ray studies.[4] Owing to their ability to accommodate various types of organic substances within their crystal lattices, naturally occurring bile acids appeared to be very useful hosts for this purpose.[5] Recently, we have found that the molecules trapped in the cholic acid **CA** and deoxycholic acid **DCA** matrices are forced to assume chiral conformation that makes possible solid state CD measurements.[6]



CA, R = OH
DCA, R = H



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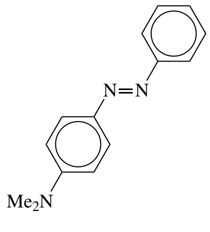

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Among potential chromophoric guest species, the photosensitive azobenzene unit is of particular interest because of its applications in optical switches and sensors, photoresponsive supramolecular systems,[7,8] liquid crystals[9] or polymers.[10] There are several reports on the induced CD studies of cyclodextrin complexes with azo dyes.[11] They are focused on the orientation of the guest molecules within the cyclodextrin cavity. Continuing an interest in the generation of chirality by inclusion complexation with optically active hosts, we report herein the CD spectra of *anti*-azobenzene **1** trapped in the crystal lattices of **CA** and **DCA**. The absolute conformation (helicity) of the guest molecule was assigned from the X-ray structure of the **CA** complex. In addition, a survey of the Cambridge Structural Database revealed that 4-(*N*,*N*-dimethylamino)azobenzene **2** (methyl yellow) crystallizes in the space group $P2_12_12_1$.[12] This means that this achiral compound forms a conglomerate, that is, a mechanical mixture of equal quantities of enantiomorphous crystals.[13] In general, each single crystal of the conglomerate should contain only one type of the enantiomeric molecules. Thus, we were able to measure the CD of **2** in the solid state and assign the absolute conformation of the constituent molecules by comparison of the Cotton effect sign with that of the **CA** complex of **1**.

2. Results and discussion

The plate-like crystals of the 1:2 inclusion complex of **1·CA** were prepared by co-crystallization of **CA** with an excess of **1** in the presence of a small amount of diethyl ether. Similarly, the **1·DCA** crystals were obtained by recrystallization of **1** and **DCA** from methanol. We also attempted to prepare the inclusion complexes of *syn*-azobenzene. Unfortunately neither **CA** nor **DCA** form inclusion crystals with this compound. Single crystals of dye **2** (yellow slabs) were grown from ethanol–chloroform.

The X-ray crystal structure of **1·CA** depicted in Figure 1 resembles those found in majority of the **CA** clathrates.[5,6] The host molecules self-assemble through intermolecular hydrogen bonds into corrugated bilayers and the empty channels between the stacked bilayers filled with the molecules of **1** organized into infinite columns. The *trans*-azo group of the guest molecule remains nearly planar [the C–N═N–C torsion angle is of −175.3(3)°, see Section 4] whereas the phenyl rings are significantly twisted from the CN═N planes in the *M* sense [the corresponding C═C–N═N torsional angles are of −21.7(5)° and −28.1(6)°]. In contrast, the molecule of **1** in the *trans*-azobenzene crystals is essentially planar.[14]

The UV–vis spectrum of **1** measured in solution, as well as in the solid state, is characterized by a weak absorption near 440 nm (ε 510), corresponding to the forbidden n–π* transition, and a strong one near 320 nm (ε 21,300), assigned to the allowed π–π* transition.[15,16] The first one is structureless while the second one has a pronounced vibrational fine structure. In the case of the *para*-substituted azobenzene derivatives the electron donating substituents shift the π–π* band to longer wavelengths whereas the position of the n–π* band remains almost unchanged.[15]

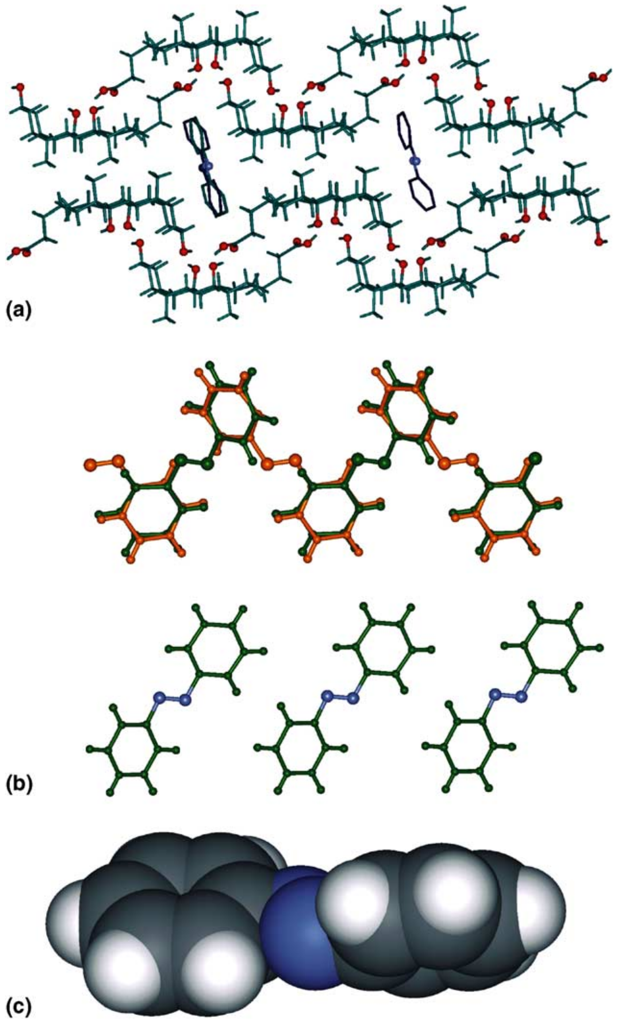

Figure 1. The crystal structure of the inclusion complex **1·CA**: (a) crystal packing viewed along the channel axis; (b) disorder of the guest molecules and their arrangement within a single channel; (c) CPK model of the twisted *anti*-azobenzene molecule.

The CD spectra of **1·CA** and **1·DCA** taken in KBr disks are presented in Figure 2. The complex **1·CA** exhibits a very strong positive Cotton effect near 450 nm and a much weaker negative one at 368 nm that can be assigned to the n–π* and π–π* excitations, respectively. The magnitude of the n–π* Cotton effect is much stronger than that reported for the induced CD spectra of the cyclodextrin complexes with azo dyes and is unequivocally due to the inherent chirality of the twisted azobenzene chromophore. The observed positive sign of the long-wavelength CD band can be correlated with the *M* helicity of the skewed aryl–N═N system of the guest molecule revealed by the crystal structure of the complex. In contrast, the chiroptical spectrum of **1·DCA** shows a weak negative Cotton effect at 450 nm and a stronger negative one with a distinct fine structure near

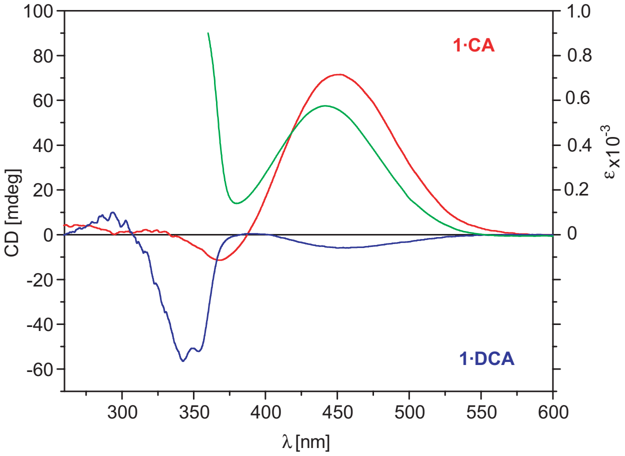

Figure 2. Solid state CD spectra of the inclusion complexes **1·CA** and **1·DCA** taken in KBr disks (red and blue line, respectively) and UV–vis spectrum of **1** measured in $CHCl_3$ (green line).

340 nm, corresponding to n–π^* and π–π^* transitions, respectively. The observed weak magnitude of the n–π^* Cotton effect suggest only negligible distortion of the guest molecule from planarity that is typical for DCA complexes.[6a] Indeed, the X-ray analysis of the **1·DCA** single crystal showed that the guest molecule is only slightly distorted from planarity. Two phenyl rings are twisted from the CN=N planes in an opposite sense [the corresponding C=C–N=N torsional angles are of 5.8(13)° and −4.9(14)° however, due to a severe guest disorder these values have to be taken with caution, see Section 4]. The guest molecules are accommodated in the α-type channels (Fig. 3) characteristic for the **DCA** host matrix including small flat or thread-like guest molecules.[17,18] The molecules of **1** are arranged with their long axis approximately parallel to the channel axis that allows them only a slight distortion from planarity.

The solid state CD spectrum of the chiral crystal of azo dye **2** shown in Figure 4 exhibits a relatively strong negative CD at 480 nm corresponding to the n–π^* transition and three positive Cotton effects at shorter wavelengths due to the π–π^* transitions of the –N=N– group and the aryl substituents. It is noteworthy that in the UV–vis spectra of **2**, the weak n–π^* band is completely overlapped by the much stronger π–π^* band near 410 nm.[19] The reported X-ray structure of **2** reveals a slight distortion of the molecule from planarity: one aryl ring is nearly coplanar with the azo group whereas the second one is twisted by 5.5°.[12] Thus the observed negative n–π^* Cotton effect can be correlated with the *P* helicity of the molecule of **2**.

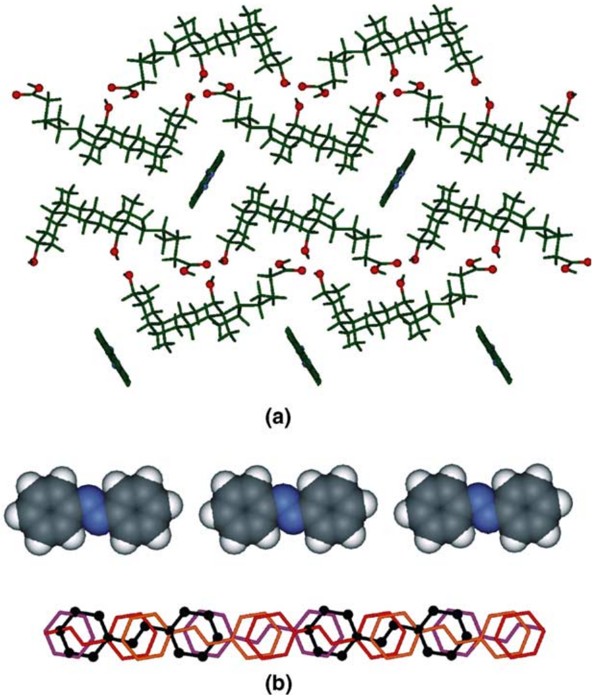

Figure 3. The crystal structure of the inclusion complex **1·DCA**: (a) crystal packing viewed along the channel axis and (b) arrangement of the guest molecules within a single channel and disorder of the guest molecules observed in the crystal.

On the other hand, the observed two intense CD bands of opposite signs might be due to exciton coupling between the electric transition moments of the helically oriented azo dye molecules in the crystal. The couplet is asymmetric and the crossover point does not strictly coincide with the absorption maximum that can be attributed to overlap with the weaker n–π^* band. It is noteworthy that analogous split-like spectra have been reported for the complexes of azo dye dimers with cyclodextrins.[11] Since the π–π^* electronic transition moment is directed approximately along the long axis of the dye, the observed sequence of the positive and negative CD bands in the couplet points to *M*-helical orientation of the neighbouring transition moments in the crystal. Furthermore, the helical orientation of the constituent molecules in the crystal has been evidenced by the X-ray structure of **2**.[12]

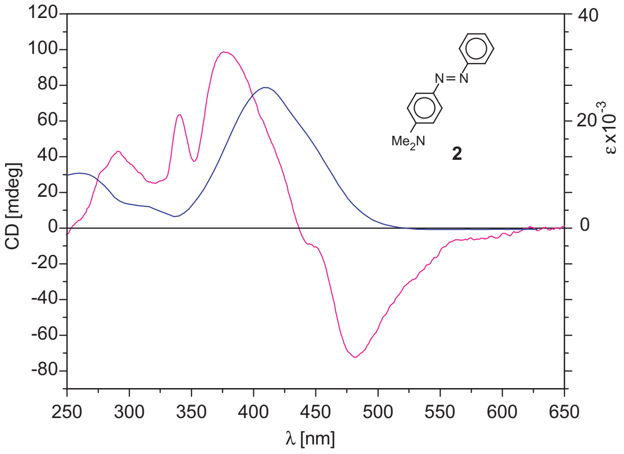

Figure 4. Solid state CD spectrum of the chiral crystal of **2** taken in KBr disk (red line) and UV–vis spectrum of **2** measured in $CHCl_3$ (blue line).

3. Conclusion

In summary, the inclusion complexation of *anti*-azobenzene in the crystal lattice of **CA** induces a strong Cotton effect in the region of the n–π* transition that results from twisting of the guest molecule. The helicity of the guest molecules can be assigned either by X-ray crystallography or deduced from the solid state CD measurements. Thus the absolute sense of the twist of the constituent molecules and their helical arrangement in the enantiomorphous crystals of methyl yellow **2** can be easily predicted from the solid state CD spectrum.

4. Experimental

The solid state CD spectra were taken with freshly prepared KBr disks and recorded with a Jasco J-715 dichrograph. A mixture of 2–5 mg of the sample and 250 mg of dried KBr was ground and formed into a disk 0.5 mm thick and with a radius of 15 mm. The disk was rotated around the optical axis and the CD recordings made for several positions in order to check a reproducibility of the spectra. The UV–vis spectra were measured with a Unicam SP-300 spectrophotometer.

4.1. X-ray structure analysis

Diffraction data were collected using a Kuma CCD diffractometer with graphite monochromated Mo Kα radiation ($\lambda = 0.71073$ Å). The structures were solved by direct methods with the program SHELXS-97.[20] Full matrix least-squares refinement was carried out with SHELXL-97.[21]

Crystal data for $C_{12}H_{10}N_2{\cdot}2C_{24}H_{40}O_5$ **1·CA**: monoclinic, $P2_1$, $a = 13.2008(8)$, $b = 8.0222(5)$, $c = 14.1689(8)$ Å, $\beta = 113.825(5)°$, $V = 51372.61(14)$ Å^3, $Z = 1$, $D_{\text{calcd}} = 1.209$ mg cm^{-3}, $T = 130(2)$ K, $R_1 = 0.0441$, $wR_2 = 0.0924$ for 2336 reflections with $I > 2\sigma(I)$. The guest molecules exhibit disorder analogous to that observed in the crystal structure of the 2:1 inclusion compound of **CA** with benzil.[6d] The nearest guest molecules packed within a single channel are not related by the crystallographic 2_1 symmetry axis directed along the channel but are transformed by the unit translation along the y axis. In consequence, the electron density maps within the channel show superposition of the two guests images related by the 2_1 axis. Unfortunately, such a disorder lowers the precision of the geometric parameters determined for the guest molecule. The guest molecule was refined with an occupancy factor of 0.5 for all atoms, with all 1–2 and 1–3 distances restrained to the expected values. Strong restraints ($\sigma = 0.005$) were imposed on the planarity of the two phenyl rings and a weak restraint ($\sigma = 0.02$) on the planarity of the CN═NC group. The torsions around the two formally single bonds between the phenyl rings and the –N═N– group were not restricted. The nonhydrogen atoms of the host and guest molecules were refined with anisotropic displacement parameters.

Crystal data for $C_{12}H_{10}N_2{\cdot}4C_{24}H_{40}O_4$ **1·DCA**: orthorhombic, $P2_12_12_1$, $a = 25.4470(10)$, $b = 13.6670(7)$, $c = 7.1722(6)$ Å, $V = 2494.4(3)$ Å^3, $Z = 1$, $D_{\text{calcd}} = 1.167$ g cm^{-3}, $T = 100(2)$ K, $R_1 = 0.0635$, $wR_2 = 0.1481$ for 2342 reflections with $I > 2\sigma(I)$. The host:guest ratio was calculated on the basis of the crystal density $\rho_m = 1.155$ g cm^{-3}, measured by the flotation method in the KI solution at 293 K and the unit-cell volume $V = 2518.8(14)$ Å^3, determined at room temperature with the Kuma KM4 point-detector diffractometer. The measured crystal density was equal to the calculated one ($\rho_x = 1.155$ g cm^{-3}) when the 4:1 **DCA**–azobenzene ratio was assumed. This stoichiometry was further confirmed by the elementary analysis (Calcd C 74.06, H 9.70, N 1.60. Found: C 74.01, H 10.16, N 1.69). Compound **1·DCA** is isostructural with **2·DCA**[18] and the guest molecules exhibit similar disorder: the nearest guest molecules packed within a single channel are related by a $2c$ translation along z. As a consequence, the observed electron density in the channel represents superposition of four different guest arrangements. Despite these difficulties, the model of the molecule of **1** could be built from the highest peaks arranged in nearly coplanar manner in the channel region. The guest molecule was refined with an occupancy factor of 0.25 for all atoms and restraints analogous to those in crystal structure of **1·CA** were imposed on the guest geometry (the torsions around the two formally single bonds between the phenyl rings and –N═N– group were not restricted). The individual isotropic displacement parameters were refined for the guest nonhydrogen atoms. To check correctness of the guest location along the channel the guest molecule was shifted at 0.3 Å steps along y and then the structure refined; the determined position of the guest corresponds with the lowest R factor for this structure.

Crystallographic data (excluding structure factors) for the structures in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication numbers CCDC 244768–244769. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK [fax: +44 (0)1223 336033 or e-mail: deposit@ccdc.cam.ac.uk].

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