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Controlling Capture and Release of Guests from Cross-Linked Supramolecular Polymers

Heng Xu and Dmitry M. Rudkevich*

Department of Chemistry & Biochemistry, The University of Texas at Arlington, Arlington, Texas 76019-0065

rudkevich@uta.edu

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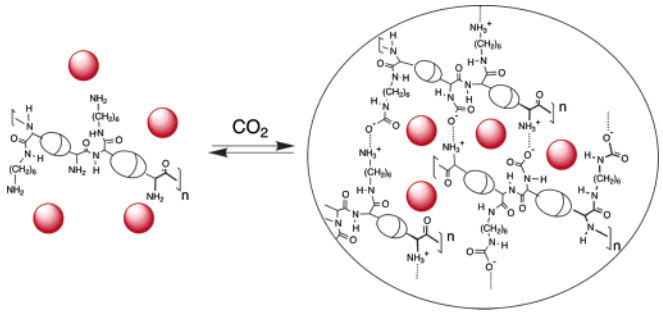
ABSTRACT



Formation of a cross-linked, porous supramolecular polymer leads to instant entrapment of organic guest species. These can be stored and then released upon changing solvent polarity, temperature, pH, and concentration.

Supramolecular polymers (SPs) represent a novel class of macromolecules in which monomeric units are held together by reversible and directional forces.[1] SPs combine features of conventional polymers with properties, resulting from the bonding reversibility. Degree of polymerization, lifetimes, physical/mechanical properties, and architectures of SPs can be switched "on−off" through the main chain self-assembly−dissociation processes. We recently introduced a strategy to build cross-linked, three-dimensional SP networks that simultaneously utilize two different forces: hydrogen bonding and reversible chemistry between CO_2 and amines.[2] Addition of CO_2 leads to carbamate salt bridges, which act as dynamic cross-linking units. Unique SP materials were prepared that either thermally release CO_2, keeping hydrogen bonding intact, or break hydrogen bonds without destroying carbamate bridges. In this communication, we show how to capture, store, and release guests with such SP materials. A number of cross-linked SPs are known;[1] however, they have not been used for guest entrapment and release.[3,4] Our results thus offer opportunities for the design of switchable, three-dimensional SPs for molecular storage. Moreover, the use of CO_2 opens gates to environmentally responsive materials and devices.

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(2) (a) Xu, H.; Rudkevich, D. M. *Chem. Eur. J.* **2004**, *10*, 5432−5442. (b) Xu, H.; Rudkevich, D. M. *J. Org. Chem.* **2004**, *69*, 8609−8617. (c) Review from this laboratory: Rudkevich, D. M.; Xu, H. *Chem. Commun.* **2005**, 2651−2659.

(3) Xu and co-workers recently described a stable metal coordination polymer that binds apolar organic molecules from aqueous solutions; see: Xing, B.; Choi, M.-F.; Xu, B. *Chem. Commun.* **2002**, 362−363. However, in contrast to our material, this gel has to be preformed *prior* to the guest entrapment.

(4) Organogels have been used for guest entrapment and release: (a) Abdallah, D. J.; Weiss, R. G. *Adv. Mater.* **2000**, *12*, 1237−1247. (b) van Esch, J. H.; Feringa, B. L. *Angew. Chem., Int. Ed.* **2000**, *39*, 2263−2266. (c) Gronwald, O.; Snip, E.; Shinkai, S. *Curr. Opin. Colloid Interface Sci.* **2002**, *7*, 148−156.

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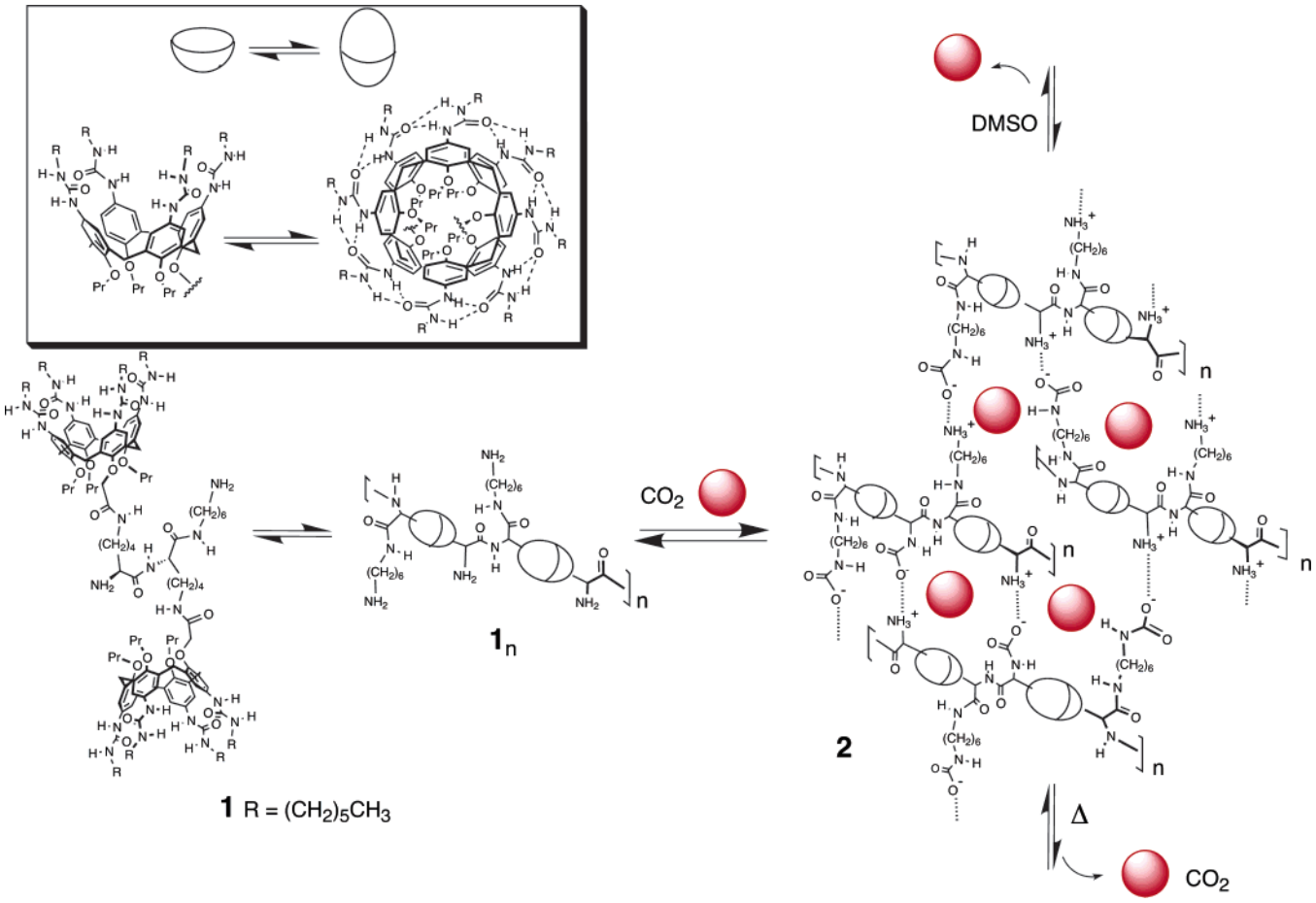

Figure 1. Biscalix[4]arene **1** forms SP chains $\mathbf{1}_n$ in an apolar solution, which can be cross-linked with CO_2 into SP gels **2**. Solvents and other organic guests can be trapped, stored, and released from **2** upon changing solvent polarity, temperature, pH, and/or concentration.

Our SP materials are formed from monomers **1** (Figure 1). In these, two calix[4]arene tetraureas are attached to a dipeptide, dilysine chain.[2] Calix[4]arene tetraureas are popular self-assembling modules that form well-defined hydrogen bonded dimers in apolar solution ($K_D \geq 10^6$ M^{-1}).[5] In monomer **1**, the calixarene tetraureas were attached to the ϵ-NH_2 lysine ends, so the dipeptide orients them in opposite directions. Such design leads to very long SP chains $\mathbf{1}_n$ with a degree of polymerization of ~300 at NMR concentrations in $CHCl_3$.[2]

Chains $\mathbf{1}_n$ possess "CO_2-philic" primary amino groups on the periphery. In an apolar solvent, once CO_2 is added, multiple carbamate salt bridges form and thus cross-link $\mathbf{1}_n$ into three-dimensional SP networks. These are gels. Scanning electron micrographs of freeze-dried samples or xerogels **2** revealed a highly developed three-dimensional network with defined pores and channels of ~5 μm.[2a] On a molecular level, multiple voids are generated between the SP calixarene chains and the lysine-carbamate bridges that have dimensions of 15−20 Å. We have now discovered that when CO_2 cross-links SP chains $\mathbf{1}_n$ in the presence of organic guests of 1−1.5 nm size, gels **2** instantly entrap them.

For this project, we used SP gel **2** to trap commercial dyes such as Coumarin 314 **3** and porphyrin **4** and employed conventional UV−vis spectrophotometry to monitor their release. At the same time, we feel that the same rules apply for other guests of comparable dimensions.

Coumarin **3** or porphyrin **4** were added to a solution of up to 4-fold excess of biscalixarene **1** in a small volume of $CHCl_3$ (~57 g/L, 20 mmol/L). CO_2 was bubbled through the solution for 1−2 min. Colored gels **2** were formed and then briefly washed with $CHCl_3$ until solvent discoloration was observed. The ^{1}H NMR analysis revealed that ~7 ± 1% of **3** and **4** was entrapped; no selectivity was detected. The guests can be stored in dried gels indefinitely and released upon gel dissipation.

The release experiments were performed at least in triplicate (Figures 2 and 3). $CHCl_3$ was added to a round-bottom flask containing guest-stuffed gels **2** (0.5−1.3 g/L), and the mixtures were mechanically shaken for an extended time. The gel slowly dissolved, releasing the dyes. Aliquots

(5) (a) Shimizu, K. D.; Rebek, J., Jr. *Proc. Natl. Acad. Sci. U.S.A.* **1995**, *92*, 12403−12407. (b) Mogck, O.; Böhmer, V.; Vogt, W. *Tetrahedron* **1996**, *52*, 8489−8496. Reviews: (c) Rudkevich, D. M. In *Calixarene 2001*; Asfari, Z., Böhmer, V., Harrowfield, J., Vicens, J., Eds.; Kluwer Academic Publishers: Dordrecht, 2001; pp 155−180. (d) Rebek, J., Jr. *Chem. Commun.* **2000**, 637−643.

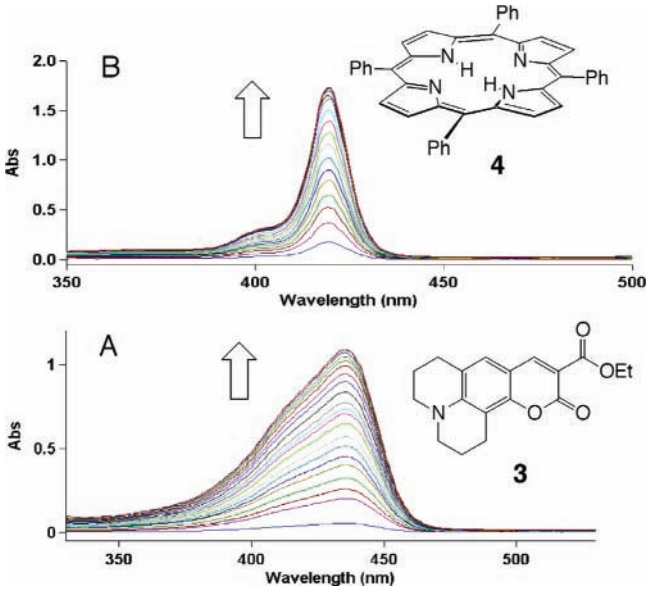

Figure 2. UV−vis spectra of coumarin **3** (A) and porphyrin **4** (B) in $CHCl_3$.

were taken every 1−3 min, and increased absorptions of coumarin **3** at $\lambda_{max} = 434$ nm and porphyrin **4** at $\lambda_{max} = 420$ (Soret-band) and 552 nm (Q-band) were monitored (Figure 2). Under these conditions at 25 °C, coumarin **3** was completely released within 40 min, and porphyrin **4** was released after 20 min. From these experiments, the release rates of 0.12 and 0.24 mmol/min, respectively, were determined (Figure 3A). These are much slower than simple dissolution of **3** and **4** under the same conditions, which occurs within seconds (>40 mmol/min).

The release appears to be concentration dependent, and using smaller volumes of $CHCl_3$ significantly slows it down. For example, when 40 times less $CHCl_3$ (20 mg/mL compared to 0.5 mg/L) was used, the ∼5-fold rate decrease (0.05 mmol/min) for porphyrin **4** was observed (Figure 3B). In addition to simple diffusion, the dissociation of carbamate salt bridges and release of CO_2 are responsible for such concentration effects. Release of CO_2 was confirmed by ^{13}C NMR spectroscopy. In the ^{13}C NMR spectrum of monomer **1** in DMSO-d_6, four C═O carbonyl signals were observed, three for the amide fragments at 175.4, 171.7, and 169.4 ppm and an intense signal for the upper rim ureas at 155.8 ppm (Figure 4).[2] Using $^{13}CO_2$ gas, we prepared the carbamate ^{13}C-labeled gel **2**. In the spectrum of the ^{13}C-labeled salt, formed upon dissolution of this gel in DMSO-d_6, in addition to the amide signals, new peaks of higher intensity appeared at ∼162 ppm. These are attributed to the carbamate HN−$^{13}C(O)O^-$ group. The signal disappeared after diluting the mixture of **2** with larger quantities of $CHCl_3$ (from 3 to 300 mL for 0.2 g of **2**; ∼20 to ∼0.2 mmol/L). That carbamate bridges can dissociate back to free amine and CO_2 in diluted apolar solution is novel.[6−8]

Faster guest release can be achieved upon increasing the solvent polarity. Addition of a competitive solvent such as

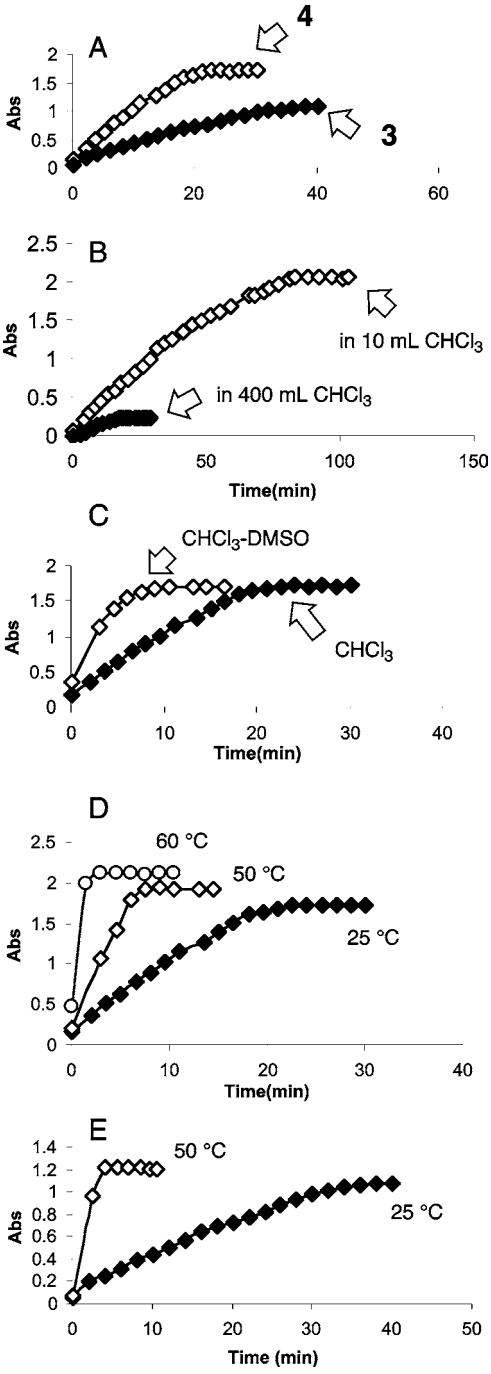

Figure 3. (A) Release curves of **3** and **4** at 25 °C at 0.5−1.3 mg/mL of **2** in $CHCl_3$. (B) Release of porphyrin **4** in $CHCl_3$ at 0.5 mg/mL (black squares) and 20 mg/mL (white squares) at 25 °C. (C) Release of porphyrin **4** in $CHCl_3$ (black squares) and $CHCl_3$−DMSO 1:1 (white squares) at 25 °C at 0.5 mg/mL of **2**. (D) Release of porphyrin **4** at 25, 50, and 60 °C at 0.5 mg/mL of **2**. (E) Release of coumarin **3** at 25 and 50 °C at 1.3 mg/mL of **2**.

DMSO breaks hydrogen bonding calixarene capsules and destroys gels **2** within minutes. At the 1:1 $CHCl_3$−DMSO ratio, the process reflects dissolution of the gel, and the release rates are now ∼4 times higher for both guests (for example, Figure 3C).

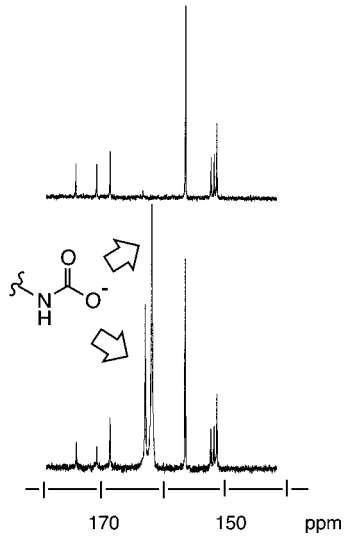

Figure 4. Portions of the ^{13}C NMR spectra (125 MHz, DMSO-d_6) of carbamate **2** (bottom) and calixarene **1** (top), obtained upon 100-fold dilution of **2** in $CHCl_3$.

Alternatively, guest departure from **2** can be accomplished through the thermal release of CO_2 (Figures 3D and 3E). The process takes place in an apolar solvent, and the calixarene capsules do not dissociate. At the same time, the carbamic salt bridges break easily. At 50 °C, coumarin **3** and porphyrin **4** were completely released within 4 and 5 min, respectively. Accordingly, release rates of 1.2 and 1.0 mmol/min, respectively, were obtained. At 60 °C, the release appeared to be even faster. For example, porphyrin **4** was released within 2 min at a rate of 2.4 mmol/min. Simple diffusion at elevated temperatures may also be responsible; however, release of CO_2 under these conditions was confirmed by ^{13}C NMR spectroscopy.

Such rather fast dissociation of otherwise stable carbamate salt bridges was somewhat unexpected[6] but promising. Indeed, this delicate property can now be used in dynamic covalent chemistry[9] for the design of reversibly formed nanostructures and combinatorial libraries. Moreover, we found that traces of acids (HCl, TFA) also catalyze dissociation of carbamate bridges in **2**.[10]

In summary, carbamate-based cross-linked supramolecular polymers can serve for entrapment and switchable release of organic guests. Conventional organogels have been effectively used to trap small organic molecules;[4] however, supramolecular polymers, with their highly directional, relatively strong, and yet reversible forces, may bring further improvements. Of particular interest are (a) the CO_2-initiated guest capture and (b) a multiparameter switch, allowing control over the release through solvent polarity, temperature, pH, concentration, etc.[11] We are currently working on encapsulation of other guests and also building selectivity into these systems.

Acknowledgment. Financial support was provided by the A. P. Sloan Foundation.

Supporting Information Available: Experimental procedures and spectra. This material is available free of charge via the Internet at http://pubs.acs.org.

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(6) Recent papers on CO_2-amine chemistry: (a) Hampe, E. M.; Rudkevich, D. M. *Tetrahedron* **2003**, *59*, 9619−9625. (b) George, M.; Weiss, R. G. *Langmuir* **2003**, *19*, 1017−1025. (c) George, M.; Weiss, R. G. *Langmuir* **2003**, *19*, 8168−8176. (d) George, M.; Weiss, R. G. *Langmuir* **2002**, *18*, 7124−7135. (e) Dell'Amico, D. B.; Calderazzo, F.; Labella, L.; Marchetti, F.; Pampaloni, G. *Chem. Rev.* **2003**, *103*, 3857−3898.

(7) Carbamate salts dissociate to amines and CO_2 in more *polar* aprotic solvents: (a) Aresta, M.; Quaranta, E. *Tetrahedron* **1992**, *48*, 1515−1530. (b) Masuda, K.; Ito, Y.; Horiguchi, M.; Fujita, H. *Tetrahedron* **2004**, *61*, 213−229.

(8) Initially, it was assumed that traces of HCl in $CHCl_3$ might be primarily responsible for carbamate dissociation in diluted solutions. However, in model experiments, using thorough prewashes with aq Na_2CO_3 and then water $CHCl_3$, the same results were obtained. Addition of HCl and TFA to the NMR samples caused slower dissociation rates than high dilution (^{13}C NMR). Finally, similar concentration effects were observed for model alkylammonium carbamates in THF, MeCN, EtOAc, CH_2Cl_2, and benzene.

(9) (a) Rowan, S. J.; Cantrill, S. J.; Cousins, G. R. L.; Sanders, J. K. M.; Stoddart, J. F. *Angew. Chem., Int. Ed.* **2002**, *41*, 898−952. (b) Lehn, J.-M. *Chem. Eur. J.* **1999**, *5*, 2455−2463.

(10) Ewing, S. P.; Lockshon, D.; Jencks, W. P. *J. Am. Chem. Soc.* **1980**, *102*, 3072−3084.

(11) Reversible carbamate bridges were used to cross-link conventional polymers; see: Carretti, E.; Dei, L.; Macherelli, A.; Weiss, R. G. *Langmuir* **2004**, *20*, 8414−8418. For noncovalent forces in conventional polymers, see: Pollino, J. M.; Weck, M. *Chem. Soc. Rev.* **2005**, *34*, 193−207.