Dynamic Nanoreceptors

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Proton-Driven Switching Between Receptors for C_{60} and C_{70}**

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We describe herein the remarkable, proton-induced transformations of supramolecular "chameleons" based on naphthalenediimides (NDIs). We demonstrate rapid, reversible, and controllable morphological switching between receptors for different fullerenes (C_{60} and C_{70}), thus allowing the selective binding of either guest in a mixture of both guests. This work is an extension of the dynamic combinatorial concept[1,2] into a new dimension: using hydrogen bonding as the exchange reaction, the response of the NDI building blocks to the presence of fullerene guests depends on the concentration of protons as a third component. The switching between the two receptors, a nanotube and a hexameric capsule (Figure 1), is under thermodynamic control (i.e., the most stable host–guest complex is dominant) and is triggered by the guest (template) present in solution.

In aprotic solvents of medium polarity such as chloroform and dichloromethane, self-recognition through hydrogen bonding causes the amino acid derived NDIs (Scheme 1) to adopt different aggregate forms, depending on the presence or absence of guests.[3–5] The NDI nanotubes are held together by classical intermolecular COOH–HOOC hydrogen bonds supplemented by weak CH···O=C bonding (Figure 1 a, c).[3] The hexameric capsule is formed in the presence of C_{70} at the expense of the nanotube and is held together by hydrogen bonds between the COOH groups (equator, Figure 1 b) and a rare, threefold hydrogen-bond pattern between the COOH group, an imide C=O group, and an acidic hydrogen atom of NDI at the pole (Figure 1 d).[5]

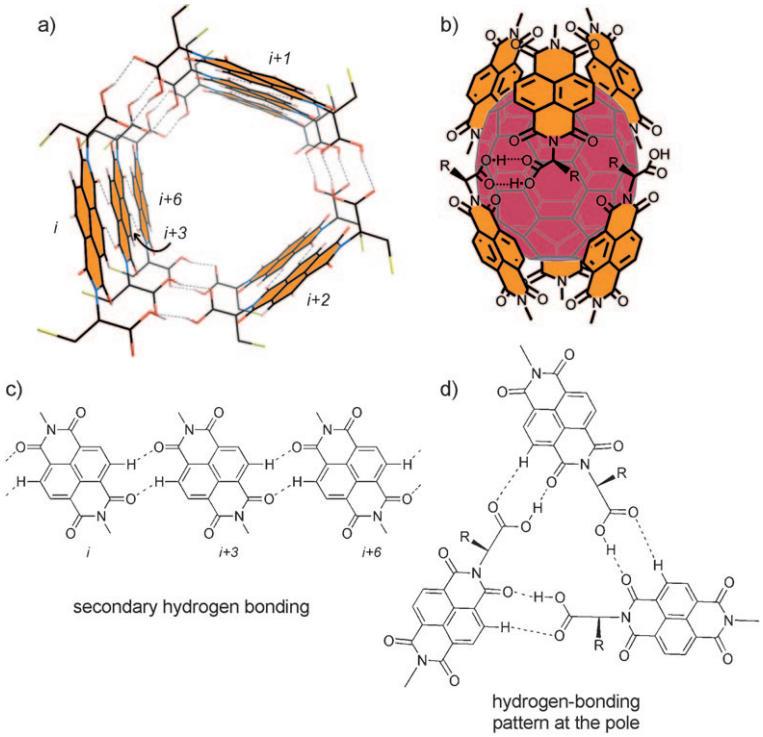
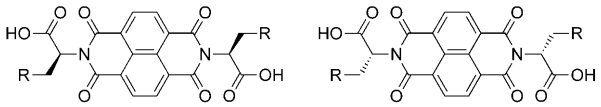


Figure 1. Representation of a) the nanotube, b) the C_{70} receptor, and c, d) the corresponding hydrogen-bonding patterns.



L-**1**: R = $(CH_2)_3NHBoc$
L-**2**: R = STrt
L-**3**: R = $CH(CH_3)_2$

D-**4**: R = OBzl

Scheme 1. Naphthalenediimides derived from amino acids used in the present work. Boc = *tert*-butyloxycarbonyl, Bzl = benzyl, Trt = trityl.

Both of these supramolecular assemblies can therefore be destroyed by offering the NDI units alternative hydrogen-bonding interactions. We originally showed that this goal could be achieved by use of a hydrogen-bond-disrupting solvent such as MeOH; this approach has the disadvantage of leading to the permanent destruction of the supramolecules. We now show that morphological switching between nanotube, hexameric receptor, and monomers is readily achieved by simple protonation–deprotonation reactions that result in the formation of dynamic, size-selective fullerene receptors, the structure and recognition properties of which depend on the position of the acid/base equilibrium (Figure 2). This work has also uncovered unexpected differences in the sensitivity to base-induced dissociation of the nanotubes derived from different amino acids.

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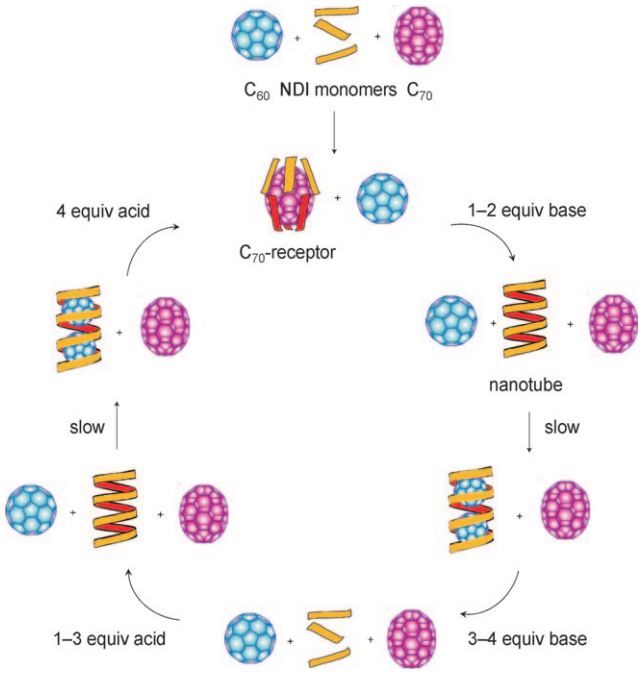

Figure 2. Representation of the proton-driven cyclic morphological switching between NDI monomers, and C_{60} and C_{70} receptors. The slow kinetics of C_{60} uptake are indicated on the arrows and detailed in the Supporting Information.

Chirooptical studies were carried out in chloroform solution with four structurally diverse hydrogen-bonded nanotubes, using triethylamine (TEA) and methanesulfonic acid (MSA) as base and acid triggers. Figure 3 shows changes in the CD spectrum of a chloroform solution of L-**1** (red trace) after sequential additions of base and acid. Addition of one equivalent of base caused a dramatic decrease of the CD signal intensity (green trace), which is attributed to the dissociation of the nanotube by the breaking of hydrogen bonds between NDI components. Subsequent addition of a stoichiometric amount of acid re-established the original spectrum (blue trace). This process is reversible, as demonstrated by the essentially complete recovery of the CD over several cycles (Figure 3, inset). Comparison of these measurements for all four NDI derivatives revealed that the amount of base required to dissociate the nanotube architecture depends on the nature of the amino acid side chain. The nanotubes of L-**2**, L-**3**, D-**4**, all with apolar substituents, required more base (four, two, and two equivalents per NDI respectively) for complete dissociation than that derived from L-**1** (one equivalent), with a polar side chain. This may be a consequence of differences in solvation and/or creation of a more nonpolar environment, which would raise the pK_a in a manner that is reminiscent of carboxylic groups in enzyme active sites.[6,7] It is not clear whether removal of, on average, one proton per $(COOH)_2$ link (which would still allow connection through a single, charge-assisted hydrogen bond) leads to the dissociation of the nanotubes or whether both protons need to be removed. In all cases, the nanotubes reassembled when MSA was added to neutralize the base (see the Supporting Information).

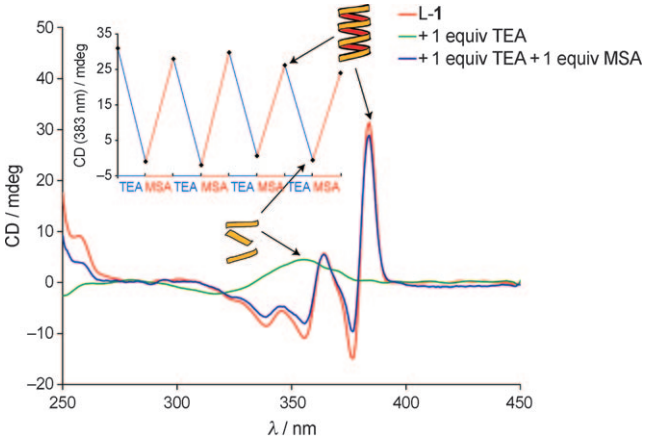

Figure 3. CD spectra of a $CHCl_3$ solution of L-**1** (7×10^{-4} M, red trace) in the presence of one equivalent of TEA (green trace) and an additional one equivalent of MSA (blue trace). Inset: demonstration of the reversibility of the base–acid-driven switch between the nanotube and free NDI components.

The NDI nanotubes are good receptors for C_{60}, which forms a tightly packed one-dimensional array inside the solvophobic cylindrical cavity.[4] One of our aims was to examine whether the C_{60} guests have any influence on the resistance of the host to base-induced dissociation. In fact, repetition of the acid/base experiments in the presence of C_{60} produced essentially identical dissociation and reassociation results (see the Supporting Information).

C_{70} behaves quite differently as a guest, thus inducing the formation of a hexameric receptor at the expense of the nanotubes.[5] This process is associated with striking spectroscopic changes that allow us to monitor the nanotube–C_{70} receptor equilibrium. The C_{70} receptor was formed by the addition of C_{70} to a solution of L-**2** in dry chloroform (NDI/C_{70} 6:1). Its formation was confirmed by an immediate color change from yellow to dark red and by the characteristic CD spectrum (Figure 4a, black trace). The addition of one equivalent of TEA to the L-**2**/C_{70} complex leads to the disassembly of the C_{70} receptor and the formation of a supramolecular nanotube, as indicated by a characteristic positive signal at 383 nm in the CD spectrum (Figure 4a, red trace). This remarkable morphological switching reveals a difference in stability of the hydrogen-bonding arrays in the C_{70} capsule and the nanotube, the latter being particularly stable when derived from L-**2**. In the case of cysteine, L-**2**, one equivalent of base (per NDI) is sufficient to destroy the C_{70} receptor but not the nanotube. Presumably, a partially deprotonated nanotube may coexist in solution with deprotonated NDIs and free C_{70}. The subsequent addition of a further three equivalents of TEA results in decrease and finally disappearance of the characteristic nanotube CD signal at 383 nm (Figure 4a, violet trace). The reversibility of the processes was confirmed by stepwise addition of equimolar amounts of acid, which initially regenerated the nanotube, and then the C_{70} receptor (Figure 4b, orange and blue traces, respectively). Furthermore, this proton-controlled morphological switching between supramolecular architectures strongly depends on the structure of the NDI

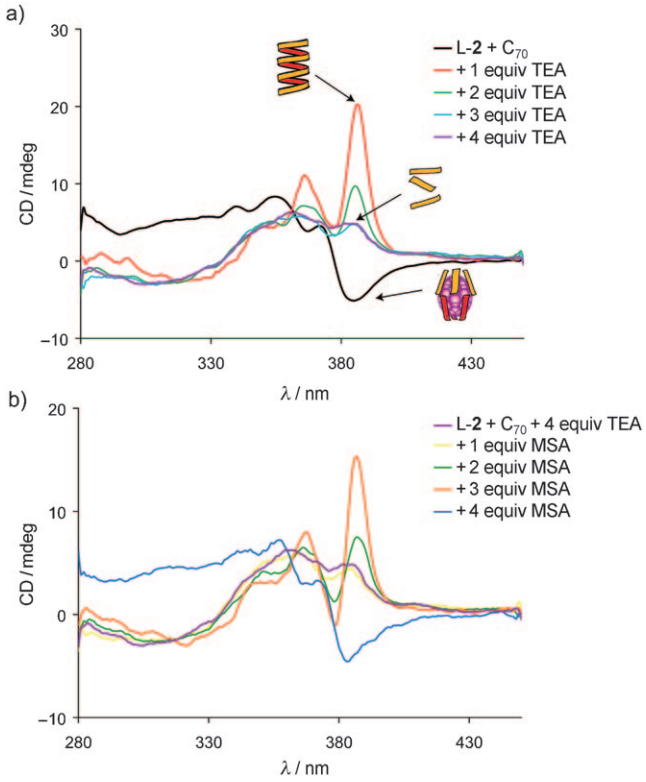

Figure 4. Evolution in the CD spectrum of a $CHCl_3$ solution of L-**2** + C_{70} (7×10^{-4} M) after addition of a) four equivalents of TEA and b) four equivalents of MSA.

component. Thus, addition of one equivalent of TEA to the C_{70} receptor involving L-**1** resulted in complete dissociation of the supramolecular architecture to give free NDI components, thus completely bypassing the nanotube phase (see the Supporting Information).

The nanotube, the C_{70} receptor, and the uncomplexed NDI molecules have distinct ^{1}H NMR spectral signatures, particularly in the aromatic region of the spectra, that provide a clear window on the switching between these three

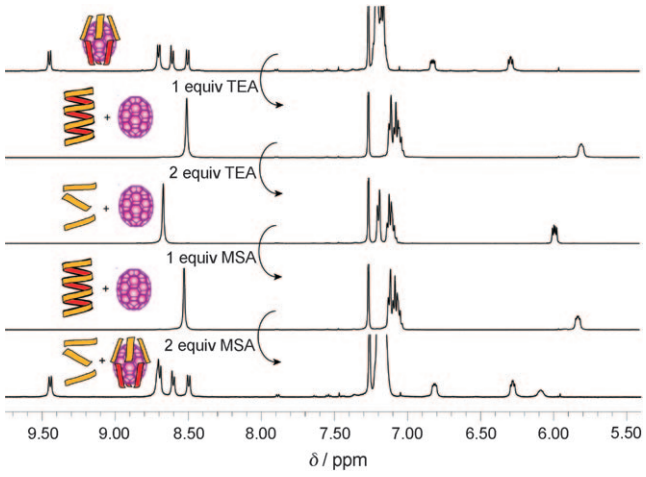

Figure 5. Part of the 500 MHz ^{1}H NMR spectra of D-**4** + C_{70} showing the acid–base-driven reversible switching between the C_{70} receptor, nanotube, and free NDI components in $CDCl_3$ at 7×10^{-4} M.

architectures. Thus, starting with a solution of D-**4**/C_{70} (NDI/C_{70} 6:1) and adding one equivalent of TEA, the signals for the C_{70} receptor ($\delta = 9.5$–8.4 ppm for the NDI core and $\delta = 6.9$, 6.1 ppm for the α-protons) were replaced by two signals at $\delta =$ 8.5 (NDI) and 5.8 ppm (α) characteristic of the nanotube structure (Figure 5).[3] Addition of a second equivalent of TEA resulted in dissociation of the nanotube to the free NDI molecules, as indicated by the sharpening and downfield shifts of the two signals to $\delta = 8.7$ and 6.0 ppm, respectively. The reversible character of the system was confirmed by progressive addition of two equivalents of MSA, which first reformed the nanotube, followed by the C_{70} receptor.[8] The switching is cyclical, as demonstrated by sequential additions of TEA and MSA (see the Supporting Information).

To further illustrate the potential of this system, we employed the two fullerene guests together in a competition experiment. The morphological switching was followed by ^{13}C NMR spectroscopy and, as in the previous experiments, this showed preferential formation of the C_{70} complex over that of the C_{60}/nanotube species in the absence of base (the four signals between $\delta = 143$–148 ppm are due to the complexed C_{70}, Figure 6a). Progressive addition of base caused in

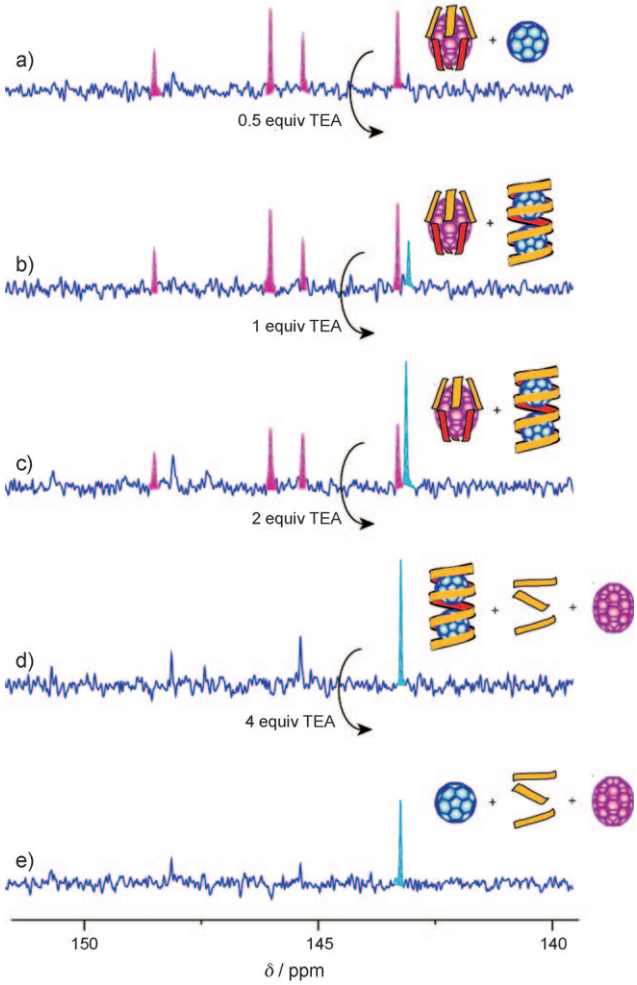

Figure 6. Part of the 125 MHz ^{13}C NMR spectra of D-**4** + C_{70} + C_{60} showing the acid–base-driven reversible switching between the C_{70} receptor, nanotube–C_{60}-based receptor, and free NDI components in $CDCl_3$ at 7×10^{-4} M.

the first instance appearance of an additional signal at 142.9 ppm, which is characteristic of C_{60} within a nanotube as part of a ternary complex with the triethylammonium ion,[9] (Figure 6b) followed by its significant amplification when more base was added (Figure 6c). At this stage, both host–guest complexes were evident but the C_{60}/nanotube species was strongly dominant. Further addition of base caused firstly complete disappearance of C_{70} receptor signals and finally disassembly of the nanotube (Figure 6d,e).

In conclusion, we have described a dynamic nanoreceptor, the morphology and recognition properties of which can be tuned by a simple acid–base equilibrium. The remarkable nature of this system was demonstrated by the controlled construction of responsive and structurally different receptors for different fullerenes (C_{60} and C_{70}) within the same reaction mixture. Although several examples of selective fullerene binding/separation have been reported,[10–15] the construction of morphologically different fullerene hosts with distinct binding properties by using the dynamic combinatorial approach has not previously been reported. The use of a third component, the proton, to switch between different dynamic combinatorial responses using the same exchange reaction is also new. In addition, by varying the side chain of the amino acid used, the relative strength of the supramolecular nanotube can be tuned. The structural characteristics of the NDI derivatives were found to play a crucial role in the morphological switching between all three supramolecular architectures. We believe that the results reported above show that NDI-based supramolecular architectures represent a significant example of a dynamic self-assembled system whose structure and properties are responsive to an external chemical stimulus.

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