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A light-operated pillar[6]arene-based molecular shuttle†

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Molecular shuttles are mechanically interlocked molecules (MIMs) in which a macrocyclic ring is able to move back-and-forth between two recognition sites (stations). The constitution and length of the linker connecting the two stations dominate the ring movement. Insertion of groups sensitive to external stimuli (pH, redox reactions and light) into the linker is a useful approach to control the ring movement. Among these stimuli, light is especially useful because it functions quickly, efficiently, and reversibly. Azobenzene derivatives are widely used as photo-responsive compounds. Their conformational change between E and Z isomers in response to visible light or ultraviolet (UV) can be exploited to construct light-operated molecular shuttles. Examples include shuttles based on macrocyclic rings such as cyclodextrins, cucurbit[n]urils and cyclobis(paraquat-p-phenylene). However, few light-operated molecular shuttles have been designed because of the need to match the sizes of the macrocyclic ring and azobenzene derivatives. In this study, we synthesised a new light-operated molecular shuttle, [2]rotaxane, consisting of a pillar[6]arene ring and an azobenzene derivative. Pillar[n]arenes, which were reported by our group in 2008, are pillar-shaped macrocyclic hosts in supramolecular chemistry. Based on their superior functionality, host–guest property, symmetric structures, and facile synthesis, various pillar[n]arene-based supramolecular assemblies and systems have been reported.

In this study, we designed a pillar[n]arene-based photo-responsive molecular shuttle using a photo-responsive host–guest complexation between azobenzene derivatives and pillar[6]arenes. From previous reports, the smaller size of the E isomers of azobenzene derivatives permits them to thread pillar[6]arene cavity (Fig. 1a). In contrast, pillar[6]arenes rarely form stable complexes with Z isomers because the latter are too bulky. Therefore, the pillar[6]arene ring can only accommodate E isomer azobenzenes.

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† Electronic supplementary information (ESI) available: Experimental section, NMR, Job plots and 1H NMR titrations, variable temperature 1H NMR. See DOI: 10.1039/d0cc03945d
We thus introduced the azobenzene group as a photo-responsive gate to control pillar[6]arene shuttling between two stations. A C4 methylene chain group flanked by N-substituted triazoles, axle 1 (Fig. 1b) was used as a station. Axle 1 forms a 1:1 host-guest complex with the pillar[6]arene 2 at 298 K in CDCl₃ ($K = 1.6 \pm 0.1 \text{ M}^{-1}$, see ESI† for detail), that is notably weaker than its corresponding complexes with pillar[5]arenes ($K > 10^4 \text{ M}^{-1}$)¹³ because of the larger cavity size of pillar[6]arenes (ca. 6.7 Å) compared with pillar[5]arenes (ca. 4.7 Å). The weak binding of the C4 station by pillar[6]arenes enables rapid shuttling between two such stations. Thus, we designed [2]rotaxane 5, a pillar[6]arene ring 2, encircling axle 3 (a central photo-responsive azobenzene gate connecting two C4 stations), capped by a pair of bulky trityl stoppers 4. The pillar[6]arene-based [2]rotaxane 5 was synthesised using a stepwise copper(i)-catalysed alkyn–azide cycloaddition (CuAAC) reaction, previously developed in our laboratory (Fig. 2A).¹³ In the rotaxane synthesis, first CuAAC reaction between axle 3 and stopper 4 produced an intermediate.

![Fig. 2](A) Synthesis of pillar[6]arene-based [2]rotaxane 5 from pillar[6]arene ring 2, stopper 4 and azobenzene axle 3. (B) $^1$H NMR spectra (CDCl₃) of (a) dumbbell 6 at 298 K. (b–d) $E$-[2]rotaxane 5 at different temperatures and (e) $Z$-[2]rotaxane 5 ($E/Z = 10/90$) at 298 K.
containing one C4 station in situ, then pseudo-[2]rotaxane structure forms. The second CuAAC reaction produces the second C4 station. However, wheel 2 cannot slip over the stopper ends, resulting in formation of [2]rotaxane 5 with two C4 stations (yield 39%). We used a large excess of the pillar[6]arene 2 to promote the complex formation, thus [2]rotaxane 5 was obtained in relatively high yield despite the low association constant.

Fig. 2B shows 1H NMR spectra of dumbbell 6 (Fig. 2B(a)) and [2]rotaxane 5 with the E isomer azobenzene (E-[2]rotaxane 5, Fig. 2B(b)) at 298 K. Both dumbbell 6 and E-[2]rotaxane 5 showed clear proton signals from the E isomer azobenzene gate (k, l; shown in purple), stopper and methylene linkers (a, b, c, j; black); however, proton signals from C4 stations and triazole groups (d–i; green, Fig. 2B(a)) were so strongly broadened in the spectra of E-[2]rotaxane 5 at 298 K (Fig. 2B(b)) that they are not visible, indicating that shuttling of the pillar[6]arene ring between the two C4 stations occurs on the NMR time scale.14 To clarify this, we obtained 1H NMR spectra of E-[2]rotaxane 5 at lower temperatures. At 213 K (Fig. 2B(d)), new proton signals appeared because the ring shuttling was now slow on the NMR time scale. New peaks (d–i; green) were observed at the similar position as the signals from the C4 station and triazole moieties of dumbbell 6 (Fig. 2B(a)), confirming that they originate from the un-covered C4 station and triazole moieties. Other new peaks were attributed to proton signals from the trityl groups covered by the pillar[6]arene ring (blue), because they were found at the similar position in the spectra of [2]rotaxane 5 at 213 K (Fig. 2B(d)). These peaks were observed in the spectra of Z-[2]rotaxane 5 even at 298 K, indicating that the Z isomer of the azobenzene gate restricted the ring to reside over one C4 station. The 1H NMR spectra of Z-[2]rotaxane 5 did not change even upon cooling to 213 K (ESI†), indicating that the Z-azobenzene functions as a “closed gate” that inhibits shuttling of pillar[6]arene ring (Fig. 3b). Photo-isomerisation of the azobenzene group between its E and Z isomers in [2]rotaxane 5 was also monitored using UV-vis absorption measurements (Fig. 4).

UV irradiation of E-[2]rotaxane 5 caused a decrease in the absorbance of E-azobenzene at 357 nm, and an increase in the absorbance of Z-azobenzene at 450 nm (Fig. 4a), indicating E-to-Z photo-isomerisation of the azobenzene group. A photo-stationary state was reached after 120 s. When the solution was left at 298 K in the dark, the absorbance of the E-azobenzene completely recovered after 2000 s, with a concomitant decrease in the absorbance of Z-azobenzene (Fig. 4b), indicating that

![Fig. 4](https://example.com/fig4.png)

**Fig. 4** Absorption spectra of [2]rotaxane 5 (25 μM in CHCl₃ at 298 K) (a) during UV light irradiation, and (b) subsequent recovery in the dark. (c) Absorbance change at 357 nm accompanying the E-to-Z and Z-to-E conversion of [2]rotaxane 5 (25 μM in CHCl₃ at 298 K) by UV irradiation in a 120 s/2000 s light–dark cycle.

Shuttling of the pillar[6]arene ring in [2]rotaxane 5 after photo-isomerisation of the azobenzene gate from E to Z isomers was investigated using 1H NMR (Fig. 2B(e)) at 298 K. When E-[2]rotaxane 5 was irradiated with UV (365 nm), new peaks appeared at 6.9 ppm, which were attributed to the Z isomer of the azobenzene gate (orange). At equilibrium, the E/Z-azobenzene ratio was 10/90, which was determined from the relative intensity of the 1H signals corresponding to E-azobenzene (peaks c and j) and Z-azobenzene (peaks C and J) in Fig. 2B(e). The new peaks at 7.55, 4.45 and 1.95 ppm were attributed to un-covered C4 stations and triazole groups (green). The other set of signals at 6.3, 6.0, 1.8 and 0.2 ppm could be attributed to C4 station and triazole groups covered by the pillar[6]arene ring (blue), because they were found at the similar position in the spectra of E-[2]rotaxane 5 at 213 K (Fig. 2B(d)). These peaks were observed in the spectra of Z-[2]rotaxane 5 even at 298 K, indicating that the Z isomer of the azobenzene gate restricted the ring to reside over one C4 station. The NH NMR spectra of Z-[2]rotaxane 5 did not change even upon cooling to 213 K (ESI†), indicating that the Z-azobenzene functions as a “closed gate” that inhibits shuttling of pillar[6]arene ring (Fig. 3b). Photo-isomerisation of the azobenzene group between its E and Z isomers in [2]rotaxane 5 was also monitored using UV-vis absorption measurements (Fig. 4).

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![Fig. 3](https://example.com/fig3.png)

**Fig. 3** Illustration of the photo-regulated molecular shuttle by [2]rotaxane 5 with (a) E and (b) Z azobenzene isomers.
Z-to-E thermal isomerisation occurred at 298 K. The above processes could be reversibly repeated at 298 K (Fig. 4c).

In summary, we have synthesised a pillar[6]arene-based photo-responsive molecular shuttle. The azobenzene derivative processes could be reversibly repeated at 298 K (Fig. 4c).

Conflicts of interest

There are no conflicts to declare.

Notes and references


14 Proton signals of c/C and j/j are still in the fast exchange limit in Fig. 2B(b). This must be because the chemical shift difference is small so that coalescence occurs at much lower temperature than for the proton pairs of which the shielding in the covered part is very strong.


16 The value of $\Delta$ at 25 °C should be viewed as having at least 5% error because this estimation includes uncertainty to determine the coalescence temperature, some approximations and extrapolations.