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Trimeric Cyclic Assemblies of Calix[4]arene-Tethered Bismerocyanines**

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Dedicated to Professor Reinhold Tacke on the occasion of his 60th birthday

The art of supramolecular chemistry originates from well-designed molecular building blocks that are equipped with receptor groups for an encoded directional self-assembly path.[1] Among the available noncovalent interactions, hydrogen-bonding and metal-ion–ligand coordination are well-known for their outstanding directionality. A plethora of cyclic assemblies have been constructed using these interactions; apart from the fact that cyclic arrays are of fascinating aesthetic beauty, cycle formation can be considered as a benchmark test for the directionality of self-assembly.[2–4] Previously, we have shown that dipolar merocyanine dyes **1** form centrosymmetric dimer aggregates with high binding constants K_D of about $10^6\,\mathrm{M}^{-1}$ in nonpolar solvents, such as 1,4-dioxane or CCl_4 (Figure 1 a,b).[5] This dimerization originates predominantly from dipole–dipole interactions between these chromophores, which possess an exceptionally large ground-state dipole moment μ_g of about 17 D owing to a major contribution of the zwitterionic resonance structure (Figure 1 a). The geometry of these dimer aggregates is highly defined, which reveals that the dipolar interactions are directional, and therefore highly promising for the construction of more demanding supramolecular architectures. Indeed, the formation of well-defined supramolecular polymers[6] and also discrete bimolecular π stacks[7] was achieved from ditopic bismerocyanine monomers that are tethered by appropriate spacers to guide self-assembly into desired architectures.[8] However, to date, cyclic arrays based on dipolar aggregation of this commonly used class of chromophores are unprecedented. Herein we report that dipolar-interaction-mediated self-assembly of properly designed bismerocyanine building blocks leads to the formation of discrete cyclic arrays of merocyanine dyes (Figure 1 c).

Our approach is based on the intermolecular aggregation of merocyanine dyes into dimeric pairs; this aggregation directs the self-assembly of appropriately tethered bismerocyanine building blocks into a cyclic geometry (Figure 1 c). To realize this concept, building block **2** was synthesized in which two merocyanine chromophores are attached at the wide upper rim of a calix[4]arene in the cone conformation (see the Supporting Information).[9,10] This calixarene–bismerocyanine conjugate has the required structural features for self-assembly into a trimeric cyclic array, as the calixarene scaffold provides structural predisposition of the chromophores, which can easily adopt an angle of 60°, as well as the structural rigidity to minimize the entropic costs for the self-assembly.[11]

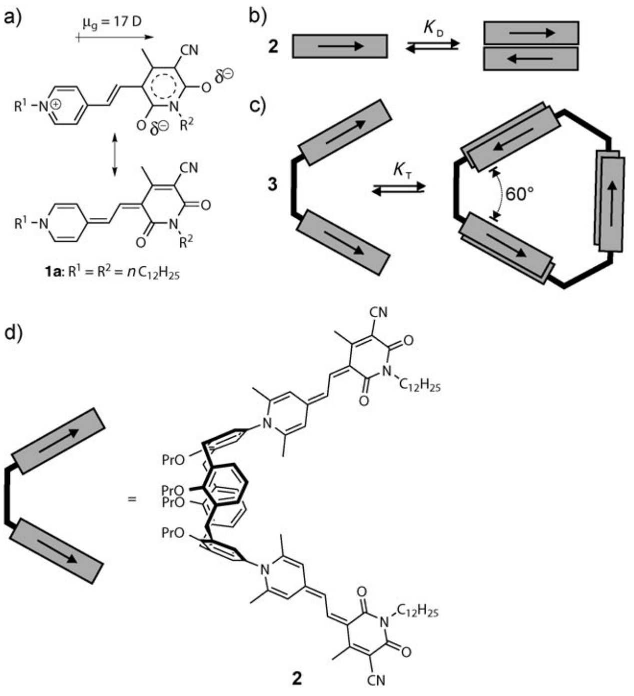

Figure 1. a) Resonance structures of highly dipolar merocyanine dyes **1**. b) Representation of the dimerization of merocyanine dyes into centrosymmetric aggregates by dipole–dipole interactions. c) The construction of cyclic trimers containing three merocyanine dimer units that are formed by self-assembly of the calixarene-tethered bismerocyanine building block **2** (d).

The self-assembly of calixarene-tethered bismerocyanine dye **2** was studied by concentration-dependent UV/Vis absorption spectroscopy (Figures 2 and 3) by using cells with path length between 0.01 and 1 cm. These investigations showed significant changes in the spectra upon variation of concentration in the range from 10^{-6} to 3×10^{-4} (Figure 2). The UV/Vis spectra in the most dilute solution can be ascribed to the pure monomeric dye with an intensive charge-

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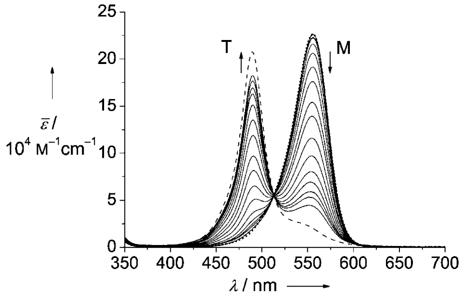

Figure 2. Concentration-dependent UV/Vis spectra of **2** ($c = 3\times10^{-4}$ to 1×10^{-6} M) in CHCl$_3$ at 298 K. The arrows indicate the decrease in the intensity of the monomer band (M; •••••) and the appearance of the trimeric aggregate band (T; -----) with increasing concentration. The spectra of pure monomeric dyes and the pure trimer aggregates were derived from the data at two different concentrations and the aggregation constants.

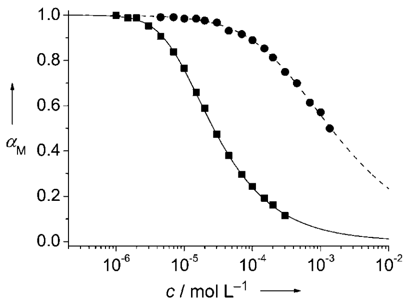

Figure 3. Fraction of monomer (α_M), calculated from UV/Vis data at certain wavelengths, as a function of dye concentration, and nonlinear regression analysis of the data points for **2** (■, at 535 nm) and **1a** (●, at 505 nm)[7] in CHCl$_3$ at 298 K based on the trimerization (——) and dimerization (-----) model.

transfer band occurring at 556 nm (denoted as M in Figure 2).[5] With increasing concentration, the intensity of the monomer band decreases, with concomitant appearance of a hypsochromically shifted absorption band at 490 nm, which can be attributed to the formation of dimeric chromophore pairs (within a trimeric cyclic array) and excitonic coupling of the two chromophores in the respective dimer units.[5,12] A second excitonic band at longer wavelength (ca. 560 nm) is indicative for a slightly twisted arrangement of the two chromophores in these dimers.[5,13] A well-defined isosbestic point at 513 nm is observed over a considerable concentration range, which clearly indicates the presence of a two-state equilibrium between the monomers and well-defined aggregates.

Both the monomer and aggregate spectra of **2** are in close agreement with the respective spectra observed for the reference dye **1a** (see the Supporting Information, Figure S1),[7] as the latter shows a maximum at 559 nm for monomer and a dimer maximum at 490 nm. Moreover, the absorption coefficients of the respective spectra of bismerocyanine **2** are about twice those obtained for mono-chromophoric **1a**. These results reveal that the spectral properties of monomeric and aggregated **2** are barely affected by the calixarene scaffold. The observed similarity of monomer absorption spectra of **1a** and **2** is quite reasonable, because the twisted arrangement of the chromophore planes with respect to the phenylene units of the calixarene scaffold in **2** disfavors further conjugation of the chromophore, whilst the repulsive interaction of the parallel oriented dipole moments prevents intramolecular aggregation in a pinched cone calixarene conformation with two closely stacked dyes.[9] More importantly, the good agreement of the aggregate spectrum of **2** to the dimer spectrum of **1a** indicates that the chromophore units of **2** form independent intermolecular chromophore pairs, which is in accordance with the cyclic trimer structure obtained from molecular modeling (see Figure 4). An extended stack arrangement, as observed for self-assemblies of other bismerocyanine dyes that show a more hypsochromically shifted aggregate band, can be excluded in the present case.[6,7]

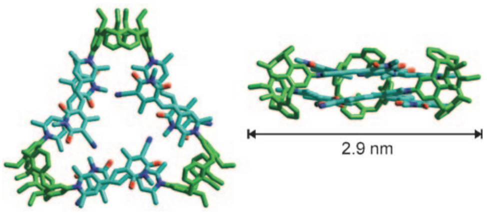

Figure 4. Top and side view of the MM+ geometry-optimized molecular model for cyclic trimers of **2**.[20] For simplicity, all alkyl substituents are replaced by methyl groups, and hydrogen atoms are omitted. Calixarenes: green; merocyanines: C pale blue, N dark blue, O red.

To elucidate the self-assembly of **2** into cyclic trimers, and to examine whether the formation of linear oligomers is feasible at all, the concentration-dependent spectral changes were evaluated according to a mathematical model [Equation (1)] that describes a two-state equilibrium between

$$\alpha_M = \sqrt[3]{\frac{1}{6K_T c_0^2} + \sqrt{\left(\frac{1}{9K_T c_0^2}\right)^3 + \left(\frac{1}{6K_T c_0^2}\right)^2}} + \sqrt[3]{\frac{1}{6K_T c_0^2} - \sqrt{\left(\frac{1}{9K_T c_0^2}\right)^3 + \left(\frac{1}{6K_T c_0^2}\right)^2}} \tag{1}$$

monomers and cyclic trimers. In this model, the fraction of monomers α_M is expressed as a function of the overall monomer concentration c_0 and the trimerization constant K_T. (For the derivation of this model see the Supporting Information).

The apparent molar absorptivity $\bar{\varepsilon}$ of the dye in solution may be expressed in the form given in Equation (2):

$$\bar{\varepsilon} = \alpha_M \varepsilon_M + (1 - \alpha_M)\varepsilon_T \tag{2}$$

where ε_M and ε_T are the molar absorptivities of a free and the trimer-bound monomer unit, respectively.

Nonlinear regression analysis of the apparent molar absorptivities of **2** at certain wavelengths as a function of dye concentration according to this cyclic trimerization model [Eq. (1) and (2)] gave an excellent fit, and yielded a trimerization constant K_T of 1.9×10^9 M^{-2} (Figure 3). The considerably increased thermodynamic stability of the trimolecular aggregates of bismerocyanine **2** with respect to the dimers of reference **1a** ($K_D = 590\,\text{M}^{-1}$)[7] is evident from the concentration at which half of the monomers are incorporated into the respective aggregates; that is, where α_M equals 0.5 (Figure 3). For **2**, this α_M value is already reached at a total monomer concentration of $2.6 \times 10^{-5}\,\text{M}$, which is nearly two orders of magnitude lower than the respective concentration for **1a** ($1.4 \times 10^{-3}\,\text{M}$). It is important to note that the formation of linear oligomers of bismerocyanine **2** by the intermolecular dimerization of the chromophores can be ruled out because the analysis of the UV/Vis dilution experiments data based on the isodesmic model[14] gave only poor fits. Furthermore, the apparent decrease of the critical self-assembly concentration (Figure 3) can hardly be explained by the formation of simple linear oligomeric chains of dimeric chromophore pairs. Theoretically, however, above a certain overall monomer concentration, known as the effective molarity *EM*, the formation of linear chains would be favored over cyclic aggregates.[15] For the present trimerization process in trichloromethane, an effective molarity *EM* of 0.145 M can be estimated (see Supporting Information). As this value of *EM* is much higher than the concentration range (3×10^{-4} to $1 \times 10^{-6}\,\text{M}$) in these studies, the formation of linear chains of bismerocyanine **2** is not feasible under the present conditions.

Further evidence for the self-assembly of bismerocyanine **2** into a trimolecular complex was obtained from mass spectrometry experiments.[16] A sample for MALDI-TOF mass spectrometry was prepared by solvent evaporation from a trichloromethane solution of **2** containing 2-[(2*E*)-3-(4-*tert*-butylphenyl)-2-methylprop-2-enylid-ene]malononitrile (DCTB) as a matrix. The mass spectrum recorded in positive-ion mode showed a peak that corresponds to the singly charged trimer cation (*m*/*z* found 4463.97, calcd for $[M_3]^+$ 4464.09),[17] along with signals that could be assigned to the singly charged dimer and monomer cation (see the Supporting Information, Figure S2). These MS data are supportive for the formation of discrete trimer aggregates in solution and partial fragmentation of trimers into the respective dimers and monomers in the gas phase.

Scanning tunneling microscopy (STM) measurements at the liquid–solid interface were performed to directly visualize the self-assembled cyclic trimer structure of dye **2**. For this purpose, a drop of a solution of **2** in 1,2,4-trichlorobenzene (TCB) was applied on a Au(111) substrate and the STM tip was immersed in the solution. TCB was used as solvent because it provides both a low vapor pressure required for STM measurements at the liquid–solid interface and nearly complete aggregation even at low concentrations owing to the lower polarity of TCB relative to that of $CHCl_3$.[18] Figure 5 shows the STM images at a tunneling current of 0.15 nA. In the large-area image, globular objects can be observed that are randomly adsorbed over the whole surface (Figure 5a). The higher-resolution image reveals that these objects are discrete and have a diameter of (3.4 ± 0.9) nm, as obtained from cross-section analysis (Figure 5b,c).

According to the MM+ geometry-optimized model of the trimolecular complex of **2** (Figure 4), the lateral dimension of the cyclic trimers from calixarene to calixarene corner is 2.9 nm. Taking into account the dimensions of the alkyl substituents at the calixarene units and at the imide nitrogen atoms of the chromophores, this value corresponds well to the diameter of the objects observed by STM. We have attempted to measure high-resolution images, such as those reported for monolayers of adsorbed organic dyes.[19] However, upon increasing the tunneling current to 0.20 nA and above, the spherical objects disappeared because of scratching of the aggregates by the tip. This effect indicates a considerable height of the aggregates and a weak aggregate–substrate interaction. From the dimensions of the obtained objects and the scratching behavior at higher tunneling current, a cyclic trimer structure, as shown in Figure 4, is very reasonable for the self-assembly of **2**.

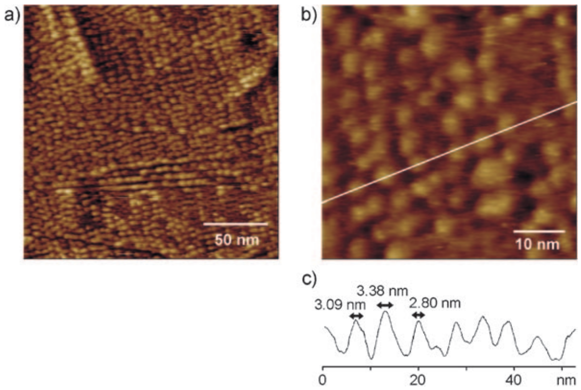

Figure 5. a,b) STM images of cyclic trimers of calixarene–bismerocyanine conjugate **2** at the Au(111)/trichlorobenzene interface ($E_{\text{bias}} = -0.6$ V, $I = 0.15$ nA). c) Cross-section analysis along the line in (b).

From the structural point of view, the aggregate model presented in Figure 4 is related to the so-called double rosette aggregates developed by Reinhoudt and co-workers, as in both systems three calix[4]arene units constitute the corners of triangular cyclic aggregate structure.[21] In the case of those double rosettes, the calixarene scaffolds are diametrically functionalized with two melamine units at the upper rim, and such calixarene–melamine conjugates form thermodynamically very stable cyclic aggregates by co-aggregation with a large variety of different barbiturates and cyanurates. These aggregates are held together by the cooperative formation of 36 hydrogen bonds and π–π stacking interactions. It was also reported that when a hydrogen-bonding barbiturate–acceptor merocyanine dye was co-aggregated, a circular array of six merocyanine chromophores was formed.[21b] UV/Vis dilution studies in trichloromethane revealed that half of these aggregates were formed at a calixarene unit concentration of $7.5 \times 10^{-5}\,\text{M}$, a value which is similar to the one found for the aggregates of calixarene–bismerocyanine conjugate **2**. However, in the latter case the aggregate is hold together only by the formation of three merocyanine dimer units through dipolar interaction between the merocyanine chromophores, and hydrogen bonds are totally absent. This comparison underlines the strength of the "dipolar aggregation" binding motif.[5]

In summary, the supramolecular construction of a novel cyclic array of merocyanine dyes containing three chromophore dimer units is achieved for the first time by employing a properly designed bismerocyanine building block tethered with a preorganizing calix[4]arene scaffold. The self-assembly of this building block was studied by concentration-dependent UV/Vis absorption and by MS and STM measurements, and evaluated by a newly introduced mathematical model for cyclic trimerization. In this work, we have demonstrated the potential of dipolar aggregation as a novel directional and specific supramolecular binding motif for the creation of more elaborate supramolecular architectures beyond simple dimer aggregates.

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Keywords: calixarenes · dipolar aggregation · dyes/pigments · macrocycles · self-assembly

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