Accelerating the Shuttling in Hydrogen-Bonded Rotaxanes: Active Role of the Axle and the End Station

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Supporting Information

ABSTRACT: The relation between the chemical structure and the mechanical behavior of molecular machines is of paramount importance for a rational design of superior nanomachines. Here, we report on a mechanistic study of a nanometer scale translational movement in two bistable rotaxanes. Both rotaxanes consist of a tetra-amide macrocycle interlocked onto a polyether axle. The macrocycle can shuttle between an initial succinamide station and a 3,6-dihydroxy- or 3,6-di-tert-butyl-1,8-naphthalimide end station. Translocation of the macrocycle is controlled by a hydrogen-bonding equilibrium between the stations. The equilibrium can be perturbed photochemically by either intermolecular proton or electron transfer depending on the system. To the best of our knowledge, utilization of proton transfer from a conventional photoacid for the operation of a molecular machine is demonstrated for the first time. The shuttling dynamics are monitored by means of UV–vis and IR transient absorption spectroscopies. The polyether axle accelerates the shuttling by ~70% compared to a structurally similar rotaxane with an all-alkane thread of the same length. The acceleration is attributed to a decrease in activation energy due to an early transition state where the macrocycle partially hydrogen bonds to the ether group of the axle. The dihydroxyrotaxane exhibits the fastest shuttling speed over a nanometer distance ($\tau_{\text{shuttling}} \approx 30$ ns) reported to date. The shuttling in this case is proposed to take place via a so-called harpooning mechanism where the transition state involves a folded conformation due to the hydrogen-bonding interactions with the hydroxyl groups of the end station.

INTRODUCTION

The control of motion on a molecular scale is one of the great challenges in present-day nanotechnology. This has led to a rapid development of mechanically interlocked molecules designed to perform a specific function in response to external stimuli.1–12 Rotaxanes constitute one of the best-studied classes of such molecules due to their potential applications in molecular switches13–16 and machines.17–22 [2]Rotaxanes are composed of a molecular wheel (macrocycle) that is mechanically interlocked onto a molecular axle (thread) by bulky stoppers. Rotaxanes often contain two or more recognition sites (stations), and the macrocycle can shuttle along the thread between these stations.23–25 Contrary to their macroscopic counterparts, the components of the molecular machines are in perpetual random motion due to thermal fluctuations.26,27 Therefore, the supplied energy, often in the form of chemical,28–33 electrochemical,34–36 or photochemical input,37–41 is used to drive the system temporarily out of equilibrium and bias the movement of the macrocycle to one direction.42,43 Light activation offers a clean energy supply without formation of byproducts and the possibility to convert solar energy directly into mechanical work. In addition, light-induced molecular motion combined with optical monitoring by means of time-resolved laser spectroscopy offers a superior time resolution for detailed kinetic studies. Examples of photochemical reactions used for the operation of [2]rotaxanes include photoduced isomerization44–46 and electron transfer,47,48 but to the best of our knowledge, excited-state proton transfer has not yet been utilized for this purpose.49

Despite the large number of molecular machines reported in the literature,50,19 few studies are aimed at elucidating the working principles and the factors influencing nanoscale motion.52–54 In particular, detailed kinetic studies of fast shuttling processes are scarce.55–58 The effect of the solvent,57,58,59 axle length,55,60 and hydrogen-bonding stations76,61 in a series of bistable hydrogen-bonded [2]rotaxanes has led to the proposition of two different shuttling mechanisms. In an earlier work, the overall shuttling was modeled as a two-step process: escape from the initial station followed by a biased random walk motion along the axle, which could explain the decrease in the shuttling rate upon increasing axle length.55 Contrary to the biased random walk model, Hirose et al. did not find any effect of the axle length, in this case a rigid axle, on the shuttling rate.54 Axle-length
independent shuttling rates were also recently reported for both rigid and flexible spacers. Another study proposed a “harpooning” mechanism in which the macrocycle is hydrogen bonded simultaneously to both stations in the transition state. Jeppesen and Flood et al. also proposed that longer linkers facilitate folding of the rotaxanes, enabling simultaneous interactions between the macrocycle and both of the stations. Second, the authors proposed that a polyether axle plays an active role in the shuttling process via interactions with the macrocycle.

Most of the rotaxanes previously studied in our group were composed of a 3,6-di-tert-butyl-1,8-naphthalimide (tBu-NI) end station, a succinamide initial station (succ), an alkane thread, and a tetra-amide macrocycle (mc). In the present study, the alkane thread has been replaced with a polyether chain (PE, C₆O₂) to investigate whether the hydrogen-bonding capability of the thread plays an active role in the shuttling process. In addition, the PE thread has been combined with the 3,6-di-tert-butyl-1,8-naphthalimide and a novel 3,6-dihydroxy-1,8-naphthalimide (dOH-NI) end stations (Chart 1) to specifically study the effect of the different end

Chart 1. Structures of the Studied Compounds

Abbreviations used throughout the text: dOH-NI = 3,6-dihydroxy-1,8-naphthalimide, tBu-NI = 3,6-di-tert-butyl-1,8-naphthalimide, PE = polyether (C₆O₂), THR = thread, and RTX = rotaxane.

shuttling takes place to reach the new equilibrium (step 2, Shutting). The produced ions spontaneously recombine on a ~100 μs time scale, yielding the neutral NI station and regenerating the base (step 3, Charge recombination). The HB affinities are restored, and the macrocycle shuttles back and rebinds the succ station, completing the photocycle (step 4, Back shuttling). Consequently, the system is reset to the initial state and ready for a new cycle without the need to replenish or add additional reagents.

An important advantage of using the proton transfer as a mechanism for the charging step is the much faster time scale of the reaction. Initial deprotonation in a preformed ground-state complex of the dOH-NI unit and a weak base takes place on a sub-nanosecond time scale, whereas the bimolecular electron transfer is dependent on the concentration of the electron donor and can take up to several tens of nanoseconds. The charging and shuttling dynamics can become indistinguishable if they occur on similar time scales.

The article is structured as follows. First, we will treat the steady-state characterization of dOH-PE-RTX and dOH-PE-THR upon addition of weak (N-methyl imidazole, NMI) and strong (1,8-diazabicyclo[5.4.0]undec-7-ene, DBU) bases in polar organic solvents, acetonitrile (MeCN) and benzonitrile (PhCN). The association constants are compared to those obtained with the N-butyl-substituted model compound, ref-dOHNI, and the effects of the macrocycle on the spectral and acid—base properties of the dOH-NI unit are discussed. Second, we present the excited-state proton transfer (ESPT)-induced shuttling experiments of the dOH-PE-RTX rotaxane in the presence of a weak base, NMI or 1,4-diazabicyclo[2.2.2]-octane (DABCO), in the visible and IR spectral region. Third,
we describe the shuttling experiments of tBu-PE-RTX using DABCO as the electron donor. The photophysical properties of tBu-NI-based rotaxanes are well-described in the existing literature and will not be discussed in detail here. Finally, we will compare our results with those obtained with a rotaxane based on an all-alkane axle and discuss the effect of the composition of the thread and the end station to the shuttling rate and mechanism.

■ RESULTS

UV–Vis Experiments on dOH-PE-THR and dOH-PE-RTX. We have shown in a previous publication that weak bases form neutral ground-state complexes with the hydroxyl groups of the dOH-NI unit that undergo a rapid ESPT upon excitation. According to the proposed operation mechanism of the dihydroxyrotaxane, the shuttling in this case is expected to occur only via the excited-state pathway. Strong bases, on the other hand, are able to deprotonate one of the hydroxyl groups in the ground state, but the protonated base remains hydrogen bonded to the deprotonated hydroxyl oxygen. If the interaction of the macrocycle toward the deprotonated dOH-NI unit is significantly stronger than that of the protonated DBU, strong bases are expected to result in translocation of the macrocycle already in the ground state. The shuttling is additionally expected to increase the acidity of the hydroxyl group due to the additional stabilization of deprotonated dOH-NI by the macrocycle. The absorption spectra of dOH-PE-THR and dOH-PE-RTX upon addition of a weak (NMI) and a strong base (DBU) in MeCN and PhCN are presented in Figures 1 and S4 (Supporting Information), respectively.

The absorption spectra of the rotaxane and the thread exhibit a red shift and a broadening upon addition of NMI. The spectra were analyzed globally with a 1:2 host/guest association model assuming noncooperative binding (i.e., $K_1 = 4K_2$; see Supporting Information for additional details, spectra, and fits), and the association constants are summarized in Table 1. The obtained species spectra for the free host ($A_H$), 1:1 complex ($A_{H1}$), and 1:2 complex ($A_{H2}$) are depicted in Figure 1 by the colored lines. The association constants of both compounds are slightly smaller than those of the model compound, ref-dOHNI, which could indicate some competition in the binding of NMI toward the initial succ station or the macrocycle. The spectral changes are similar in all cases. Nevertheless, formation of the ground-state complexes between the dOH-NI unit and NMI is not significantly influenced by the presence of the thread or the macrocycle.

The absorption spectra upon addition of DBU exhibit a drastic decrease in the absorption band of the neutral form with a concomitant rise of a new long-wavelength absorption band. These changes are likely due to the deprotonation of one of the hydroxyl groups in the ground state, leading to a significant red shift in the absorption spectrum. The absorption spectra upon addition of DBU are shown in Figure 1.
The excitation wavelength was 385 nm. MeCN. Negative intensities due to emissive processes are removed for clarity. (B) 2D representation of the same spectra. (C) Decays monitored at equilibrium constant for deprotonation (i.e., decreased p

- The band attributed to the 1:1 complex of the ground-state ion pair (deprotonated dOH-NI + protonated DBU). Clear changes are observed between the thread and the rotaxane. First, the rotaxane responds much more readily to the addition of DBU (notice the different concentration ranges in Figure 1B). Second, the spectrum of the ground-state anion of the rotaxane is significantly blue-shifted (463 nm vs 486 nm in MeCN), narrower and higher in intensity. The differences must originate from the presence of the macrocycle. We have shown in a previous publication that hydrogen-bonding interactions to deprotonated hydroxyl oxygen atoms in related 1,8-naphthalimide photoacids greatly stabilize the ground-state anion, causing a blue shift of the spectrum.64-67 The blue shift observed for the rotaxane suggests that the macrocycle stabilizes the ground-state anion of dOH-NI presumably via hydrogen bonding to the deprotonated hydroxyl oxygen. Moreover, the narrowing of the band could be due to exclusion of the solvent around the dOH-NI station by the macrocycle in the shuttled state. We expect to observe similar spectral changes upon shuttling of the macrocycle in the time-resolved experiments.

- To quantify the observed differences between the thread and the rotaxane, the spectra upon addition of DBU were analyzed with a modified 1:2 association model. Due to the low concentration range of DBU, the concentration of 1:2 complexes, where one DBU is associated with each of the hydroxyl groups, is very low and does not need to be considered. However, we account for a competitive association channel which presumably corresponds to a binding of one DBU molecule to the initial succ station without significant spectral changes (see Supporting Information for additional details, spectra, and fits). Hence, we only determined the equilibrium constant for the deprotonation of one of the hydroxyl group by DBU, which can be compared with the corresponding Kt value of ref dOHNI. In both solvents, Kt of dOH-PE-THR is comparable to that of the reference compound. On the contrary, dOH-PE-RTX exhibits a significantly higher Kt in both solvents. Similarly to the above case, this can be explained by stabilization of the ground-state anion by the macrocycle resulting in an increased equilibrium constant for deprotonation (i.e., decreased pKt value). Similar remote control of acid–base properties has been recently reported in the case of other bistable [2]rotaxanes.53,68

- The shuttling rates were measured using a time-resolved UV–vis transient absorption setup in the presence of weak bases, DABCO (c = 60 mM) and NMI (c = 200 mM) in MeCN and PhCN. As discussed in the previous section, weak bases form neutral ground-state complexes with the hydroxyl groups which undergo sub-nanosecond ESPT and eventually produce the ground-state anion in approximately 14 ns.64 The shuttling is expected to occur due to the increased hydrogen-bonding affinity of the mc toward the deprotonated dOH-NI station. Based on the steady-state absorption measurements in the presence of DBU, translocation of the mc induces a significant blue shift and narrowing of the ground-state anion absorption band due to hydrogen bonding of the mc to the deprotonated hydroxyl oxygen. Representative time-resolved transient absorption spectra of dOH-PE-RTX in the presence of 60 mM DABCO in MeCN are presented in Figure 2. The remaining time-resolved spectra, together with the fits, are presented in the Supporting Information (Figures S23–S28).

- The transient spectra of dOH-PE-RTX in the presence of weak bases contain both negative and positive contributions from emissive and absorptive processes, respectively (see Figure 2A,B and Figure S1 for the full spectra). Excitation of the ground-state complex results in formation of excited-state ion pair species with wavelength-dependent multiexponential dynamics.24 We therefore focused on the broad transient absorption band of the ground-state anion formed with t80 ≈ 14 ns and centered initially around 500 nm. During the first 100 ns, this band undergoes a significant narrowing from the red side around 480–570 nm and an increase in intensity around 440–480 nm, in excellent agreement with the observed spectral differences between the thread and the rotaxane in the presence of DBU. Moreover, the spectral evolution observed for the rotaxane could be qualitatively reproduced either from the steady-state spectra of the thread and the rotaxane in the presence of DBU or from the transient absorption spectra of the ground-state anions (Figures S4 and S5, Supporting Information). Therefore, the observed spectral changes can be attributed to an association of the macrocycle with the deprotonated dOH-NI end station.

- In order to disentangle several overlapping contributions, the temporal evolution was analyzed with multiexponential functions at selected wavelengths. The time constant of the shuttling (reflected in the narrowing and blue shift of the ground-state anion band) was obtained as an average of four individually fitted wavelengths (see Supporting Information for details). Two representative fits are presented in Figure 2C. The shuttling is observed as a clear decay of the signal at the long-wavelength side (524 nm, green circles) and as a slight increase around the peak maximum (465 nm, red squares). The large negative feature around t = 0 is due to fluorescence,
whereas the fast rise at 524 nm and decay at 465 nm are mostly due to the formation and decay of the excited anionic species, respectively. In MeCN, the excited-state decay occurs on the same time scale as the shuttling process ($\tau_{\text{shuttling}} = 26$ ns $\approx 2 \tau_{\text{ES}}$), but in PhCN, these two processes are clearly distinguishable in time ($\tau_{\text{shuttling}} = 53$ ns $\approx 4 \tau_{\text{ES}}$). However, the spectral changes attributed to the shuttling are very similar in both solvents corroborating the analysis of the shuttling rates. Moreover, shuttling rates were independent of concentration and the type of the weak base in both solvents (Table S1, Supporting Information).

**IR Experiments on dOH-PE-THR and dOH-PE-RTX.** We performed IR experiments to obtain structural information about the species involved in the shuttling process. First, we will show the steady-state Fourier transform infrared (FTIR) spectra of the neutral and anionic forms of dOH-PE-THR and dOH-PE-RTX followed by the time-resolved UV-pump/IR-probe measurements. Due to the strong IR absorption of NMI resulting from the formation and decay of the excited anionic species, vide infra) have been observed for related compounds and can be attributed to an increased electron density on the aromatic system. An additional band appears at 1600 cm$^{-1}$ in the spectrum of the rotaxane and is attributed to the aromatic ring vibration of the dOH-NI station. In the bare thread, the succ vibrations do not shift, whereas in the rotaxane, both the succ and the mc vibrations exhibit shifts. Upon deprotonation, the amide II vibration of the succ station is shifted outside of the spectral window, resulting in decreased absorption at 1540 cm$^{-1}$. The amide II vibration of the mc is expected to exhibit a blue shift from $\sim$1530 to $\sim$1555 cm$^{-1}$, but this is not clearly seen due to the overlapping contributions from other vibrations. The amide I of the mc is red-shifted to $\sim$1650 cm$^{-1}$ and overlaps with the symmetric CO-stretch vibration of the imide carbonyl. The amide I of the mc is red-shifted to $\sim$1540 cm$^{-1}$ due to the hydrogen bonding with the mc. Additionally, dOH-PE-RTX shows the amide I and amide II vibrations (peaks 4, red) of the mc.

The spectra of both compounds show large changes upon deprotonation by DBU. All major peaks of the dOH-NI station are shifted to lower frequencies, as indicated in Figure 3 by the dashed lines. Similar red shifts upon deprotonation (or formation of radical anion, vide infra) have been observed for related compounds and can be attributed to an increased electron density on the aromatic system. An additional band appears at 1600 cm$^{-1}$ in the spectrum of the rotaxane and is attributed to the aromatic ring vibration of the dOH-NI station. In the bare thread, the succ vibrations do not shift, whereas in the rotaxane, both the succ and the mc vibrations exhibit shifts. Upon deprotonation, the amide II vibration of the succ station is shifted outside of the spectral window, resulting in decreased absorption at 1540 cm$^{-1}$. The amide II vibration of the mc is expected to exhibit a blue shift from $\sim$1530 to $\sim$1555 cm$^{-1}$, but this is not clearly seen due to the overlapping contributions from other vibrations. The amide I of the mc is red-shifted to $\sim$1650 cm$^{-1}$ and overlaps with the symmetric CO-stretch vibration of the imide carbonyl. The amide I of the mc is red-shifted to $\sim$1540 cm$^{-1}$ due to the hydrogen bonding strength of the mc to the anionic dOH-NI end station. We expect to observe similar changes in our time-resolved UV–IR transient absorption experiments.

The time-resolved IR measurements were carried out with identical concentrations as the time-resolved UV–vis measurements. The samples were excited at $\lambda_{\text{exc}} = 355$ nm and monitored with mid-IR pulses over the range from 1540 to 1730 cm$^{-1}$. The short time scale transient IR spectra of dOH-PE-THR and dOH-PE-RTX ($c \approx 100 \mu$M) in the presence of

Figure 3. Example structures of the rotaxane highlighting the most relevant functional groups seen in the spectral window. The FTIR spectra of the (C,D) neutral and (E,F) anionic forms of (left) dOH-PE-THR and (right) dOH-PE-RTX in MeCN-$d_3$, together with the assignment of the relevant vibrations. The spectra of the anionic forms were measured in the presence of DBU.
DABCO ($c = 60 \text{ mM}$) in MeCN-$d_4$ are presented in Figure 4B,C, respectively. Selected frequencies for representative fits of dOH-PE-RTX spectra are numbered in Figure 4C. The spectra were fitted globally with either a mono- (dOH-PE-THR) or a biexponential (dOH-PE-RTX) function combined with a bimolecular recombination and convolved with a simulated IRF with a Gaussian time profile (see Supporting Information for details). The resulting species-associated difference spectra (SADS) are shown in the bottom parts of Figure 4B,C. Example fits of the rotaxane spectra and the concentration profiles of different species are presented in Figure 4D. The reaction scheme for the rotaxane is depicted in Figure 4A. Due to the sub-nanosecond ESPT, the first observed species corresponds to the excited-state anion, which is formed during the excitation pulse.

Both compounds exhibit similar spectral evolution at short delay times ($<$20 ns). Excitation results in bleach of the species (peak 1, red) attributed to a red shift of the amide II vibration of the succ station due to the departure of the mc; (ii) the amide I vibration of the succ station shifts from 1633 cm$^{-1}$ (peak 3, blue in Figure 4D) to 1681 cm$^{-1}$ (peak 5, orange) due to the increased hydrogen-bonding strength of the mc upon arrival to the dOH-NI station; (iv) the amide I vibration of the mc shifts from 1665 to 1655 cm$^{-1}$ (peak 4, orange) due to the increased hydrogen-bonding strength on the dOH-NI station. The observed shifts in the hydrogen-bonding are in excellent agreement with those obtained from the UV–vis and FTIR measurements between the thread and the rotaxane.

The SADS show the previously assigned changes more clearly at each step. The first species is assigned to the deprotonated excited-state anion (Figure 4A). The thread exhibits only two decay components which are almost identical to those of the ES anion and GS anion (preshuttling of the rotaxane (blue and green in Figure 4B,C, respectively). The additional component of the rotaxane (red in Figure 4C) is attributed to the shuttling process and exhibits spectral features which can be attributed to departure of the mc from the succ station and hydrogen bonding between the dOH-NI station. The obtained time constants for the rotaxane are $\tau_{ES} = 12 \pm 3$ ns for the excited-state decay of the anion and $\tau_{shuttling} = 38 \pm 4$ ns for the shuttling process. The values are in reasonable agreement with those obtained from the UV–vis measurements ($\tau_{ES} = 14 \pm 1$ ns and $\tau_{shuttling} = 25 \pm 4$ ns). The final shuttling rates are summarized in Table 2 and represent the average values from all of the measurements (UV–vis and IR).
and the errors represent the corresponding standard deviations.

Table 2. Average Shuttling Time and Rate (1/τ_{shuttling})

<table>
<thead>
<tr>
<th>Compound</th>
<th>Solvent</th>
<th>τ_{shuttling} (ns)</th>
<th>k_{shuttling} (×10^7 s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>dOH-PE-RTX</td>
<td>MeCN</td>
<td>30 ± 6</td>
<td>3.4 ± 0.8</td>
</tr>
<tr>
<td>tBu-PE-RTX</td>
<td>MeCN</td>
<td>160 ± 20</td>
<td>0.64 ± 0.08</td>
</tr>
<tr>
<td>tBu-C₆-RTX</td>
<td>MeCN</td>
<td>270 ± 30</td>
<td>0.37 ± 0.04</td>
</tr>
<tr>
<td>dOH-PE-RTX</td>
<td>PhCN</td>
<td>53 ± 5</td>
<td>1.9 ± 0.2</td>
</tr>
<tr>
<td>tBu-PE-RTX</td>
<td>PhCN</td>
<td>720 ± 70</td>
<td>0.14 ± 0.02</td>
</tr>
</tbody>
</table>

*The errors represent the standard deviations from multiple measurements (UV–vis and IR). The shuttling rate as predicted by the model in ref 55.

**Figure 5**. The peak positions, indicated by markers in Figure 5, were obtained by fitting the spectra with a Gaussian band-shape function around the peak maximum. The shuttling rate in MeCN as determined from the UV–vis experiments is 1/τ_{shuttling} = 143 ± 4 ns. The measurements were repeated with a higher concentration of DABCO (c = 60 mM), which yielded nearly an identical shuttling rate (Figure S30). The shuttling rate at the lower DABCO concentration in PhCN was, however, significantly smaller than that at higher DABCO concentration (780 ns vs 660 ns, Figures S31 and S32). This is most likely due to the relatively slow formation of the radical ion pairs (~200 ns) in more viscous PhCN. As the formation lifetime of the radical ion pairs approaches that of the shuttling, the processes become less distinguishable.

Representative nanosecond UV–IR transient absorption spectra of tBu-PE-RTX (c ~ 100 μM) in the presence of DABCO (c = 10 mM) in MeCN-δ were presented in Figure 6A.

**Figure 6**. (A) UV–IR transient absorption spectra of tBu-PE-RTX (c ~ 100 μM) in the presence of DABCO (c = 10 mM). The decay of the triplet state (t < 90 ns) is left out for clarity, and the first spectrum represents the transient spectrum of the radical anion. The spectra are normalized to the bleach of the symmetric CO-vibration peak at ~1700 cm⁻¹. The temporal behavior of this peak is determined only by the recombination of the radical ion pair. The normalization thus removes the contribution of the overall decay from the signal, and the observed spectral changes are solely due to the formation of the radical anion and the subsequent shuttling process. A global fit of the five main peaks using a biexponential model described in the Supporting Information are presented in Figure 6B. The decay of the triplet state (t > 10 ns) is left out for clarity, and the first spectrum represents the transient spectrum of the radical anion. The spectra are normalized to the bleach of the symmetric CO-vibration peak at ~1700 cm⁻¹. The temporal behavior of this peak is determined only by the recombination of the radical ion pair. The normalization thus removes the contribution of the overall decay from the signal, and the observed spectral changes are solely due to the formation of the radical anion and the subsequent shuttling process. A global fit of the five main peaks using a biexponential model described in the Supporting Information are presented in Figure 6B.

**Figure 6**. (B) Decay curves of the relevant absorption peaks indicated in (A). The solid lines represent the best fits with a global biexponential model at t > 10 ns.
Scheme 2. Schematic Representation of the Free Energy Landscapes of the Structurally Different Rotaxanes as a Function of the Shuttling Coordinate**

**The dashed free energy surface of dOH-PE-RTX (right) corresponds to the unfolded geometry, whereas the solid line represents that of the folded geometry.

Figure 6B. Further details on the analysis and interpretation of data can be found in ref 55.

Similarly to dOH-PE-RTX, the spectra exhibit ground-state bleach signals of the aromatic ring vibration (1633 cm\(^{-1}\)) and the antisymmetric (1666 cm\(^{-1}\)) and symmetric (1700 cm\(^{-1}\)) CO vibrations of the fBu-NI station upon excitation. The strongest positive peak (peak 2, black) attributed to the symmetric CO vibration of the radical anion gradually shifts to a lower frequency (peak 1, red). This is attributed to the hydrogen bonding of the mc to the imide carbonyls of the fBu-NI station. The increased hydrogen-bonding strength is also seen as induced absorption due to the shift of the amide I vibration of the mc (peak 4, orange). The departure of the mc is observed as a loss of the hydrogen-bonded succ vibration (1633 cm\(^{-1}\), peak 3, blue) and appearance of the free succ vibration (1655 cm\(^{-1}\), peak 5, green). Global fitting of the five main peaks yields a shuttling rate of \(1/k_{\text{shuttling}} = 180 \pm 10\) ns, slightly longer than that observed in the UV-vis experiments. The slight differences in shuttling rates can be attributed to the different analysis methods and sample preparation conditions (see below). The shuttling time/rate constants are summarized in Table 2 and represent the average values from all the measurements (UV-vis and IR) and the errors are the corresponding standard deviations.

** DISCUSSION **

The aim of the study was to elaborate on the effect of the molecular composition of the different constituents on the shuttling speed and mechanism in hydrogen-bonded rotaxanes. All the shuttling time/rate constants are summarized in Table 2. A schematic representation of the energy landscapes of the structurally different rotaxanes as a function of the shuttling coordinate is presented in Scheme 2.

The shuttling rates of fBu-NI-based rotaxanes with alkane threads have been previously studied in our group. Measurements on a series of rotaxanes with varying lengths of the alkane threads (\(-(\text{CH}_2)_n-\) with \(n = 5, 9, 12, \) and 16) allowed us to propose a model that describes the rate as a function of the chain length.55 Because the study did not include fBu-C\(_n\)-RTX, the rate as predicted by the model was used in calculating the acceleration due to the introduction of oxygen atoms. Introduction of oxygen atoms in the thread increases the shuttling rate by \(\sim 70\%\) (\(1/k_{\text{shuttling}} = 160\) ns) compared to the predicted rate for fBu-C\(_n\)-RTX (\(1/k_{\text{shuttling}} = 270\) ns). We believe that there can be two possible effects resulting in the faster shuttling.

First, the nearest oxygen atom to the succ station can facilitate the escape of the mc from the initial station. Instead of simultaneous breakage of four hydrogen bonds, the mc can break two hydrogen bonds from one side of the succ station and re-form two weaker hydrogen bonds to the nearest ether oxygen. This lowers the activation energy for the escape of the macrocycle (see Scheme 2), which is considered to be the rate-limiting step in the shuttling process.55,57 A \(\sim 70\%\) acceleration in the shuttling rate is equal to a decrease of 0.3 kcal/mol in the free energy of activation. The decrease in free energy is comparable to differences in hydrogen-bond strengths between ether and carbonyl groups.57 Jeppesen and Flood et al. also proposed that polyether threads assist in preparation of an early transition state lowering the total activation energy for the escape of the macrocycle, which supports our interpretation.

The second possible effect for the acceleration could be the presence of minute amounts of water in the “dry” solvents.72 Water has been shown to “lubricate” the shuttling process; that is, the rate is accelerated in the presence of water.56 The acceleration was observed only at rather high concentrations of water (lowest studied concentration was 1 v/v %), but the study was done using fBu-C\(_n\)-RTX that lacks oxygen atoms in the thread. Additional oxygen atoms offer a preferential hydrogen-bonding site for water molecules increasing the sensitivity. The shuttling rates determined from the time-resolved IR measurements were slightly smaller for both rotaxanes, which could indicate a lower residual water content. This can be attributed to differences in the sample preparation methods. The samples for the IR measurements were prepared in a glovebox, whereas a Schlenk technique under nitrogen flow was used for the UV-vis experiments.

dOH-PE-RTX exhibits surprisingly fast shuttling rates and, to the best of our knowledge, is the fastest photoswitchable molecular shuttle of this length scale reported to date. The polyether thread can only partially account for the observed acceleration. Therefore, we need to reconsider the shuttling mechanism. The fluorescence lifetime of the rotaxane in neat MeCN and PhCN is significantly shorter than those of the thread and the model ref-dOH-NI end station (see section S6, Supporting Information). This suggests that the macrocycle interacts with the dOH-NI end station, and the rotaxane is at least partly folded in its lowest-energy conformation. More-
over, the oxygen atoms on the PE thread may induce bending of the thread facilitating the folding. Thus, it is reasonable to suggest that the shuttling also takes place in the folded state, significantly altering the free energy landscape as depicted in Scheme 2. The hydroxyl groups of the dOH-NI unit can hydrogen bond to the mc in the neutral form. After formation of the anion the mc can “slip” over the thread to hydrogen bond to deprotonated oxygen of the dOH-NI station. Such a “harpooning” mechanism has already been suggested for similar rotaxanes. In this mechanism, the mc simultaneously hydrogen bonds to both stations in the transition state before departure from the initial station.

Another important difference between the two rotaxanes is the lack of clear changes in the imide carbonyl vibrations of dOH-PE-RTX upon shuttling compared to tBu-PE-RTX, which exhibits a distinct red shift of symmetric CO-stretch vibration of the NI station upon arrival of the mc (peaks 1 and 2 in Figure 6). However, the spectra of both compounds exhibit distinct changes that can be attributed to the departure of mc from the succ station and increased hydrogen-bonding strength of the mc in the final state. In addition, the UV−vis spectra show a clear interaction between the macrocycle and dOH-PE-RTX upon shuttling compared to the lack of clear changes in the imide carbonyl vibrations of tBu-PE-RTX, which can be further stabilized by hydrogen bonding to the negatively charged oxygen results in a blue shift of the anion absorption band. Moreover, the electron density in the deprotonated ground-state anion is largely localized on the aromatic oxygen, whereas in the radical anion of the tBu-NI station, the negative charge is delocalized on the naphthalimide carbonyl groups. A possible shuttling mechanism demonstrating both the folded geometry and hydrogen bonding to the deprotonated hydroxyl oxygen is presented in Figure 7. In this mechanism the deprotonated NI unit “pulls” the mc away from the succ station in a folded geometry and undergoes a conformational reorientation in the final state.

■ CONCLUSIONS

We have investigated the influence of the chemical structure of the constituent parts on the shuttling dynamics in two novel hydrogen-bonded rotaxanes. Comparison with previously reported compounds allowed us to separately study the effect of the thread and the end station on the shuttling rate and mechanism. Introduction of additional oxygen atoms on the thread of the previously studied tBu-NI-based rotaxane accelerates the shuttling by ~70%. This is attributed to a decreased activation energy for the escape of the macrocycle from the initial station, which is considered to be the rate-limiting step in the shuttling process. The additional oxygen atoms assist in preparation of an early transition state, where the macrocycle partially escapes the initial station and forms weaker hydrogen bonds to the nearest ether oxygen.

The shuttling of the macrocycle in dOH-PE-RTX is accelerated by a factor of ~10, and to the best of our knowledge, it is the fastest photoswitchable molecular shuttle of this length scale (~1 nm) reported to date. The shuttling in this rotaxane is proposed to take place in a folded conformation similar to the “harpooning” mechanism reported in the literature. The hydrogen-bonding capability of the dOH-NI end station favors folding already in the initial state. Upon photochemical charging, the macrocycle can slip over the thread to hydrogen bond the end station, resulting in much faster shuttling speed. In addition, the macrocycle is assumed to mainly hydrogen bond to the negatively charged deprotonated hydroxyl group instead of the imide carbonyl groups observed for tBu-PE-RTX.

Hydrogen-bond-donating and -accepting abilities of all constituting moieties have a direct and active effect on the shuttling dynamics. This is due to the competing interactions between the macrocycle, the stations, and the thread. Therefore, the shuttling mechanisms of chemically different hydrogen-bonded rotaxanes should be carefully evaluated and a derivation of a general mechanism may not be feasible. Our findings, however, contribute to the development and design of next generation photoswitchable [2]rotaxanes with increased shuttling rates and novel charging mechanisms.

■ EXPERIMENTAL SECTION

Synthesis. The synthesis of the novel PE thread compounds largely follows the previously reported procedures for the rotaxanes with all-alkane threads. Instead of an alkane-based precursor, tert-butyl(2-(2-(2-aminoethoxy)ethoxy)ethyl)carbamate was used to for PE threads. The dOH-NI-based compounds were synthesized using a 3,6-dibenzoate-protected NI precursor. The final dihydroxy products were obtained after deprotection under basic conditions. Detailed synthetic procedures and characterizations are reported in the Supporting Information.

■ ASSOCIATED CONTENT

§ Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/jacs.9b10005.
Details on materials, sample preparation, measurement techniques, and data analysis methods, demonstration of the spectral changes associated with the shuttling process, determination of the association constants from the absorption spectra, additional shuttling experiments, steady-state and time-resolved fluorescence experiments, synthesis, characterization, and NMR spectra of the target compounds (PDF)

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Notes
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M. Artificial Molecular-Level Machines: Which Energy To Make


(49) Examples of utilization of photoinduced proton release as a trigger mechanism for molecular machines and switches exist in the literature. However, all reported examples are based on either irreversible photoacid generators or metastable state photoacids. Utilization of conventional excited-state acids has not been demonstrated. See ref 12 for a recent review on photoswitchable molecular machines.


