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Pyrene appended bile acid conjugates: Synthesis and a structure–gelation property study

SHREEDHAR BHAT[a,b], ARTO VALKONEN[a], JUHA KOIVUKORPI[a], ANUPAMA AMBIKA[b], ERKKI KOLEHMAINEN[a,*], UDAY MAITRA[b,*] and KARI RISSANEN[a,*]

[a]Department of Chemistry, Nanoscience Center, University of Jyväskylä, 40014 Jyväskylä, Finland
[b]Department of Organic Chemistry, Indian Institute of Science, Bangalore 560 012, India
e-mail: erkki.t.kolehmainen@jyu.fi; maitra@orgchem.iisc.ernet.in; kari.t.rissanen@jyu.fi

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Abstract. A wide variety of novel compounds obtained by combining two types of known organogelators, viz., bile acid alkyl amides and pyrene alkanoic acids, were synthesized and screened for their gelation ability. The 3α esters of 1-pyrene butyric acid (PBA) of alkylamides of deoxycholic acid (DCA) turned out to be effective in the gel formation with many organic solvents although the gelation has to be triggered by the addition of a charge transfer (CT) agent 2,4,7-trinitrofluorenone (TNF). The special feature of these molecules is that the organogelation is achieved only after derivatizing the acid moiety of the 1-pyrenealkanoic acids. Additionally, the gelation properties can be fine-tuned by inserting different functional groups at the bile acid side chain. The gels obtained are deep red in colour and optically transparent up to 2% w/v. The SEM studies of the obtained xerogels revealed bundled rod-like morphology without specialized branching.

Keywords. Pyrene; bile acid; 2,4,7-trinitrofluorenone; two component gel; scanning electron microscopy.

1. Introduction

'Gels' are classified in many ways.[1] An 'organogel' is a poorly-crystalline, non-glassy thermoreversible solid-like material composed of a liquid organic phase entrapped in a structured network.[2] The liquid can be e.g., an organic solvent, a mineral oil or a vegetable oil. Organogels can be either derived from a polymer or from small molecules. These molecules self-assemble into elongated fibrous structures through highly specific molecular interactions in an organic solvent. The gelling agents, so called 'small molecule gelling agents' are gaining popularity in the gelling of a wide range of organic solvents to form organogels,[3] which are attractive materials for many applications. Many of the low molecular weight organogelators (LMOGs) display thixotropy — they become fluid when agitated, but resolidify when resting. During the past two decades, a wide range of LMOGs have been discovered that range from alkanes[4] to alkanoic acids, steroids to vitamin C,[5] nucleosides to DNA.[6] The gelation process necessarily creates novel fibrous supramolecular structures which can be characterized by microscopy and scattering studies. Applications of organogels include, among many others,[7] drug delivery.[8] By replacing the liquid with a gas it is possible to prepare aerogels, materials with exceptional properties including very low density, high specific surface areas, and excellent thermal insulation properties.[9]

The exact mechanism of the gelation of organic solvents by LMOGs is not known. Although it is generally accepted that intermolecular forces such as H-bonding,[10] electrostatic attractions and/or π–π stacking interactions are necessary to stabilize LMOG assemblies. It has also been demonstrated that London dispersion forces alone can be sufficient.[11] The large variety of structurally different gelators show that H-bonding, but also electrostatic, π–π or charge transfer interactions may lead to self-assembling networks build up from long often entangled fibres (whiskers).[12] Furthermore, it has been shown that appropriate gelators can physically form liquid crystalline phases.[13]

The gelation properties can be modified by both chemical and physical means. Chemically, the gelation process can be controlled by pH, ionic strength and additives.[14] Stimuli-responsive assembly of low molecular weight materials (MW < 1000) have been intensively studied in gels, micelles, vesicles, and synthetic membranes.[15] Sound,[16,17] light[18–20] and electrochemical

*For correspondence

controls[21] have been explored as a means of switching molecular aggregations without the use of chemical stimuli. However, providing a method of control that is instant, positive (i.e., converting sol to aggregate), and reversible, while also being versatile and practical, remains a challenge.

Moreover, organogels commonly suffer from instability, for instance, due to crystallization or lack of mechanical robustness. Furthermore, despite major achievements in supramolecular chemistry to achieve controlled self-assembly of organic molecules,[22] until now most low molecular weight gelators have been found by serendipity rather than by design. Recently, Hanabusa *et al.*,[23] Feringa *et al.*[24] as well as Maitra *et al.*[25] succeeded in the systematic design of novel gelators for organic solvents by exploiting the self-assembling properties of amide, urea and urethane groups.[26]

Our interest on the design of new materials prompted us to connect the existing gelator motifs into hybrid structures and study their gelation properties in solution. We envisioned that by adding a pyrene moiety into a bile acid derived organogelators would lead to an interesting new type of molecules that could give rise to novel self-assembling systems. Our previous reports introduce CT gelation of pyrene analogues. In this article, we describe the 'structure–gelation' property of a new class of gelators designed by covalently linking the two well-known gelator moieties (viz., derived from pyrene and bile acid).

2. Experimental

2.1 *Methods*

2.1a *Spectroscopy*: Absorption spectra were recorded on a Shimadzu UV2100 spectrometer equipped with a thermoelectric variable-temperature set-up. FT-IR spectra were recorded on a Jasco-70 FT-IR spectrometer or on a Perkin Elmer Spectrum GX FT-IR spectrophotometer either by making a thin film of the compounds on a NaCl plate from a chloroform solution or using KBr pellets. One-dimensional ^{1}H, ^{13}C, and ^{13}C DEPT-135 NMR spectra were recorded in dilute $CDCl_3$-solutions at 30°C with Bruker Avance DRX 500 (or DPX 250) FT NMR spectrometer equipped with an inverse detection dual probehead (BBI) and z-gradient accessory working at 500.13 MHz for proton and at 125.77 for carbon-13, respectively. The ^{1}H and ^{13}C chemical shifts were referenced to the signal of internal TMS ($\delta = 0.00$ ppm). Variable temperature (VT) H and ^{13}C NMR spectra were recorded on a JEOL 300 MHz spectrometer. ESI-QTOF MS spectra were recorded on a Micromass Q-TOF micro mass spectrometer. The gelation tests were carried out in pyrex test tubes with a diameter of 8 mm and a length of 70 mm.

2.1b *Gelation tests*: The compound and powdered TNF (typically 1:1, $C_{gelator}$ 1% w/v) were mixed in a test tube. The suspension in the corresponding solvent was warmed on a water bath maintained at 90°C until all the solid material dissolved forming a clear solution. The hot sol was allowed to gel at ambient temperature without external disturbance. For SEM imaging, the samples were prepared by placing 10 μL of a hot solution on a carbon tape pasted on sample stubs, and after drying the samples for 24 h they were subjected to gold coating using DC sputtering (50 Å) for 38 s and examined using a *QUANTA 200* scanning electron microscope with a single crystal of LaB6 as the emitter.

2.1c *Gel melting*: The gel–sol transition behaviour was characterized by gel melting. The gel melting was estimated by the 'inverted test tube' method. Briefly, gels were made in 8 mm × 70 mm tubes, sealed at the open end, and placed upside down in a water/oil bath whose temperature was increased slowly (2°C/min). The temperature at which the gel fell was recorded as $T_{gel,-sol}$ which was usually within ± 2°C in multiple measurements.

2.2 *Materials*

2.2a *General*: All the glassware were acid rinsed prior to wash with deionized water and dried in a hot oven. All the organic solvents were analytical grade or were distilled prior to use. Chloroform and dichloromethane were distilled over CaH_2, THF and toluene over sodium/benzophenone ketyl, and pyridine and Et_3N over KOH, respectively. All the reagents were purchased from Aldrich and used as received. 1-Pyrene carboxylic acid and 1-aminopyrene were prepared starting from pyrene as reported earlier.[23b] 1-Pyrene butyric acid and 1-pyrene dodecanoic acid were prepared according to our previous reports.[27] TLC was performed on pre-coated silica gel plates (Merck) and stained with iodine vapour, or with LB (Liebermann Buchard) stain, or observed under UV light. Column chromatography was carried out on 100 ± 200 mesh silica gel on gravity columns.

2.2b *Compound* ***4***: 3,7,12-Triformylcholic acid (0.25, 0.50 mmol, m.p. 204–205°C),[28] hexadecyalamine (0.15 g, 0.62 mmol) and DMAP (6 mg, 0.05 mmol) were dissolved in dry DCM. To this stirring mixture was added DCC (0.124 g, 0.6 mmol) pinch by pinch for 2 minutes. The resulting mixture was stirred further for 12 h. The dicyclohexyl urea (DCU) precipitates were filtered and the filtrated was diluted with 10 mL of DCM. The DCM layer was washed with saturated $NaHCO_3$ solution (2 × 5 mL) and water (2 × 5 mL). The organic layer was dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The product obtained was further purified by column chromatography over silica gel with EtOAc/DCM as eluent. The final product was obtained as a white solid (0.22 g, Yield 60%), m.p. 45–46°C. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 1177, 1644, 1723, 1645, 1724, 2854, 2926, 3313. ^{1}H NMR (250 MHz, $CDCl_3$): δ 0.75 (s, 3H), 0.83–0.90 (m, 6H), 1.25 (br s, 22 H), 1.28–2.16 (steroidal CH, CH_2, alky CH2), 3.23 (m, 1H), 4.71 (m, 1H), 5.054 (d, J = 2.5 Hz, 1H), 5.26 (br s, 1H), 5.35 (m, 1H). ^{13}C NMR (63 MHz,$CDCl_3$): δ 12.16, 14.07, 17.60, 22.33, 22.66, 22.79, 25.57, 26.91, 27.19, 28.58, 29.28, 29.33, 29.53, 29.57, 29.63, 29.67, 31.35, 31.47, 31.90, 32.77, 33.53, 34.29, 34.47, 34.53, 34.85, 37.76, 39.53, 40.83, 42.97, 45.04, 47.38, 70.69, 73.73, 76.49, 160.50, 172.95.

2.2c *Compound* ***5***: 3,12-Diformyl deoxycholic acid (0.25 g, 0.5 mmol),[29] hexadecyalamine (0.15, 0.62 mmol), and DMAP (6 mg, 0.05 mmol) were dissolved in dry DCM. To this stirring mixture was added DCC (0.124 g, 0.6 mmol) pinch by pinch for 2 minutes. The resulting mixture was stirred further for 12 h. The DCU formed were filtered and the filtrated was diluted with 10 mL of DCM. The DCM layer was washed with saturated $NaHCO_3$ (2 × 5 mL) and water (2 × 5 mL). Dried over anhydr. Na_2SO_4 and concentrated under reduced pressure (0.25 g, m.p. 61–63°C). Then, the crude material was directly subjected to deformylation reaction by stirring the methanolic solution of triformyl amide over K_2CO_3 (0.40 g, 2.9 mmol) for 4–5 h. After the reaction the suspension was filtered and the filtrate was concentrated under reduced pressure. The crude material was extracted into ethyl acetate (15 mL) and washed with saturated solution of $NaHCO_3$ (2 × 5 mL) and water (2 × 5 mL). The organic layer was dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The product obtained was further purified by column chromatography over silica gel with EtOH/DCM as eluent. The final product was obtained as a white solid (0.185 g, Yield 85%), m.p. 85–87°C. Anal. Calcd. (%) for $C_{40}H_{73}NO_3 + 11/2\ H_2O$: C, 74.71; H, 11.92; N, 2.18. found C-74.43, H-11.95, N-2.60. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 1044, 1378, 1467, 1643, 2850, 2621, 3400 cm^{-1}. ^{1}H NMR (250 MHz, $CDCl_3$): $\delta = 0.679$ (s, 3H), 0.807–0.911 (m, 6H), 0.981 (d, J = 6.0 Hz, 3H), 1.02–1.19 (m, 4H), 1.26 (br s, 30H), 1.3–1.9 (m, steroidal CH, CH_2 and alkyl), 3.21(m, 2H), 3.59 (m, 1H), 3.97 (br s, 1H), 5.36 (m, 1H). LRMS (ESI): m/z found 639.02. HRMS (ESI): m/z Calcd. for $C_{40}H_{73}NO_3Na$ 638.5488; found 638.5507.

2.2d *Compound* ***6***: Hexadecyl 3,7,12-triformylcholamide (0.20, 0.28 mmol) was stirred over K_2CO_3 (0.38, 2.8 mmol) in 2.0 mL MeOH for 4–5 h. After the reaction the suspension was filtered and the filtrate was concentrated under reduced pressure. The crude material was extracted into ethyl acetate (15 mL) and washed with saturated solution of $NaHCO_3$ (2 × 5 mL) and water (2 × 5 mL). The organic layer was dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The product obtained was further purified by column chromatography over silica gel with EtOH/DCM as eluent. The final product was obtained as a white solid (0.15 g, Yield 85%), m.p. 81–83°C. Anal. Calcd. (%) for $C_{40}H_{73}NO_4 + 1/2\ H_2O$: C, 74.95; H, 11.64; N, 2.18; found C, 75.03; H, 11.65, N, 1.97. ^{1}H NMR (250 MHz, $CDCl_3$): δ 0.667 (s, 3H Me-18), 0.84–0.87 (br s, triplet merged to singlet, 6H), 0.982 (d, J = 5.75 Hz, 3H), 1.25 (br s, 22H), 1.3–2.22 (m, steroidal, CH, CH2 and alkyl CH2), 2.84 (br s, 4H), 3.22 (m, 2H), 3.43 (m, 1H), 3.82 (br s, 1H), 3.95 (br s, 1H), 5.95 (m, 1H). ^{13}C NMR (63 MHz,$CDCl_3$): δ 12.47, 14.08, 17.45, 22.43, 22.66, 23.26, 26.39, 26.98, 27.56, 28.15, 29.34, 29.59, 29.64, 29.69, 30.42, 31.74, 33.14, 34.75, 35.32, 39.48, 39.58, 39.66, 41.54, 41.69, 46.40, 46.56, 68.48, 71.90, 73.12, 173.92. HRMS (ESI): m/z Calcd. for $C_{40}H_{73}NO_4 + Na$: 655.5471; found 655.5519.

2.2e *Compound* ***7***: 3,7,12-Triacetyl cholic acid (1.00 g, 1.85 mmol),[30] DCC (0.46 g, 2.22 mmol) and DMAP (23 mg, 0.186 mmol) were dissolved in dry DCM (10 mL). To this stirred mixture was added isopropylamine (0.19 mL, 2.22 mmol) drop-wise for 5 minutes. The resulting mixture was stirred for additional 12 h. The DCU formed were filtered and the filtrate was diluted with 10 mL of DCM. The DCM layer was washed with sat. $NaHCO_3$ (2 × 5 mL) and water (2 × 5 mL). The DCM layer was dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The crude material was further purified by column

chromatography over silica gel using EtOAc/DCM as the eluent. The pure white product was obtained as a solid powder (0.58 g, Yield 55%), m.p. 92–93°C, Anal. Calcd. (%) for $C_{33}H_{53}NO_7 + 1\ H_2O$: C-66.75, H- 9.33, N- 2.35; found C-66.67, H-9.15, N- 2.40. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 1024, 1248, 1377, 1537, 1647, 1736, 2872, 2943, 2965, 3315, 3385 cm^{-1}. ^1H NMR (250 MHz, $CDCl_3$): δ 0.700 (s, 3H Me-18), 0.792 (d, J = 6.25 Hz, 3H Me-21), 0.888 (s, 3H Me-19), 1.20–1.99 (steroidal, CH, CH_2) 2.01 (s, 3H), 2.05 (s, 3H), 2.12 (s, 3H), 4.05 (m, 1H), 4.55 (m, 1H), 4.88 (d, J = 2.75 Hz, 1H), 5.06 (br s, 1H), 5.278 (d, J = 7.75 Hz, 1H). ^{13}C NMR (63 MHz,$CDCl_3$): δ 12.43, 14.38, 16.87, 21.20, 21.60, 21.64, 21.77, 22.74, 22.97, 23.01, 25.77, 27.08, 27.43, 29.09, 31.45, 31.81, 33.93, 34.53, 34.83, 34.91, 34.97, 37.97, 41.16, 41.39, 43.59, 46.41, 47.73, 60.54, 70.89, 74.27, 75.62,170.49, 170.65, 170.67, 172.51. HRMS (ESI): m/z Calcd. for $C_{33}H_{53}NO_7 + Na$: 598.3687; found 598.3675.

2.2f *Compound **8***: A mixture containing *iso*-propyltriacetyl cholamide (0.25 g, 0.43 mmol), KOH (0.25 g, 4.5 mmol) and MeOH (2.0 mL) were refluxed at 80°C for 8–10 h. After completion (monitored by TLC), the reaction mixture was cooled in ice bath and neutralized with dil. HCl. The product was extracted into chloroform (15 mL) and washed with saturated solution of $NaHCO_3$ (2 × 5 mL) and water (2 × 5 mL), dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The product obtained was further purified by chromatography over silica gel with EtOH/DCM as eluent (0.15 g, Yield 75%), m.p. 242–244°C. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 732, 1078, 1464, 1547, 1646, 2866, 2929, 3410, 3432 cm^{-1}. Anal. Calcd. (%) for $C_{27}H_{47}NO_4 + 2$ 1/2 H_2O: C, 65.68; H, 10.41; N, 2.83; found C, 65.78; H, 9.70; N, 1.99. ^1H NMR (250 MHz, $CDCl_3$): δ 0.671 (s, 3H Me-18), 0.876 (s, 3H Me-19), 0.984 (d, J = 6.3 Hz Me-21), 1.129 (d, J = 6.5 Hz, 6H), 1.26–2.30 (m, steroidal, CH, CH2), 2.62 (br s, 4H). 3.43 (m, 1H), 3.823 (d, J = 2.25 Hz, 1H), 3.96 (br s, 1H), 4.07 (m, 1H), 5.57 (d, J = 7.75 Hz, 1H).[13] C NMR (63 MHz,$CDCl_3$): δ 12.71, 17.70, 22.68, 22.99, 23.47, 26.66, 27.80, 28.43, 30.74, 31.92, 33.70, 34.97, 35.60, 35.61, 39.73, 39.89, 41.39, 41.75, 41.98, 46.68, 46.96, 68.67, 72.14, 73.30, 173.16. HRMS (ESI): m/z Calcd. for $C_{27}H_{47}NO_4 + Na$: 473.3436; found 473.3447.

2.2g *Compound **10***: *Iso*-Propyl cholamide (0.27 g, 0.60 mmol), 12-(1-pyrene) dodecanoic acid (0.12 g, 0.30 mmol) and DMAP (4 mg, 0.03 mmol) were mixed with dry DCM. To this stirring mixture was added DCC (0.062 g, 0.3 mmol) pinch by pinch for few minutes. The resulting solution was stirred for 5 h. DCU was removed by filtration and the filtrate was diluted with 10 mL of DCM. DCM layer was washed with saturated $NaHCO_3$ solution (2 × 5 mL) and water (2 × 5 mL). The organic layer was dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The product obtained was further purified by column chromatography over silica gel with EtOAc/DCM as eluent. The final product was obtained as pale yellow foam (0.052 g, Yield 11%), m.p. 86–87°C. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 845, 1182, 1543, 1727, 2853, 2927, 3326, 3445. Anal. Calcd. (%) for $C_{55}H_{77}NO_4 + 1\ H_2O$: C, 77.70; H, 9.36; N, 1.65; found C, 77.70; H, 9.06; N, 1.99. ^1H NMR (250 MHz $CDCl_3$): δ 0.67 (s, 3H Me-18), 0.88 (s, 3H Me-19), 0.97 (d, J = 6 Hz, 3H Me-21), 1.13 (d, J = 6.5 Hz, 6H), 1.22–2.33 (steroidal CH, CH_2 and alkyl CH_2), 3.27 (t, J = 7.5 Hz, 2H), 3.81 (brs, 1H), 3.95 (br s, 1H), 4.08 (m, 1H), 4.58 (m, 1H), 5.35 (d, J = 7.5 Hz, 1H), 7.86 (d, J = 8 Hz, 1H), 7.93–8.17 (m, 7H), 8.28 (d, J = 10 Hz). ^{13}C NMR (63 MHz,$CDCl_3$): δ 12.73, 14.40, 17.66, 21.23, 22.67, 23.00, 23.37, 25.15, 25.28, 25.84, 26.88, 26.96, 27.72, 28.49, 29.37, 29.46, 29.63, 29.78, 30.02, 31.79, 32.14, 33.67, 33.81, 34.16, 34.66, 34.89, 35.05, 35.12, 35.46, 35.47, 39.69, 41.40, 42.28, 46.73, 47.15, 49.34, 60.56, 68.45, 73.19, 74.23, 123.75, 124.80, 124.95, 124.97, 125.30, 125.95, 126.65, 127.27, 127.44, 127.74, 128.82, 129.89, 131.17, 131.67, 137.58, 172.93, 173.71. LRMS (ESI): m/z Calcd. for $C_{55}H_{77}NO_4$ + Na: 854.57; found 854.40.

2.2h *Compound **11***: *Iso*-Propyl cholamide (0.10 g, 0.22 mmol), 12-(1-pyrene)dodecanoic acid (0.11 g, 0.28 mmol) and DMAP (3 mg, 0.02 mmol) were mixed with dry DCM. To this stirring mixture DCC (0.055 g, 0.26 mmol) was added pinch by pinch for few minutes. The resulting solution was stirred for 12 h. The precipitates of DCU was removed by filtration and the filtrate was diluted with 10 mL of DCM. DCM layer was washed with saturated $NaHCO_3$ solution (2 × 5 mL) and water (2 × 5 mL). The organic layer was dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The product obtained was further purified by column chromatography over silica gel with EtOAc/DCM as eluent. The final product was obtained as pale yellow foam (0.04 g, Yield 15%), m.p. 70–71°C. Anal. Calcd. (%) for $C_{83}H_{107}NO_6 + 1\ H_2O$: C, 80.87; H, 8.91; N, 1.14; found C, 80.67; H, 9.59; N, 1.12. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 845, 1182, 1543, 1727, 2853, 2927, 3385, 3417. ^1H NMR (500 MHz $CDCl_3$):

δ 0.66 (s, 3H Me-18), 0.89 (s, 3H Me-19), 0.96 (d, J = 6.5 Hz, 3H Me-21), 1.113 (d, J = 6.5 Hz, 6H), 1.14–2.11 (steroidal, CH, CH_2), 3.28–3.35 (m, 4H), 3.95 (br s, 1H), 4.05 (m, 1H), 4.58 (m, 1H), 4.885 (d, J = 2.5 Hz, 1H), 5.14 (d, J = 7.5 Hz), 7.81–7.85 (m, 2 H), 7.93–8.02 (m, 6H), 8.05–8.10 (m, 4H), 8.12–8.14 (m, 4H), 8.24–8.27 (m, 2H). ^{13}C NMR (126 MHz,$CDCl_3$): δ 12.73, 14.41, 17.72, 21.23, 22.72, 23.02, 23.24, 24.50, 24.90, 25.16, 25.25, 25.32, 25.54, 25.74, 25.96, 26.65, 26.94, 27.54, 28.37, 28.77, 29.37, 29.39, 29.58, 29.67, 29.73, 29.79, 29.81, 29.84, 29.86, 30.02, 30.06, 31.06, 31.58, 31.85, 32.13, 32.16, 32.98, 33.80, 34.00, 34.18, 34.57, 34.99, 35.02, 35.17, 35.33, 38.38, 41.17, 41.40, 42.37, 46.79, 47.50, 49.37, 60.57, 70.77, 78.01, 73.98, 74.31, 123.73, 124.80, 124.95, 124.97, 125.30, 125.31, 125.93, 126.65, 127.27, 127.42, 127.73, 128.83, 129.90, 131.07, 131.68, 137.54, 173.31, 173.55. HRMS (ESI): m/z Calcd. for $C_{83}H_{107}NO_6Na$: 1236.7996; found 1236.8005.

2.2i *Compound* ***13***: Hexadecyl cholamide (0.15 g, 0.24), 12-(1-pyrene)dodecanoic acid (0.12 g, 0.30 mmol) and DMAP (3.5 mg, 0.03 mmol) were mixed with dry DCM (1.0 mL). To this stirred mixture was added DCC (0.062 g, 0.3 mmol) pinch by pinch for few minutes. The resulting solution was stirred for 5 h. DCU was removed by filtration and the filtrate was diluted with 10 mL of DCM. DCM layer was washed with saturated $NaHCO_3$ solution (2 × 5 mL) and water (2 × 5 mL). The organic layer was dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The product obtained was further purified by column chromatography over silica gel with EtOAc/DCM as eluent. The final product was obtained as pale yellow foam (0.12 g, Yield 50%), m.p. 54–55°C. Anal. Calcd. (%) for $C_{68}H_{103}NO_5 + 11/2\ H_2O$: C, 78.41; H, 10.25; N, 1.34; found C, 78.18, H, 9.80; N, 0.92. IR, $\tilde{\nu}$/cm^{-1} (KBr): 844, 1465, 1547, 1645, 1728, 2853, 2924, 3324, 3384, 3419. ^{1}H NMR (500 MHz $CDCl_3$): δ 0.68 (s, 3H), 0.86–0.89 (m, 6H), 1.004–1.13 (m, 6H), 1.25–1.27 (br peak, 42 H), 1.34–2.35 (steroidal CH, CH_2, alkylCH_2), 3.24 (br s, 2H), 3.33 (t, J = 8 Hz, 2H), 4.57 (m, 1H), 7.87 (d, J = 7.5 Hz), 7.97–8.16 (m, 7H), 8.282 (d, J = 9 Hz, 1H). ^{13}C NMR (126 MHz,$CDCl_3$): δ 12.43, 14.08, 17.65, 22.39, 22.67, 23.26, 25.08, 25.37, 25.71, 26.61, 26.84, 26.92, 27.52, 28.17, 29.19, 29.27, 29.34, 29.43, 29.57, 29.59, 29.64, 29.65, 29.69, 29.813, 31.91, 31.93, 33.60, 34.53, 34.68, 34.86, 34.90, 35.19, 35.20, 39.34, 40.03, 41.22, 42.12, 46.44, 68.33, 73.10, 73.99, 123.53, 124.59, 124.74, 124.76, 125.10, 125.72, 126.45, 127.06, 127.53, 128.62, 129.69, 130.96, 131.46, 137.36, 173.43. HRMS (ESI): m/z Calcd. for $C_{68}H_{103}NO_5$ + Na: 1036.7734; found 1036.7737.

2.2j *Compound* ***14***: Hexadecyl deoxycholamide (0.20 g, 0.33 mmol), 4-(1-pyrene) butyric acid (0.112 g, 0.39 mmol) and DMAP (6 mg, 0.05 mmol) were mixed with dry DCM. To this stirring mixture DCC (0.083 g, 0.4 mmol) was added pinch by pinch for 5 min. The resulting solution was stirred for 5 h. DCU was removed by filtration and the filtrate was diluted with 10 mL of DCM. DCM layer was washed with saturated $NaHCO_3$ solution (2 × 5 mL) and water (2 × 5 mL). The organic layer was dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The product obtained was further purified by chromatography over silica gel with EtOAc/DCM as eluent. The final product was obtained as pale yellow foam (0.17 g, Yield 60%), m.p. 65–68°C. IR, $\tilde{\nu}$/cm^{-1} (KBr): 844, 1383, 1645, 1728, 2853, 2924, 3440. ^{1}H NMR (250 MHz $CDCl_3$): δ 0.65 (s, 3H), 0.86–0.95 (m, 6H), 0.96 (d, J = 6 Hz), 1.02–1.1.20 (m, 3H), 1.26 (br s, 30H), 1.30–2.50 (steroidal CH, CH_2 and alkyl CH_2), 3.22 (m, 2H), 3.38 (t, J = 8 Hz, 2H), 3.94 (br s, 1H), 4.75 (m, 1H), 5.46 (m, 1H), 7.86 (d, J = 8 Hz, 1H), 7.94–8.18 (m, 7H), 8.31 (d, J = 9.25 Hz, 1H). ^{13}C NMR (63 MHz,$CDCl_3$): δ 12.93, 14.29, 17.63, 22.87, 23.28, 23.77, 26.20, 26.78, 27.13, 27.19, 27.65, 28.92, 29.51, 29.54, 29.75, 29.79, 29.89, 31.93, 32.11, 32.45, 33.04, 33.79, 33.86, 34.30, 34.62, 35.09, 35.34, 36.16, 39.76, 42.10, 46.67, 47.49, 48.48,73.28, 74.46, 123.56, 124.91, 125.01, 125.05, 125.20, 125.28, 125.98, 126.85, 127.57, 127.68, 128.94, 130.15, 131.12, 131.62, 136.02, 173.17, 173.63. LRMS (ESI): m/z found 908.76. HRMS (ESI): m/z Calcd. for $C_{60}H_{87}NO_4$ + Na: 908.6533; found 908.6570.

2.2k *Compound* ***15***: Hexadecyl cholamide (0.12 g, 0.195 mmol), 12-(1-pyrene) dodecanoic acid (0.1 g, 0.25 mmol) and DMAP (2.5 mg, 0.02 mmol) were mixed with dry DCM. To this stirring mixture DCC was added pinch by pinch for few minutes. The resulting solution was stirred for 5 h. DCU was removed by filtration and the filtrate was diluted with 10 mL of DCM. DCM layer was washed with saturated $NaHCO_3$ solution (2 × 5 mL) and water (2 × 5 mL). The organic layer was dried over anhydr. Na_2SO_4 and concentrated under reduced pressure. The product obtained was further purified by column chromatography over silica gel with EtOAc/DCM as eluent. The final product was obtained as pale yellow foam (0.11 g, Yield 55%), m.p. 52–54°C. Anal. Calcd. (%)

for $C_{68}H_{103}NO_4 + 2\ H_2O$: C, 78.94; H, 10.42; N, 1.37; found C, 78.55; H, 10.02; N, 1.92. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 844, 1181, 1465, 1643, 1731, 2852, 2924. 3380. ^{1}H NMR (250 MHz $CDCl_3$): δ 0.57 (s, 3H), 0.77 (s, 3H), 0.92 (t, J = 7 Hz, 3H), 1.01 (d, J = 6 Hz, 3H), 1.26–2.01 (m, steroidal, alkyl CH, CH_2), 3.06–3.25 (m, 4H), 3.81 (br s, 1H), 4.79 (t, J = 6.25 Hz, 1H), 4.97 (m, 1H), 7.72–8.01 (m, 8H), 8.23 (d, J = 9.25, 1H). ^{13}C-NMR (C_6D_6, 63 MHz): δ 13.33, 14.71, 17.99, 23.46, 23.60, 24.31, 25.75, 25.88, 26.72, 26.89, 27.55, 27.70, 29.51, 29.91, 30.05, 30.18, 30.24, 30.35, 30.49, 30.56, 30.69, 31.60, 32.51, 32.61, 32.69, 33.22, 33.30, 33.93, 34.25, 34.62, 35.32, 35.61, 35.98, 36.62, 39.98, 42.52, 47.14, 47.72, 48.71, 73.29, 74.48, 124.22, 125.39, 125.56, 125.60, 126.15, 126.20, 126.41, 127.28, 129.57, 130.71, 131.89, 132.40, 137.83, 172.73, 173.07. LRMS (ESI): m/z found 1020.90. HRMS (ESI): m/z Calcd. $C_{68}H_{103}NO_4Na$ 1022.7852; found 1022.7860.

2.2l *Compound **15** + Compound **24** (TNF)*: Compound **15** (5.5 mM) and TNF (5.5 mM) were dissolved in benzene [D_6] and NMR spectrum was recorded. ^{1}H NMR (250 MHz, C_6D_6): δ 0.59 (s, 3H), 0.79 (s, 3H), 0.92 (t, J = 6.75 Hz, 3H), 1.019 (d, J = 6 Hz, 3H), 1.17–2.06 (m, steroidal, alkyl, CH, CH_2), 2.28 (t, J = 7.5 Hz, 2H), 3.04–3.19 (m, 4H), 3.83 (br s, 1H), 4.82 (t, J = 6 Hz, 1H), 4.95 (m, 1H), 7.32 (d, J = 8.5 Hz, 1H), 7.42–7.67 (m, 8H), 7.902 (d, J = 2 Hz,), 7.945 (br s, 0.5 H), 8.05–8.07 (m, 2H). ^{13}C NMR (126 MHz, C_6D_6): δ 13.35, 14.73, 18.00, 23.48, 23.63, 24.34, 25.44, 25.91, 26.75, 27.22, 27.56, 27.73, 28.27, 29.54, 29.95, 30.09, 30.20, 30.28, 30.38, 30.51, 30.58, 30.70, 31.62, 32.30, 32.53, 32.70, 33.23, 33.30, 34.03, 34.10, 34.27, 34.66, 35.34, 35.64, 36.03, 36.65, 40.00, 42.56, 47.17, 47.77, 48.75, 73.33, 74.51, 119.45, 122.01, 124.08, 125.07, 125.27, 125.34, 125.49, 125.61, 126.51, 127.10, 127.44, 127.69, 127.82, 130.08, 130.11, 131.31, 131.78, 136.06, 137.83, 137.95, 138.67, 142.88, 144.46, 148.81, 150.09, 172.77, 173.13, 185.41.

2.2m *TNF (Compound **24**) ^{1}H-NMR (500 MHz, C_6D_6)*: δ 7.41 (d, J = 8.5 Hz, 1H), 7.63 (d, J = 2 Hz, 0.5H), 7.64 (d, J = 2.5 Hz, 0.5 H), 8.05 (d, J = 2.5 Hz, 1H), 8.11 (d, J = 2 Hz, 1H), 8.16 (d, J = 2.5 Hz, 1H).^{13}C NMR (126 MHz, C_6D_6): δ 119.79, 122.35, 125.24, 127.53, 129.07, 129.10, 130.38, 136.27, 138.13, 138.91, 143.11, 144.82, 149.18, 150.33, 185.69, 208.46.

2.2n *Compound **16***: The starting compound, dodecyl deoxycholate, was prepared by reacting deoxycholic acid (0.5 g, 1.27 mmol) and 1-dodecylbromide (0.375 g, 1.5 mmol) in the presence of DBU (0.225 g, 1.48 mmol) in 3 mL DMF as the solvent. The reaction mixture was stirred at 60°C for 12 h. After the reaction, the reaction mixture was poured into a beaker containing dil. HCl solution (20 mL) and the procuct was extracted with DCM (20 mL × 2). The organic layer was washed with dil. HCl (10 mL × 2), sat. $NaHCO_3$ solution (10 mL × 2), followed by water wash (10 mL × 2). The solvent was removed under reduced pressure and the product was dried under high vacuum. The yeild (0.66 g, 93%) of the reaction was nearly quantitative. Then 1-pyrene butyric acid (0.25 g, 0.87 mmol) and dodecyldeoxycholate in dry DCM was stirred at 25°C in the presence of DCC (0.186 g, 0.9 mmol) and a catalytic amount of DMAP (0.01 g, 0.08 mmol) for 24 h. The DCU formed was filtered. The filtrate was washed with sat. $NaHCO_3$ solution (10 mL), followed by water wash (10 mL). The organic layer was concentrated after drying over anhydr. Na_2SO_4. The product was chromatographed on a silica gel column using EtOAc/DCM as the eluent (0.21 g, Yield 30%), Anal. Calcd. (%) for $C_{55}H_{76}O_5 + H_2O$: C, 79.09; H, 9.41; found C, 78.78; H, 9.43. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 828, 1181, 1466, 1639, 1733, 2850, 2928. 3040. ^{1}H NMR (300 MHz $CDCl_3$): δ 0.66 (s, 3H), 0.85–0.93 (m, 6H), 0.97 (d, J = 6 Hz, 3H), 1.2–2.5 (steroidal CH, CH_2, alkyl CH_2), 3.96 (br s, 1H), 4.05 (t, J = 6.6 Hz, 3H), 4.75 (m, 1H), 7.85 (d, 7.8 Hz, 1H), 7.94–8.08 (m, 3H), 8.08–8.20 (m, 4H), 8.31 (d, 9.3 Hz, 1H). ^{13}C NMR (75 MHz,$CDCl_3$): δ 12.88, 14.26, 17.42, 22.83, 23.29, 23.86, 26.12, 26.31, 26.80, 27.33, 27.66, 28.83, 29.42, 29.49, 29.80, 30.59, 31.13, 31.59, 32.07, 32.50, 33.05, 33.78, 34.29, 35.36, 35.46, 36.22, 36.61, 42.29, 46.66, 47, 45, 48.37, 64.59, 71.81, 73.25, 123.60, 124.91, 125.05, 125.22, 125.35, 126.00, 126.88, 127.61, 127.66, 128.99, 130.17, 131.19, 131.70, 131.67, 136.08, 173.19, 174.50. LRMS (ESI): m/z found 841. HRMS (ESI): m/z Calcd. $C_{55}H_{76}O_5Na$ 840.1952; found 840.1947.

2.2o *Compound **17***: 1-Pyrene butyric acid (0.25 g, 0.87 mmol) was dispersed in 2.5 mL dry DCM. To this dispersion was added oxalyl chloride (0.13 g, 1.02 mmol), a catalytic amount of DMF (5 μL). The mixture was stirred for 2 h at 25°C. The solvents were removed using a KOH trap connected between the vacuum pump and the sample. The acid chloride so obtained was dissolved in 1 mL of dry DCM

and added to a mixture containing methyl deoxycholate (0.3 g, 0.74 mmol) and dry pyridine (2 mL) drop by drop for 30 min. The mixture was stirred for 2 h. After the reaction, the mixture was quenched with 10 mL of dil.HCl. The product was extracted with DCM (20 mL × 2) and washed with dil. HCl (10 mL), sat. $NaHCO_3$ solution (10 mL), followed by water wash (10 mL). The organic layer was concentrated after drying over anhydr. Na_2SO_4. The product was chromatographed on a silica gel column using EtOAc/DCM as the eluent (0.08 g, Yield 14%), Anal. Calcd. (%) for $C_{44}H_{54}O_5 + H_2O$: C, 77.61; H, 8.29; found C, 77.42; H, 7.99. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 832, 1185, 1458, 1649, 1730, 2849, 2928. 3046. ^1H NMR (300 MHz $CDCl_3$): δ 0.67 (s, 3H), 0.91 (s, 3H), 0.97 (d, J = 5.7 Hz, 3H), 1.0–2.5 (m, steroidal CH, CH_2), 3.39 (t, J = 7.2 Hz, 2H), 3.67 (s, 3H), 3.96 (br s, 1H), 4.79 (m, 1H), 7.86 (d, 7.8 Hz, 1H), 7.97 (d, 7.8 Hz, 1H), 8.01–8.07 (m, 2H), 8.09–8.21 (m, 4H), 8.32 (d, 9.3 Hz, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 12.93, 17.53, 23.31, 23.80, 26.22, 26.82, 27.16, 27.21, 27.58, 28.95, 31.12, 31.27, 32.47, 33.05, 33.90, 34.35, 34.64, 35.12, 35.25, 36.20, 42.11,46.72, 47.57, 48.51, 51.67, 73.31, 74.45, 123.59, 124.93, 125.05, 125.23, 125.33, 125.99, 126.88, 127.60, 127.68, 128.98, 130.18, 131.17, 131.69, 131.66, 136.09, 173.20, 174.94. LRMS (ESI): m/z found 686. HRMS (ESI): m/z Calcd. $C_{44}H_{54}O_5Na$ 685.8995; found 685.8989.

2.2p *Compound **23***: 1-Pyrene butyric acid (0.25 g, 0.87 mmol) was dissolved in 2 mL DMF. To this clear solution DBU (0.152 g, 0.99 mmol) was added dropwise and stirred for 15 min. 1-Dodecyl bromide (0.25, 1.0 mmol) was added to above solution maintained at 60°C. The resulting mixture was stirred for additional 6 h. The progress of the reaction was monitored by TLC. After the disappearance of the starting material, DMF was distilled off under reduced pressure. The residue was extracted into DCM (25 mL × 2). The organic layer was washed with dil. HCl (10 mL × 2) followed by water (10 mL) and dried over anhydr. Na_2SO_4. The crude material was obtained after the solvent removal was further purified over silica gel column using DCM/PE as the eluent. The final product was isolated as pale yellow oil (0.32 g, Yield 84%), Anal. Calcd. (%) for $C_{31}H_{38}O_2$: C, 84.12; H, 8.65; found C, 78.78; H, 9.43. IR, $\tilde{\nu}/cm^{-1}$ (KBr): 789, 821, 1211, 1458, 1649, 1741, 2849, 2925. 3048. ^1H NMR (300 MHz $CDCl_3$): δ 0.85 (t, J = 6.5 Hz, 3H), 1.18–1.35 (m, 20 H), 2.17 (m, 2H), 2.35 (t, J = 5 Hz, 2H), 3.38 (t, J = 7 Hz, 2H), 3.65 (t, J = 6 Hz, 2H), 7.85 (d, 7.8 Hz, 1H), 7.96 (d, 7.8 Hz, 1H), 8.00–8.05 (m, 2H), 8.07–8.19 (m, 4H), 8.30 (d, 9.25 Hz, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 14.26, 22.83, 26.12, 26.51, 29.42, 29.49, 29.80, 30.59, 32.07, 32.64, 33.22, 35.46, 36.61, 64.59, 123.63, 124.89, 125.01, 125.23, 125.33, 125.97, 126.89, 127.63, 127.69, 128.97, 130.15, 131.17, 131.68, 131.71, 136.06, 173.22. LRMS (ESI): m/z found 466. HRMS (ESI): m/z Calcd. for $C_{31}H_{38}O_2Na$ 465.6313; found 465.6320.

3. Results and discussion

The synthesis of bile acid derivatives **4**–**8**, pyrene bile acid conjugates **10**, **11**, **13**–**17** and pyrene derivative **23** was achieved using common organic synthesis techniques (chart 1, see experimental section for details) and the gelation tests were performed in a set of different organic solvents.

To our disappointment the compounds **9**–**18** either remained in solution or precipitated within 12 h of testing and no sign of gelation was detected. However, an intense red coloured charge transfer (CT) complex was formed when trinitrofluorenone, TNF (**24**, chart 1) was added into solutions of **9**–**18**. The gelation tests were made at 1:1% w/v of the gelator and TNF in an organic solvent. The gelation was visually confirmed by turning the test tube upside down and monitoring the flow of the gel. The observations were carried out at room temperature (25°C) in organic solvent listed in table 1.

3.1 *Gelation studies*

We have introduced a few pyrene analogues and bile acid analogues as potent gelators of organic solvents. As both pyrene[25b] and bile acid[25c] moieties are known as potent structural fragments in gelling these moieties were first tested separately in gelation. No gelation was seen with the simplest pyrene molecule 1-pyrene carboxylic acid (**19**) or its mixture with 1-aminopyrene (**20**) (prepared by heating the 1:1 mixture of the amine and acid in an organic solvent during the test), even in the presence of an equivalent amount of CT agent, TNF. Similarly, no gelation was seen with the 1:1 conjugate of deoxycholic acid or cholic acid and 1-aminopyrene in the presence of an equivalent amount of TNF. The mixture precipitated out in most of the organic solvents used for the study. PBA alone (**21**) or in the presence of TNF does not gel organic solvents. Both **21** and **21**+**TNF** remain in solution when mixed in benzene, toluene and chlorobenzene. However, when 1-decanol or cyclohexanol was used, a gelatinous precipitate, yet

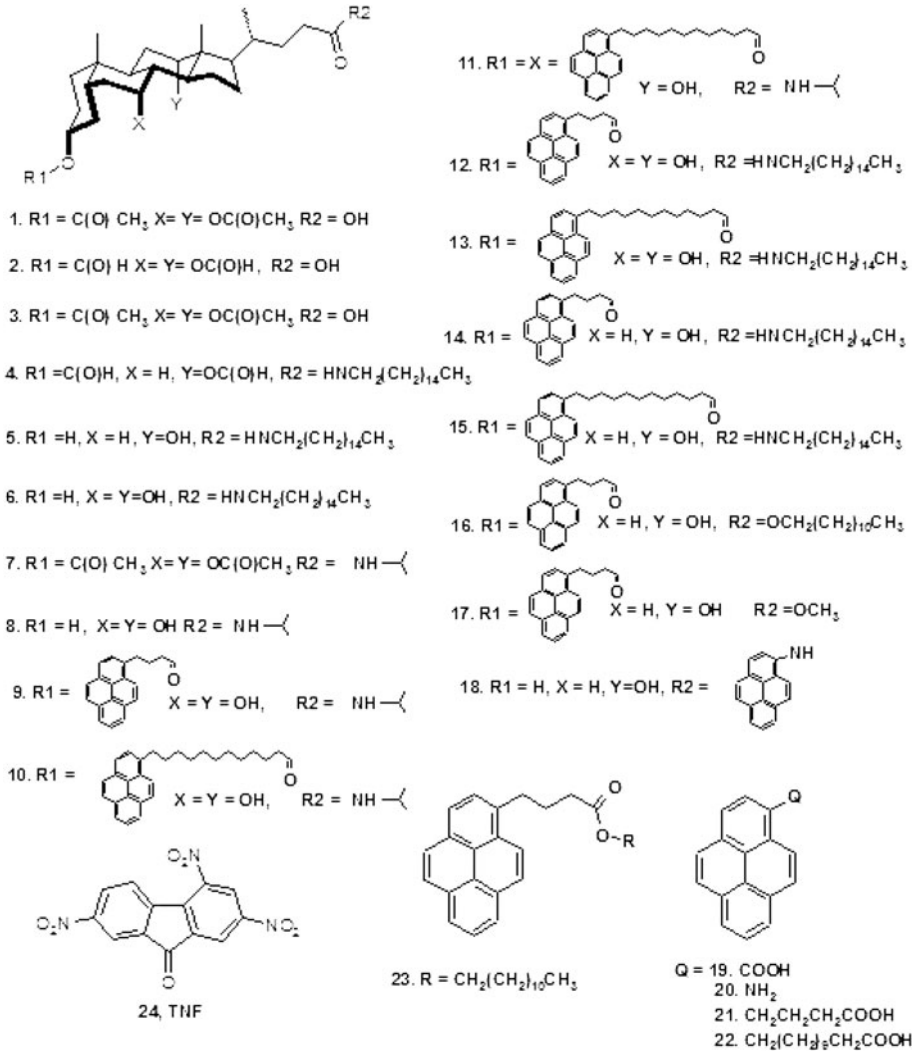

Chart 1. Gelator molecules used in the present study.

not a gel, was observed. This finding is interesting since when a longer alkyl chain used, viz., compound **22**, strong CT gels in many organic solvents are formed as shown by us previously.[24]

Interestingly, PBA esters of bile acid conjugates (esterification of 3α-OH) formed strong gels in a number of organic solvents in the presence of TNF. Compounds **14**, **16**, and **17** formed strong organogels in a variety of organic solvents (table 1). The PBA ester of a cholamide (**14**) formed a strong CT gel in aromatic hydrocarbon solvents like benzene similar to reported cholamides (compound **5**, not a CT gel).[31] These organogels were characterized by various physical techniques and are discussed in detail in the proceeding sections. Other cholamides like *iso*-propyl cholamide (compound **8**),[32] a known gelator, do not show gelation if used with the corresponding PBA amide (**9**) in the tested solvents. However, the PBA esters of cholates **16** and **17** do gel higher alcohols and cyclohexanol (table 1). Thus the gelated solvent systems can be changed by modifying the bile acid side chain.

The length of the connection moiety between the pyrene and bile acid part of the gelators plays an important role (viz., compounds **14** and **15**). If pyrene-1-dodecanoic acid (**15**) is used instead of PBA, the gelation properties are lost (within the tested solvent range; listed in table 1), **14** does gel benzene, whereas **15** does not. This is in line with our previous observations that the presence of pyrene moiety on the bile acid side chain normally leads to loss of gelation properties.[24]

At this point, the role of the bile acid backbone on the gelation is very important. This is further highlighted by observation that a very small variation of the bile acid skeleton will influence gelation. Compound **13** with one

Table 1. Gelation profile of compounds **14**, **16**, and **17** in different organic solvents ($C_{gelator}$ 1% w/v, 1:1 TNF).

Solvent	**14** + **24**[a]	**16** + **24**[a]	**17** + **24**[a]	**23** + **24**[a]
Benzene	G	S	S	S
Toluene	S	S	S	S
Dichlorobenzene	S	S	S	S
1-Chlrobenzene	S	S	S	S
Cyclohexane	S	GP	Ss	S
Acetonitrile	Ss	S	S	P
CCl_4	S	S	S	S
Cyclohexanol	S	GP	G	S
1-Decanol	S	G	G	S
Isopropanol	Ss	GP	GP	Ss
Ethanol	Ss	Ss	Ss	Ss
Water	I	I	I	I

[a] = I: Insoluble, S: Solution, Ss: Sparingly Soluble, G: Strong Gel, GP: Gelatinous Precipitate, P: Precipitate

OH group more than **14**, does not form gel with benzene as **14** does. We believe that the bile acid backbone provides a rigid central core aggregation behaviour of which can be modulated by the substituents on it and linked to it. It seems that the PBA moiety attached at the position 3 of the bile backbone facilitates the multidimensional growth (when TNF is added) of the preliminary aggregates formed, thus leading to gel formation. The pyrene-1-dodecanoic acid esters of bile analogues (compounds **13** and **15**), however, failed to gel organic solvents probably due to the lack of right hydrophobic–hydrophilic balance. These molecules may also be too flexible to have the needed growth of the aggregates when compared to PBA esters.

The pyrene derivatives reported here are functionalized at the alkyl end of the pyrene that is different from pyrene derivatives studied in our earlier reports.[25a–b] Our initial discovery of aromatic donor-substituted bile acid derivatives, such as **25** (chart 2), gelled certain organic solvents in the presence of TNF as the acceptor prompted us to examine the role of the bile acid moiety in these gelators. Some of these pyrene analogues were found to gel even when the bile portion of the molecule was replaced by a simple alkyl chain (e.g., compound **26**).

To address this question, a pyrene analogue was synthesized following standard protocols in which the bile acid moiety was replaced by simple alkyl chains connected to the pyrene through an ester linkage (compound **23**). This compound formed a deep red CT complex, which remained in solution even after 4 days, no gel formation was observed (table 1). The above gelation findings clearly indicate that pyrene-based gelators need the presence of a bile unit with an ester or amide linkages between them in order to be an efficient gelator.

3.2 *Absorption characteristics*

During the gelation of the compounds **14**, **16** and **17**, a clear colour change was observed with TNF, caused by an increase in the charge-transfer interaction (CT) during the gelation. This prompted us to study the gelation of these compounds by UV-Visible spectroscopy. Absorption spectroscopic studies were performed with compound **23** in the presence and absence of TNF (conc. of **23** and TNF is 10 μM). At this concentration no CT band could be seen. However, the band was seen at 0.5 mM of **23** and TNF.

Similar studies performed for compound **17** (0.6 mM) with TNF (0.6 mM) showed a band width λ_{max} 575 nm (figure 1), which is indicative of the formation of a charge transfer complex. Transformation from sol to gel or from gel to sol has a clear effect on the intensity of the charge transfer band. The charge transfer band intensity decreased when the gel was converted into sol and *vice versa*. However, there is no

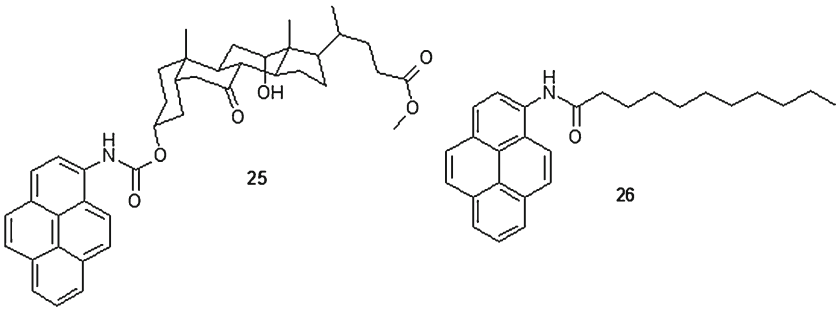

Chart 2. Reference molecules used in this study.

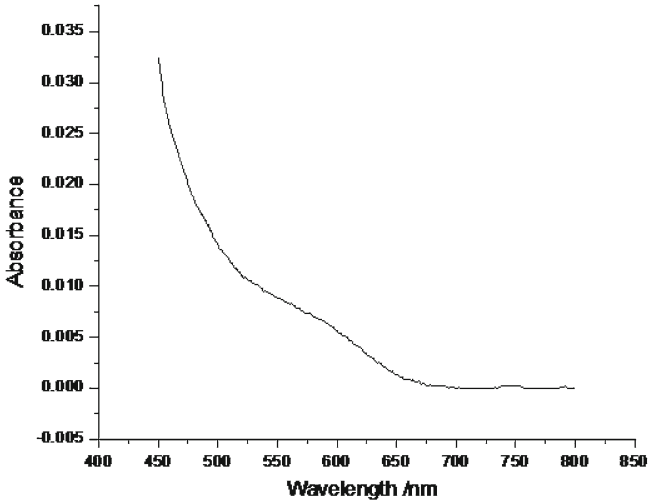

Figure 1. Absorption spectrum of compound **17** (0.6 mM) with TNF (0.6 mM).

additional band nor change in the λ_{max} was detected between the cycles of sol-to-gel or gel-to-sol.

3.3 *Gel melting*

Although the gels (table 1) were formed by the entropic factors a small contribution from the enthalpy is always present. To dissolve the gelator in a given solvent, heat must be supplied to the system. Once the gel is formed, there exists a temperature at which the gel melts back to form a sol. The gel–sol transition was recorded by the upside down test tube method. The temperature at which the gel started flowing was taken as the transition point. The CT gel **14** (1% w/v in benzene, 1:1 TNF) melted at 55°C and became clear solution at 70°C. The gels of compound **16** and **17** in 1-decanol exhibited slightly lower T_{gel} values (42°C and 45°C respectively) compared to benzene gels of **14**. The T_{gel} value observed in this class of organogels is smaller compared to other TNF gels and close to the individual powder melting point of the gelators. The CT gels of **14**, **16** and **17** are thermoreversible.

3.4 *^1H NMR studies*

The sol–gel transition process monitored by NMR showed a significant difference on the proton signals. ^{1}H NMR spectra were recorded for a benzene [D_6] gel of **16** at various temperatures. A well-ordered pattern turned into a complex broad pattern when the sol was allowed to gel during the NMR experiment. The transition from gel–sol was studied by plotting the chemical shift (figure 2) and the width of the NMR signals against temperature.

A variable temperature ^{1}H NMR (figure 3) is in accordance with the melting studies. At 60°C, the broad signals observed at low temperatures transformed into sharp patterns. The broadness of the signals at low temperatures is probably attributed to the poor relaxation in the gel state that transformed into a sharp signal when gel–sol transition took place. There was appreciable shift in the δ_{NH} of gelator **14** on going from the sol to gel

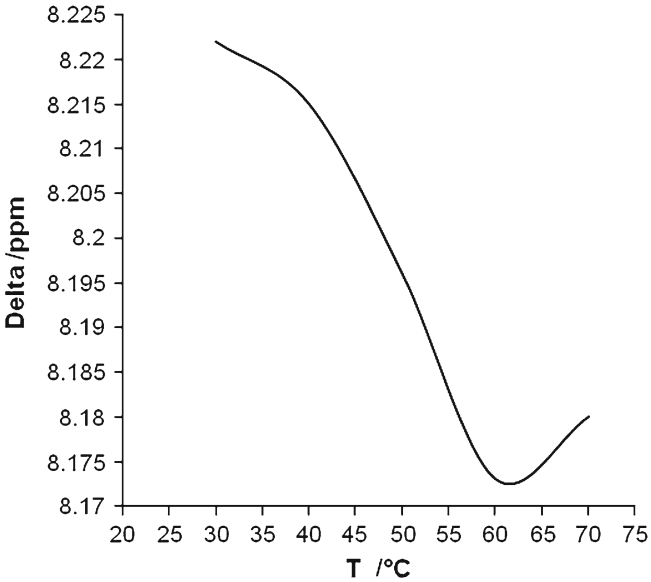

Figure 2. A plot of chemical shift of a pyrene proton *vs.* experimental temperature for CT gel of compound **14** (5.5 mM) with TNF (5.5 mM) in benzene [D_6].

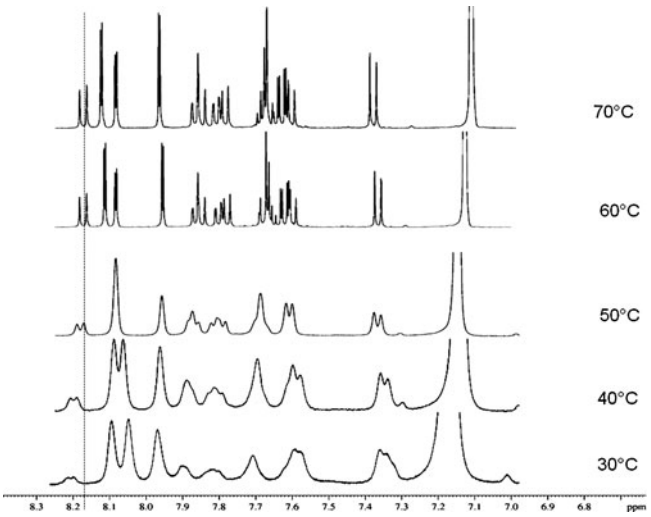

Figure 3. A plot of variable temperature ^{1}H NMR of compound **14** (5.5 mM) + TNF (5.5 mM) in benzene [D_6]. Mainly the aromatic portion of the spectrum is shown here.

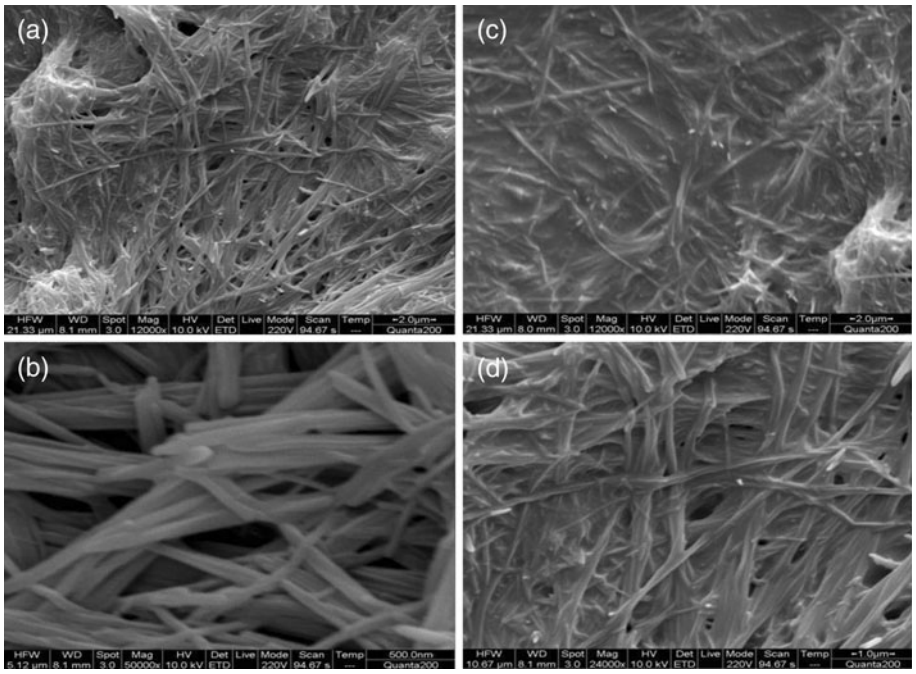

Figure 4. The SEM images of xerogels. **a** and **b**: Compound **14** + TNF (1:1, 1% w/v) in benzene; **c** and **d**: Compound **17** + TNF (1:1; 1% w/v) in 1-decanol.

phase. This indicated that the side-chain functionality present on the bile acid has a crucial role on the gelation of this class of gelators. In addition, the chemical shifts of methylene groups of butyric acid also shifted considerably during the gelation (compound **14**). It appears that the growth of the aggregates has a strong connection with the spacer used between pyrene and bile acid. The TNF is probably acting as an initiator that influences the growth of the aggregates, which in turn leads to gelation of the system. The TNF protons in the gel showed a strong variation in the ^{1}H NMR chemical shifts. It was clearly observed that the doublets of TNF at 8.05 (d, J = 2.5 Hz, 1H), and 8.11 (d, J = 2 Hz, 1H) appears as a broad singlets when they form a gel with compound **14**. When the temperature is increased both of the signals merge into a broad singlet at 50°C and finally they appear as two doublets after complete melting (figure 3). This implies a strong change in the chemical environment during gel–sol transition.

3.5 *Gel morphology*

The topography of the gels was characterized by the electron microscopy. The SEM images of the xerogels of compounds **14** and **16** are shown in the figure 4. The images revealed the presence of infinitely long interconnected rod-like structures with a rod diameter of about 50 nm. The rods are mostly bundled and the individual rods are rarely seen. These rods reveal no branching and the overall structure can thus be considered as an open-type network. The fractures of the network seen in some parts of the image are probably due to the faster evaporation of the solvent benzene at room temperature during sample preparation.

3.6 *Chirality of the supramolecular aggregates*

The exact relation between molecular chirality and supramolecular chirality is not very clear. In some cases, the racemic and achiral molecules form chiral aggregates.[33] Many of the reported hydrogels derived from deoxycholate and its conjugates have been shown to exhibit supramolecular helicity.[34] The gelators **14**, **16**, and **17** have been derived from homochiral bile acid systems. However, no such supramolecular helicity or chiral signatures could be extracted from SEM analysis.

4. Conclusions

We have synthesized different pyrene and bile acid-pyrene derivatives with interest of their self-association properties in various organic and aqueous solvents. Among the compounds prepared the PBA esters of bile

acid analogues were found to gel many organic solvents in the presence of TNF through the formation of a charge transfer complex. The gels obtained are optically transparent and deep red in colour attributed to the charge transfer band. The addition of TNF seems to grow and strengthen the smaller aggregates ultimately leading to the gelation of the solvents. A structure–gelation property studies revealed that the length of the alkyl spacer between pyrene and ester carbonyl situated at position 3 of the bile acids is one of the limiting factors for the gelation. The side chain functionality and the structure is the second factor which can be available for fine tuning the gelation abilities of this class of organogelators. The replacement of a bile acid moiety by a simple alkyl chain highlighted the importance of bile acid backbone in this gelator class. The gels are thermoreversible and stable to several cycles of melting and cooling. A highly entangled rod-like structures were seen from the xerogels with no signature of supramolecular chirality.

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