Bacterial S-layers are very useful surfaces for artificial bionanotechnological applications.[34] For example their use of as superstructures for artificial arrays where their underlying, crystalline order on the nanoscale allows facile formation of nanoscale components that can adhere to proteins. The S-layer is chemically removed from the bacterium and divided into individual subunits. A key feature of isolated S-layers is their ability to self-assemble into two-dimensional arrays, either in solution or on a solid support, such as a silicon wafer, metal surface, lipid film or liposome. Binding an enzyme such as glucose oxidase to an S-layer surface attached to an electrode and measuring the current passing through electrode as the oxidase reacts with the glucose makes a useful glucose sensor, for example. In another application, self-assembled S-layers can be exposed to metal-salt solutions followed by slow reaction with a reducing agent, such as hydrogen sulfide. This procedure gives nanoparticle superlattices that match the lattice spacing and symmetry of the underlying S-layer. Because the precipitation of the metal complexes is confined to the pores of the S-layer, the nanoparticles take on the pore morphology. This procedure has been used to make CdS quantum dots for example. We will return to the interesting properties of nanoparticles and quantum dots in the final chapter.

14.7 Supramolecular Gels

Smith, D. K., 'Molecular gels – nanostructured soft materials', in *Organic Nanostructures*, Atwood, J. L. and Steed, J. W. (eds), Wiley-VCH: Weinheim, 2008.

Gels are a colloidal state of matter that are commonplace in everyday life, *e.g.* jelly (or jell-o), toothpaste, contact lenses, hair gel, meat jelly *etc.* Fundamentally a gel is characterised by the following properties.[35]

- A two (or more) component system, comprising a fibrous solid-like phase (typically *ca.* 1 % by weight) immobilising a much larger liquid volume.
- A continuous structure with macroscopic dimensions that is permanent on the timescale of an analytical experiment
- Solid-like in its rheological behaviour (Box 14.1)

Gels also typically exhibit a melting point, T_{gel}, a temperature above which the gel converts to an isotropic solution and a typical way of preparing gels is to dissolve the gelator in the warm solution and allow to cool below the T_{gel}. Thus for example the geminal bis(urea) gelators of type **14.11** form thermoreversible gels at concentrations of less than 3 mM that are stable at temperatures over 100 °C.[36] There have also been recent reports of gels induced by sonication (as in metallogelator **14.12**)[37] or photochemical rearrangements (as in **14.13** which changes from a microsphere to gel morphology upon irradiation).[38] In the case of a *hydrogel* the liquid component is water, while for an *organogel* it is an organic solvent. An *aerogel* has a gas as the fluid phase instead of a liquid while *metallogels* are gels in which the fibre components are linked together in some way by metal ions. A particularly striking aerogel is formed by **14.14** which can gel supercritical CO_2. Careful depressurisation to remove the CO_2 gives an aerogel without collapse of the gel matrix because the outgassing CO_2 as no surface tension.[39] A nice example of a metallogel comes from the reaction of $LaCl_3$ with 1H-5-(2-pyridyl)tetrazole (**14.15**) which gels reversibly when treated with an excess of triethylamine in ethanol. Addition of a mixture of ethanol and isopropanol gives crystals of $[La(\mathbf{14.15}\text{-H})_3(H_2O)_3]\cdot 4H_2O$.

On the macroscale gels do not flow and hence a simple test for a gel is to invert its container – if it lands on the floor with a splash it is probably not a gel! On the microscale the solid-like component generally comprises fibrillar bundles of high aspect ratio and in the case of chiral gelators can adopt

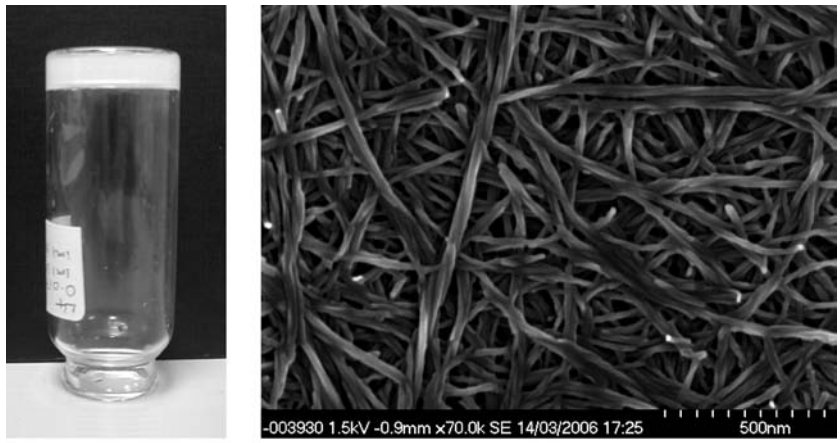
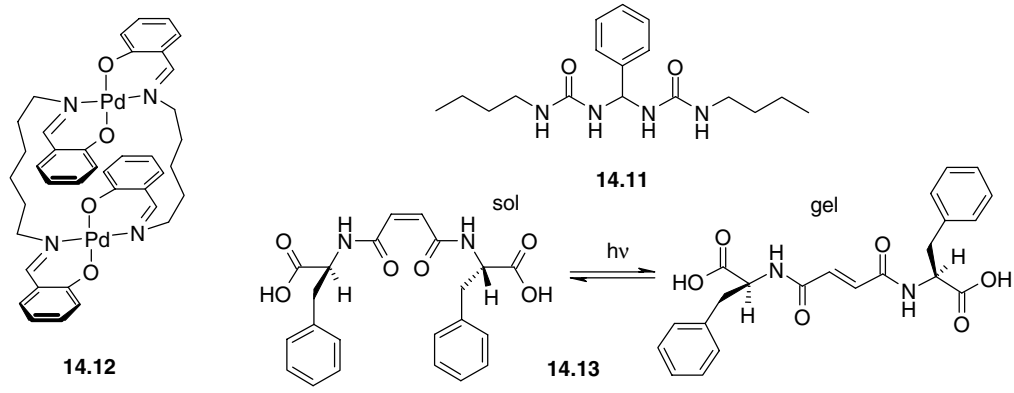


Figure 14.21 (a) a typical gel passing the 'inversion test', (b) SEM micrograph of a dried gel (xerogel) made from a chiral gelator showing helical fibrils.[3]

a helical morphology, Figure 14.21. Some gels also exhibit *thixotropy*, they flow when shaken but re-form on standing. The mechanical forces involved in shaking are enough to temporarily break the bonds holding the gel fibres together.



Despite their solid appearance, within the gel the liquid component is mobile and is only held by capillary forces. The solid network can be either a covalent polymer or a supramolecular assembly of small molecules. The latter class of compound, termed *low molecular weight gelators* (LMWG) of which **14.11–14.15** are examples, is perhaps of most interest to supramolecular chemists. Perhaps the most well known gels are metal oxide based polymeric materials produced by the sol-gel process. The sol-gel process involves the hydrolysis and polycondensation of monomeric metal salts such as early transition

metal or silicon alkoxides to produce a mixture of colloidal particles *ca.* 2–200 nm in size dispersed in a solvent in solution (a *sol*). The sol matures, forming longer, more highly cross-linked chains involving M–O–M or M–OH–M bridges to give a continuous inorganic network containing the liquid phase – the *gel*. The liquid is then removed by drying leaving a rigid, highly porous material (*an aerogel*). The process is typically employed in the ceramics industry, where the sol phase allows dopants such as colours to be readily added. The aerogel can also be fired at high temperatures for increased mechanical strength. Materials made by the sol-gel process, often in the presence of a cast or a template have a broad range of technological applications in optics, electronics, energy, space, sensing and biosensing, controlled drug release and chromatography. The classic sol-gel reaction is the acid hydrolysis of tetraethyl orthosilicate leading to the formation of fibrous or monolithic SiO_2; a process known since the 1880s.

In addition to these 'inorganic' polymers, organic polymeric materials such as gelatin (a hydrolysed form of collagen) and abiotic covalent polymers also form gels. The gels arise from the mutual entanglement of the polymer chains. Thus in order to form similar supramolecular gels, LMWG compounds must aggregate to produce long supramolecular polymers that can in turn associate laterally and cross-link to produce analogous fibrillar structures. Clearly the formation of such long-lived aggregates from solutions of small molecules is very much akin to the process of crystallisation and indeed gelation has been described as a kind of arrested crystallisation, or 'crystallisation gone wrong'. Unlike crystallisation, however, gelation is directional with rapid growth occurring in only one direction along the strand axis. Thus LMWG are commonly compounds that for strong interactions such as hydrogen bonds in one direction while forming only weaker (*e.g.* van der Waals) interactions in the other two. Typical examples of LMWG include strong hydrogen bond donor/acceptors such as bis(ureas), amides, fatty acids, steroids and nucleobases.

The mechanism of aggregation of LMWG in water is generally dominated by hydrophobic interactions, whereas in organic solvents hydrogen bonding dominates. Like the formation of many supramolecular polymeric structures, gel aggregation is hierarchial. Figure 14.23 shows a schematic diagram of a proposed mechanism for the assembly of rod-like chiral peptides into helical fibres in water. The dark surfaces are hydrophobic while light surfaces are hydrophilic and are therefore exposed to the medium. The difference in these surface energies leads to the helical shape. In organic media hydrogen bonding as in the classic urea α-tape motif (Figure 14.22a) becomes

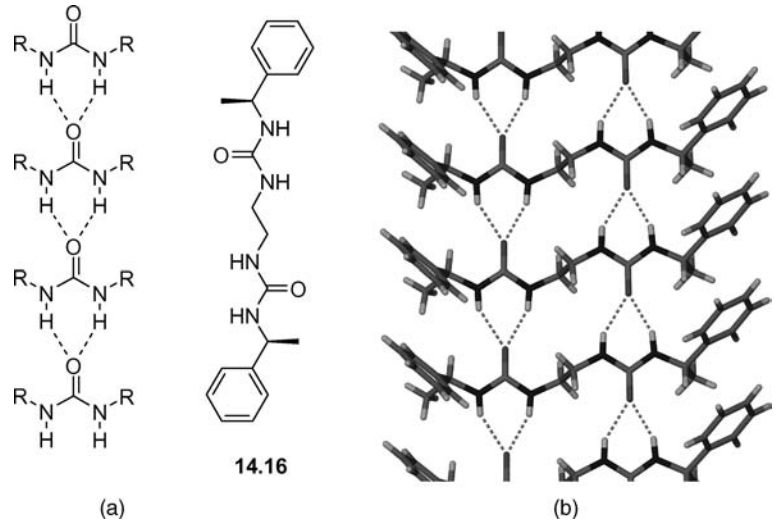


Figure 14.22 (a) Urea α-tape motif and (b) X-ray crystal structure of **14.16** showing the urea tape hydrogen bonding. PXRD studies confirm that the crystal structure is the same phase as the xerogel.[40]

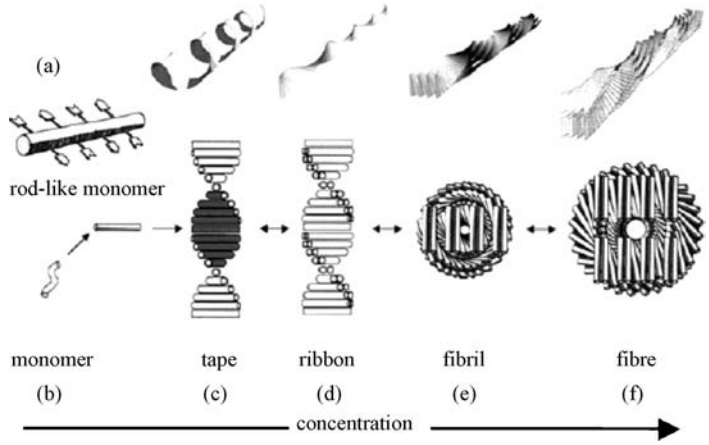


Figure 14.23 Schematic model for the assembly of rod-like chiral peptides into helical fibres of the type found in gels (reproduced with permission from [41]).

more important. Figure 14.22b shows the X-ray crystal structure of the chiral bis(urea)gelator **14.16** which forms an anti-parallel arrangement of urea tape hydrogen bonds.[40] X-ray powder diffraction measurements confirm that the structure of the single crystal and the xerogel are the same. We have seen this kind of urea self-association in Section 10.6.1 in the context of the formation of molecular capsules; the process is the same here except that an infinite polymer is formed instead of a closed hydrogen bonded ring. Ureas are also excellent anion-binding functional groups and indeed addition of *ca.* 10 mole % of tetrabutylammonium salts of anions such as Cl^- or OAc^- to gels of **14.16** disrupts the urea tape hydrogen bonding resulting in gels with lower G' and lower yield stresses. In contrast, anions such as BF_4^- that are only weakly bound have much less effect.

One of the potentially most interesting properties of LMWG systems is the reversibility of the supramolecular interactions between the gelator molecules, suggesting the possibility of dynamic behaviour such as self-healing or slow release. Supramolecular gels are highly topical but much of the research in the field remains serendipitous. Some of the possible and actual uses (and abuses) of supramolecular gels are listed below.

- Lithium greases, a well characterised blend of mineral oil and the lithium salt of 12-hydroxystearic acid that exhibits a fibrillar self-assembled structure
- Napalm – an infamous gel originally made up of the aluminium salts of napthelenic and palmitic acids mixed with petrol. Used widely by the military from the second world war onwards, burning napalm sticks to its victim causing severe burns and rapid local deoxygenation. Moden napalm uses a polymer additive to achieve gelation.
- Tissue engineering – gels can act as a form of nanoscaffolding encouraging the growth of slow growing tissue such as nerves through peptide based gels.
- Drug delivery – many drugs are already formulated as polymer gels for oral delivery. Small molecule based gels offer the possibility if slow release or a sudden burst of drug from a chemically triggered get-sol transition.
- Templating or transcribing self-assembled morphology – gels have been used extensively as growth regulators for the preparation of metallic nanoparticles or as templates for the formation of porous polymers. Soft gel structures have also been transcribed into hard inorganic morphologies

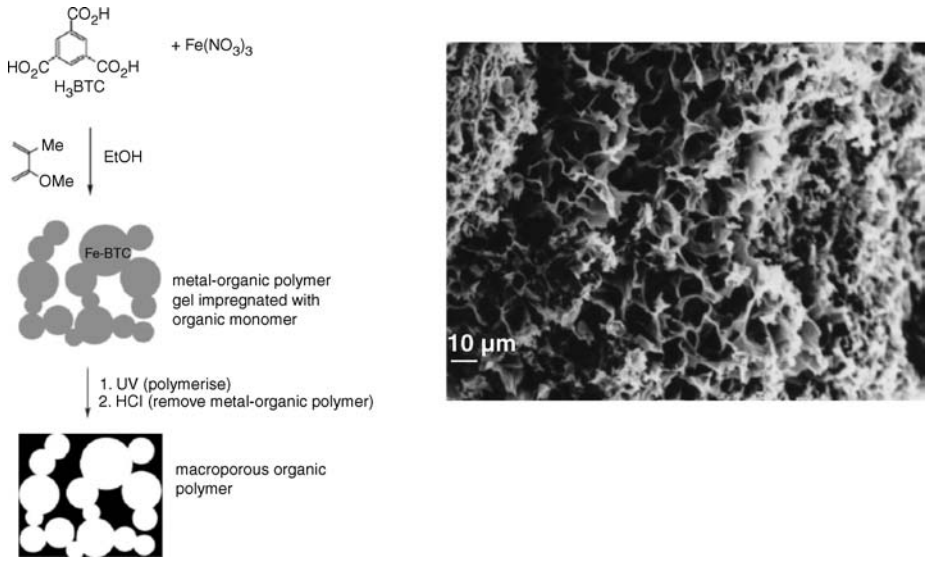


Figure 14.24 Templation of a covalent polymer (PMMA) by a supramolecular metallogel of iron(III) benzene tricarboxylate (BTC) (reproduced by permission of The Royal Society of Chemistry).

such as CdS 'nanohelices'. An interesting report describes the formation of the covalent polymer polymethylmethacrylate (PMMA) from an ethanol solution of the metallogel formed from $Fe(NO_3)_3$ and trimesic acid (benzene 1,3,5-tricarboxylic acid). After washing away the gel (taking advantage of its supramolecular nature) a spongy covalent polymer is left where the pores may reflect the solvent pockets within the gel phase, Figure 14.24.[42]

- Molecular electronics – the long, fibrillar nature of gels strongly suggests that they might find applications in the construction of molecular wires.
- Sensing – compound **14.17** is a poor gelator in itself but undergoes a reaction with β-lactamase enzyme to produce **14.18** which is a good gelator. β-Lactamase catalysed hydrolysis of a β-lactam