ORGANIC
LETTERS

2006
Vol. 8, No. 7
1371−1373

Organogels Derived from Tetranitrated Crown Ethers

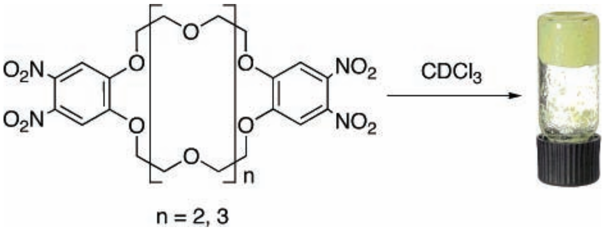
Steven J. Langford,* Melissa J. Latter, Vei-Lin Lau, Lisandra L. Martin, and Adam Mechler

School of Chemistry, Monash University, Clayton, Victoria, Australia 3800

Steven.Langford@sci.monash.edu.au

Received January 17, 2006

ABSTRACT



The 3,3′,4′4′-tetranitrodibenzocrown ethers TNDB24C8 and TNDB30C10 form organogels with chloroalkanes at 3% w/v. Atomic force microscopy and scanning electron microscopy have been used to characterize the superstructure of the gels. Gels prepared using TNDB30C10 and $CHCl_3$ are more fibrous and are ordered into elongated domains attributable to exposed parts of intermingled fibers. Differential scanning calorimetry shows that the gel aids in the formation of supercooled $CHCl_3$ ($\Delta T = 21$ K, $\Delta H_{av} = 19.0 \pm 1.5$ kJ mol^{-1}) and that the gel liquefies at 307 K.

The ability of organic compounds to gel in the presence of organic liquids and aqueous solutions, i.e., the so-called low molecular weight gelators (LMWG), has been a phenomenon receiving significant and recent attention because of their application in synthesis, separations, drug delivery, materials science, sensing, and biomimetics.[1−12] The gelation process is a result of an ordered supramolecular event either between LMWG molecules in a particular solvent or between LMWG molecules and the solvent. In all cases, this event leads to the formation of aggregated fibrous structures which are stabilized by noncovalent interactions resulting in solvent entrapment within the entangled network.[2−10] The types of low molecular weight organic molecules capable of forming gels include single compounds such as cholesterols,[2] coumarins,[3] amido alcohols,[4] saccharides,[5] ureas,[6] metallocomplexes,[7] amino acids,[8] terpenes,[9] tetrathiafulvalenes,[10] and dendritic building blocks[11] as well as binary systems.[12] Shinkai's group reported the first example of a gelator comprising a crown ether unit and demonstrated the versatility of this compound to gel with a wide variety of organic solvents at concentrations <1 wt %.[13] In this case, however,

---

(1) (a) de Loos, M.; Feringa, B. L.; van Esch, J. H. *Eur. J. Org. Chem.* **2005**, 3615−3631. (b) Sangeetha, N. M.; Maitra, U. *Chem. Soc. Rev.* **2005**, *34*, 821−836. (c) Estroff, L. A.; Hamilton, A. D. *Chem. Rev.* **2004**, *104*, 1201−1217. (d) Terech, P.; Weiss, R. G. *Chem. Rev.* **1997**, *97*, 3133−3159.

(2) (a) Geiger, C.; Stanescu, M.; Chen, L.; Whitten, D. G. *Langmuir* **1999**, *15*, 2241−2245. (b) Wang, R.; Geiger, C.; Chen, L.; Swanson, B.; Whitten, D. G. *J. Am. Chem. Soc.* **2000**, *122*, 2399−2400.

(3) Yu, H.; Mizufune, H.; Uenaka, K.; Moritoki, T.; Koshima, H. *Tetrahedron* **2005**, *61*, 8932−8938.

(4) Valkonen, A.; Lahtinen, M.; Virtanen, E.; Kaikkonen, S.; Kolehmainen, E. *Biosens. Bioelectron.* **2004**, *20*, 1233−1241.

(5) Luboradzki, R.; Pakulski, Z.; Sartowska, B. *Tetrahedron* **2005**, *61*, 10122−10128.

(6) Wurthner, F.; Hanke, B.; Lysetska, M.; Lambright, G.; Harms, G. S. *Org. Lett.* **2005**, *7*, 967−970.

(7) Naota, T.; Koori, H. *J. Am. Chem. Soc.* **2005**, *127*, 9324−9325.

(8) (a) Suzuki, M.; Nanbu, M.; Yumoto, M.; Shirai, H.; Hanabusa, K. *New. J. Chem.* **2005**, *29*, 1439−1444. (b) Miravet, J. F.; Escuder, B. *Org. Lett.* **2005**, *7*, 4791−4794.

(9) Bag, B. G.; Maity, G. C.; Pramanik, S. R. *Supramol. Chem.* **2005**, *17*, 383−385.

(10) Wang, C.; Zhang, D.; Zhu, D. *J. Am. Chem. Soc.* **2005**, *127*, 16372−16373.

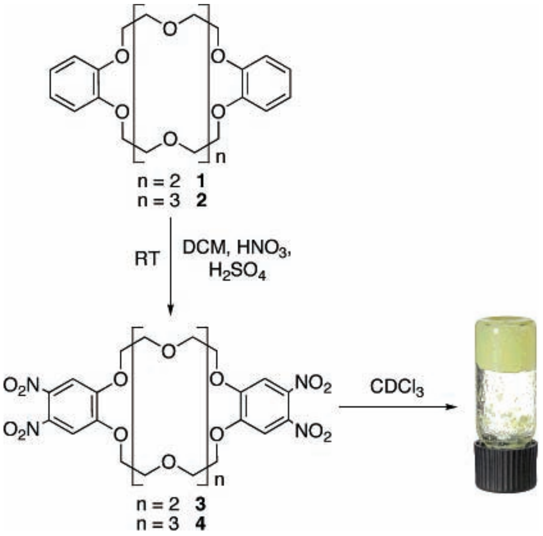
(11) Love, C. S.; Chechik, V.; Smith, D. K.; Ashworth, I.; Brennan, C. *Chem. Commun.* **2005**, 5647−5649.

(12) (a) Bao, C.; Lu, R.; Jin, M.; Xue, P.; Tan, C.; Liu, G.; Zhao, Y. *Org. Biomol. Chem.* **2005**, *3*, 2508−2512. (b) Jung, J. H.; Lee, S. J.; Rim, J. A.; Lee, H.; Bae, T.-S.; Lee, S. S.; Shinkai, S. *Chem. Mater.* **2005**, *17*, 459−462.

(13) (a) Kawano, S.; Fujita, N.; Shinkai, S. *Chem. Commun.* **2003**, 1352−1353. (b) Jung, J. H.; Kobayashi, H.; Masuda, M.; Shimizu, T.; Shinkai, S. *J. Am. Chem. Soc.* **2001**, *123*, 8785−8789. (c) Shinkai, S.; Murata, K. *J. Mater. Chem.* **1998**, *8*, 485−495.

10.1021/ol060142j CCC: $33.50

Scheme 1. Synthesis of Tetranitrodibenzocrown Ethers **3** and **4**



gel formation was largely attributed to the appended cholesterol moiety.[12b] This realization prompted the design of two novel crown-ether-based gelators that utilize the host–guest relationship between diquat and dibenzocrown ethers, hydrogen bonding, and London dispersive forces to gel in aromatic solvents at 5.0 wt %. Here, we describe the selective gelation phenomenon exhibited by tetranitrodibenzo-24-crown-8 (**3**) and tetranitrodibenzo-30-crown-10 (**4**) in chlorinated solvents at 3.0 wt % and report on the gel's superstructure by atomic force microscopy (AFM) and scanning electron microscopy (SEM) imaging.

The electron-deficient crown ethers **3** (TNDB24C8) and **4** (TNDB30C10) were prepared in good yields by biphasic nitration ($CH_2Cl_2/HNO_3/H_2SO_4$) of dibenzocrown ethers **1** and **2**, as shown in Scheme 1.[14]

Addition of chloroform to either **3** or **4** (3 wt %) yields a compound with a viscous gel-like morphology (Scheme 1).[15] The gelation process was most efficient at minimum concentrations of 1.5 and 3 w/v % for **3** and **4**, respectively.[16] Comparisons were also made to dibenzocrown ethers **1** and **2** which were found to be inefficient gelators at similar concentrations.

The scope for crown ethers **3** and **4** to gel as a function of solvent was investigated for 15 different solvent systems, and the results are listed in Table 1. The larger crown ether **4** is a very specific gelator, only aggregating in chloroform solution at the tested concentration. Crown ether **3** was less selective, forming a gel in 2-chloroethanol and 1,2-dichloroethane as well as chloroform. This difference in selectivity as well as the fact that neither crowns gel in CH_2Cl_2 at a similar concentration indicate the specific nature of the interactions between the crown ether and the solvent. Interestingly, the smaller crown TNDB18C6 precipitates in all solvents at the concentration tested.

Table 1. Gelation Ability of Crown Ethers **3** and **4** at 3 w/v %[a]

solvent	TNDB24C8**3**	TNDB30C10**4**
chloroform[b]	G	G
dichloromethane	P	P
2-chloroethanol	G	L
1,2-dichloroethane	G	P
p-chlorotoluene	P	P
carbon tetrachloride	P	P
acetone	P	P
benzene	I	P
toluene	P	P
acetonitrile	P	P
methanol	P	P
ethanol	P	P
ethyl acetate	P	P
tetrahydrofuran	P	P
dimethylformamide	L	L

[a] Gelation was assigned after heating **3** or **4** in the respective solvents and monitoring the sample with time upon cooling. The ability to invert the vial without sample movement resulted in the classification of a gel (G). In some cases, incomplete gelation (I) was observed where it appeared that the sample had some gelatenous features but also had liquid properties upon vial inversion. L = liquid; P = precipitate. [b] Deuterated solvent yields a gel as well.

Differential scanning calorimetry (DSC)[17] of gels **3** and **4** in $CHCl_3$ was carried out over the temperature range 173–363 K. Cooling a sample of either gel to <173 K yields a sharp exotherm at $T_{max} = 189$ K ($\Delta H_{av} = 19.0 \pm 1.5$ kJ mol^{-1}) attributable to the spontaneous crystallization of supercooled $CHCl_3$. In essence, the gel form assists in supercooling chloroform to 21 K below its freezing point. Warming the solution results in an endotherm at $T_{max} = 212$ K ($\Delta H = 19.0 \pm 1.5$ kJ mol^{-1}), consistent with the melting of $CHCl_3$ and regelation. Continued heating leads to a second and smaller endotherm with onset at 307 ± 3.0 K in both instances attributable to the liquification of the gel. This is consistent with anecdotal evidence that the gels liquify if hand warmed and regel upon cooling.

Characterization of the superstructure of the gel made with **4** in chloroform was undertaken by atomic force microscopy (AFM).[18] To maintain the integrity of the gel, AFM studies were conducted in an aqueous environment (Figure 1) to preclude any superstructural variation in the gel upon drying.[19] Control experiments using optical microscopy revealed that the gel maintains structure under these conditions. AFM imaging of the gel revealed a soft and easily

---

(14) Duggan, S. A.; Fallon, G.; Langford, S. J.; Lau, V.-L.; Satchell, J. F.; Paddon-Row, M. N. *J. Org. Chem.* **2001**, *66*, 4419–4426.

(15) Tetranitrodibenzo-18-crown-6 was found to be an inefficient gelator because of its low solubility in the solvents tested.

(16) ^{1}H NMR spectroscopic experiments on **4** in $CDCl_3$ showed no significant differences between liquid and gel states for both proton and carbon spectra in the presence of an external standard apart from an expected broadening.

(17) DSC was conducted on a TA Q100 instrument using a ramping method starting at 40 °C with 10 °C/minute.

(18) The application of AFM to measure gel structures is rare, likely because of the complexity of such measurements; however, the visualization of fibrous structures has been reported in ref 11.

(19) Samples were imaged in ultrapure water. This technique was employed to overcome the problem associated with the collapse of the gel once the solvent was removed.

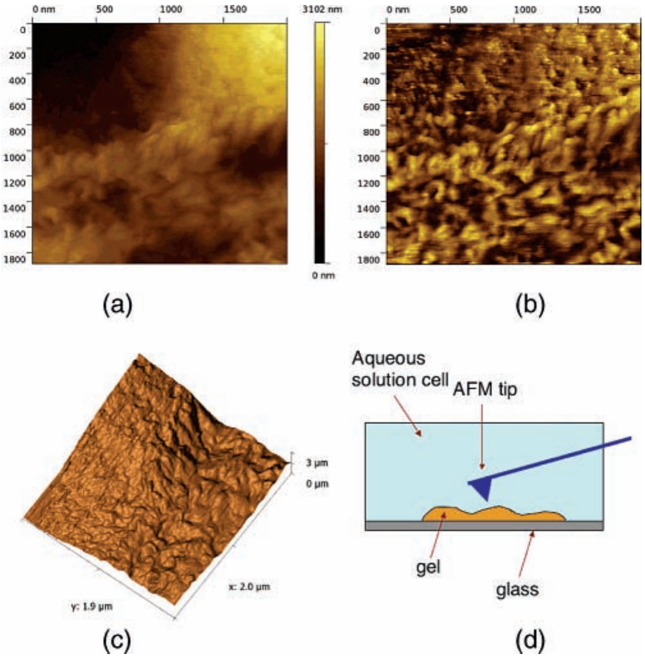


Figure 1. AFM images of the gel formed between **4** and $CHCl_3$. (a) Top view. (b) Local contrast enhanced. (c) 3D-rendered representation. (d) Schematic of AFM solution cell.

deformable structure.[20] There is a slight hysteresis between scanning from left to right and right to left, indicating that even the nanonewton range tapping forces can deform the gel. The flat substrate surface (glass cover slip, surface roughness = 1−10 nm) provides an *in situ* reference (top left-hand corner of Figure 1a). The gel is ordered into elongated domains of approximately 350 nm thickness (Figure 1b, with local contrast enhancement), which are attributable to the exposed parts of intermingled fibers close to the edge of the gel. Despite the softness of the gel, the surface maintained structure upon repeated imaging. Interestingly, the adsorption properties of the gel formed by **3** on glass differ from those of **4** under the same conditions. This is surmised as a difference in stability of each gel as a thin layer.

Scanning electron micrograph (SEM) images of the gels from frozen samples were also obtained, and representative images taken of **3** and **4** are shown in Figure 2.[21] A relatively porous framework was observed in each case which appears to be composed of a well-developed network of fibrils. Further magnification of a sample of **4** revealed the intertwining of some fibrils by each other (Figure 2b). SEM imaging of **3** revealed a less-structured network consistent with the AFM findings obtained for **3**.

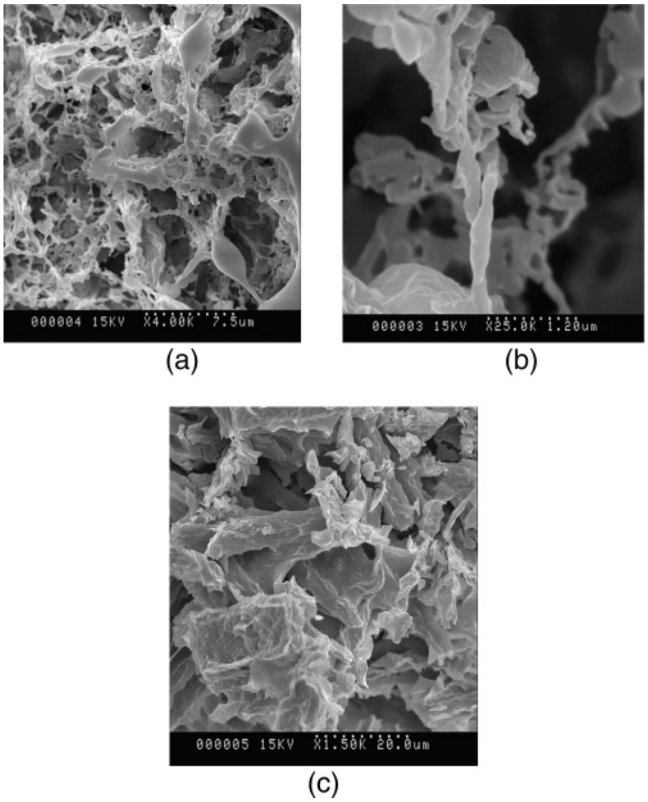


Figure 2. SEM images of freeze-dried gel **4** showing (a) micrometer-scaled fibril network and (b) detail of ribbons that appear to be interwined by each other. (c) SEM image of freeze-dried gel **3**.

In conclusion, we have reported the novel gelation ability of two electron-deficient crown ethers at low wt % of chlorinated solvent. More studies aimed at elucidating the supramolecular structure of the gel and its stability for application are underway.[22] The thermotropic behavior of the gel may find uses as a component of a temperature indicator, for example, in heat-sensitive packaging applications. This work is also being developed at present.

Acknowledgment. This work was supported by the Australian Research Council Grant DP0556313. V.-L.L. wishes to thank the Australian Government for an APRA with which to support this research. We also thank J. Clark of Monash Medical Imaging for SEM images.

Supporting Information Available: AFM and SEM images for TN24C8 **3**. This material is available free of charge via the Internet at http://pubs.acs.org.

OL060142J

---

[20] We used an NT-MDT “NTEGRA” AFM with a 100 μm 3D closed-loop scanner to obtain topography images of gels **3** and **4**. Mikromasch NSC 36 B probes (tip apex radius of ∼10 nm, tip height of ∼15 μm, cantilever length of 90 μm, spring constant of ∼1.75 N/m) were used in low-amplitude (∼20 nm) tapping modes. These conditions allow imaging with tapping forces in the nanonewton range, which is essential to minimize the deformation of the gel upon interaction with the probe. Image processing was performed with WsXM 4.0 (www.nanotec.es) and Gwyddion 1.13 (www.gwyddion.net) freewares.

[21] Images were recorded using a Hitachi S570 SEM operating at 15 kV. Samples prepared by freeze-drying were transferred to a carbon tab which was gold-sputter coated prior to imaging.

[22] Without inviting speculation on the structure of the gel, we have recently described the X-ray structure of **4** from acetonitrile solution. See: Belousoff, M.; Langford, S. J.; Lau, V.-L.; Latter, M. J. *Acta Crystallogr., Sect. E* **2005**, *E61*, 3284−3285.