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Photoresponsive melamine·barbiturate hydrogen-bonded assembly†

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UV-irradiation of hydrogen-bonded assembly between *trans*-azobenzene-incorporated melamine and barbiturate in chloroform drastically suppressed transformation from soluble cyclic rosette into insoluble tape-like polymers.

Controlling supramolecular structure of self-assembled molecules and the assembly process thereof by external stimuli, such as light, is a powerful strategy to elevate various molecular self-assemblies to dynamic molecular devices. A combination of *N*,*N′*-disubstituted melamine and barbiturate (or isocyanurate) is one of the most promising supramolecular building blocks; these coaggregate using complementary DAD·ADA triple hydrogen bonds and that provides three different supramolecular architectures, *i.e.*, discrete cyclic hexamers (rosettes) and two polymeric tape-like assemblies (linear and crinkled tapes).[1] The pioneering studies by Whitesides's group demonstrated that introduction of bulky substituents (*e.g.*, 4-*tert*-butylphenyl) into melamine results in the preferential formation of rosettes.[2] Although the mechanical principle of this remained controversial,[3–5] the supramolecular architecture of melamine·barbiturate assemblies can be controlled photochemically when geometrically photoswitchable molecules are incorporated into melamine as *N*-substituents. We herein report the assembly of melamine **1** bearing photoresponsive azobenzene units with 5,5-diethyl barbituric acid **2** (Fig. 1), in which *trans* → *cis* photoisomerization of azobenzene units stabilized the rosette assembly in solution.

Melamine **1** is endowed with the ability to alter the bulkiness of *N*-substituents by *trans*–*cis* isomerization of azobenzene units (**1EE**, **1EZ** and **1ZZ**, where **E** and **Z** represent the *trans* and *cis* conformations of one azobenzene unit in a molecule, respectively). The *cis*-azobenzene unit in **1** is expected to be more bulky than the *trans*-one with respect to the hydrogen bonding direction, *i.e.*, toward the neighboring molecules in an assembly. Molecular modeling of **1EE** and **1EZ** shown in Fig. 1 nicely shows the plausibility of the expectation.

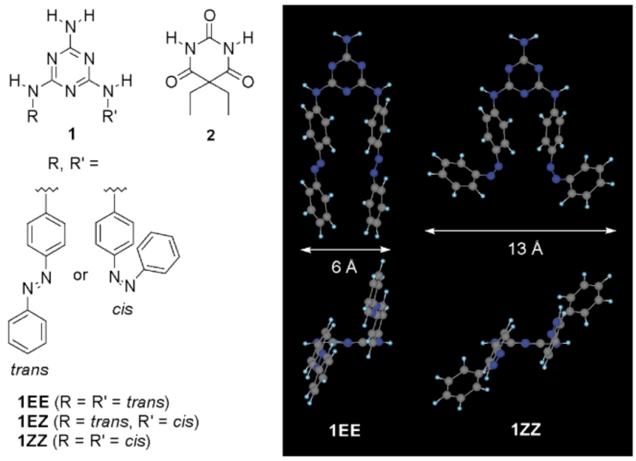

Fig. 1 Molecular structures of **1** and **2** and the computer-optimized structures of **1EE** and **1ZZ** (upper, top views; lower, views from azobenzene unit).

Solubility of the melamine·barbiturate assemblies in non-polar solvents is one of the good indicators for determining the supramolecular architectures.[3,6] Generally, discrete rosettes show very high solubility in comparison with the each complement alone and the competing polymeric tapes. When an equimolar mixture of solid samples of conformationally pure **1EE** (> 99%) and **2** was suspended in chloroform (up to [**1EE**] = [**2**] = 100 mM) at 15 °C, both components were dissolving slowly—dissolution continued for approximately 5 min, leaving a trace solid. Gentle heating at 40 °C gave a completely homogeneous solution within seconds. Given the very low solubility of **1EE** (< 1.6 mM) and **2** (< 0.5 mM) alone in chloroform even at 60 °C, the significant increase in solubility demonstrates the preferential formation of rosette (**1EE**·**2**)$_3$ (step (i) in Scheme 1). ^{1}H NMR spectrum of the assembly in CDCl$_3$ (5–40 mM) exhibited the NH and NH$_2$ proton signals of **1EE** in a largely downfield-shifted region (δ = 9.73 and 7.10, respectively),† consistent with well-defined rosettes as reported by Whitesides *et al.*[3]

Aging the assembly solution (40 mM) in the dark at 15 °C gave significant precipitates within 100 h (Fig. 2a, left). The isolated precipitates exhibited very low solubility in chloroform even under the reflux conditions (< 1.3 mM). This excludes the possibility that the precipitates are formed *via* the inter-supramolecular (hierarchical) aggregation of rosettes. The low solubility also manifests that the precipitates are not random mixtures of individually precipitated **1EE** and **2**, because under the same conditions, such a random mixture should dissolve in chloroform as step (i) in Scheme 1. Indeed, an IR spectrum (ATR) recorded for the precipitates exhibited C=O stretching modes of **2** in the region of 1640–1800 cm^{-1}, strikingly different from those recorded for **2** alone (Fig. 2b).[7] For example, no peak was observed at around 1764 cm^{-1} for the precipitates, whereas an intense peak was observed at 1764 cm^{-1} for **2** alone.‡ In the precipitates, the corresponding peak must have shifted to lower frequency region, very likely due to the formation of DAD·ADA hydrogen bonding. Thus, the combination of the IR spectral result and the low solubility of the precipitates (step (iii) in Scheme 1) leads us to conclude that the observed precipitation is a consequence of accumulation of insoluble tapes (**1EE**·**2**)$_n$, which initially equilibrated with rosettes in a small proportion in the solution, but owing to their low solubility, they gradually precipitated at the expense of rosettes (step (ii) in Scheme 1). Supporting evidence for this comes from the absolute 1 : 1 stoichiometry of **1EE** : **2** in the precipitates, confirmed by the ^{1}H NMR spectrum of the precipitates redissolved in DMSO-d_6.

A photoisomerization experiment was performed for the assembly solution of **1EE** and **2** in CDCl$_3$ (40 mM) by irradiation at 380 nm.§ Photoisomerization of **1EE** progressed efficiently and 1 h irradiation gave the photostationary state in which the *trans* : *cis* ratio of the azobenzene moieties of **1** was 12 : 88 (**1EE** : **1EZ** : **1ZZ** = 5 : 15 : 80), as monitored by ^{1}H NMR spectroscopy. The NH and NH$_2$ proton signals of **1**

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† Electronic Supplementary Information (ESI) available: preparation and characterization of melamine **1**, ^{1}H-NMR spectra of the assembly between **1** and **2** before and after irradiation. See http://www.rsc.org/suppdata/cc/b3/b305528k/

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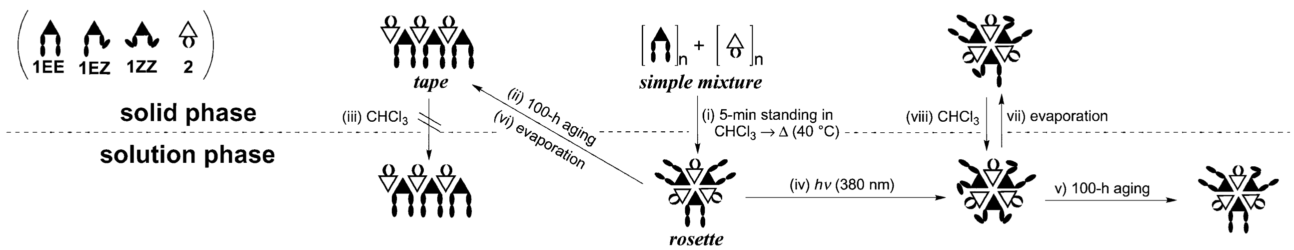

Scheme 1 Schematic representation of the aggregation of **1** and **2**.

emerged at δ = 9.73/9.53 and 7.05 ppm, respectively. A control experiment by irradiating **1EE** alone attributed the splitting of the NH proton signal to the presence of NH carrying the *cis*-azobenzene unit, the proton resonance of which was shifted upfield in comparison with that of NH carrying the *trans*-isomer ($\Delta\delta$ = 0.20 ppm) by the ring current effect of the terminal aromatic ring of the *cis*-azobenzene unit. The finding that the NH and NH$_2$ proton signals of **1** remained in the characteristic region for the formation of rosettes indicates that assembly $(\mathbf{1}\cdot\mathbf{2})_3$ remained intact upon isomerization of the azobenzene unit (step (iv) in Scheme 1).

Remarkably, when the above irradiated solution was aged in the dark at 15 °C for 100 h, no precipitation was observed (Fig. 2a, right) and the situation continued over more than 300 h. The half-life of the *cis*-azobenzene unit to thermal isomerization was *ca.* 70 h by ^{1}H NMR spectroscopy.† Because of exponential thermal *cis* $\rightarrow$ *trans* conversion, 22% of *cis*-isomers remained 170 h after irradiation (**1EE** : **1EZ** : **1ZZ** = 60 : 36 : 4), and after approximately 340 h, all *cis*-isomers thermally transformed into *trans*-isomers. After a few days from the complete disappearance of *cis*-isomer, precipitates was observed. The solubility test and IR spectroscopic analysis confirmed the precipitates to be composed of tapes. These sequential results demonstrate that **1ZZ** and **1EZ** possessing *cis*-azobenzene unit(s), even if they are present to a minor extent, suppress transformation of soluble rosettes into insoluble tapes (step (v) in Scheme 1).

The principle of the result described above can be reasonably explained as follows by invoking the recently described Timmerman model.[4] *Trans* $\rightarrow$ *cis* isomerization of the azobenzene unit in **1** must induce considerable steric repulsion between the neighboring molecules, especially when **1** is embedded in the tape-like supramolecular structures. This, in turn, affords considerable perturbation to the flatness of the tapes, and thereby increasing their solubilities to an extent comparable to that of rosettes. Thus, the rosette $\leftrightarrows$ tape equilibrium in the solution is retained for longer in comparison with the unirradiated assembly. More interestingly, the suppression of the precipitation by small proportions of **1ZZ** and **1EZ** (for example, 170 h after irradiation) suggests that a small proportion of melamine bearing bulky substituents embedded in a tape might perturb the flatness of the tape to a large extent.

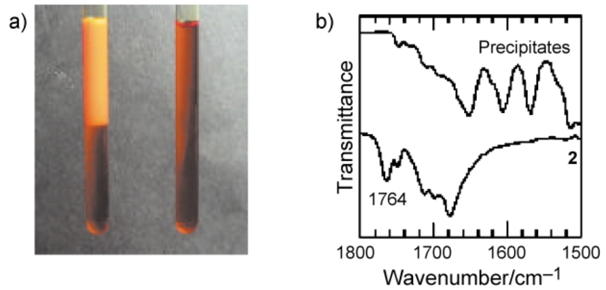

Fig. 2 (a) Photograph of the CDCl$_3$ solution of the assembly $(\mathbf{1EE}\cdot\mathbf{2})_3$ (40 mM), aged for 100 h without (left) and with preliminary irradiation at 380 nm for 1 h (right). (b) IR spectra of the precipitates (upper) and **2** alone (lower).

Finally, we investigated how the isomerization of azobenzene units in **1** affects the assembly between **1** and **2** in the solid state. Slow evaporation of the chloroform solution of the assembly between **1EE** and **2** (approximately 24 h for complete evaporation) afforded a powder the IR spectrum and solubility of which are identical to those obtained during 100 h aging. This indicates that the powder was composed of tapes (step (vi) in Scheme 1). In contrast, when the solution was irradiated at 380 nm for 1 h prior to 24 h evaporation, the resulting powder instantaneously dissolved in chloroform completely, even at 15 °C with a high solubility ($>$100 mM). Considering that the simple equimolar mixture of solid samples of two components requires 5 min standing and gentle heating to dissolve completely (step (i) in Scheme 1), the instantaneous dissolution of the powder even at 15 °C indicates preformation of rosettes in the powder. *Trans* $\rightarrow$ *cis* photoisomerization of **1** increases the solubility of competing tapes, which results in the precipitation of **1** and **2** in the rosette motif (steps (vii) and (viii) in Scheme 1). This striking result clearly demonstrates the possibility that the supramolecular structure of hydrogen-bonded assemblies in the solid state can be photochemically controlled.

We have reported the melamine·barbiturate assembly, which is for the first time endowed with photoswitching properties. Photoisomerization of azobenzene units on melamine indirectly increases the thermodynamic stability of the rosette in the solution, that can be retained as the supramolecular structure in the solid state when the solvent is removed. Application of photoswitching properties of melamine **1** analogues to further complex aggregates is under investigation in our laboratory.

Notes and references

‡ **1** has no infrared absorption in the region of 1660–1800 cm^{-1}.

§ Irradiation was performed on a fluorimeter equipped with a 150 W xenon lamp (20 nm spectral bandwidth) in the NMR tube.

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