Supporting Information


Stefan Schoder, Christoph A. Schalley

Institut für Chemie und Biochemie, Freie Universität Berlin, Takustraße 3, 14195 Berlin, Germany

*e-mail: c.schalley@fu-berlin.de

Table of contents

1. Experimental details S2
   1.1. General methods S2
   1.2. Synthetic procedures S2
2. NMR, UV/Vis and Fluorescence Spectroscopy and Mass Spectrometry S3
   2.1. $^1$H NMR signal assignment for complex $(PH^+)_2@Q$ S4
   2.2. Reversibility of the complex formation of $(PH^+)_2@Q$ S7
   2.3. Fluorescence spectra of $P, PH^+$ and $(PH^+)_2@Q$ S8
   2.4. Determination of the association constant with ITC S9
   2.5. Mass spectrum of $(PH^+)_2@Q$ S10
   2.6. $^1$H NMR signal assignment for complex $PH^+N@Q$ S11
   2.7. $^1$H NMR spectrum of $V^{2+}N@Q$ S12
   2.8. $^1$H NMR signal assignment for complex $PV^{2+}@Q$ S13
   2.9. Structure assignment of $PV^{2+}@Q$ S14
   2.10. Reversibility of the formation of $PV^{2+}@Q$ S15
   2.11. Cyclic voltammetry S16
   2.12. Formation of the complex $(V^{2+})_2@Q$ S17
   2.13. $^1$H NMR signal assignment for a four-step square network S18
   2.14. Control experiment of state I and II regarding $Na_2S_2O_4$ S19
   2.15. Reduction of state I S20
   2.16. Acidification of state III S21
3. References S22
1. Experimental Details

1.1. General Methods

All reagents were commercially available and used without further purification. Thin-layer chromatography (TLC) was performed on aluminum sheets coated with silica gel 60/F254 (Merck KGaA). Column chromatography was performed on silica gel 60 (Merck 40 - 60 nm, 230 - 400 mesh). Melting points were determined on a stuart SMP30 apparatus and are uncorrected. $^1$H NMR, $^{13}$C NMR and $^1$H, $^1$H COSY spectra were recorded on Bruker ECX 400 MHz or Bruker AVANCE III 700 MHz NMR spectrometers with a triple inverse cryoprobe on the latter instrument. All chemical shifts are reported in ppm with the residual undeuterated solvents as the internal standards. Coupling constants (J) are given in Hz. UV/Vis spectra were recorded on Varian Cary 50 Bio spectrophotometer. Fluorescence spectra were recorded on a PERKIN ELMER LS50B spectrophotometer. Electrospray-ionization time-of-flight- resolution mass spectrometric (ESI-TOF-HRMS) experiments were conducted on an Agilent 6210 ESI-TOF mass spectrometer. Ethyliouogen derivate EV$^{2+}{(I)}_2$ was prepared according to literature procedure.$^1$

1.2. Synthetic procedures.

\[ \text{2-(2-(2-(4-Iodophenoxy)ethoxy)ethoxy)ethan-1-ol (S1)$^2$} \]

\[ \begin{align*}
\text{I-} & \text{OH} + \text{TosO} - \text{O} - \text{O} - \text{OH} \xrightarrow{K_2CO_3, \text{DMF}} 100 \degree \text{C, 24 h} \text{I-} & \text{O} - \text{O} - \text{O} - \text{O} - \text{OH}
\end{align*} \]

Compound S1 was prepared according to a modified literature procedure.$^2$ 4-Iodophenol (1.00 g, 4.55 mmol, 1.0 equiv.), 2-(2-(2-hydroxyethoxy)ethoxy)ethyl 4-methylbenzenesulfonate (1.66 g, 5.46 mmol, 1.2 equiv.) and K$_2$CO$_3$ (1.57 g, 11.38 mmol, 2.5 equiv.) were dissolved in DMF (15 mL) and heated to 100 °C for 24 h. The reaction was quenched with a saturated aqueous NH$_4$Cl solution, extracted with EtOAc (3 x 15 mL) and dried with MgSO$_4$. The crude product was purified by column chromatography (SiO$_2$, DCM/MeOH = 100:0, 100:1 − 10:1) giving S1 (1.02 g, 2.90 mmol, 64%) as a yellowish oil. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ = 7.53 (d, $J = 9.1$ Hz, 2H, H$_d$), 6.69 (d, $J = 9.1$ Hz, 2H, H$_d$), 4.10 – 4.06 (m, 2H, OCH$_2$), 3.86 – 3.82 (m, 2H, OCH$_2$), 3.75 – 3.67 (m, 6H, OCH$_3$), 3.62 – 3.58 (m, 2H, OCH$_2$) ppm.
2-(2-(2-(4-(Pyridin-4-yl)phenoxy)ethoxy)ethoxy)ethan-1-ol (P)

S1 (863 mg, 2.45 mmol, 1.00 eq.), pyridin-4-ylboronic acid (903 mg, 7.35 mmol, 3.00 eq.), Pd(PPh_3)_4 (113 mg, 0.49 mmol, 4 mol-%) and KOAc (962 mg, 9.8 mmol, 4.00 eq.) were dissolved in DMF (50 mL) under Ar atmosphere and heated to 100 °C for 48 h. The reaction was quenched with H_2O, extracted with EtOAc (3 x 50 mL), filtered over celite, washed with NaCl aq. (1 x 25 mL) and dried with MgSO_4. The crude product was purified by column chromatography (SiO_2, DCM/MeOH = 150:0, 150:1 – 15:1) giving P (153 mg, 0.50 mmol, 21%) as a colourless powder. \^H NMR (700 MHz, D_2O) δ 8.68 (d, J = 6.9 Hz, 2H, H_a), 8.25 (d, J = 7.0 Hz, 2H, H_b), 7.95 (d, J = 8.8 Hz, 2H, H_c), 7.21 (d, J = 8.8 Hz, 2H, H_d), 4.34 – 4.31 (m, 2H, OCH_2), 3.96 – 3.94 (m, 2H, OCH_2), 3.80 – 3.78 (m, 2H, OCH_2), 3.74 – 3.72 (m, 2H, OCH_2), 3.72 – 3.70 (m, 2H, OCH_2), 3.65 – 3.62 (m, 2H, OCH_2) ppm. \^C NMR (176 MHz, Deuterium Oxide) δ 161.41, 157.27, 140.60, 129.87, 126.93, 123.23, 115.68, 71.67, 69.81, 69.41, 68.92, 67.26, 60.32 ppm. ESI-TOF-HRMS: m/z calcd for [C_{17}H_{21}NO_4+H]^+ 304.1543, found 304.1565; calcd for [C_{17}H_{21}NO_4+Na]^+ C_{17}H_{21}NO_4 326.1363, found 326.1353. M.p. 110.2 – 110.7 °C.
Figure S2. $^1$H NMR spectrum (700 MHz, D$_2$O, 298 K) of P.

Figure S3. $^{13}$C NMR spectrum (176 MHz, D$_2$O, 298 K) of P.
2,2'-((((Naphthalene-2,6-diylbis(oxy))bis(ethane-2,1-diyl))bis(oxy))bis(ethane-2,1-diyl))bis(oxy))bis(ethan-1-ol) (N)³

Compound N was prepared according to a modified literature procedure.³ 2,6-Dihydroxynaphthalene (500 mg, 3.12 mmol, 1.0 eq.), 2-(2-(2-hydroxyethoxy)ethoxy)ethyl 4-methylbenzenesulfonate (2.48 g, 7.80 mmol, 2.5 eq.) and K₂CO₃ (2.18 g, 15.6 mmol, 5.0 eq.) were dissolved in DMF (15 mL) and heated to 100 °C for 48 h. The reaction was quenched with H₂O, extracted with EtOAc (3 x 15 mL), washed with NaCl aq. (1 x 15 mL) and dried with MgSO₄. The crude product was purified by column chromatography (SiO₂, DCM/MeOH = 100:0, 100:1 – 10:1) giving N (303 mg, 0.713 mmol, 23%) as a colourless powder. ¹H NMR (700 MHz, D₂O) δ 7.83 (d, J = 8.9 Hz, 2H, Hₙ), 7.40 (d, J = 2.5 Hz, 2H, H₂), 7.28 (dd, J = 8.9, 2.5 Hz, 2H, Hₙ), 4.38 – 4.33 (m, 4H, OCH₂), 4.00 – 3.96 (m, 4H, OCH₂), 3.83 – 3.79 (m, 4H, OCH₂), 3.77 – 3.73 (m, 4H, OCH₂), 3.74 – 3.70 (m, 4H, OCH₂), 3.67 – 3.63 (m, 4H, OCH₂) ppm.

Figure S4. ¹H NMR spectrum (700 MHz, D₂O, 298 K) of N.
2. NMR, UV/Vis, Mass and Fluorescence Experiments Complementary to those in the Main Text

2.1. $^1$H NMR signal assignment for complex $(PH^+)_2@Q$

Figure S5. Partial $^1$H NMR spectra (700 MHz, 298 K, D$_2$O, 1.0 mM) of the compounds depicted. a) PH$^+$ (pH 4), b) a 2:1 mixture of PH$^+$ and Q in acidic (pH 4) and c) basic (pH 10) medium, d) P (pH 10). The high-field shift of all four protons in the cucurbituril complex (a to b) indicate that the guest is fully threaded in the host and - in accordance with literature reports$^4$ - forms the 2:1 complex $(PH^+)_2@Q$. Subsequent deprotonation (c) results in the NMR of deprotonated compound P (d) indicating the complete dissociation of the complex. DCl (35% in D$_2$O) and K$_2$CO$_3$ were used to (de)protonate.
2.2. Reversibility of the formation of \((PH^+)_2@Q\)

Figure S6. UV/Vis spectra of a 0.06 mM solution of \((PH^+)_2@Q\) (black line), after deprotonation (red line) and after subsequent protonation (green line). Recovery of the original band after the protonation indicates the reversibility of the formation of \((PH^+)_2@Q\).
2.3. Fluorescence spectra of P, PH+ and (PH+)$_2$@Q

*Figure S7.* Fluorescence spectra of P, PH+, (PH+)$_2$@Q and a mixture of P and Q all at the same concentration; excitation at 366 nm. The fluorescence red shift and the remarkable increase of the 2:1 complex (PH+)$_2$@Q are in line with similar phenylpyridinium derivates.\(^5\) Unprotonated P is not emitting and consequently a mixture of P and Q is neither.
2.4. Determination of the association constant with ITC

ITC titration experiment was carried out on a VP-ITC from Microcal Inc. at 25 °C in a 60 mM phosphate buffer (pH=5). The host was in the sample cell at a concentration of 0.03 mM, and the guest was in the syringe at a concentration of 1.0 mM. A titration consisted of 30 consecutive injections of 2-10 µL with at least 250 s intervals between injections. The first data point was removed from the data set prior to curve fitting. Heats of dilution were checked by titration well beyond saturation or by titration of the guest into a buffer solution and subtracted from the normalized enthalpies. The data were analyzed with Origin 7.0 software, using the sequential binding sites model. The binding constant was calculated as an average of several experiments.

![ITC data for the titration of Q (0.03 mM) with PH+ (1.0 mM) in a 60 mM phosphate buffer (pH=5) at 25 °C. ΔH1 = -6618 cal/mole, ΔS1 = 10.9 cal/mole*K, ΔG1 = -9867 cal/mole; ΔH2 = -7423 cal/mole, ΔS2 = -1.9 cal/mole*K, ΔG2 = -6857 cal/mole.](Image)

*Figure S8.* ITC data for the titration of Q (0.03 mM) with PH+ (1.0 mM) in a 60 mM phosphate buffer (pH=5) at 25 °C. ΔH1 = -6618 cal/mole, ΔS1 = 10.9 cal/mole*K, ΔG1 = -9867 cal/mole; ΔH2 = -7423 cal/mole, ΔS2 = -1.9 cal/mole*K, ΔG2 = -6857 cal/mole.
2.5. Mass spectrum of (PH\(^+\))\(_2@Q\)

*Figure S9*. ESI-TOF mass spectrum of a mixture of PH\(^+\) and Q. This signal of (PH\(^+\))\(_2@Q\) is not very intense as charge repulsion leads to quick fragmentation in the gas phase. Because of the used settings of the instrument the signal for the 1:1 complex PH\(^+\)@Q cannot be seen.
2.6. $^1$H NMR signal assignment for complex PH$^+$/N@Q

Figure S7. Partial $^1$H NMR spectra (700 MHz, 298 K, D$_2$O, 1.0 mM) of a) (PH$^+)_2$@Q (pH 4), b) a 3:1:2 mixture of PH$^+$, N and Q in acidic (pH 4) medium c) an equimolar mixture of PH$^+$, N and Q in acidic (pH 4) medium, d) N, e) an equimolar mixture of P, N and Q in basic (pH 10) medium, f) P (pH 4). DCI (35% in D$_2$O) and K$_2$CO$_3$ were used to (de)protonate. Addition of N to complex (PH$^+)_2$@Q results in the formation of a new complex. Spectrum b) shows a mixture of the two complexes (PH$^+)_2$@Q and PH$^+$N@Q in a 1:1 stoichiometry coming from a 3:1:2 mixture of PH$^+$, N and Q. If the guests and the host are in a 1:1:1 mixture (spectrum c) the 1:1:1 complex PH$^+$N@Q does not form exclusively. The ratio between the two complexes cannot be predicted, resulting in signals for the unbound free N.

This leads to the assumption, that the binding constants of the inclusion of the second guest are similar. Deprotonation (spectrum e) of PH$^+$ in the 1:1:1 mixture of spectrum c) leads in the superposition of the signals of the free guests P and N indicating the dissociation of the complexes.
2.7. $^1$H NMR spectrum of V$^{2+}$N@Q

Figure S8. Partial $^1$H NMR spectrum (700 MHz, 298 K, D$_2$O, 1.0 mM) of V$^{2+}$N@Q with strong high field shifts of the signals of the protons on N similar to a literature-known complex. $^6$
2.8. $^1$H NMR signal assignment for complex PV$^{2+}$@Q

Figure S12. Partial $^1$H NMR spectra (700 MHz, 298 K, D$_2$O, 1.0 mM) of (a) P (pH 10), (b) (PH$^+$)$_2$@Q (pH 4), (c) a 2:1:1 mixture of PH$^+$, V$^{2+}$ and Q in acidic (pH 4) medium resulting in the formation of (PH$^+$)$_2$@Q and free V$^{2+}$ (pH 4), (d) a 1:1:1 mixture of P, V$^{2+}$ and Q in basic (pH 10) medium resulting in the formation of PV$^{2+}$@Q, (e) complex V$^{2+}$@Q and (f) V$^{2+}$. DCl (35% in D$_2$O) and K$_2$CO$_3$ were used to (de)protonate. Spectrum c) shows that the formation of complex (PH$^+$)$_2$@Q is favored over the formation of complex V$^{2+}$@Q due to the higher binding constant of the 2:1 complex. After deprotonation of PH$^+$ (spectrum d) a new complex is formed including P, V and Q which can be attributed to the pi-donor-pi-acceptor complex PV$^{2+}$@Q.
Figure S13. Partial $^1\text{H}$-$^1\text{H}$ COSY NMR spectra (700 MHz, 278 K, D$_2$O, 1.0 mM) of a 1:1:1 mixture of P, V$^{2+}$ and Q in basic conditions. The signals for the complex V$^{2+}$@Q are known and can be assigned. Because of the low solubility of the complex and because of the shielding of the cucurbituril the cross peaks for the complex cannot be seen. The new set of signals (marked with dashed squares) are attributed to the new viologen containing complex PV$^{2+}$@Q. The viologen experiences the same shielding resulting in no visible cross peaks at this low concentration.
2.10. Reversibility of the formation of PV$^{2+}$$\odot$Q

*Figure S14.* UV/Vis spectra of a 1:1:1 mixture of PH$^+$, V$^{2+}$ and Q in acidic conditions (black line), after deprotonation (red line), after consecutive protonation (blue line) and subsequent deprotonation (cyan line) (6 µM V$^{2+}$). In acidic conditions the absorption maximum corresponds to the complex (PH$^+$)$_2$$\odot$Q. Inlay shows the charge-transfer band of the formed complex PV$^{2+}$$\odot$Q. Recovery of the original band after the protonation indicates the reversibility of the formation of the complex.
2.11. Cyclic voltammetry

Redox-potentials reported in this study were obtained by cyclic voltammetry. Measurements were carried out in aqueous solutions with 0.1 M electrolyte and 1 mM analyte concentration using a three-electrode configuration (glassy carbon working electrodes, Pt counter electrode, Ag wire as pseudoreference) and an Autolab PGSTAT302N potentiostat. The decamethylferrocene/decamethylferrocenium ([FeCp₂⁺]/[FeCp₂⁺]) couple was used as the internal reference for all measurements to ensure maximum comparability. Energy differences were calculated according to the equation \( \Delta G = -nF\Delta E \).

Figure S95. Cyclic voltammetry measurements of a) \( V^{2+} \), b) \( (V^{n+})_2@Q \) and c) measurements of \( P, PH^+ \) and \( (PH^+)_2@Q \).
2.12. Formation of the complex \((V^{**})_2@Q\)

Figure S16. UV/Vis spectra of the shown complexes before (top structures) and after reduction (bottom structures) with \(\text{Na}_2\text{S}_2\text{O}_4\). In all mixtures reduction leads to the formation of the complex \((V^{**})_2@Q\).
2.13. $^1$H NMR signal assignment for a four-step square network

*Figure S17.* Partial $^1$H NMR spectra (700 MHz, 298 K, D$_2$O, 1.0 mM) of (a) $(PH^+)_2@Q$, (b) mixture I, a 2:1:2 mixture of $PH^+$, $V^{2+}$, $N$ and $Q$ in acidic (pH 4) medium, (c) $V^{2+}N@Q$, (d) mixture II, a 2:1:2 mixture of $P$, $V^{2+}$, $N$ and $Q$ in basic (pH 10) medium, (e) $P$ (pH 10) and (f) $N$. Spectrum b) shows the signals for the two complexes $(PH^+)_2@Q$ and $V^{2+}N@Q$ and resembles state I. Subsequent deprotonation of $PH^+$ (spectrum d) shows the signal for complex $V^{2+}N@Q$ and free $P$ indicating the dissociation of the complex $(PH^+)_2@Q$ and therefore resembling state II. To avoid formation of $PV^{2+}@Q$ a slight excess of $N$ was used, resulting in a set of signals for free $N$. 
2.14. Control experiment of state I and II regarding Na$_2$S$_2$O$_4$

*Figure S18.* Partial $^1$H NMR spectra (700 MHz, 298 K, D$_2$O, 1.0 mM) of a) a 2:1:2 mixture of PH$^+$, N and Q in acidic (pH 4) medium (corresponding to state I without V$^{2+}$), b) the same solution after addition of Na$_2$S$_2$O$_4$, c) N, d) a 2:1:2 mixture of P, N and Q in basic (pH 10) medium (corresponding to state II without V$^{2+}$) after addition of Na$_2$S$_2$O$_4$, e) P (pH 10). Addition of reductant to the acidic mixture (a to b) does not result in the formation of a new complex. Therefore, the reaction mixture is not affected by the addition of Na$_2$S$_2$O$_4$. The same holds true under basic conditions (d) which is a superposition of the signals of the free guests.
2.15. Reduction of state I

Figure S19. This UV/Vis experiment shows the reduction of state I (an acidic mixture) to state IV (a reduced state in acidic medium). Because of the fast reoxidation of viologen in acidic medium a solution mixture should be prepared which is just slightly acidic. The black line corresponds to a 2:1:1:2 mixture of PH⁺, V²⁺, N and Q in H₂O (24 µM V²⁺). It should be noted that due to solubility reasons the solution is slightly acidic. To assure just a slightly acidic solution the original mixture (black line) was deprotonated with 2 µL 1.5M NaOH (red line; lying under the blue line) and slowly acidified. After the first addition of 1.4 µL of 1M HCl (blue) the solution is still basic. After the second addition of 1.4 µL of 1M HCl (green) the solution is acidic representing state I. Reduction with Na₂S₂O₄ (pink line) results in the expected absorption maxima of state IV. The intensity of the signal is weak, because of the fast reoxidation while the measurement.
2.16. Acidification of state III

*Figure S20.* This UV/Vis experiment shows the acidification of state III (a reduced state in basic medium) to state IV (a reduced state in acidic medium). The black line corresponds to a 2:1:1:2 mixture of P, V$^{2+}$, N and Q in H$_2$O (24 µM V$^{2+}$) after addition of 1 µL 1.5M NaOH (black line). It should be noted that due to solubility reasons the solution was slightly acidic before. Reduction with Na$_2$S$_2$O$_4$ (green line) results in the expected absorption maxima of state III (depicted by arrow a). After addition of 1.4 µL 1M HCl (b) (grey lines) state IV is reached. The absorption maxima decreases rapidly (arrow b) because of reoxidation resulting in the reoxidised state (blue line) within 2 minutes.
References