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Hierarchical structure of a self-assembled xerogel

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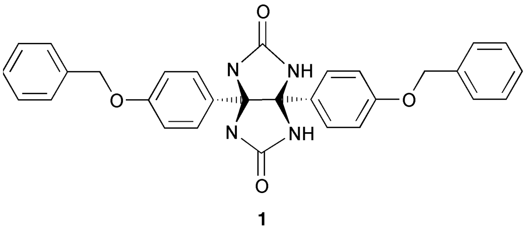
Removal of the liquid from a glycoluril-based gel produces a macroporous solid (a xerogel) comprised of closely packed fibers that assemble into highly convoluted sheets.

Glycoluril, the bicyclic product of glyoxal reacting with two equivalents of urea, is a molecule with a long history. For three decades, after first being synthesized by Schiff in 1877, glycoluril attracted a fair amount of attention until it faded into the dusty archives of science.[1] Poor solubility of glycoluril and its derivatives in water and organic solvents probably hastened the flagging interest. In the 1980s, however, a renaissance in glycoluril chemistry became apparent. This renewed awareness of glycoluril was driven by its various applications in the design of supramolecular architectures. Among these we find molecular clips and baskets,[2] supramolecular capsules,[3] self-complimentary facial amphiphiles,[4] and complexes of cucurbituril[5] (a macrocyclic condensation product of glycoluril with formaldehyde).

In the course of studying a variety of alkoxyphenyl-substituted glycolurils, we encountered an unexpected ability of the compounds to rigidify organic liquids into so-called organogels. Organogels are a growing class of supramolecular assemblies with potential applications in oil chemistry, nutrition, cosmetics and pharmacology.[6] Diverse molecular structures, among them derivatives of urea,[7] are already known to immobilize organic liquids. Such organogels are categorized as 'physical gels' in that they are formed by low-molecular weight organic molecules that self-assemble into fibrous structures upon cooling of their solutions. The fibers, held together by non-covalent forces, create a network that entrains solvent within the interstices. Removal of the solvent by evaporation or filtration results in a collapsed mat of fibers called a xerogel. The present manuscript focuses on the structure of a xerogel prepared from a glycoluril derivative.

The compound in question, the di(benzyloxyphenyl)-substituted glycoluril **1**, is drawn below. It was obtained by refluxing a stirred mixture of 1.0 g 4,4′-dibenzyloxybenzil, 4 mL CF_3CO_2H, and 400 mg freshly powdered urea in 150 mL benzene while collecting water in a Dean–Stark trap.[8] After 50 h, the solvent was removed under reduced pressure, leaving a solid that was washed with two 50 mL portions of the following solvents: $CHCl_3$, boiling MeOH, $CHCl_3$ and *n*-pentane to give 51% of the pure compound. Characterization consisted of ^1H NMR, ^{13}C NMR, HRMS and elemental analysis.†



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The gelation ability of the glycouril derivative was checked by heating suspensions in various organic liquids such as propan-1-ol, decan-1-ol, toluene, DMSO, DMF and benzyl alcohol. Compound **1** proved insoluble in hot propan-1-ol, decan-1-ol, and toluene. On the other hand, clear solutions were obtained in hot DMSO, DMF and benzyl alcohol. Upon cooling these solutions, the compound remained dissolved in DMSO, but rapidly precipitated from DMF. Only with benzyl alcohol, however, did we observe, at a concentration of 20 mg mL^{-1}, the formation of a self-supporting opaque gel that could be turned upside down in a vial without flow or deformation. The gel is thermoreversible and stable for months at room temperature, whereas it is irreversibly destroyed when shaken vigorously.

Light microscopy (400 ×) on a small portion of the gel (Fig. 1) revealed flexible fibers several hundred μm long and about 2 μm in diameter (often radiating from central points). We assume (partly on the basis of our previous X-ray data on unrelated gel systems[9]) that the fibers in Fig. 1 are a composite of parallel 'elementary' fibers with molecular dimensions (*i.e.* diameters of *ca.* 2.5 nm corresponding to hydrogen-bonded dimers of **1**).

A xerogel was prepared from the **1**/benzyl alcohol gel by filtration. Thus, a portion of gel was placed in a Büchner funnel

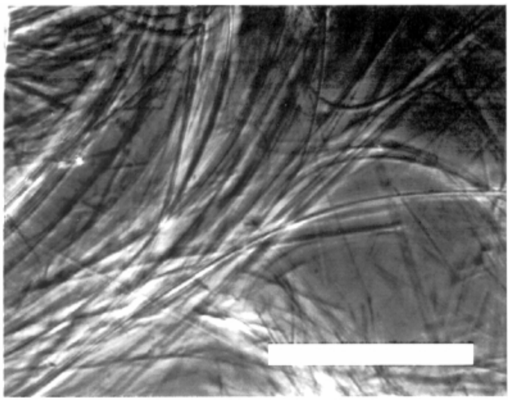

Fig. 1 Optical photomicrograph of the gel **1**/benzyl alcohol (400 ×, scalebar: 60 μm).

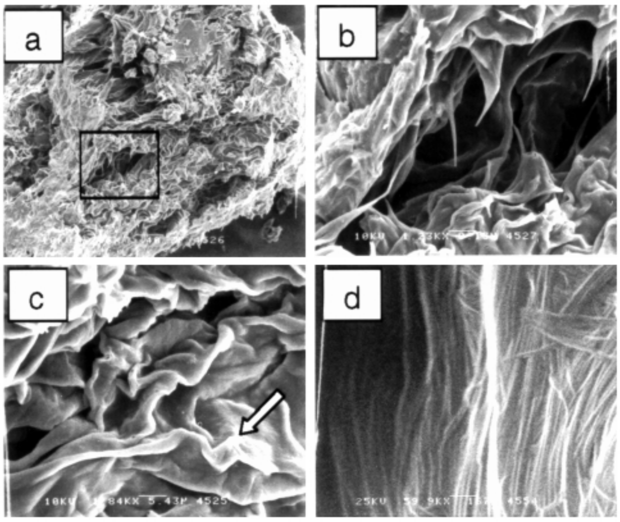

Fig. 2 SEM images of the xerogel obtained from the gel **1**/benzyl alcohol; (a) 246 ×, scalebar: 40.7 μm; (b) 1230 ×, scalebar: 8.13 μm; (c) 1840 ×, scalebar: 5.43 μm; (d) 59 900 ×, scalebar: 167 nm.

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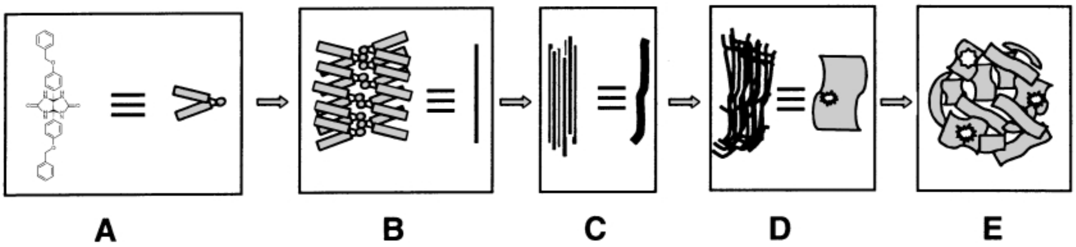

Fig. 3 Schematic representation of the hierarchical levels of the xerogel of **1**.

with a fritted disk, and the solvent was removed under suction for 6 h while a mild N_2 pressure was applied from above. Remaining traces of solvent were then removed under reduced pressure with the aid of a vacuum pump. The resulting xerogel, a brittle material of resin-like appearance, was attached to a metal stub with conductive carbon tape and coated with 3 nm Cr using a Denton DV-602 Cr coater. Representative SEM images were obtained at the lower [Fig. 2(a)–(c)] and upper [Fig. 2(d)] stage of an ISI DS-130 LaB_6 electron microscope.

Macroscopic fibers, as observed by light microscopy, can no longer be found. Instead, we see in Fig. 2(a) (246 × instrumental magnification) a highly convoluted material with pore sizes ranging from *ca.* 5 μm to *ca.* 20 μm. Fig. 2(b) offers a closer look at the concavity framed in Fig. 2(a), using now as 1230 × instrumental magnification. The inside of the orifice is replete with folds, indentations and spikes. Fig. 2(c) at a 1840 × instrumental magnification shows how the xerogel is comprised of curved, wrinkled and interconnected sheets. Also seen in Fig. 2(c) is a further underlying fine structure which is particularly noticeable in smoother areas such as that marked with an arrow. At a magnification of 59 900 × [Fig. 2(d)] the fibrous nature of this fine structure becomes apparent. Although the macroscopic fiber bundles observed by light microscopy did not survive the drying process, much smaller fibers, with diameters down to 15 nm and several μm length, remain intact. These microfibers pack themselves into craggy sheet-like structures.

Based on these observations, we can describe this xerogel as a hierarchical structure as depicted schematically in Fig. 3. At the lowest level of structure we postulate single molecules of **1** (**A**) self-assembling into fibers (**B**) *via* hydrogen bonding between the glycoluril head groups. The molecular structure of these elementary fibers is still unknown (a problem that besets most organogel work). The elementary fibers then form bundles (**C**) with diameters of *ca.* 15 nm which are visible by SEM at 60 000 × magnification. These bundles align and pack side-by-side, thereby forming sheets (**D**). Owing to the high disorder and curvature of these sheets, and to their multiple junctions with one another, cavities are formed to give a macroporous solid (**E**). Although individual fibers are curved and seemingly flexible, the bulk material composed of the fibers is hard and brittle. Close packing and interweaving of the fibers into a sponge-like network produces a fairly rigid microstructure.

The gel-to-xerogel transformation upon solvent removal can be understood in terms of our model. As seen in Fig. 4, the organogel is composed of 2 μm fibers (visible by light microscopy) which in turn are composed of 15 nm fibers (visible by SEM). Below our resolution capabilities lie the 2.5 nm elementary fibers. When the gel is dried, the macroscopic fiber bundles disappear, leaving the nanoscopic bundles which self-assemble into the sheets that comprise the xerogel. No comparable transformation has been reported thus far; usually the structure of the original gel is either faithfully preserved or else completely destroyed.

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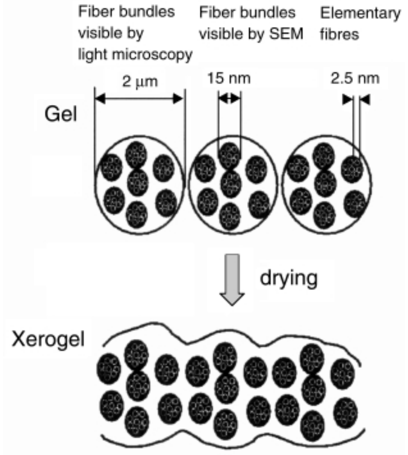

Fig. 4 Schematic representation of cross-sections through fiber bundles in the organogel and through a sheet in the xerogel of **1**.

Notes and references

† δ_H(DMSO-d_6, 400 MHz): 7.65 (s, 4H, –NH), 7.35 (m, 8H, ar. H, benzyl), 7.28 (m, 2H, ar. H, benzyl), 6.97 (d, 4H, J = 8.9 Hz, ar. H), 6.74 (d, 4H, J = 8.9 Hz, ar. H), 4.98 (s, 4H, benzyl, CH_2); δ_C(DMSO-d_6, 100 MHz): 160.6, 157.8, 136.9, 130.7, 128.4, 128.3, 127.7, 127.5, 113.7, 81.6, 69.0; Anal. calc. for $C_{30}H_{26}N_4O_4$: C, 71.13; H, 5.17; N, 11.06; found C, 70.70; H, 5.08; N, 11.08%; HRMS: calc. for $C_{30}H_{26}N_4O_4Li$ $(M + Li)^+$ m/z 513.2114, found 513.2120.

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