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Novel host–guest organogels as stabilized by the formation of crown–ammonium pseudo-rotaxane complexes

Shin-ichiro Kawano, Norifumi Fujita and Seiji Shinkai*

Department of Chemistry and Biochemistry, Graduate School of Engineering, Kyushu University, 6-10-1 Hakozaki, Higashi-ku, Fukuoka 812-8581, Japan. E-mail: seijitcm@mbox.nc.kyushu-u.ac.jp

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A dibenzo-24-crown-8 derivative bearing two cholesterol groups is either insoluble in or precipitates from most organic solvents, but its pseudo-rotaxane complex with a diammonium guest acts as a good gelator of aromatic solvents.

Organogels are thermoreversible, viscoelastic materials consisting of low molecular-weight compounds self-assembled into complex three-dimensional networks.[1–9] The aggregation of gelator molecules into fibrous networks is driven by multiple, weak interactions such as dipole–dipole, van der Waals, and hydrogen-bonding interactions.[1–9] Gelators are thus generally classified, according to their driving force for molecular aggregation, into two categories: non-hydrogen bond-based gelators and hydrogen bond-based gelators. Cholesterol derivatives[2] are examples of the former category, while amide-,[3] urea-,[4] and saccharide-based[5] compounds fall into the latter category. Basically, the gel architecture is constructed by assembling low molecular-weight compounds and, therefore, strongly reflects the molecular shape of unit components. This means that if one can change the structure of the unit components reversibly, it leads to the reversible control of gelation properties. As far as we are aware, such successful examples are very limited.[10,11] We previously synthesized a few crown-based gelators bearing two cholesterol moieties.[12] These gelators tend to adopt a folded conformation due to the efficient intramolecular cholesterol–cholesterol interaction.[12] On the other hand, Stoddart and others have demonstrated that alkylammonium ions can thread the larger crown rings.[13] Judging from the complexation mode, the complexes *cannot* adopt the folded conformation: that is, one can expect that the folded conformation would be converted to the extended one upon the guest inclusion. With these ideas in mind, we synthesized gelator **1** consisting of one dibenzo-24-crown-8 moiety and two cholesterol moieties and evaluated whether guests **2** and **3** really induce a significant change in the superstructures in the organogel phase (the structures are shown in Scheme 1). Compound **4** was used as a non-binding reference guest.

Compound **1** was synthesized by the reaction of diaminodibenzo-24-crown-8 and cholesteryl chloroformate. The product is a mixture of *trans* : *cis* = 5 : 4 (confirmed by ^{1}H NMR spectroscopy and HPLC analysis). The purity was ascertained by HPLC analysis and elemental analysis.

The stoichiometry of the complex and the guest-induced conformational change were evaluated using a ^{1}H NMR spectroscopic method in the sol phase [benzene-d_6 : MeCN-d_3 = 5 : 1 (v/v)], because no useful information could be obtained in the gel phase on account of the serious peak broadening. The concentration of this sol solution resulted in the gel, suggesting that the structure formed in the gel phase reflects that formed in the sol phase. The ^{1}H NMR spectrum of a mixture of **1** (2.0 mmol dm^{-3}) gave three aromatic peaks at 6.71, 7.00 and 7.25 ppm (protons C, B and A, respectively; for the assignment see the structure in Fig. 1) and one NH peak at 7.02 ppm. When **3** (1.0 mmol dm^{-3}) was added, all peaks shifted to lower magnetic field (6.74, 7.06 and 7.30 ppm for the aromatic peaks and 7.30 ppm for the NH peak). This observation suggests that when **3** threads the crown ring in **1**, the protons move from the shielded region to the deshielded region. This change is fully commensurate with an expected conformational change from the folded one to the extended one (Fig. 2).[14] In Fig. 1, a chemical shift change for proton B is plotted against the molar ratio of **3** : **1**. A clear breakpoint appears at [**3**]/[**1**] = 0.5, indicating that **3** threads two crown rings of **1** forming a pseudo-rotaxane structure.

The gelation ability of **1** was tested for 13 different solvents with 19 mmol dm^{-3} of **1**. The results are summarized in Table 1. Compound **1** shows only 3 "G" results (for cyclohexane, methylcyclohexane and diphenyl ether) and 9 "P" or "I" results (for abbreviations see footnote *b* in Table 1), indicating that the gelation ability of **1** is not so high because of the poor solubility (mainly in polar solvents). Very interestingly, when guest **3** was added to aromatic solutions (benzene, toluene and *p*-xylene) containing **1** (19 mmol dm^{-3}), they were transformed into the gels (Table 1). As far as we are aware, this is a rare example of the organogel being stabilized by a host–guest-type interaction.[12,15] We confirmed that the sol–gel phase-transition temperature (T_{gel}) is enhanced by the addition of guests **2** and **3**.

As shown in Fig. 3, the T_{gel} values for **1** obtained in cyclohexane rise monotonously with increasing **2** concentration. This result suggests that the extended conformation is more advantageous than the folded conformation to the

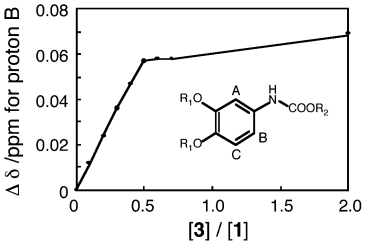


Fig. 1 Plot of $\Delta\delta$ for proton B against [**3**]/[**1**]; 25 °C, [**1**] = 2.0 mmol dm^{-3} (constant), benzene-d_6 : MeCN-d_3 = 5 : 1 (v/v), R_1: crown ether moiety, R_2: cholesteryl moiety.

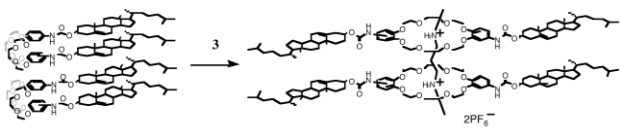
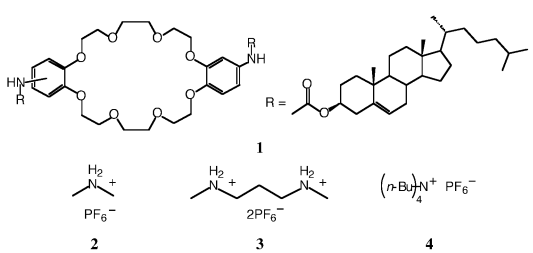


Fig. 2 Conformational change induced by complexation of **3** proposed on the basis of the spectral results.



Scheme 1

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Table 1 Gelation properties of compound **1** in the absence and the presence of **2**, **3** or **4** at 25 °C[a]

	State[b]			
Solvent	**1**	**1** + **2**	**1** + **3**	**1** + **4**
Cyclohexane	G[c]	G[c]	G[c]	
Methylcyclohexane	G[c]	G[c]	G[c]	
Benzene	PG	P	**G**[c]	P
Toluene	P	P	**G**[c]	P
p-Xylene	P	P	**G**[c]	P
Diphenyl ether	G	G	G	
Hexane	I	I	I	
Water	I	I	I	
Other solvents[d]	P	P	P	

[a] Concentration of [**1**] is 19 mmol dm^{-3} (25 g dm^{-3}), [**2** or **4**] = 19 mmol dm^{-3} and [**3**] = 9.6 mmol dm^{-3}. [b] G: gel, PG: partial gel, P: precipitation, I: insoluble when heated. [c] Gel at [**1**] = 7.7 mmol dm^{-3} (10 g dm^{-3}), [**2** or **4**] = 7.7 mmol dm^{-3} and [**3**] = 3.8 mmol dm^{-3}. [d] Acetonitrile, 1-butanol, DMF, DMSO and methanol all gave P results in these columns.

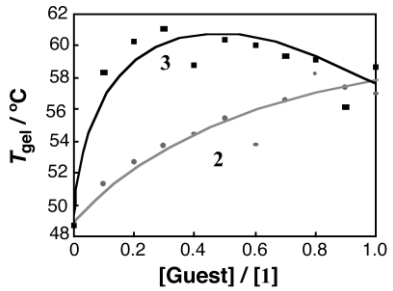

Fig. 3 Plots of T_{gel} *vs.* [guest]/[**1**] in cyclohexane; [**1**] = 23 mmol dm^{-3}.

formation of one-dimensional aggregates, which is considered to be a prerequisite for the gel formation.[5] A plot of T_{gel} *vs.* [**3**]/[**1**] gives a maximum around [**3**]/[**1**] = 0.4–0.5. This maximal molar ratio is complementary to the stoichiometry obtained from the ^{1}H NMR titration (Fig. 1) and implies that the pseudo-rotaxane complex with the 1 : 2 stoichiometry is particularly favourable to the gel formation. On the other hand, the addition of **4** (quaternary ammonium salt) scarcely affects the T_{gel}, indicating that the gel stabilization effect observed for **2** and **3** is due to the crown–ammonium hydrogen-bonding interaction.

To obtain visual images of the superstructures which may reflect the guest-induced conformational change, we took the SEM pictures of the xerogels prepared from the frozen samples of the benzene sols and gels (Fig. 4). The benzene sol of **1** (3.8 mmol dm^{-3}) gave microcrystals with a structure like a dahlia flower (Fig. 4a). When the concentration was enhanced up to 7.7 mmol dm^{-3}, the phase became a partial gel and the xerogel showed a sheet-like structure (Fig. 4c). The results suggest that **1** *a priori* tends to aggregate into the two-dimensional assembly. In contrast, the benzene sol containing **1** (3.8 mmol dm^{-3}) and **3** (1.9 mmol dm^{-3}) resulted in a fibrous structure with 40–250 nm diameters (Fig. 4b). This picture indicates that in the presence of guest **3**, the growth of the one-dimensional aggregate is already initiated even in the sol phase. As expected, the well-developed network structure of the fibrils with 50–250 nm diameters was recognized in the xerogel obtained from the benzene gel containing **1** (7.7 mmol dm^{-3}) and **3** (3.8 mmol dm^{-3}).

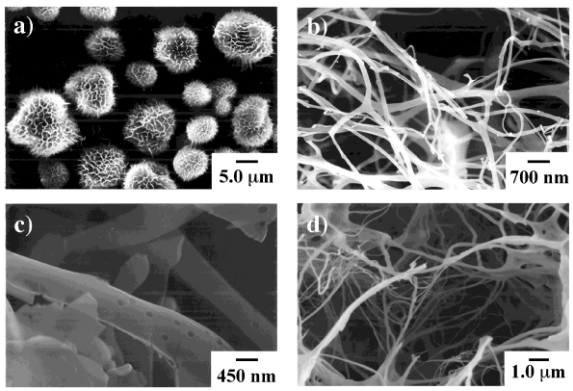

Fig. 4 SEM images of xerogels prepared from (a) benzene sol of **1** (3.8 mmol dm^{-3}), (b) benzene sol of **1** (3.8 mmol dm^{-3}) + **3** (1.9 mmol dm^{-3}), (c) benzene partial gel of **1** (7.7 mmol dm^{-3}) and (d) benzene gel of **1** (7.7 mmol dm^{-3}) + **3** (3.8 mmol dm^{-3}).

In conclusion, the present paper demonstrates that the pseudo-rotaxane formation between the host gelator and the guest additive changes the host gelator conformation, which eventually enhances the gelation ability. To the best of our knowledge, this is the first example of gelation ability being efficiently controlled by precise molecular recognition. This novel finding that the phase transition is induced by the host–guest interaction will be applicable to drug delivery systems, collection of waste materials and pollutants, and recovery of precious bio-active compounds, *etc.*

Notes and references

1 For recent reviews see P. Terech and R. G. Weiss, *Chem. Rev.*, 1997, **97**, 3133; J. H. van Esch and B. L. Feringa, *Angew. Chem., Int. Ed.*, 2000, **39**, 2263; O. Gronwald and S. Shinkai, *Chem. Eur. J.*, 2001, **7**, 4328 and references therein.

2 P. Terech, I. Furman and R. G. Weiss, *J. Phys. Chem.*, 1995, **99**, 9558; K. Murata, M. Aoki, T. Suzuki, T. Harada, H. Kawabata, T. Komori, F. Ohseto, K. Ueda and S. Shinkai, *J. Am. Chem. Soc.*, 1994, **116**, 6664; T. D. James, K. Murata, T. Harada, K. Ueda and S. Shinkai, *Chem. Lett.*, 1994, 273.

3 K. Hanabusa, K. Okui, K. Karaki and H. Shirai, *J. Chem. Soc., Chem. Commun.*, 1992, 1371; K. Hanabusa, Y. Yamada, M. Kimura and H. Shirai, *Angew. Chem., Int. Ed.*, 1996, **35**, 1949; K. Hanabusa, A. Kawakami, M. Kimura and H. Shirai, *Chem. Lett.*, 1997, 191.

4 J. van Esch, F. Schoonbeek, M. de Loos, H. Kooijman, A. L. Spek, R. M. Kellogg and B. L. Feringa, *Chem. Eur. J.*, 1999, **5**, 937.

5 K. Yoza, Y. Ono, K. Yoshihara, T. Akao, H. Shinmori, M. Takeuchi, S. Shinkai and D. N. Reinhoudt, *Chem. Commun.*, 1998, 907; K. Yoza, N. Amanokura, Y. Ono, T. Akao, H. Shinmori, M. Takeuchi, S. Shinkai and D. N. Reinhoudt, *Chem. Eur. J.*, 1999, **5**, 2722; R. Luboradzki, O. Gronwald, M. Ikeda, S. Shinkai and D. N. Reinhoudt, *Tetrahedron*, 2000, **56**, 8697.

6 M. de Loos, J. van Esch, I. Stokroos, R. M. Kellogg and B. L. Feringa, *J. Am. Chem. Soc.*, 1997, **119**, 12675; N. Tamaoki, S. Shimada, Y. Okada, A. Belaissaoui, G. Kruk, K. Yase and H. Matsuda, *Langmuir*, 2000, **16**, 7545.

7 H. Kobayashi, M. Amaike, J. H. Jung, A. Friggeri, S. Shinkai and D. N. Reinhoudt, *Chem. Commun.*, 2001, 1038.

8 S. W. Jeong, K. Murata and S. Shinkai, *Supramol. Sci.*, 1996, **3**, 83.

9 T. Ishi-i, Y. Ono and S. Shinkai, *Chem. Lett.*, 2000, 808; J.-E. Sohna and F. Fages, *Chem. Commun.*, 1997, 327.

10 M. de Loos, J. van Esch, R. M. Kellog and B. L. Feringa, *Angew. Chem., Int. Ed.*, 2001, **40**, 613.

11 S. A. Ahmed, X. Sallenave, F. Fages, G. Mieden-Gundert, W. M. Müller, U. Müller, F. Vögtle and J.-L. Pozzo, *Langmuir*, 2002, **18**, 7096; L. Frkanec, M. Jokic, J. Makarevi, K. Wolsperger and M. Zinic, *J. Am. Chem. Soc.*, 2002, **124**, 9716; H. Kobayashi, K. Koumoto, J. H. Jung and S. Shinkai, *J. Chem. Soc., Perkin Trans. 2*, 2002, 1930.

12 J. H. Jung, Y. Ono, K. Sakurai, M. Sano and S. Shinkai, *J. Am. Chem. Soc.*, 2000, **122**, 8648; J. H. Jung, H. Kobayashi, M. Masuda, T. Shimizu and S. Shinkai, *J. Am. Chem. Soc.*, 2001, **123**, 8785.

13 R. Ashton, E. J. T. Chrystal, P. T. Glink, S. Menzer, C. Schiavo, N. Spencer, J. F. Stoddart, P. A. Tasker, A. J. P. White and D. J. Williams, *Chem. Eur. J.*, 1996, **6**, 709; P. R. Ashton, M. C. T. Fyfe, P. T. Glink, S. Menzer, J. F. Stoddart, A. J. P. White and D. J. Williams, *J. Am. Chem. Soc.*, 1997, **119**, 12514.

14 In the XRD analyses, the xerogel of **1** gave a peak for 3.3 nm whereas the **1** + **3** complex gave a new peak for 4.4 nm with a decrease in the 3.3 nm peak. The molecular sizes of the folded and extended structures were estimated to lie 2.6 and 5.2 nm, respectively, from the molecular models.

15 H. Engelkamp, S. Middlebeek and R. J. M. Nolte, *Science*, 1999, **284**, 785.