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Supramolecular Control of Fluorescence through Reversible Encapsulation

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Abstract: The *trans* to *cis* isomerization of 4,4′-dimethylazobenzene by the nonchemical stimuli light and heat alters its guest binding properties, allowing control over encapsulation of a second guest. We show here how this remote control for reversible encapsulation can be used as a supramolecular fluorescence on/off switch. If *trans*-4-ethyl-4′-methylstilbene is used as the second guest its fluorescence is altered depending on whether it is free in solution or encapsulated. We demonstrate that the change in fluorescence is indeed a consequence of the controlled encapsulation state of the stilbene by correlation of fluorescence and ^{1}H NMR data.

We recently reported the use of 4,4′-dimethylazobenzene **1** (Figure 1A) to control the traffic of guest molecules in and out of capsular compartments.[1] The *trans*-conformation of **1** is a good guest for capsule **2·2**. On irradiation with 365 nm light, isomerization of **1** into its *cis*-form causes it to break out of the assembly and allows uptake of another guest from the solution. Since the process is reversed by heat, the *trans*/*cis* isomerization of **1** becomes an off/on switch for access to the capsule — and the special attributes of its inner space. For **2·2** these include its ability to alter the fluorescence of the guest,[2] stabilize reactive species,[3] contort guest conformations,[4] and, upon coencapsulation, create new stereochemical relationships[5] and accelerate bimolecular reactions.[6] These phenomena are encountered with many types of reversible encapsulation systems,[7] but in the present work we take advantage of the idiosyncratic shape of **2·2** and apply the switching mechanism to manipulate the *fluorescence* of a guest by light and heat (Figure 1). Use of photonic inputs to control photophysical properties such as fluorescence[8] is highly desirable for the construction of photonic devices, e.g., light controlled molecular logic gates.[9]

The fluorescence of stilbenes is well-understood[10] and varies with the environment: intense fluorescence is observed when stilbenes are tightly surrounded by antibodies,[11] while modest fluorescence results in typical organic media. In the capsule **2·2**, *trans*-4-methyl-4′-ethylstilbene (*trans*-**3**) must assume a twisted shape with a dihedral angle of ∼40° between the two aromatic planes (Figure 1B) and its fluorescence is efficiently quenched.[12]

A direct competition for the capsule **2·2** between 1 equiv of stilbene *trans*-**3** and 2 equiv of the shorter *trans*-**1** results in encapsulation of only the azo compound as shown by the ^{1}H NMR spectrum (Figure 2B). Since *trans*-**3** is not encapsulated it shows high fluorescence at 388 nm upon excitation with 318 nm light (Figure 2A). Irradiation of this solution with 365 nm light leads to guest exchange: after 50 min *trans*-**3** is completely encapsulated and only weak fluorescence (ca. 15-fold weaker emission) is observed. Heating this solution to 160 °C for 2 min restores the starting state. This cycle (Figure 1C) can be repeated many times; five iterations are shown in Figure 2. For every fluorescence measurement, the corresponding ^{1}H NMR spectrum of *the same solution* was taken. This established a perfect correlation between guest occupation and fluorescence intensity. Some loss of performance over time is attributable to accumulation of small amounts of weaker fluorescent *cis*-stilbene (*cis*-**3**).

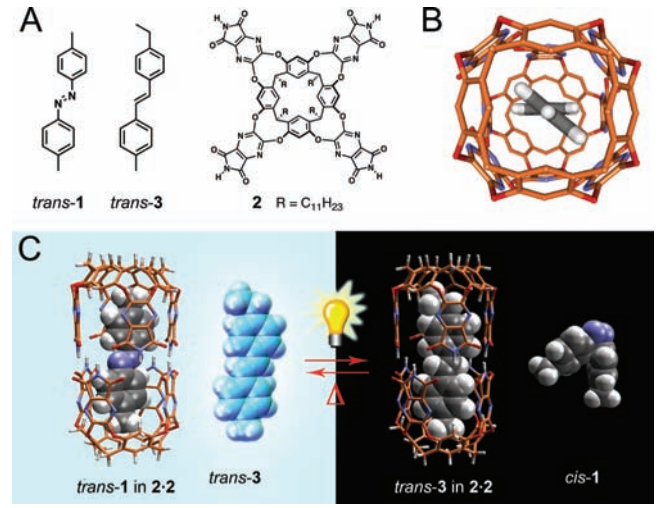

Figure 1. A supramolecular fluorescence-switching device. (A) Azobenzene *trans*-**1**, stilbene *trans*-**3**, and **2**. (B) Encapsulated *trans*-stilbene **3** assumes a twisted conformation in **2·2** (top view). (C) *trans*-**3** fluoresces when it is free in solution. Upon irradiation azobenzene *cis*-**1** is expelled from the capsule, *trans*-**3** is encapsulated, and its fluorescence is quenched. Heating restores the starting point.

In addition, a solution of encapsulated *trans*-**3** was treated with 2 equiv of *trans*-**1** and slow exchange over several days was observed. Every time a ^{1}H NMR spectrum was measured, the corresponding fluorescence was also measured. A direct correlation was found between the amount of stilbene *trans*-**3** released into the solution and fluorescence intensity (Figure 2SI).

To establish that fluorescence change was indeed caused by encapsulation of *trans*-**3**, additional control experiments were undertaken (Figure 3). Again, fluorescence measurements and ^{1}H NMR measurements were correlated in each case.

The fluorescence intensity of *trans*-**3** encapsulated in **2·2** is the same as the low fluorescence observed in the "full" system (Figure 3, exp. 2). Free stilbene *trans*-**3** in solution (Figure 3, exp. 3) shows 10 times higher fluorescence than it does in the full system. In both cases irradiation and heating have insignificant effect on the fluorescence and on the ^{1}H NMR spectra. Addition of *trans*-**1** to free *trans*-**3** (Figure 3, exp. 4) leads to 4-fold reduction of fluorescence. After irradiation, fluorescence intensity doubles and according to ^{1}H NMR 95% of *trans*-**1** is converted into *cis*-**1**. The initial fluorescence intensity is restored upon heating the solution for 2 min after which all *cis*-**1** is

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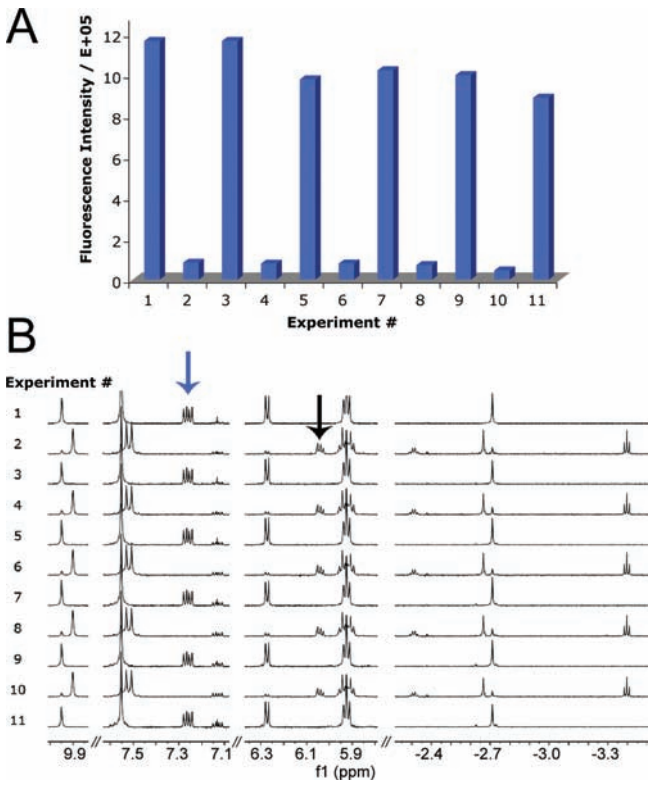

Figure 2. Reversible fluorescence intensity switching by light and heat. Five cycles of guest exchange and concomitant fluorescence change are shown. The numbers shown correspond to paired experiments for fluorescence measurement and ^{1}H NMR spectra. Odd experiment numbers indicate heating steps (160 °C for 2 min); even numbers indicate irradiation steps (365 nm for 50 min at 20 °C). (A) Fluorescence measured at 388 nm on excitation at 318 nm. (B) Corresponding ^{1}H NMR spectra for each step. The blue arrow indicates proton signals of free *trans*-**3** in solution; the black arrow indicates two aromatic proton signals of encapsulated *trans*-**3**.

converted to *trans*-**1**. Thus, *trans*-**1** quenches the fluorescence of *trans*-**3** much more efficiently than *cis*-**1** does.

To establish the influence of capsule **2·2** on stilbene fluorescence, 2 equiv of 4,4′-dimethylbenzanilide (**4**) were used to occupy the capsule. The fluorescence intensity of that assembly is low and indifferent to 365 nm light or heat (Figure 3, exp. 5). Added *trans*-**3** stays outside of the capsule but now only shows approximately half of the fluorescence intensity observed for free *trans*-**3** in solution (Figure 3, exp. 6). Again, 365 nm light and heat have no effect on the fluorescence. Adding *trans*-4-*n*-hexyl-4′-ethylazobenzene **5**, which is not a guest for **2·2**, leads to a further 4-fold decrease of fluorescence intensity (Figure 3, exp. 7). Irradiation of this solution with 365 nm light enhances fluorescence 2-fold, and 85% of *cis*-**5** is obtained. Subsequent heating yields *trans*-**5**, and fluorescence intensity has decreased back to the starting point.

These experiments establish that the intrinsic fluorescence behavior for combinations of azobenzenes and stilbenes can be reversed by reversible encapsulation. In the presence of azobenzenes the fluorescence of *trans*-**3** *increases* upon irradiation with 365 nm light because *cis*-azobenzenes quench the fluorescence less efficiently compared to their *trans*-forms. In the supramolecular system, the same external stimulus has the reverse effect on fluorescence intensity. Now, irradiation leads to encapsulation of *trans*-**3** and very efficient *quenching* of its fluorescence.

In summary, we have demonstrated how the external stimuli light and heat can be used to control encapsulation of a guest and thereby manipulate its fluorescence. The fluorescence on/off property we observe in our system is a result of the supramolecular events of

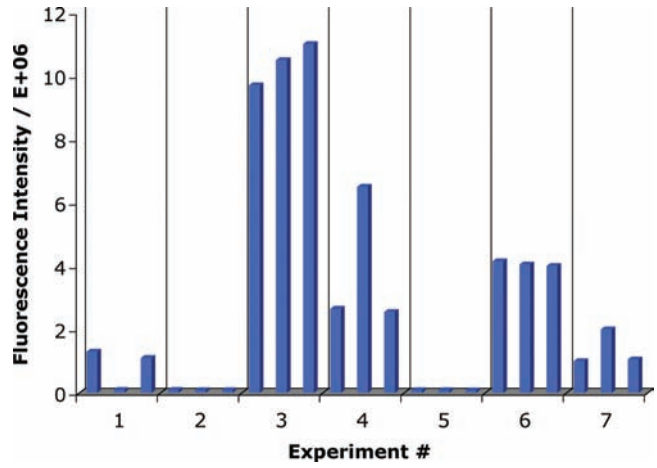

Figure 3. Contributions of the components of the supramolecular system to fluorescence intensity under the switching conditions. Fluorescence was measured at 388 nm on excitation with 318 nm light. Each experiment shown consists of three steps: heating (160 °C for 2 min), irradiation (365 nm for 50 min at 20 °C), and repeat of the heating. (1) *trans*-**3** + *trans*-**1** + **2·2**; (2) *trans*-**3** in **2·2**; (3) *trans*-**3**; (4) *trans*-**3** + *trans*-**1**; (5) **4** in **2·2**; (6) **4** in **2·2** + *trans*-**3** in solution; (7) **4** in **2·2** + *trans*-**3** + **5** in solution. See Supporting Information for ^{1}H NMR spectra.

encapsulation and cannot be achieved by less than complete combinations of the components. We aim to incorporate these findings and those of encapsulated 4,4′-dimethylbenzil[2] in future optically addressable devices such as Boolean logic gates.

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Supporting Information Available: Experimental procedures, fluorescence spectra, and ^{1}H NMR spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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