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Tuneable Side-Chain Supramolecular Polymer

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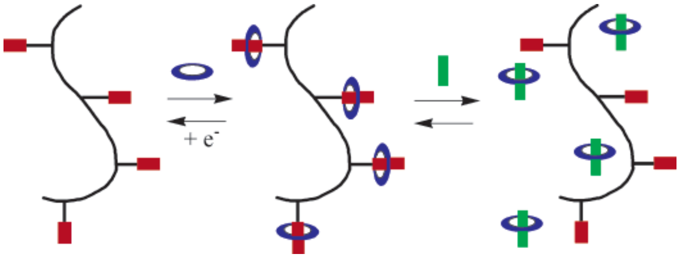
ABSTRACT



A random copolymer containing 1,5-dialkyloxynaphthalene moieties has been synthesized using atom-transfer radical polymerization. We have shown that this polymer has the ability to form complexes with the tetracationic cyclophane cyclobis(paraquat-*p*-phenylene) (CBPQT^{4+}) and that electrochemical reduction of the cyclophane or the addition of a competing guest for the cavity of the cyclophane results in disassembly of the supramolecular polymer.

The self-assembly of relatively small building blocks via specific noncovalent interactions into a variety of supramolecular polymers has received considerable attention.[1] The rapid development of macromolecules of this type has largely gone hand-in-hand with recent advances in the construction of highly specific and effective host−guest complexes.[2] A promising method of constructing supramolecular polymers will continue to be through use of pseudorotaxane architectures, as these systems can be reversibly assembled in a range of environments and subsequently disassembled through the intervention of an external stimulus.[3] Pseudorotaxanes created from the electron-deficient cyclophane cyclobis(paraquat-*p*-phenylene) (CBPQT^{4+}) and electron-rich dialkoxyaryl units have arguably become one of the most important building blocks for the creation of functional systems with near-binary redox controllable recognition properties.[4] For example, as the reduction of the cyclophane unit results in the expulsion

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(1) For recent reviews, see: (a) *Supramolecular Polymers*; Ciferri, A., Ed.; Taylor & Francis: Florida, 2005. (b) Brunsveld, L.; Folmer, B. J. B.; Meijer, E. W.; Sijbesma, R. P. *Chem. Rev.* **2001**, *101*, 4071−4097.

(2) Schrader, T., Hamilton, A. D., Ed. *Functional Synthetic Receptors*; Wiley-VCH: Weinheim, 2005.

(3) For examples of polypseudorotaxanes, see: (a) Raymo, F. M.; Stoddart, J. F. *Trends Polym. Sci.* **1996**, *4*, 208−211. (b) Raymo, F. M.; Stoddart, J. F. *Chem. Rev.* **1999**, *99*, 1643−1663. (c) Fyfe, M. C. T.; Stoddart, J. F. *Coord. Chem. Rev.* **1999**, *183*, 139−155. (d) Gong, C.; Gibson, H. W. In *Molecular Rotaxanes, Catenanes and Knots*; Sauvage, J.- P., Dieterich-Buchecker, C. O., Eds.; Wiley-VCH: Weinheim, 1999; pp 277−321. (e) Harada, A. *Acc. Chem. Res.* **2001**, *34*, 456−464. (f) Kim, K. *Chem. Soc. Rev.* **2002**, *31*, 96−107. (g) Takata, T.; Kihara, N.; Furusho, Y. *Adv. Polym. Sci.* **2004**, *171*, 1−75. (h) Huang, F.; Gibson, H. W. *Prog. Polym. Sci.* **2005**, *30*, 982−1018. (i) Wenz, G.; Han, B.-H.; Müller A. *Chem. Rev.* **2006**, *106*, 782−817. (j) Leung, K. C.-F.; Mendes, P. M.; Magonov, S. N.; Northrop, B. H.; Kim, S.; Patel, K.; Flood, A. H.; Tseng, H.-R.; Stoddart, J. F. *J. Am. Chem. Soc.* **2006**, *128*, 10707−10715.

(4) Anelli, P. L.; Ashton, P. R.; Ballardini, R.; Balzani, V.; Delgado, M.; Gandolfi, M. T.; Goodnow, T. T.; Kaifer, A. E.; Philp, D.; Pietraszkiewicz, M.; Prodi, L.; Reddington, M. V.; Slawin, M. V.; Spencer, A. M. Z.; Stoddart, J. F.; Vicent, C.; Williams, D. J. *J. Am. Chem. Soc.* **1992**, *114*, 193−218.

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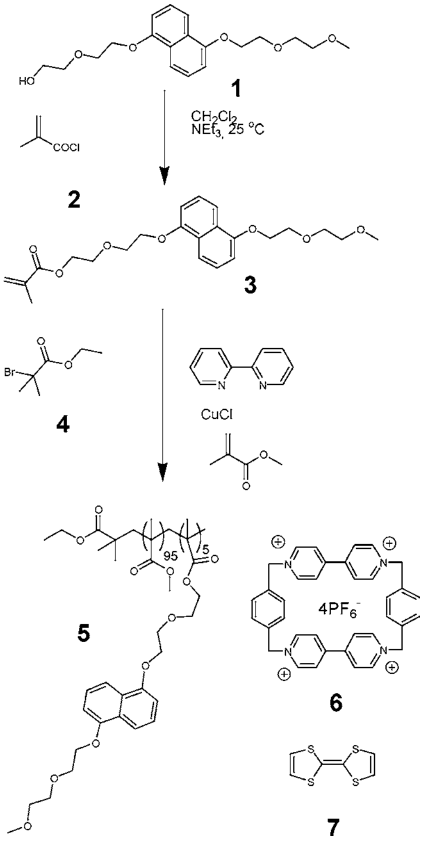
of the electron-rich unit from its cavity, systems of this type could be incorporated into the side chains of polymers as a means of reversibly modifying their structure and function.[5] Here, we report the synthesis of a 1,5-dialkyloxynaphthalene functionalized random copolymer and its subsequent tuneable complexation with CBPQT^{4+}.

Scheme 1



Scheme 1 outlines the synthesis of polymer **5** (see also Supporting Information). Compound **3** was synthesized in good yield from **1** and methacryloyl chloride **2**. To furnish a polymer with a well-defined composition, architecture, and functionality, we have exploited the well-documented ability of atom-transfer radical polymerization (ATRP) to synthesize polymers of this type.[6] Compound **3** readily undergoes copper-mediated atom-transfer copolymerization with methyl methacrylate and initiator **4**, to produce copolymer **5**. ^{1}H NMR spectroscopy confirmed the incorporation of **3** within the random copolymer **5**, by the appearance of broad resonances in the aromatic region for the naphthalene moieties and similarly broad signals for methylene protons of the ethylene glycol groups. Comparison of the integrals for the signals of the naphthalene groups and methyl groups of the methacrylate moieties gave an estimated ratio of 5:95 (**3**/methyl methacrylate). Gel permeation chromatography performed on polymer **5** gave M_n = 10 300 and M_w = 12 400, which corresponds to a polydispersity of 1.20.

^{1}H NMR spectroscopy was used to investigate the addition of polymer **5** to a solution of **6** in acetonitrile-d_3 (see Supporting Information). A significant broadening of the CBPQT^{4+} proton resonances was observed upon the addition of aliquots of polymer **5**, which is indicative of the cyclophane being connected to the larger polymer architecture.[7] The addition of excess polymer eventually led to the resonances becoming so broad that they were indistinguishable from the baseline. Furthermore, the addition of polymer **5** to a solution of **6** resulted in the immediate formation of a purple solution, which is characteristic of complexes of this type.[8]

We have investigated the binding event between polymer **5** and compound **1** with **6** using UV−vis titrations (see Supporting Information). When aliquots of **6** were titrated into solutions of **5** or **1** in acetonitrile, significantly differing binding processes were observed. For compound **1**, a single binding mode was observed (K_a = 25 000 M^{-1}).[8] When experiments were repeated for polymer **5**, two different binding modes were observed, presumably resulting from pseudorotaxane formation (i.e., “inside” binding, K_a = 25 000 M^{-1}) and nonpseudorotaxane formation (i.e., “alongside” binding, K_a = 1500 M^{-1}), respectively.[9] The second binding event suggests that upon the addition of the polymer some of the naphthalene units do not act as a thread for the cyclophane, and alongside binding appears to be more favorable for these units, presumably due to steric hindrance from the polymer backbone.

To probe the effect complexation between **5** and **6** has in modulating the properties of the polymer in solution, we have undertaken dynamic light scattering (DLS) experiments (see Supporting Information). Aliquots of **6** were titrated into a solution of **5** (1×10^{-4} M), and the resultant change in polymer size was recorded. When initial experiments were performed on polymer **5** alone, an average hydrodynamic diameter (h.d.) of 6.9 nm was obtained. The average h.d. was then determined upon the addition of aliquots of **6** and revealed that complex formation affected the size (and hence conformation) of the polymer. At low equivalents of **6**, the average h.d. slightly increased from 6.9 to 8.1 nm. This increase is likely to be due to the threading of **6** onto exposed naphthalene units on the polymer. At higher concentrations of **6** (>5 equiv), the average h.d. (5.5 nm) of the polymer decreased, indicating the formation of a more compact polymeric architecture. More interestingly, the complex decreased in size relative to both the uncomplexed polymer **5** (∼1.5 nm decrease) and the resulting complex obtained upon the addition of low concentrations of **6** (∼2.5 nm

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(5) (a) Pollino, J. M.; Weck, M. *Chem. Soc. Rev.* **2005**, *34*, 193−207. (b) South, C. R.; Higley, M. N.; Leung, K. C.-F.; Lanari, D.; Nelson, A.; Grubbs, R. H.; Stoddart, J. F.; Weck, M. *Chem.−Eur. J.* **2006**, *12*, 3789−3797.

(6) For a recent review, see: Matyjaszewski, K.; Chem, Y. *Chem. Rev.* **2001**, *101*, 2921−2990.

(7) Sanders, J. K. M.; Hunter, B. K. *Modern NMR Spectroscopy*, 2nd ed.; Oxford University Press: Oxford, U.K., 1993; pp 208−211.

(8) Ashton, P. R.; Gomez-Lopez, M.; Iqbal, S.; Preece, J. A. Stoddart, J. F. *Tetrahedron Lett.* **1997**, *38*, 3635−3638.

(9) Asakawa, M.; Dehaen, W.; L’Abbé, G.; Menzer, S.; Nouwen, J.; Raymo, F. M.; Stoddart, J. F.; Williams, D. J. *J. Org. Chem.* **1996**, *61*, 9591−9595.

decrease). The result suggests that the secondary binding mode of **6** to **5** generates a more compact structure. The alongside binding, as implied by the UV titration data, may generate a collapse of the supramolecular polymer creating this smaller observed structure.

We next turned our attention to whether complex formation could be controlled using an external stimulus. First, we have explored the effect of heating the complexes formed between **5** and **6** and between **1** and **6** using variable-temperature UV−vis (VT-UV−vis) experiments. Separate solutions of **1** and **5** saturated with excess **6** were heated to 75 °C, and the intensity of the absorption band at 520 nm was measured (see Supporting Information). The absorbance intensity at 520 nm decreased for both solutions containing **1** and **5** as the samples were heated. However, the extent of the decrease in intensity was different for **1** and **5**. For experiments undertaken with **1**, the solution maintained a faintly purple color even at elevated temperatures. However, experiments performed with **5** demonstrated a decrease in absorbance intensity, which leveled off to zero at around 65 °C. Thus, this behavior suggests that complexes formed between **5** and **6** were easier to break up at higher temperatures than complexes formed between **1** and **6**.

Variable-temperature DLS (VT-DLS) experiments were also used to evaluate complex stability at elevated temperatures. The h.d. of the complex formed between **5** and excess **6** (∼15 equiv) was compared to parent polymer **5** upon heating the sample. The complex exhibited a 5.5 nm structure up to about 65 °C and then decreased to 4 nm at 80 °C, whereas the parent polymer steadily decreased in size across the same temperature range (3.5 nm at 80 °C) (see Supporting Information). Thus, in agreement with the VT-UV−vis data, the VT-DLS data indicate that after 65 °C the supramolecular polymer formed between **5** and **6** disassembles, providing a polymer species of a dimension that is close to that of parent polymer **5**.

Second, we have exploited the well-documented ability of reducing the cyclophane to its diradical dicationic state to induce pseudorotaxane dethreading.[4] To investigate whether this methodology can be extended to the present system, we have recorded the cyclic and square wave voltammograms of compound **6** (dissolved in acetonitrile containing 0.1 M Bu_4NPF_6) upon the addition of aliquots of **1** or **5** (Figure 1).[10] In both cases, a negative shift in the first reduction wave was observed, presumably due to donor−acceptor interactions (resulting from complex formation between the naphthalene and cyclophane moieties) destabilizing the diradical dication state of the cyclophane. The reduction potential of the second reduction wave is largely unaffected, indicating the naphthalene/$CBPQT^{4+}$ complex disassembles when the cyclophane is first reduced. However, the voltammetry data obtained for **5** and **1** differed in their ability to destabilize the diradical dicationic state of **6**. At low concentrations of **5** or **1**, similar shifts in the reduction potential of **6** were observed. Upon the addition of further aliquots of **5** or **1** to **6**, the voltammetry data indicated that these processes gave rise to differing electrochemical environments for the cyclophane unit. Compound **1** provided a maximum shift of −70 mV for the redox wave corresponding to the formation of the diradical dicationic state of **6**, whereas the addition of polymer **5** gave rise to only a −40 mV shift.

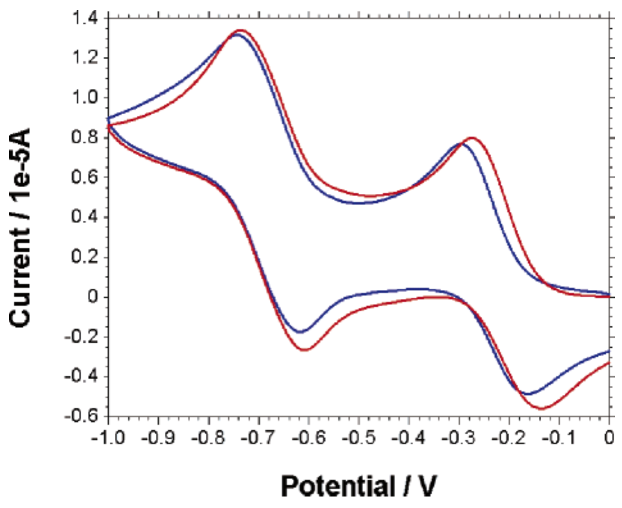

Figure 1. Cyclic voltammogram of **6** (∼6 × 10^{-4} M) (red line) and upon the addition of **5** (blue line) (∼3 × 10^{-4} M). Recorded in a CH_3CN solution containing 0.1 M Bu_4NPF_6 (vs Ag/AgCl). Scan rate = 125 mV s^{-1}.

As an alternative strategy for disassembling the supramolecular polymer, we have explored the addition of TTF (**7**) to a solution of **5** and **6**,[11] as it is well-established that TTF is an effective guest $CBPQT^{4+}$-based cyclophane.[12] The addition of aliquots of **7** to a cuvette containing **5** and **6** immediately resulted in the formation of an emerald-green solution characteristic of TTF−$CBPQT^{4+}$ complexes, corresponding to the appearance of a charge-transfer band centered around 863 nm (Figure 2). The absorption at 520 nm significantly reduces upon the addition of **7**. Thus, the UV−vis data are consistent with the TTF unit disrupting supramolecular polymer formation between **5** and **6**.

To further prove the ability of **7** to disrupt supramolecular polymer formation, we have investigated the change in the ^1H NMR spectra of an admixture of **5** and **6** upon the addition of **7** (see Supporting Information). Immediately upon the addition of **7** to the NMR tube, the signals corresponding to the cyclophane became less broad, indicating that the cyclophane units are no longer bound to the polymer.

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[10] The electrolyte solution (0.1 M) was prepared from recrystallized Bu_4NPF_6 using spectroscopic grade acetonitrile. A three-electrode configuration was used with a Pt disc working electrode, a Ag/AgCl reference electrode, and a platinum wire as the counter electrode. The solution was vigorously purged with nitrogen prior to recording the electrochemical data. All voltammetry measurements were recorded under a nitrogen atmosphere.

[11] Credi, A.; Montalti, M.; Balzani, V.; Langford, S. J.; Raymo, F. M.; Stoddart, J. F. *New J. Chem.* **1998**, *22*, 1061−1065.

[12] For examples, see: (a) Devonport, W.; Blower, M. A.; Bryce, M. R.; Goldenberg, L. M. *J. Org. Chem.* **1997**, *62*, 885−887. (b) Ashton, P. R.; Balzani, V.; Becher, J.; Credi, A.; Fyfe, M. C. T.; Mattersteig, G.; Menzer, S.; Nielsen, M. B.; Raymo, F. M.; Stoddart, J. F.; Venturi, M.; Williams, D. J. *J. Am. Chem. Soc.* **1999**, *121*, 3951−3957. (c) Nielsen, M. B.; Jeppesen, J. O.; Lau, J.; Lomholt, C.; Damgaard, D.; Jacobsen, J. P.; Becher, J.; Stoddart, J. F. *J. Org. Chem.* **2001**, *66*, 3559−3563. (d) Philp, D.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Williams, D. J. *J. Chem. Soc., Chem. Commun.* **1991**, 1584−1586.

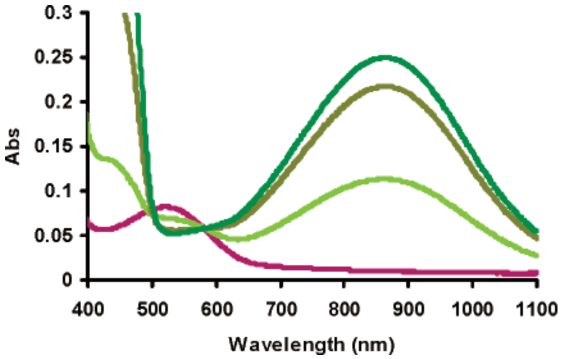

Figure 2. UV−vis spectra of the complex formed between **5** (∼1 × 10^{-4} M) and **6** (∼2 × 10^{-4} M) (maroon line) and upon the addition of 1 (light green line), 5 (brown−green line), and 10 (dark green line) equiv of **7** (relative to **6**). Recorded in CH_3CN at 298 K.

Furthermore, the cyclophane resonances are shifted (compared to the spectra of **6**), providing further evidence for the formation of TTF−CBPQT^{4+} pseudorotaxanes and thus disruption of the initial supramolecular polymer.[12d]

In conclusion, we have shown that we can form supramolecular polymers between **5** and **6** and that this complexation modulates the degree of polymer folding. Furthermore, we have shown that complexation can be disrupted by either the electrochemical reduction of the cyclophane or the addition of a competing guest for the cavity of the cyclophane. Further work in our laboratory will develop water-soluble analogues of the systems described here in an effort to extend this methodology to biologically relevant systems. Our work in this area will be reported in due course.

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Supporting Information Available: Full synthetic details pertaining to the preparation of **5** and characterization of the resulting supramolecular polymers formed with **6**. This material is available free of charge via the Internet at http://pubs.acs.org.

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