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A Redox-Switchable Molecular Zipper

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MAIN TEXT

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ABSTRACT: The design and synthesis of artificial molecular switches (AMSs) displaying architectures of increased complexity would constitute significant progress in meeting the challenging task of realizing artificial molecular machines (AMMs). Here, we report the synthesis and characterization of a molecular shuttle composed of a cyclobis(paraquat-4,4'-biphenylene) cyclophane ring and a dumbbell incorporating a cyclobis(paraquat-*m*-phenylene) cyclophane 'head' and a bifurcated, tawse-like, 'tail' composed of two oligoether chains, each containing a 1,5-dioxynaphthalene ring. In its reduced state the ring-in-ring recognition motif, between the *meta* and *para* bisradical dicationic cyclophanes (rings) defines the [2]rotaxane, whereas in the oxidized state, the cyclobis(paraquat-4,4'-biphenylene) cyclophane encircles the two 1,5-dioxynaphthalene rings in the bifurcated 'tail'. The redox-controlled molecular shuttling, which can be likened to the action of a zipper in the macroscopic world, exhibits slow kinetics dampened by the opening and closing of the bifurcated 'tail' of the molecular shuttle. Cyclic voltammetry reveals that this slow shuttling is associated with electrochemical hysteresis.

INTRODUCTION

Ever since the first redox-switchable molecular shuttle was reported¹ in 1994, the mechanical bond² has provided the literature with a plethora of molecular switches.³ Taking advantage of the constraint imposed by the mechanical link, such mechanically interlocked molecules (MIMs) have been found to display unique chemical,⁴ physical⁵ and electronic properties.⁶ Although bistable rotaxanes are frequently referred to⁷ as potential AMMs, there are very few examples of rotaxane-based molecular machines⁸ capable of performing work at the single-molecule level. 'Machine-like' characteristics have been reached by rotaxane-based molecular muscles⁹ in which large-amplitude contractile motions¹⁰ were achieved successfully in response to an external stimulus. In

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recent years, strategies have emerged¹¹ for scaling up these motions by incorporating the AMSs within materials. Sophisticated supramolecular polymers made of repeating units of rotaxanebased molecular muscles – i.e., daisy chains – have been reported in the literature¹² that induce macroscopic responses in bulk materials – i.e., sol-gel transitions, gel actuators, etc. – upon expansion or contraction of the individual AMSs. Designing new classes of materials, based on redox-active rotaxanes, is nowadays of considerable interest because of the increasing demand for smart responsive materials, offering the advantage of bulk physical properties that can be altered either chemically or electrochemically.

Rotaxanes utilizing various redox-driven switches, such as those incorporating redox-active donor-acceptor recognition motifs, metallo-mechanomolecules and redox-tunable hydrogenbonds have been reported¹³ in the literature. In particular, the recent harnessing¹⁴ of radical-pairing interactions to form strong inclusion complexes between the cyclobis(paraquat-p-phenylene) radical cation (CBPQT^{2(+•)}) and viologen derivatives (V^{+•}) ([MV \subset CBPQT]^{3(+•)}: K_a (MeCN, ITC) = $(5.04 \pm 0.63) \times 10^4$ M⁻¹, **MV** refers to methyl viologen)¹⁵ led to the emergence of radicaltemplate directed strategies¹⁶ for synthesizing MIMs. Recent efforts toward expanding this binding motif led¹⁷ to the discovery of a relatively strong 1:1 host–guest complex ($[m-CBPQT \subset MS]^{4(+\circ)}$: K_a (MeCN, UV–Vis–NIR) = (1.12 ± 0.08) × 10⁵ M⁻¹) between a square-shaped bisradical dicationic cyclobis(paraquat-4,4'-biphenylene) ($MS^{2(+\cdot)}$) and a smaller *m*-xylylene-linked isomer of CBPQT^{2(+•)}, namely, the bisradical dicationic m-CBPQT^{2(+•)}. This ring-in-ring complex displays promising features for applications in AMSs and AMMs: it alternates between strong association in its reduced state and strong repulsion in its oxidized state and, furthermore, exhibits relatively slow kinetics of association and dissociation. A ring-in-ring [2]rotaxane (BBRⁿ⁺) incorporating the $[m-CBPQT \subset MS]^{4(+)}$ recognition motif by including $m-CBPQT^{2(+)}$ in its

dumbbell component was found¹⁸ (Figure 1a) to conserve these features, as indicated by electrochemical hysteresis for switching between states with highly distinct electronic properties. Utilizing this ring-in-ring recognition motif, we have designed a rotaxane $Zip-R^{n+}$ which operates by the shuttling motion of the MSⁿ⁺ cyclophane¹⁹ between two recognition sites — one stabilized by radical-pairing in its reduced state ($Zip-R^{4(+)}$) and the other ($Zip-R^{8+}$) stabilized by π -donor/ π -acceptor interactions in its oxidized state. This [2]rotaxane was synthesized in two parts — one part of the dumbbell incorporates m-CBPQT⁴⁺, while the second part consists of two oligoether 'tails', each incorporating 1,5-dioxynaphthalene (DNP) rings and terminated by bulky groups to prevent (Figure 1b) the dethreading of the MS⁴⁺ cyclophane. Upon oxidation, Coulombic repulsion between the two tetracationic cyclophanes (i.e., MS⁴⁺ and *m*-CBPQT⁴⁺) obliges the MS⁴⁺ ring to move away from the electron poor bipyridinium units in the direction of the electron-rich DNP rings in the two bifurcated strands, thereby forcing the two tawse-like 'tails' to come together in a zip-like manner. Although [3]rotaxanes displaying two dumbbells encircled by one ring have been reported in the literature,²⁰ the uniqueness of this architecture resides in a single doubly threaded dumbbell, thus affording a [2]rotaxane which constitutes a redox-controlled molecular shuttle. The novelty of this MIM lies in its ability to couple long-range translational movement with large-amplitude orthogonal expansion and contraction, commensurate with the permitted branching and forced linearity of the 'tails' in a manner similar to the opening and closing of a zipper — hence providing a fundamental basis for an alternative design for a molecular muscle. In this paper we describe the synthesis and characterization of this redox-switchable molecular zipper, as well as the differences in its properties associated with the $Zip-R^{4(+)}/Zip-R^{8+}$ redox states. Remarkably, the architectural singularity of this rotaxane — i.e., shuttling of the large square-shaped cyclophane along the bifurcated tawse-like dumbbell — was found to feature

 similar, but more highly amplified, electronic properties than those displayed by other molecular shuttles.

RESULTS AND DISCUSSION

Radical templation, followed by *in situ* copper(I)-catalyzed azide–alkyne cycloaddition²¹ (CuAAC), was selected^{16c} as a strategy for preparing **Zip-R**⁴⁽⁺⁺⁾. This tetraradical tetracationic [2]rotaxane is formed from a derivative of *m*-CBPQT²⁽⁺⁺⁾ that bears, on one side, a bulky end group to prevent $MS^{2(++)}$ from slipping off the dumbbell, and on the other side, an azide group for the cycloaddition. This functionalized cyclophane²² was obtained (Scheme S1) in four steps from the known 4,6-dibromo-*m*-xylylene²³ in a 20% overall yield. Notably, the two aryl groups do not interfere with the macrocyclization step, which was achieved in similar yield (45%) to other *m*-CBPQT·4PF₆ derivatives by employing pseudo-high-dilution conditions in refluxing MeCN. The second molecular component used to form (Scheme 1) the dumbbell of Zip-R⁴⁽⁺⁺⁾ is a half-dumbbell alkyne derivative (HD-Alkyne), which was synthesized as depicted in Scheme S2 (see SI) in four steps (overall yield: 36%) starting with 4-tris(4-tert-butylphenyl)phenol, which has previously been employed²⁴ as a stopper in rotaxanes.²⁵

The **Zip-R**·8PF₆ rotaxane was obtained (Scheme 1) in a one-pot, two-step synthesis starting with the formation of the inclusion complex $[m-N_3-Ar_2-CBPQT \subset MS]^{4(++)}$ upon reduction of a 1:1 ratio mixture of **MS**·4PF₆ and *m*-N₃-Ar₂-CBPQT·4PF₆ with copper powder in MeCN. The (MeCN)₄Cu⁺ formed as a byproduct catalyzes the cycloaddition between $[m-N_3-Ar_2-CBPQT \subset MS]^{4(++)}$ and the half-dumbbell, **HD**-Alkyne, added in a CH₂Cl₂/MeCN mixture (1:2). The [2]rotaxane, initially obtained in its tetraradical tetracationic form, **Zip-R**·4PF₆, was oxidized subsequently by exposure to air to afford **Zip-R**·8PF₆ in a 25% overall isolated yield after purification. ¹H NMR spectroscopic monitoring of the reaction indicates that the [2]rotaxane is formed with an *in situ* yield of 40% after 7 days at 30 °C while the dumbbell component (**DB**·4PF₆) is formed in about 20% yield. The rest of the reaction mixture is composed of starting materials that did not react after 7 days due to the very low solubility of the **HD**-Alkyne in MeCN. The reaction time was not extended because of the degradation of the reagents after an extended period, i.e., after 7 days. Thus, we estimate that ca 15% of the rotaxane was 'lost' during the multiple steps of purification, which included solvent washes, reverse phase chromatography, and salt metathesis. Mass spectrometry confirmed the identity of the [2]rotaxane as shown (Figure S3) in the SI. The [*m*-N₃-Ar₂-CBPQT⊂MS]⁴⁽⁺⁺⁾ inclusion complex was characterized by UV–Vis–NIR (Figure

S4) and ¹H NMR spectroscopy (Figure S25). An electronic absorption band characteristic of radical-pairing was observed at 958 nm, very close to the NIR band observed¹⁷ for the [*m*-**CBPQTCMS**]⁴⁽⁺⁺⁾ inclusion complex ($\lambda_{max} = 941$ nm). Such an intense NIR absorption band (Abs = 0.44 at 0.06 mM in MeCN) is evidence of the formation of a relatively strong tetraradical tetracationic complex. Crystals of [*m*-N₃-Ar₂-CBPQT**CMS**]⁴⁽⁺⁺⁾ were obtained by vapor diffusion of ¹Pr₂O into a solution of **MS**·4PF₆ (1 eq) and *m*-N₃-Ar₂-CBPQT·4PF₆ (1 eq) in MeCN after reduction to their radical states using zinc dust, allowing us to obtain (Figure 2 and S1) the solid-state superstructure of this inclusion complex. The formation of the 1:1 host–guest complex revealed an ideal distance (3.2 Å) for radical-pairing interactions between the eclipsed bipyridinium units in the host (**MS**²⁽⁺⁺⁾) and the bipyridinium units present in the guest (*m*-N₃-Ar₂-CBPQT**CMS**]⁴⁽⁺⁺⁾ inclusion complex, the bipyridinium units of the inner and outer cyclophanes are oriented perpendicularly, i.e., close to the orientation that would provide²⁶ maximum overlap of the SOMOs π orbitals.

The mechanically interlocked nature of the [2]rotaxane was revealed by the ¹H (Figure 3a), DOSY (Figures S14–S15), ¹³C (Figure S16) and 2D correlated (Figures S17–S20) NMR spectra of the **Zip-R**·8PF₆ in CD₃CN. The resonances associated with the DNP protons (H_{24} , H_{26} and $H_{28/28'}$), are shifted dramatically upfield to the region 4.30–5.75 ppm, confirming (Figure 3a) that the electron deficient cyclophane is encircling the electron rich DNP units. Although the multiplicity and the number of resonances cannot be resolved at room temperature for H₂₄ and H₂₆, we observed two doublets ($\delta = 4.45$ and 4.52 ppm) which can be assigned to the protons H₂₈ and H₂₈. We presume that these protons give rise to the most upfield shifted of the resonances as a result of $[C-H\cdots\pi]$ interactions with the 4,4'-biphenylene units of the MS⁴⁺ cyclophane. The ability of the electron deficient MS⁴⁺ cyclophane to encircle two 1,5-dioxynaphthalene (DNP) units bounded by polyether loops thus forming a ring-in-ring complex has been reported previously by Forgan et $al.^{27}$ [π ··· π], [C–H··· π] and [C–H···O] interactions were found to be involved in the complex formation.²⁸ Although indications of the formation of such interactions could not be observed in the NOESY spectrum (Figure S19), the ROESY spectrum displayed the expected spatial correlations (Figure S20) for the MS⁴⁺ cyclophane encircling the DNP units. Indeed, the resonances associated with the interlocked cyclophane protons (H2, H15, H8, H9 and H25) showed spatial correlations with the oligoether protons and the DNP protons, namely, H₂₄, H₂₆ and H_{28/28'}. Hence, we are of the opinion that the formation of the donor-acceptor recognition motif within the **Zip-R⁸⁺** is driven by a combination of $[\pi \cdots \pi]$, $[C-H \cdots \pi]$ and $[C-H \cdots O]$ interactions.

The synthesis (see SI) and NMR spectroscopic characterization (Figures S9–S10) of the dumbbell²⁹ were carried out to provide the reference chemical shifts for the dumbbell component of the rotaxane. Comparing the ¹H NMR spectrum of the **Zip-R**·8PF₆ with that of its dumbbell (Figure 3e) provides clear evidence of the mechanically interlocked nature of the [2]rotaxane with

characteristic DNP proton resonances obtained for $H_{24/26/28}$ of the dumbbell, in contrast to the upfield resonances observed for these protons in the rotaxane. As expected, the resonances of the smaller cyclophane within **Zip-R**·8PF₆ and its dumbbell are comparable to the resonances (Figure 3b) of *m*-N₃-Ar₂-CBPQT·4PF₆, except for H₅ and H₁₇, which are shifted downfield on the account of their proximity to the triazole group.

Variable temperature ¹H NMR spectra which were recorded (Figure S13) for **Zip-R**·8PF₆ between 293 and 338 K revealed a resonance for H₁₅ that, at lower temperatures, overlaps with the aromatic protons of the stoppers (H_{13/14}). Likewise, the signal for H₁₁ was confirmed as overlapping with the resonances for H_{10/12}. Increasing the temperature also provided evidence for the assignment of the protons (H₁₉, H₂₀, H₂₉) on the *para*-substituted *m*-xylylene linker. Indeed, those protons are subjected to shielding induced by the shuttling of the MS⁴⁺ cyclophane that is favored at high temperature. The proton resonances (H₂₄, H₂₆, H_{28/28}·) associated with the DNP units exhibit selective broadening at 338 K, and are significantly shifted downfield compared to the corresponding proton signals in the spectrum collected at 293 K. We assume that higher temperatures also favor the rotation of MS⁴⁺ around the DNP units along with enhanced movements of the polyether chains, presumably causing the loss of the [C–H···O] interactions. This hypothesis is supported by the downfield shift and broadening of the bipyridinium proton H₁₅ resonance, which is possibly involved in [C–H···O] interactions.

The characterization of **Zip-R**·4PF₆ was also carried out by ¹H NMR spectroscopy (Figure 4a), taking advantage of our recent observation¹⁷ that tetraradical tetracationic ring-in-ring complexes possess singlet electronic ground states which, at low enough temperatures, permit^{18, 30} their ¹H NMR characterization as diamagnetic organic species. ¹H NMR spectra were recorded after reduction of **Zip-R**·8PF₆ with zinc dust in CD₃COCD₃, stirring at room temperature for 10 min to

afford complete conversion to $Zip-R^{4(+\cdot)}$. The shuttling of the cyclophane away from the DNP recognition units explains why the resonances (Figure 4a) attributed to the protons $H_{24/26/28}$ were found at typical chemical shifts for DNP protons (7.8-6.9 ppm), consistent with the resonances observed (Figure 3e) for the DNP protons in the dumbbell. Most of the resonances expected for **Zip-R**⁴⁽⁺⁾ can be observed at 25 °C in CD₃COCD₃, apart from signals expected for the radical ring-in-ring portion of the rotaxane. As with other tetraradical tetracationic ring-in-ring complexes and superstructures, decreasing the temperature, in this case to 218 K, allows the full spectrum to be visualized. Accordingly, ¹H NMR spectra (Figure 4b) were recorded at several temperatures between 298 and 218 K. The resolution of broad signals into individual resonances allowed us to propose an assignment for each signal in the spectrum. It is worth noting that the solid-state superstructure (Figure 2) of the $[m-N_3-Ar_2-CBPQT \subset MS]^{4(+\cdot)}$ complex revealed long range [C–H··· π] interactions (d = 4.4 and 4.6 Å) between the protons H_{6/7} and the π -faces of the bitolyl units of the MS^{2(+•)} cyclophane. Consistent with these interactions being conserved in solution, the resonances of the innermost bipyridinium protons H_6 and H_7 are shifted upfield dramatically so to the region 3.8–3.6 ppm. Although these resonances overlap with the broad collection of resonances associated with the aliphatic protons H_{30-41} , integration of this region confirmed the presence of signals for H₆ and H₇. This observation was supported by the direct observation of the expected signals (Figure S25) between 3.8–3.5 ppm for the $[m-N_3-Ar_2-CBPQT \subset MS]^{4(+\cdot)}$ complex. By comparison with the geometry of the complex, it is to be expected within the rotaxane, that the bipyridinium protons H_2 and H_2 , are the least shielded within the recognition motif and were assigned to the most downfield new resonances at 8.0-8.1 ppm. The resonance observed at 5.7 ppm can be assigned to H_{15} , shifted upfield on account of the shielding provided by the bipyridinium units of the inner cyclophane. The selective broadening of the cyclophane resonances

at 25 °C has been attributed¹⁸ previously to a thermally accessible triplet state at room temperature and was supported¹⁷ by DFT calculations on $[m-CBPOT \subset MS]^{4(+\cdot)}$.

UV–Vis–NIR spectroscopy (Figure 5a) was used to probe the conversion between the Zip-R⁸⁺ and **Zip-R**^{4(+•)}. The reduction of **Zip-R**⁸⁺ was conducted in MeCN using zinc dust, and the resulting **Zip-R**^{4(+•)} displays a characteristic NIR band centered on 958 nm for the bipyridinium radicalpairing. The reversibility of the interconversion between Zip-R⁸⁺ and Zip-R^{4(+•)} upon chemical reduction/oxidation was also followed by ¹H NMR spectroscopy. Spectra were recorded (Figure S26) for the switch between $Zip-R^{8+}$ and $Zip-R^{4(+)}$, followed by the oxidation back to $Zip-R^{8+}$ in air. The final ¹H NMR spectrum for the re-oxidized species, recorded without any purification, shows a recovery of more than 95% of the **Zip-R⁸⁺** with a minimal amount (5%) of degradation when compared with the initial spectrum. The interconversion between the redox states was investigated in more details by cyclic voltammetry. The cyclic voltammogram (CV) of $Zip-R\cdot 8PF_6$ recorded (Figure 5b) at 100 mV/s with ferrocene as an internal standard displayed three redox states — (i) the octacationic rotaxane ($Zip-R^{8+}$), (ii) the tetraradical tetracationic rotaxane ($Zip-R^{8+}$), $\mathbf{R}^{4(+)}$) and (iii) the neutral form of the rotaxane (Zip- \mathbf{R}^{0}). Both Zip- $\mathbf{R}^{4(+)}$ /Zip- \mathbf{R}^{0} and Zip- \mathbf{R}^{8+} / $Zip-R^{4(+)}$ redox couples exhibit non-trivial profiles with multiple waves or shoulders associated with each interconversion. The consistency of the CVs over several cycles suggests that switching between the three redox states is reversible chemically, as expected since the mechanically interlocked nature of the molecule prevents dissociation of the components.

The oxidation of **Zip-R⁴⁽⁺⁺⁾** to **Zip-R⁸⁺** gives rise (Figure 6a) to two oxidation waves at a scan rate of 100 mV/s, suggesting the occurrence of slow dynamic processes that were investigated further at scan rates of 20–10,000 mV/s. In order to reduce interference from electrode fouling, a low concentration of the analyte was used, resulting in relatively small current peaks that were,

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nevertheless, well-defined when the capacitive current was subtracted from the CVs. The redox couple exhibits a large peak separation with a single, yet different, oxidation wave observed at both high scan rates (10,000 mV/s with $\Delta E_p = 140$ mV and $E_{oxl} = -0.66$ V) and low scan rates (20 mV/s with $\Delta E_p = 140$ mV and $E_{ox2} = -0.55$ V), while the two oxidation waves are observed when scan rates between 100-1000 mV/s are employed. It is worth noting that the dumbbell component redox couple exhibits (Figure S27b) a single reversible redox wave at scan rates between 5–5000 mV/s, suggesting that the splitting of the oxidation waves of $Zip-R^{8+}$ arises from the dynamics of the mechanically interlocked components. A unique reduction wave was observed for Zip-R⁸⁺ regardless the scan rate applied, though increasing the scan rate broadens this peak and shifts it towards more negative potentials ($E_{red} = -0.80$ V for **Zip-R**·8PF₆ at 10,000 mV/s). Meanwhile, when low scan rates are applied ($E_{\rm red} = -0.69$ V for **Zip-R**·8PF₆ at 20 mV/s), the reduction wave appears sharper and more positive, indicating stabilization of the radical state upon the formation of the ring-in-ring recognition motif. Assuming that the rotaxane undergoes two-electron redox processes — like the individual cyclophanes — we postulate that the innermost cyclophane is the first to be reduced ($E_{\rm red} = -0.74$ V for MS·4PF₆ and $E_{\rm red} = -0.71$ V for the dumbbell DB·4PF₆ at 200 mV/s), thus affording (Figure 6b) the intermediate $Zip-R^{(6+)(2-)}p$. It is to be expected that the electron rich surroundings of MS⁴⁺ within the **Zip-R**⁽⁶⁺⁾⁽²⁾ b will result in its stabilization towards</sup>reduction, shifting the required potential for reduction to the $Zip-R^{4(+)}p$ state to more negative potentials compared to that required for reduction of the free cyclophane. At slower scan rates, equilibration to the more stable $Zip-R^{4(+)}$ state occurs quickly enough to cause the reduction wave to be shifted towards positive potentials while, at rapid scan rates, there is less time for the two cyclophanes in either the $Zip-R^{(6+)(2-)}D$ or $Zip-R^{4(++)}D$ intermediates to associate, resulting in a more negative and broadened reduction wave, corresponding to the complete reduction to the Zip-

 $\mathbf{R}^{4(++)}_{\mathbf{D}}$ metastable co-conformation. Furthermore, applying intermediate scan rates led to the observation of two waves of oxidation which display different ratios. Increasing the scan rate induces a decrease of the initially unique oxidation wave at -0.55 V (20 mV/s), while another oxidation wave at a more negative potential ($E_{ox1} = -0.65$ V) arises and becomes the predominant oxidation wave at scan rates $\geq 1,000$ mV/s. The more positive oxidation wave presumably corresponds to the presence of an electronically stabilized ground state co-conformation **Zip**- $\mathbf{R}^{4(++)}_{\mathbf{A}}$, which has time to form fully at low scan rates, while the more negative oxidation wave corresponds to the metastable co-conformation **Zip**- $\mathbf{R}^{4(++)}_{\mathbf{D}}$ that does not have time to convert to the ground-state co-conformation at rapid scan rates. It is worth noting that the very slow scan-rate regime allows observation (Figure S29) of **Zip**- $\mathbf{R}^{4(++)}$ interconversion as a quasi-reversible process (5 mV/s with $\Delta E_p = 100$ mV).

The CVs of **Zip-R⁸⁺** indicate similar switching dynamics to those previously observed¹⁸ for the 'Box-in-Box' Rotaxane (**BBR⁸⁺** in Figure 1a), which were attributed to a combination of (i) the slow rate of the $MS^{2(+)}$ cyclophane encircling the smaller *m*-CBPQT²⁽⁺⁺⁾ cyclophane that results from strong charge repulsion and the tight fit of the ring-in-ring recognition motif, and (ii) the strong association of the two cyclophanes in the doubly radically paired state which causes them to dissociate slowly unless electrons are first removed.

Qualitative comparison of the CVs of **BBR**·8PF₆ and **Zip-R**·8PF₆ revealed that the rate constant (k_1) for the association of the cyclophanes in **Zip-R**^{4(+•)}_D is much lower than for the analogous process in **BBR**^{4(+•)}_D. In particular, the appearance (Figure S33) of an oxidation wave for the metastable co-conformation occurs¹⁸ at a lower scan rate for the molecular zipper (50 mV/s for **Zip-R**^{4(+•)}_D, versus 1,000 mV/s for **BBR**^{4(+•)}_D), and likewise, the oxidation wave attributed to the ground-state co-conformation disappears almost entirely at 10,000 mV/s for **Zip-R**⁸⁺ but is still

weakly observable for **BBR**⁸⁺ at a scan rate of 50,000 mV/s. Considering that **Zip-R**·8PF₆ and **BBR** \cdot 8PF₆ appear to exhibit similar mechanisms of switching, but at different rates, the CV data for Zip-R⁸⁺ was examined using computational fitting of simulated CVs to the experimental data based on the mechanism depicted in Figure 6b. The CVs collected at 200 mV/s and 1,000 mV/s were matched with simulated CVs (Figures S36–S37), resulting in good agreement between experimental and simulated data for k_1 values of 0.23 s⁻¹ and 0.56 s⁻¹, respectively. These matchings, however, produced k_2 values (8.2 s⁻¹ and 6.94 s⁻¹) that are larger than the k_1 values, which is unrealistic considering the higher charge repulsion between the cyclophanes in the Zip- $\mathbf{R}^{(6+)(2)}$ state compared with the Zip- $\mathbf{R}^{4(+)}$ state, which should render association of the cyclophanes faster for the tetraradical tetracationic state than for the bisradical hexacationic state. Thus, simulations of the CVs between 20 and 10,000 mV/s were also performed with manual variation of the k_1 value, while keeping $k_2 \leq k_1$ and $k_{-1} \ll k_1$ to ensure that the results are chemically reasonable. Values of $k_1 = 1.2 \text{ s}^{-1}$, $k_{-1} = 0.008 \text{ s}^{-1}$, $k_2 = 0.8 \text{ s}^{-1}$, and $k_{-2} = 35 \text{ s}^{-1}$ provided (Figures S34–S35) simulated CVs that showed good agreement with the experimental data, particularly with respect to the first appearance of the oxidation wave of $Zip-R^{4(+)}D$ at 50 mV/s and the disappearance of the oxidation wave of $Zip-R^{4(+)}A$ at 10,000 mV/s. These results indicate that the conversion of $Zip-R^{4(+)}D$ to $Zip-R^{4(+)}A$ occurs at one to two orders of magnitude more slowly $(k_1 \approx 0.23 - 1.2 \text{ s}^{-1})$ than the corresponding process for converting **BBR**^{4(+•)}_D to **BBR**^{4(+•)}_A $(k_{1-\text{BBR}} \approx 10-25 \text{ s}^{-1})$, Figure 6c). The decreased rate of association of the two cyclophanes in **Zip**- $\mathbf{R}^{4(+\bullet)}$ can be attributed to hindered shuttling of the MS^{2(+•)} cyclophane across the double-stranded dumbbell, which is to be expected, based on the entropically unfavorable requirement that the two strands of the dumbbell become press together to enable passage of the tightly fitting outer cyclophane.

In view of the CV data collected for this molecular zipper, electrochemical hysteresis was revealed. The ideal size complementarity displayed by the ring-in-ring recognition motif, while providing for strong binding of the cyclophanes once they are overlapped, imposes a steric constraint upon their initial association, resulting in slow kinetics of association and dissociation for both the **Zip-** $\mathbf{R}^{\mathbf{8}+}$ and the **BBR**^{$\mathbf{8}+$}. The structural features of the molecular zipper provoke an even more exaggerated electrochemical hysteresis for the switching between **Zip-** $\mathbf{R}^{\mathbf{8}+}$ and **Zip-** $\mathbf{R}^{\mathbf{4}(+\bullet)}$, as revealed by an even slower rate constant for the association of the two cyclophanes in the metastable co-conformation **Zip-** $\mathbf{R}^{\mathbf{4}(+\bullet)}_{\mathbf{D}}$ when forming the ground-state co-conformation **Zip-** $\mathbf{R}^{\mathbf{4}(+\bullet)}_{\mathbf{A}}$.

CONCLUSIONS

In summary, we have reported the synthesis of an octacationic bistable [2]rotaxane, based on a ring-in-ring radical-radical templation motif, and demonstrated that this mechanically interlocked molecule with a doubly threaded dumbbell containing 1,5-dioxynaphthalene rings, incorporated within oligoether chains terminated by stoppers, displays a mechanical-like motion — reminiscent of zippering — that can be redox driven. This molecular zipper exhibits slow kinetics associated with the redox-driven switching of a ring between two different recognition sites on a bifurcated, tawse-like, dumbbell. The slow kinetics of the redox-driven switching reflect the rigid preorganization of the tetraradical tetracationic ring-in-ring recognition motif and the steric and electronic constraints associated with the opening and closing of the doubly stranded dumbbell component. The large-amplitude motion, which accompanies switching, could result in large conformational changes if the switches were to be embedded in polymeric chains rather than in the relatively short 'tails' of a doubly stranded dumbbell. We envisage that this molecular zipper

could be useful in the late-stage functionalization of polymers and, in so doing, provide an efficient route to the construction of mechanical actuators.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information includes experimental details, including synthesis, crystal data, mass spectrometry, NMR and UV–Vis–NIR spectra and CV supportive figures. This material is available free of charge via the Internet at <u>http://pubs.acs.org</u>.

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Notes

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Captions of Scheme and Figures

Scheme 1. Synthesis of the $Zip-R\cdot 8PF_6$ rotaxane by radical templation and copper(I)-catalyzed cycloaddition.

Figure 1. Electrochemically driven actuation of: (a) the 'Box-in-Box' rotaxane ($BBR^{4(+)}/BBR^{8+}$) and (b) the molecular zipper ($Zip-R^{4(+)}/Zip-R^{8+}$) — donor–acceptor interactions underpin the contracted state ($Zip-R^{8+}$) and radical-pairing interactions underpin the extended state ($Zip-R^{4(+)}$).

Figure 2. X-Ray crystal structures of the complex: $[m-N_3-Ar_2-CBPQT\subset MS]^{4(++)}$. The tetraradical tetracationic complex was crystallized as its PF_6^- salt — the counterions were omitted for the sake of clarity. $MS^{2(++)}$ is shown in blue and $m-N_3-Ar_2-CBPQT^{2(++)}$ in purple. a) View of the $[m-N_3-Ar_2-CBPQT\subset MS]^{4(++)}$ aligned perpendicular to the page. b) Eclipsed view of the $[m-N_3-Ar_2-CBPQT\subset MS]^{4(++)}$ and representation of the long range $[C-H\cdots\pi]$ interactions (distances measured from the carbon atom — CH — to the center of the aromatic ring). c) View of the $[m-N_3-Ar_2-CBPQT\subset MS]^{4(++)}$ with the bipyridinium units of $MS^{2(++)}$ aligned perpendicular to the page. d) View of the $[m-N_3-Ar_2-CBPQT\subset MS]^{4(++)}$ with the bipyridinium units of $MS^{2(++)}$ aligned perpendicular to the page. d) View of the $[m-N_3-Ar_2-CBPQT\subset MS]^{4(++)}$ with the bipyridinium units aligned parallel with the page.

Figure 3. ¹H NMR Spectra at 298 K (500 MHz, CD₃CN): (a) Zip-R·8PF₆ (2.14 mM). Partial spectrum: 9.0–3.2 and 1.5–1.0 ppm, (b) *m*-N₃-Ar₂-CPBQT·4PF₆, (c) MS·4PF₆, (d) Zip-R·8PF₆ and (e) DB·4PF₆. Partial spectra: 9.0–3.5 ppm.

Figure 4. ¹H NMR (600 MHz, CD₃COCD₃) spectrum characterization of the **Zip-R**·4PF₆ (2.2 mM): (a) Partial spectrum (9.0–3.5 and 1.5–1.2 ppm) at 298 K. (b) Partial spectra (9.0–3.5 ppm) collected over a temperature range of 298–218 K.

Figure 5. Reversible switching between the redox states: **Zip-R**^{4(+•)} and **Zip-R**⁸⁺: (a) UV–Vis–NIR spectra of the **Zip-R**·8PF₆ (0.035 mM) and **Zip-R**·4PF₆ (0.030 mM) at 298 K in MeCN. (b) CV of the **Zip-R**·8PF₆ in a 0.1 M [Bu₄N]|[PF₆] MeCN electrolyte solution (0.13 mM) recorded at 100 mV/s at 298 K. The current was normalized, and the potentials referenced to ferrocene as an internal standard.

Figure 6. Zip-R⁸⁺/Zip-R⁴⁽⁺⁺⁾ Interconversion: (a) CVs of Zip-R-8PF₆ (0.05 mM) in a 0.1 M [Bu₄N]|[PF₆] MeCN electrolyte solution at various scan rates (20–10,000 mV/s) with a potential window that includes only the **Zip-R⁸⁺** and **Zip-R⁴⁽⁺⁺⁾** states of the rotaxane. The current was normalized and the potentials were referenced to ferrocene as an internal standard. The CVs of the electrolyte in the absence of redox-active analytes were substracted from the raw data at each scan rate, and the original CVs are provided in Figures S31–S32. (b) Proposed mechanism for the **Zip-R⁸⁺/Zip-R⁴⁽⁺⁺⁾** interconversion. A stands for associated, **D** stands for dissociated. (c) Schematic representation of the **BBR⁴⁽⁺⁺⁾** BBR⁴⁽⁺⁺⁾ aequilibrium.



Scheme 1

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Figure 3

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Figure 6





















