Study of an Organogelator by Diffusion-Ordered NMR Spectroscopy

2 AUTHORS:

Murali Dama
University of Leipzig
10 PUBLICATIONS **30** CITATIONS

SEE PROFILE

Stefan Berger
University of Leipzig
**289** PUBLICATIONS **4,658** CITATIONS

SEE PROFILE

Article

Study of an Organogelator by Diffusion-Ordered NMR Spectroscopy

Murali Dama and Stefan Berger*

Institute of Analytical Chemistry, University of Leipzig, Johannisallee 29, 04103 Leipzig, Germany

ABSTRACT: The low-molecular weight organogelator 2,3-di-*n*-decyloxyanthracene was synthezised and dissolved in dimethyl sulfoxide. With diffusion-ordered NMR spectroscopy, the temperature dependence of the diffusion coefficients was measured and a clear hysteresis of the gelation was observed between 320 and 330 K. This hysteresis was interpreted with respect to different entanglement behavior on heating and cooling. No alignment of the gelator with respect to the magnetic field was found despite its 14 π-electrons.
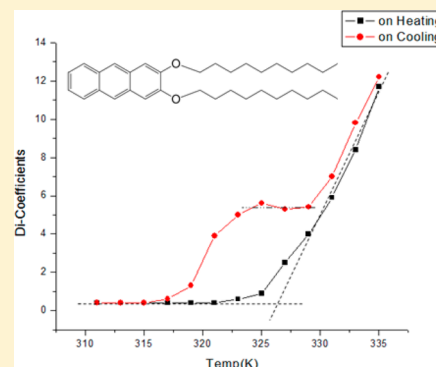
■ INTRODUCTION

Organogels have recently attracted great research interest because of their potential applications in several research areas such as optoelectronics, sensing, biomedicine, and engineered fuels.[1] Low-molecular weight organogelators (LMOGs) are molecules whose molecular mass is less than 3000 g/mol and will form corresponding organogels in a wide variety of organic solvents.[2−5] Several noncovalent interactions such as electrostatic, dipole−dipole, hydrogen bonding, and π−π interactions often involve the self-organization of these LMOGs into an entangled supramolecular three-dimensional fibrous network in organic solvents.[6] For recent reviews on supramolecular polymer gels, please see the literature.[7−11] Only a small amount of LMOGs is needed to immobilize a considerable amount of a solvent into a gel. An organogel is usually prepared by heating the gelator molecule in an appropriate solvent until the solution becomes isotropic. Subsequently, the mixture is cooled to room temperature; the molecules then start to self-assemble into fibrous aggregates, networks, eventually yielding a gel.[12] This gelation occurs at a certain critical concentration depending on the gelator molecule and the solvent. This gelation process is thermo-reversible. By measuring ^{1}H NMR spectra of these organogels at different temperatures, one can observe the gelation of the organogels. However, it is not possible to find the exact gelation point and a probable hysteresis of the process through normal ^{1}H NMR spectroscopy.

Diffusion NMR has been applied in a variety of studies involving organic, inorganic, and organometallic chemistry, including the problems related to the characterization of molecules and complexes with respect to size and shape. In addition, it has also been used for the investigation of intermolecular interactions.[13−17] Pulsed field-gradient (PFG) NMR spectroscopy has become the method of choice for measuring diffusion in solutions in both chemical and biological systems.[19,20] In principle, the diffusion coefficient of a certain

molecular species under given conditions (for example, solvent and temperature) depends on its "effective" molecular weight, size, and shape.

Therefore, it is evident that diffusion can be used to map intermolecular interactions that play an important role in molecular recognition processes essential for supramolecular and combinatorial chemistry.[21−23]

Previously, there have been studies of gelation behavior of biomolecules by using a variety of NMR methods, including relaxation and diffusion.[24] For the study of a gelatin gel in H_2O, we observed[18] a clear hysteresis. For designed organogelator systems, PFG NMR has been used to study the gelling agent *trans*-(1R,2R)-bis(undecylcarbonylamino)cyclohexane (TCH)/toluene system by observing diffusion coefficients, but we did not observe a significant hysteresis as in the case of gelatin.[25] There is therefore a need for more studies of organogels to determine their behavior in solution.

Here we are studying the 2,3-di-*n*-decyloxyanthracene (DDOA) organogelator in a dimethyl sulfoxide (DMSO) solution through diffusion-ordered NMR spectroscopy (DOSY). DDOA forms thermo-reversible gels with alcohols,[26] amines, and alkanes.[27] The DDOA gelator can form an organogel at low concentrations ($\sim$5 × 10$^{−3}$ mol/L) by binding a considerable number of solvent molecules. van der Waals and dipole−dipole interactions are the driving forces for gel formation in the case of DDOA in nonprotic solvents.[27] DDOA has three fused aromatic rings (anthracene structure) and two long chain alkoxy substituents in the *ortho* position located at positions 2 and 3 (Figure 1).

One additional reason to undertake this work was the hope that the 14 π-electrons of the anthracene unit would be sufficient to introduce a very small degree of alignment with
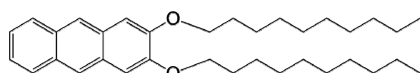
Figure 1. Chemical formula for the organogelator molecule DDOA.

respect to the magnetic field. This should make the observation of residual dipolar couplings[28] possible, especially because a deuterium quadrupolar splitting has been observed for anthracene[29] and birefringence was reported for DDOA.[30]

■ EXPERIMENTAL SECTION

DDOA was synthesized as reported elsewhere,[27] and the DDOA organogel was prepared in a DMSO-d_6 solution at a concentration of 0.5% (w/w). For all NMR experiments, a Bruker DRX 400 spectrometer equipped with a BBO probe was used. A reference ^{1}H NMR spectrum was acquired using 32K time domain data points with a spectral width of 10 ppm. The free induction decays (FIDs) were weighted with an exponential function of lb = 0.3 Hz, Fourier-transformed, and baseline corrected.

First, we observed the gelation process manually by heating the DDOA/DMSO mixture to 335 K and then cooling it to 298 K. We found that it formed an isotropic liquid at 335 K, and the gel forms between 315 and 325 K. Then we recorded ^{1}H NMR spectra of the DDOA/DMSO gelation system from 335 to 311 K to observe the gelation point. We found that the proton integrals decrease with a decrease in temperature because of the formation of a gel as shown in Figure 2 and in
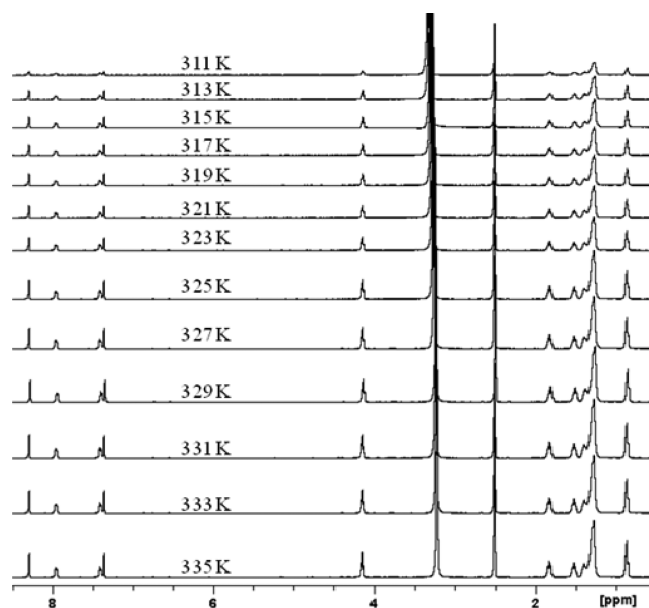

Figure 2. Comparison of ^{1}H NMR spectra of DDOA in DMSO in the liquid state 335 K (bottom) to the gel state at 311 K (top) with a 2 K variation for each spectrum.

Tables 1 and 2. However, it is difficult to find the exact gelation point and to determine the behavior of the DDOA gelator molecule based on these normal ^{1}H NMR spectra. Therefore, we measured DOSY spectra for the DDOA/DMSO gel system to gather more accurate gelation information.

For diffusion measurements, the stimulated echo sequence[31] with a longitudinal eddy current delay (LED) of 5 ms was used. A spectral width of 10 ppm was used in the proton dimension

Table 1. ^{1}H NMR Intensities of DDOA in a DMSO-d_6 Solution

chemical shift (δ)	intensity at 335 K
8.25	2H
7.98	2H
7.45	2H
7.23	2H
4.20	2H
1.83	4H
1.37	4H
1.25−1.20	24H
0.88	6H

Table 2. ^{1}H NMR Intensities versus Temperature for DDOA in a DMSO-d_6 Solution at δ 4.20

temp (K)	intensity change at δ 4.20 (DDOA)
335	1.00
333	1.00
331	1.05
329	0.85
327	0.79
325	0.76
323	0.42
321	0.42
319	0.40
317	0.36
315	0.31
313	0.20
311	0.18

of the diffusion experiments; 32K data points were recorded in four transients with a recycle delay of 5 s. The FIDs were multiplied with an exponential window, Fourier-transformed, and baseline-corrected. A gradient pulse ($\delta \times 0.5$) of 1 ms was selected for our experiments, and the diffusion time (Δ) was varied from 15 to 30 ms depending on the temperature for diffusion encoding. The gradient ramp was calculated from 0.844 to 40.112 linearly in 16 steps.

Equation 1 was used to determine the diffusion coefficient D from the measured signal integral I:[21]

$$I = I_0 \exp\left[-D(\gamma g \delta)^2 \left(\Delta - \frac{\delta}{4} - \frac{\tau}{2}\right)\right] \tag{1}$$

where I_0 represents the starting signal intensity, D is the desired diffusion coefficient, γ is the gyromagnetic ratio of protons, and g represents the gradient strength. δ is the length of the pulsed field gradients and Δ their distance in time. The term $\delta/4$ is due to the sine shape of the applied gradients, and τ is the eddy current delay.

The instrument temperature was varied in steps of 2 K in the range between 311 and 335 K. For each experiment, an equilibration period of 5 min was allowed after stabilization of the temperature.

For acquisition, TOPSPIN version 1.3 (Bruker) was used and TOPSPIN version 3.0 was used for processing and integration of the spectra. The obtained two-dimensional DOSY spectra (Figure 3) were divided into 16 one-dimensional (1D) spectra, and the first 1D spectrum was integrated. The integration regions were exported and used for the 15 other 1D spectra. For determination of the diffusion coefficients, Origin version 6.1 was used for nonlinear regression.
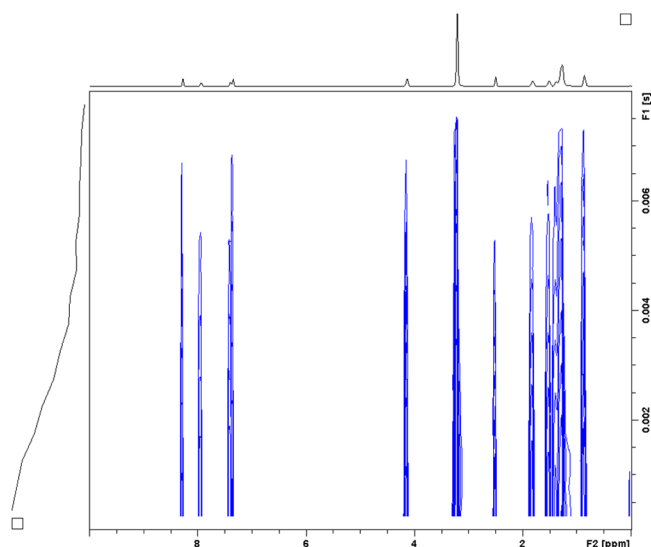
Figure 3. Unprocessed DOSY spectrum of DDOA in DMSO-d_6 at 335 K.

RESULTS AND DISCUSSION

The obtained diffusion coefficients are plotted in Figure 4. Upon cooling this DDOA/DMSO gelation system from its
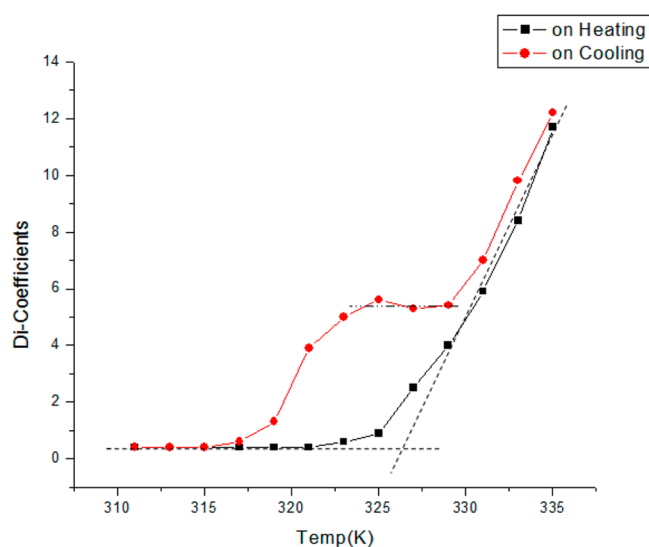

Figure 4. Temperature dependence of the diffusion coefficient D for the cooling (red) and heating (black) regime obtained by fitting the integrals of the more shielded aliphatic signals of DDOA to eq 1.

liquid state (335 K), we observed that the diffusion coefficients decreased with temperature until it reached 329 K (Figure 4). Then, interestingly, these diffusion coefficients were almost stable until the temperature 325 K, and after that, the diffusion coefficients decreased again with temperature. Therefore, at 329 K, the gelator DDOA molecules start forming a gel through noncovalent interactions. Thus, the gelation point is 329 K on cooling for the present DDOA/DMSO gelation system.

Upon heating the DDOA gel from 311 K, we observed that the gel is stable up to 321 K, and there was no change in diffusion coefficients. With further heating, the diffusion coefficients increased slowly as shown in Figure 4. One can clearly see two types of slopes in the heating curve, and they are interacting nearly at 326 K. Therefore, from Figure 4, one can observe that the gelation point of the DDOA/DMSO gelation system is nearly 326 K upon being heated. The heating regime of the DDOA/DMSO gelation system is different from the cooling regime. Figure 4 shows a clear hysteresis, and it reveals the behavior of the DDOA/DMSO gelation system as expected.

However, all attempts to detect an alignment of the gel and hence an alignment of dissolved analytes by measuring residual dipolar couplings[28] in strong magnetic fields from 9.4 to 18.8 T have been unsuccessful.

Opposite to the case for gelatin,[18] but similar to the case for our previously investigated TCH gelator,[25] the diffusion coefficients do not increase on further cooling after having reached the gelation point. This behavior is consistent with the monodisperse solution of the designed gelator.

Instead of measuring the diffusion coefficients, one may also calculate the ratio of analyte and solvent integrals and inspect their temperature dependence, which leads to a gelation characteristic; however, it is not as accurate as the diffusion data.

Our molecular interpretation of the hysteresis picture is as follows. Upon being heated, the molecules stay entangled unless at ~326 K enough energy is available to introduce free diffusion. Once the molecules cool, however, the entanglement has already set in at 329 K and the diffusion coefficients remain stable at a medium level, indicating a rather soft gel, before this suddenly solidifies below 320 K. This transition region between 320 and 330 K is probably most interesting for studying the behavior of analytes dissolved in the gel for different sorts of switching processes. We also obtained similar types of hysteresis but no alignment in the magnetic field for other organogels such as the 1-methyl-2,4-bis(N'-octadecaneureido)-benzene (MBOB)[32] gelator in toluene, the oligo(p-phenyl-enevinylene) derivative (OPV1)[33] in toluene, and the triethoxysilane-appended bis(urea)[34] gelator in toluene. Therefore, we expect that this method could be applied to other organogel systems to determine their exact gelation points and their hysteresis using DOSY.

CONCLUSION

In conclusion, we have shown in this work that the LMOG molecule DDOA forms thermo-reversible gels in DMSO that can be well characterized by DOSY but does not give an alignment in the magnetic field.

AUTHOR INFORMATION

Corresponding Author
*Institute of Analytical Chemistry, University of Leipzig, Johannisallee 29, D-04103 Leipzig, Germany. E-mail: stberger@rz.uni-leipzig.de. Fax: +49 341 9736115. Phone: +49 341 9736101.

Notes
The authors declare no competing financial interest.

ACKNOWLEDGMENTS

ABBREVIATIONS

LMOGs, low-molecular weight organogelators; DOSY, diffusion-ordered NMR spectroscopy; DDOA, 2,3-di-n-decyloxyan-thracene; DMSO, dimethyl sulfoxide

■ REFERENCES

(1) Sahoo, S.; Kumar, N.; Bhattacharya, C.; Sagiri, S. S.; Jain, K.; Pal, K.; Ray, S. S.; Nayak, B. Organogels: Properties and Applications in Drug Delivery. *Des. Monomers Polym.* **2011**, *14*, 95−108.

(2) Abdallah, D. J.; Weiss, R. G. Organogels and Low Molecular Mass Organic Gelators. *Adv. Mater.* **2000**, *12*, 1237−1247.

(3) Van Esch, H. J.; Feringa, B. L. New Functional Materials Based on Self-Assembling Organogels: From Serendipity towards Design. *Angew. Chem., Int. Ed.* **2000**, *39*, 2263−2266.

(4) Terech, P.; Weiss, R. G. Low Molecular Mass Gelators of Organic Liquids and the Properties of Their Gels. *Chem. Rev.* **1997**, *97*, 3133−3160.

(5) Bieser, A. M.; Tiller, J. C. Structure and Properties of an Exceptional Low Molecular Weight Hydrogelator. *J. Phys. Chem. B* **2007**, *111*, 13180−13187.

(6) Lehn, J. M.; Atwood, J. L.; Davies, J. E. D.; MacNicol, D. D.; Vögtle, F. *Comprehensive Supramolecular Chemistry*; Pergamon: New York, 1996.

(7) Yan, X.; Xu, D.; Chi, X.; Chen, J.; Dong, S.; Ding, X.; Yu, Y.; Huang, F. A Multiresponsive, Shape-Persistent, and Elastic Supramolecular Polymer Network Gel Constructed by Orthogonal Self Assembly. *Adv. Mater.* **2012**, *24*, 362−369.

(8) Dong, S.; Zheng, B.; Xu, D.; Yan, X.; Zhang, M.; Huang, F. A Crown Ether Appended Super Gelator with Multiple Stimulus Responsiveness. *Adv. Mater.* **2012**, *24*, 3191−3195.

(9) Yan, X.; Zhou, M.; Chen, J.; Chi, X.; Dong, S.; Zhang, M.; Ding, X.; Yu, Y.; Shao, S.; Huang, F. Supramolecular Polymer Nanofibers via Electrospinning of a Heteroditopic Monomer. *Chem. Commun.* **2011**, *47*, 7086−7088.

(10) Zheng, B.; Wang, F.; Dong, S.; Huang, F. Supramolecular Polymers Constructed by Crown Ether-Based Molecular Recognition. *Chem. Soc. Rev.* **2012**, *41*, 1621−1636.

(11) Yan, X.; Wang, F.; Zheng, B.; Huang, F. Stimuli-Responsive Supramolecular Polymeric Materials. *Chem. Soc. Rev.* **2012**, *41*, 6042−6065.

(12) Hench, L. L.; West, J. K. The Sol-Gel Process. *Chem. Rev.* **1990**, *90*, 33−72.

(13) Morris, G. A. Diffusion-Ordered Spectroscopy (DOSY). *Encycl. Nucl. Magn. Reson.* **2002**, *9*, 35−44.

(14) Morris, G. A.; Barjat, H. High Resolution Diffusion Ordered Spectroscopy. *Anal. Spectrosc. Libr.* **1997**, *8*, 209−226.

(15) Pregosin, P. S.; Kumar, P. G. A.; Fernandez, I. Pulsed Gradient Spin−Echo (PGSE) Diffusion and ^{1}H, ^{19}F Heteronuclear Overhauser Spectroscopy (HOESY) NMR Methods in Inorganic and Organometallic Chemistry: Something Old and Something New. *Chem. Rev.* **2005**, *105*, 2977−2998.

(16) Pregosin, P. S.; Martinez-Viviente, E.; Kumar, P. G. A. Diffusion and NOE NMR Spectroscopy. Applications to Problems Related to Coordination Chemistry and Homogeneous Catalysis. *Dalton Trans.* **2003**, *21*, 4007−4014.

(17) Brand, T.; Cabrita, E. J.; Berger, S. Intermolecular Interaction As Investigated by NOE and Diffusion Studies. *Prog. Nucl. Magn. Reson. Spectrosc.* **2005**, *46*, 159−196.

(18) Brand, T.; Richter, S.; Berger, S. Diffusion NMR as a New Method for the Determination of the Gel Point of Gelatin. *J. Phys. Chem. B* **2006**, *110*, 15853−15857.

(19) Cohen, Y.; Avram, L.; Frish, L. Diffusion NMR Spectroscopy in Supramolecular and Combinatorial Chemistry: An Old Parameter—New Insights. *Angew. Chem., Int. Ed.* **2005**, *44*, 520−554.

(20) Stejskal, O. E.; Tanner, J. E. Spin Diffusion Measurements: Spin Echoes in the Presence of a Time-Dependent Field Gradient. *J. Chem. Phys.* **1965**, *42*, 288−292.

(21) (a) Lehn, J. M. *Supramolecular Chemistry Concepts and Perspectives*; VCH: Weinheim, Germany, 1995. (b) Steed, J. W.; Atwood, J. L. *Supramolecular Chemistry*; Wiley: New York, 2000.

(22) (a) Atwood, J. L.; Davis, J. E. D.; MacNicol, D. D.; Vögtle, F.; Lehn, J. M. *Comprehensive Supramolecular Chemistry*; Pergamon: Oxford, U.K., 1996; pp 1−10. (b) Chakravarti, A. A Compelling Genetic Hypothesis for a Complex Disease: *PRODH2/DGCR6* Variation Leads to Schizophrenia Susceptibility. *Proc. Natl. Acad. Sci. U.S.A.* **2002**, *99*, 4755−4756.

(23) Bannwarth, W.; Felder, E. *Combinatorial Chemistry: A Practical Approach*; Wiley-VCH: Weinheim, Germany, 2000.

(24) Shapiro, Y. E. Structure and Dynamics of Hydrogels and Organogels: An NMR Spectroscopy Approach. *Prog. Polym. Sci.* **2011**, *36*, 1184−1253.

(25) Brand, T.; Nolis, P.; Richter, S.; Berger, S. NMR Study of the Gelation of a Designed Gelator. *Magn. Reson. Chem.* **2008**, *46*, 545−549.

(26) Brotin, T.; Untermöhlen, R.; Fages, F.; Bouas-Laurent, H.; Desvergene, J. P. A Novel Small Molecular Luminescent Gelling Agent for Alcohols. *J. Chem. Soc., Chem. Commun.* **1991**, *6*, 416−418.

(27) Pozzo, J. L.; Clavier, G. M.; Colomes, M.; Laurent, H. B. Different Synthetic Routes towards Efficient Organogelators: 2,3-Substituted Anthracenes. *Tetrahedron* **1997**, *53*, 6377−6390.

(28) Trigo-Mourino, P.; Navarro-Vázquez, A.; Ying, J.; Gil, R. R.; Bax, A. Structural Discrimination in Small Molecules by Accurate Measurement of Long-Range Proton−Carbon NMR Residual Dipolar Couplings. *Angew. Chem., Int. Ed.* **2011**, *50*, 7576−7580.

(29) Lohman, J. A. B.; MacLean, C. Alignment Effects on High Resolution NMR Spectra, Induced by the Magnetic Field. *Chem. Phys.* **1978**, *35*, 269−274.

(30) Shklyarevskiy, I. O.; Jonkheijm, P.; Christianen, P. C. M.; Schenning, A. P. H. J.; Del Guerzo, A.; Desvergne, J. P.; Meijer, E. W.; Maan, J. C. Magnetic Alignment of Self-Assembled Anthracene Organogel Fibers. *Langmuir* **2005**, *21*, 2108−2112.

(31) Wu, D.; Chen, A.; Johnson, C. S., Jr. An Improved Diffusion-Ordered Spectroscopy Experiment Incorporating Bipolar-Gradient Pulses. *J. Magn. Reson., Ser. A* **1995**, *115*, 260−264.

(32) Xiong, Y.; Liu, Q.; Wang, H.; Yang, Y. Self-Assembly of a Dialkylurea Gelator in Organic Solvents in the Presence of Centrifugal and Shearing Forces. *J. Colloid Interface Sci.* **2008**, *318*, 496−500.

(33) Ajayaghosh, A.; George, J. S. First Phenylenevinylene Based Organogels: Self-Assembled Nanostructures via Cooperative Hydrogen Bonding and π-Stacking. *J. Am. Chem. Soc.* **2001**, *123*, 5148−5149.

(34) Piepenbrock, M. M.; Clarke, N.; Foster, A. J.; Steed, W. J. Anion Tuning and Polymer Templating in a Simple Low Molecular Weight Organogelator. *Chem. Commun.* **2011**, *47*, 2095−2097.