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COMMUNICATIONS

Published on Web 10/14/2003

Chiroptical Switching in a Bistable Molecular Shuttle

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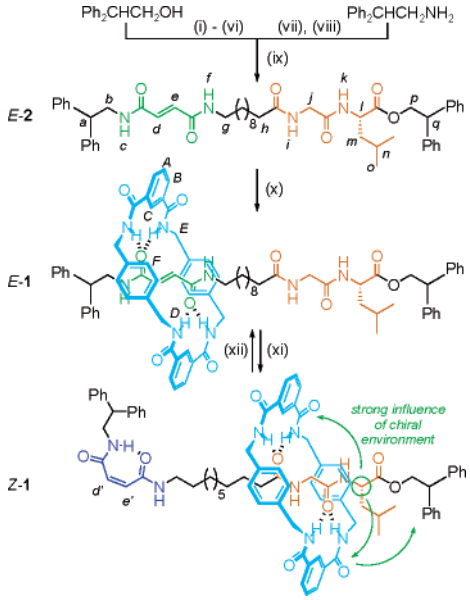
Although various methods for switching the positions of macrocycles in bistable rotaxane-based molecular shuttles have been developed,[1] exploiting such movements to trigger property changes has thus far received little attention.[2,3] Here we demonstrate one of the first examples of a property change achieved through a large amplitude translational motion in a rotaxane, a chiroptical switch in which light-induced shuttling of the macrocycle along the thread produces a strong induced circular dichroism (ICD) response when the macrocycle is hydrogen-bonded to a chiral peptide station.

Chiral dipeptides have previously been shown to induce an asymmetric response in the aromatic ring absorption bands of intrinsically achiral components of [2]rotaxanes through tight intercomponent binding in nonpolar solvents.[4,5] The effect can be "switched off" by adding a polar solvent (e.g., MeOH) to break the hydrogen-bonding interactions between macrocycle and thread. Although triggered changes in optical properties are currently utilized in optical data storage and processing, waveguides, and other photonics applications,[6] a solvent change is clearly unlikely to prove useful as a means of switching such real-world devices. However, the breaking (and making) of intercomponent interactions

Scheme 1. Synthesis of Bistable Molecular Shuttles *E*/*Z*-**1**[a]



[a] Reaction conditions: i) *N*-Boc-L-leucine, 4-(dimethylamino)pyridine (4-DMAP), 1-(3-dimethylaminopropyl)-3-ethyl-carbodiimide hydrochloride (EDCI), $CHCl_3$, 94%. ii) trifluoroacetic acid (TFA), $CHCl_3$, quantitative. iii) *N*-Boc-glycine, 4-DMAP, EDCI, $CHCl_3$, 91%. iv) TFA, $CHCl_3$, quantitative. v) *N*-Boc-11-aminoundecanoic acid, 4-DMAP, EDCI, $CHCl_3$, 82%. vi) TFA, $CHCl_3$, quantitative. vii) fumaric acid monoethylester, 4-DMAP, EDCI, $CHCl_3$, 85%. viii) EtOH, NaOH, 91%. ix) 4-DMAP, EDCI, DMF, 74%. x) *p*-xylylenediamine, isophthaloyl dichloride, Et_3N, $CHCl_3$, 58%. xi) EITHER 254 nm, CH_2Cl_2, 20 min, 56% OR 254 nm, CH_3CN, 20 min, 49% OR 350 nm, benzophenone, CH_2Cl_2, 20 min, 70% xii) EITHER 312 nm, CH_2Cl_2 or CH_3CN, 20 min, 62% OR 400−670 nm, cat. Br_2, CH_2Cl_2, 2 min, >95% OR 130 °C, $C_2H_2Cl_4$, 6 days, 95%.

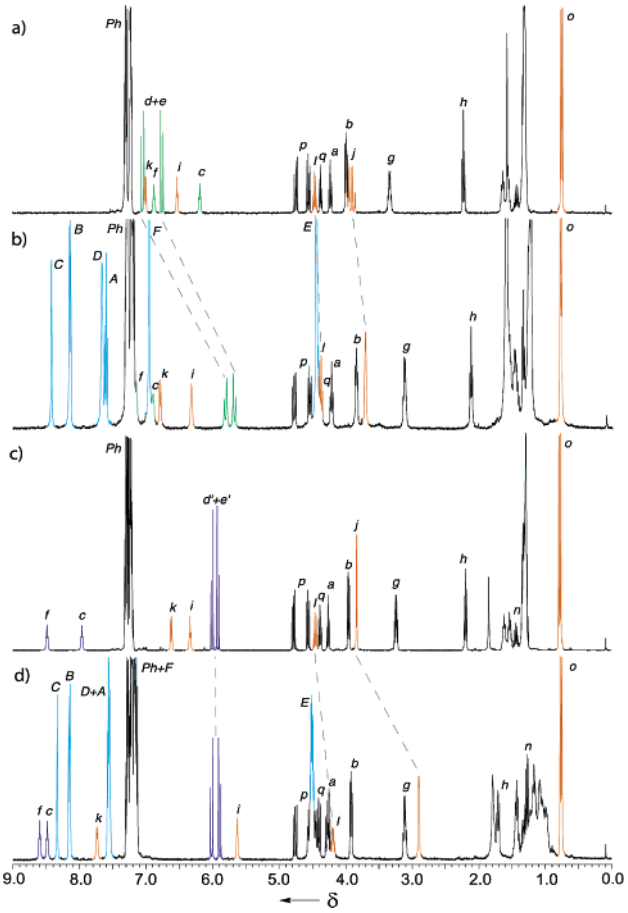


Figure 1. ^1H NMR spectra (400 MHz in $CDCl_3$ at 298 K) of (a) fumaramide thread *E*-**2**, (b) fumaramide rotaxane *E*-**1**, (c) maleamide thread, *Z*-**2**, (d) maleamide rotaxane *Z*-**1**. The assignments correspond to the lettering shown in Scheme 1.

is also a feature of positionally bistable molecular shuttles. Accordingly, it seemed possible that optical properties could be influenced solely by switching the position of a macrocycle in a molecular shuttle that incorporates a chiral peptide "station".

Such a bistable shuttle, *E*/*Z*-**1**, is shown in Scheme 1. The idea is that in *E*-**1** the macrocycle resides over the strongly macrocycle-binding fumaramide portion of the thread and the asymmetric center is not close enough to any aromatic rings to influence their absorption spectrum. Upon photoisomerization of the olefin station (*E*-**1**→*Z*-**1**), the ring moves to the glycyl-L-leucine (Gly-Leu) unit, locking the molecule in a co-conformation where aromatic rings (principally those of the C-terminal stopper[4]) are held in a well-expressed chiral environment. The change in the position of the macrocycle should thus manifest itself in terms of a measurable change in the CD response.

Molecular shuttle *E*-**1** was synthesized from thread *E*-**2** in 58% yield (Scheme 1). Comparison of the ^1H NMR spectra of the

10.1021/ja036665t CCC: $25.00

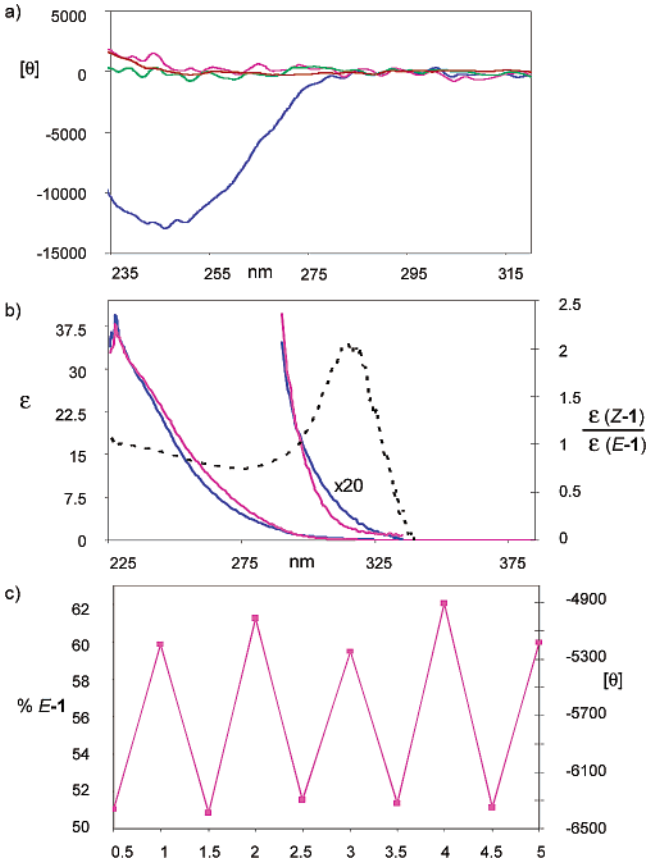


Figure 2. (a) CD spectra (0.1 mM in $CHCl_3$) at 298 K of *Z*-**1** (blue), *E*-**1** (purple), *E*-**2** (green), and *Z*-**2** (red). (b) UV−vis spectra of *E*-**1** (purple) and *Z*-**1** (blue) in $CHCl_3$ at 298 K, $[\epsilon] = mM^{-1}\cdot cm^{-1}$. Dotted line represents the *Z*-**1**/*E*-**1** absorption ratio. (c) Percentage of *E*-**1** in the photostationary state (from ^1H NMR data, 400 MHz, CD_3CN, 298 K) after alternating irradiation at 254 nm (half integers) and 312 nm (integers) for five complete cycles. The right-hand *Y* axis shows the CD absorption at 246 nm.

E-rotaxane and thread (Figure 1, a and b) shows the excellent discrimination of the macrocycle toward the different stations. While the Gly-Leu protons are only slightly affected by the aromatic shielding effect of the macrocycle, the *E*-olefin protons are significantly shifted upfield (∼1.2 ppm), confirming that the co-conformer having the macrocycle over the olefin station is the major translational isomer in *E*-**1**.

Light-induced *E*→*Z* isomerization[7] of the fumaramide unit reverses[8] the macrocycle-binding affinity of the two stations in the molecular shuttle because the *cis*-olefin (maleamide) is largely self-satisfying in terms of H-bonding and the amide carbonyl groups are no longer suitably orientated for binding to the macrocycle.[7] The ^1H NMR spectra of *Z*-**1** and *Z*-**2** (Figure 1, c and d) reveal the concomitant change in the position of the macrocycle. The *Z*-olefin protons $H_{d'}$ and $H_{e'}$ occur at almost identical chemical shifts in rotaxane and thread, whereas the Gly methylene protons are now shielded by 0.9 ppm.

The shuttle design works remarkably well. When the macrocycle is tightly bound close to the Leu residue in *Z*-**1**, the aromatic rings of the rotaxane do, indeed, experience a well-expressed chiral environment as evidenced by CD spectroscopy. Of the two rotaxanes and two threads, *only* rotaxane *Z*-**1** gives a CD response, which is both strong (−13k deg cm^2 $dmol^{-1}$) and, for the L-enantiomer, negative (Figure 2a). The absence of any detectable signal for the *E*-rotaxane shows that the CD signal is genuinely only generated by controlling the position of the macrocycle in the shuttle.

The most efficient ways of interconverting the rotaxane diastereomers are photochemical: 350 nm, catalytic benzophenone sensitizer, CH_2Cl_2, 70% for *E*-**1**→*Z*-**1** and 400−670 nm, catalytic Br_2, CH_2Cl_2, >95% for *Z*-**1**→*E*-**1** (Scheme 1). However, a modest difference in the electronic absorption spectra of *E*-**1** and *Z*-**1** (Figure 2b) results in different photostationary states for the isomers at 254 (56% *Z*-**1** in CH_2Cl_2; 49% *Z*-**1** in CH_3CN) and 312 nm (38% *Z*-**1** in either CH_2Cl_2 or CH_3CN), meaning that even for this first-generation system a large net change (>1500 deg cm^2 $dmol^{-1}$) in elliptical polarization can be achieved solely through irradiation with light of different wavelengths. The photoisomerizations are highly reproducible with five complete switching cycles (*E*-**1**→*Z*-**1**→*E*-**1**) carried out with no decomposition detectable by NMR or CD spectroscopy (Figure 2c).

In conclusion, we have demonstrated a system where a large amplitude displacement of a macrocycle along a thread elicits a chiral optical response. In addition to this being a novel mode of switching to be explored for possible photonic and data storage applications, control of the expression of chirality in switchable interlocked systems through hiding or revealing chiral subunits could find important applications in areas where chiral transmission from one chemical entity to another underpins a physical or chemical response, such as the seeding of supertwisted nematic liquid crystalline phases or asymmetric synthesis.

Acknowledgment. This work was supported by the European Union Future and Emerging Technology Program *MechMol* and the EPSRC. D.A.L. is an EPSRC Advanced Research Fellow (AF/982324).

Supporting Information Available: Experimental procedures and spectral data for all new compounds (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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JA036665T