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Expanding Dendrons. The Photoisomerism of Folded Azobenzene Dendrons

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Many of the potential applications envisaged for dendrimers[1] require a capacity to extrinsically manipulate global structural properties via the long-range action of a local trigger.[2] Azobenzene chromophores have been extensively studied as conformational triggers in dendrimers[3] because the photochemical $E \rightarrow Z$ isomerization induces a large change in structure and dipole moment.[4] However, whereas significant conformational transitions have been induced in peptides,[5] and synthetic helical polymers[6] and oligomers,[7] relatively small photoinduced structural changes have been observed in azobenzene functionalized dendrimers because the flexible nature of their structures decouples local and global motions.[8] In contrast, larger structural changes were observed in rigid polyphenylene[9] and phenylacetylene[10] dendrimers. These systems uniformly experience a *collapse* in hydrodynamic volume (up to 38%[9]) upon irradiation that decreases with generation. We reasoned that the structural consequence of a local perturbation would be maximal within a dynamically folded dendron exhibiting a compact, folded conformational state.[11] Herein, we report a folded azobenzene dendron system that exhibits a compact helical conformation in the stable *E* form that *expands* significantly upon exposure to light. The extent of the structural response to light depends on the type of folding and increases with generation.

The helical conformational preference of the dendrons is established by the *E* geometry of the azo linkage in conjunction with the syn−syn conformational preferences of the 2-methoxyisophthalamide and pyridine-2,6-dicarboxamide dendritic repeat units. The 2-methoxyisophthalamides (2-OMe-IPA) exhibit a syn−syn conformational preference similar to that of the pyridine-2,6-dicarboxamides, owing to intramolecular hydrogen-bonding interactions between the amide-NHs and the 2-methoxy oxygen.[12] Photoisomerization from the *E* to *Z* form disrupts this folded state in a manner that decreases packing efficiency and leads to an increase in hydrodynamic volume (Figure 1).

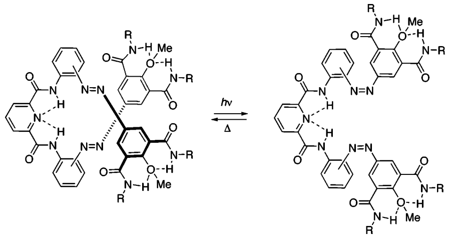

Figure 1. Photoswitchable dendrons: photoisomerization induces a reversible disruption of the helical folded state.

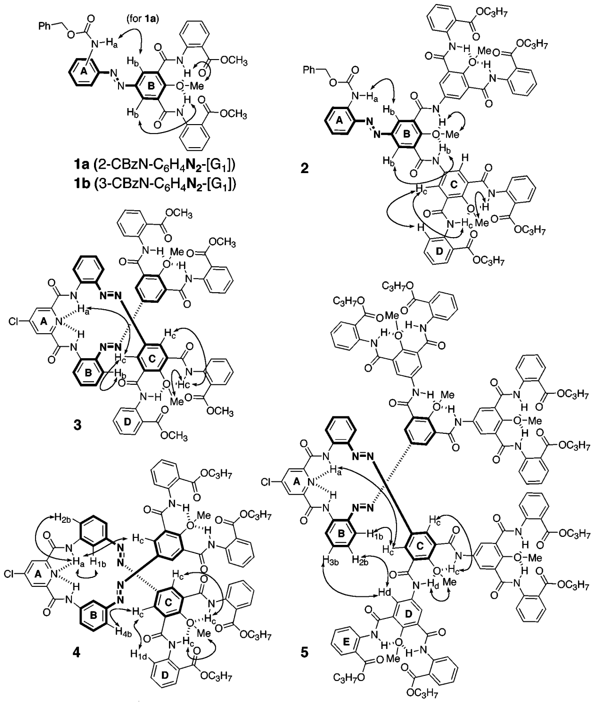

Figure 2. NOESY ^{1}H NMR cross-peaks for photoswitchable dendrons **1**−**5**.

Monte Carlo conformational searching (AMBER) of **3** and **4** (Supporting Information) indicated that both the *E*-2- and *E*-3-acylaminophenylazo linkages position the 2-methoxyisopthalamide branch points above and below the plane defined by the focal pyridine-2,6-dicarboxamide. This helical conformation places the **B** ring protons at the first shell in close proximity to those of ring **C** present on the adjacent dendritic branch on the second shell. Two-dimensional NOESY ^{1}H NMR spectroscopy in $\mathrm{CDCl_3}$ revealed the presence of close contacts between protons Hb and Hc in **3** and between H4b and Hc in **4** (Figures 2 and 3). Similar close contacts were evident between protons H1b and Hc on adjacent branches of the first and second shells of third generation dendron **5**. Additionally, NOESY cross-peaks occurred between H2b and H3b of the first shell with Hd on ring **D** of the third shell. The corresponding cross-peaks between protons on rings **A** and **B** of the focal phenylazo linkage in 2- and 3-CBzN-$\mathrm{C_6H_4}\mathbf{N}_2$-[G1] (**1a**/**b**) and 2-CBzN-$\mathrm{C_6H_4}\mathbf{N}_2$-[G2] (**2**) were not observed, consistent with this conformational preference. NOESY cross-peaks between the amide NH protons and both the methoxyl and aromatic protons of the 2-OMe-IPA linkages were also observed in all dendrons. These close contacts reflect the occurrence of both the syn−syn and syn−anti forms in the conformational ensemble that occur as a consequence of the greater flexibility of 2-OMe-IPA linkage as compared with the 2,6-pyridine-2,6-dicarboxamide branch point, which does not exhibit these cross-peaks in **3** and **5**.[13]

Whereas the *m*-acylamino substituted azobenzene linkages in **1b** and **4** exhibit $\pi \rightarrow \pi^*$ and very weak $n \rightarrow \pi^*$ absorptions at ca. 320 and 440 nm, respectively,[14] the *o*-acylamino substitution in structures **1a**, **2**, **3**, and **5** structures induces a large red-shift of the $\pi \rightarrow \pi^*$ band to ca. 400 nm (Supporting Information). This causes the long wavelength component of this transition to overlap with the $n \rightarrow \pi^*$ band centered near 440 nm.[15] Irradiation of the dendrons with 350 nm light induced an $E \rightarrow Z$ isomerization to take place, as evidenced by a decrease in the 320/400 nm absorption. The amount of *Z*-isomer at the photostationary state (PSS) was determined by ^{1}H NMR for **1**−**4**, and by UV−vis for **5**,[16] using the formula $(A_0 - A_{\mathrm{PSS}(320/400)})/A_0$ where A_0 and $A_{\mathrm{PSS}(320/400)}$

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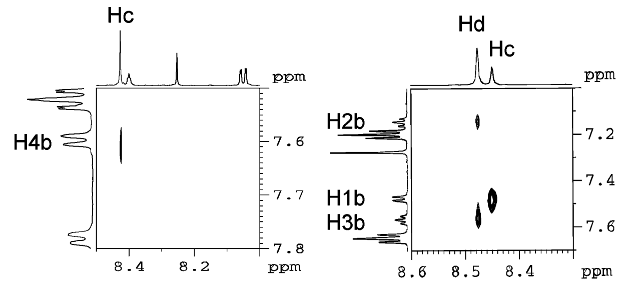

4 **5**

Figure 3. 2D ^{1}H-^{1}H NOESY spectra of **4** and **5**.

Table 1. Hydrodynamic Volumes[a] of *E* State (Dark) and at the PSS

				dark[c]		irradiated at 350 nm		
compd	%Z^{b} UV	%Z^{b} NMR	V_v (Å^3)	V_h (Å^3)	V_h/V_{vw}	$V_{h(PSS)}$ (Å^3)	V_h/V_{vw} (PSS)	$V_h/V_{h(PSS)}$
1a	58	59	610	757	1.24	827	1.36	1.13 ± 0.035
1b	23	63	678	1076	1.59	564	0.83	0.52 ± 0.120
2	39	41	1285	2228	1.73	2056	1.6	0.97 ± 0.045
3	38	38	1103	1371	1.24	1877	1.7	1.32 ± 0.048
4	33	53	1238	1496	1.21	2632	2.12	1.77 ± 0.140
5	20		2453	3666	1.49	5364	2.19	1.47 ± 0.016

[a] Determined by DOSY−NMR in $CDCl_3$ (1.3×10^{-4} M) at 27 °C. These conditions provided sharp, reproducible ^{1}H NMR spectra consistent with the presence of monomeric species in solution. [b] Measured in $CDCl_3$ within 10 min of irradiation. PSS attained within 10 min for UV and 1 h for ^{1}H NMR experiments. [c] Dark incubated for 18 h at room temperature.

represent the $\pi \rightarrow \pi^*$ absorptions before and after irradiation (Table 1). This formula assumes a neglible absorption of the *Z* isomer at 320/400 nm. Comparison of the *Z* isomer content, determined by UV−vis and ^{1}H NMR spectroscopy, at the PSS supports this assumption for the *o*-linked dendrons **1a**−**3** and **5**, but not for *m*-linked dendrons **1b** and **4.** Overall, $E \rightarrow Z$ photoisomerism was partially suppressed when the azo linkage was incorporated into the folded dendron structure (e.g., **1a** → **3**, **1b** → **4**, and **2** → **5**). The $Z \rightarrow E$ thermal isomerization rates of **1**−**5** were in the range of 10^{-5} s^{-1} at room temperature, and the barriers were relatively invariant ($\Delta G^{\ddagger}$ (298 K) = 22.5−24.75 kcal/mol, see SI for $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$), which indicates that the suppressed isomerization was not due to faster thermal reversion to the *E* form at higher generations. The suppression of photoisomerization at higher dendron generation mirrors the behavior of helical azobenzene oligomers and is likely a consequence of the compact, folded structure of the dendrons.[7]

Comparison of the hydrodynamic radii (V_h) of **1**−**5**, measured by DOSY−NMR spectroscopy,[17] to the calculated van der Waals radii[18] (V_{vw}) indicated the presence of compact conformational states in the dark-incubated *E* forms (Table 1).[19] Measured hydrodynamic volumes of the ensemble of *Z/E* isomers at the PSS following irradiation at 350 nm revealed that, whereas **1**−**2** exhibited either a decrease or minimal increase in volume, the hydrodynamic volumes of **3**, **4**, and **5** *expanded* by 32, 77, and 47%, respectively. It is noteworthy that the amount of expansion increases with generation (e.g., **3** and **5**). The 47% expansion in the volume of **5** at the PSS is particularly significant given that only 20% of the azo linkages existed in the *Z* form at the photostationary state. The striking increase in photoexpansion going from the *o*- to *m*-acylamino isomers, **3** and **4**, is likely due to a difference in the folding of *E*-isomers. Monte Carlo conformational searching (SI) suggests that the *o*-linkage in **3** creates a helical conformation that splays the dendritic branches at a 180° angle, whereas the *m*-linkage in **4** orients the dendritic branches at a 14° angle that promotes face-to-face packing of the dendritic surfaces. Photoisomerization disrupts this packing arrangement in a manner that induces a larger increase in volume compared with that of the *o*-linked dendron **3**.

In conclusion, we have described a series of azobenzene dendrons that adopt compact helical conformations in the *E*-azo form. Photoisomerization disrupts this folded conformation in a manner that decreases the packing efficiency and results in large structural expansions. Folded photoresponsive materials provide an opportunity to investigate how local conformational fluctuations can be correlated with global structural motions to maximize the structural response to a triggering event.

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Supporting Information Available: Synthetic procedures and characterization, NOESY and UV−vis spectra, and thermal $Z \rightarrow E$ activation parameters/rates for **1**−**5**; stereodepictions of lowest energy conformers of **3** and **4**. This material is available free of charge via the Internet at http://pubs.acs.org.

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