Electronic Supplementary Material (ESI) for Chemical Communications

Axle component separated ion-pair recognition by a neutral heteroditopic [2]rotaxane

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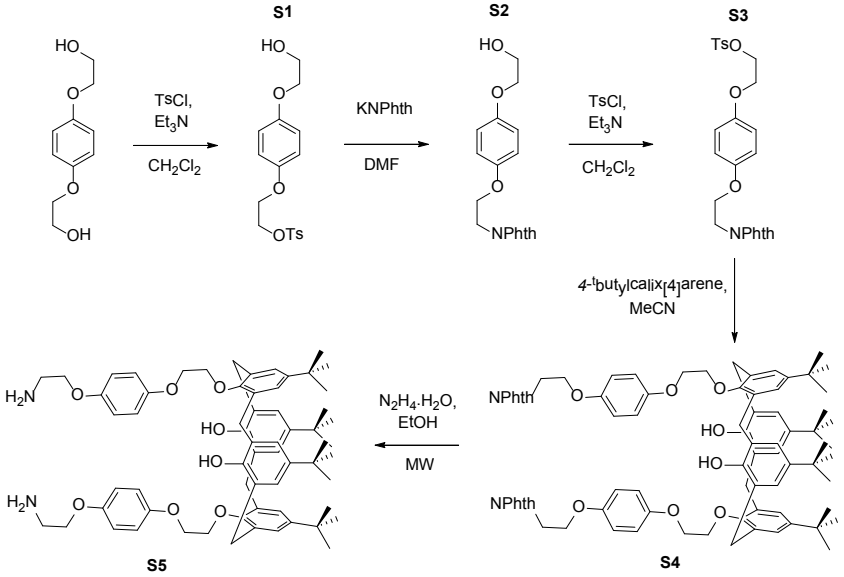
S1 Experimental

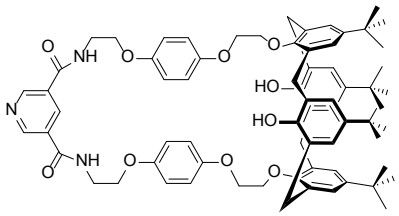
The Calix[4]arene macrocycle precursor was synthesised according to a previously reported procedure,[1] as depicted in Scheme S1.



Scheme S1.1: Synthesis of calix[4]arene macrocycle precursor

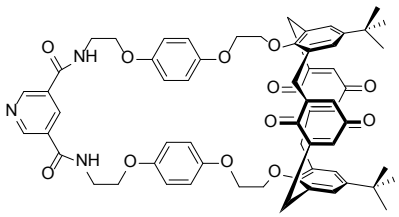
The pyridine N-oxide bis-azide threads **2**[2] and **3**[3] and alkyne-functionalised terphenyl stopper **4**[4] were synthesised as previously described.

Calix[4]arene macrocycle S6



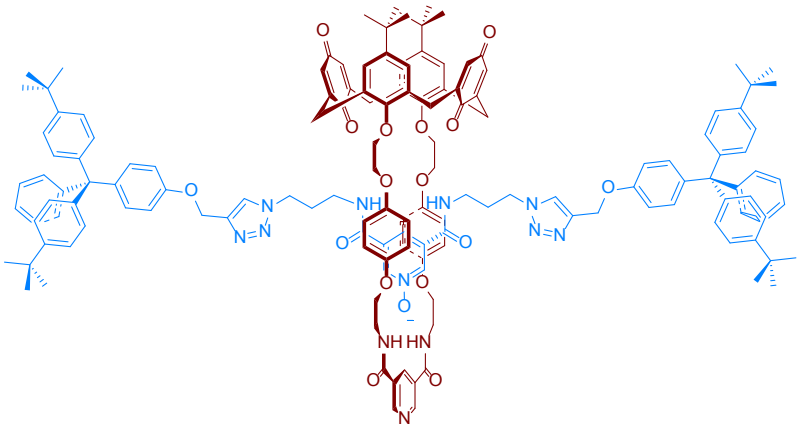
Calix[4]arene macrocycle precursor **5** (530 mg, 0.526 mmol) was dissolved in dry CH_2Cl_2 (20 mL). Pyridine-3,5-dicarbonyl dichloride (0.631 mmol) was dissolved in CH_2Cl_2 (20 mL). The solutions were added dropwise *via* syringe pump to a solution of Et_3N (0.293 mL, 2.11 mmol) in dry CH_2Cl_2 (200 mL) over 3 hours under an N_2 atmosphere. The reaction was stirred for a further 18 hours after which the solvent was washed with 1 M citric $acid_{(aq)}$ (100 mL), sat. $NaHCO_{3(aq)}$ (100 mL) and brine (100 mL) and dried over $MgSO_4$. The crude material was purified by column chromatography (silica; CH_2Cl_2/MeOH; 98:2) to give the compound as a white solid (563 mg, 94%). ^{1}H NMR (300 MHz, $CDCl_3$) δ_H 9.18 (2H, s, Ar*H*), 8.36 (1H, s, Ar*H*), 7.42 (2H, s, O*H*), 7.18 (2H, br.s, N*H*), 7.06 (4H, s, Ar*H*), 6.91-6.76 (12H, m, Ar*H*), 4.40 (4H, d, J = 12.9 Hz, C*H*), 4.36-4.23 (8H, m, , CH_2), 4.11 (4H, br.s, CH_2), 3.84 (4H, br.s, CH_2), 3.33 (4H, d, J = 13.5 Hz), 1.28 (18H, s, ^{t}*Bu*), 1.00 (18H, s, ^{t}*Bu*) ^{13}C NMR (75 MHz, $CDCl_3$) δ_C 165.1, 153.3, 152.7, 151.5, 150.5, 150.0, 147.1, 141.6, 132.7, 129.3, 127.9, 125.7, 125.2, 116.2, 115.7, 74.2, 67.4, 67.3, 39.8, 34.0, 33.8, 31.7, 31.0; ESI-HRMS: found *m/z* = 1160.5966, calculated 1160.5971 for $[M + Na]^+$.

Calix[4]diquinone macrocycle 1



Thallium (III) trifluoroacetate (2.69 g, 4.95 mmol) was suspended in dry CH_2Cl_2 (20 mL) at 0°C under N_2 in the absence of light. A solution of calix[4]arene macrocycle **S6** (563 mg, 0.495 mmol) in CH_2Cl_2 (20 mL) and trifluoroacetic acid (5 mL) was added simultaneously and the reaction was stirred at 0°C for 35 minutes. The reaction was quenched with H_2O (10 mL) and stirred vigorously for 10 minutes. This was repeated twice and the organic layer dried over $MgSO_4$. Purification by gradient column chromatography (silica; acetone/hexane; 75:25→100:0) and preparative thin layer chromatography (silica; CH_2Cl_2/MeOH, 95:5) afforded **2** as a bright orange solid (172 mg, 33%). ^{1}H NMR (300 MHz, $CDCl_3$) δ_H 9.17 (2H, s, Ar*H*), 8.54 (1H, s, Ar*H*), 6.93-6.76 (12H, m , Ar*H*), 6.70 (4H, s, C*H*), 4.17-4.04 (8H, m, C*H,* CH_2), 3.98-3.80 (12H, m, CH_2), 3.30 (4H, d, J = 12.9 Hz, C*H*), 1.14 (18H, s, ^{t}*Bu*) ^{13}C NMR (75 MHz, $CDCl_3$) δ_C 186.7, 185.6, 165.3, 153.9, 152.7, 150.9, 147.1, 146.5, 133.1, 129.8, 129.4, 126.9, 115.4, 72.6, 67.2, 67.0, 39.8, 34.1, 32.7, 31.4; ESI-HRMS: found *m/z* = 1076.4323, calculated 1076.4304 for $[M + Na]^+$.

Rotaxane 11



Calixdiquinone macrocycle **1** (30.0 mg, 0.0283 mmol) and sodium perchlorate (3.84 mg, 0.0313 mmol) were dissolved in $CHCl_3$ (10 mL) and stirred under N_2 for 16 hours. Stopper alkyne **4** (30.39 mg, 0.0625 mmol), N-oxide **3** (10.86 mg, 0.313 mmol) $Cu^I(MeCN)_4PF_6$ (2.08 mg, 0.00554 mmol), tris[(1-benzyl-1*H*-1,2,3-triazol-4-yl)methyl]amine (TBTA)

(2.22 mg, 0.0042 mmol) and diisopropylethylamine (DIPEA) (0.01 mL) were added and the reaction was stirred at ambient temperature for 36 hours under N_2. The reaction was subsequently washed with 0.25 M $EDTA_{(aq)}$ (3 × 10 mL) and the solvent removed *in vacuo*. Purification by size exclusion chromatography (SX-3; $CHCl_3$) and preparative thin layer chromatography (silica; CH_2Cl_2/MeOH; 99:1→97:3) afforded the compound as yellow solid (41.5 mg, 62 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ_H 9.32 (2H, d, ^4J = 2.2 Hz, pyridine isophthalamide Ar*H*), 9.08 (1H, t, ^4J = 2.0 Hz, pyridine isophthalamide Ar*H*), 8.59 (2H, s, pyridine N-oxide isophthalamide Ar*H*), 8.35 (2H, br.s, N*H*), 7.91 (2H, br.s, N*H*), 7.75 (2H, s, triazole Ar*H*), 7.46 (1H, s, pyridine N-oxide isophthalamide Ar*H*), 7.25-7.04 (30H, m, stopper Ar*H*), 6.90-6.80 (12H, m, stopper, calix Ar*H*, quinine C*H*), 6.58 (4H, d, ^3J = 8.9 Hz, hydroquinone Ar*H*), 6.31 (4H, d, ^3J = 8.9 Hz, hydroquinone Ar*H*), 5.16 (4H, br.s, calix C*H*, CH_2), 4.38 (4H, t, ^3J = 7.0 Hz, CH_2), 4.09 (4H, s, CH_2), 3.96 (4H, s, CH_2), 3.88-3.80 (8H, m, CH_2), 3.41 (4H, s, CH_2), 3.29 (4H, d, ^2J = 11.3 Hz, calix C*H*), 2.22 (4H, s, CH_2), 2.15 (4H, br.s, CH_2), 1.30 (36H, s, ^{t}*Bu*), 1.11 (18H, s, , ^{t}*Bu*) ^{13}C NMR (500 MHz, $CDCl_3$) δ_C 185.9, 166.3, 162.2, 156.4, 152.9, 152.5, 148.7, 147.9, 147.5, 147.4, 144.6, 144.1, 140.5, 140.3, 133.2, 132.8, 131.4, 130.9, 129.4, 129.0, 127.5, 126.0, 124.4, 123.5, 115.5, 114.4, 113.5, 67.6, 67.2, 63.7, 62.1, 48.3, 40.7, 37.7, 34.5, 34.4, 31.6, 31.6; remaining quaternaries undetected; ESI-HRMS: found *m/z* = 1210.0753, calculated 1210.0764 for $[M + 2Na]^{2+}$.

S2: Characterisation data for [2]rotaxane 5

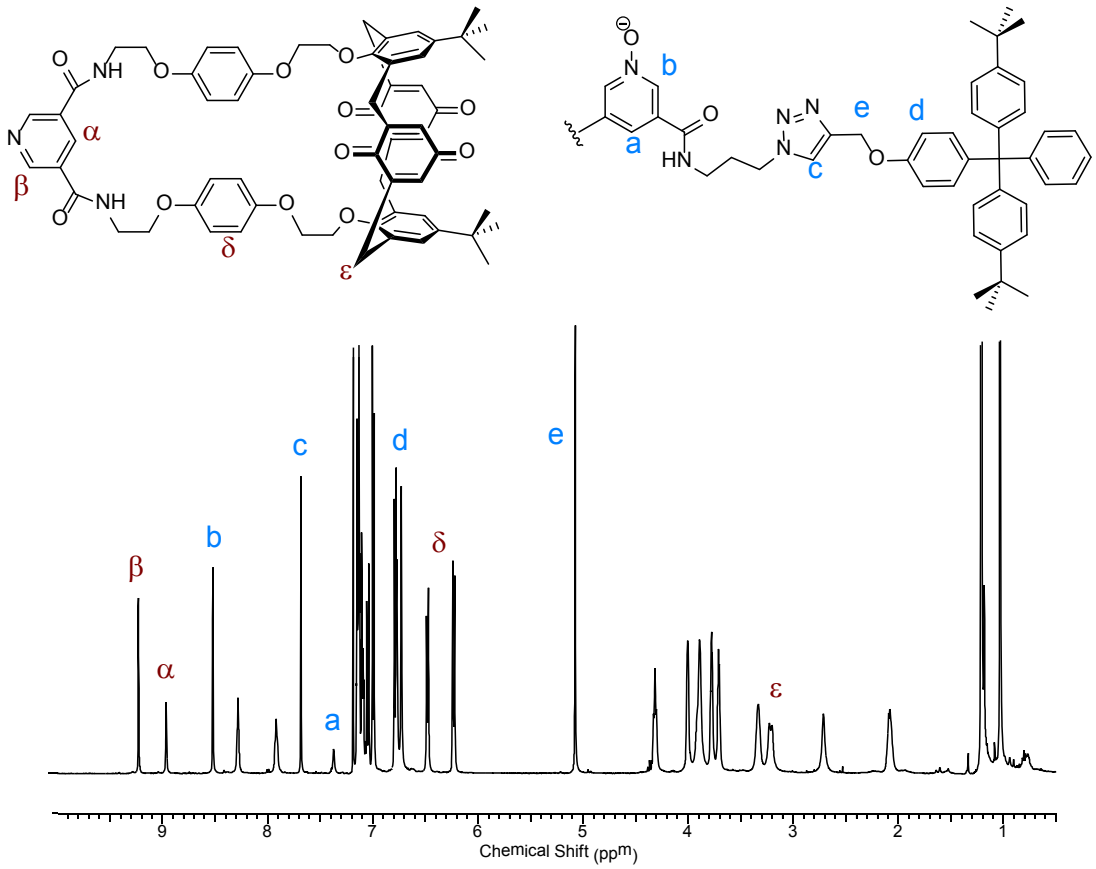


Figure S2.1: Assigned ^{1}H NMR spectrum of heteroditopic [2]rotaxane **5** (500 MHz, $CDCl_3$, 298 K)

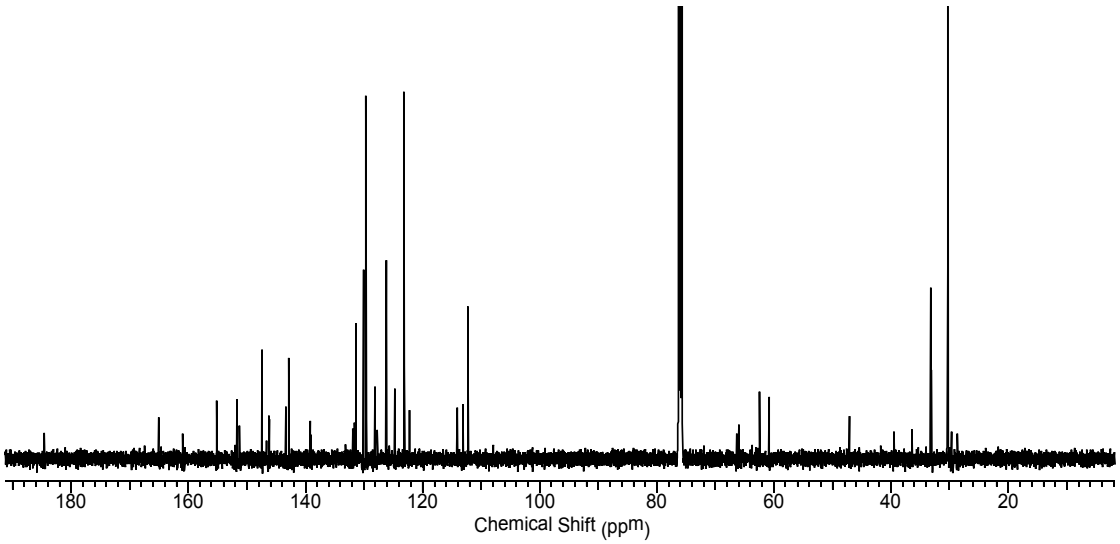


Figure S2.2: ^{13}C spectrum of heteroditopic [2]rotaxane **5** (125 MHz, $CDCl_3$, 298 K)

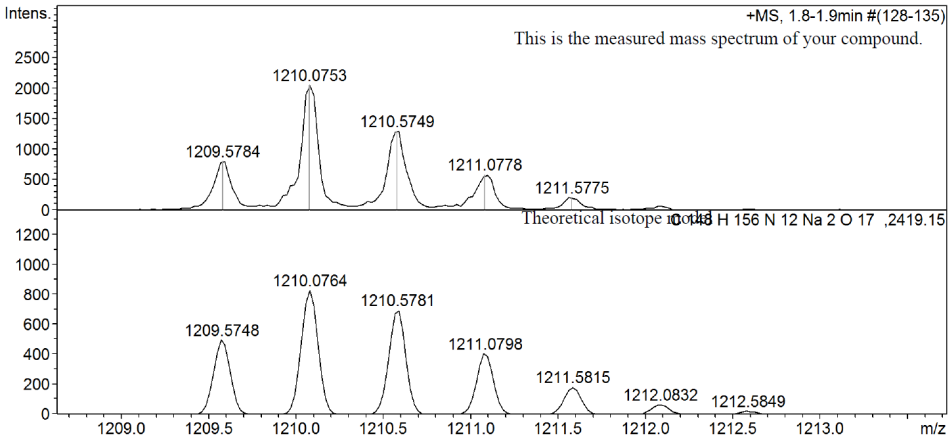


Figure S2.3: ESI-HRMS heteroditopic [2]rotaxane **5**

S3; Conformational Studies of [2]rotaxane

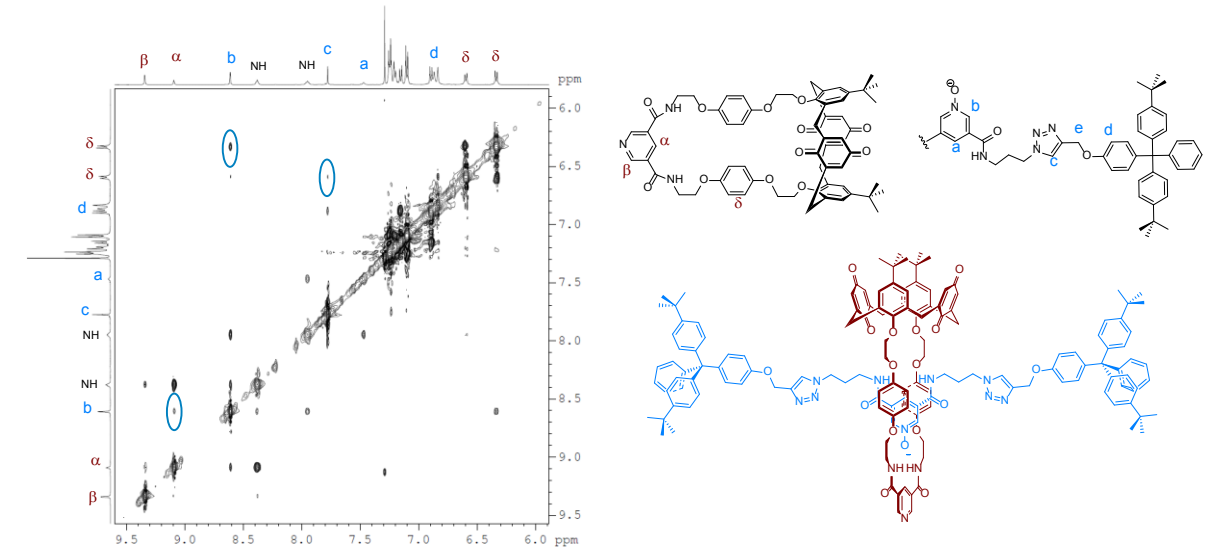


Figure S3.1: ^{1}H-^{1}H ROESY NMR of [2]rotaxane **5** (500 MHz, $CDCl_3$, 298 K)

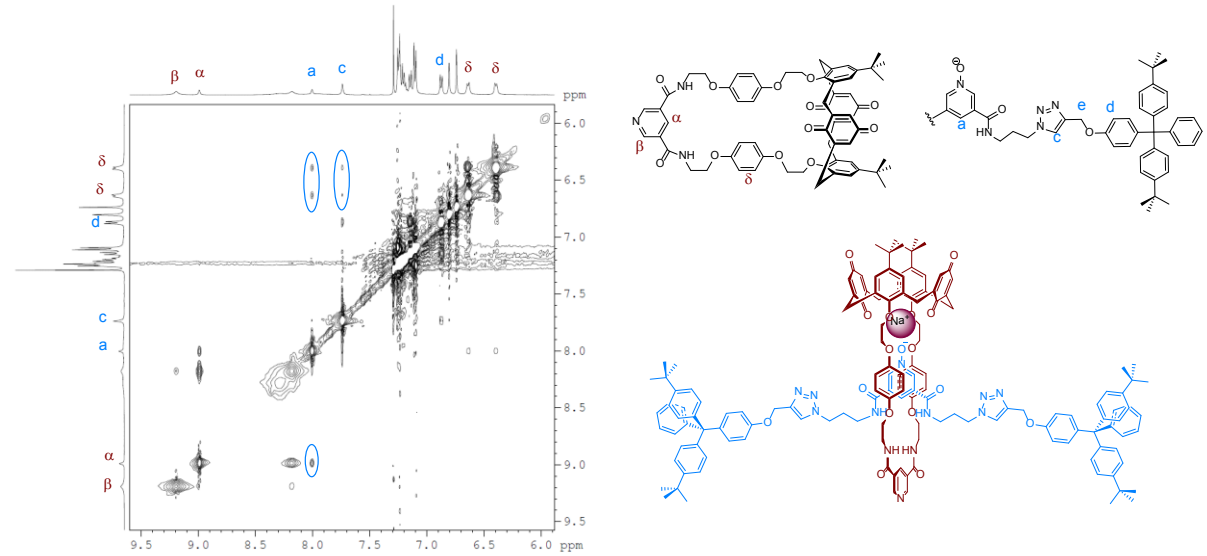


Figure S3.2: ^{1}H-^{1}H ROESY NMR of [2]rotaxane **5** plus 1 equivalent of sodium triflate (500 MHz, $CDCl_3$, 298 K)

S4: ^{1}H NMR Titration Protocol

Titrations were conducted on either a 500 MHz Oxford Instruments Varian Plus or a Bruker Avance III 500 MHZ spectrometer at 298K. Initial sample volumes were 500 µL. The starting host concentration was 1.5 mM for all titrations. All anions were added as their *n*-tetrabutylammonium salts. Cations were added as their non-coordinating salts; lithium hexafluorophosphate, sodium triflate and potassium hexafluorophosphate were used. Seventeen aliquots of the anion guest were added until a total of ten equivalents had been added. Spectra were recorded upon each addition and thorough mixing of the sample.

Stability constants were obtained by analysis of the titration data using WinEQNMR2 data fitting software.[5] Comparison of the calculated binding isotherm with that obtained experimentally confirmed that in all cases the binding fitted a 1:1 binding model.

S4.1: 1 to 1 [2]pseudorotaxane Studies

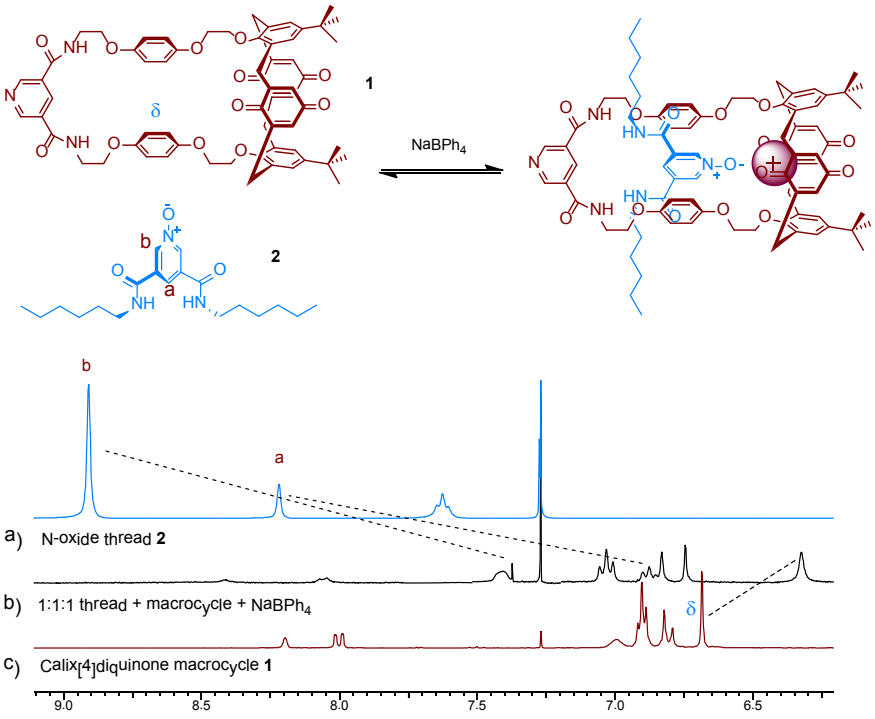


Figure S4.1: 1:1 [2]pseudorotaxane formation templated by sodium tetraphenylborate (300 MHz, $CDCl_3$, 298 K)

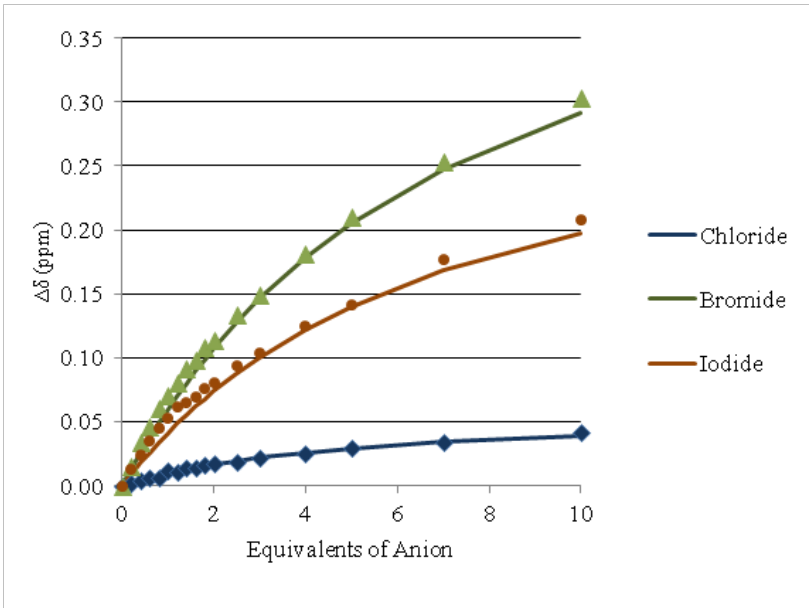


Figure S4.2: Changes in the internal axle proton *a* of [2]rotaxane **5** upon increasing amounts of anion in the absence of a metal cation ($CDCl_3/CD_3OD$ 4:1, 298 K); points represent data points, continuous lines represent calculated curves)

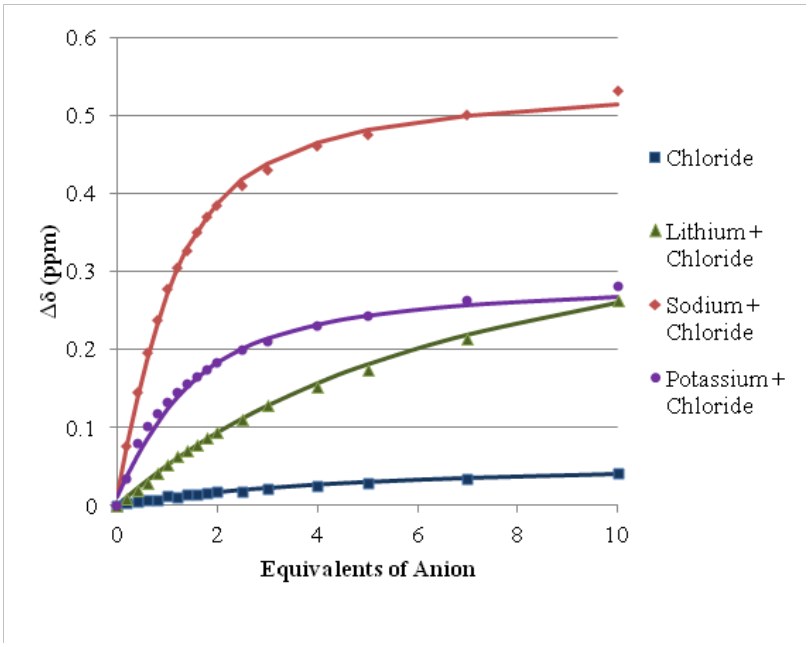


Figure S4.3: Changes in the internal axle proton *a* of [2]rotaxane **5** upon increasing amounts of anion in the absence and in the presence of a metal cation ($CDCl_3/CD_3OD$ 4:1, 298 K); points represent data points, continuous lines represent calculated curves)

S5: X-ray Crystallography

Single crystals of calixdiquinone macrocycle **1** were grown by vapour diffusion of diisopropyl ether into a solution of chloroform. Data were collected on using synchrotron radiation on Beam I19 at Diamond Light Source ($\lambda = 0.68890$ Å). The diffractometer was equipped with a Cryostream N_2 open-flow cooling device,[6] and the data were collected at 100 K. Series of ω-scans were performed in such a way as to collect a half-sphere of data to a maximum resolution of 0.77 Å. Cell parameters and intensity data (including inter-frame scaling) were processed using CrysAlis Pro.[7] The structure was solved by charge-flipping using SUPERFLIP,[8] the output of which was a structure in the spacegroup P -1. Refinement was conducted using full-matrix least-squares on F^2 within the CRYSTALS suite.[9] Non – hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms were generally visible in the difference map and their positions and displacement parameters were refined using restraints prior to inclusion into the model using ride constraints.[10]

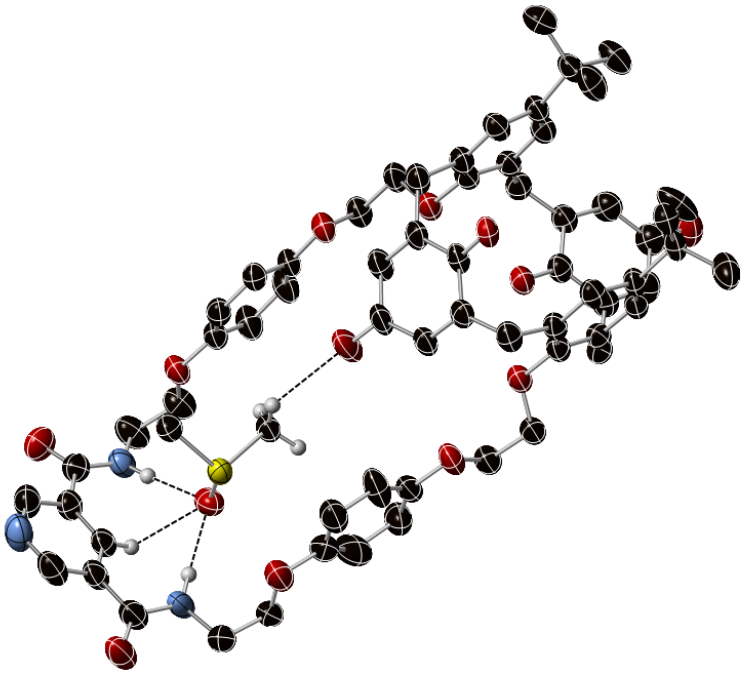


Figure S5.1: Single crystal X-ray structure of macrocycle **1** (Non hydrogen bonding hydrogens have been omitted for clarity, ellipsoids plotted at 50 % probability)

Crystallographic data for the structure has been deposited with the Cambridge Crystallographic Data Centre, CCDC: 970552. Copies of these data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

S6: References

1. M. D. Lankshear, N. H. Evans, S. R. Bayly and P. D. Beer, *Chemistry – A European Journal*, 2007, 13, 3861-3870.
2. J. M. Mercurio, F. Tyrrell, J. Cookson and P. D. Beer, *Chem. Commun.*, 2013.
3. F. Zapata, O. A. Blackburn, M. J. Langton, S. Faulkner and P. D. Beer, *Chem. Commun.*, 2013, 49, 8157-8159.
4. A. V. Leontiev, C. A. Jemmett and P. D. Beer, *Chemistry – A European Journal*, 2011, 17, 816-825.
5. M. J. Hynes, J. Chem. Soc., Dalton Trans., 1993, 311-312.
6. Cosier, J.; Glazer, A. M. J. Appl. Cryst. 1986, 19, 105-107.
7. Agilent Technologies, CrysAlisPro, 2011.
8. L. Palatinus, G. Chapuis, J. Appl. Cryst. 1997, 40, 786-790.
9. P. W. Betteridge, J. R. Carruthers, R. I. Cooper, K. Prout, D. J. Watkin, J. Appl. Cryst. 2003, 1487.
10. R.I. Cooper, A.L. Thompson, D.J. Watkin, J. Appl. Crystal., 2010, 43, 1017-1022.