Molecular Devices

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Controlling Molecular Rotary Motion with a Self-Complexing Lock**

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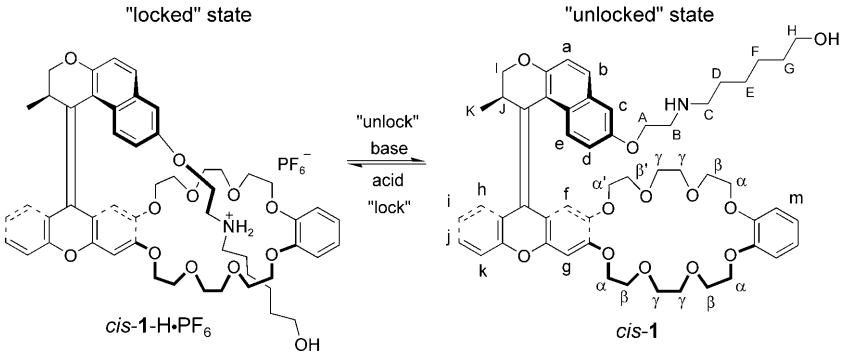
Biological motors, such as the kinesin or myosin linear and ATPase rotary motor systems,[1] have been a source of inspiration for the development of a variety of artificial molecular mechanical devices[2] (including switches, shuttles, muscles, and rotors) and of elegant molecular motor systems.[3] Self-complexing and self-assembling systems[4] represent important dynamic compounds that play a prominent role in the field of molecular recognition and molecular devices. The uses of such supramolecular systems add attractive features to the construction of advanced nanoscale molecular machinery because of their potential to undergo controllable intramolecular complexation in response to a particular stimulus.

Of these self-assembling systems, secondary dialkylammonium ions ($R_2NH_2^+$) are well-known for their ability to thread through, for example, a dibenzo[24]crown-8 (DB24C8) ring to give a [2]pseudorotaxane,[5] owing to a combination of strong [+N–H···O] hydrogen bonding and [C–H···O] interactions. Upon deprotonation of the $R_2NH_2^+$ moiety, the two [+N–H···O] hydrogen bonds are eliminated, and the [2]pseudorotaxanes are dethreaded. Although several groups[6] have combined both the dibenzo[24]crown-8 and dialkylammonium ion structural motifs into a single system, most of these feature versatile intermolecular complexation rather than unique intramolecular self-complexation.

Herein we report the design, characterization, and operation of a lockable[7] light-driven molecular rotary motor featuring a self-complexing [1]pseudorotaxane system. By taking advantage of the complexation between the $R_2NH_2^+$ and the DB24C8 units in the system, acid–base-controlled threading–dethreading movements can be utilized to unlock or lock the molecular rotary motor. The design of the molecular system with a self-complexing lock is illustrated in Scheme 1. The molecular system *cis*-**1**-H·PF_6 is composed of 1) a second-generation light-driven molecular motor[8–10] based on an overcrowded alkene, in which the molecular rotor (2,6-dioxonaphthalene, upper half) rotates 360° relative to the stator (xanthene, lower half) upon repetitive photochemical *trans–cis* isomerizations and subsequent thermal irreversible helix inversion steps, 2) a DB24C8 macrocyclic ring incorporated into the xanthene lower stator half, which can act as a socket for the dialkylammonium moiety, and 3) a $R_2NH_2^+$ moiety attached to the upper rotor half by a short spacer, which can insert itself as a plug into the DB24C8 macrocycle socket. The free OH group at the end of the arm can be easily functionalized to construct interlocked rotaxanes. *cis*-**1**-H·PF_6 was prepared in 20 steps (Schemes S1–S4 in the Supporting Information) and characterized by ^1H and ^{13}C NMR spectroscopy and high-resolution mass spectrometry.[11]



Scheme 1. The chemical structure of a lockable light-driven molecular motor featuring a self-complexing [1]pseudorotaxane system and the acid–base-controlled threading–dethreading (locking–unlocking) movements.

The ^1H NMR spectrum (500 MHz, 298 K) of the hexafluorophosphate salt *cis*-**1**-H·PF_6 (Figure 1a), recorded in [D_6]DMSO, has similar splitting patterns as the spectrum of the unprotonated *cis*-**1** in CD_2Cl_2 (Figure 1b),[6a] which can be rationalized by attributing it to the uncomplexed species, that is, the dialkylammonium ion does not reside inside the DB24C8 cavity.[6c] A more complicated ^1H NMR spectrum of *cis*-**1**-H·PF_6 was obtained in CD_2Cl_2 (Figure 1c), as is evident in the region $\delta = 3.5$–4.4 ppm corresponding to the resonances of the protons in the DB24C8 ring, that is, formation of a complex. The signals of H_A (H_B or H_C) were split owing to the unsymmetric structure of the DB24C8 ring in the self-complexing system. The NOEs (Figures S2 and S3 in the Supporting Information) observed between the protons in the dialkylammonium arm and protons of the crown ether ring (from H_A to H_α, $H_{B,C}$ to $H_{\beta,\gamma}$), as well as the NOEs observed between H_A and H_m in the aromatic part of the macrocycle ring provide good evidence for the complexation of the

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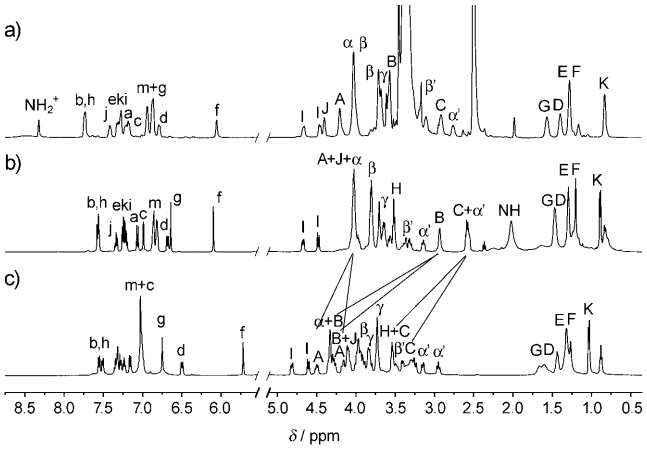


Figure 1. ^{1}H NMR spectra (500 MHz, 298 K) of a) *cis*-**1**·H·PF_6 in [D_6]DMSO, b) *cis*-**1** in CD_2Cl_2, c) *cis*-**1**·H·PF_6 in CD_2Cl_2. The protons of each compound were assigned using ^{1}H–^{1}H COSY NMR spectroscopy.[11] The resonance of $H_{\alpha'}$ (or $H_{\beta'}$) was shifted upfield from that of H_α (or H_β), owing to the shielding effect of the upper half in the *cis* isomer. The assignments correspond to the structure shown in Scheme 1.

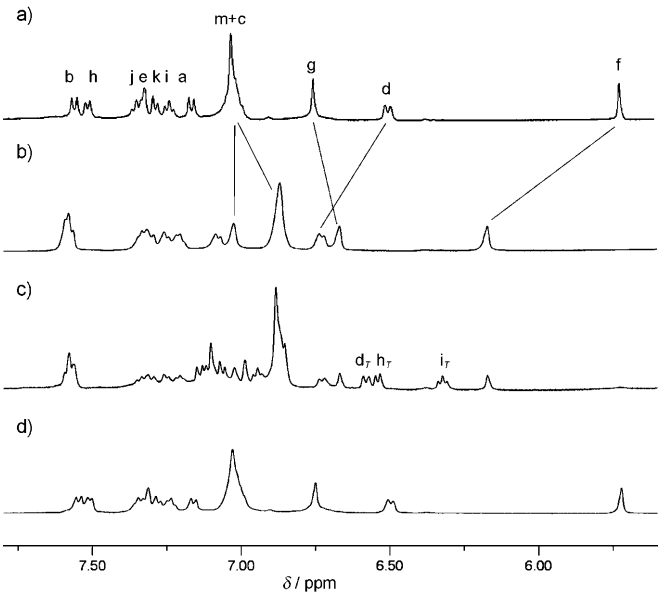


Figure 2. Partial ^{1}H NMR spectra of a) *cis*-**1**·H·PF_6, b) after addition of 1.1 equiv DBU, c) irradiation of sample (b) at 365 nm at room temperature for 2 h, and d) reprotonation with addition of 1.3 equiv TFA to sample (b) in CD_2Cl_2. The assignments correspond to Scheme 1. d_T, h_T, i_T donate H_d, H_h, H_i of the *trans*-stable isomer.

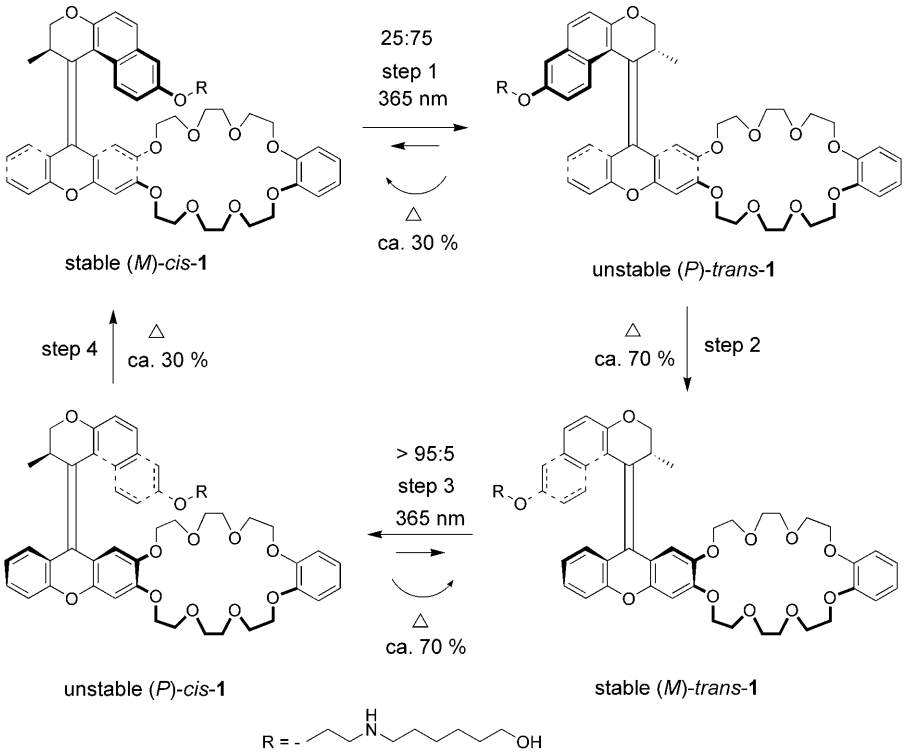
dialkylammonium moiety and the DB24C8 ring. Electrospray ionization mass spectrometry (ESI-MS) showed a single peak at *m*/*z* 906.44, which corresponds to the single positively charged ion $[M-PF_6]^+$. No peak corresponding to the dimer, trimer, or polymer was found in the mass spectrum. From ^{1}H NMR and NOESY spectroscopy and ESI-MS spectrometry, we conclude that *cis*-**1**·H·PF_6 can self-complex to form the [1]pseudorotaxane in a less polar solvent such as CD_2Cl_2.

To study the chemically driven threading and dethreading movements in this self-complexing system, 1,8-diazabicyclo-[5.4.0]undec-7-ene (DBU) was used to deprotonate the dialkylammonium ion moiety.[12] Addition of 1.1 equiv DBU in CD_2Cl_2 resulted in the elimination of the hydrogen bonding between the dialkylammonium ion and the DB24C8 ring and the dethreading of the pseudorotaxane. As a result, the structure of the deprotonated species became less crowded, and the downfield shifts of the resonances for H_f (from $\delta = 5.7$ to 6.2 ppm) and H_d (from $\delta = 6.5$ to 6.8 ppm) were detected (Figure 2b). When 1.3 equiv trifluoroacetic acid (TFA) was added to this solution, the original spectrum was regenerated completely, thus indicating a return to the self-complexing [1]pseudorotaxane structure (Figure 2d).

Irradiation of *cis*-**1**·H·PF_6 in CD_2Cl_2 at 365 nm did not result in any change in the ^{1}H NMR spectrum. After addition of 1.1 equiv DBU, irradiation at 365 nm at room temperature resulted in the formation of a mixture of *trans*- and *cis*-stable isomers with a ratio of 55:45 (Figure 2c).[13] We attribute this change in photochemical behavior to the fact that in the self-assembling [1]pseudorotaxane system, the hydrogen-bonding interactions between the $R_2NH_2^+$ unit and the DB24C8 macrocycle are strong enough to prevent the conformational changes needed for the rotational motion of the rotor part, that is, the motor is in a "locked" state. After deprotonation, the motor is in an "unlocked" state, and photoisomerization is allowed.

To verify that this molecule can function as a rotary molecular motor after deprotonation, the photochemical and thermal isomerization of stable *cis*-**1** and stable *trans*-**1** was also investigated with low-temperature ^{1}H NMR spectroscopy (Figures S7 and S8 in the Supporting Information). Upon irradiation of *cis*-**1** (365 nm, 3 h, −25 °C) in CD_2Cl_2, new signals corresponding to the unstable *trans* isomer appeared. In the photostationary state (PSS) of the first photoequilibrium (step 1 in Scheme 2), around 75% unstable *trans*-**1** is present.[14] Upon standing for 30 min at 20 °C in the dark, conversion of the unstable *trans*-**1** to the expected stable *trans*-**1** isomer is observed. Careful analysis revealed that not all unstable *trans*-**1** was converted to stable *trans*-**1**: in a competing process 30% of the unstable *trans*-**1** was thermally converted back to stable *cis*-**1**. After the first thermal step (step 2 in Scheme 2), the ratio between *trans*-**1** and *cis*-**1** was therefore around 47:53.

Similar experiments starting with *trans*-**1** indicated a highly selective *trans*-to-*cis* photoisomerization. Starting with stable *trans*-**1**, the ratio of unstable *cis*-**1** and stable *trans*-**1** was determined to be 95:5 in the PSS of the second photoequilibrium (step 3 in Scheme 2). In the second thermal step (step 4 in Scheme 2), competing thermal processes also operate, that is, a forward helix inversion (minor pathway, 30%) and a backward *cis*-to-*trans* isomerization (major pathway, 70%) take place simultaneously. After the second thermal step, the ratio between *cis*-**1** and *trans*-**1** was around 30:70. Compared with the first thermal step, the backward *cis*-to-*trans* isomerization significantly increased in the second thermal step, which is attributed to the drastically enhanced steric interactions between the two parts of the molecules that slip past each other when the thermal helix inversion happens from unstable *cis*-**1** (step 4). This competing thermal isomer-



Scheme 2. Photochemical and thermal isomerization processes involved with the rotary cycle of motor **1**. Competing thermal processes are the forward helix inversion and the backward *cis–trans* isomerization. Racemic motors were used for the NMR spectroscopy studies; single enantiomers are shown for clarity.

ization pathway has not been observed with the previously described light-driven molecular motors based on the overcrowded alkenes, except for a push–pull system.[15] In the latter case, the unusual behavior is attributed to a large polarizing effect on the central olefinic bond evident from a resonance structure featuring a single bond connecting the rotor and the stator as the central axis. In the case of *cis*-**1**, the enhanced steric hindrance for helix inversion opens a competitive thermal *cis*-to-*trans* isomerization. It should be noted that this backward thermal pathway leaves the overall unidirectionality intact; steps 2 and 4 are still strictly unidirectional, as evident from ^{1}H NMR spectroscopic analysis of the thermal and photochemical steps during the overall forward process.

The locking–unlocking properties of the molecular system were also demonstrated using low-temperature UV/Vis spectroscopy. Upon irradiation (365 nm, −20 °C) of *cis*-**1**-H·PF_6 in CH_2Cl_2, no change was observed in the UV/Vis absorption spectrum (Figure 3 a). This finding means that even at very low concentration (10^{-5} mol L^{-1}), the system is kept in the "locked" state. Addition of excess DBU led to a small red shift of the spectrum (Figure 3 b). Subsequent irradiation resulted in the appearance of a long-wavelength band around 423 nm in the UV/Vis spectrum (Figure 3 c), which is due to the enhanced twist of the central olefinic bond and is characteristic for the unstable *trans*-**1**.[9] A clear isosbestic point was observed around 387 nm, indicating a unimolecular process. Subsequent warming of the sample to room temperature resulted in the disappearance of the long-wavelength band, thus indicating thermal isomerization and formation of the stable isomers (Figure 3 d). Similar experiments starting with *trans*-**1** indicated a corresponding *trans*-to-*cis* isomerization in the unlocked state, as shown in the Supporting Information.[11,16,17]

In conclusion, we have demonstrated the operation of a lockable light-driven molecular motor based on a self-complexing [1]pseudorotaxane system. By taking advantage of the complexation between the $R_2NH_2^+$ moiety and the DB24C8 macrocycle ring present in the system, as well as its acid–base switching properties in solution, the locking and unlocking of the molecular motor can be achieved. These results represent an important step towards fabricating more advanced molecular devices and achieving control of integrated nanomechanical motion at the single-molecule level.

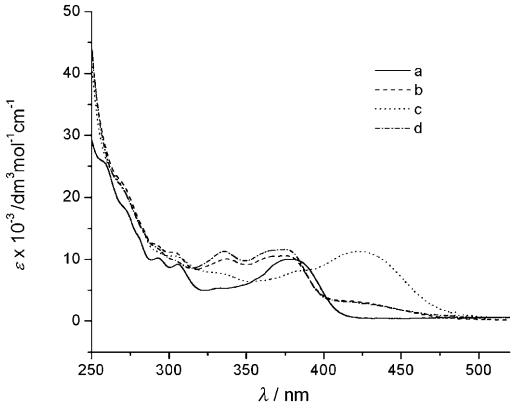


Figure 3. UV/Vis spectra (CH_2Cl_2, −20 °C) of a) *cis*-**1**-H·PF_6, b) after addition of 10 equiv of DBU, c) the photostationary state mixture after irradiation at 365 nm at −20 °C for 2 h, and d) the mixture of stable isomers after warming at room temperature for 20 min in the dark.

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[11] The Supporting Information includes full experimental procedures and characterization data for the target compound *cis*-**1**-H·PF_6 and its intermediates and UV/Vis and ^{1}H NMR spectral data of stable and unstable isomers of motor **1.**

[12] Tributylamine, triethylamine, and diisopropylethylamine were also used to deprotonate the dialkylammonium ion, but the deprotonation was incomplete in each case, even if a large excess of base was added.

[13] The Gibbs free energy of activation of the thermal isomerization steps in the motor without any substituent is rather low (19.9 kcal mol^{-1}), corresponding to a half-life of 77 s at room temperature. In this case, unstable isomers could not be observed at room temperature upon irradiation, owing to fast thermal helix inversion.

[14] Under conditions in which no thermal isomerization occurred, a secondary, slower photochemical process was also observed in which stable *cis*-**1** isomerized directly to stable *trans*-**1**. Continued irradiation ultimately gave a photostationary state containing all three isomers of **1** in a 100:20:7 ratio of unstable *trans*/stable *cis*/unstable *cis*. Only trace amounts of stable *trans*-**1** were observed, as it was converted into unstable *cis*-**1** quantitatively upon irradiation; for an extensive analysis of competing processes in molecular motors, see, for example, E. M. Geertsema, S. J. van de Molen, M. Martens, B. L. Feringa, *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 16919 – 16924.

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[16] Compared with the case without DBU, the ratios between the unstable form and the stable form were enhanced in the presence of DBU upon irradiation of both *cis*-**1** and *trans*-**1** isomers at low temperature in the UV/Vis measurements. This result is attributed to some photodegradation of CH_2Cl_2, which can produce trace amounts of HCl that effect the isomerization at very low concentration. Addition of base can neutralize the traces of acid and promote the photochemical conversion.

[17] The presence of an ammonium group does not interfere with the photochemistry.

