A New Class of Selective Low-Molecular-Weight Gelators Based on Salts of Diaminotriazinecarboxylic Acids

Olivier Lebel,[†] Marie-Ève Perron,[†] Thierry Maris,[†] Sylvia F. Zalzal,[‡] Antonio Nanci,[‡] and James D. Wuest*[,†]

Département de Chimie, Université de Montréal, Montréal, Québec H3C 3J7, Canada, and Laboratoire de Recherche sur les Tissus Calcifiés et Biomatériaux, Faculté de Médecine Dentaire, Université de Montréal, Montréal, Québec H3C 3J7, Canada

Received January 9, 2006. Revised Manuscript Received May 14, 2006

New low-molecular-weight gelators can be discovered by an approach that integrates classical methods for identifying potential gelators with strategies recently developed by crystal engineers to build porous molecular networks. This hybrid approach has yielded a potent new class of selective gelators based on salts of 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylic acids. These compounds lack the high degree of conformational flexibility and long alkyl chains typical of classical gelators, and Na^+ and DMSO play specific roles in the mechanism of gelation. Scanning electron microscopy and atomic force microscopy showed that the resulting gels consist of elemental nanofibers that are approximately 30−100 nm in width, and X-ray diffraction yielded the structure of needle-shaped crystals of a gelator obtained directly from its gel. The crystals are constructed from bilayers, with the hydrophobic aryl groups of the gelators interacting intermolecularly to form the core of the bilayers and polar triazinecarboxylate headgroups aligned on the surface. The polar surfaces then stack in a process directed by the formation by multiple intermolecular hydrogen bonds and chelation of Na^+. The hybrid approach that led to the discovery of these gels promises to yield other new molecular materials at the boundary between gels and crystalline solids.

Introduction

Gels are semisolid materials in which liquids have been immobilized by low concentrations of solutes. The broad utility of gels has made the search for new gelators a very active area of science. Despite this effort, our understanding of the formation of gels remains incomplete, and our ability to correlate the structure of molecules with their ability to form gels is poor. Typically, gelation occurs when solvent is trapped in three-dimensional networks built from suitable solutes. In gels formed by polymeric gelators, the networks arise from the entanglement and interaction of covalently bonded chains, whereas in gels formed by low-molecular-weight gelators, the networks are held together by multiple noncovalent interactions. The behavior of low-molecular-weight gelators is a subject of special interest,[1−3] in part because the networks are derived from fully defined compounds, thereby allowing detailed structural characterization of the resulting gels.

Potentially instructive but virtually unexplored analogies exist between low-molecular-weight gelators and molecules that interact to form crystalline solid networks in which large quantities of solvent are included.[4] In both materials, solvent is trapped in networks formed reversibly by molecular association. Gelators are typically more effective and can immobilize solvent even at concentrations less than 1 wt %; however, crystalline molecular solids can also include impressive quantities of solvent, with the networks them-

* To whom correspondence should be addressed. E-mail: james.d.wuest@umontreal.ca.

[†] Département de Chimie, Université de Montréal.

[‡] Faculté de Médecine Dentaire, Université de Montréal.

(1) Sangeetha, N. M.; Maitra, U. *Chem. Soc. Rev.* **2005**, *34*, 821−836. Estroff, L. A.; Hamilton, A. D. *Chem. Rev.* **2004**, *104*, 1201−1217. van Esch, J. H.; Feringa, B. L. *Angew. Chem., Int. Ed.* **2000**, *39*, 2263−2266. Abdallah, D. J.; Weiss, R. G. *Adv. Mater.* **2000**, *12*, 1237−1247. Terech, P.; Weiss. R. G. *Chem. Rev.* **1997**, *97*, 3133−3159.

(2) For recent studies of low-molecular-weight gelators, see: Shirakawa, M.; Fujita, N.; Shinkai, S. *J. Am. Chem. Soc.* **2005**, *127*, 4164−4165. Mohmeyer, N.; Schmidt, H.-W. *Chem.—Eur. J.* **2005**, *11*, 863−872. Moniruzzaman, M.; Sundararajan, P. R. *Langmuir* **2005**, *21*, 3802−3807. Bhuniya, S.; Park, S. M.; Kim, B. H. *Org. Lett.* **2005**, *7*, 1741−1744. Suzuki, M.; Sato, T.; Kurose, A.; Shirai, H.; Hanabusa, K. *Tetrahedron Lett.* **2005**, *46*, 2741−2745. Trivedi, D. R.; Ballabh, A.; Dastidar, P. *J. Mater. Chem.* **2005**, *15*, 2606−2614. Griffiths, P. C.; Côte, M.; James, R.; Rogueda, P. G.; Morgan, I. R.; Knight, D. W. *Chem. Commun.* **2005**, 3998−4000. Brosse, N.; Barth, D.; Jamart-Grégoire, B. *Tetrahedron Lett.* **2004**, *45*, 9521−9524. van Bommel, K. J. C.; van der Pol, C.; Muizebelt, I.; Friggeri, A.; Heeres, A.; Meetsma, A.; Feringa, B. L.; van Esch, J. *Angew. Chem., Int. Ed.* **2004**, *43*, 1663−1667. Čaplar, V.; Žinić, M.; Pozzo, J.-L.; Fages, F.; Mieden-Gundert, G.; Vögtle, F. *Eur. J. Org. Chem.* **2004**, 4048−4059. George, M.; Snyder, S. L.; Terech, P.; Glinka, C. J.; Weiss, R. G. *J. Am. Chem. Soc.* **2003**, *125*, 10275−10283. Babu, P.; Sangeetha, N. M.; Vijaykumar, P.; Maitra, U.; Rissanen, K.; Raju, A. R. *Chem.—Eur. J.* **2003**, *9*, 1922−1932. Wang, G.; Hamilton, A. D. *Chem. Commun.* **2003**, 310−311. Hashimoto, M.; Ujiie, S.; Mori, A. *Adv. Mater.* **2003**, *15*, 797−800. Maji, S. K.; Malik, S.; Drew, M. G. B.; Nandi, A. K.; Banerjee, A. *Tetrahedron Lett.* **2003**, *44*, 4103−4107. Schmidt, R.; Adam, F. B.; Michel, M.; Schmutz, M.; Decher, G.; Mésini, P. J. *Tetrahedron Lett.* **2003**, *44*, 3171−3174.

(3) Kumar, D. K.; Jose, D. A.; Das, A.; Dastidar, P. *Chem. Commun.* **2005**, 4059−4061.

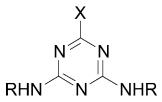
(4) For previous work that reports initial exploration of the relationship between designing gels and engineering porous crystalline solids, see: Kumar, D. K.; Jose, D. A.; Dastidar, P.; Das, A. *Chem. Mater.* **2004**, *16*, 2332−2335. Carr, A. J.; Melendez, R.; Geib, S. J.; Hamilton, A. D. *Tetrahedron Lett.* **1998**, *39*, 744−7450.

10.1021/cm060056d CCC: $33.50
Published on Web 07/13/2006

selves constituting less than 25 wt % in the most impressive examples observed so far.[5] Moreover, porous crystalline networks assembled from suitably flexible molecules are known to be able to change their shape without losing crystallinity, placing their mechanical properties between those of gels and normal rigid solids.[6]

These intriguing analogies call for further exploration of molecular materials that lie at the boundary between gels and crystalline solids. As part of this exploration, we have begun to study the behavior of special hybrid molecules that have structures combining features of typical gelators with those of compounds predisposed to form porous crystalline networks. In principle, this approach may allow strategies developed by crystal engineers to be used to create new classes of low-molecular-weight gelators.

Crystal engineers have established that molecules able to form multiple directional interactions tend to crystallize as open networks related to those of gels rather than normal close-packed structures.[7,8] Such compounds can be constructed conveniently by attaching sites of association to suitable molecular cores. Particularly effective sticky sites of association can be derived from 1,3,5-triazine-2,4-diamine (**1**), a compact molecule with multiple sites that can accept and donate hydrogen bonds according to dependable motifs.[5,9] This suggested that we might be able to explore the boundary between gels and crystalline solids by studying chimeric low-molecular-weight arylaminotriazines incorporating the following dual features: (1) an amphiphilic structure composed of a hydrophobic aromatic domain and a polar heterocyclic headgroup, as frequently encountered in the field of gelation; (2) a relatively compact and rigid structure of high symmetry designed to interact with neighbors according to well-established directional preferences, as typically seen in the field of crystal engineering. This approach has led us to discover that salts of 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylic acids (**2**) define a potent new class of selective gelators.



1 (X = H, R = H)

2 (X = COOH, R = aryl)

(5) Malek, N.; Maris, T.; Simard, M.; Wuest, J. D. *J. Am. Chem. Soc.* **2005**, *127*, 5910−5916. Fournier, J.-H.; Maris, T.; Wuest, J. D. *J. Org. Chem.* **2004**, *69*, 1762−1775.

(6) Saied, O.; Maris, T.; Wuest, J. D. *J. Am. Chem. Soc.* **2003**, *125*, 14956−14957.

(7) Simard, M.; Su, D.; Wuest, J. D. *J. Am. Chem. Soc.* **1991**, *113*, 4696−4697.

(8) Wuest, J. D. *Chem. Commun.* **2005**, 5830−5837.

(9) Laliberté, D.; Maris, T.; Demers, E.; Helzy, F.; Arseneault, M.; Wuest, J. D. *Cryst. Growth Des.* **2005**, *5*, 1451−1456. Demers, E.; Maris, T.; Wuest, J. D. *Cryst. Growth Des.* **2005**, *5*, 1227−1235. Laliberté, D.; Maris, T.; Wuest, J. D. *J. Org. Chem.* **2004**, *69*, 1776−1787. Laliberté, D.; Maris, T.; Sirois, A.; Wuest, J. D. *Org. Lett.* **2003**, *5*, 4787−4790. Sauriat-Dorizon, H.; Maris, T.; Wuest, J. D.; Enright, G. D. *J. Org. Chem.* **2003**, *68*, 240−246. Brunet, P.; Demers, E.; Maris, T.; Enright, G. D.; Wuest, J. D. *Angew. Chem., Int. Ed.* **2003**, *42*, 5303−5306. Le Fur, E.; Demers, E.; Maris, T.; Wuest, J. D. *Chem. Commun.* **2003**, 2966−2967.

Experimental Section

Biguanides **3a**−**e** and **3h**−**k** were prepared by published methods.[10] All other reagents were commercial products that were used without further purification. NMR spectra were recorded at 25 °C unless another temperature is specified.

1,5-Bis(4-iodophenyl)biguanide Hydrochloride (3f·HCl). 4-Iodoaniline (3.04 g, 13.9 mmol) and sodium dicyanimide (0.618 g, 6.94 mmol) were added to a mixture of aqueous HCl (1.00 M, 13.9 mL, 13.9 mmol) and C_2H_5OH (5 mL), and the mixture was heated at reflux for 12 h. The mixture was then cooled to 25 °C, and the resulting precipitate was separated by filtration and dissolved in a small amount of DMF. Toluene was added and the precipitate was filtered out, washed with C_2H_5OH, and dried in air. The crude material was then purified by recrystallization from a large volume of hot H_2O. The crystals were dried under vacuum to give 1,5-bis(4-iodophenyl)biguanide hydrochloride (**3f**·HCl; 1.56 g, 2.88 mmol, 41%) as a colorless solid: mp 251−252 °C; ^{1}H NMR (400 MHz, DMSO-d_6) δ 10.21 (s, 2H), 7.64 (d, ^3J = 8.6 Hz, 4H), 7.60 (s, 4H), 7.14 (d, ^3J = 8.6 Hz, 4H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 157.7, 138.9, 138.3, 124.1, 88.9; HRMS (ESI) calcd for $C_{14}H_{14}I_2N_5$ *m/e* 505.9333, found 505.9344. Anal. Calcd for $C_{14}H_{14}ClI_2N_5$: C, 31.05; H, 2.61; N, 12.93. Found: C, 31.11; H, 2.49; N, 12.63.

1,5-Bis[4-(hexyloxy)phenyl]biguanide Hydrochloride (3g·HCl). 4-(Hexyloxy)aniline (3.00 g, 15.5 mmol) was added to a mixture of aqueous HCl (1.00 M, 15.5 mL, 15.5 mmol) and C_2H_5OH (10 mL). Sodium dicyanimide (0.691 g, 7.76 mmol) was added, and the mixture was heated at reflux for 12 h. The mixture was then cooled to 25 °C, and the resulting precipitate was separated by filtration, washed with ethyl acetate, and dried under vacuum to yield pure 1,5-bis[4-(hexyloxy)phenyl]biguanide hydrochloride (**3g**·HCl; 2.98 g, 6.08 mmol, 78%) as a colorless solid: mp 230−231 °C; ^{1}H NMR (400 MHz, DMSO-d_6) δ 9.77 (s, 2H), 7.31 (s, 4H), 7.19 (d, ^3J = 8.9 Hz, 4H), 6.86 (d, ^3J = 8.9 Hz, 4H), 3.91 (t, ^3J = 7 Hz, 4H), 1.68 (quint, ^3J = 7 Hz, 4H), 1.40 (quint, ^3J = 7 Hz, 4H), 1.29 (m, 8H), 0.87 (t, ^3J = 7 Hz, 6H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 157.9, 156.5, 131.4, 124.7, 115.4, 68.5, 31.9, 29.6, 26.1, 23.0, 14.8; HRMS (ESI) calcd for $C_{26}H_{40}N_5O_2$ *m/e* 454.3177, found 454.3174. Anal. Calcd for $C_{26}H_{40}ClN_5O_2$: C, 63.72; H, 8.23; N 14.29. Found: C, 63.45; H, 8.19; N, 14.15.

Methyl 4,6-Bis(phenylamino)-1,3,5-triazine-2-carboxylate (4a). Dimethyl oxalate (0.354 g, 3.00 mmol) and a solution of $NaOCH_3$ in CH_3OH (25% w/w, 0.01 mL, 0.04 mmol) were added to a solution of 1,5-diphenylbiguanide (**3a**; 0.253 g, 1.00 mmol) in CH_3OH (30 mL), and the mixture was heated at reflux for 12 h. The mixture was then cooled to 25 °C, and H_2O was added until a colorless precipitate formed. The precipitate was separated by filtration, washed with H_2O, and dried under vacuum to provide methyl 4,6-bis(phenylamino)-1,3,5-triazine-2-carboxylate **(4a**; 0.205 g, 0.64 mmol, 64%) as a colorless solid. The product could be used without further purification, but a sample for analysis was obtained by crystallization from toluene: mp 167−168 °C; IR (KBr) 3300−2800 (br), 1750, 1637, 1607, 1582, 1532, 1512, 1480, 1448, 1220, 1019, 757 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79 (br s, 2H), 7.56 (br d, ^3J = 8 Hz, 4H), 7.34 (t, ^3J = 8 Hz, 4H), 7.15 (t, ^3J = 8 Hz, 2H), 3.93 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$, 10 °C) δ 164.6, 163.6, 163.4, 137.4, 129.0, 124.7, 121.4, 53.7; HRMS (ESI) calcd for $C_{17}H_{16}N_5O_2$ *m/e* 322.1298, found 322.1297. Anal. Calcd for $C_{17}H_{15}N_5O_2$: C, 63.54; H, 4.71; N. 21.79. Found: C, 63.76; H, 4.59; N, 21.39.

(10) LeBel, O.; Maris, T.; Duval, H.; Wuest, J. D. *Can. J. Chem.* **2005**, *83*, 615−626.

Methyl 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylates **4b**−**e** and **4h**−**k** were synthesized by analogous procedures.

Methyl 4,6-Bis[(4-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (4b): yield 84%; mp 156−157 °C; IR (KBr) 3400−2800 (br), 3344, 1745, 1622, 1580, 1508, 1452, 1432, 1411, 1357, 1307, 1228, 1181, 1012, 828, 815, 794 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.75 (s, 2H), 7.43 (d, ^3J = 8.4 Hz, 4H), 7.13 (d, ^3J = 8.4 Hz, 4H), 3.89 (s, 3H), 2.35 (s, 6H); ^{13}C NMR (125 MHz, $CDCl_3$, 10 °C) δ 164.5, 163.6, 163.2, 135.0, 134.1, 129.4, 121.4, 53.5, 21.0; HRMS (ESI) calcd for $C_{19}H_{20}N_5O_2$ *m*/*e* 350.1611, found 350.1615. Anal. Calcd for $C_{19}H_{19}N_5O_2$: C, 65.32; H, 5.48; N, 20.04. Found: C, 65.43; H, 5.36; N, 19.90.

Methyl 4,6-Bis[(4-methoxyphenyl)amino]-1,3,5-triazine-2-carboxylate (4c): yield 75%; mp 149−150 °C; IR (KBr) 3600−2800 (br), 1752, 1616, 1583, 1536, 1504, 1438, 1418, 1356, 1303, 1247, 1215, 1182, 1034, 1029, 828, 799 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.73 (s, 2H), 7.41 (d, ^3J = 8.3 Hz, 4H), 6.85 (d, ^3J = 8.5 Hz, 4H), 3.87 (s, 3H), 3.80 (s, 6H); ^{13}C NMR (125 MHz, $CDCl_3$, 10 °C) δ 164.5, 163.7, 163.1, 156.6, 130.4, 123.0, 114.0, 55.6, 53.8; HRMS (ESI) calcd for $C_{19}H_{20}N_5O_4$ *m*/*e* 382.1509, found 382.1508. Anal. Calcd for $C_{19}H_{19}N_5O_4 \cdot 0.5H_2O$: C, 58.46; H, 5.16; N, 17.94. Found: C, 57.99; H, 5.06; N, 17.57.

Methyl 4,6-Bis[(4-cyanophenyl)amino]-1,3,5-triazine-2-carboxylate (4d): yield 69%; mp 281−282 °C; IR (KBr) 3400−2900 (br), 3349, 3308, 2232, 1738, 1610, 1573, 1555, 1501, 1461, 1428, 1416, 1226, 1008, 833, 787 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 10.78 (br s, 2H), 7.89 (m, 4H), 7.76 (m, 4H), 3.87 (s, 3H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 164.1, 163.5, 163.0, 143.0, 132.9, 120.2, 119.1, 104.6, 52.8; HRMS (ESI) calcd for $C_{19}H_{14}N_7O_2$ *m*/*e* 372.1203, found 372.1202. Anal. Calcd for $C_{19}H_{13}N_7O_2 \cdot 0.5$ H_2O: C, 60.00; H, 3.71; N, 25.78. Found: C, 60.46; H, 3.43; N, 26.00.

Methyl 4,6-Bis[(4-bromophenyl)amino]-1,3,5-triazine-2-carboxylate (4e): yield 79%; mp 168−169 °C; IR (KBr) 3600−2800 (br), 3279, 1754, 1629, 1598, 1572, 1520, 1485, 1450, 1433, 1402, 1352, 1300, 1219, 1179, 1074, 1009, 822, 788 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 10.49 (br s, 2H), 7.64 (m, 4H), 7.52 (d, ^3J = 7.4 Hz, 4H), 3.88 (s, 3H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 164.1, 163.6, 163.3, 138.0, 131.3, 122.6, 115.0, 52.6; HRMS (ESI) calcd for $C_{17}H_{14}Br_2N_5O_2$ *m*/*e* 477.9508, found 477.9504. Anal. Calcd for $C_{17}H_{13}Br_2N_5O_2 \cdot 0.5$ H_2O: C, 41.83; H, 2.89; N, 14.35. Found: C, 41.85; H, 2.92; N, 13.94.

Methyl 4,6-Bis[(2-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (4h): yield 59%; mp 229−230 °C; IR (KBr) 3300−2800 (br), 1752, 1620, 1616, 1575, 1525, 1460, 1442, 1395, 1357, 1221, 748 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.80 (d, ^3J = 7.7 Hz, 2H), 7.33 (br s, 2H), 7.19 (d, ^3J = 7.5 Hz, 2H), 7.14 (br s, 2H), 7.08 (t, ^3J = 7 Hz, 2H), 3.96 (s, 3H), 2.28 (s, 6H); ^{13}C NMR (125 MHz, $CDCl_3$, 10 °C) δ 165.0, 163.9, 163.7, 135.6, 130.6, 129.7, 126.4, 125.2, 123.6, 53.8, 18.3; HRMS (ESI) calcd for $C_{19}H_{20}N_5O_2$ *m*/*e* 350.1611, found 350.1610. Anal. Calcd for $C_{19}H_{19}N_5O_2$: C, 65.32; H, 5.48; N 20.04. Found: C, 65.29; H, 5.50; N 20.05.

Methyl 4,6-Bis[(3-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (4i): yield 78%; mp 138−139 °C; IR (KBr) 3300−2800 (br), 1749, 1629, 1586, 1529, 1488, 1453, 1428, 1353, 1222, 1166, 1030, 780 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.57 (br s, 2H), 7.36 (m, 4H), 7.23 (t, ^3J = 8 Hz, 2H), 6.96 (d, ^3J = 8 Hz, 2H), 3.98 (s, 3H), 2.33 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.6, 163.6, 163.5, 138.9, 137.3, 128.8, 125.3, 121.6, 118.2, 53.6, 21.4; HRMS (ESI) calcd for $C_{19}H_{20}N_5O_2$ *m*/*e* 350.1611, found 350.1613. Anal. Calcd for $C_{19}H_{19}N_5O_2$: C, 65.32; H, 5.48; N, 20.04. Found: C, 65.06; H, 5.50; N, 19.82.

Methyl 4,6-Bis[(2-bromophenyl)amino]-1,3,5-triazine-2-carboxylate (4j). The crude product was filtered on a short silica pad using ethyl acetate as eluent: yield 69%; mp 198−199 °C; IR (KBr) 3300−2800 (br), 3224, 3073, 1753, 1610, 1567, 1525, 1440, 1423, 1360, 1286, 1216, 1015, 758, 732 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 8.21 (br s, 2H), 7.76 (s, 2H), 7.59 (dd, ^3J = 8 Hz, ^4J = 1 Hz, 2H), 7.29 (m, 2H), 7.02 (dt, ^3J = 8 Hz, ^4J = 1 Hz, 2H), 4.04 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.7, 164.3, 163.4, 135.3, 132.7, 127.7, 125.6, 123.7, 115.4, 53.7; HRMS (ESI) calcd for $C_{17}H_{14}Br_2N_5O_2$ *m*/*e* 477.9508, found 477.9506.

Methyl 4,6-Bis[(3,5-dimethylphenyl)amino]-1,3,5-triazine-2-carboxylate (4k): yield 96%; T_g 72 °C; IR (KBr) 3400−2800 (br), 1753, 1620, 1588, 1526, 1433, 1344, 1261, 1221, 1163, 1054, 842, 793 cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) δ 7.63 (s, 2H), 7.13 (s, 4H), 6.77 (s, 2H), 3.93 (s, 3H), 2.26 (s, 12H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.6, 163.6, 163.5, 138.6, 137.2, 126.2, 119.0, 53.5, 21.3; HRMS (ESI) calcd for $C_{21}H_{24}N_5O_2$ *m*/*e* 378.1924, found 378.1920. Anal. Calcd for $C_{21}H_{23}N_5O_2$: C, 66.83; H, 6.14; N, 18.55. Found: C, 66.86; H, 6.38; N, 18.57.

Methyl 4,6-Bis[(4-iodophenyl)amino]-1,3,5-triazine-2-carboxylate (4f). A solution of $NaOCH_3$ in CH_3OH (25% w/w, 0.80 mL, 3.5 mmol) was diluted with CH_3OH (50 mL), 1,5-bis(4-iodophenyl)biguanide hydrochloride (**3f**·HCl; 1.45 g, 2.68 mmol) was added, and the mixture was stirred at 25 °C for 15 min. Dimethyl oxalate (0.949 g, 8.04 mmol) was then added, and the mixture was heated at reflux for 12 h. The mixture was cooled to 25 °C, and H_2O was added until a white precipitate formed. The precipitate was separated by filtration, washed with H_2O, and dried under vacuum to provide methyl 4,6-bis[(4-iodophenyl)amino]-1,3,5-triazine-2-carboxylate **(4f**; 0.932 g, 1.63 mmol, 61%) as a colorless solid, which could be used without further purification: mp 129−130 °C; ^1H NMR (400 MHz, DMSO-d_6) δ 10.45 (s, 2H), 7.65 (br d, ^3J = 8 Hz, 4H), 7.50 (m, 4H), 3.87 (s, 3H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 164.1, 163.5, 163.3, 138.5, 137.1, 122.8, 86.8, 52.6; HRMS (ESI) calcd for $C_{17}H_{14}I_2N_5O_2$ *m*/*e* 573.9231, found 573.9222. Anal. Calcd for $C_{17}H_{13}I_2N_5O_2 \cdot 0.5$ H_2O: C, 35.08; H, 2.42; N, 12.03. Found: C, 35.52; H, 2.65; N, 11.42.

Methyl 4,6-bis[4-(hexyloxy)phenyl)amino]-1,3,5-triazine-2-carboxylate (**4g**) was synthesized from 1,5-bis[4-(hexyloxy)phenyl]-biguanide hydrochloride (**3g**·HCl) by an analogous procedure.

Methyl 4,6-Bis[4-(hexyloxy)phenyl)amino]-1,3,5-triazine-2-carboxylate (4g). The crude product was filtered through a short pad of silica using acetone as eluent: yield 96%; mp 127−128 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 7.74 (s, 2H), 7.43 (d, ^3J = 8.4 Hz, 4H), 6.87 (d, ^3J = 8.4 Hz, 4H), 3.97 (t, ^3J = 7 Hz, 4H), 3.94 (s, 3H), 1.80 (quint, ^3J = 7 Hz, 4H), 1.49 (m, 4H), 1.36 (m, 8H), 0.93 (t, ^3J = 7 Hz, 6H); ^{13}C NMR (125 MHz, $CDCl_3$, 10 °C) δ 164.5, 163.8, 163.1, 156.1, 130.3, 122.9, 114.5, 68.3, 53.7, 31.7, 29.3, 25.8, 22.7, 14.2; HRMS (ESI) calcd for $C_{29}H_{40}N_5O_4$ *m*/*e* 522.3075, found 522.3073. Anal. Calcd for $C_{29}H_{39}N_5O_4 \cdot 0.5H_2O$: C, 65.64; H, 7.60; N, 13.20. Found: C, 65.49; H, 7.63; N, 13.34.

4,6-Bis(phenylamino)-1,3,5-triazine-2-carboxylic Acid (5a). Aqueous NaOH (1.0 M, 5.5 mL, 5.5 mmol) was added to a solution of methyl 4,6-bis(phenylamino)-1,3,5-triazine-2-carboxylate **(4a**; 0.176 g, 0.548 mmol) in C_2H_5OH (30 mL), and the mixture was heated at reflux for 3 h. The mixture was then cooled to 25 °C, and aqueous HCl (1.0 M, 10 mL 10 mmol) was added. The resulting precipitate was separated by filtration, washed successively with H_2O and acetone, and dried under vacuum to afford 4,6-bis(phenylamino)-1,3,5-triazine-2-carboxylic acid **(5a**; 0.163 g, 0.530 mmol, 97%) as a colorless solid that required no further purification: mp 275 °C (dec); IR (KBr) 3300−2700 (br), 1700, 1657, 1610, 1592, 1561, 1498, 1450, 1381, 1341, 1318, 1235, 786, 754, 701 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 13.6 (br s, 1H), 10.24 (s, 2H), 7.75 (m, 4H), 7.32 (m, 4H), 7.06 (m, 2H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.4, 164.9, 164.2, 138.9, 128.5, 123.1,

120.8; HRMS (ESI) calcd for $C_{16}H_{14}N_5O_2$ *m*/*e* 308.1142, found 308.1143. Anal. Calcd for $C_{16}H_{13}N_5O_2$: C, 62.53; H, 4.26; N, 22.79. Found: C, 62.08; H, 4.35; N, 22.34.

4,6-bis(arylamino)-1,3,5-triazine-2-carboxylic acids **5b**−**k** were synthesized from the corresponding methyl esters **4b**−**k** by analogous procedures.

4,6-Bis[(4-methylphenyl)amino]-1,3,5-triazine-2-carboxylic acid (5b): yield 87%: mp 276 °C (dec); IR (KBr) 3600−2500 (br), 3089, 1695, 1633, 1699, 1546, 1509, 1427, 1376, 1336, 1319, 1235, 1185, 1083, 946, 871, 817, 793 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 13.6 (br s, 1H), 10.13 (br s, 2H), 7.59 (m, 4H), 7.12 (d, ^3J = 7.4 Hz, 4H), 2.28 (s, 6H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.2, 164.9, 164.1, 136.2, 132.1, 128.9, 120.7, 20.4; HRMS (ESI) calcd for $C_{18}H_{18}N_5O_2$ *m*/*e* 336.1455, found 336.1456. Anal. Calcd for $C_{18}H_{17}N_5O_2$: C, 64.47; H, 5.11; N, 20.88. Found: C, 63.92; H, 5.11; N, 20.72.

4,6-Bis[(4-methoxyphenyl)amino]-1,3,5-triazine-2-carboxylic acid (5c): yield 86%; mp 289 °C (dec); IR (KBr) 3600−2600 (br), 3082, 1693, 1641, 1608, 1565, 1543, 1511, 1424, 1384, 1233, 832, 787 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 10.01 (s, 2H), 7.56 (m, 4H), 6.90 (d, ^3J = 8.3 Hz, 4H), 3.74 (s, 6H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.0, 164.1, 164.1, 155.3, 131.7, 122.5, 113.6, 55.2; HRMS (ESI) calcd for $C_{18}H_{18}N_5O_4$ *m*/*e* 368.1353, found 368.1361. Anal. Calcd for $C_{18}H_{17}N_5O_4$: C, 58.85; H, 4.66; N, 19.06. Found: C, 58.70; H, 5.05; N, 19.02.

4,6-Bis[(4-cyanophenyl)amino]-1,3,5-triazine-2-carboxylic acid (5d): yield 94%; mp 208 °C (dec); IR (KBr) 3600−2600 (br), 3288, 1724, 1612, 1583, 1503, 1412, 1226, 1178, 834, 786 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 10.77 (s, 2H), 7.98 (m, 4H), 7.83 (d, ^3J = 7.8 Hz, 4H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.4, 164.4, 164.2, 143.2, 133.0, 120.2, 119.2, 104.6; HRMS (ESI) calcd for $C_{18}H_{12}N_7O_2$ *m*/*e* 358.1046, found 358.1052. Anal. Calcd for $C_{18}H_{11}N_7O_2 \cdot H_2O$: C, 57.60; H 3.49; N, 26.12. Found: C, 57.87; H, 3.22; N, 26.35.

4,6-Bis[(4-bromophenyl)amino]-1,3,5-triazine-2-carboxylic acid (5e): yield 95%; mp 290 °C (dec); IR (KBr) 3500−2600 (br), 3088, 1696, 1614, 1551, 1488, 1422, 1403, 1373, 1234, 1075, 821, 768 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 13.7 (br s, 1H), 10.39 (s, 2H), 7.68 (m, 4H), 7.51 (d, ^3J = 8.4 Hz, 4H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.3, 164.7, 164.1, 138.2, 131.3, 122.5, 114.9; HRMS (ESI) calcd for $C_{16}H_{12}Br_2N_5O_2$ *m*/*e* 463.9352, found 463.9349. Anal. Calcd for $C_{16}H_{11}Br_2N_5O_2 \cdot 1/2H_2O$: C, 40.53; H, 2.55; N, 14.77. Found: C, 40.48; H, 2.60; N, 14.57.

4,6-Bis[(4-iodophenyl)amino]-1,3,5-triazine-2-carboxylic acid (5f): yield 85%; mp 389 °C (dec); ^1H NMR (400 MHz, DMSO-d_6) δ 13.71 (br s, 1H), 10.38 (s, 2H), 7.68 (d, ^3J = 8.3 Hz, 4H), 7.54 (m, 4H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.2, 164.7, 164.1, 138.7, 137.1, 122.8, 86.7; HRMS (APPI) calcd for $C_{16}H_{12}I_2N_5O_2$ *m*/*e* 559.9075, found 559.9098. Anal. Calcd for $C_{16}H_{11}I_2N_5O_2 \cdot H_2O$: C, 33.30; H, 2.27; N, 12.14. Found: C, 32.87; H, 2.10; N, 11.83.

4,6-Bis[(4-hexyloxyphenyl)amino]-1,3,5-triazine-2-carboxylic acid (5g): yield 90%; mp 464 °C (dec); ^1H NMR (400 MHz, DMSO-d_6) δ 9.98 (s, 2H), 7.52 (br s, 4H), 6.87 (d, ^3J = 9 Hz, 4H), 3.94 (t, ^3J = 7 Hz, 4H), 1.70 (quint, ^3J = 7 Hz, 4H), 1.41 (quint, ^3J = 7 Hz, 4H), 1.30 (m, 8H), 0.88 (t, ^3J = 7 Hz, 6H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.0, 164.0, 164.0, 154.7, 131.5, 122.5, 114.2, 67.5, 31.0, 28.7, 25.2, 22.0, 13.8; HRMS (ESI) calcd for $C_{28}H_{36}N_5O_4$ *m*/*e* 506.2773, found 506.2785. Anal. Calcd for $C_{28}H_{37}N_5O_4 \cdot H_2O$: C, 63.98; H, 7.48; N, 13.32. Found: C, 63.40; H, 7.48; N, 13.33.

4,6-Bis[(2-methylphenyl)amino]-1,3,5-triazine-2-carboxylic acid (5h): yield 84%; mp 230 °C (dec); IR (KBr) 3300−2700 (br), 3099, 1695, 1641, 1619, 1536, 1462, 1397, 1335, 786, 747 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 13.5 (br s, 1H), 9.33 (s, 2H), 7.37 (m, 2H), 7.18 (m, 2H), 7.11 (m, 2H), 7.07 (m, 2H), 2.19 (s, 6H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.8, 165.1, 164.9, 136.2, 132.8, 130.1, 126.2, 125.7, 125.3, 17.9; HRMS (ESI) calcd for $C_{18}H_{18}N_5O_2$ *m*/*e* 336.1455, found 336.1460. Anal. Calcd for $C_{18}H_{17}N_5O_2 \cdot 1/2H_2O$: C, 62.78; H, 5.27; N, 20.34. Found: C, 63.03; H, 5.17; N, 20.27.

4,6-Bis[(3-methylphenyl)amino]-1,3,5-triazine-2-carboxylic acid (5i): yield 75%; mp 240 °C (dec); IR (KBr) 3300−2700 (br), 3125, 2919, 1701, 1662, 1618, 1602, 1556, 1486, 1453, 1424, 1372, 1333, 797, 768 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 13.6 (br s, 1H), 10.15 (s, 2H), 7.52 (m, 4H), 7.20 (t, ^3J = 7.6 Hz, 2H), 6.88 (d, ^3J = 7.2 Hz, 2H), 2.26 (s, 6H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.2, 164.8, 164.1, 138.7, 137.7, 128.3, 123.8, 121.2, 117.9, 21.1; HRMS (ESI) calcd for $C_{18}H_{18}N_5O_2$ *m*/*e* 336.1455, found 336.1454. Anal. Calcd for $C_{18}H_{17}N_5O_2 \cdot 1/4H_2O$: C, 63.61; H, 5.19; N, 20.61. Found: C, 63.68; H, 5.19; N, 20.63.

4,6-Bis[(2-bromophenyl)amino]-1,3,5-triazine-2-carboxylic acid (5j): yield 58%; mp 240 °C (dec); IR (KBr) 3500−2700 (br), 3408, 3377, 1747, 1723, 1600, 1575, 1513, 1442, 1288, 1237, 1208, 1023, 1001, 786, 746 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 9.50 (s, 2H), 7.64 (d, ^3J = 7.2 Hz, 2H), 7.57 (d, ^3J = 7.4 Hz, 2H), 7.32 (m, 2H), 7.13 (m, 2H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 166.0, 164.9, 164.89, 136.2, 132.5, 128.2, 127.8, 127.2, 119.8; HRMS (ESI) calcd for $C_{16}H_{12}Br_2N_5O_2$ *m*/*e* 463.9352, found 463.9347. Anal. Calcd for $C_{16}H_{11}Br_2N_5O_2$: C, 41.32; H, 2.38; N, 15.06. Found: C, 41.11; H, 2.52; N, 14.90.

4,6-Bis[(3,5-dimethylphenyl)amino]-1,3,5-triazine-2-carboxylic acid (5k): yield 80%; mp 143 °C (dec); IR (KBr) 3500−2800 (br), 3193, 2922, 1693, 1657, 1622, 1597, 1568, 1539, 1374, 845 cm^{-1}; ^1H NMR (400 MHz, DMSO-d_6) δ 13.6 (br s, 1H), 10.03 (s, 2H), 7.27 (s, 4H), 6.70 (s, 2H), 2.19 (s, 12H); ^{13}C NMR (100 MHz, DMSO-d_6) δ 165.2, 164.9, 164.1, 138.6, 137.4, 124.7, 118.6, 21.0; HRMS (ESI) calcd for $C_{20}H_{22}N_5O_2$ *m*/*e* 364.1768, found 364.1766. Anal. Calcd for $C_{20}H_{21}N_5O_2 \cdot H_2O$: C, 62.98; H, 6.08; N, 18.36. Found: C, 63.27; H, 6.42; N, 18.48.

Sodium 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylates 6a−**k.** 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylic acids **5a**−**k** were finely ground and treated at 25 °C with aqueous NaOH (1.0 M). The resulting solids were separated by filtration, washed successively with H_2O and acetone, and dried under vacuum to give pure samples of the corresponding sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylates **6a**−**k** as colorless solids.

Evaluation of Sodium 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylates 6a−**k as Gelators of DMSO.** Appropriate quantities of sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylates **6a**−**k** were placed in small vials, and DMSO (1 mL) was added. The mixtures were heated at reflux for about 10 s until homogeneous solutions were formed. The solutions were allowed to stand for 20 min at 25 °C. The vials were then turned upside down, and samples were considered successfully gelled if the solvent was completely immobilized.

Measurement of T_{gel} by Modulated Differential Scanning Calorimetry (DSC).[11] Measurements were made with a TA Instruments Q1000 calorimeter, using a 60 s period and heating/cooling rates of 2 °C/min from −40 to 120 °C. The results reported were recorded after an initial cycle of melting and resolidification.

Measurement of T_{gel} by the Dropping-Ball Method.[12] A sample of gel of fixed volume (1 mL) and known concentration was placed in a standard 15 mm vial, and a small steel ball (330 mg, 4.4 mm diameter) was suspended on top of the sample. The vial was heated in a thermostated oil at the rate of 5 °C/min. The

(11) Reading, M.; Luget, A.; Wilson, R. *Thermochim. Acta* **1994**, *238*, 295−307.
(12) Takahashi, A.; Sakai, M.; Kato, T. *Polym. J.* **1980**, *12*, 335−341.

temperature at which the ball dropped to the bottom of the gel was recorded as T_{gel}.

Effect of Added Sodium Salts on the Ability of Sodium 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylates 6a−g to Gel DMSO. To samples of gels of fixed volume (1 mL) and known concentration, various amounts of sodium salts were added, and the mixtures were heated until homogeneous solutions were obtained. The solutions were allowed to stand for 20 min at 25 °C, and the normal criterion was then used to determine whether the resulting material was a gel.

Variable-Temperature NMR Spectroscopy. ^{1}H NMR spectra of samples in DMSO-d_6 were recorded on a Bruker AMX-300 spectrometer.

Optical Microscopy. Gels were examined by putting a sample on a microscope slide and placing a cover glass over it. The samples were analyzed on a Linkam LTS 350 heating stage at 25−200 °C, using a heating rate of 10 °C/min. The samples were examined under polarized light using a BX51 Olympus microscope under dark-field conditions.

Scanning Electron Microscopy. Samples of gels formed by dissolving salts **6a**−**g** in DMSO (1.5−3.0 mg/mL) were spread on aluminum stubs and observed in the solvated state using a JEOL 6460 LV variable-pressure scanning electron microscope operated at 15−20 kV and 30−50 Pa. For higher resolution imaging, similar samples were dried under vacuum and examined uncoated using a JEOL 7400F field-emission scanning electron microscope operated at 1 kV.

Atomic Force Microscopy. Gels prepared by dissolving salt **6b** in DMSO (3.0 mg/mL) were spin-cast on quartz. Imaging was carried out in tapping mode using a JEOL JSPM-5200 atomic force microscope in air or under vacuum at ~10^{-6} Torr. Super-sharp silicon tips (SSS-NCHR, Nanosensors, Neuchâtel, Switzerland) with a radius of curvature of ~2 nm were used to minimize the tip-convolution effect. The software used for manipulating images was WSxM, version 2.2 (Nanotec Electrónica, Madrid, Spain).

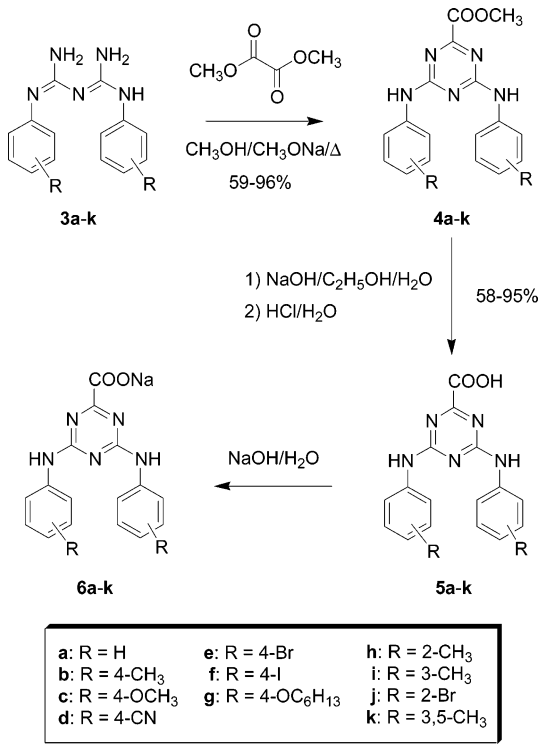
Crystallization of Sodium 4,6-Bis[(4-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (6b). Crystals suitable for X-ray diffraction were obtained from a gel made by dissolving salt **6b** (5 mg) in DMSO (1 mL) in a vial with a diameter of 15 mm. Tiny needles were produced when the sample was left undisturbed at 25 °C for 2 weeks.

Determination of the Structure of Sodium 4,6-Bis[(4-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (6b) by X-ray Crystallography. X-ray diffraction data were collected at 100 K with Cu Kα radiation using a Bruker SMART 6000 CCD diffractometer equipped with a rotating anode generator. The structure was solved by direct methods using SHELXS-97 and refined with SHELXL-97.[13] All non-hydrogen atoms were refined anisotropically, whereas hydrogen atoms were placed in ideal positions and refined as riding atoms. Salt **6b** proved to crystallize in the monoclinic space group $P2_1/c$ with $a = 15.8524(3)$ Å, $b = 10.4636(2)$ Å, $c = 15.8729(3)$ Å, $\beta = 105.0208(9)°$, $V = 2542.93(8)$ Å^3, $D_{calcd} = 1.342$ g/cm^3, and $Z = 4$. Full-matrix least-squares refinements on F^2 of 314 parameters led to final residuals $R_1 = 0.0401$ and $wR_2 = 0.0996$ for 4580 reflections with $I > 2\sigma(I)$.

Results and Discussion

Synthesis of Sodium 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylates 6a−k. Synthesis of the principal compounds investigated is outlined in Scheme 1. Methyl 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylates **4a**−**k** were prepared by condensing 1,5-diarylbiguanides **3a**−**k**[10] with excess dimethyl oxalate in CH_3OH,[14] typically with added CH_3ONa. In most cases, a catalytic amount of base was sufficient; however, when the aryl groups had strongly electron-withdrawing groups, 1 equiv of base was needed, and when the aryl groups had strongly electron-donating substituents, no base was required. Basic hydrolysis of methyl esters **4a**−**k**, followed by neutralization, provided the corresponding carboxylic acids **5a**−**k**, which were then converted into sodium salts **6a**−**k** by treatment with aqueous NaOH.

Scheme 1



Selective Gelation of DMSO by Sodium 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylates 6a−g. The simple parent compound sodium 4,6-bis(phenylamino)-1,3,5-triazine-2-carboxylate (**6a**) and its *para*-substituted derivatives **6b**−**g** all proved to be highly efficient and selective gelators of DMSO, with minimum gelator concentrations in the range 0.09−0.22 wt % (Table 1). In contrast, *ortho*- and *meta*-substituted analogues **6h**−**k** failed to gel DMSO, even in saturated solutions. Salts **6a**,**c**,**e** also gelled DMF temporarily, but precipitates formed within several hours. Salts **6a**−**k** all have low solubility in most solvents, so potentially effective concentrations could be attained only in mixtures containing DMSO, DMF, or similar solvents. In tests with a wide range of cosolvents, gelation occurred only in mixtures containing at least 75% DMSO by volume, suggesting that DMSO plays a crucial role in inducing salts **3a**−**g** to form gels. Esters **4a**−**k** and free acids **5a**−**k** did not gel any solvents examined, showing the importance of ionic interactions in forming the observed gels. Furthermore, salts of acids **5a**−**k** with Li^+, K^+, Ag^+, NH_4^+, $Me_2NH_2^+$, Me_4N^+, and Bu_4N^+ did not give gels, indicating that Na^+ has a special effect.

(13) Sheldrick, G. M. *SHELXS-97, Program for the Solution of Crystal Structures, and SHELXL-97, Program for the Refinement of Crystal Structures*; Universität Göttingen: Göttingen, Germany, 1997.

(14) Overberger, C. J.; Shapiro, S. L. *J. Am. Chem. Soc.* **1954**, *76*, 93−96.

Table 1. Minimum Gelator Concentrations for Salts 6a−g

		min gelator concentration			
gelator	R	mg/mL	mM	wt %	DMSO molecules/gelator molecule
6a	H	2.5	7.6	0.22	1900
6b	4-Me	2.0	5.6	0.18	2600
6c	4-OMe	2.5	6.4	0.22	2200
6d	4-CN	2.0	5.3	0.18	2700
6e	4-Br	1.0	2.1	0.09	7000
6f	4-I	1.0	1.7	0.09	8400
6g	4-OC_6H_{13}	1.5	2.8	0.13	5100

Although the aryl substituents of gelators **6a**−**g** have both electron-donating and electron-withdrawing substituents, the efficiency of gelation remains similar, establishing that electronic effects are not significant.

Salts **6a**−**g** have certain elementary structural features found in many previously identified gelators, including an apolar aryl region and a headgroup that is ionic and can form multiple hydrogen bonds. In other ways, however, salts **6a**−**g** are structurally distinctive and define a new class of low-molecular-weight gelators. In particular, they have a notably low degree of conformational flexibility and do not require the long alkyl chains found in many other gelators. In parent salt **6a**, for example, conformational changes are limited to rotations around a total of five single bonds: two N−Ph bonds; three exocyclic C−C and C−N bonds at the 2, 4, and 6 positions of the triazine core. Few effective gelators with such low degrees of conformational mobility have ever been reported.[15] Moreover, previous examples have typically had nonplanar structures with low symmetry, whereas salts **6a**−**g** can adopt rigorously planar conformations and have high symmetry. In these ways, the structures of salts **6a**−**g** depart significantly from those of conventional gelators and approach closely those of small rigid molecules normally preferred for engineering crystalline solids.

Stability of Gels Formed in DMSO by Sodium 4,6-Bis-(arylamino)-1,3,5-triazine-2-carboxylates 6a−g. The observed gels can be disrupted by agitation or heating, but cooling then causes the gels to reform thermoreversibly. If undisturbed, gels formed by solutions of salts **6a**,**c**−**g** in DMSO are stable indefinitely, but under suitable conditions salt **6b** can be induced to crystallize slowly from its gel. Modulated differential scanning calorimetry (DSC) was used to measure the temperatures T_{gel} of sol−gel transitions for salts **6a**−**g** in DMSO,[11] and the results are summarized in Table 2. All gelators showed broad endotherms with onset temperatures as low as 30 °C and maxima typically near 70 °C. A representative thermogram, shown in Figure 1, reveals that the endotherms are weak and poorly defined, presumably due to the low concentrations of gelators. The corresponding exotherms could not be observed on cooling, but all gels were disrupted by heating to form transparent viscous liquids that reverted to gels when cooled. The dropping-ball method for estimating T_{gel} yielded similar results in most cases (Table 2).[12] Figure 2 provides values of T_{gel} as a function of the concentration of gelator for the representative case of parent salt **6a**. As expected, T_{gel} rises in an approximately linear manner as the concentration increases, reaching 111 °C at 8.0 mg/mL (0.7 wt %).

Table 2. Temperatures of Sol−Gel Transitions (T_{gel}) for Salts 6a−g As Measured by Modulated Differential Scanning Calorimetry (DSC)[11] and the Dropping-Ball Method[12] [a]

			T_{gel} (°C)	
gelator	R	[gelator] (mg/mL)	DSC	dropping ball
6a	H	3.0	35−68	74
6b	4-Me	2.5	33−50	47
6c	4-OMe	3.0	35−65	62
6d	4-CN	2.5	30−69	25
6e	4-Br	1.5	40−68	56
6f	4-I	1.5	55−72	53
6g	4-OC_6H_{13}	2.0	40−72	47

[a] In the DSC measurements, the first value reported corresponds to the onset of the peak and the second value corresponds to the maximum.

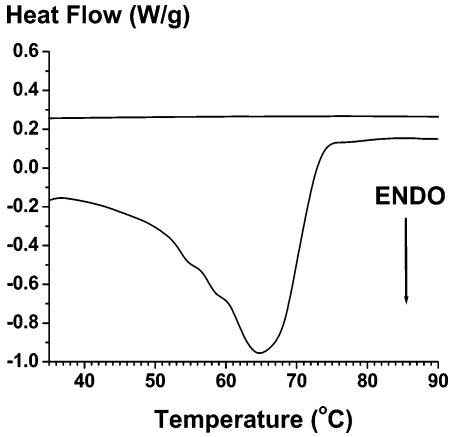


Figure 1. Representative thermogram, obtained by modulated differential scanning calorimetry,[11] for the gel formed by dissolving sodium 4,6-bis-(arylamino)-1,3,5-triazine-2-carboxylate **6c** in DMSO (3.0 mg/mL). Signals for reversible heat flow, irreversible heat flow, and modulated heat flow are omitted for clarity.

Effect of Added Na^+ on the Stability of Gels Formed in DMSO by Sodium 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylates 6a−g. The tolerance of the observed gels to added Na^+ was examined by measuring the minimum gelator concentrations as a function of [Na^+]. Figure 3 provides data for the representative case of parent salt **6a**. These data show that (1) substantial quantities (up to 13 equiv) of nonbasic salts such as NaI, $NaOSO_2CF_3$, and $NaBF_4$ can be added without changing the minimum gelator concentration dramatically and (2) the minimum gelator concentration increases linearly with [Na^+]. In contrast, more basic salts such as $NaOOCCH_3$ disrupt gelation at low concentrations, presumably by breaking hydrogen bonds

(15) For selected examples, see: Yoza, K.; Ono, Y.; Yoshihara, K.; Akao, T.; Shinmori, H.; Takeuchi, M.; Shinkai, S.; Reinhoudt, D. N. *Chem. Commun.* **1998**, 907−908. Vassilev, V. P.; Simanek, E. E.; Wood, M. R.; Wong, C.-H. *Chem. Commun.* **1998**, 1865−1866. Hanabusa, K.; Matsumoto, Y.; Miki, T.; Koyama, T.; Shirai, H. *Chem. Commun.* **1994**, 1401−1402.

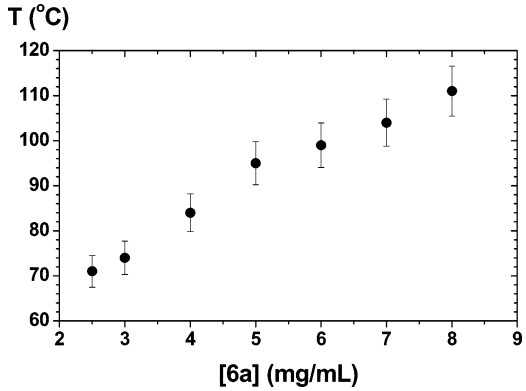


Figure 2. T_{gel} as a function of gelator concentration for the gel formed by dissolving sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylate **6a** in DMSO, as measured by the dropping-ball method.[12]

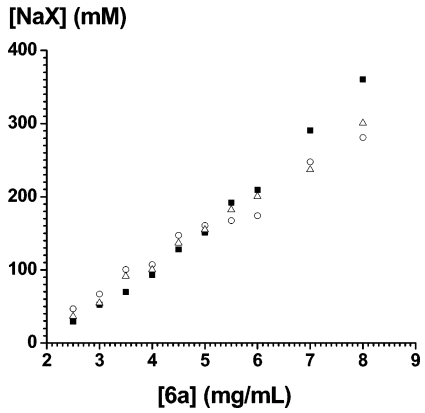


Figure 3. Minimum concentrations of sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylate **6a** required to gel DMSO, as a function of the concentration of added NaI (○), $NaOSO_2CF_3$ (■), and $NaBF_4$ (△).

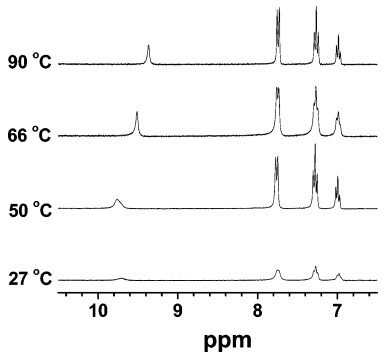


Figure 4. Downfield region of ^{1}H NMR spectra of sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylate **6a** in DMSO-d_6 at 27 °C (below T_{gel}), 50 °C (below T_{gel}), 66 °C (near T_{gel}), and 90 °C (above T_{gel}).

between gelators or by interfering with their ionic interactions with Na^+.

Spectroscopic Studies of Gels Formed in DMSO by Sodium 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylates 6a−g. In a representative study, ^{1}H NMR spectra of samples of parent salt **6a** were recorded in DMSO-d_6 at 27 °C (below T_{gel}), 50 °C (below T_{gel}), 66 °C (near T_{gel}), and 90 °C (above T_{gel}), and the downfield regions are shown in Figure 4. Resolution of the aromatic peaks increased with temperature, presumably because rotation around the exocyclic C−NHAr bonds of (arylamino)triazine units becomes faster.[10] Pronounced upfield shifts of the N−H signals, from δ 9.71 in the gel (both at 27 and 50 °C) to δ 9.37 in solution at 90 °C, are consistent with disrupted hydrogen bonding, leading to lower ordering of the gelator at higher temperatures. Broad absorption in the N−H stretching region made complementary studies of association by FTIR spectroscopy uninformative.

Morphology of Gels Formed in DMSO by Sodium 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylates 6a−g. The morphology of gels produced by sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylates **6a−g** was examined by optical microscopy, variable-pressure scanning electron microscopy (SEM), field-emission SEM, and atomic force microscopy (AFM). Representative micrographs of samples containing parent salt **6a** are shown in Figures 5−8, and further images are provided in the Supporting Information. The optical micrograph in Figure 5a corresponds to the native gel at 27 °C, and Figure 5b shows the appearance after extensive removal of DMSO by evaporation at 200 °C.[16] Under both conditions, the samples contain tight mats of distinct fibers, which are particularly evident on the periphery of the dried sample (Figure 5b). The similarity of images obtained under different conditions suggests that the creation of fibrous networks is a characteristic and persistent feature of the self-assembly of salts **6a−g** in DMSO.

Additional images of gels produced by dissolving sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylates **6a−g** in DMSO were obtained by variable-pressure SEM under conditions of relatively high pressure (30−50 Pa) to ensure slow evaporation of DMSO and minimal deviation of samples from their native gelled states. Figure 6a confirms that parent salt **6a** again forms networks of fibers under these conditions. Figure 6b shows the fibers at higher magnification and establishes that they are approximately 0.2 μm in width and 5 μm in length. Variable-pressure SEM micrographs of gels formed by sodium salts **6c** (3.0 mg/mL) and **6e** (1.5 mg/mL) both show similar networks of fibers.[17]

More detailed images, obtained by field-emission SEM using uncoated samples (Figure 7), confirm that the basic fibrous structure is maintained when the gel is exposed to high vacuum, and they reveal that the coarse fibers shown at low resolution in Figures 5 and 6 are in fact spaghetti-like bundles of finer elemental fibers, with widths of about 50−100 nm. Similarly, images obtained by AFM, using samples of gel formed by sodium salt **6b** (3.0 mg/mL) spin-cast on quartz, showed bundles of small fibers approximately 30 nm in diameter (Figure 8).

Crystallization of Sodium 4,6-Bis(arylamino)-1,3,5-triazine-2-carboxylate (6b) from DMSO and Determination of Its Structure by X-ray Diffraction. 1,5-Diphenylbiguanide (**3a**) and its monohydrochloride (**3a**·HCl) are amphiphilic molecules that have a close structural relationship to 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylic acids **5a−k**, esters **4a−k**, and salts **6a−k**. Biguanide **3a**, salt **3a**·HCl, and related compounds are known to crystallize to form

(16) Analysis by ^{1}H NMR spectroscopy confirmed that sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylates did not decompose during the formation of xerogels.

(17) For additional images, see the Supporting Information.

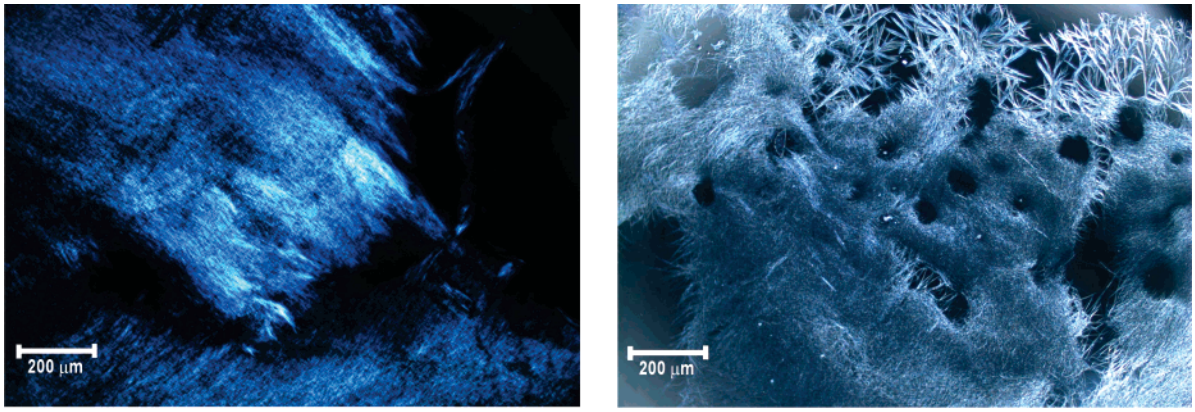


Figure 5. (a) Dark-field optical micrograph of the native gel formed by a 3.0 mg/mL solution of sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylate **6a** in DMSO at 27 °C. (b) Optical micrograph showing a similar sample after extensive removal of DMSO by evaporation at 200 °C.

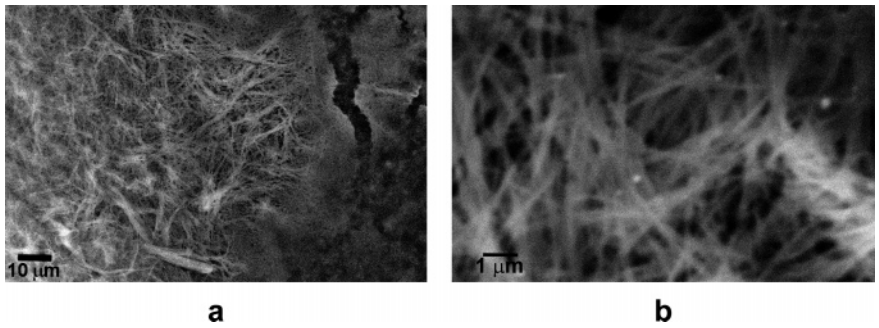


Figure 6. Variable-pressure scanning electron micrographs obtained at relatively high pressure (30−50 Pa), showing the fibrous network structure of the gel formed by a 3.0 mg/mL solution of sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylate **6a** in DMSO at 27 °C. Micrographs a and b correspond to enlargements of 1000-fold and 10 000-fold, respectively.

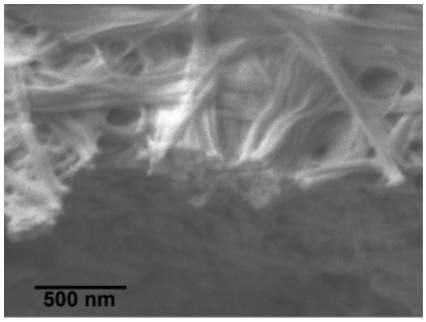


Figure 7. Field-emission scanning electron micrograph of an uncoated sample prepared by drying the gel formed by dissolving sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylate **6a** in DMSO (3.0 mg/mL). The image reveals that the fibrous networks shown in Figures 5 and 6 are composed of elemental nanofibers.

networks constructed from bilayers, with hydrophobic aryl tails interacting to form the core and polar biguanide headgroups aligned on the surface.[10] The bilayers then stack in a process controlled in part by multiple intermolecular hydrogen bonds formed by the biguanide units, which either interact directly (in the case of neutral biguanides) or indirectly via bridging chloride ions (in the case of biguanidinium hydrochlorides). Such molecules therefore incorporate chimeric features expected to give rise to materials near the boundary between gels and crystalline solids. Specifically, they have amphiphilic structures composed of a hydrophobic aromatic domain and a polar headgroup, as frequently encountered among gelators. On the other hand, their structures are compact, relatively rigid, symmetric, nearly planar, and able to associate with neighbors according to well-established directional interactions, as typically seen in molecules used to engineer crystalline solids with predictable structures.

The structures of analogues **3a** and **3a**·HCl, as well as those of other hydrogen-bonded networks derived from diaminotriazines,[5,9] strongly suggest that the elemental supramolecular nanofibers observed directly by SEM and AFM in gels formed by sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylates **6a**−**g** are assembled analogously from bilayers held together by the combined forces of hydrogen bonding, aryl interactions, and specific coordination of Na^+. To test this hypothesis, we attempted to grow crystals of salts of 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylic acids and determine their structure. After much effort, we found that we could induce the gel prepared by dissolving sodium salt **6b** in DMSO to deposit crystals of the gelator in the form of tiny needles, which proved to be suitable for X-ray diffraction using an instrument equipped with a rotating anode source and special focusing optics. Obtaining suitable crystals of a known gelator directly from its gel is a very unusual achievement,[3] and it makes the resulting structure particularly likely to reveal how the gel itself is organized.

Crystals of salt **6b** were found to belong to the monoclinic space group $P2_1/c$ and to correspond to an inclusion compound of composition **6b**·2DMSO. Views of the structure appear in Figures 9−12. Like analogous 1,5-diarylbiguanides and their salts, salt **6b** favors a conformation **I** in which both aryl substituents are directed away from the polar

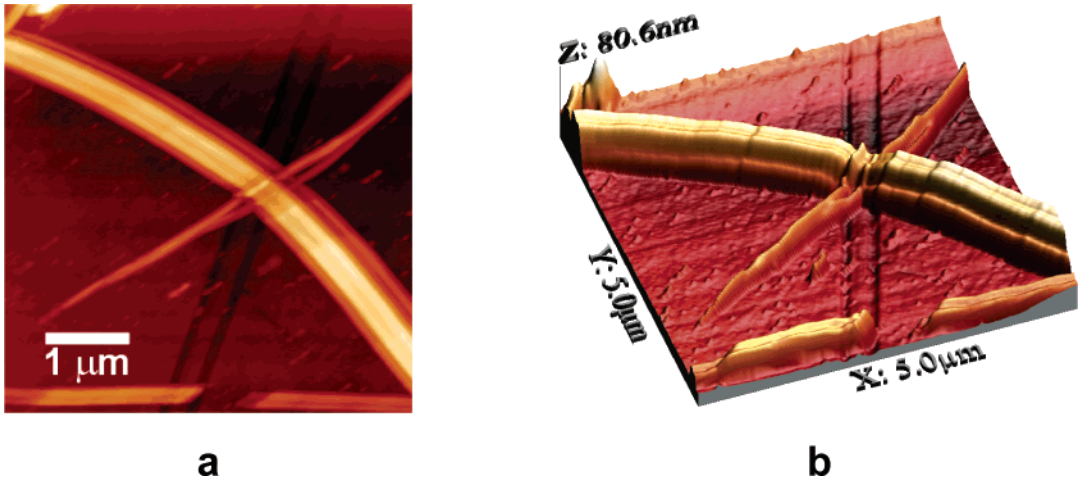


Figure 8. Tapping-mode atomic force micrographs of gel fibers spin-cast onto quartz from a 3.0 mg/mL solution of sodium 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylate **6b** in DMSO. The images were recorded under reduced pressure (10^{-6} Torr). Micrographs a and b correspond to two- and three-dimensional views of a bundle of fibers. The elemental nanofibers that compose the bundle are approximately 30 nm in diameter.

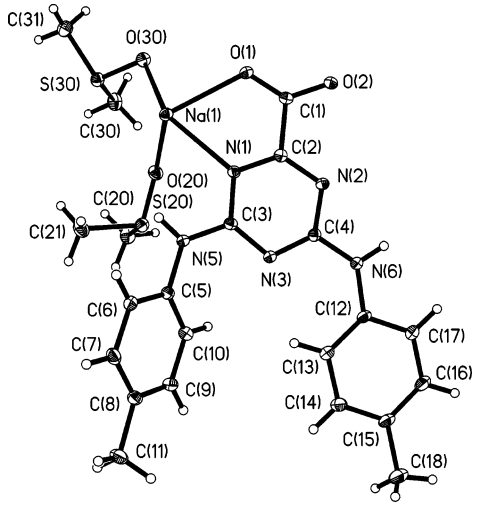


Figure 9. View of the structure of sodium 4,6-bis[(4-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (**6b**) when crystallized from the gel it forms in DMSO. Displacement ellipsoids are drawn at the 30% probability level, and hydrogen atoms are represented by spheres of arbitrary radius.

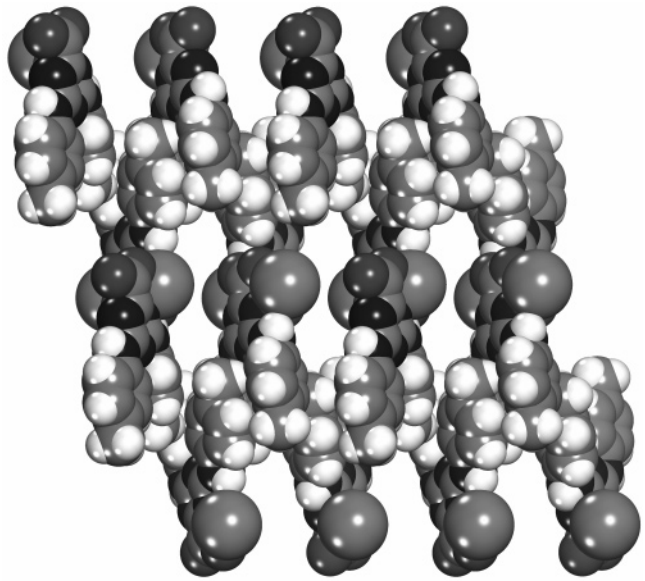


Figure 10. View along the *b* axis of the structure of crystals of sodium 4,6-bis[(4-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (**6b**) as obtained from its gel in DMSO. The image reveals distinct bilayers in the *bc* plane, with hydrophobic aryl cores and polar triazinecarboxylate headgroups. The view shows a 1 × 1 × 2 array of unit cells with atoms represented by spheres of van der Waals radii. Atoms of hydrogen appear in white, carbon and sodium in light gray, oxygen in dark gray, and nitrogen in black. Molecules of DMSO have been omitted for clarity.

headgroup rather than alternatives **II** or **III** (Figure 9). The aryl groups in conformation **I** are too far apart to interact intramolecularly, but their orientation enhances the amphiphilic nature of compound **6b** and favors the assembly of bilayers characteristic of analogous biguanides and their salts. As expected, the observed C−N bond lengths are similar to those found in other aminotriazines, the carboxylate group lies close to the plane of the triazine ring (dihedral angle 8.1(1)°), hybridization of the exocyclic N atoms is sp^2, and the N−H and N−Ar bonds in each −NHAr group lie close to the plane of the triazine ring. One of the aryl substituents is essentially coplanar, whereas the other forms an angle of 41.4(1)° with the triazine ring.

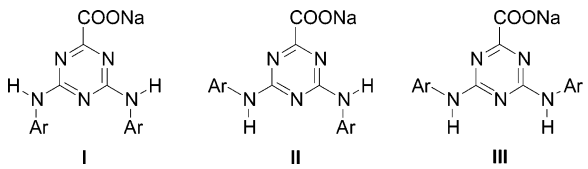


Figure 10 confirms that the structure of salt **6b** can be considered to consist of bilayers with polar surfaces and hydrophobic interiors featuring intermolecular aryl interactions similar to those observed in related biguanides and biguanidinium salts.[10] An additional view of the aryl interactions is provided by Figure 11. Similar compact arrangements of aryl groups can presumably be attained with the parent salt **6a** and the other *para*-substituted derivatives **6c**−**g** but not with *ortho*- and *meta*-substituted analogues. This accounts for the failure of compounds **6h**−**k** to serve as gelators.

The bilayers lie perpendicular to the *a* axis, and their polar surfaces stack along the *a* axis in a process directed by the formation of multiple hydrogen bonds and coordination of Na^+ (Figure 12). Each Na^+ bridges two molecules of salt **6b**, which serve as bidentate ligands in which Na^+ is chelated by an O atom provided by COO^- and by an adjacent N atom of the triazine ring. In addition, each Na^+ binds two

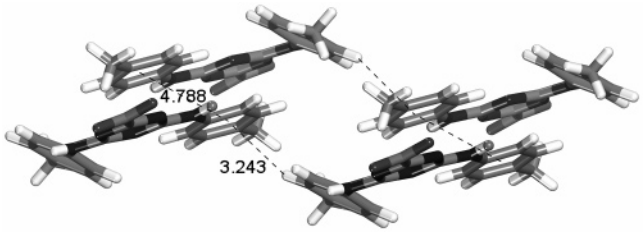


Figure 11. View along the *a* axis of the structure of crystals of sodium 4,6-bis[(4-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (**6b**) as obtained from its gel in DMSO. The image provides a detailed view of aromatic interactions in the bilayers. In each molecule, the aryl group closest to the plane of the triazine ring participates in a face-to-face aromatic interaction with the corresponding aryl group of a neighboring molecule. The aryl group that lies out of the plane of the triazine ring engages in an edge-to-face aromatic interaction with the other aryl group of another molecule. Center-to-center and H-to-center distances for the aromatic interactions are shown in Å, and molecules of DMSO have been omitted for clarity.

molecules of DMSO (Figure 12b). Each carboxylate group interacts with two Na^+ ions and simultaneously accepts an intermolecular hydrogen bond donated by a nearby −NHAr group. The donors are the −NHAr groups with aryl substituents that lie closest to the plane of the triazine ring, and the other −NHAr group of each molecule does not participate in hydrogen bonding. In the resulting structure, the multipoint binding of Na^+, the particular geometry of its chelation, and the inclusion of coordinated DMSO help explain why gelation is selective and occurs only when (1) significant quantities of DMSO are present and (2) suitable 4,6-bis-(arylamino)-1,3,5-triazine-2-carboxylates are in the form of their Na^+ salts.

Unfortunately, we were unable to establish an unambiguous correlation between the structure of salt **6b**, as determined by single-crystal X-ray diffraction, and that of its gel, as revealed by studies using X-ray powder diffraction under various conditions. In the native gel, low crystallinity and scattering from retained DMSO prevented us from obtaining useful data, whereas dried samples gave inconsistent powder diffraction patterns, presumably because molecules of DMSO critical for maintaining crystallinity were lost. Nevertheless, features that appear in the structure of sodium 4,6-bis-(arylamino)-1,3,5-triazine-2-carboxylate **6b** account neatly for the characteristic morphology of the gels formed by all salts **6a**−**g**. In particular, growth of crystals with the characteristic bilayer structure shown in Figure 10 may be relatively slow in the *a* and *b* directions, which are especially rich in sites for hydrogen bonding, coordination of Na^+, and interaction with DMSO. Figure 12 reveals that the aryl groups are largely confined to the *ab* plane, making the corresponding surface one of high energy in DMSO and favoring the formation of fibers by rapid growth along *c*. As a result, we suggest that the elemental nanofibers observed by field-emission SEM and AFM have a similar internal structure and that their characteristic morphology results logically from the need to minimize surfaces most weakly solvated by DMSO. The widths of the nanofibers (which correspond to slow growth along the *a* and *b* axes) are equivalent to approximately 50 unit cells, and their lengths (which result from fast growth along the *c* axis) typically exceed 1000 unit cells. Partial desolvation of the polar surfaces perpendicular to the *c* axis should create potential points of junction where the fibers can associate by hydrogen bonding and coordination of Na^+, leading to the formation of cross links and aggregation in bundles, as shown in Figures 7 and 8.

When previous studies of gelation have reported structural studies using single-crystal X-ray diffraction, the crystals investigated have typically been those of gelators grown under conditions where gelation does not occur or they have been those of nongelators with related structures. Although such studies are of interest, they do not necessarily reveal the true structure of the gels. In contrast, we have solved the structure of a gelator crystallized directly from its gel. Moreover, the gross structural features observed, including the amphiphilic nature of salt **6b**, its organization in bilayers, and the intermolecular association of its polar headgroup by

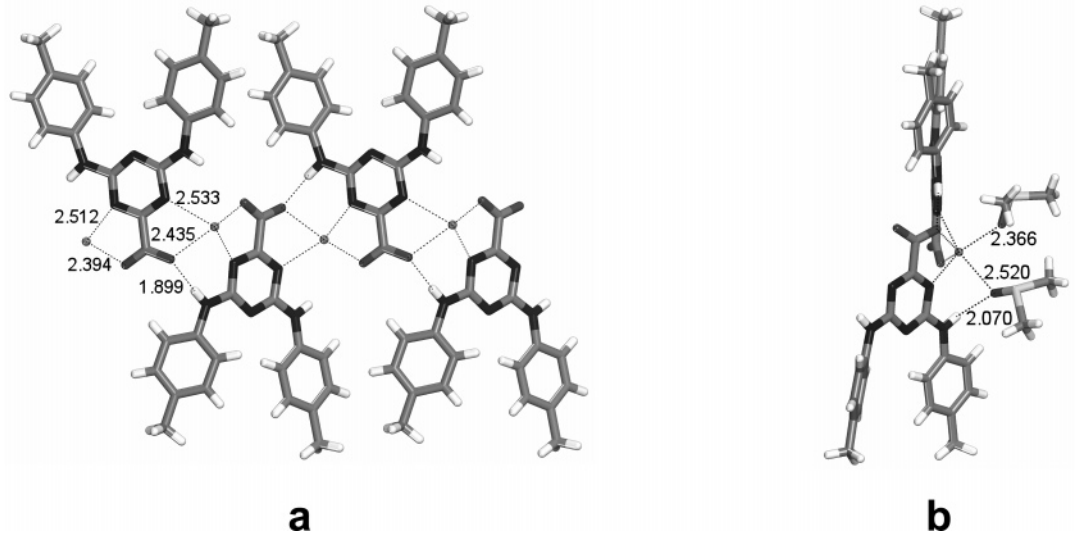


Figure 12. (a) View along the *c* axis of the structure of crystals of sodium 4,6-bis[(4-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (**6b**) as obtained from its gel in DMSO. The image shows how the polar triazinecarboxylate headgroups interact by forming hydrogen bonding and chelating Na^+. The view establishes that these interactions are confined primarily to the *ab* plane. Important O−Na, N−Na, and O···H distances are shown in Å. (b) View along the *b* axis, showing how the included molecules of DMSO are bound by hydrogen bonding and coordination to Na^+. Key O−Na and O···H distances are given in Å.

hydrogen bonding and ionic interactions, are closely analogous to those observed in a series of related structures.[10] Finally, the observed structure accounts persuasively for every characteristic feature of the gels, including (1) the failure of *ortho*- and *meta*-substituted analogues **6h**−**k** to serve as gelators, (2) the selective gelation of DMSO, (3) the need for Na^+ salts of 4,6-bis(arylamino)-1,3,5-triazine-2-carboxylates, and (4) the formation of long nanofibers. The ability of the observed structure to account for all of these features suggests that the crystals and the native gel have closely similar architectures.

Conclusions

Our work demonstrates how new low-molecular-weight gelators can be discovered by an approach that integrates classical methods for identifying potential gelators with strategies recently developed by crystal engineers to build porous molecular networks. This hybrid approach has yielded a new class of gelators based on salts of diaminotriazinecarboxylic acids. These compounds do not require the high degree of conformational flexibility and long alkyl chains found in many other gelators, and their mechanism of gelation shows a selective dependence on Na^+ and DMSO. We have acquired a detailed understanding of the morphology and underlying molecular structure of the resulting gels by using a combination of microscopy and X-ray diffraction, which has allowed us to solve the structure of crystals of a gelator obtained directly from its gel. The hybrid approach that led to the discovery of these gelators promises to yield other new molecular materials at the boundary between gels and crystalline solids.

Acknowledgment. We are grateful to the Natural Sciences and Engineering Research Council of Canada, the Ministère de l'Éducation du Québec, the Canada Foundation for Innovation, and the Canada Research Chairs Program for financial support. In addition, we thank Prof. Jurgen Sygusch for providing access to a Bruker SMART 6000 CCD diffractometer equipped with a rotating anode. We are also grateful to Dr. Alexandra Furtos for obtaining mass spectra and to Dr. Ji-Hyun (Daniel) Yi for recording AFM images.

Supporting Information Available: Additional SEM and AFM images and further crystallographic details, including ORTEP drawings and tables of crystallographic data, atomic coordinates, anisotropic thermal parameters, and bond lengths and angles for sodium 4,6-bis[(4-methylphenyl)amino]-1,3,5-triazine-2-carboxylate (**6b**). This material is available free of charge via the Internet at http://pubs.acs.org.

CM060056D