J|A|C|S COMMUNICATIONS

Published on Web 09/03/2009

Switching and Extension of a [c2]Daisy-Chain Dimer Polymer

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Received July 16, 2009; E-mail: rhg@caltech.edu

In an effort to miniaturize devices for a variety of applications, many researchers have begun to explore systems derived from examination of nature.[1] The elegance and complexity of biological systems provides a wealth of inspiration for synthetic chemists. A particularly intriguing challenge for materials scientists is mimicking the extension and contraction of natural fibers. One approach is to use switchable noncovalent interactions to guide the extending and contracting of macromolecules. Recently, the utilization of supramolecular chemistry to self-assemble complex molecular networks coupled with dynamic covalent chemistry[2] has facilitated the synthesis of a variety of interlocked molecules.[3] One class of these compounds, [c2]daisy-chain dimers[4] (DCDs, Figure 1a and 1b), appeared to be a promising molecular actuator candidate due to the switchable conformation[5] of the dimer upon removal of coordinating interactions. It has been proposed that incorporation of mechanically interlocked species into macromolecular materials will impart unique properties[6] to those materials not achievable via traditional covalent linkages, and to this end, several reports of interlocked polymeric species have recently emerged.[7,8] In particular, DCDs incorporated within polymers have shown facile switching behavior.[8b] Herein, we report the synthesis of a DCD whose structural topology enhances the stability of the contracted state and subsequent incorporation of this DCD into linear polymers that undergo a significant conformational change upon extension of the dimeric units.

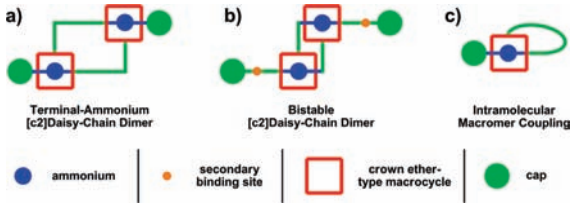
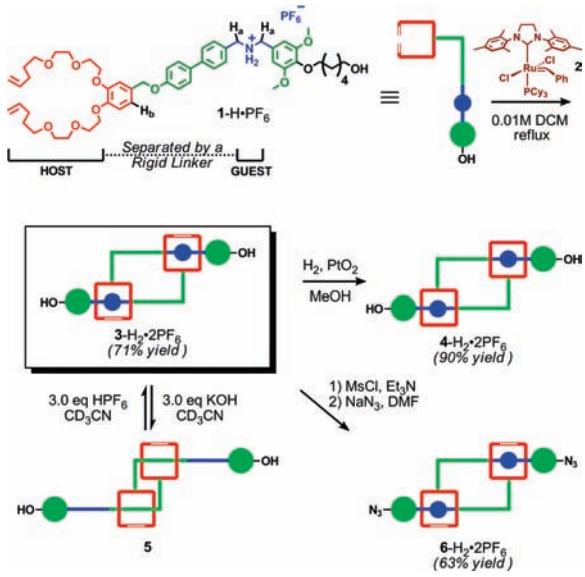


Figure 1. Graphical representation of a [c2]daisy-chain dimer containing adjacent cap and ammonium moieties (a), a bistable [c2]daisy-chain dimer (b), and an intramolecularly coupled macromer (c).

Synthesis of a DCD involves the pairing and interlocking of two self-complementary macromers (molecules that contain both host and guest recognition moieties bound covalently within the same compound).[4a,8] One common protocol utilizes the threading of an ammonium-containing fragment through the dibenzo-24-crown-8 ether or other recognition moiety of a partner macromer followed by a "capping" reaction[9] to prevent dethreading of the complex. This technique gives DCDs in good yield and allows introduction of a second, albeit significantly weaker binding site near the cap of the dimer (Figure 1b).[5a,d,8b] The rapid, reversible "switching" of such dimers from extended to contracted conformations has been clearly demonstrated.[5a–c,8b]

In contrast to reversible capping reactions, the dynamic ring-closing metathesis (RCM) reaction, catalyzed by functional group tolerant ruthenium alkylidene complexes,[10] has enabled the synthesis of

Scheme 1. Graphical Representation of the Synthesis of [c2]Daisy-Chain Dimer **3**-H_2·$2PF_6$, Hydrogenated Derivative **4**-H_2·$2PF_6$, Decoordinated Dimer **5**, and Diazide Analogue **6**-H_2·$2PF_6$



[2]catenanes,[11] [2]rotaxanes,[12] and other interlocked species.[13] DCDs have also been synthesized by RCM, where the two diolefinic polyether fragments of each macromer encircle and close around an appropriately substituted dibenzylammonium ion of a partner macromer, giving the interlocked DCD.[8a] We believed that designing a DCD with a strongly coordinating binding site near the cap of the dimer would enhance the stability of the contracted state and produce a "stronger" molecular actuator (Figure 1a). With this criterion in mind, we envisaged macromer structure **1**-H·PF_6 (Scheme 1) to be a promising target. A long, rigid biphenyl linker between the host and guest residues was incorporated to minimize the formation of self-complexed monomer[14] (Figure 1c), promote dimer preassembly via macromer-macromer $\pi-\pi$ slipped-stacking interactions, and enhance the linearity of the dimer, aiding elongation via slippage of the rod-like backbone through the closed crown ether-type rings. Synthesis of **1**-H·PF_6 was accomplished in 13 steps.[15]

Treatment of self-complementary macromer **1**-H·PF_6 with olefin metathesis catalyst (H_2IMes)(PCy_3)$(Cl)_2$Ru=CHPh (**2**) furnished the desired interlocked DCD **3**-H_2·$2PF_6$ in 71% isolated yield (Scheme 1). Confirmation of the interlocked nature of the product was achieved through a variety of characterization techniques. High-resolution mass spectrometry showed a dicationic species corresponding to the proposed DCD **3**-H_2·$2PF_6$. Further evidence for the interlocked nature of the product was observed in the increased complexity of the ^{1}H NMR spectrum, a result of the presence of both (*E*) and (*Z*) olefin isomers and a mixture of diastereomers.[4a] Full assignment of the ^{1}H NMR

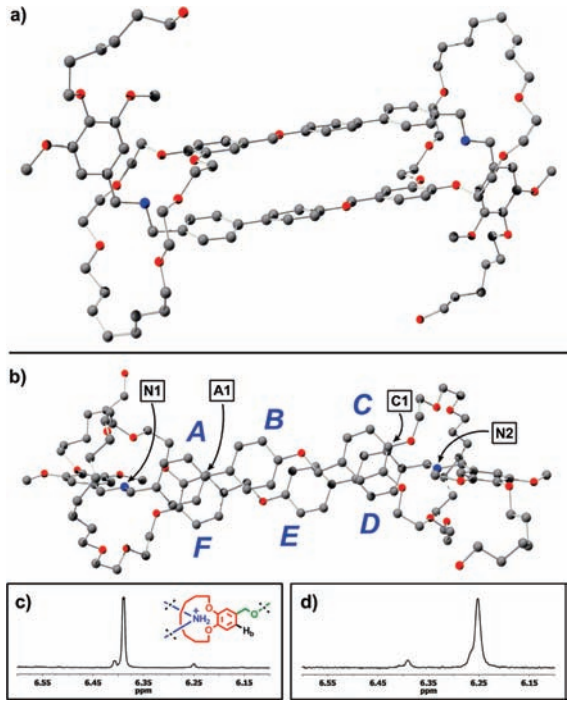


Figure 2. ORTEP representation of **4**-H_2·2PF_6: side-on view (a) and top-down view (b), showing $\pi-\pi$ slipped-stacking interactions between rings **A** and **F** as well as **C** and **D** (average interplanar distance: 3.4 Å). Hydrogen atoms, counterions, and solvent molecules have been omitted for clarity. Partial ^{1}H NMR spectrum of **4**-H_2·2PF_6 corresponding to the signal from H_b of the racemate (c) and mesoform (d).

spectrum was accomplished using a complementary set of two-dimensional NMR techniques.[15]

In addition to NMR spectroscopy and mass spectrometry characterization of **3**-H_2·2PF_6, we prepared the saturated analogue **4**-H_2·2PF_6, which readily produced X-ray quality crystals (Figure 2a and 2b).[16] The solid-state structure unambiguously confirmed the interlocked nature of **4**-H_2·2PF_6, with the crown ether-type arms encircling the ammonium of a partner macromer. In contrast to other reports of such compounds,[4a,8a] we observed the mesoform of **4**-H_2·2PF_6 in the solid state structure. We attribute this phenomenon to the presence of strong $\pi-\pi$ slipped-stacking interactions[17] (average "backbone"-to-"backbone" distance of 3.4 Å) between rings **A** and **F** as well as **C** and **D** (Figure 2b), imparting enhanced stability to the mesoform of the dimer. Due to inversion of one crown-aryl ring (either **C** or **F**) prior to interlocking, the racemic form of **4**-H_2·2PF_6 is likely unable to simultaneously engage in extensive $\pi-\pi$ slipped-stacking interactions and strong crown ether-ammonium hydrogen bonding interactions, resulting in limited crystallinity. Evidence for the distinct environment of crown-aryl proton H_b (Scheme 1) of each diastereomer is observed in the ^{1}H NMR spectrum (Figure 2c and 2d), confirming the altered alignment of the crown-aryl rings. Evidence from the crystal structure provided insight into the expected extension distance of the deprotonated forms of **3**-H_2·2PF_6 and **4**-H_2·2PF_6. One scenario would involve sliding of the dimer backbone through the crown-type macrocycles until ring **A** aligned over ring **D** in a conformation similar to ring **C** in the bound state. In this case, the measured distance between A1 to C1 (a 10.7 Å extension distance) can be related to the binding-site-to-binding-site dimer length from N1 to N2 (18.3 Å), giving an extension of 58%. This value is very similar to the largest known extension percent of synthetic interlocked molecular actuators (66%).[18]

To demonstrate utility as a molecular actuator, switching between bound and unbound conformations of **3**-H_2·2PF_6 must be easily and rapidly accomplished. Addition of a solution of potassium hydroxide in D_2O to **3**-H_2·2PF_6 in CD_3CN (Scheme 1) quickly affected ammonium deprotonation to give the unbound analogue **5**. Due to the absence of a secondary binding site, the ^{1}H NMR spectrum broadens significantly upon deprotonation (Figure 3), indicating conformational heterogeneity possible only upon removal of crown-ammonium coordinating interactions. Heteronuclear single quantum coherence (HSQC) NMR analysis[15] of the deprotonated dimer confirmed an upfield shift (from 4.5 ppm to 3.7 ppm) of the resonance of the benzylic protons H_a adjacent to the ammonium, suggesting deprotonation. Furthermore, the resonance of proton H_b shifts downfield to 7.0 ppm and coalesces, indicating the presence of a variety of conformations distinct from the native forms of **3**-H_2·2PF_6. Upon addition of an equivalent amount of hexafluorophosphoric acid, the original ^{1}H NMR spectrum of **3**-H_2·2PF_6 was restored, completing the switching and showing facile return of the dimer to the contracted, bound conformation.

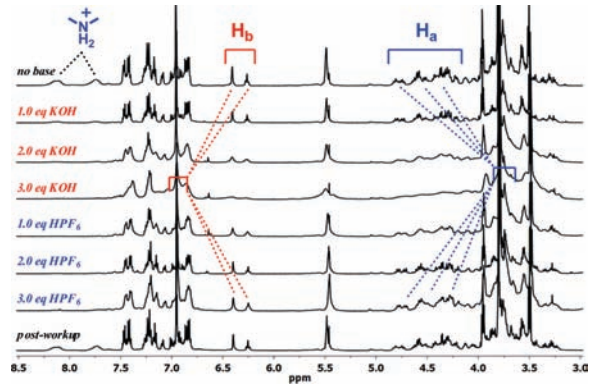
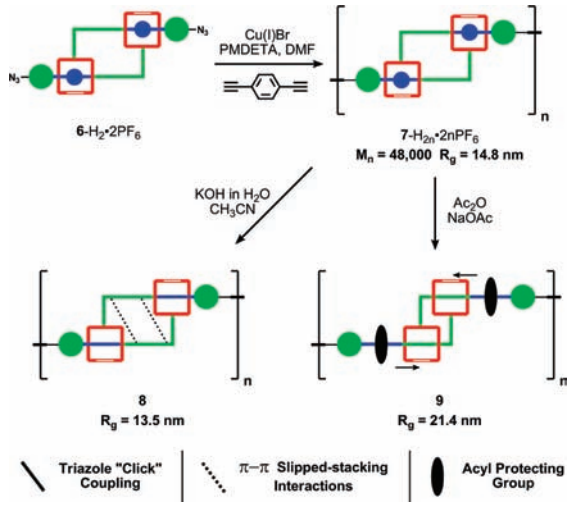


Figure 3. Partial ^{1}H NMR spectrum of **3**-H_2·2PF_6 depicting the switching from bound to unbound conformations upon addition of 3.0 equiv of KOH and subsequent recoordination upon addition of 3.0 equiv of HPF_6. An aqueous workup restores ammonium proton resonances.

In preparation for materials synthesis, the terminal alcohols of **3**-H_2·PF_6 were converted to mesylates and subsequently treated with sodium azide to give diazide **6**-H_2·2PF_6 (Scheme 1). Use of a copper catalyst and *N*,*N*,*N*′,*N*″,*N*″-pentamethyldiethylenetriamine ligand facilitated the Huisgen 1,3-dipolar cycloaddition "click" reaction[19] between **6**-H_2·2PF_6 and 1,4-diethynylbenzene to give the step-growth linear polymer **7**-H_{2n}·2*n*PF_6 (Scheme 2). Gel permeation chromatography (GPC)[20] coupled with multiangle laser light scattering (MALLS) detection analysis of **7**-H_{2n}·2*n*PF_6 showed that the polymer had a molecular weight (MW) of 48 000 g mol^{-1} and a radius of gyration (R_g) of 14.8 nm. Since each DCD unit is ~2.5 nm and the degree of polymerization is ~22, we would expect the polymer to have an R_g value of 27.5 nm if it were fully extended. The measured value (14.8 nm) indicates that the polymer, while not perfectly rod-shaped, appears to be mostly linear and is not excessively folded. Like the monomeric dimer, the polymer could be readily deprotonated to produce neutral analogue **8** (Scheme 2). Reprotonation of **8** to regenerate **7**-H_{2n}·2*n*PF_6 was rapidly achieved by treatment with HPF_6, and five cycles of switching were performed with excellent polymer stability. By MALLS analysis, **8** had an R_g of 13.5 nm, indicating the dimeric units within the deprotonated polymer remained in the contracted conformation. This effect is likely due to a combination of $\pi-\pi$ slipped-stacking interactions of the dimer aryl rings and limited solubility in the GPC eluent,[20] favoring the collapsed, contracted conformation of the polymer and preventing systematic extension of the dimeric units. However, ^{1}H NMR analysis of **8** in a good solvent (DCM)[15] revealed conformational heterogeneity similar to that observed in the monomeric dimer, confirming the ability of the dimer units in the polymer to slide upon deprotonation. In application, the DCD-containing materials will

Scheme 2. Graphical Representation Depicting Synthesis of Linear "Click" Polymer **7**-H_{2n}·$2n$$PF_6$, Decoordinated Polymer **8**[a], and Extended Acylated Polymer **9**[a]



[a] Deprotonation of **7**-H_{2n}·$2n$$PF_6$ (R_g = 14.8 nm) to generate **8** did not induce lengthening (R_g = 13.5 nm), likely due to poor solubility and $\pi-\pi$ slipped-stacking interactions, but acylated polymer **9** showed a 48% increase in size (R_g = 21.4 nm).

be placed under an external load, readily inducing a lengthening of the dimeric units. To mimic the effect of such a force and demonstrate the extension ability of the DCD polymer, we employed acylation of **7**-H_{2n}·$2n$$PF_6$ to increase the steric bulk of the amines and force slippage of the crown-type rings to give extended analogue **9** (Scheme 2). MALLS showed **9** had an R_g of 21.4 nm, which indicated a size increase of 48% compared to the contracted analogue. This value closely matched the anticipated dimer extension percent and showed that the polymer dimensions were dramatically impacted by the switchable DCD units.

In conclusion, utilization of olefin metathesis has enabled the synthesis of a [c2]daisy-chain dimer with the ammonium binding site near the cap of the dimer. A deprotonated DCD possessing such a structural attribute will more forcefully seek to restore coordinating interactions upon reprotonation, enhancing its utility as a synthetic molecular actuator. Dimer functionalization facilitated incorporation into linear polymers, with a 48% size increase of an unbound, extended analogue of the polymer demonstrating slippage of the dimer units. Ongoing work is directed at further materials studies, with particular focus on ascertaining the effects of the switchable dimer linkages when the polymer is under mechanical load. Additionally, we are exploring the synthesis of macroscopic networks containing the DCD units and analyzing the correlation between molecular-scale extension–contraction manipulations and resulting macroscale changes.

Acknowledgment. We thank Dr. Erin Guidry and Prof. J. Fraser Stoddart for useful discussions. The ruthenium metathesis catalyst was received as a generous gift from Materia, Inc. We thank Lawrence M. Henling for X-ray crystallographic data. The work was supported by the Office of Naval Research through its MURI program and the NSF (NSF CHE-0809418).

Supporting Information Available: Complete experimental procedures as well as full characterization. This material is available free of charge via the Internet at http://pubs.acs.org.

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JA905924U