ORIGINAL ARTICLE

Circular dichroism and theoretical calculations of pinacyanol dimer inclusion in γ-cyclodextrin

Sa'ib J. Khouri · Daniel Richter · Volker Buss

Abstract Aggregation of pinacyanol chloride is strongly enhanced through inclusion into γ-cyclodextrin, which was studied using both UV/Visible, derivative and Circular Dichroism (CD) spectroscopy. The intensities at 546 and at 507 nm were increased with the growing ratio of γ-cyclodextrin to dye. Both aggregates were shown to be optically active. CD spectra with two and three oppositely signed excitonic bands were shown. The structures of the aggregates have been analysed and discussed in terms of qualitative H-type aggregation and quantitative based on OSCI program. Applying eight different parameter sets aggregates of pinacyanol chloride ranging in size from 2 to 20 dye molecules were considered. The calculated energy splitting was adjusted, via the transition dipole length, to the experimentally observed band shift. Rotational strengths associated with the CD absorptions were calculated and used to obtain an estimate of the inherent twist of the dimer aggregate inside the γ-cyclodextrin cavity.

Keywords Pinacyanol dye · γ-Cyclodextrin · Circular dichroism · Aggregation · Exciton theory

Introduction

Cyclodextrins are cyclic oligosaccharides, formed by α-1,4-linked glucopyranose subunits with a truncated-shape cone that contain a hydrophobic cavity in the center [1]. Cyclodextrins are one of the most important hosts to include guest molecules into their cavities altering their physical and chemical properties through the formation of inclusion complexes [2, 3]. In the chiral environment of a cyclodextrin cavity, the achiral molecules can exhibit induced circular dichroism (ICD), which is widely applied to obtain important information about the complex structure [4].

Carbocyanine dyes have been used as guest molecules with cyclodextrins (α-, β-, or γ-) by using circular dichroism spectroscopy to study the aggregation process of carbocyanines at different conditions [5–9]. In this work, the dye of interest is 1,1′-diethyl-2,2′-carbocyanine chloride (pinacyanol chloride, Scheme 1), which has received wider attention because of its application as a saturable absorber, mode-locker, and sensitizer in imaging technology [10, 11]. UV/Vis and induced circular dichroism spectroscopy were used in this study to investigate the interaction between pinacyanol chloride (achiral) and γ-cyclodextrin in aqueous solutions under different concentrations of both reactants [7–9, 12], followed by theoretical calculations to simulate the dye aggregates of the type present in the cyclodextrin cavity.

According to the exciton theory, the dimer or higher forms of dye molecules are treated as point dipoles. Interaction of the transition dipoles splits the excited state of the dye aggregate into levels according to the number of monomers in the aggregate, the result of this splitting is reflected in the UV/Vis and CD spectra. For a dimer aggregate, two levels result with energies and intensities according to the geometry-dependent interaction term. The energy gap between the two defined exciton states is called Davydov splitting [13, 14].

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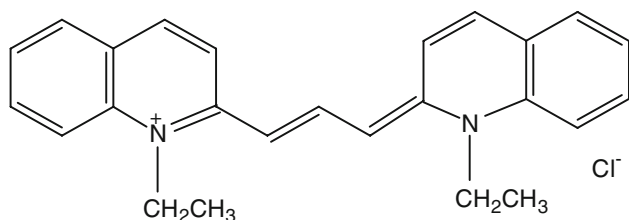
Scheme 1 Pinacyanol chloride

Materials and methods

Materials

γ-Cyclodextrin sample is a gift from Wacker-Chemie GMBH, München and was used as received. 1,1′-diethyl-2,2′-carbocyanine chloride (Pinacyanol chloride) was obtained from Sigma. Triple distilled water was used throughout the study.

Experimental methods

The solutions needed for studying were prepared by using a fixed volume (4.00 mL) using a stoppered rolled rim glasses regarding the size of measuring cell (to maintain the same conditions and precision for all samples). Measuring cells were used with different optical path lengths as appropriate.

The UV/Vis-spectra were recorded by using a Perkin-Elmer Lambda 5 spectrophotometer. Circular Dichroism spectra were obtained using an AVIV circular dichroism spectrometer, Model 62DS. Both instruments were connected to a personal computer for data collection in ASCII-file format.

Computational method

The theoretical calculations are based on the coupled oscillator theory (OSCI) of extended dipoles [15, 16], and modified for chiral aggregates [17], which was developed to calculate the oscillator and the rotatory strength of a coupled dye system using an input data set derived from the UV/Vis-transition of a single dye.
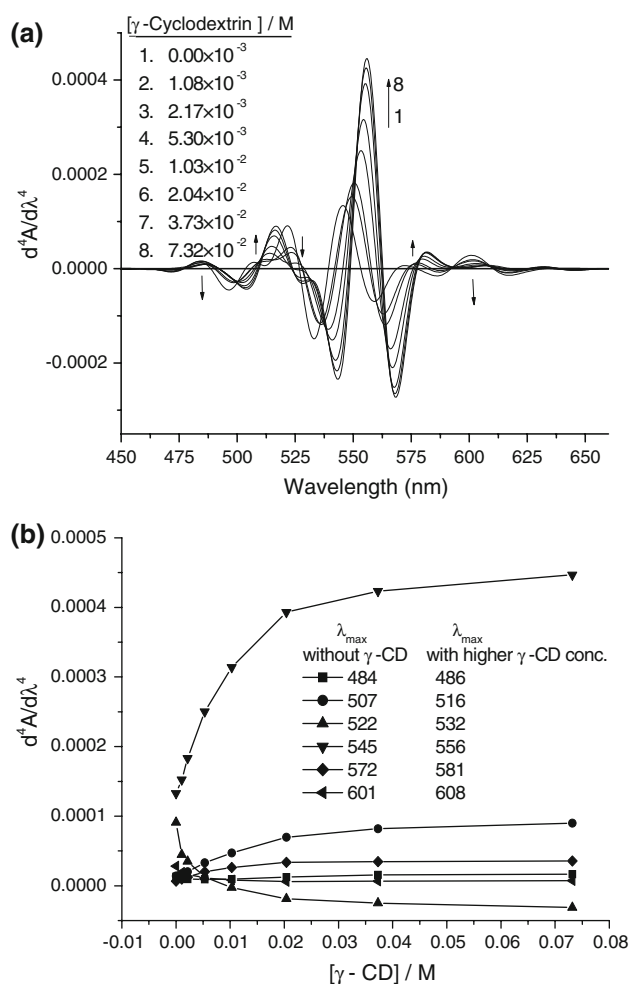
Results and discussion

Figure 1a shows the effect of γ-cyclodextrin on the visible spectra of pinacyanol chloride (2.0×10^{-4} M) in aqueous solution. The UV/Vis spectrum of the free pinacyanol chloride (number 1) shows a mixture of several components, which were attributed to monomer, dimer, and higher aggregate at the wavelengths 600, 545, and 507 nm,
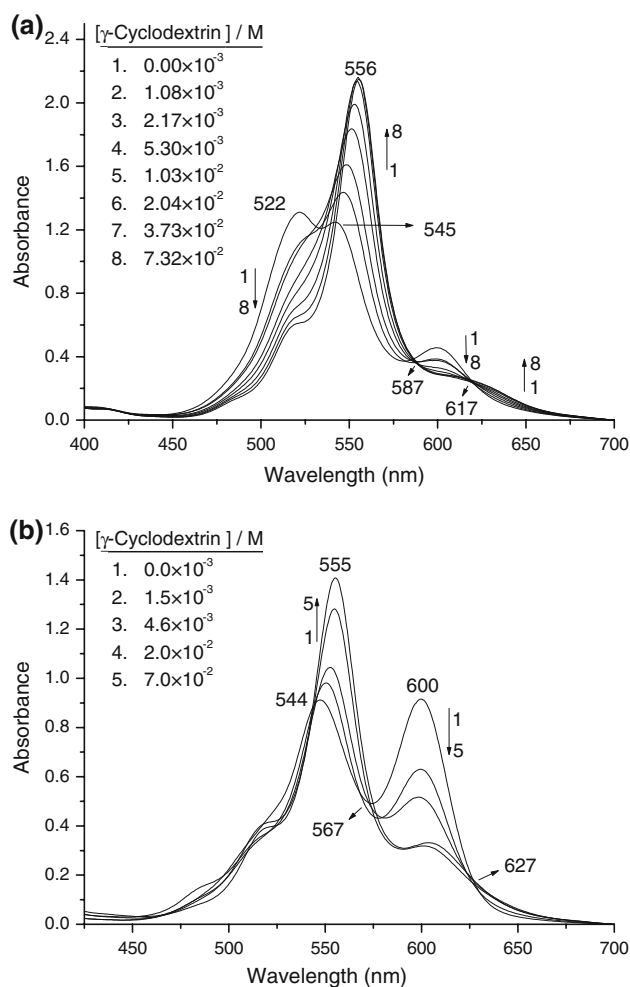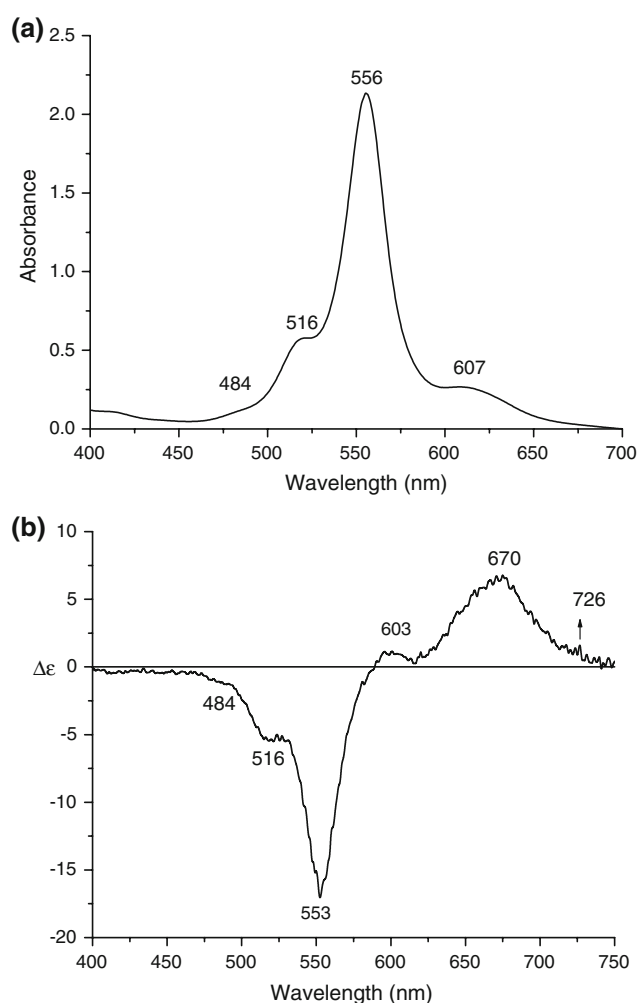

Fig. 1 a The effect of γ-cyclodextrin added to an aqueous solution of pinacyanol chloride (2.0×10^{-4} M); 0.10 cm cell at room temperature. b The effect of γ-cyclodextrin added to an aqueous solution of pinacyanol chloride (1.5×10^{-5} M); 1.00 cm cell at room temperature

respectively [18, 19]. The addition of γ- cyclodextrin to this mixture resulted in a decrease in the intensity of the absorption at 600 and 522 nm, and an increase in the intensity of the absorption at 545 nm. This increase is accompanied by a red shift, reaching a value of 556 nm at higher γ-cyclodextrin concentrations. The presence of two isosbestic points at 587 and 617 nm is noted as the host concentration is increased. Figure 1b shows the effect of added γ-cyclodextrin on the visible spectra of pinacyanol chloride (1.5×10^{-5} M) in aqueous solution, in which the dye molecules are present mainly as monomers and dimers [19]. In this case the addition of γ-cyclodextrin leads to a decrease in the intensity of the band at 600 nm and increase in the intensity of the band at 545 nm. This accompanied by a significant shift toward lower energy. Three isosbestic points are visible and appear at 567, 627, and 544 nm.

(a)

[γ-Cyclodextrin] / M
1. 0.00×10^{-3}
2. 1.08×10^{-3}
3. 2.17×10^{-3}
4. 5.30×10^{-3}
5. 1.03×10^{-2}
6. 2.04×10^{-2}
7. 3.73×10^{-2}
8. 7.32×10^{-2}

(b)

λ_{max} without γ-CD | λ_{max} with higher γ-CD conc.
484 | 486
507 | 516
522 | 532
545 | 556
572 | 581
601 | 608

Fig. 2 **a** The fourth derivative of the spectra shown in Fig. 1a. **b** The peak heights of the bands in Fig. 2a as a function of the γ-cyclodextrin concentration

(a)

(b)

Fig. 3 The visible absorption spectrum (**a**) and the CD spectrum (**b**) of pinacyanol chloride (7.5 × 10^{-5} M) and γ-cyclodextrin (1.0 × 10^{-1} M) in aqueous solution; 0.20 cm cell at room temperature

Figure 2a shows the fourth derivative spectra of all UV/Vis-spectra given in Fig. 1a. The changes in the intensity of the absorption bands and the red shifts of the bands maxima become clearer and can be measured quantitatively [20], as indicated in Fig. 2b. The intensity increase of the bands at 507, 545 and 572 nm, and the intensity decrease of the bands at 484, 522, and 601 nm are clearly visible in Fig. 2b. The increase of the dimer band at 545 nm indicates a favourable interaction between pinacyanol chloride as dimer and the γ-cyclodextrin host, probably occurring inside the cyclodextrin cavity. The intensity increase of the band at 507 nm, which we have attributed to one of the higher aggregates, probably a trimer, indicates likewise that the cyclodextrin host promotes this aggregation. However, for steric reasons this interaction must occur outside the cavity or through partial inclusion. The decrease in the intensity of the band at 522 nm, which we have attributed to the vibronic band of the dimer, may be a consequence of the different kind of interaction in the dimer or of the change of the environment from aqueous to organic non-polar inside the cyclodextrin cavity.

Figure 3 depicts the visible absorption and the circular dichroism spectrum of an aqueous solution of 7.5 × 10^{-5} M pinacyanol chloride with 1.0 × 10^{-1} M γ-cyclodextrin. The CD-spectrum shows two main absorption bands at 553 (18,080 cm^{-1}, negative) and 670 nm (14,925 cm^{-1}, positive) in addition to a small positive band at 603 nm (16,500 cm^{-1}) and two shoulders at 516 and 484 nm. The mean of these two main energies is 16,500 cm^{-1} or 603 nm, which is identical to the position of the monomer absorption band. It can be safely assumed that the two bands correspond to the two exciton states of the dye in its dimeric aggregation state. The weak negative band at 516 nm (19,380 cm^{-1}), the positive CD band at 603 (16,500 cm^{-1}) and the positive shoulder at 726 nm (13,770 cm^{-1}), which can be seen clearly in Fig. 3b, are

ascribed tentatively to the trimer form of pinacyanol chloride. These three bands have an average energy of 16,575 cm^{-1}, which is identical to the energy of the monomer at 603 nm (16,500 cm^{-1}), and the trimeric aggregates generate three exciton states [21].

The interaction of dyes under favourable circumstances may result in the formation of delocalised exciton states with energy separations depending on the relative orientation of the monomers [11]. In a chiral environment the exciton states may acquire rotational strengths enabling their identification in a CD spectrum. The exciton states of a dimer always have opposite signs, and they are displaced symmetrically from the absorption of the monomer; this behaviour is shown by the two bands at 553 and 670 nm. Such a dimer shows no absorbance at the monomer energy in the UV/Vis or CD spectrum. From the intensity of the exciton states one can deduce qualitatively the relative orientation of the two components of the dimer. If, as in Fig. 3a only the high-energy component of the dimer bands is visible, the two components aggregate in a face-to-face (H-type) manner with an acute angle between their long axes. In a trimer, the three monomer excitations split into three exciton states, of which two are again symmetrically displaced from the monomer absorption, and the third is observed at the wavelength, where the monomer absorbs [21]. This appears to be a valid interpretation of the three additional bands in Fig. 3a as discussed above.

In Fig. 3b the negative and the positive CD bands at 553 and 670 nm, respectively, have an approximately Gaussian shape, in spite of the presence of shoulders beside the bands. The rotational strengths associated with these bands were evaluated directly from the measured spectrum using the formula, which applies to the evaluation of approximately Gaussian shaped curves as in the following equation:

$$R = 0.696 \times 10^{-42} \sqrt{\pi} \times 3,300 (\Delta\varepsilon^{\mathrm{max}})(\Delta_\lambda / \lambda^{\mathrm{max}})$$

where Δ_λ is the half-width of the absorption band (in nm) at 1/e times its height ($0.368\Delta\varepsilon^{\mathrm{max}}$), e is the base of the natural logarithm. The values obtained are respectively, -2.16×10^{-39} and 1.50×10^{-39} cgs units for the two bands. Theoretically, the two values should be the same [13]; their mean absolute value is 1.83×10^{-39} cgs units, and this value will be used in the coupled oscillator calculations [22]. From a visible spectrum of pinacyanol chloride in pure ethanol, in which the dye is present in an approximately pure monomer state in the concentration range between 10^{-6} and 10^{-4} M, the oscillator strength of the absorption band is derived with a value of 0.7037. The electric transition moment and the length of the transition moment are found to be 3.175889×10^{-29} cm and 1.982 Å respectively.

Modeling the pinacyanol aggregation with OSCI

The blue-shifted aggregate spectra of pinacyanol chloride in aqueous solution provide strong evidence for a face-to-face one-dimensional arrangement of the dye molecules [23]. In order to model these aggregates, calculations were performed by using a program known as the coupled oscillator model ("OSCI") [15–17]. This program needs, as input file, the data for the isolated dye excitations, in particular the absorption maximum (in nm) and the length and the charge of each of the dipole contributing to the aggregate. The data sets for pinacyanol aggregate have been obtained in the preceding section. For calculating the interaction matrix, a model of the aggregate is built in 3-dimensional space, and from the Cartesian coordinates the interaction matrix is set up using the extended dipole model for calculating the interaction potential.

There is an adjustable parameter in the model in that the length and the charge of the extended dipoles can be adjusted to best fit the experimental data, with the restriction that the product of the transition moment length and charge has to be constant. With this in mind, eight different parameter sets were developed and applied to 9 molecular aggregates of pinacyanol of different aggregate size. Four different combinations of transition dipole lengths and charges all leading to the same transition dipole moment of 3.175889×10^{-29} cm were combined each with two different distances of the monomer molecular planes in the aggregate, 3.5 and 4.0 Å. Table 1 lists the entry data for the eight different sets that were be used in the coupled oscillator program. With each of the eight data sets, nine stacked dye aggregates were calculated, which differed in the numbers of monomers ranging from 2 to 20. There was no internal twist applied to the aggregates, i.e., they were achiral. The calculated blue shifts of the highest energy exciton states of each aggregate with each set of entry data are depicted graphically in Fig. 4.

Figure 4 shows graphically the calculated wavelength shifts of the nine aggregates calculated with the eight

Table 1 The eight different entry sets for the OSCI program

| Model number	Dipole charge/10^{-20} C	Dipole length/Å	Monomer distance/Å
1	16.0219	1.9821	3.5
2	8.01095	3.9642	3.5
3	4.00547	7.9284	3.5
4	2.00274	15.857	3.5
5	16.0219	1.9821	4.0
6	8.01095	3.9642	4.0
7	4.00547	7.9284	4.0
8	2.00274	15.857	4.0
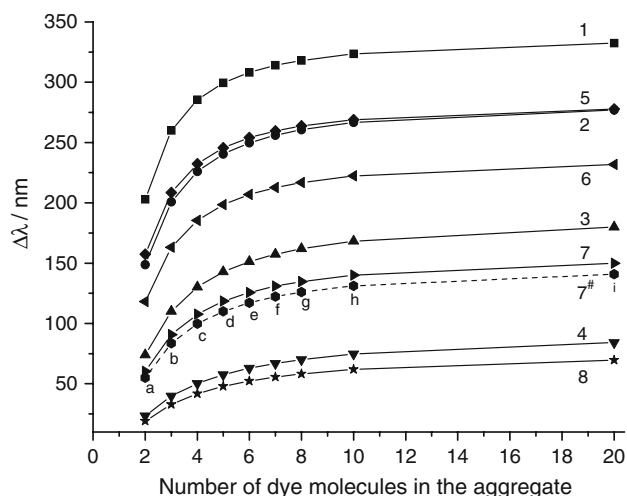
Fig. 4 The blue shift of pinacyanol chloride as a function of its aggregation state calculated with different values of dipole length and charge

Fig. 5 Rotational strength as a function of the twisted angle of the pinacyanol dimer

different data sets. The experimentally observed wavelength shift of the dimer relative to the monomer is 55 nm [18]. The data set that comes closest to this value is number 7, which gives a blue shift of 540.6 nm. By fine-tuning the dipole length and charge to 8.50 Å and 3.7361×10^{-20} C, respectively, the experimental result is reproduced quantitatively, i.e., wavelength shift is 55 nm. We call this dipole, together with the distance of 4 Å and 0° angle twist the data set number 7*. The maximum wavelength values belong to the points from a to i in Fig. 4 are respectively 546, 517.5, 491, 484, 479, 475, 470, and 460 nm.

With increasing aggregate size the blue-shift increases, but not in a linear manner, but approaching a limiting value instead. With an aggregate size of 20 stacked dye molecules, the limit is not quite reached, but a good estimate is obtained where the infinite aggregate might absorb. The used data sets differ significantly in the predicted blue-shift of the infinite aggregate, from about 60 nm for set number 8 to more than 340 nm for set number 1. With the set which reproduces the dimer shift rather well (number 7*) the calculated wavelength shift of the very large aggregate is 125 nm, which corresponds to an absorption maximum at 476 nm in surprisingly good agreement with the value found for the limiting aggregate (Fig. 4).

The experimental value for the rotational strength of the two exciton states of the pinacyanol dimer in γ-cyclodextrin is 1.83×10^{-39} cgs units. If this rotational strength is due to a twist of the two dye molecules against each other, OSCI allows calculating the twist angle. For this, different twist angles are used as input data, together with the data derived before, and oscillator and rotational strengths calculated on the basis of the assumed structure. Entering the data of set number 7* into OSCI and increasing the twist angle in steps of 0.3°, one thus obtains the rotational
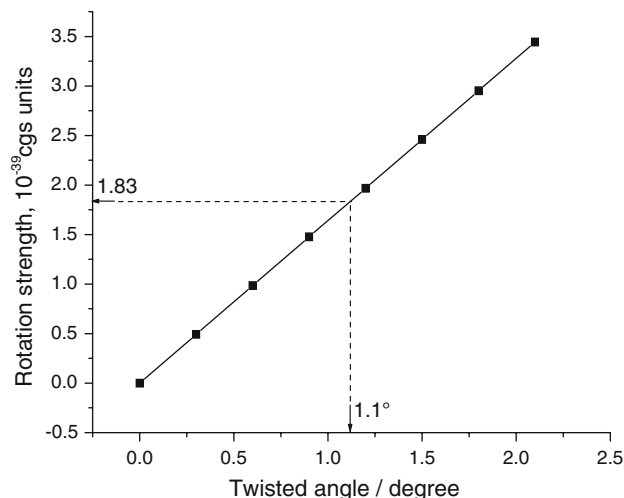
strength as a function of the twist angle of the dye molecules against each other. Figure 5 shows that this function is linear: the greater the twist, the greater the rotational strength. The angle, which is appropriate to the observed rotational strength from the CD spectrum, is 1.1°.

The difference between the spontaneous aggregation of pinacyanol chloride in water and the aggregation promoted by γ-cyclodextrin is tremendous: instead of a complex concentration dependent equilibrium involving at least four different entities, γ-cyclodextrin promotes the formation of one major aggregate, which on all accounts corresponds to a face-to-face (H-type) dimer. Both the intensities of the absorption bands and the shift of the absorption maximum in addition to the formation of isosbestic points attest to this. In Fig. 1, the increase in the intensity of the dimer band as a result of adding γ-cyclodextrin proves the formation of the dimeric form at the cost of other forms. The red shift of the absorption maximum due to the change of the medium from water (polar) to the non-polar microenvironment inside the cavity is an indication that the dimer forms inside γ-cyclodextrin ring, which is located at the central portion of the methane chain of the dye.

In the dimer, the dye molecules are twisted slightly against each other, as was proven by the visible CD-spectra with their oppositely signed absorption bands displaced symmetrically from the monomer absorption. The twist, and the preference of one sense of twist over the other, is a consequence of the chiral surface provided by the cyclodextrin cavity. Analysis of the CD-spectra in terms of the exciton model and the numeric calculation of rotational strength using the extended dipole model leads to a calculated splitting, the Davydov splitting, which can be adjusted via the electric transition moments, to agree with the experimentally observed splitting. Modelling the

pinacyanol chloride with OSCI gives a value of 1.1° as the twisting angle of the dimer in the γ-cyclodextrin cavity. The positive sign of the twisting angle is deduced from the positive sign of the long wavelength CD band (positive exciton chirality).

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