Supplementary Material (ESI) for Chemical Communications

A New Synthetic Route to Chloride Selective [2]Catenanes

Supplementary Information

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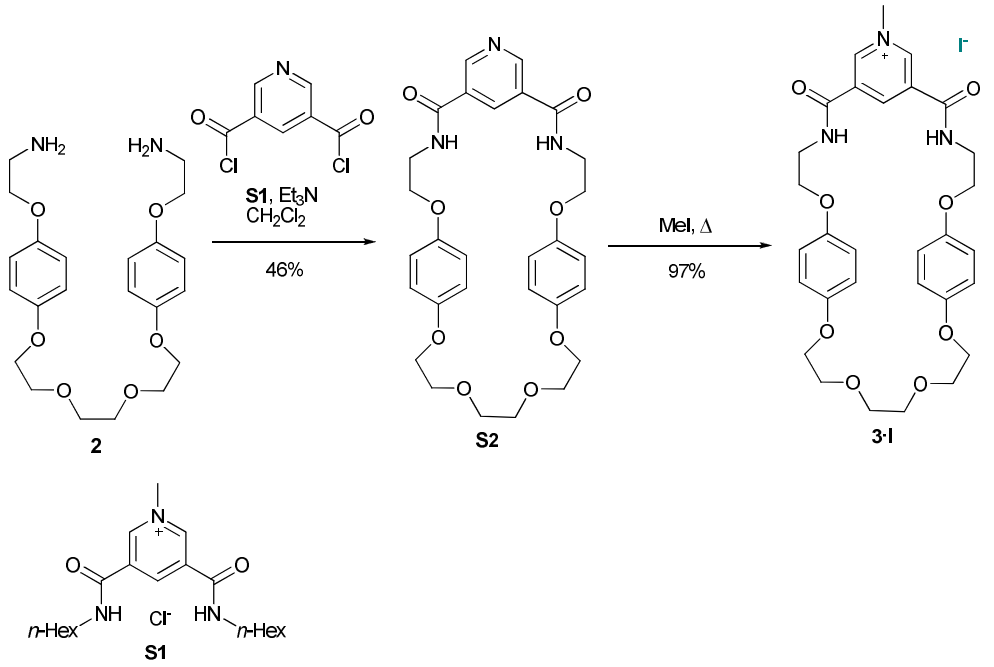
PART I: SYNTHESIS AND CHARACTERISATION

General Considerations. Commercially available solvents and chemicals were used without further purification unless stated. Where dry solvents were used, they were degassed with nitrogen, dried by passing through an MBraun MPSP-800 column and then used immediately. Water was deionized and microfiltered using a Milli-Q Millipore machine.

^{1}H and ^{13}C{^{1}H} spectra were recorded on a Varian Mercury-VX 300 spectrometer. Mass spectrometry was carried out on a Bruker micrOTOF spectrometer.

The synthesis of bis amines **1**[1] and **2**[2] and template **S1**[3] are reported elsewhere. Macrocycle **3**·I was prepared according to Scheme S1.

Synthesis of Macrocycle 3·I



Scheme S1. Synthesis of Macrocycle **3**·I

Macrocycle S2:

3,5-Pyridine dicarbonyl dichloride (233 mg, 1.14 mmol) was dissolved in dry CH_2Cl_2 (10 mL) and added dropwisely to a solution of bis-amine **2** (479 mg, 1.14 mol), **S1** (438 mg, 1.14 mmol) and Et_3N (0.5 mL) in dry CH_2Cl_2 (40 ml). The reaction mixture was stirred under N_2 for 1 h and then cooled to RT. The solution was washed with 10% $HCl_{(aq)}$ (2 × 100 mL) and water (2 × 100 mL), the organic layer dried over anhydrous $MgSO_4$, and the solvent was removed *in vacuo*. The resulting yellow gummy solid was purified using silica gel column chromatography (95:5 CH_2Cl_2/MeOH) to give a white solid (0.292 g, 46%).

^{1}H NMR δ_H (300 MHz, $CDCl_3$): 9.21 (2H, s, pyridinium H^2 & H^6), 8.19 (1H, s, pyridinium H^4), 6.77 (8H, s, hydroquinone Ar*H*), 6.74 – 6.69 (2H, m, N*H*), 4.11 (4H, t, ^3J = 5.0 Hz, CH_2), 4.05 (4H, t, ^3J = 5.0 Hz, CH_2), 3.90 – 3.82 (8H, m, CH_2), 3.72 (4H, s, CH_2); ^{13}C NMR δ_C (75.5 MHz, $CDCl_3$) 165.0, 151.7, 136.4, 131.5, 129.2, 121.3, 115.8, 115.2, 70.9, 69.7, 68.2, 67.0, 39.7; HRMS (ESI): *m/z* calc for $C_{29}H_{33}N_3O_8$: 552.2340; found: 552.2342 $[M + H]^+$.

Macrocycle 3·I:

Macrocycle **S2** (50 mg, 0.09 mmol) and MeI (2 mL) were heated at reflux under N_2 for 16 hr. The reaction mixture was cooled to RT and the MeI removed *in vacuo* to yield a pale yellow solid (61.1 mg, 97%).

^{1}H NMR δ_H (300 MHz, $CDCl_3$) 9.45 (1H, s, pyridinium *H*^{4}), 9.01 (2H, s, pyridinium *H*^{2} & *H*^{6}), 8.96 (2H, t, ^3J = 5.3 Hz, N*H*), 6.76 (4H, d, ^3J = 8.8 Hz, hydroquinone Ar*H*), 6.60 (4H, d, ^3J = 8.8Hz, hydroquinone Ar*H*), 4.18 – 4.15 (8H, m, C*H*$_2$), 4.00 – 3.95 (4H, m, C*H*$_2$), 3.85 – 3.81 (8H, m, C*H*$_2$), 3.71 (3H, s, N^+CH_3); ^{13}C NMR δ_C (75.5 MHz, $CDCl_3$) 161.4, 152.4, 152.1, 147.3, 140.3, 134.0, 115.8, 114.7, 70.7, 69.9, 67.6, 65.9, 48.5, 40.1; HRMS (ESI): *m/z* calc. for $C_{30}H_{36}N_3O_8$·I: 566.2497; found: 566.2487.

Synthesis of Catenanes

Catenane 4·Cl:

Macrocycle **3**·I (75 mg, 0.108 mmol), and bis-amine **1** (50.1 mg, 0.108 mmol) were dissolved in dry CH_2Cl_2 (20 mL) and the solution stirred under N_2 for 5 min. Triethylamine (0.038 mL, 0.27 mmol) was added, followed immediately by isophthaloyl dichloride (22 mg, 0.108 mmol) in dry CH_2Cl_2 (2 mL) and the resulting solution stirred under N_2 for 1 h at RT. The solution was washed with 10% $HCl_{(aq)}$ (2 × 20 mL) and H_2O (2 × 20 mL), and the organic phase dried over anhydrous $MgSO_4$ and the solvent removed *in vacuo*. The crude yellow solid was purified by preparative TLC (9:1 CH_2Cl_2/MeOH & 9:1 EtOAc/MeOH) to give a pale yellow solid (45 mg, 35%).

^{1}H NMR δ_H (300 MHz, 1:1 $CDCl_3$/CD_3OD) 9.14 (1H, s, pyridinium *H*^{4}), 8.77 (2H, s, pyridinium *H*^{2} & *H*^{6}), 8.74 (1H, s, isophthalamide *H*^{2}), 8.51 (2H, t, ^3J = 5.3 Hz, isophthalamide N*H*), 8.44 (2H, t, ^3J = 4.4 Hz, pyridinium N*H*), 8.11 (2H, d, ^3J = 7.9 Hz, isophthalamide *H*^{4} & *H*^{6}), 7.62 (1H, t, ^3J = 7.9 Hz, isophthalamide *H*^{5}), 6.72 (4H, d, ^3J = 9.4 Hz, pyridinium macrocycle hydroquinone ArH), 6.67 (4H, ^3J = 9.4 Hz, pyridinium macrocycle hydroquinone ArH), 6.39 (4H, d, ^3J = 9.1 Hz, isophthalamide macrocycle hydroquinone ArH), 6.21 (4H, d, ^3J = 9.1 Hz, isophthalamide macrocycle hydroquinone ArH), 4.25 (3H, s, N^+CH_3), 4.01 – 4.05 (8H, m, C*H*$_2$), 3.80 – 3.83 (8H, m, C*H*$_2$), 3.58 – 3.75 (28H, m, C*H*$_2$); ^{13}C NMR δ_C (75.5 MHz, 1:1 $CDCl_3$/CD_3OD) 168.4, 161.5, 153.9, 153.6, 153.4, 152.6, 146.2, 139.3, 134.5, 133.9, 132.1, 129.9, 125.7, 116.4, 115.6, 115.5, 115.3, 71.3, 71.2, 71.1, 70.6, 70.3, 68.6, 68.5, 66.8, 66.5,

50.1, 41.1, 40.9. HRMS (ESI): *m/z* calc. for $C_{62}H_{74}N_5O_{17}$·Cl: 1160.5074, found 1160.5225 $[M - Cl]^+$.

Catenane 4·PF_6**:**

Catenane **4**·Cl (45 mg, 0.0376 mmol) was dissolved in $CHCl_3$ (20 mL) and washed with 1M $NH_4PF_{6(aq)}$ (8 × 20 mL), and H_2O (2 × 20 mL). The organic layer was dried over anhydrous $MgSO_4$, and the solvent removed *in vacuo* to give a yellow solid (47 mg, 95%).

^{1}H NMR δ_H (300 MHz, 1:1 $CDCl_3$/CD_3OD) 9.00(1H, s, pyridinium *H*^{4}), 8.54 (2H, s, pyridinium *H*^{2} & *H*^{6}), 8.31 (2H, t, ^3J = 5.0 Hz, pyridinium N*H*), 8.29 (1H, s, isophthalamide *H*^{2}), 8.03 (2H, dd, ^3J = 7.8 Hz, ^4J = 1.7 Hz, isophthalamide *H*^{4} & *H*^{6}), 7.94 (2H, t, ^3J = 5.5 Hz, isophthalamide N*H*), 7.61 (2H, t, ^3J = 4.4 Hz, isophthalamide *H*^{5}), 7.62 (1H, t, ^3J = 7.8 Hz, isophthalamide *H*^{5}), 6.71 (4H, d, ^3J = 9.5 Hz, pyridinium macrocycle hydroquinone Ar*H*), 6.66 (4H, ^3J = 9.5 Hz, pyridinium macrocycle hydroquinone Ar*H*), 6.47 (4H, d, ^3J = 9.1 Hz, isophthalamide macrocycle hydroquinone Ar*H*), 6.29 (4H, d, ^3J = 9.1 Hz, isophthalamide macrocycle hydroquinone Ar*H*), 3.98 – 4.04 (11H, m , C*H*$_2$ & N^+C*H*$_3$), 3.87 (4H, t, ^3J = 4.7 Hz, C*H*$_2$), 3.73 – 3.81 (8H, m, C*H*$_2$), 3.64 – 3.67 (12H, m, C*H*$_2$), 3.56 – 3.60 (8H, m, C*H*$_2$), 3.48 – 3.49 (4H, m, C*H*$_2$); ^{13}C NMR δ_C (75.5 MHz, 1:1 $CDCl_3$:CD_3OD) 168.5, 161.8, 161.7, 153.7, 153.6, 153.2, 152.6, 146.1, 141.7, 134.9, 134.2, 131.6, 129.8, 125.6, 116.1, 115.8, 115.5, 115.3, 78.5, 71.2, 71.0, 70.5, 70.3, 68.5, 68.2, 67.1, 66.6, 41.2, 40.4; ^{19}F NMR δ_F (282.4 MHz, 1:1 $CDCl_3$:CD_3OD) –72.5 (d, ^1J = 710 Hz, P*F*$_6^-$); ^{31}P NMR δ_P (121.6 MHz, 1:1 $CDCl_3$:CD_3OD) –140.2 (sept, ^1J = 710 Hz, *P*F_6^-); HRMS (ESI): *m/z* calc. for $C_{62}H_{74}N_5O_{17}$·PF_6 calc. 1160.5074, found 1160.5225 $[M - PF_6]^+$.

Catenane 5·Cl**:**

Macrocycle **3**·I (62.5 mg, 0.09 mmol), and bis-amine **2** (43.4 mg, 0.09 mmol) were dissolved in dry CH_2Cl_2 (20 mL) and the solution stirred under N_2 for 5 min. Triethylamine (0.032 mL, 0.225 mmol) was added, followed immediately by isophthaloyl dichloride (18 mg, 0.09 mmol) in dry CH_2Cl_2 (2 mL) and the resulting solution stirred under N_2 for 1 h at RT. The solution was washed with 10% $HCl_{(aq)}$ (2 × 20 mL) and H_2O (2 × 20 mL), and the organic phase dried over anhydrous $MgSO_4$ and the solvent removed *in vacuo*. The crude yellow solid was purified by

preparative TLC (93:7 $CHCl_3$:MeOH & 8:2 EtOAc:MeOH) to give a pale yellow solid (28.3 mg, 29%).

^{1}H NMR δ_H (300 MHz, $CDCl_3$) 9.55 (1H, s, pyridinium H^4), 9.23 (2H, s, pyridinium H^2 & H^6), 9.15 (1H, s, isophthalamide H^2), 8.61 (2H, s, isophthalamide N*H*), 8.50 (2H, s, pyridinium N*H*), 8.27 (2H, d, ^3J = 7.7 Hz, isophthalamide H^4 & H^6), 7.61 (1H, t, ^3J = 7.7 Hz, isophthalamide H^5), 6.75 (8H, q, ^3J = 9.3 Hz, pyridinium macrocycle hydroquinone Ar*H*), 6.24 (4H, d, ^3J = 8.8 Hz, isophthalamide macrocycle hydroquinone Ar*H*), 5.98 (4H, d, ^3J = 8.8 Hz, isophthalamide macrocycle hydroquinone Ar*H*), 4.56 (3H, s, N^+CH_3), 3.47 – 4.11 (40H, m, CH_2); ^{13}C NMR δ_C (75.5 MHz, 1:1 $CDCl_3$/CD_3OD) 168.3, 161.5, 153.4, 152.1, 147.0, 138.9, 134.4, 133.2, 132.0, 129.4, 125.9, 116.3, 115.5, 115.0, 114.3, 78.4, 71.4, 71.1, 70.7, 70.3, 68.5, 67.6, 66.7, 66.0, 41.1, 40.9, 40.7; HRMS (ESI): *m/z* calc. for $C_{60}H_{70}N_5O_{16}Cl$ $[M - Cl]^+$ 1116.4812 found 1116.4756.

Catenane 5·PF_6:

Catenane **5**·Cl (39 mg, 0.03 mmol) was dissolved in $CHCl_3$ (20 mL) and washed with 1M $NH_4PF_{6(aq)}$ (8 × 20 mL), and H_2O (2 × 20 mL). The organic layer was dried over anhydrous $MgSO_4$, and the solvent removed *in vacuo* to give a yellow solid (42 mg, 100%).

^{1}H NMR δ_H (300 MHz, $CDCl_3$) 8.88 (2H, s, pyridinium H^2 & H^6), 8.73 (1H, s, pyridinium H^4), 8.36 (1H, s, isophthalamide H^2), 7.98 (2H, dd, ^3J = 7.8 Hz, ^4J = 1.6 Hz, isophthalamide H^4 & H^6), 7.91 (2H, br s, pyridinium N*H*), 7.61 (1H, t, ^3J = 7.8 Hz, isophthalamide H^5), 6.61 – 6.68 (8H, m, pyridinium macrocycle hydroquinone Ar*H*), 6.25 (4H, d, ^3J = 9.1 Hz, isophthalamide macrocycle hydroquinone Ar*H*), 6.14 (4H, d, ^3J = 9.1 Hz, isophthalamide macrocycle hydroquinone Ar*H*), 4.36 (3H, s, N^+CH_3), 3.93 – 4.00, (8H, m, CH_2), 3.82 (4H, s, CH_2), 3.68 – 3.76 (20H, m, CH_2), 3.65 (4H, s, CH_2), 3.52 (4H, br s, CH_2); ^{13}C NMR δ_C (75.5 MHz, 1:1 $CDCl_3$/CD_3OD) δ (ppm): 168.4, 161.5, 153.6, 153.2, 153.1, 151.9, 146.6, 140.2, 134.7, 133.5, 131.4, 129.7, 126.3, 115.9, 115.5, 115.1, 114.4, 78.3, 71.3, 71.2, 70.6, 70.4, 68.4, 67.6, 66.5, 66.4, 40.9, 40.2; ^{19}F NMR δ_F (282.4 MHz, 1:1 $CDCl_3$/CD_3OD) –72.7 (d, ^1J = 710 Hz, PF_6^-); ^{31}P NMR δ_P (121.6 MHz, 1:1 $CDCl_3$/CD_3OD) -140.1 (sept, ^1J = 710 Hz, PF_6^-); HRMS (ESI): *m/z* calc. for $C_{60}H_{70}N_5O_{16}$·PF_6: 1116.4812; found: 1116.4815 $[M - PF_6]^+$.

^{1}H and ^{13}C{1H} spectra of catenanes

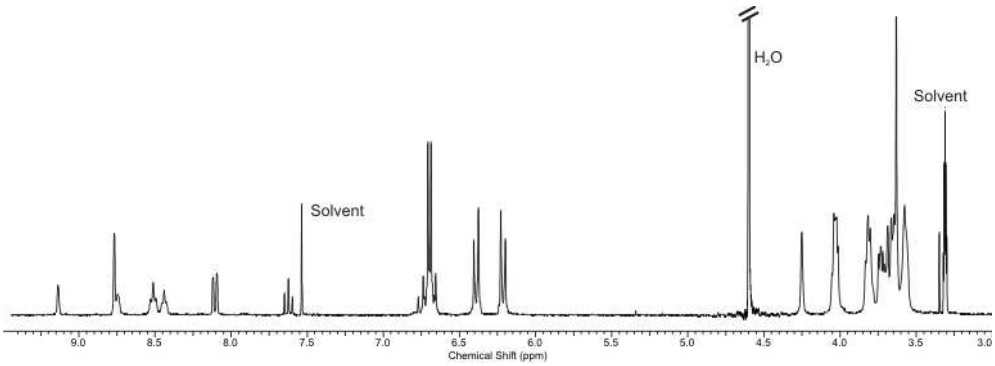


Figure S1. ^{1}H NMR spectrum of **4**·Cl (1:1 $CDCl_3/CD_3OD$, 300 MHz, 293 K)

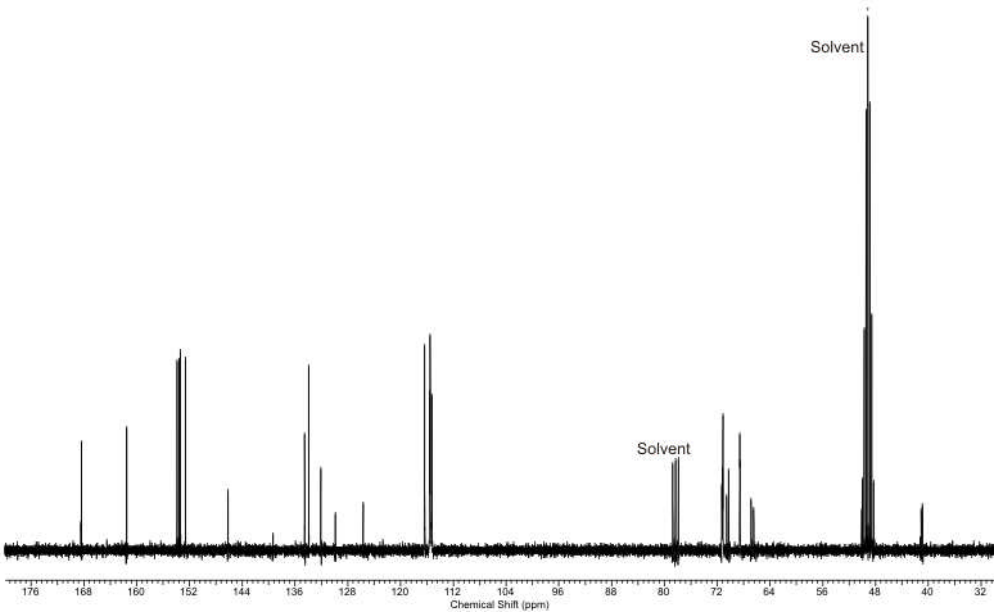


Figure S2. ^{13}C{^{1}H} NMR spectrum of **4**·Cl (1:1 $CDCl_3/CD_3OD$, 300 MHz, 293 K)

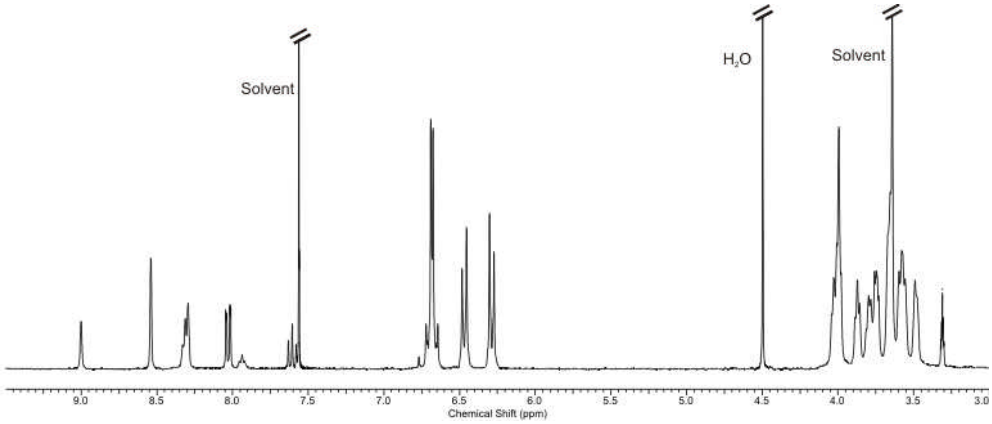


Figure S3. ^{1}H NMR spectrum of **4**·PF_6 (1:1 $CDCl_3$/CD_3OD, 300 MHz, 293 K)

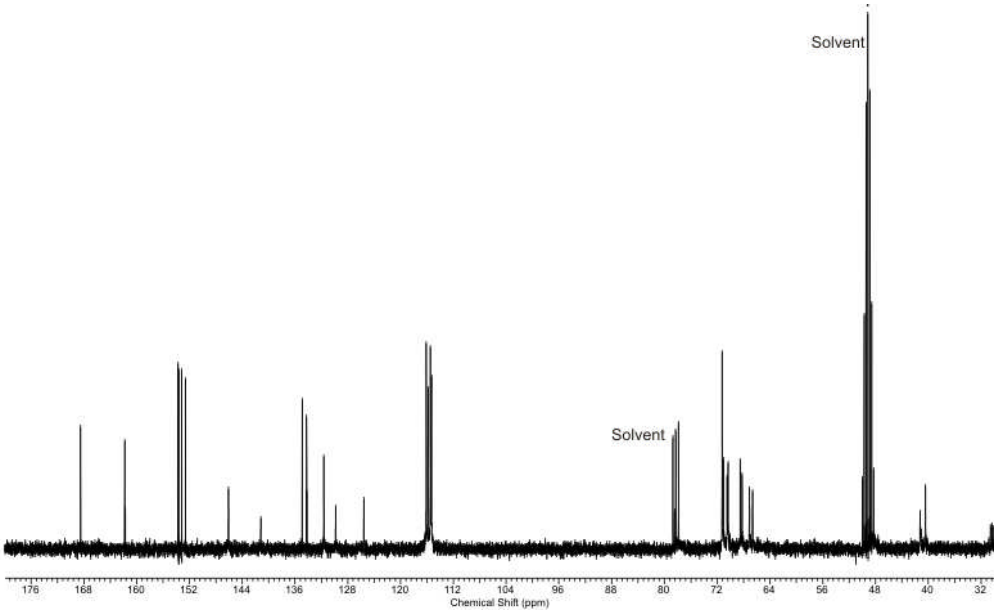


Figure S4. $^{13}C\{^{1}H\}$ NMR spectrum of **4**·PF_6 (1:1 $CDCl_3$/CD_3OD, 300 MHz, 293 K)

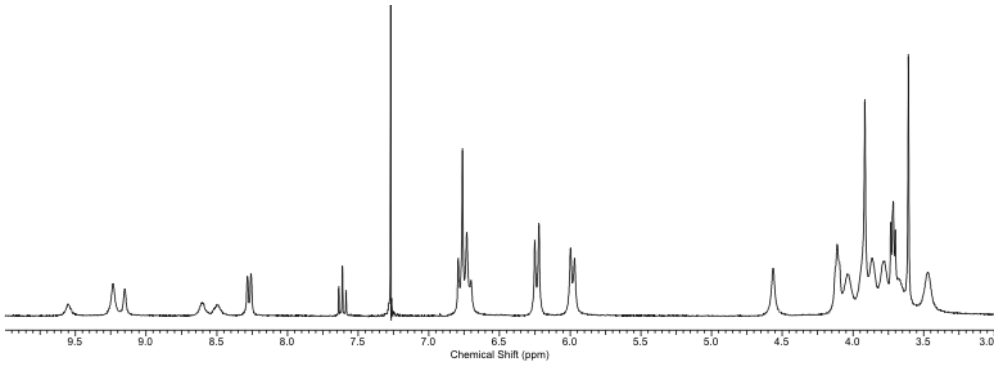


Figure S5. ^{1}H NMR spectrum of **5**·Cl (1:1 $CDCl_3$, 300 MHz, 293 K)

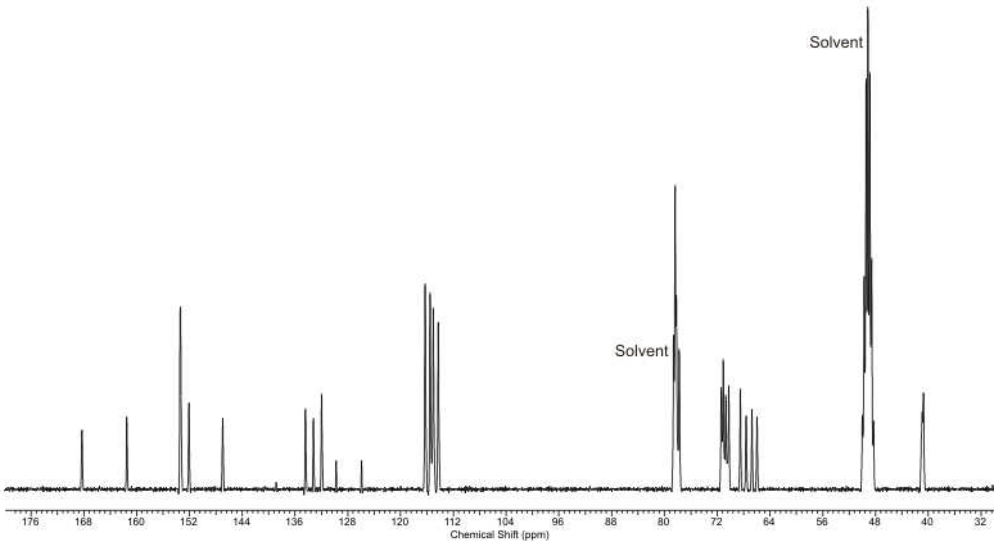


Figure S6. $^{13}C\{^{1}H\}$ NMR spectrum of **5**·Cl (1:1 $CDCl_3/CD_3OD$, 300 MHz, 293 K)

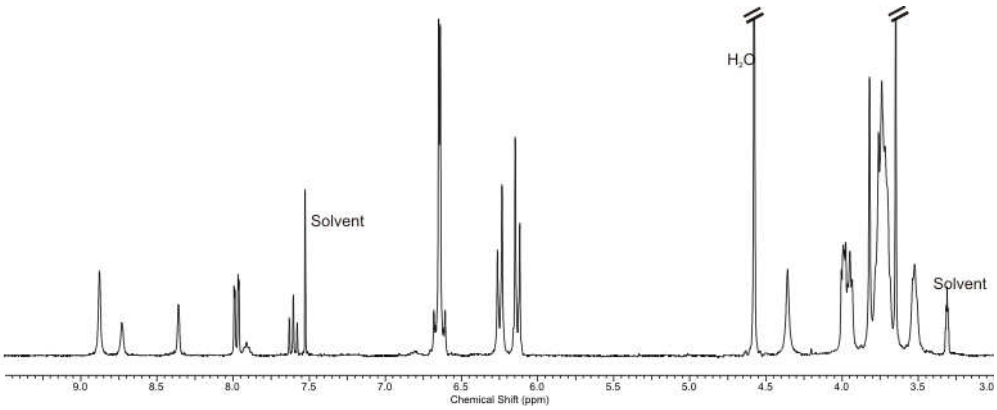


Figure S7. ^{1}H NMR spectrum of **5**·PF_6 (1:1 $CDCl_3/CD_3OD$, 300 MHz, 293 K)

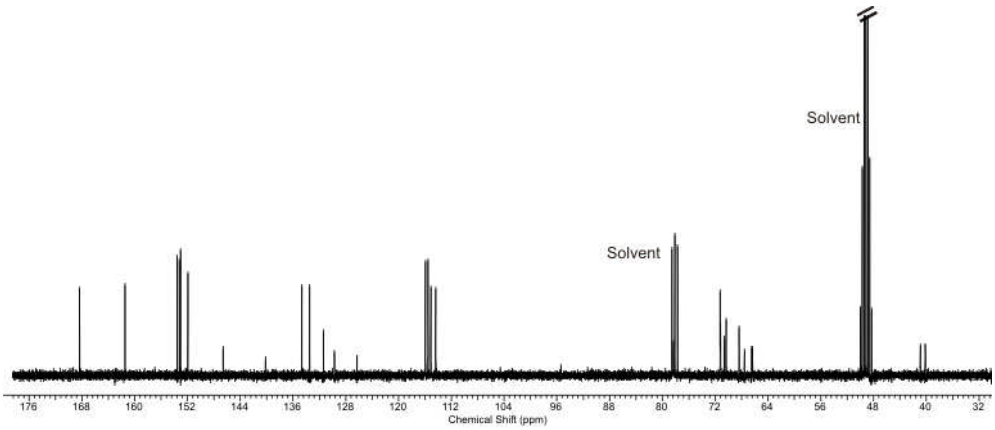


Figure S8. $^{13}C\{^{1}H\}$ NMR spectrum of **5**·PF_6 (1:1 $CDCl_3/CD_3OD$, 300 MHz, 293 K)

^{1}H -^{1}H ROESY spectrum of [2]catenane 5·Cl

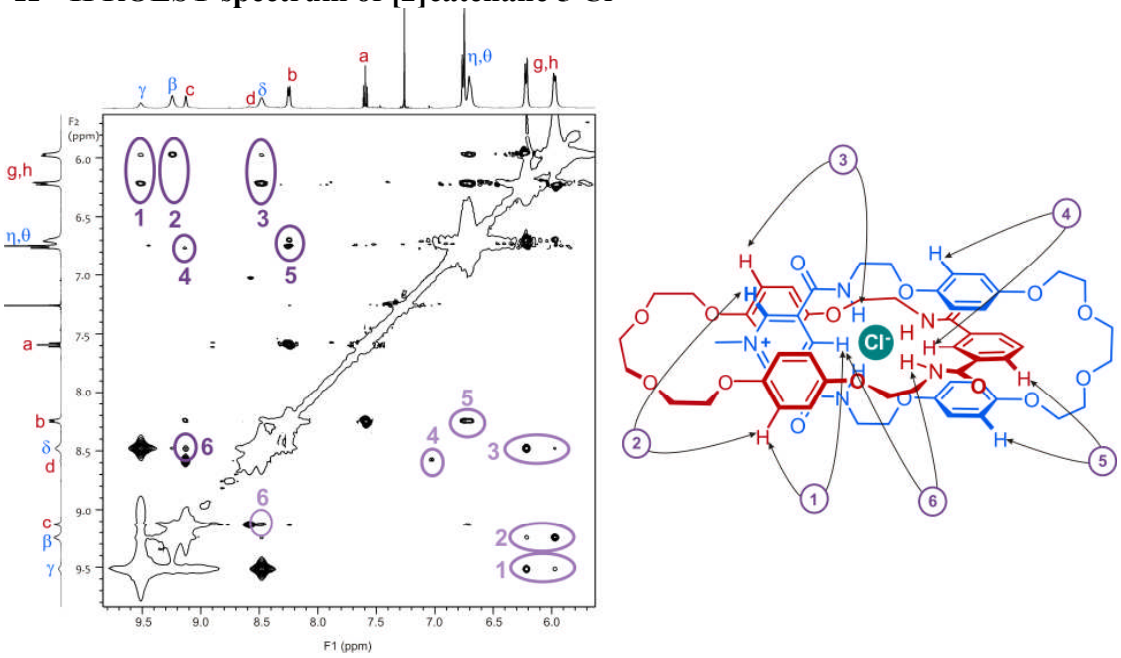


Figure S9. ^{1}H -^{1}H ROESY spectrum of [2]catenane **5**·Cl in $CDCl_3$ at 293 K. Cross couplings are shown on the schematic diagram on the right.

Cross coupling interactions exist between hydroquinone protons of the neutral macrocyclic component and the pyridinium protons exemplified by correlations **1**($\gamma \rightarrow g,h$), **2**($\beta \rightarrow g,h$) and **3**($\delta \rightarrow g,h$). A through space correlation **6** ($\gamma \rightarrow d$) also exists between amide protons of both macrocycles as they converge into the cleft to bind chloride. Interactions **4** ($b \rightarrow \eta,\theta$) and **5** ($c \rightarrow \eta,\theta$) reveal the isophthaloyl and hydroquinone protons are also in close proximity.

PART II: ^{1}H NMR TITRATIONS

Titration Protocol

^{1}H NMR spectra were recorded on a Varian Unity Plus 500 spectrometer. Typically, a solution of guest was added to a solution of the host at 293K. The chemical shift of the *ortho* pyridinium proton β, *para* pyridinium proton γ and cavity isophthalamide proton *c* of the host was monitored for seventeen titration points (for 0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.5, 3.0, 4.0, 5.0, 7.0 and 10.0 equivalents of added guest). The resulting data were analysed using the WinEQNMR2[4] computer program in experiments where association of guest and host was fast on the NMR timescale.

Anion binding titration experiments were carried out using the salt of the non-complexing tetrabutylammonium (TBA) cation as the guest species, titrated into the host species [2]catenanes **4**·PF_6 and **5**·PF_6. A 0.0954 moldm^{-3} solution of anion was added to 0.5 mL of a 0.00191 moldm^{-3}solution of [2]catenanes. The volumes of salt solution added were 10 x 2 μl, 2 x 5 μl, 2 x 10 μl, 1 x 20 μl, and 1 x 30 μl.

The values of the observed chemical shift and the guest concentration were entered into winEQNMR2 for every titration point, and estimates for the binding constant, limiting chemical shifts and binding stoichiometry made. The parameters were refined using non-linear least squares analysis to obtain the best fit between observed and calculated chemical shifts; the program plots the observed shift versus the guest concentration, revealing the accuracy of the experimental data and the suitability of the model used. The input parameters were varied until the best-fit values of the stability constants, together with their errors, converged.

Binding Isotherms

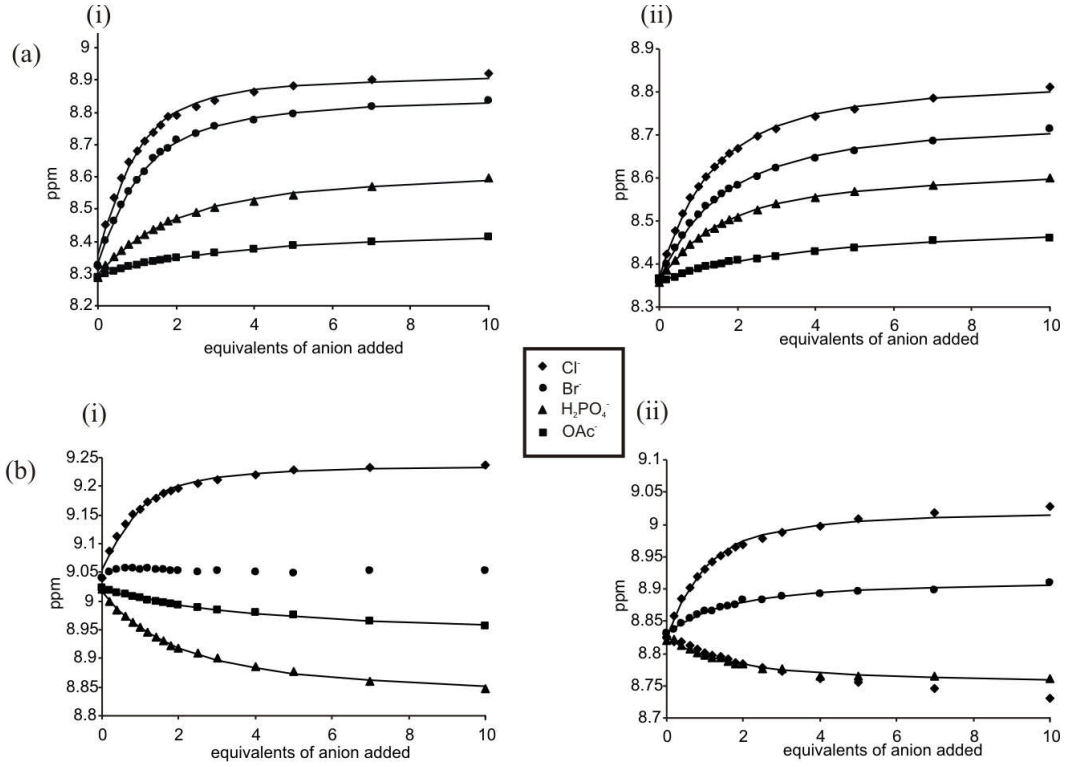


Figure S10. Chemical shift perturbations of (a) proton *c* and (b) proton γ on addition of Cl^-, Br^-, $H_2PO_4^-$ and OAc^-(as TBA salts) to a solution of (i) **4**·PF_6 and (ii) **5**·PF_6 in 1:1 $CDCl_3/CD_3OD$ at 1.91 x 10^{-3} M and 293 K. Symbols represent experimental data points; continuous lines represent calculated curves. *winEQNMR2 was unable to calculate association constants for **4**·Br and **5**·OAc by monitoring proton γ.

PART III: CRYSTALLOGRAPHIC INFORMATION

Experimental Crystal Structure Data

Data were collected using graphite monochromated Mo Kα radiation (λ = 0.71073 Å) on a Nonius KappaCCD diffractometer. The diffractometer was equipped with a Cryostream N_2 open-flow cooling device,[5] and the data were collected at 150(2) K. Series of ω-scans were performed to a maximum resolution of 0.77 Å. Cell parameters and intensity data (including inter-frame scaling) were processed using the DENZO-SMN package.[6] The structures were solved with SUPERFLIP,[7] and refined on F^2 in CRYSTALS.[8] Molecular graphics were produced with CrystalMaker.

Catenane **4**·Cl·0.68$CHCl_3$; Moiety Formula $C_{32}H_{38}N_2O_9$, $C_{30}H_{36}N_3O_8$, Cl, 0.68($CHCl_3$); M = 1277.94; triclinic space group P $\bar{1}$; yellow prism; a = 11.8388(1) Å, b = 17.4493(1) Å, c = 17.8692(2) Å, α = 114.1468(4)°, β = 97.4460(4)°, γ = 102.6071(4)°, V = 3186.35(5) $Å^3$, T = 150 K μ = 0.218 mm^{-1}. 26903 reflections measured, 14487 independent reflections (R_{int} = 0.025). The final R_1 values were 0.0512 ($I > 2\sigma(I)$). The final $wR(F^2)$ value was 0.1217 ($I > 2\sigma(I)$). The final R_1 value was 0.0645 (all data). The final $wR(F^2)$ value was 0.1342 (all data). A portion of the five-oxygen macrocycle was disordered and was modelled over two sites with refined occupancy of 0.680(2) and 0.320(2). The cocrystallised chloroform was found to be related to the major component of the macrocycle disorder, and the occupancy of the chloroform and the disordered macrocycle were modelled together. Additional areas of electron density were observed near the chloroform, but no attempts gave a stable refinement even with considerable geometric and vibrational restraints. The residual electron density was therefore not modelled, and results in a level "C" alert in CheckCIF. Non-hydrogen atoms were refined with anisotropic displacement parameters. Further details are available within the CIF.

ORTEPS-III for Crystal Structures

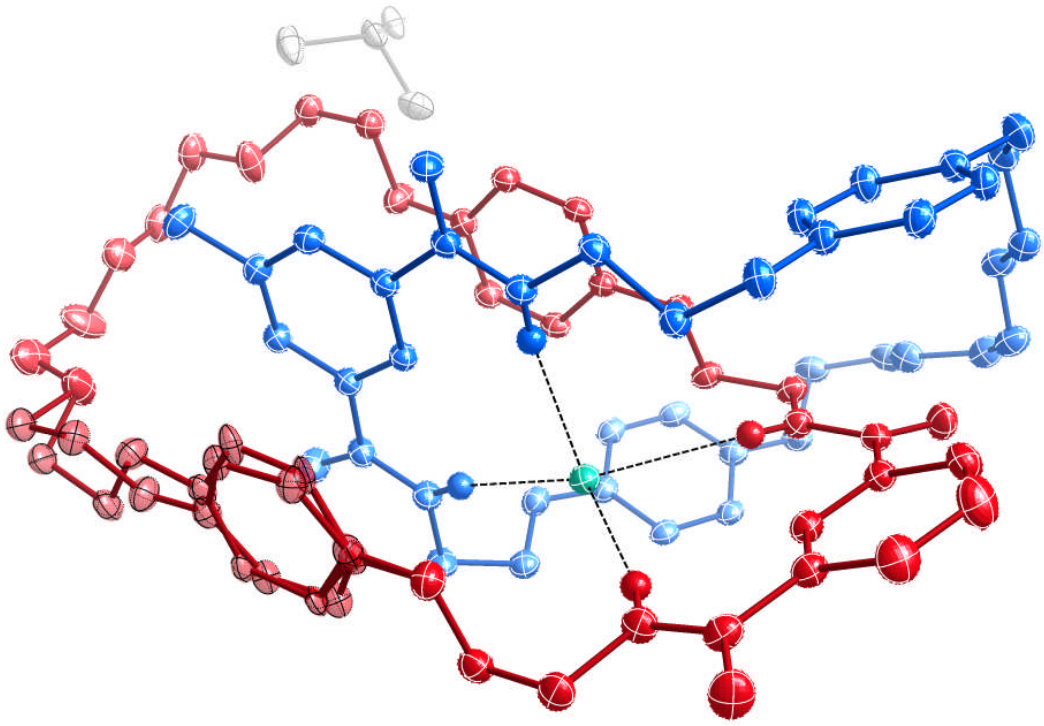


Figure S11. X-ray crystal structure of rotaxane **4**·Cl. Ellipsoids shown at 50% probability. Non-protic hydrogen atoms omitted for clarity.

Crystal data for catenane **5**·PF_6·H_2O: $C_{60}H_{72}F_6N_5O_{17}P_1$, M = 1280.22, triclinic, a = 9.74820(10) Å, b = 14.2731(2) Å, c = 23.7801(3) Å, α = 74.5452(5)°, β = 78.3493(5)°, γ = 85.1917(5)°, V = 3121.77(7) Å^3, T = 150 K, space group $P\bar{1}$, Z = 2, 52283 reflections measured, 14264 independent reflections (R_{int} = 0.030). The final R_1 values were 0.0501 ($I > 2\sigma(I)$). The final $wR(F^2)$ values were 0.1095 ($I > 2\sigma(I)$). The final R_1 values were 0.0785 (all data). The final $wR(F^2)$ values were 0.1321 (all data). A water molecule was located in addition to the catenane. All hydrogens could be observed in the difference map, and after assigning geometric positions, they were refined against the data using restraints. The resulting positions were in keeping with hydrogen bonding requirements. Non-hydrogen atoms were refined with anisotropic displacement parameters. Further details are available within the CIF.

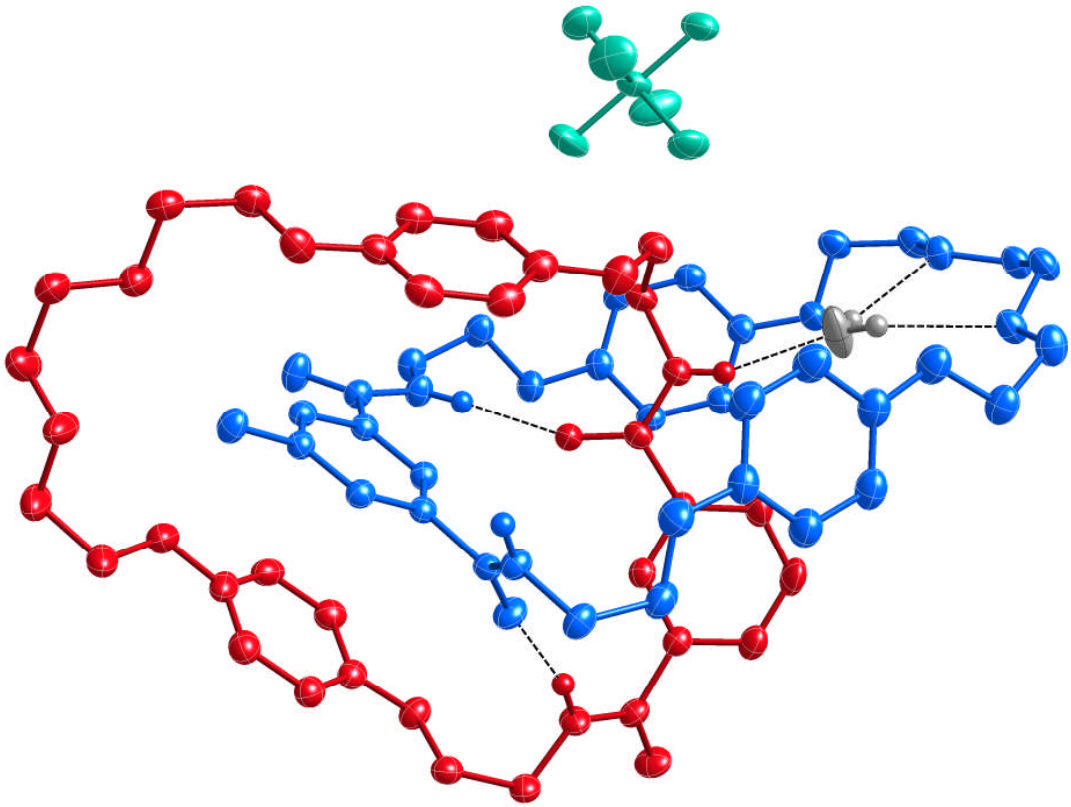


Figure S12. X-ray crystal structure of rotaxane **5**·PF_6. Ellipsoids shown at 50% probability. Non-protic hydrogen atoms omitted for clarity.

PART IV: REFERENCES

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