Electronic Supplementary Information

A four-component organogel based on orthogonal chemical interactions

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Content :

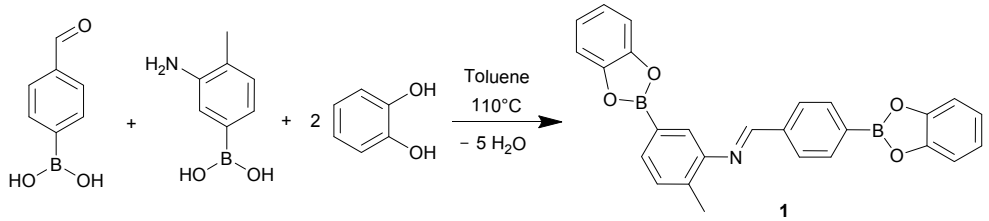
1. Experimental

1.1 General

All reactants and solvents were purchased from Sigma-Aldrich, Fluka, Acros, Fluorochem and Alfa Aesar, and were used without further purification. NMR spectra were recorded with a Bruker Avance DPX 400 spectrometer with the residual solvent as internal standard. ITC measurments were performed on a GE MicroCal VP-ITC system. The microwave syntheses were performed using a Biotage Initiator 2.0 microwave synthesizer (400W). The N-donor ligands **D2** and **D3**,[1,2] as well as 2-phenyl-1,3,2-benzodioxaborole[3] were prepared according to literature procedures.

1.2 Synthesis and characterization

Synthesis of diester **1**

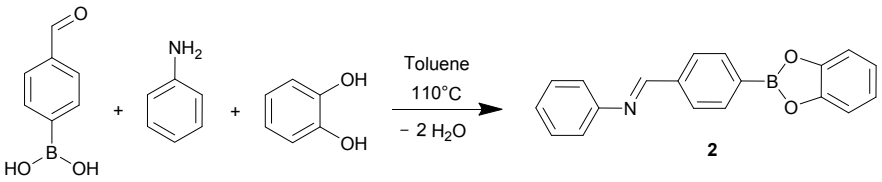


Catechol (220.2 mg, 2.0 mmol), 4-formyl-benzeneboronic acid (150.0 mg, 1.0 mmol), 4-methyl-3-aminobenzeneboronic acid (151.0 mg, 1.0 mmol) and toluene (50 mL) were added to a round-bottom flask. The mixture was heated under reflux for 4 h using a Dean-Stark trap and then cooled down to room temperature. The product was isolated by filtration and recrystallized from toluene to give **1** in the form of white crystalline needles. Yield: 353 mg, 82 %. ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.55 (s, 1 H, imine), 8.22 (d, J = 8.1 Hz, 2 H, CH_{ar}), 8.07 (d, J = 8.2 Hz, 2 H, CH_{ar}), 7.89 (dd, J = 7.4, 1.3 Hz, 1 H, CH_{ar}), 7.67 (d, J = 1.2 Hz, 1 H, CH_{ar}), 7.39 (d, J = 7.6 Hz, 1 H, CH_{ar}), 7.37–7.28 (m, 4 H, CH from catechol), 7.22–7.06 (m, 4 H, CH from catechol), 2.48 (s, 3 H, Me). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ 159.68 (imine), 151.04, 148.65, 148.62, 139.76, 137.39, 135.49, 132.89, 130.65, 128.60, 123.86, 123.13, 122.95, 112.83, 112.68, 18.50 (Me) (B-C was not observed due to quadrupole broadening). HRMS (APPI) calc'd for $[M]^+$: 431.15037, found: 431.14932. Elemental anal. calc'd. for ($C_{26}H_{19}B_2NO_4$): C (72.45), H (4.44), N (3.25). Found: C (72.54), H (4.46), N (3.26).

Alternative procedure for synthesis of **1**

A 20 mL microwave vial was charged with the same amount of starting materials, 15 mL of toluene and sealed. The mixture was heated to 170 °C at 400 W for 15 min. As the reaction flask cooled down, the product crystallized. The product was isolated by filtration and washed with cold toluene. Yield: 338 mg, 78 %.

Synthesis of 1-(4-(benzo[1,3,2]dioxaborol-2-yl)phenyl)-N-phenylmethanimine **2**



Catechol (220.2 mg, 1.0 mmol), 4-formyl-benzeneboronic acid (150.0 mg, 1.0 mmol), aniline (91.3 µL, 1.0 mmol) and toluene (50 mL) were added to a round-bottom flask. The mixture was heated under reflux for 4 h using a Dean-Stark trap and then cooled down to room temperature. The product was isolated by filtration and recrystallized from cyclohexane to give **2** in the form of an orange powder. Yield: 222 mg, 74 %. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.53 (s, 1 H, imine), 8.20 (d, J = 8.1 Hz, 2 H), 8.03 (d, J = 8.1 Hz, 2 H), 7.42 (dd, J = 8.8, 6.8 Hz, 2 H), 7.37 – 7.31 (m, 2 H), 7.29 – 7.23 (m, 3 H), 7.21 – 7.12 (m, 2H). ^{13}C NMR (100.6 MHz, $CDCl_3$): δ 160.05 (imine), 151.96, 148.61, 139.62, 135.47, 129.36, 128.57, 126.45, 123.12, 121.06, 112.82 (B-C was not observed due to quadrupole broadening). HRMS (APPI) calc'd for $[M+H]^+$: 300.1199, found: 300.1194.

1.3 Screening of the 4-component reaction

A mixture of catechol (0.4 mmol), formylbenzene-boronic acid (0.2 mmol), aminobenzeneboronic acid (0.2 mmol) and divalent N-donor ligand (0.2 mmol) were mixed in toluene (50 mL). The resulting solution was heated to reflux using a Dean-Stark trap. After 4 h, the volume was reduced to obtain a 1.0 wt % concentration of compounds and the flask was allowed to cool down. Gelation test was achieved by a simple inversion test.

1.4 Critical gel concentration of GEL1

A 1.0 wt % sample of **GEL1** in the appropriate solvent (610 mg) was prepared in a glass vial with stoichiometric amounts of **D2** (1.8 mg, 10 µmol) and **1** (4.3 mg, 10 µmol). Gelation was induced by a heating-cooling cycle. After cooling down to room temperature, vial-inversion test was used to confirm gelation (if the sample stands upside-down without any flow of matter). The sample was then diluted and the procedure repeated until the gelation was not strong enough for the sample to be self-supporting. The lowest concentration at which the gel could stand the vial-inversion was noted as the critical gel concentration.

1.5 Determination of $T_{sol\text{-}gel}$

1.0 wt % samples of **GEL1** in the appropriate solvent (610 mg) were prepared in glass vials with stoichiometric amounts of **D2** (1.8 mg, 10 µmol) and **1** (4.3 mg, 10 µmol). Gelation was induced by a heating-cooling cycle. The gels were then immersed in an oil bath warmed up at 40 °C for 5 minutes and then inversed. If the samples were still in the gel state, the oil bath temperature was increased by 5 °C and the procedure was repeated. The temperature at which a gel could no longer stand the vial-inversion test was noted as the $T_{sol\text{-}gel}$.

2. Titrations

2.1 ^{1}H-NMR Titrations

A NMR tube was filled with a solution of **1** in $CDCl_3$ (1.0 mM). A solution of N-methylimidazole (20 mM) and **1** (1.0 mM) was then added in small aliquots to the NMR tube, until the concentration of the N-donor was 8.0 mM. After each addition, a ^{1}H NMR spectrum was recorded (Figure S1). Attempts to calculate the binding constants K_{a1} and K_{a2} were performed with Origin 8.5, using a 1:2 binding model:[4]

$$\Delta\delta = \frac{\delta_{\Delta HL}K_{a1}[L] + \delta_{\Delta HLL}K_{a1}K_{a2}[L]^2}{1 + K_{a1}[L] + K_{a1}K_{a2}[L]^2}$$

However, the calculated values were not reliable, as different initial values resulted in different binding constants.

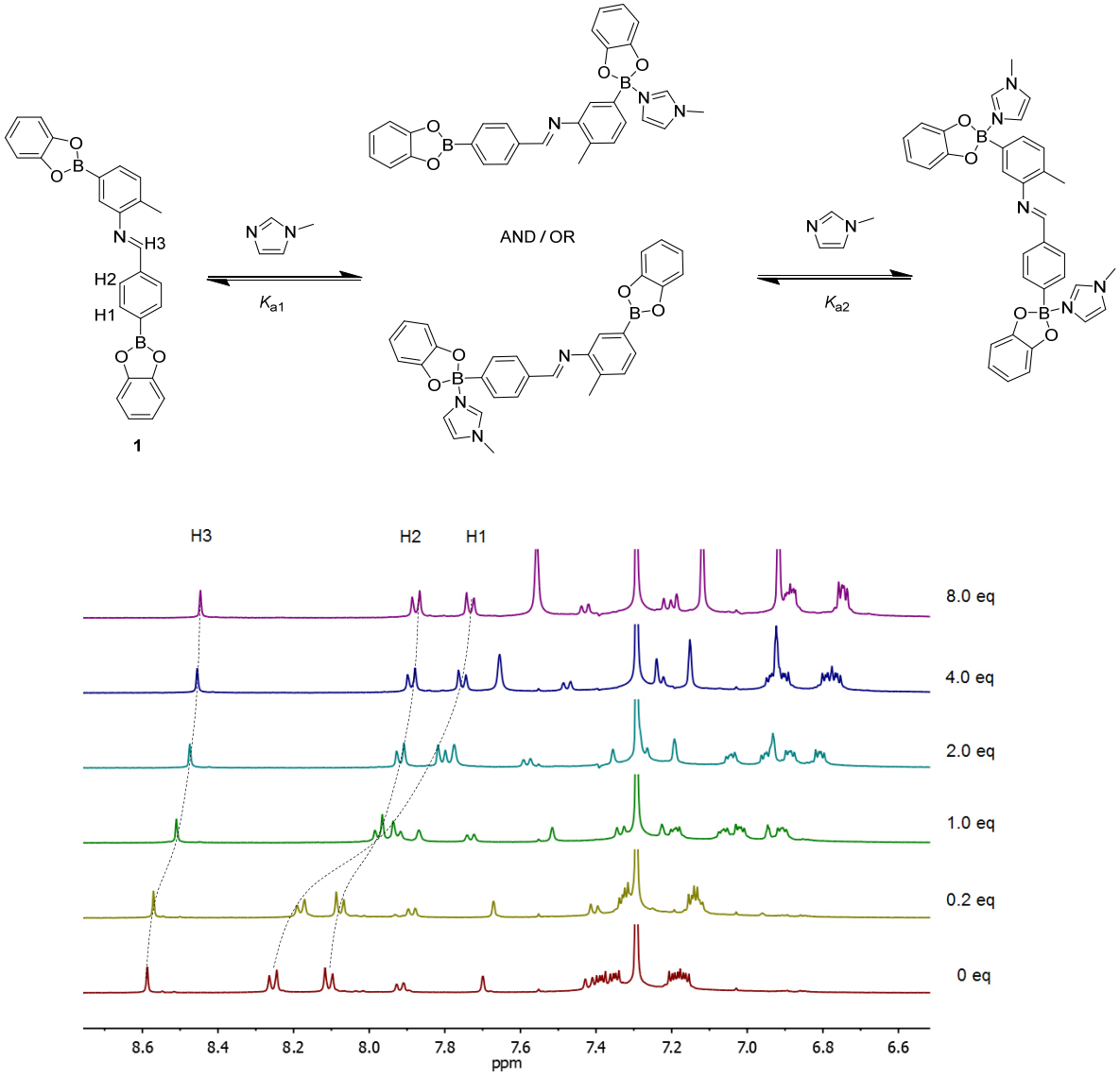


Figure S1. ^{1}H NMR titration of **1** with N-methylimidazole in $CDCl_3$.

2.2 ITC measurements

Freshly distilled chloroform was used for the titration. Injection of a solution of N-methylimidazole (30 mM) from the injector syringe to the measurement cell containing a solution of **1** (0.5 mM) was done by 45 sequential additions of 2.5 µL separated by 240 seconds. The heat of injections, binding enthalpies and binding constants were obtained by data analysis with NITPIC (integration) and SEDPHAT (curve fitting), assuming two identical and non-interacting binding sites.[5] Three independent measurements were performed from the same batch of ester **1**.

$$K_{a1} = 4.4(\pm 0.7) \times 10^3\ M^{-1}$$

$$K_{a2} = 1.1(\pm 0.2) \times 10^3\ M^{-1}$$

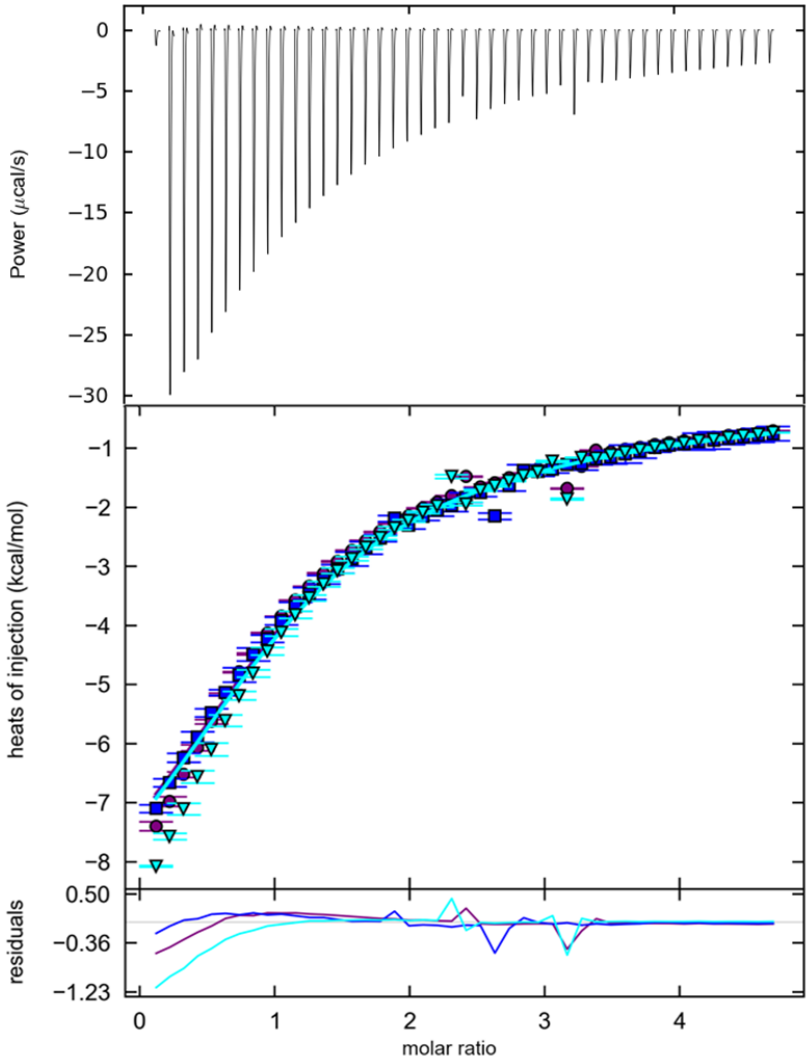


Figure S2. ITC data for a titration of **1** with N-methylimidazole in chloroform.

2.3 Fitting of ^{1}H NMR data with K_{a1} and K_{a2} obtained from ITC

The binding constants K_{a1} and K_{a2} obtained from the ITC data were used to fit the NMR data (Figure S3). Using the typical 1:2 binding model equation shown below, a reasonably good fit was obtained.

$$\Delta\delta = \frac{\delta_{\Delta HL} K_{a1}[L] + \delta_{\Delta HLL} K_{a1} K_{a2}[L]^2}{1 + K_{a1}[L] + K_{a1} K_{a2}[L]^2}$$

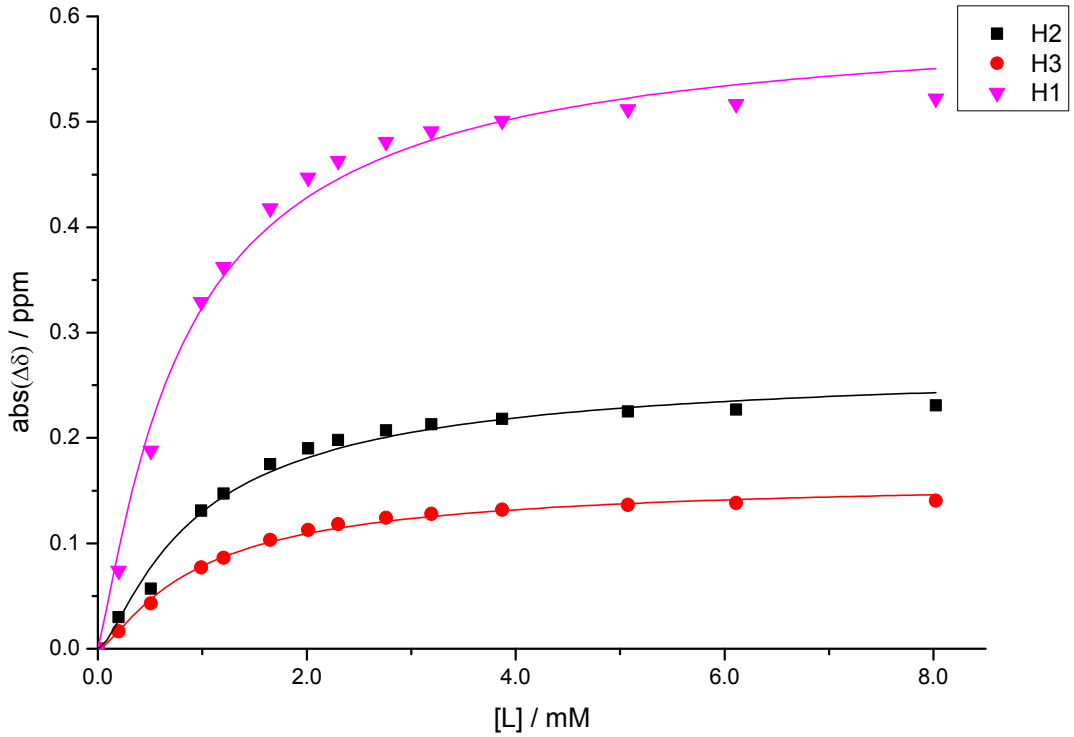


Figure S3. Fit of the binding isotherms from ^{1}H NMR titrations using the binding constant derived from ITC measurements.

3. Chemical stimulus tests

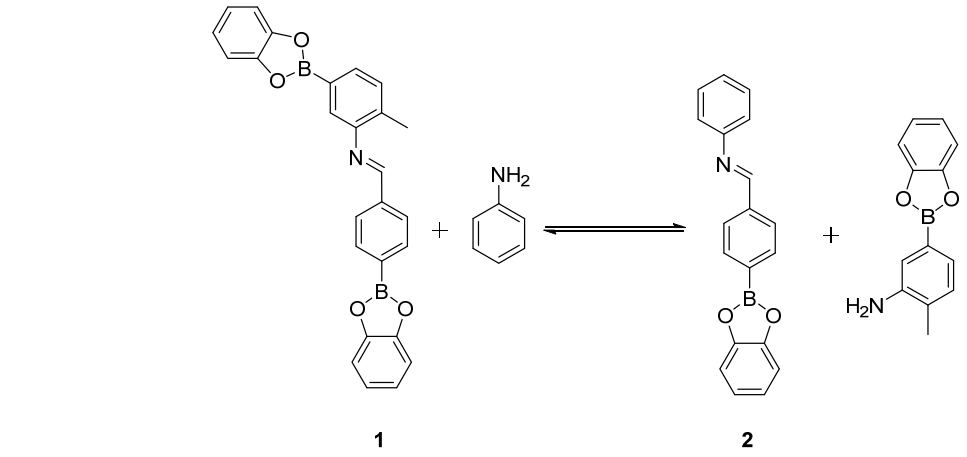
Figure S4. Photographs of **GEL1** before (left) and after (right) treatment with different chemical stimuli.

Samples of **GEL1** (0.5 wt %) were prepared in small glass vials by mixing 2.13 mg (4.94 mmol) of **1** and 0.87 mg (4.94 mmol) of **D2** in 600 mg of dry toluene. The mixtures were heated to dissolve the starting materials and allowed to cool down to room temperature to afford gelation. To test the gel disruption capability of the different compounds, an excess of the respective chemical was used. For methanol, aniline and N-methylimidazole, 5 μL of liquid were dropped on top of the gel. For 4,5-dichlorocatechol, 5 mg of solid material were placed on top of the gel. Gel breaking was confirmed after an incubation time of 15 minutes by vial-inversion test. After ~1 h, a clear homogenous solution was obtained (Figure S4), except for catechol for which a white precipitate was observed.

4. ^{1}H NMR Competition experiments

4.1 Reaction of 1 with aniline

To examine the reaction of aniline with compound **1**, an NMR tube was charged with 1.0 mg (2.3 µmol) of **1**, 0.22 mg (2.3 µmol) of aniline and 500 µL of $CDCl_3$. A ^{1}H NMR spectrum was recorded immediately after preparation. The spectrum showed the signals of a new imine (Figure S5), which could be identified as compound **2** by comparison with the ^{1}H NMR spectrum of a pure sample (the synthesis of imine **2** is described on page S3). These results show that a fast transamination reaction takes place.



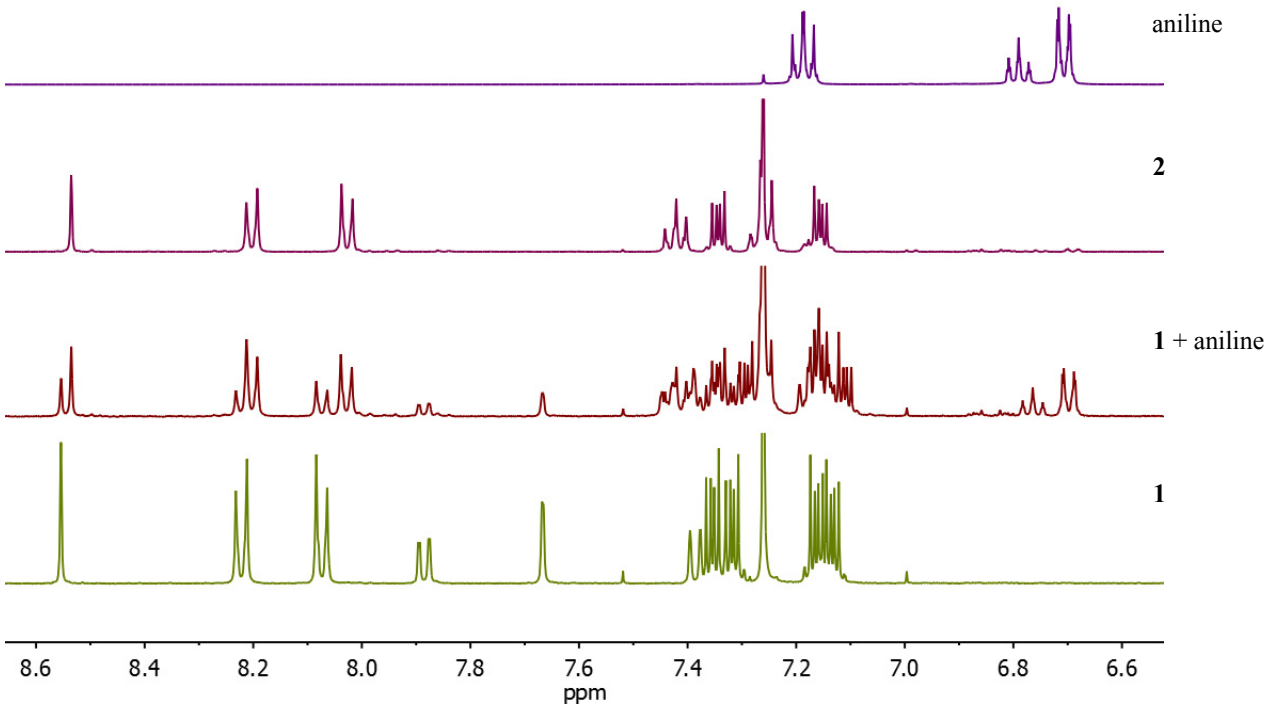


Figure S5. ^{1}H NMR ($CDCl_3$) spectra of aniline, imine **2**, a mixture of **1** and aniline, and pure **1**.

4.2 Reaction of 1 with methanol

An excess of methanol (20 µL, 493 µmol) was added to a solution of **1** (1.0 mg, 2.3 µmol) in $CDCl_3$ (500 mL) and the solution was mixed for 30 seconds using a vortex shaker. A ^{1}H NMR spectrum was then recorded. It showed that catechol had been liberated (Figure S6).

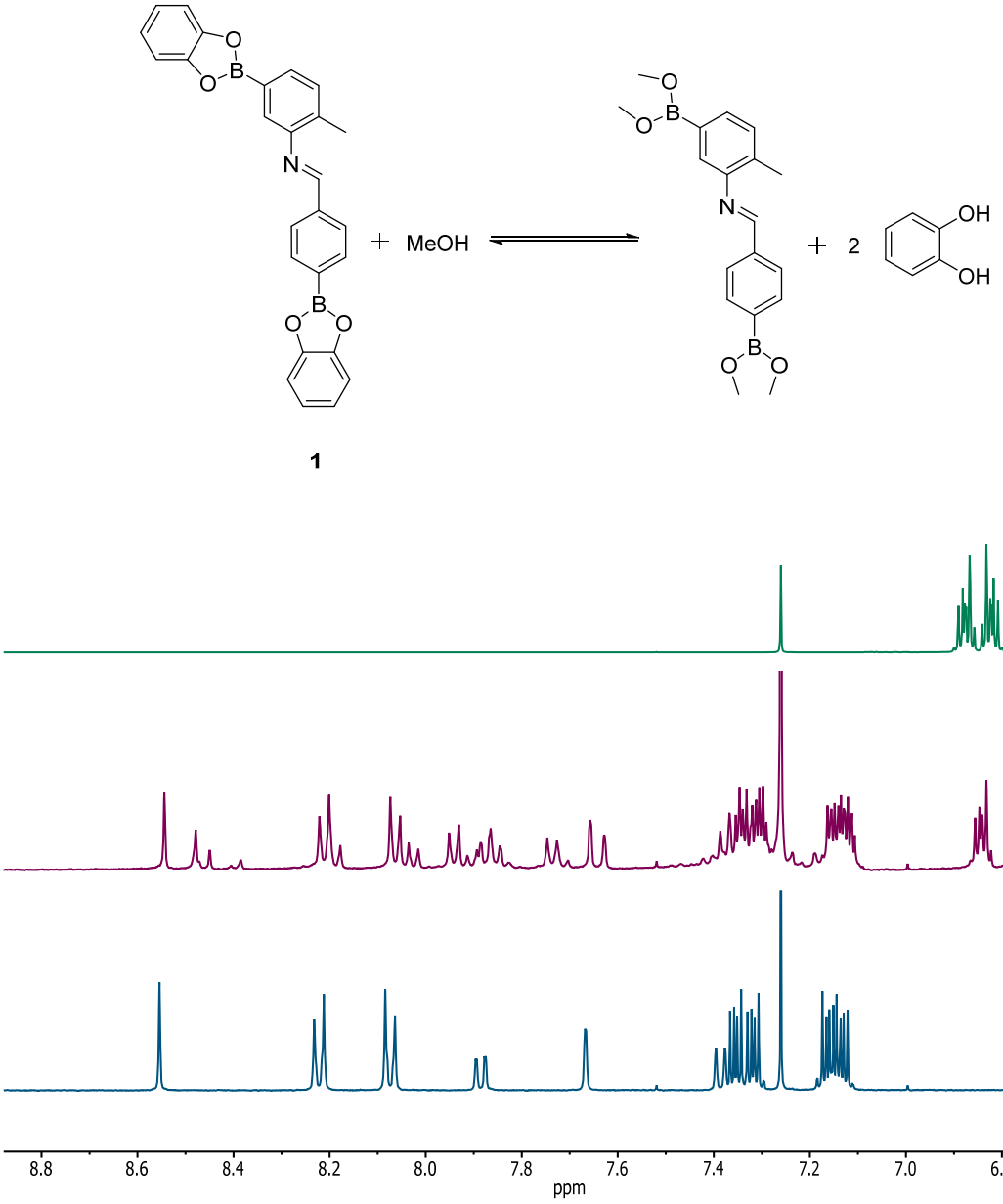


Figure S6. ^{1}H NMR spectrum ($CDCl_3$) of catechol, a mixture of **1** and methanol, and pure **1**.

4.3 Reaction of 1 with catechol C2

An excess of dichlorocatechol **C2** (1.5 mg, 8.4 µmol) was added to a solution of **1** (1.0 mg, 2.3 µmol) in $CDCl_3$ (500 mL) and the solution was mixed for 30 seconds using a vortex shaker. A ^{1}H NMR spectrum was then recorded. It showed that catechol had been liberated (Figure S7).

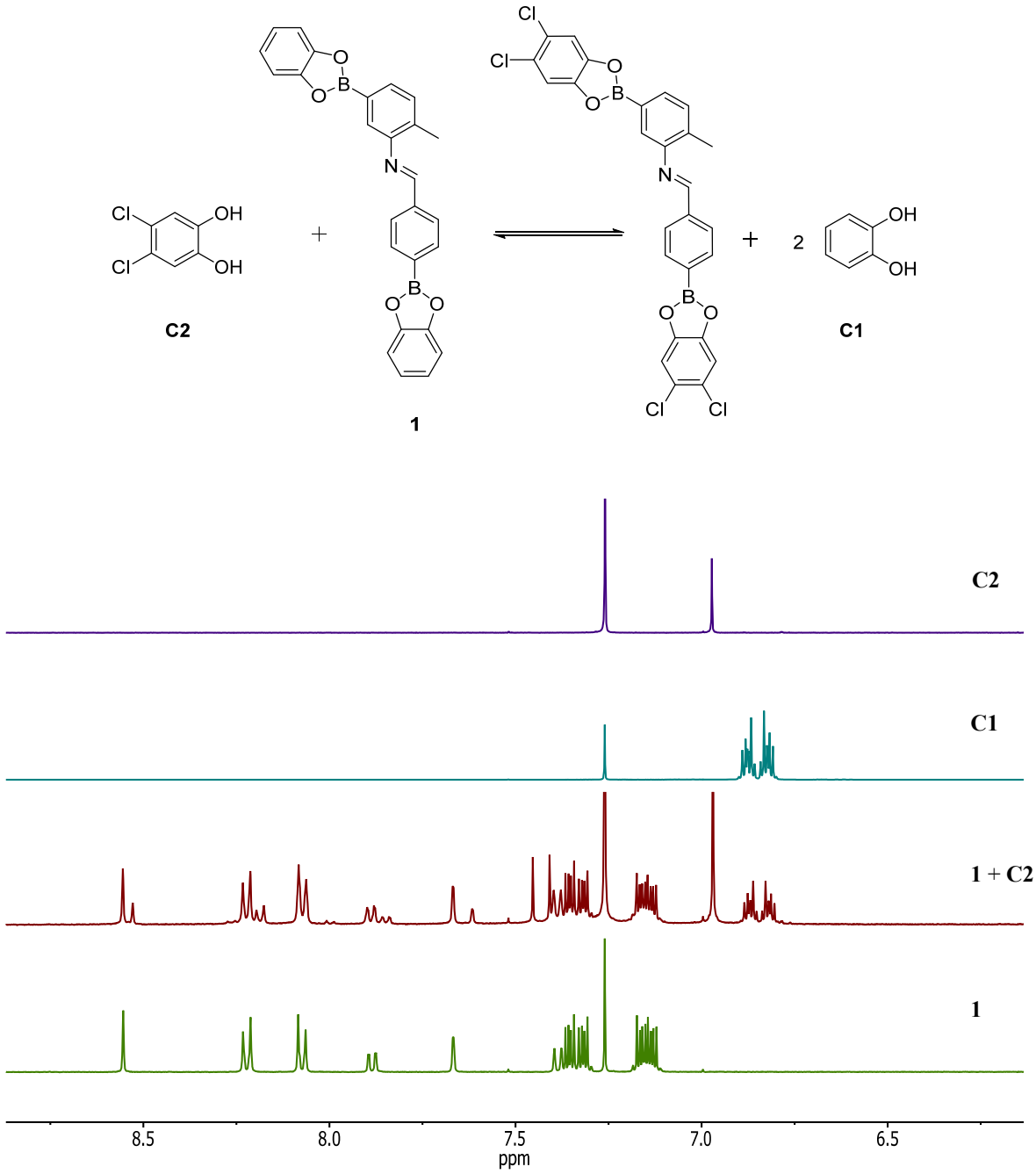


Figure S7. ^{1}H NMR spectra ($CDCl_3$) of the catechols **C2** and **C1**, a mixture of **1** and **C2**, and pure **1**.

4.4 Reaction of 1 with catechol C3

Two equivalents of 4-tertbutylcatechol **C3** (0.8 mg, 4.6 µmol) were added to a solution of **1** (1.0 mg, 2.3 µmol) in $CDCl_3$ (500 mL) and the solution was mixed for 30 seconds using a vortex shaker. A ^{1}H NMR spectrum was then recorded. It showed that catechol had been liberated (Figure S8).

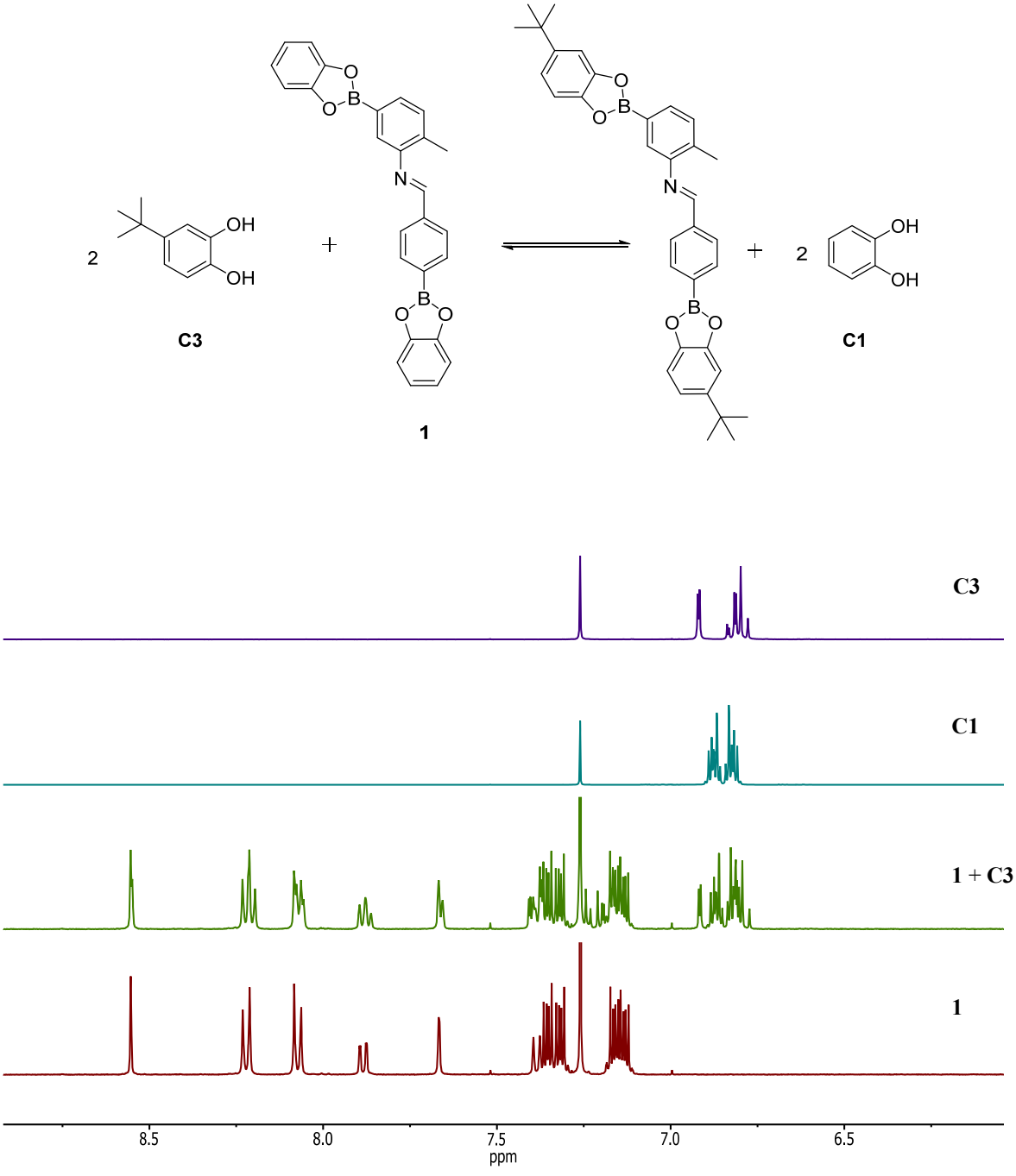


Figure S8. ^{1}H NMR spectra ($CDCl_3$) of the catechols **C3** and **C1**, a mixture of **1** and **C3**, and pure **1**.

4.5 Competition between aniline and N-methylimidazole

2-Phenyl-1,3,2-benzodioxaborole (3.9 mg, 20 µmol) and N-methylimidazole (1.6 µL, 20 µmol) were dissolved in $CDCl_3$ (500 µL) in an NMR tube and a first spectrum was recorded. Aniline (1,9 µL, 20 µmol) was then added to the solution and another spectrum was recorded. A comparison of the spectra of the mixtures with those of aniline and N-methylimidazole shows that mainly N-methylimidazole is bound to the ester (Figure S9).

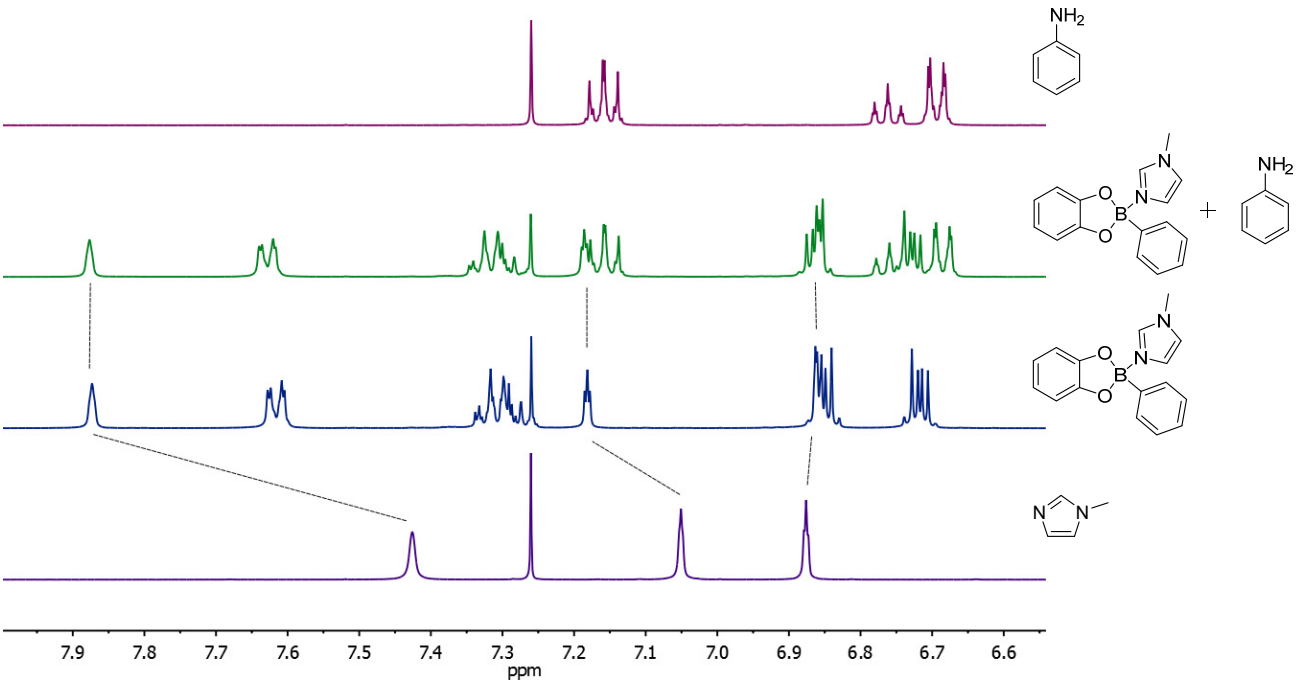


Figure S9. ^{1}H NMR spectra ($CDCl_3$) of aniline, a mixture of 2-phenyl-1,3,2-benzodioxaborole, N-methylimidazole and aniline, a mixture of 2-phenyl-1,3,2-benzodioxaborole and N-methylimidazole, and N-methylimidazole.

5. Scanning electron microscopy

A small amount of **GEL1** in the appropriate solvent was wiped on an aluminum stub and air-dried over 4 days. A 7 nm layer of osmium was then coated onto the sample to improve the contrast of the measurement and the stability of the sample. Observations were done with a Zeiss NVision 40 scanning electron microscope with 2.0 kV operating voltage. In all cases, we observed spherical aggregates along with a variable amount of fibrous structures.

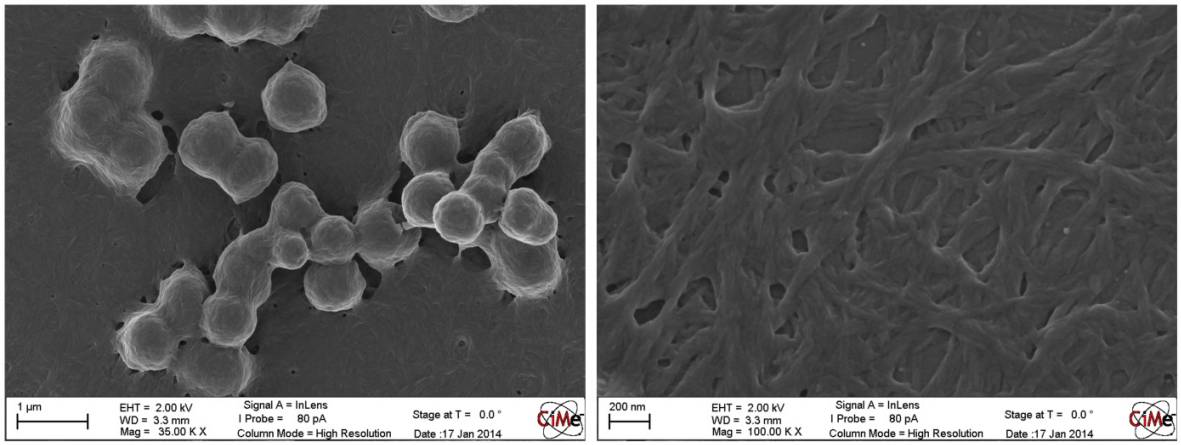


Figure S10. SEM images of a xerogel obtained by air-drying **GEL1** (0.5 wt %) in toluene over 4 days.

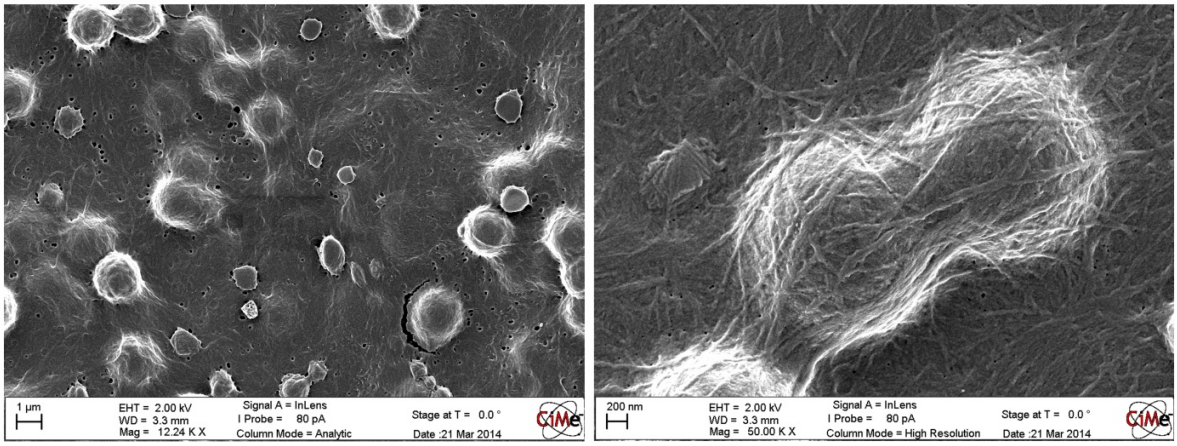


Figure S11. SEM images of a xerogel obtained by air-drying **GEL1** (1.0 wt %) in chlorobenzene over 4 days.

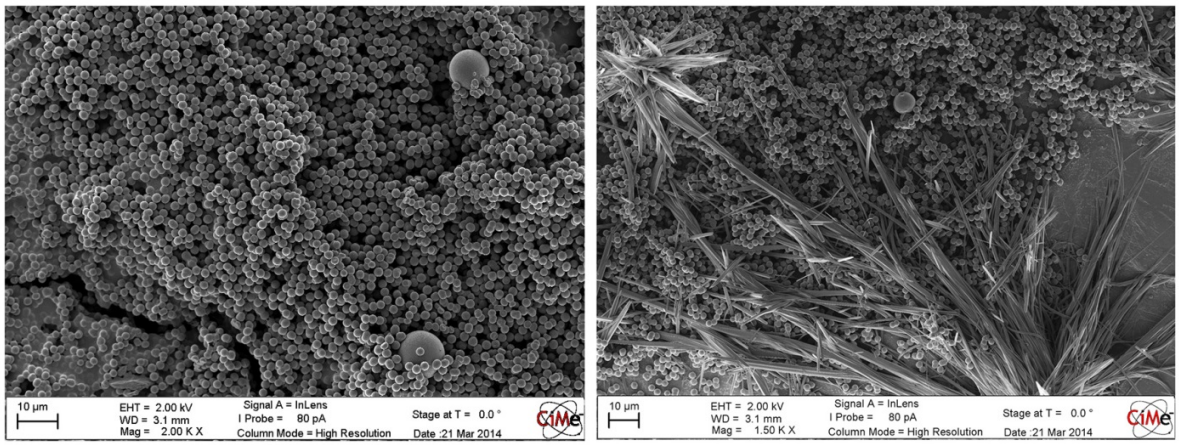


Figure S12. SEM images of a xerogel obtained by air-drying **GEL1** (1.0 wt %) in 1,2,4-trichlorobenzene over 4 days.

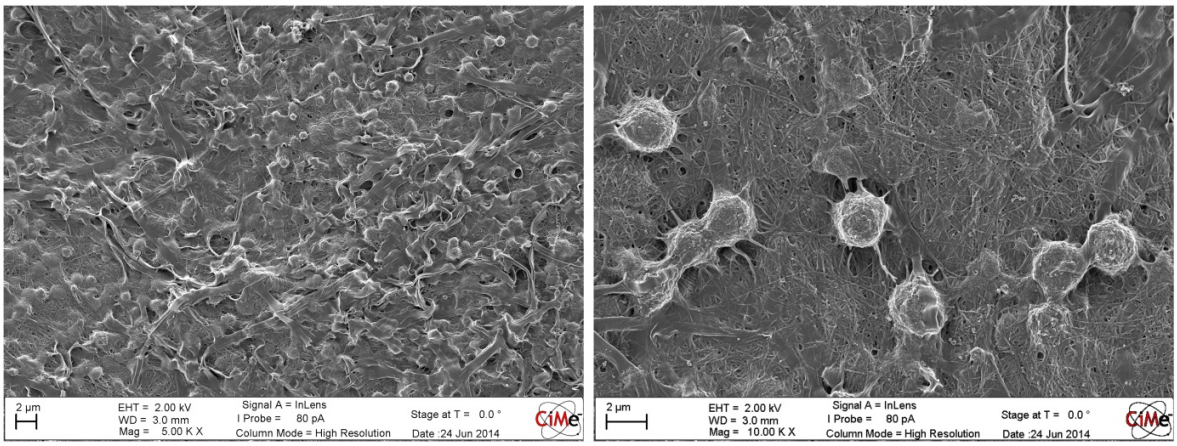


Figure S13. SEM images of a xerogel obtained by air-drying **GEL1** (0.5 wt %) in carbon tetrachloride over 4 days.

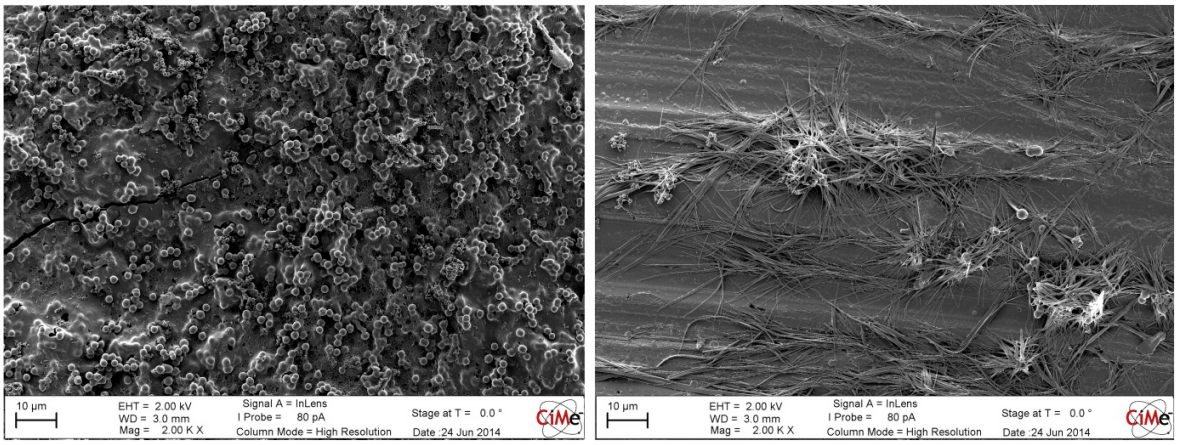


Figure S14. SEM images of a xerogel obtained by air-drying **GEL1** (1.0 wt %) in *o*-xylene over 4 days.

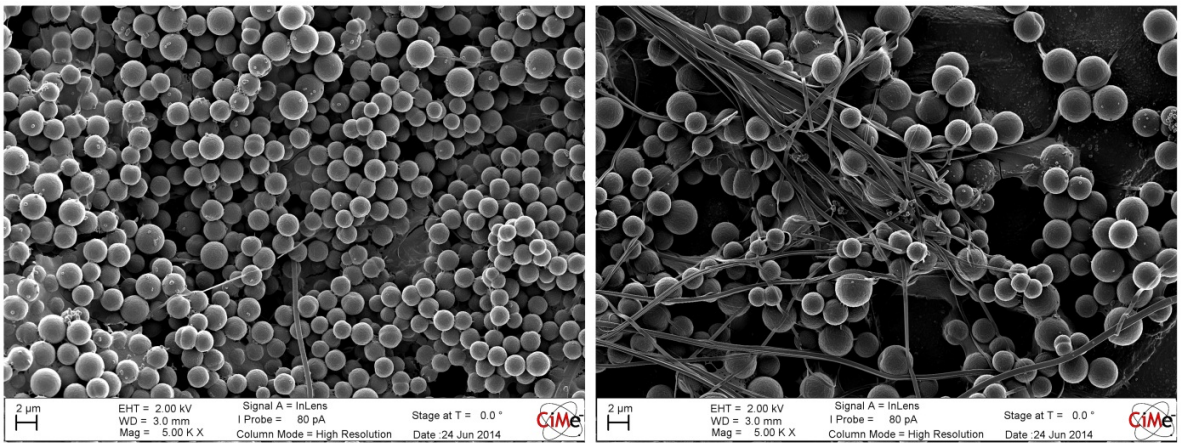


Figure S15. SEM images of a xerogel obtained by air-drying **GEL1** (1.0 wt %) in *m*-xylene over 4 days.

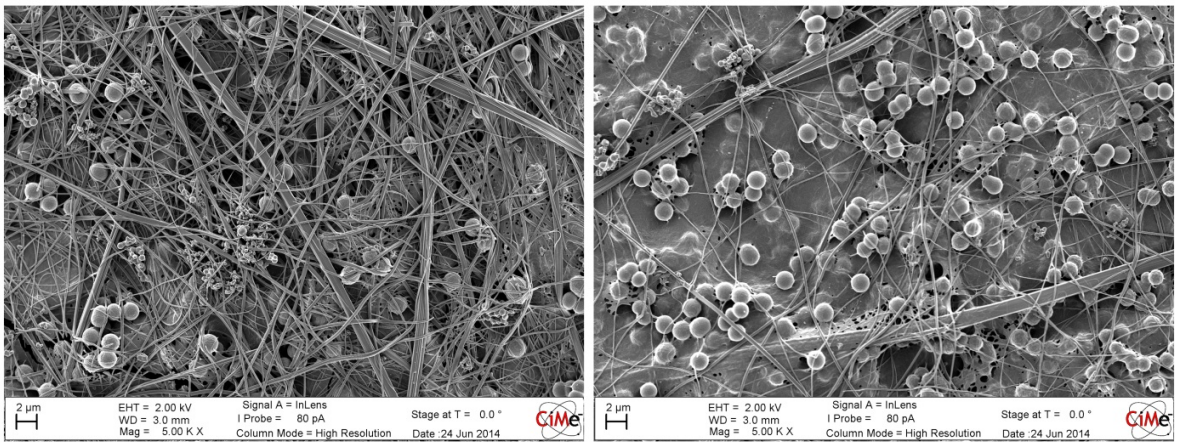


Figure S16. SEM images of a xerogel obtained by air-drying **GEL1** (1.0 wt %) in *p*-xylene over 4 days.

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6. Wide-angle X-ray scattering

1.0 wt % **GEL1** samples were prepared in toluene and *p*-xylene by mixing **1** (15.0 mg, 34.8 μmol) and **D2** (6.1 mg, 34.8 μmol) in the appropriate solvent (2.1 g). Suspensions were heated to dissolve the starting materials and allowed to cool down to room temperature to afford homogeneous gels. The solvent was then rapidly removed under high vacuum using a diffusion pump. The resulting xerogel was dispersed on a silicon plate and submitted to the measurement (Figure S17).

X-ray powder diagrams were recorded, with spinning sample, on an X'Pert MPD PRO from PANalytical equipped with CuKa radiation, a secondary graphite (002) monochromator and an X'Celerator detector operated in scanning mode. Measurement were performed from 3° to 42°, with step size of 0.008°, a time of 463.55 s/step, a beam-mask of 10 mm and an automatic divergence slit (irradiated length=10 mm).

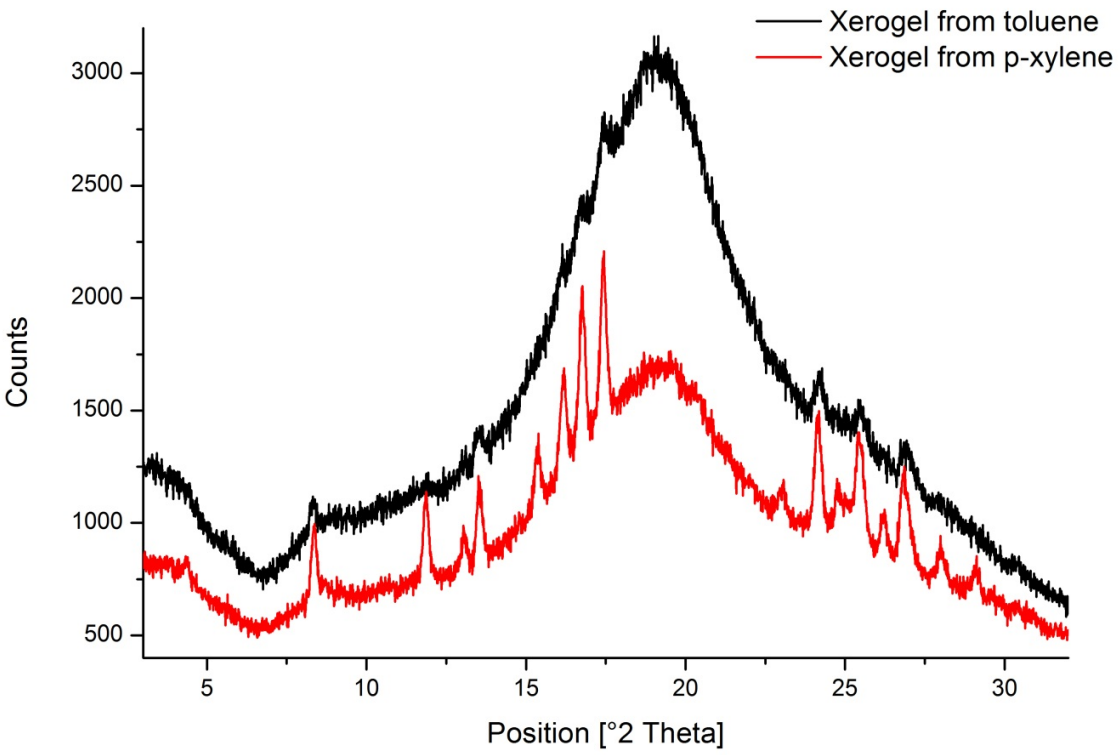

Figure S17. Wide-angle X-ray scattering of xerogels **GEL1** from toluene (black) and *p*-xylene (red).

7. Post-modification of GEL1 in toluene

To examine the mechanical behavior of **GEL1** and **GEL1-C3**, both sample were prepared from **1** (35.0 mg, 81.2 µmol) and **D2** (14.3 mg, 81.2 µmol) in 4.9 g (5.7 mL) of toluene. The suspensions were heated to dissolve the starting materials and allowed to cool down to room temperature. To one of the gels, additional 13.5 mg (81.2 µmol) of **C3** were added, and the sample was submitted to an additional heating-cooling cycle to afford a homogeneous gel of **GEL1-C3**. A metallic sphere of 7 g was placed on top of each sample and pictures were taken after 10 seconds, 2 minutes, and 5 minutes, respectively. The modified **GEL1-C3** (Figure S18, sample on the left side) was more resistant towards penetration of the metal sphere compared to the non-modified **GEL1** (Figure S18, sample on the right side). A similar increase in resistance was not observed when **C1** instead of **C3** was added to **GEL1**.

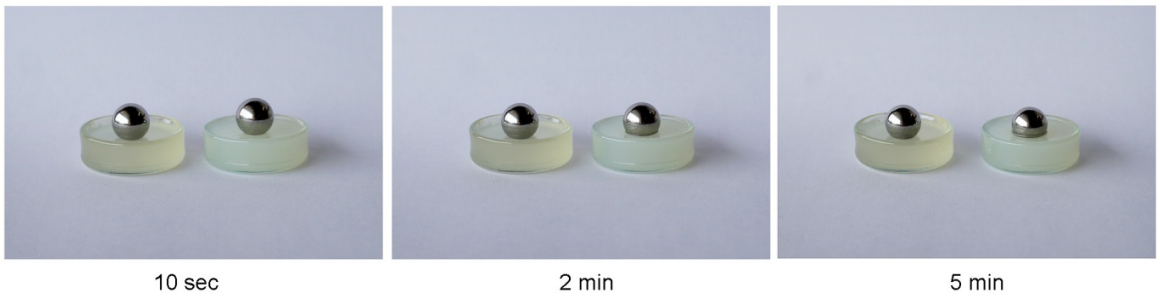

Figure S18. Pictures of **GEL1** (right sample) and **GEL1-C3** (left sample) with a 7 g metallic sphere on top after 10 seconds, 2 minutes, and 5 minutes.

8. NMR spectra

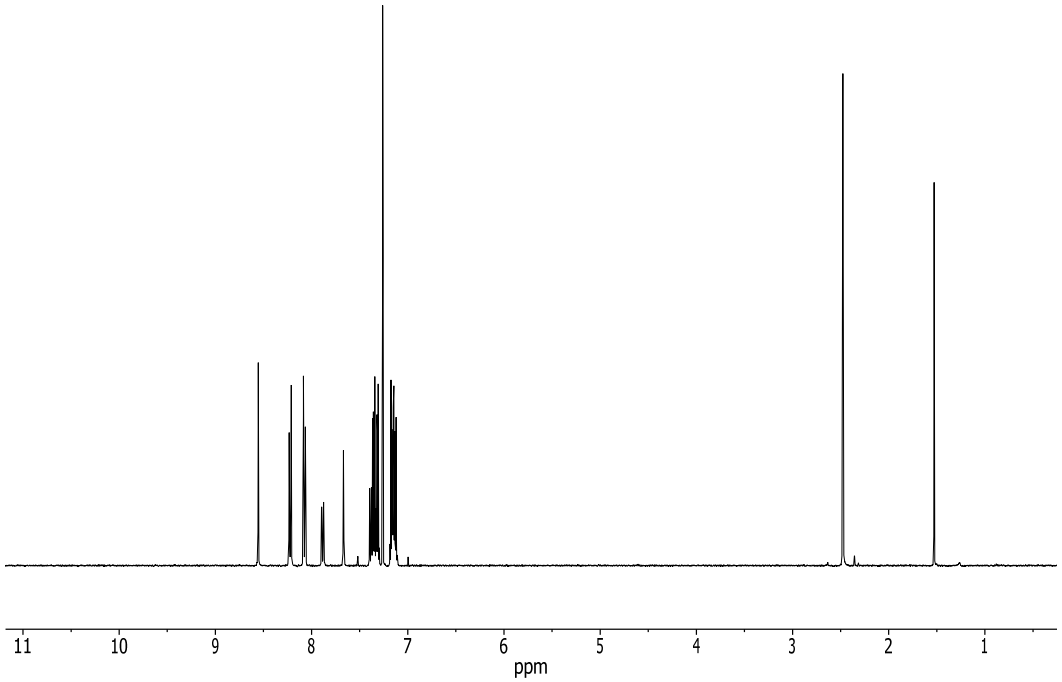

Figure S19. ^{1}H NMR spectrum of **1** in $CDCl_3$.

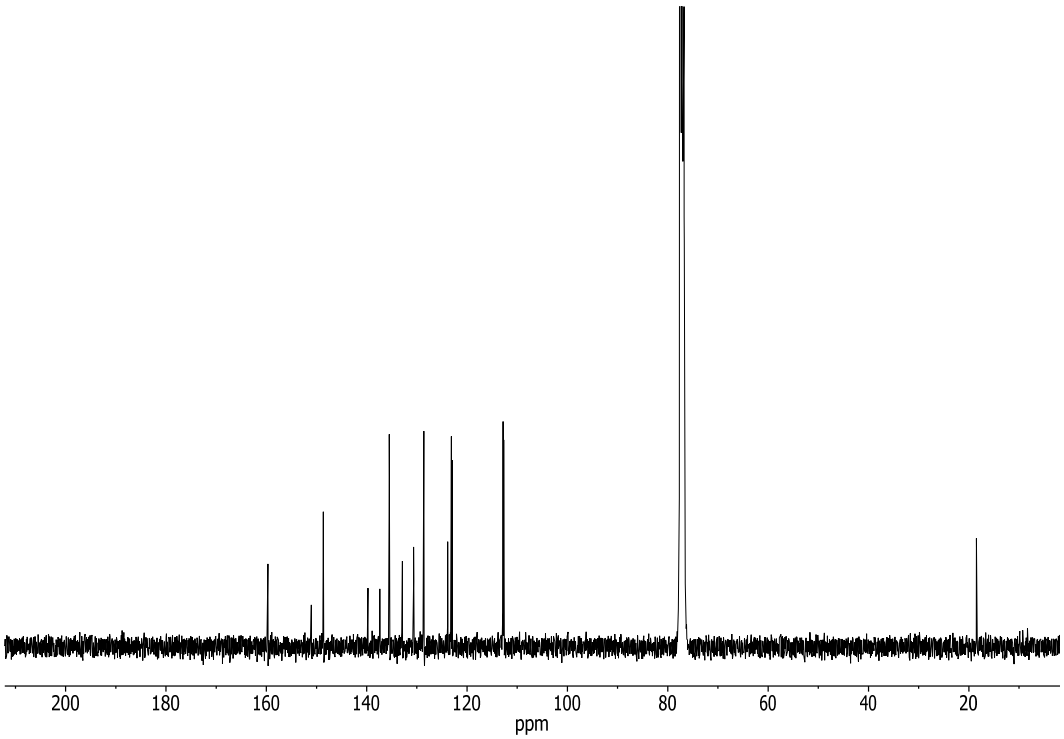

Figure S20. ^{13}C-NMR spectrum of **1** in $CDCl_3$.

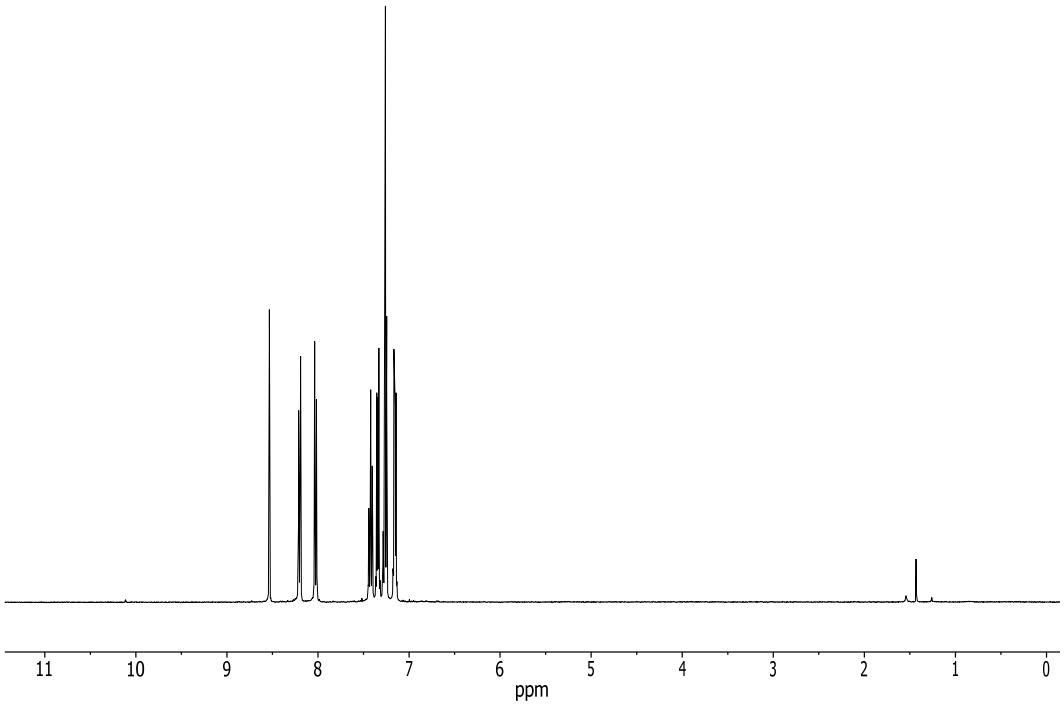

Figure S21. ^{1}H NMR spectrum of **2** in $CDCl_3$.

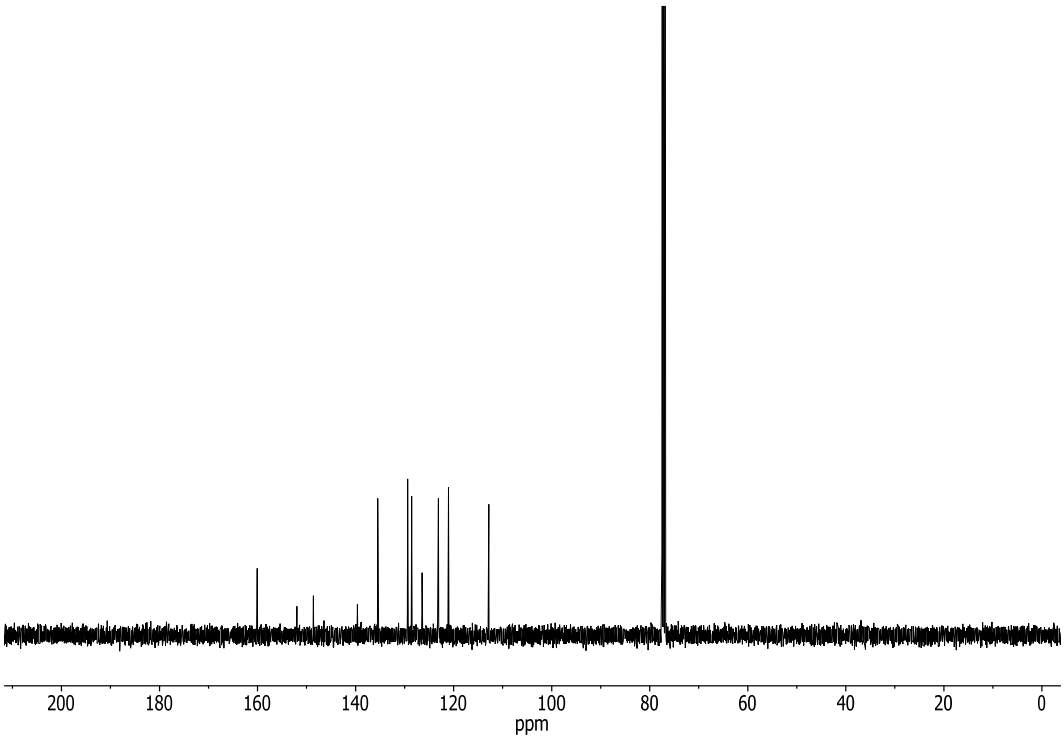

Figure S22. ^{13}C-NMR spectrum of **2** in $CDCl_3$.

9. References

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