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COMMUNICATION

A transparent photo-responsive organogel based on a glycoluril supergelator[†][‡]

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The synthesis of an azo-benzene glycoluril supergelator is reported. The control over the gel/sol state can be accomplished by irradiation and heat, but also (in a unidirectional sense) by incorporation of the glycoluril into a more stable supramolecular assembly.

Gels are intensely studied materials with diverse applications ranging from drug delivery, sensing, surface engineering and hardening liquid waste.^{1,2} Organogels are formed by the assembly of low molecular weight organic molecules into entangled three-dimensional networks that entrap solvent molecules. There is considerable interest in the development of gels responsive to external stimuli with a special focus on photo-responsive organogels.^{3–15} Easy and reversible manipulation of the sol–gel state is especially desirable for the creation of gel-based smart materials.¹⁶ We report here the synthesis and characterization of glycolurils **2–4** bearing azobenzene substituents. Glycoluril **2** was found to act as a photoresponsive supergelator that can be switched reversibly from the gel to the sol state by irradiation.

Glycolurils are versatile building blocks for a variety of host-structures in supramolecular chemistry.^{17–19} Nevertheless, we know of only one report of a glycoluril forming a supramolecular gel: compound **1** gels at 20 mg mL⁻¹ in benzyl alcohol, a relative high concentration.^{17,20} Accordingly, we prepared new glycolurils **2–4** with azobenzenes on their peripheries to explore the possibility of influencing their aggregation properties by light (Fig. 1).

The synthetic routes are outlined in Scheme 1. Buchwald– Hartwig-type reaction of bromoarenes **8**, **9** and **10** (commercially available or prepared from 1,3,5-tribromobenzene **7** and **5** or **6** in two steps) with *t*-butyl-carbazate (**11**) was unsuccessful,²¹ but the use of 2-di-*t*-butylphosphino-2',4',6'-triisopropylbiphenyl (**12**) as ligand yielded the desired regio-isomers of the hydrazinecarboxylates 13, 14 and 15 in 17-27% yield. Another palladium catalyzed coupling to 4,4'-dibromobenzil gave compounds 16, 17 and 18 in 50–77% yield. After oxidation to the corresponding azobenzenes using NBS,²² the glycoluril heterocyles were installed by refluxing the benzils in the presence of urea and TFA in a Dean–Stark-apparatus to yield 2, 3 and 4 in 32–48% yields over the two steps.

Glycolurils 2, 3, and 4 were tested for their gelation properties in a variety of different solvents, and the results are given in Table 1. The glycolurils were added to the solvent, the mixtures were heated to nearly the boiling point then allowed to cool to 20 °C. While compounds 3 and 4 did not form gels at the initial test concentrations of 30 mg mL⁻¹, compound 2 gelated DMSO, CCl₄, anisole, *p*-xylene, mesitylene and toluene (Table 1). Subsequently the minimum gelation concentrations of 2 were determined for these solvents. The best gelation ability of 2 was observed in toluene, where a transparent gel was formed at concentrations as low as 0.06% (w/v) at 20 °C. Therefore 2 can be regarded as a supergelator—a group of exceptional low molecular weight gelators, which are effective at concentrations below 0.1% (w/w).¹

We investigated the microscopic structure of the tolueneorganogel by transmission electron microscopy (TEM, Fig. 2). The TEM image of the xerogel of glycoluril 2 indicates that molecules of 2 are self-assembled into an entangled network of thin fibers with lengths up to tens of micrometers.



Fig. 1 Structures of benzil 1 and azo-benzils 2-4.

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[‡] Electronic supplementary information (ESI) available: Experimental details, synthetic procedures and characterization data for compounds 2–18, ¹H-NMR spectrum of assembly 20. See DOI: 10.1039/ c1cc11354b

Scheme 1 Syntheses of azo-glucolurils 2-4.

Table 1 Results of the gelation experiments with compound 2 (at 30 mg mL $^{-1})$ at 20 $^{\circ}\mathrm{C}$

Solvent	State ^a
Toluene	G $(0.06\%; 0.6 \text{ mg mL}^{-1})$
Mesitylene	G $(0.08\%; 0.8 \text{ mg mL}^{-1})$
p-Xylene	G $(0.09\%; 0.9 \text{ mg mL}^{-1})$
Anisole	G $(0.15\%; 1.5 \text{ mg mL}^{-1})$
CCl ₄	G $(1.0\%; 10 \text{ mg mL}^{-1})$
DMSO	G $(3.0\%; 30 \text{ mg mL}^{-1})$
CHCl ₃ , THF, Et ₂ O, Ethyl acetate,	S
Pyridine,	
Benzene, Benzyl alcohol, DMF	Р
<i>n</i> -Hexane, Cylohexane, Acetone,	Ι
Water, MeCN, MeOH, EtOH	

^{*a*} G = gel; S = solution; P = precipitate at 20 °C; I = insoluble. For gels the minimum gelation concentration at 20 °C are given.

Fig. 2 TEM images of the xerogel obtained from organogel (0.1%) (w/v) 2 in toluene) after evaporation of the solvent under vacuum. Magnification of 25 000, scale bar: 500 nm.

The diameter of the fibers is approx. 26 nm (see SI^{\dagger}). What structural features are responsible for the gelation abilities of **2**? H-bonding motifs and π -surfaces are found in a variety of

organogels¹ and are likely contributors to the gelation properties of **2**. Since compounds **2–4** contain the same glycoluril H-bonding features, it is likely that the larger π -surface in **2** is responsible for the gelation ability of these compounds.

The influence of light on the sol/gel state was next investigated. Typically, azobenzenes can be isomerized between trans- and cis-conformations by irradiation with light at 365 nm. Irradiation of gel-samples led to a phase transition to the sol-state (Fig. 3, top). To quantify the *trans-/cis-* ratio in the gel state, sol state and photo-stationary state ¹H-NMR studies were performed (for discussion see SI[†]): We found that the featureless spectra recorded in D_{12} -mesitylene (0.1% m/v of 2) were turned into well-resolved ones by addition of 40% (v/v) of D8-THF followed by agitation, just before NMR-acquisition. The cis/trans ratios could now be determined by integration of the well-separated proton signals of these species. In the gelstate only the trans/trans isomer was observable, whereas after the phase transition to the sol-state 11% cis/cis-, 37% trans/ cis- and 52% trans/trans-glycoluril 2 were detected. Accordingly, switching 30% of the azobenzene moieties of glycoluril 2 from their *trans*- into the corresponding *cis*-conformation disrupts the entangled gel structure severely enough to revert the system back to the sol state. At the photo-stationary state 19% cis/cis-, 30% trans/cis- and 51% trans/trans-glycoluril 2 were detected. Interestingly, attempts to convert samples af ter the phase transition (11% cis/cis-, 37% trans/cis- and 52% trans/trans-glycoluril 2) back to the trans/trans- isomeric gel by the use of irradiation with 450 nm-even after extended irradiation-failed: 11% cis/cis- and 89% trans/transglycoluril 2 were detected. Although the cis/cis-isomer resisted isomerisation by irradiation (450 nm), heating any sample (160 °C, 1 min) and then allowing it to cool to 20 °C in the dark, readily regenerated the (all trans/trans) gel-state.

Fig. 3 Influencing the gel/sol sate of glycoluril **1** by light or by the formation of a more stable capsule assembly. For **19** and **20**: peripheral alkyl groups and most glycoluril substituents have been removed.

Transformation of the gel into a sol-state through assembly of a different supramolecular structure was also established (Fig. 3). Addition of cavitand 19 (0.5 eq.) and a suitable guest (*n*-tetradecane, 0.25 eq.) to a gel sample of 2 in D_{12} -mesitylene, followed by heating (to allow a homogenous distribution of all components) resulted (after allowing the sample to cool to 20 °C) in a solution of an extended capsular assembly, 23 which was characterized as 20 by ¹H NMR (see SI[†]). In each of these capsular assemblies four glycolurils 2 are efficiently bound between two cavitands in a chiral belt by a network of hydrogen bonds (green dotted lines in Fig. 3) and therefore are excluded from assembling into the gel fiber-structure (Fig. 2). The minimum required concentration of added capsule components has been determined for a mesitylene-gel sample of 2 at 0.4% (m/v): The sample lost its ability to support its weight at a concentration of 1.2 mM in cavitand 19. At this concentration of 19, the remaining concentration of 'free' gelator 2 (not bound in assembly 20) was reduced to 0.8 mM or 0.1% (w/v)-slightly above the minimum gelation concentration of 0.08% (w/v) in the original sample (Table 1). Thus, the main contribution of the capsular assembly to disruption of the gel structure can be regarded as a dilution effect.

It is known that fluoride ions also efficiently compete with urea-H-bonds and this interaction has been used to exert control over the gel-sol state.^{24,25} A similar effect of fluoride can be observed with gelator **2**: After addition of 0.5 eq of TBAF to a mesitylene gel sample (0.4% m/v, see SI[†]), the sample lost the ability to support its own weight.

In conclusion, we have shown that azobenzene-appended glycoluril 2 is a supergelator, which forms transparent gels with a variety of solvents. The control over the gel/sol state of 2 can be accomplished by irradiation and heat, or (in a unidirectional sense) by its incorporation in a more stable supramolecular assembly.

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