A water-soluble pillar[10]arene: synthesis, pH-responsive host–guest complexation, and application in constructing a supra-amphiphile

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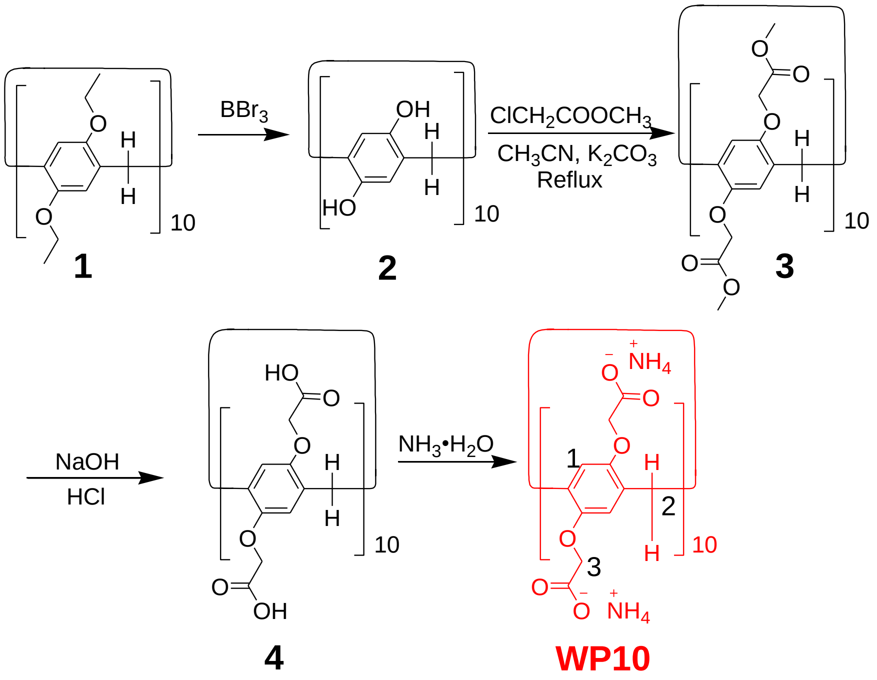
Electronic Supplementary Information

1. Materials and methods

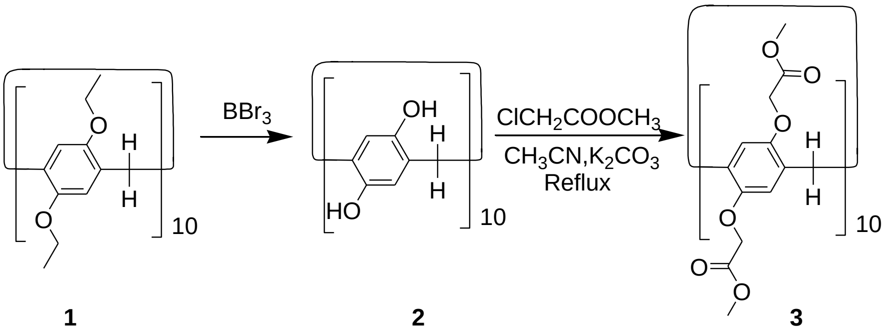
All reagents were commercially available and used as supplied without further purification. Solvents were either employed as purchased or dried according to procedures described in the literature. Compound **1**[S1] was synthesized according to a published literature procedure. NMR spectra were recorded with a Bruker Avance DMX 400 spectrophotometer or a Bruker Avance DMX 500 spectrophotometer with the deuterated solvent as the lock and the residual solvent or TMS as the internal reference. Low-resolution electrospray ionization mass spectra (LRESI-MS) were obtained on a Bruker Esquire 3000 Plus spectrometer (Bruker-Franzen Analytik GmbH Bremen, Germany) equipped with an ESI interface and an ion trap analyzer. High-resolution electrospray ionization mass spectra (HRESI-MS) were obtained on a Bruker 7-Tesla FT-ICR mass spectrometer equipped with an electrospray source (Billerica, MA, USA). The melting points were collected on a SHPSIC WRS-2 automatic melting point apparatus. The fluorescence experiments were conducted on a RF-5301 spectrofluorophotometer (Shimadzu Corporation, Japan). UV-vis spectroscopy was performed on a Shimadzu UV-2550 instrument at room temperature.

*2. Synthesis of compounds **WP10** and **G2***

Scheme S1. Synthetic route to **WP10**.



*2.1. Synthesis of compound **3***



To a solution of **1** (0.499 g, 0.280 mmol) in dried chloroform (25 mL) was added largely excessive boron tribromide. The mixture was stirred at room temperature for 12 h. Then the mixture was added into ice water. The resulting precipitated product **2** was collected by filtration, washed with water and dried completely under vacuum. To a solution of **2** in CH_3CN (50 mL) was added methyl chloroacetate (2.59 g, 24.0 mmol) and K_2CO_3 (3.31 g, 24.0 mmol). The mixture was heated to 80 ℃ under nitrogen gas protection for 24 h. Then the reaction mixture was cooled to room temperature and filtered. The filter cake was washed with chloroform (3 × 20 mL). Then the filtrate was concentrated under vacuum, and then the residue was purified by column chromatography on silica gel with dichloromethane/ethyl acetate (4:1 *v*/*v*) as the eluent to get product **3** as a white solid (320 mg, 43% for two steps), m.p. 161.5–162.8 ℃. The ^{1}H NMR spectrum of **3** is shown in Fig. S1. ^{1}H NMR (400 MHz, chloroform-*d*, 293 K) δ (ppm): 6.89 (s, 20H), 4.52 (s, 40H), 3.89 (s, 20H), 3.65 (s, 40H). The ^{13}C NMR spectrum of **3** is shown in Fig. S2. ^{13}C NMR (100 MHz, chloroform-*d*, 293 K) δ (ppm): 169.48, 149.89, 128.05, 114.97, 65.80, 51.78, 30.94, 30.15. LRESIMS is shown in Fig. S3: *m*/*z* 1348.9 $[M + 2NH_4]^{2+}$ (100%). HRESIMS: *m*/*z* calcd for $[M + 2NH_4]^{2+}$ $C_{130}H_{148}O_{60}N_2$, 1348.4297; found 1348.4290, error −0.5 ppm.

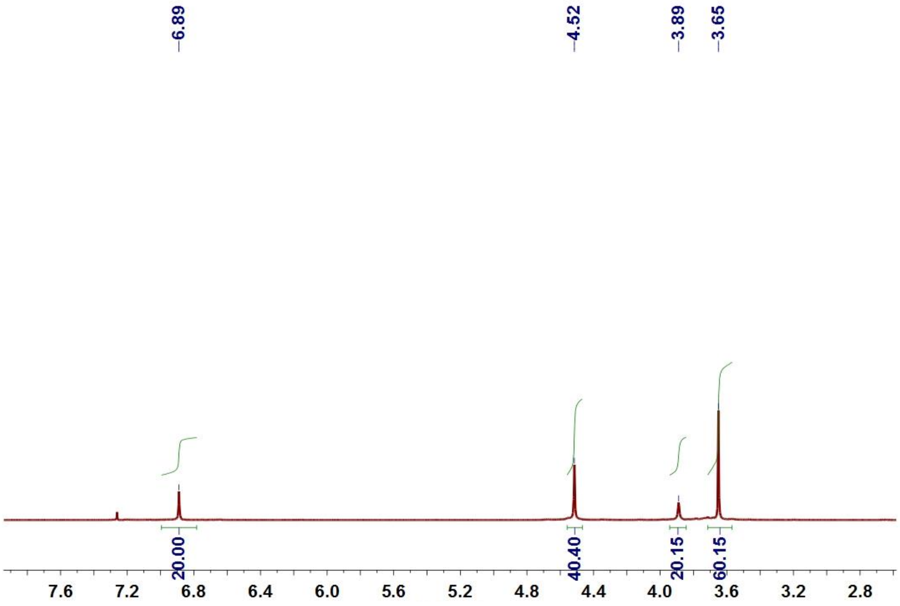


Fig. S1. ^{1}H NMR spectrum (400 MHz, chloroform-*d*, 293K) of **3**.

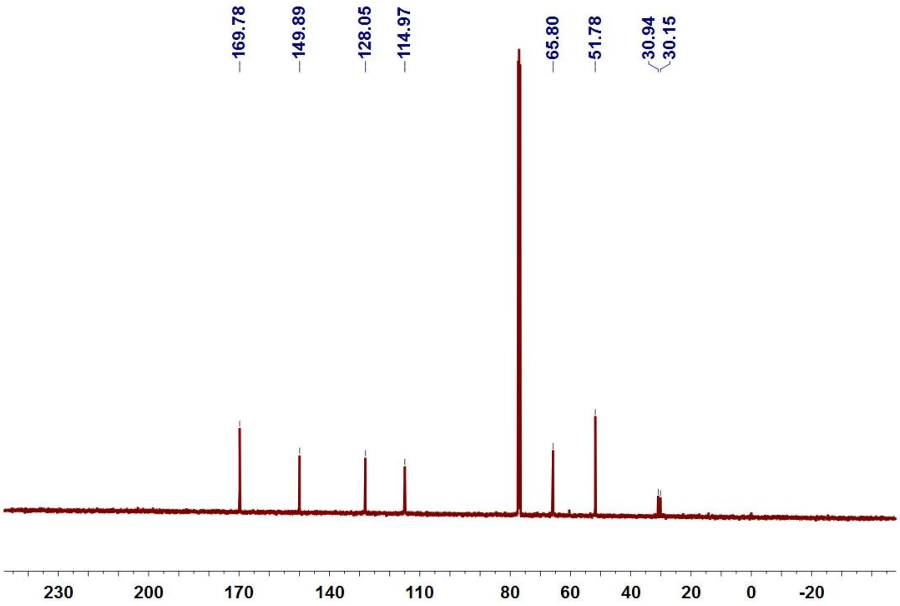


Fig. S2. ^{13}C NMR spectrum (100 MHz, chloroform-*d*, 293K) of **3**.

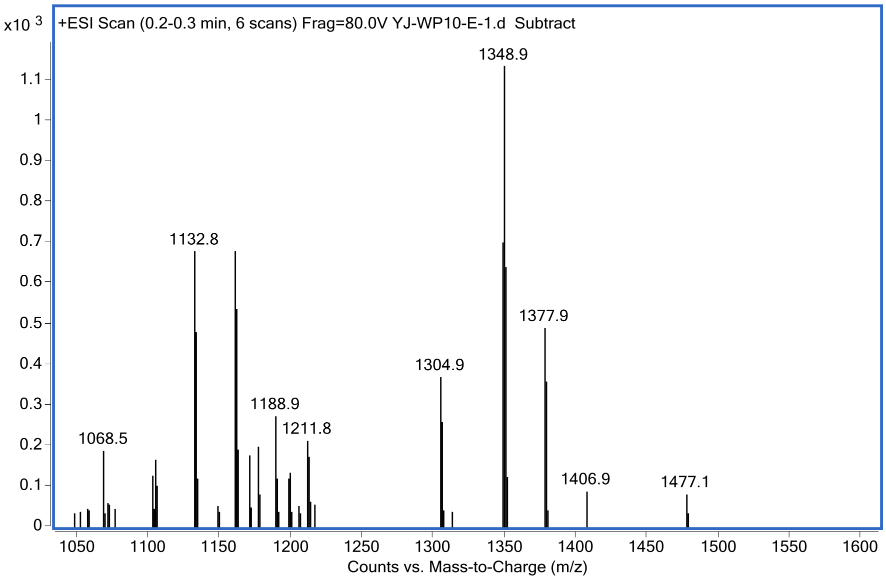
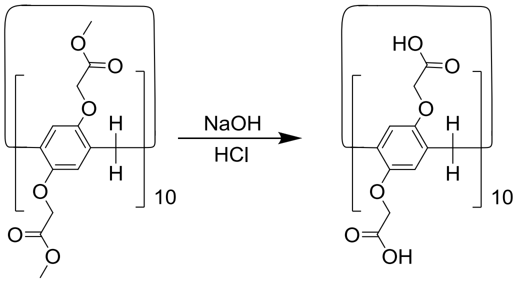


Fig. S3. Electrospray ionization mass spectrum of **3**. Assignment of the main peak: *m*/*z* 1348.9 $[M + 2NH_4]^{2+}$.

*2.2. Synthesis of compound **4***



3 **4**

A solution of **3** (300 mg, 0.113 mmol) in ethyl alcohol (30 mL) was treated with 40% aqueous sodium hydroxide (20 mL) at reflux for 12 h. Then the reaction mixture was evaporated, diluted with water (20 mL) and acidified with aqueous HCl. The resulting precipitate was filtered, washed with water and dried to give product **4** (230 mg, 86%) as a white powder, m.p. 201.7–203.2 ℃. The ^{1}H NMR spectrum of **4** is shown in Fig. S4. ^{1}H NMR (400 MHz, DMSO-d_6, 293 K) δ (ppm): 12.88 (s, 20H), 6.90 (s, 20H), 4.52 (s, 40H), 3.73 (s, 20H). The ^{13}C NMR spectrum of **4** is shown in Fig. S5. ^{13}C NMR (100 MHz, DMSO-d_6, 293 K) δ (ppm): 169.36, 148.14, 125.85, 113.24 and 63.81. LRESIMS is shown in Fig. S6: *m*/*z* 1212.9 $[M + 2Na]^{2+}$ (100%). HRESIMS: *m*/*z* calcd for $[M - 2H]^{2-}$ $C_{110}H_{98}O_{60}$, 1189.2314; found 1189.2293, error −2 ppm.

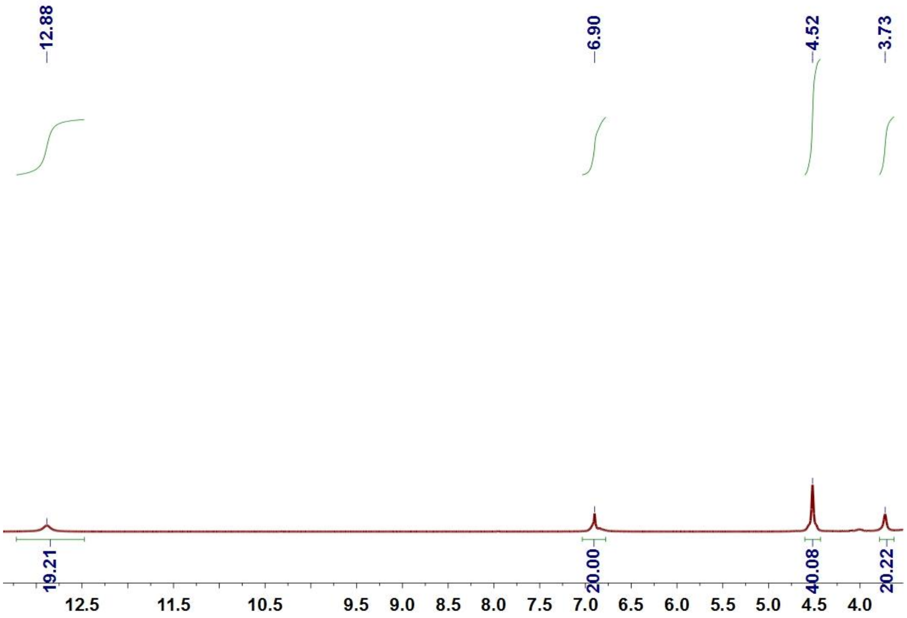


Fig. S4. ^{1}H NMR spectrum (400 MHz, DMSO-d_6, 293K) of **4**.

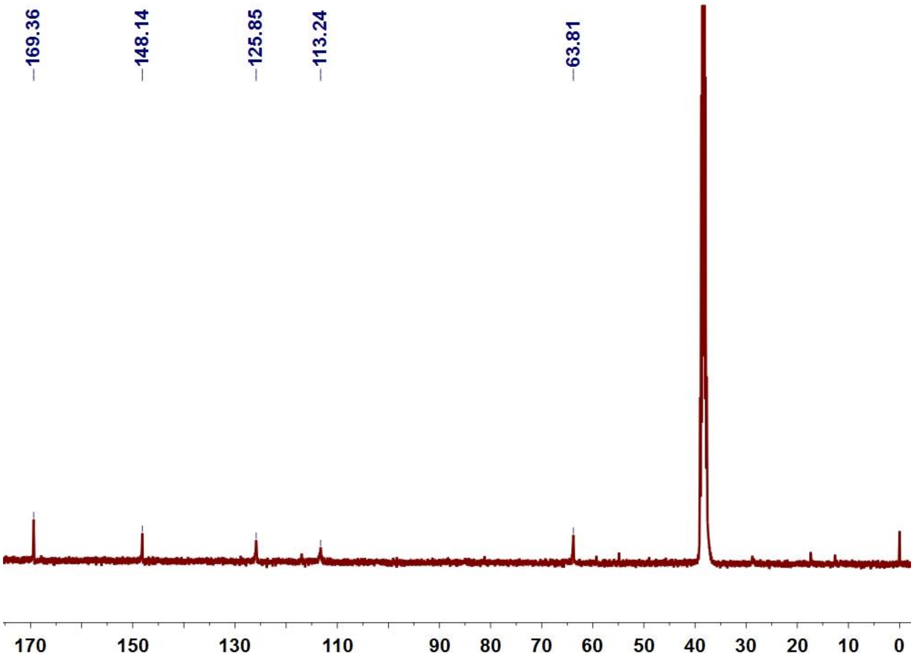


Fig. S5. ^{13}C NMR spectrum (100 MHz, DMSO-d_6, 293K) of **4**.

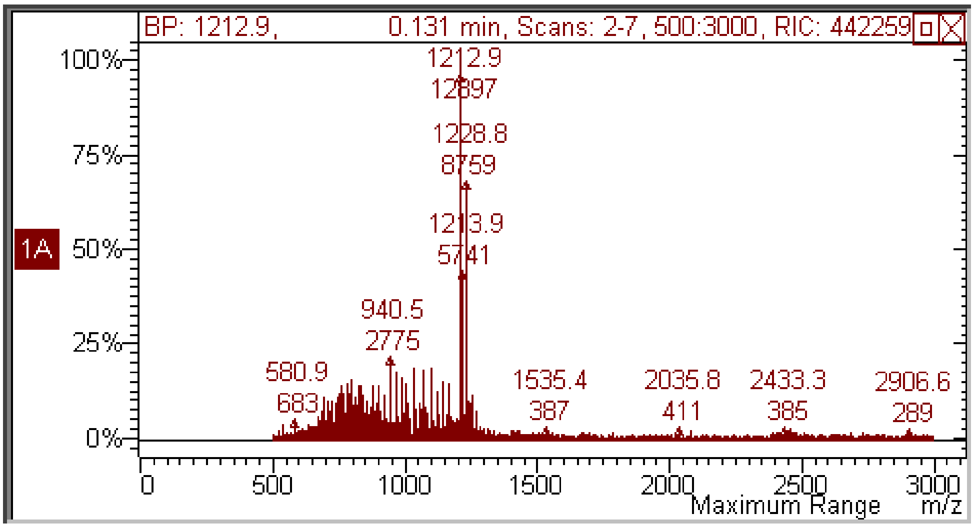
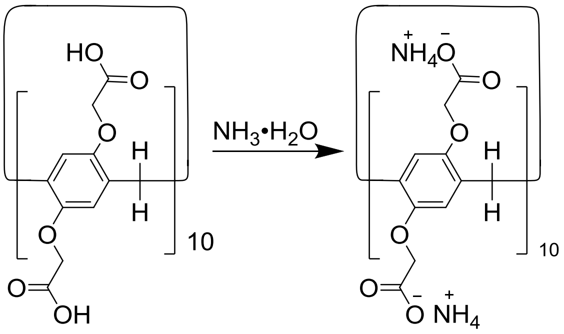


Fig. S6. Electrospray ionization mass spectrum of **4**. Assignment of the main peak: *m/z* 1212.9 $[M + 2Na]^{2+}$.

2.3. Synthesis of compound ***WP10***



4 **WP10**

A mixture of **4** (200 mg, 0.0840 mmol) and $NH_3{\cdot}H_2O$ (50 mL, 14 M) was stirred at room temperature for 2 h. The solvent was evaporated under reduced pressure and the residue was dried in vacuum. The product **WP10** was obtained as a yellow solid (0.21 g, 92%), m.p. 219.9–222.1 ℃. The ^{1}H NMR spectrum of **WP10** is shown in Fig. S7. ^{1}H NMR (400 MHz, D_2O, 293 K) δ (ppm): 6.59 (s, 20H), 4.18 (s, 40H), 3.83 (s, 20H). The ^{13}C NMR spectrum of **WP10** is shown in Fig. S8. ^{13}C NMR (100 MHz, D_2O, 293 K) δ (ppm): 177.01, 150.27, 128.21, 115.70 and 68.30. LRESIMS is shown in Fig. S9: *m*/*z* 1189.3 $[M - 20NH_4 + 18H]^{2-}$. HRESIMS: *m*/*z* calcd for $[M - 18NH_4 + 16H]^{2-}$ $C_{110}H_{104}N_2O_{60}$, 1206.258; found 1206.2535, error −4 ppm.

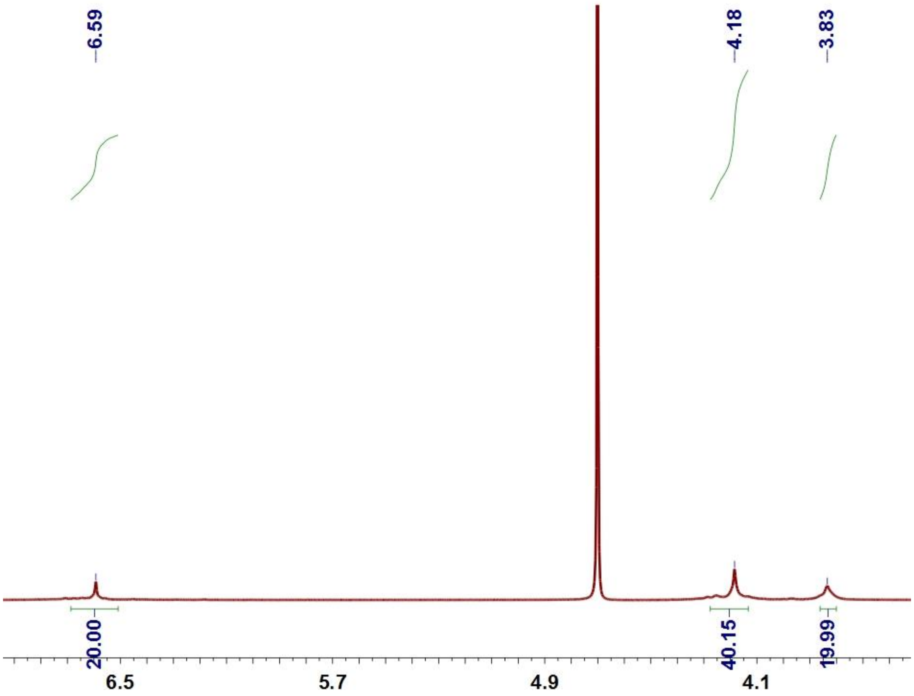


Fig. S7. ^{1}H NMR spectrum (400 MHz, D_2O, 293K) of **WP10**.

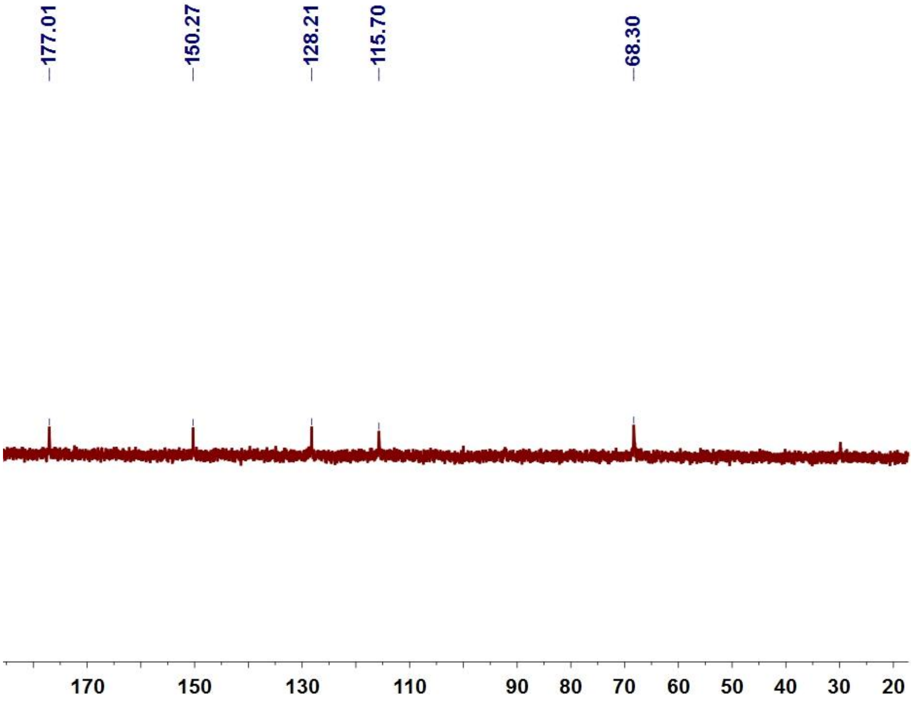


Fig. S8. ^{13}C NMR spectrum (100 MHz, D_2O, 293K) of **WP10**.

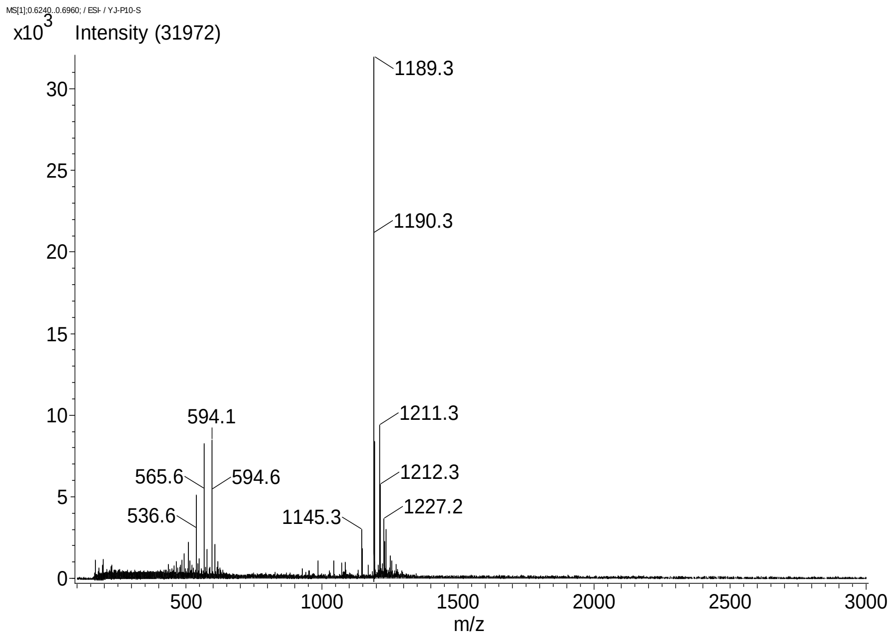
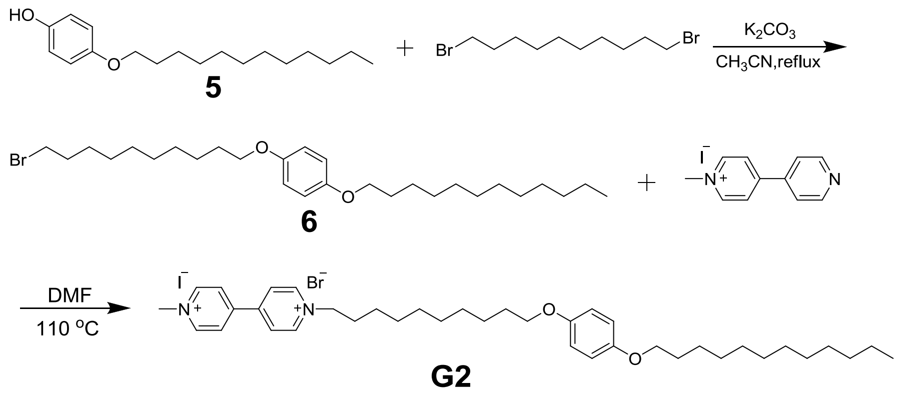


Fig. S9. Electrospray ionization mass spectrum of **WP10**. Assignment of the main peak: *m/z* 1189.3 $[M - 20NH_4 + 18H]^{2-}$.

*2.4. Synthesis of compound **G2***



To a solution of **5** (2.98 g, 10.0 mmol) in CH_3CN (500 mL) were added (30.0 g, 100 mmol) 1,10-dibromodecane and K_2CO_3 (13.8 g, 100 mmol). The mixture was stirred at reflux for 12 h. Then the reaction mixture was cooled to room temperature and filtered. The filtrate was concentrated under vacuum, and then the residue was purified by column chromatography on silica gel with dichloromethane/petroleum ether (1:10 *v*/*v*) as the eluent to get product **6** (2.57 g, 52%). Then compound **6** (2.49 g, 5.00 mmol) and excessive 1-methyl-4,4'-bipyridinium iodide were added to 200 mL of DMF and heated to 110 ^{o}C overnight. After complete reaction, the mixture was cooled down and filtered, the precipitate was washed with DMF (30 mL × 3), and product **G2** was obtained as an orange solid (3.51 g, 88%), m.p. 79.5–80.3 ℃. The ^{1}H NMR spectrum of **G2** is shown in Fig. S10. ^{1}H NMR (400 MHz, DMSO, 293 K) δ(ppm): 9.40 (d, J = 4 Hz, 2H), 9.30 (d, J = 4 Hz, 2H), 8.78 (m, 4H), 6.81 (s, 4H), 4.68 (t, J = 8 Hz, 2H), 4.44 (s, 3H), 3.86 (t, J = 8 Hz, 4H), 1.98 (d, J = 8 Hz, 2H), 1.65 (m, 4H), 1.30 (m, 30H), 0.85 (t, *J* = 8 Hz, 3H). The ^{13}C NMR spectrum of **G2** is shown in Fig. S11. ^{13}C NMR (100 MHz, D_2O, 293 K) δ (ppm): 146.61, 126.54, 126.53, 126.06, 115.21, 67.76, 28.95, 28.73, 28.37, 25.48, 22.06 and 13.93. LRESIMS is shown in Fig. S12: *m*/*z* 294.4 [M – Br – I]$^{2+}$. HRESIMS: *m*/*z* calcd for [M – Br – I]$^{2+}$ $C_{39}H_{60}N_2O_2^{2+}$, 294.2322; found 294.2314, error −3 ppm.

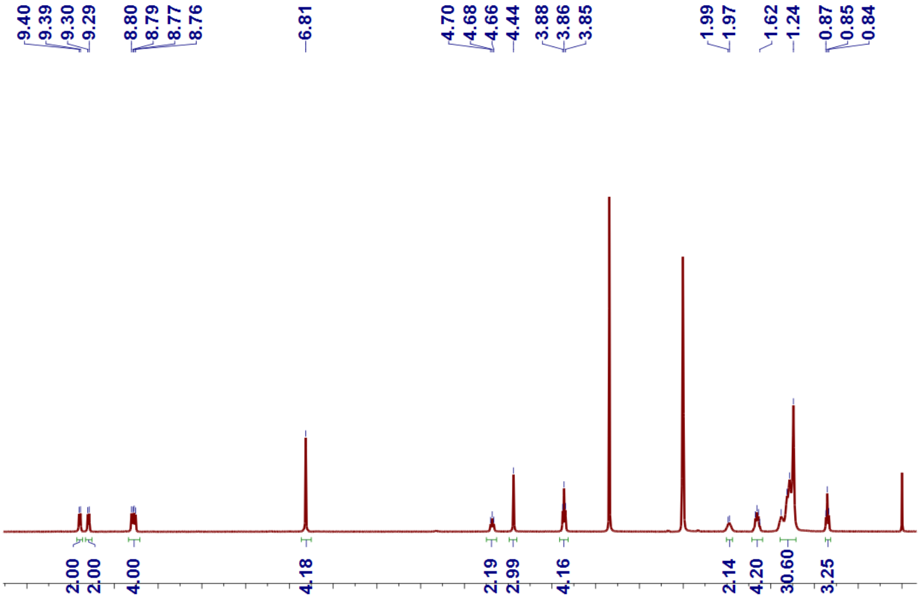


Fig. S10. ^{1}H NMR spectrum (400 MHz, DMSO, 293K) of **G2**

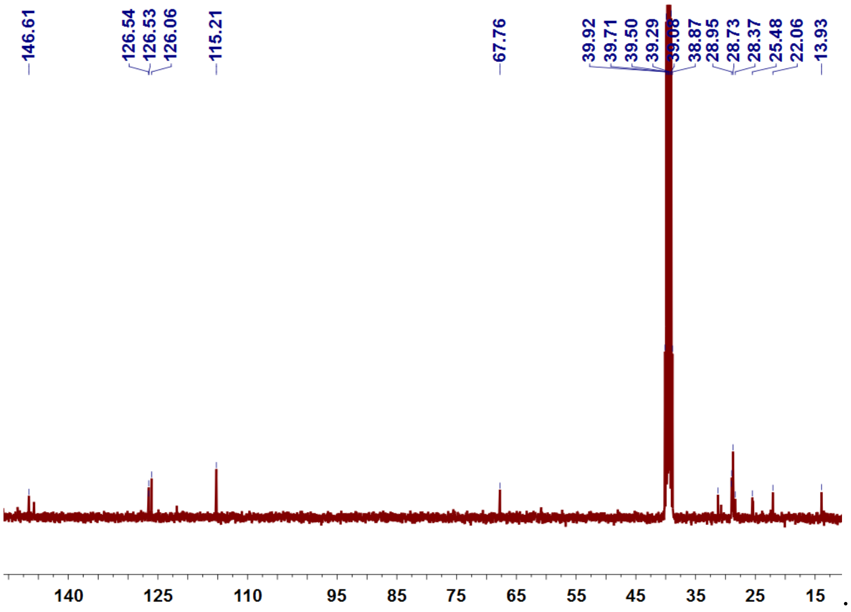


Fig. S11. ^{13}C NMR spectrum (100 MHz, DMSO, 293K) of **G2**.

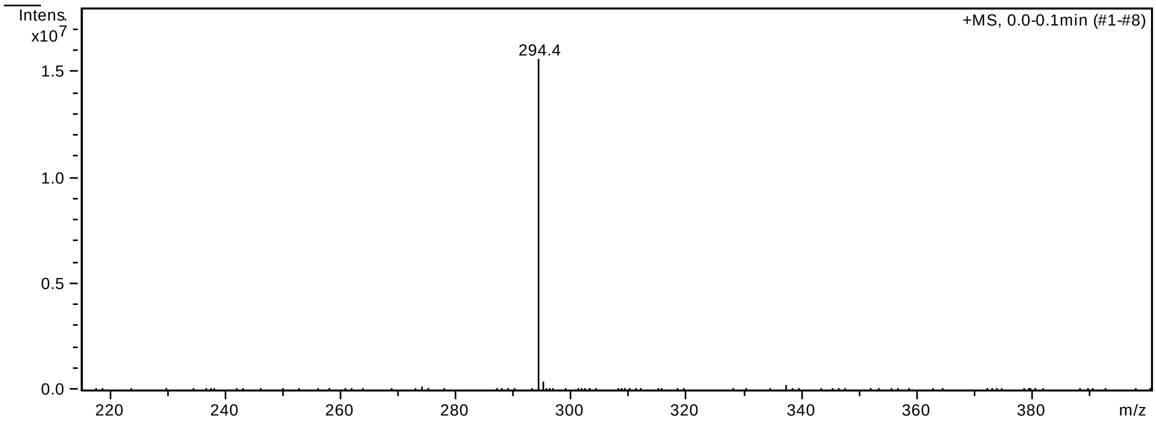


Fig. S12. Electrospray ionization mass spectrum of **G2**. Assignment of the main peak: *m*/*z* 294.4 $[M - Br - I]^{2+}$.

*3. Fluorescence titration experiments of **WP10** and **G** in water*

To determine the stoichiometry and association constant for the complexation between **WP10** and **G**, fluorescence titration experiments were done with solutions which had a constant concentration of **WP10** (5.00×10^{-6} M) and varying concentrations of **G**. By a non-linear curve-fitting method, the association constant (K_a) of **WP10⊃G** was determined. By a mole ratio plot, 1:1 stoichiometry was obtained for the complexation between **WP10** and **G**.

The non-linear curve-fitting was based on the equation:

$$\Delta F = (\Delta F_\infty/[H]_0)\ (0.5[G]_0 + 0.5([H]_0+1/K_a) - (0.5\ ([G]_0^{\ 2} + (2[G]_0\ (1/K_a - [H]_0)) + (1/K_a + [H]_0)^2)^{0.5}))$$

Where ΔF is the fluorescence intensity change at 328 nm at $[H]_0$, ΔF_∞ is the fluorescence intensity change at 328 nm when **WP10** is completely complexed, $[G]_0$ is the initial concentration of **G**, and $[H]_0$ is the fixed initial concentration of **WP10**.

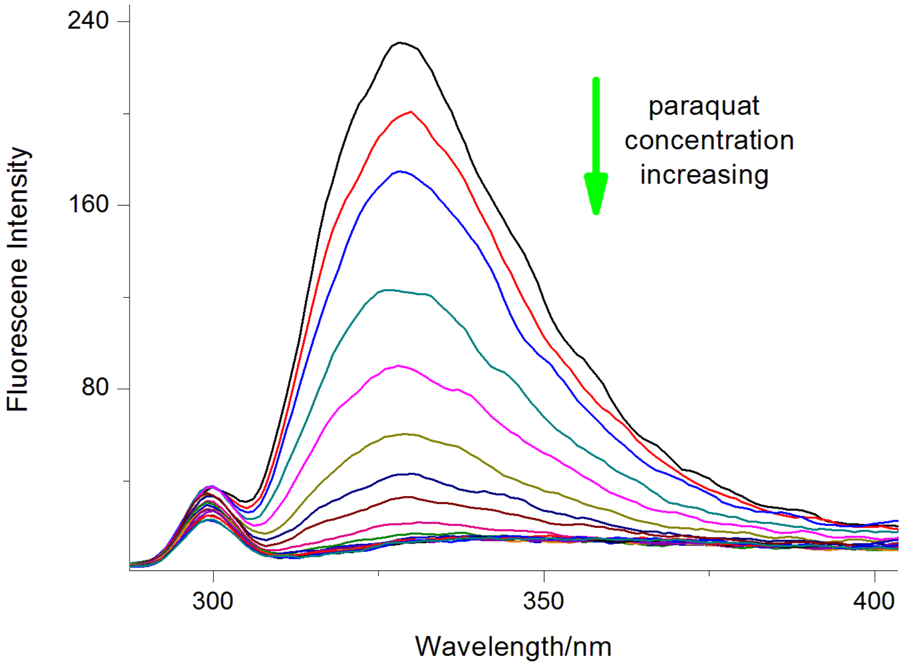


Fig. S13. Fluorescence spectra of **WP10** at a concentration of 5.00 × 10^{-6} M in aqueous solution at room temperature upon gradual addition of paraquat **G**.

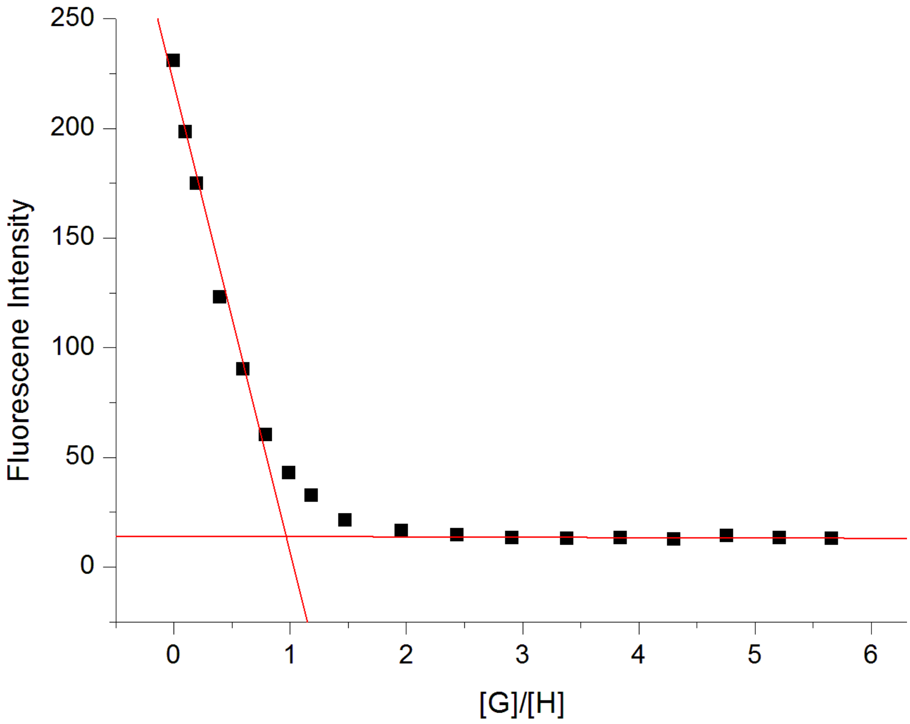


Fig. S14. Mole ratio plot for **WP10** and **G**, indicating a 1:1 complexation stoichiometry.

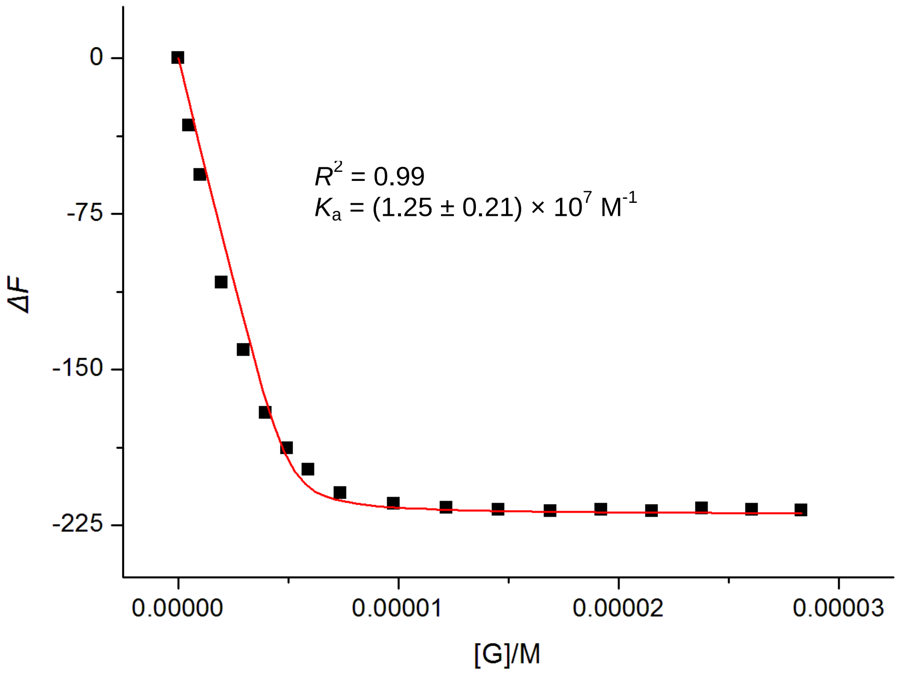


Fig. S15. The fluorescence intensity changes of **WP10** upon addition of **G**. The red solid line was obtained from the non-linear curve-fitting method based on the above equation.

*4. UV-vis spectroscopy investigation of the complexation between **WP10** and **G** in water*

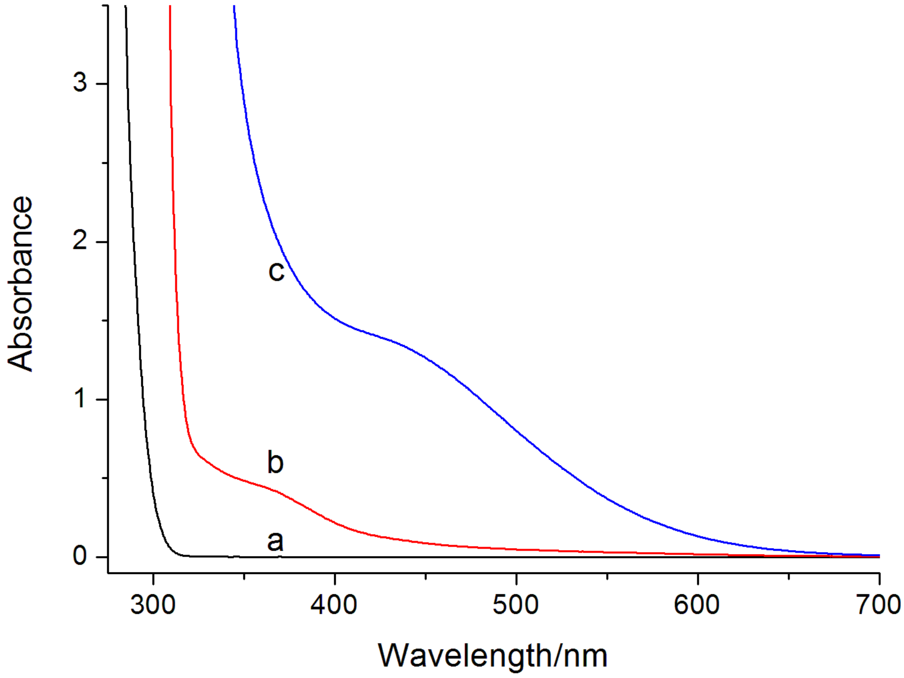


Fig. S16. UV-vis spectra of (a) 1.00 × 10^{-3} M **G**, (b) 1.00 × 10^{-3} M **WP10**, and (c) 1.00 × 10^{-3} M **WP10** with equimolar **G** in water at room temperature.

*5. 2D NOESY NMR spectrum of **WP10⊃G***

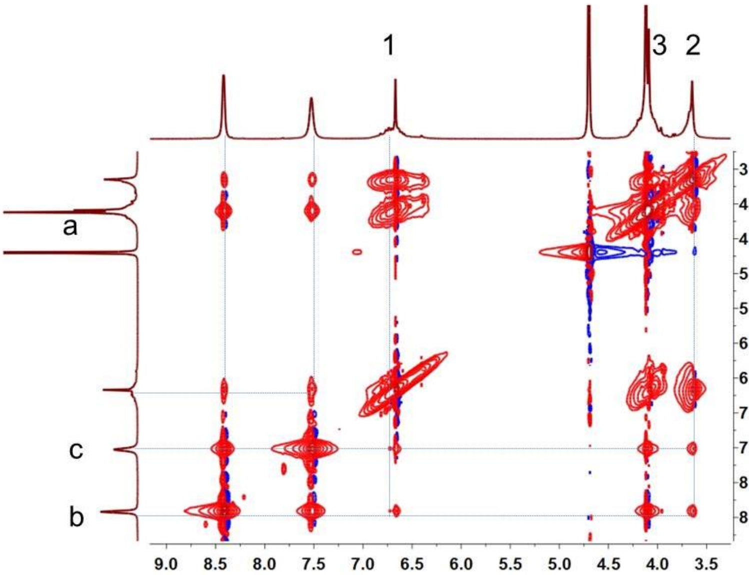


Fig. S17. 2D NOESY NMR (500 MHz, D_2O, 293 K) spectrum of a solution of **WP10** (5.00 mM) and **G** (5.00 mM).

6. ^{1}H NMR spectra of pH-responsive experiments

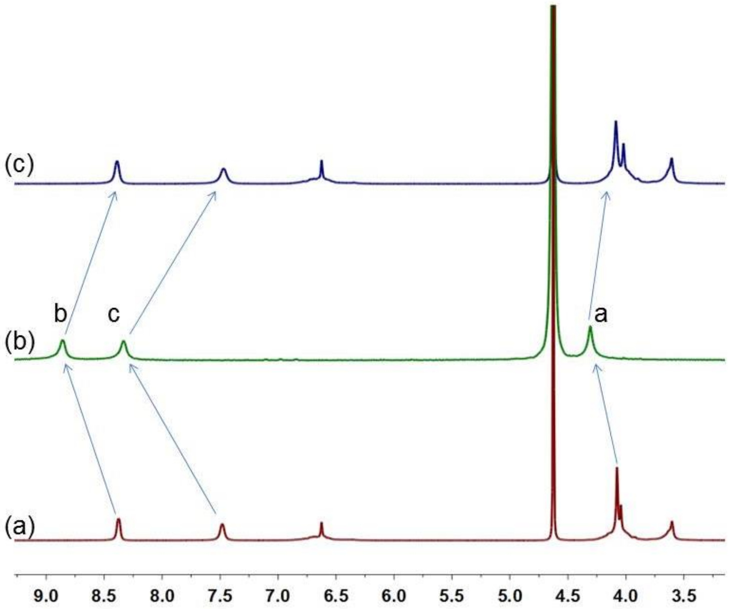


Figure S18. Partial ^{1}H NMR spectra (400 MHz, D_2O, 293 K): (a) 1.00 mM **G** and **WP10**; (b) after adding 2.0 μL aqueous DCl solution (20%) to (a); (c) after adding 1.0 μL aqueous NaOD solution (30%) to (b).

*7. Critical aggregation concentration (CAC) determination of **G2** and **WP10⊃G2***

Some parameters such as the conductivity, osmotic pressure, fluorescence intensity and surface tension of the solution change sharply around the critical aggregation concentration. The dependence of the solution conductivity on the solution concentration is used to determine the critical aggregation concentration. Typically, the slope of the change in conductivity versus the concentration below CAC is steeper than the slope above the CAC. Therefore, the junction of the conductivity-concentration plot represents the CAC value. To measure the CAC value of **G2** (or **WP10⊃G2**), the conductivities of the solutions at different concentrations were determined. By plotting the conductivity versus the concentration, we estimated the CAC value of **G2** (or **WP10⊃G2**).

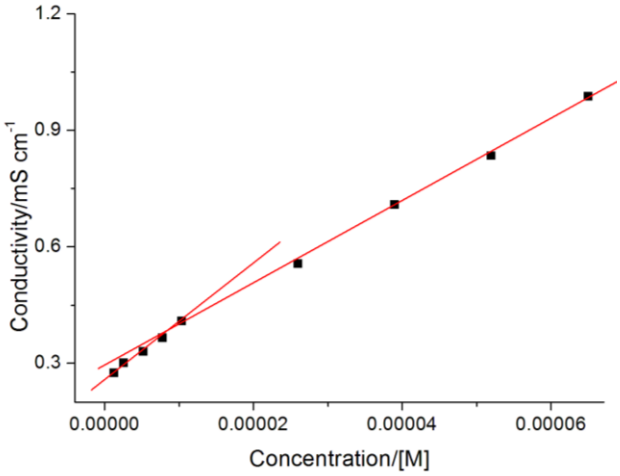


Fig. S19. The concentration-dependent conductivity of **G2**. The critical aggregation concentration (CAC) was determined to be 8.87×10^{-6} M.

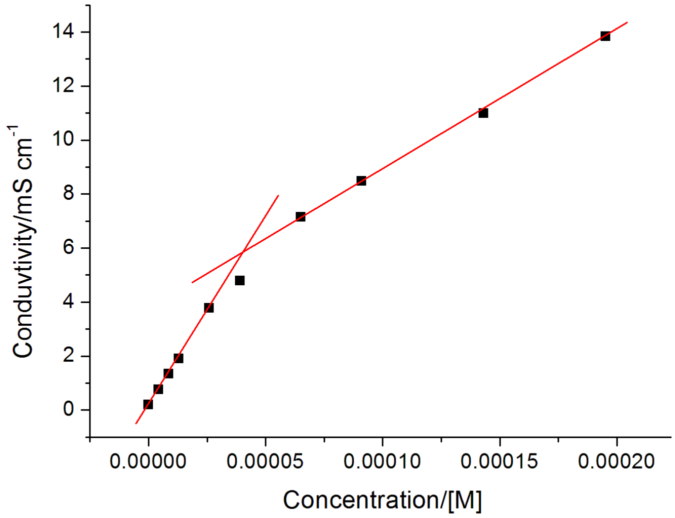


Fig. S20. The concentration-dependent conductivity of **WP10⊃G2**. The critical aggregation concentration (CAC) was determined to be 4.06×10^{-5} M.

*8. Electrospray ionization mass spectrum of **WP10** and **G***

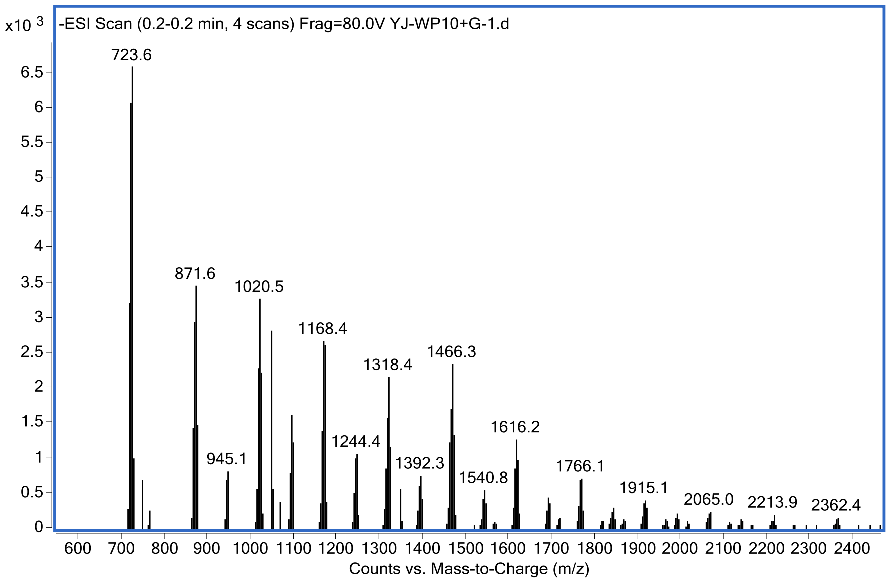


Fig. S21. Negative electrospray ionization mass spectrum of **WP10** and **G** in H_2O. Mass fragments at *m/z* 1392.3 and 723.6, corresponding to [**WP10**⊃**G** – 2I – $7NH_4$ + 3H]$^{2-}$ and [**WP10**⊃**G** – I – $8NH_4$ + 3H]$^{4-}$, respectively. This indicated the 1:1 complexation stoichiometry between **WP10** and **G**.

References:

S1. X.-B. Hu, Z. Chen, L. Chen, L. Zhang, J.-L. Hou and Z.-T. Li, *Chem. Commun.*, 2012, **48**, 10999–11001.