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,[11] 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.[10] 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 (R₂NH₂⁺) 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 R₂NH₂⁺ 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 R₂NH₂⁺ 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-I-H·PF₆ 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 R₂NH₂⁺ moiety attached to the upper rotor half by a short spacer, which can insert itself as a plug into the DB24C8 macrocyclic socket. The free OH group at the end of the arm can be easily functionalized to construct interlocked rotaxanes. cis-I-H·PF₆ was prepared in 20 steps (Schemes S1–S4 in the Supporting Information) and characterized by ¹H and ¹³C NMR spectroscopy and high-resolution mass spectrometry.[11]

The ¹H NMR spectrum (500 MHz, 298 K) of the hexafluorophosphate salt cis-I-H·PF₆ (Figure 1a), recorded in [D₆]DMSO, has similar splitting patterns as the spectrum of the unprotonated cis-I in CDCl₃ (Figure 1b),[10] which can be rationalized by attributing it to the uncomplexed species, that is, the dialkylammonium ion does not reside inside the DB24C8 cavity.[11] More complicated ¹H NMR spectrum of cis-I-H·PF₆ was obtained in CD₂Cl₂ (Figure 1c), as is evident in the region Δ=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 H₅ (H₆ or H₇) 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 H₇ to H₇, H₆C to H₄a), as well as the NOEs observed between H₇ and H₆b 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$_8$]DMSO, b) cis-1 in CD$_2$Cl$_2$, c) cis-1-H·PF$_6$ in CD$_2$Cl$_2$. The protons of each compound were assigned using $^1$H–$^1$H COSY NMR spectroscopy$^{[1]}$. The resonance of H$_d$ (or H$_i$) was shifted upfield from that of H$_a$ (or H$_b$), owing to the shielding effect of the upper half in the cis isomer. The assignments correspond to the structure shown in Scheme 1.

dialkylammonium moiety and the DB24C$_8$ 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 spectroscopy, we conclude that cis-1-H·PF$_6$ can self-complex to form the [1]pseudorotaxane structure (Figure 2d).

To study the chemically driven threeding and dethreeding 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$_2$Cl$_2$ resulted in the elimination of the hydrogen bonding between the dialkylammonium ion and the DB24C$_8$ 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$_a$ (from $\delta$ = 5.7 to 6.2 ppm) and H$_b$ (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 (Figure 2b). When 1.3 equiv trifluoroacetic acid (TFA) was added to this solution, the original spectrum was regenerated (Figure 2b).

Irradiation of cis-1-H·PF$_6$ in CD$_2$Cl$_2$ 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$_2$NH$_2$ unit and the DB24C$_8$ 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, $-25^\circ$C) in CD$_2$Cl$_2$, 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$^\circ$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-
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·PF₆ in CH₂Cl₂, no change was observed in the UV/Vis absorption spectrum (Figure 3a). This finding means that even at very low concentration (10⁻³ 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 3b). Subsequent irradiation resulted in the appearance of a long-wavelength band around 423 nm in the UV/Vis spectrum (Figure 3c), which is due to the enhanced twist of the central olefinic bond and is characteristic for the unstable trans-1. 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 3d). Similar experiments starting with trans-1 indicated a corresponding trans-to-cis isomerization in the unlocked state, as shown in the Supporting Information.

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 R₂NH₂⁺ 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 toward fabricating more advanced molecular devices and achieving control of integrated nanomechanical motion at the single-molecule level.

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[11] The Supporting Information includes full experimental procedures and characterization data for the target compound cis-1-H·PF6, and its intermediates and UV/Vis and 1H NMR spectral data of stable and unstable isomers of motor I.

[12] Tributylamine, triethylamine, and disopropylethylamine 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 kcalmol−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 I in a 100:20:7 ratio of unstable trans/stable cis/unsuitable 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.


[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 CH2Cl2, which can produce trace amounts of HCl that affect 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.