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A Bistable Pretzelane

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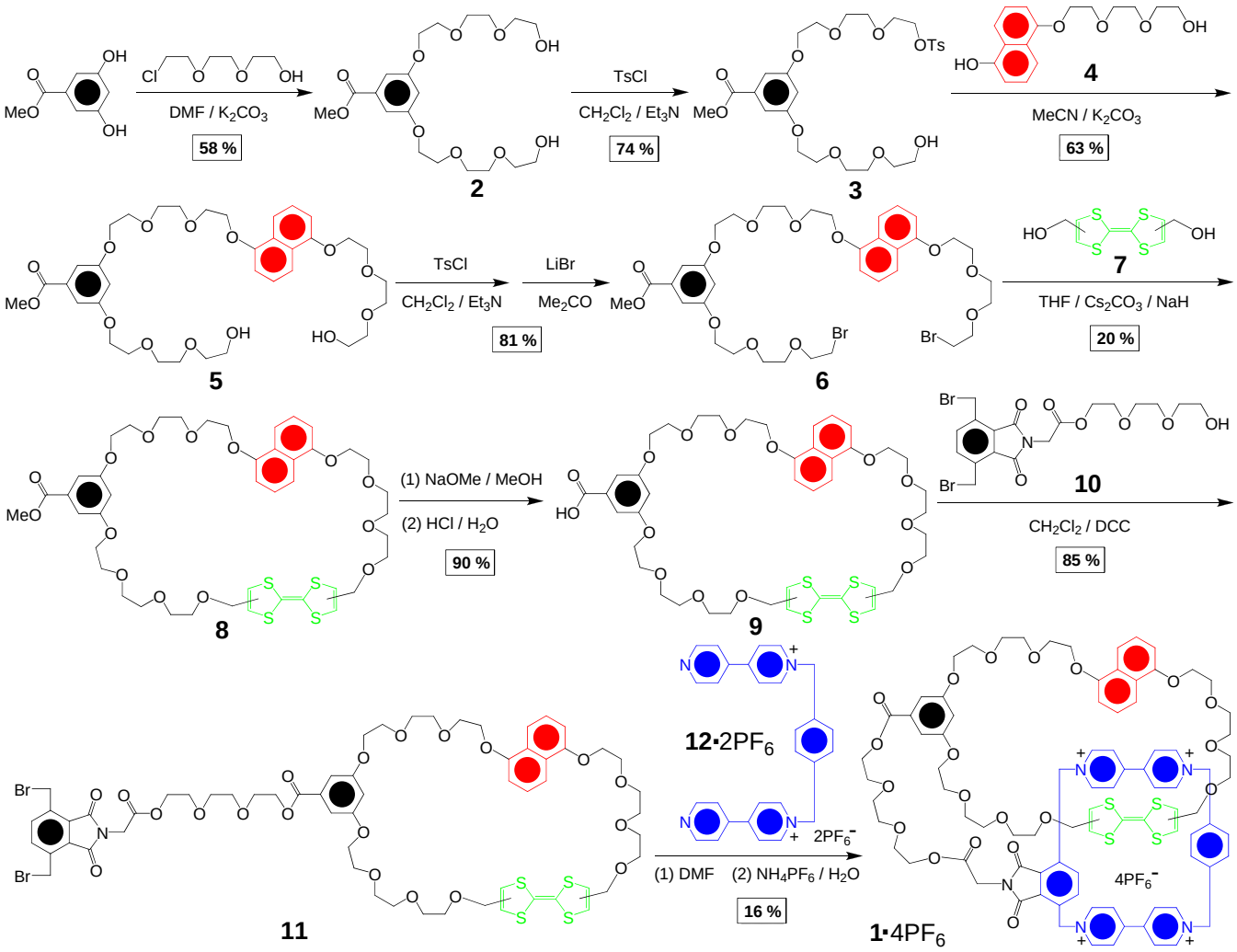
General. All reagents were purchased from Aldrich and were used without further purification. The starting materials **12**•2PF_6 salt[S1] and **13**[S2] were prepared according to literature procedures. Deuterated solvents (Cambridge Isotope Laboratories) for nuclear magnetic resonance (NMR) spectroscopic analyses were used as received. NMR Spectra were recorded on a Bruker Avance 500 or 600 spectrometer at 25 °C. Chemical shifts were reported in parts per million (ppm) downfield from the Me_4Si resonance which was used as the internal standard when recording ^1H NMR spectra. Electrospray ionization (ESI) mass spectra were measured on an IonSpec FT-ICR mass spectrometer. High-resolution matrix-assisted laser desorption/ionization spectra (HR-MALDI) were measured on an AppliedBiosystems DE-STR MALDI time-of-flight mass spectrometer. The reported molecular mass (*m*/z) values were the most abundant monoisotopic mass. UV-Vis spectra were recorded at room temperature on a Varian 100 Bio instrument. Electrochemical experiments were carried out at 298 K in Ar-purged MeCN, with a Gamry multipurpose instrument (reference 600) interfaced to a PC. Cyclic voltammetry experiments were performed using a glassy carbon working electrode (0.018 cm^2, Cypress Systems). Its surface was polished routinely with 0.05 μm alumina-water slurry on a felt surface immediately before use. The counter electrode was a Pt coil and the reference electrode was an Ag/AgCl electrode. The concentration of the sample and supporting electrolyte tetrabutylammonium hexafluorophosphate (**TBA**•PF_6) were 1.0×10^{-3} mol L^{-1} and 0.1 mol L^{-1}, respectively. In the differential pulse voltammetry (DPV) experiments, the pulse height, pulse width, step height, and step time were set to 50 mV, 50 ms, 5 mV, and 500 ms, respectively. Spectroelectrochemical experiments were made in a custom-built optically-transparent thin layer electrochemical (OTTLE) cell with an optical path of 2 mm, using a Pt grid as working electrode, a Pt wire as counter electrode, and an Ag wire pseudo-reference electrode. Experimental errors: potential values, +/– 10 mV; absorption maxima, +/– 2 nm.

Synthesis. See **Scheme S1** for the details.



Scheme S1 Template-directed synthesis of the bistable pretzelane **1**•$4PF_6$.

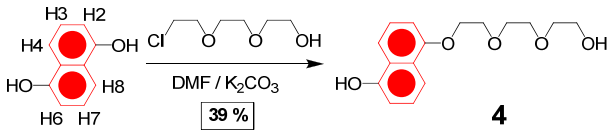
2: A mixture of methyl 3,5-dihydroxybenzoate (3.00 g, 17.8 mmol), 2-[2-(2-chloroethoxy) ethoxy]ethanol (6.62 g, 39.3 mmol), and K_2CO_3 (9.84 g, 71.2 mmol) in dry DMF (200 mL) was stirred for 3 d at 80 °C under an atmosphere of Ar. After the solvent had been removed under reduced pressure, the residue was triturated with CH_2Cl_2 and the precipitated salts were removed by filtration. The filtrate was concentrated under reduced pressure to yield a crude product, which was subjected to column chromatography (SiO_2, EtOAc : MeOH = 97:3) to give compound **2** (4.48 g, 58 %) as an oil. ^{1}H NMR (500 MHz, CD_2Cl_2, ppm): δ 3.61–3.72 (m, 16H, OCH_2CH_2O), 3.87–3.90 (m, 7H, OCH_2CH_2O and

CO_2CH_3), 4.17–4.19 (m, 4H, OCH_2CH_2O), 6.80 (s, 1H, Ar-H), 7.21 (s, 2H, Ar-H). ^{13}C NMR (125 MHz, CD_2Cl_2, ppm): δ 52.1, 62.4, 70.3, 70.8, 105.5, 106.1, 131.8, 144.7, 166.6.

3: A solution of TsCl (1.50 g, 7.90 mmol) in CH_2Cl_2 (30 mL) was added dropwise to a solution of **2** (4.00 g, 9.25 mmol), Et_3N (3 mL, 21.5 mmol), and DMAP (10.0 mg, 0.08 mmol) in CH_2Cl_2 (150 mL) at 0 °C under an atmosphere of Ar. The mixture was warmed up to room temperature over the course of stirring for 16 h. After the precipitated salts were filtered off and the solvent had been evaporated under reduced pressure, the residue was purified by column chromatography (SiO_2, EtOAc : MeOH = 99:1) to give compound **3** (3.43 g, 74 %) as an oil. ^{1}H NMR (500 MHz, CD_2Cl_2, ppm): δ 2.43 (s, 3H, OTs-CH_3), 3.56–3.68 (m, 14H, OCH_2CH_2O), 3.82–3.86 (m, 7H, OCH_2CH_2O and CO_2Me), 4.06–4.13 (m, 6H, OCH_2CH_2O), 6.69 (s, 1H, Ar-H), 7.17 (s, 2H, Ar-H), 7.35–7.38 (d, *J* = 7.5 Hz, 2H, OTs-H), 7.76–7.78 (d, *J* = 8.2 Hz, 2H, OTs-H). ^{13}C NMR (125 MHz, CD_2Cl_2, ppm): δ 22.1, 52.5, 62.6, 68.4, 70.2, 70.9, 105.6, 106.3, 128.8, 130.9, 131.7, 141.3, 144.7, 166.3.

4: See **Scheme S2**. A solution of 2-[2-(2-chloroethoxy)ethoxy]ethanol (4.89 g, 29.0 mmol) in DMF (50 mL) was added dropwise to a solution of 1,5-dihydroxynaphthalene (4.80 g, 30.0 mmol) and K_2CO_3 (8.29 mg, 60.0 mmol) in DMF (200 mL) at 80 °C under an atmosphere of Ar. The reaction mixture was maintained under these conditions for 3d, before the solvent was removed under reduced pressure. The residue was triturated with EtOAc and the precipitated salts were removed by filtration. The filtrate was concentrated under reduced pressure to yield a crude product, which was subjected to column chromatography (SiO_2, EtOAc) to afford compound **4** (3.31 g, 39 %). ^{1}H NMR (500 MHz, CD_2Cl_2, ppm): δ 3.62–3.63 (d, 2H, OCH_2CH_2O), 3.72–3.74 (m, 4H, OCH_2CH_2O), 3.81–3.82 (m, 2H, OCH_2CH_2O), 4.01–4.02 (d, 2H, OCH_2CH_2O), 4.31–4.32 (d, 2H, OCH_2CH_2O), 6.86–6.88 (d, *J* = 7.4 Hz, 1H, Ar-H), 6.91–6.92 (d, *J* = 7.2 Hz, 1H, Ar-H), 7.28–7.31 (t, *J* = 7.8 Hz, 1H, Ar-H), 7.36–7.39 (t,

J = 8.0 Hz, 1H, Ar-H), 7.79–7.82 (t, *J* = 9.7 Hz, 2H, Ar-H). ^{13}C NMR (125 MHz, CD_2Cl_2, ppm): δ 61.5, 69.9, 70.5, 71.1, 108.1, 111.8, 115.7, 116.6, 125.7, 126.9, 127.4, 128.6, 153.5, 154.2.



Scheme S2 Synthesis of **4**. The protons of the DNP unit are defined alongside the structural formula.

5: A mixture of **3** (1.77 g, 3.02 mmol), **4** (0.88 g, 3.02 mmol), K_2CO_3 (0.83 g, 6.04 mmol), LiBr (20.0 mg, 0.23 mmol), and [18]crown-6 (20.0 mg, 0.08 mmol) in anhydrous MeCN (100 mL) was heated under reflux for 16 h. After cooling down to room temperature, the reaction mixture was filtered and the solid was washed with Me_2CO. The combined organic solution was concentrated and the residue was purified by column chromatography (SiO_2, EtOAc : MeOH = 96:4) to give compound **5** (1.34 g, 63 %) as a brown oil. ^{1}H NMR (500 MHz, CD_2Cl_2, ppm): δ 3.60–3.61 (d, 4H, OCH_2CH_2O), 3.69–3.70 (d, 8H, OCH_2CH_2O), 3.80–3.90 (m, 11H, OCH_2CH_2O and CO_2CH_3), 4.00 (s, 4H, OCH_2CH_2O), 4.11–4.15 (m, 8H, OCH_2CH_2O), 4.31 (s, 4H, OCH_2CH_2O), 6.73 (s, 1H, Ar-H), 6.90 (s, 2H, Ar-H), 7.21 (s, 2H, Ar-H), 7.37–7.42 (m, 2H, Ar-H), 7.87–7.88 (d, *J* = 2.7 Hz, 2H, Ar-H). ^{13}C NMR (125 MHz, CD_2Cl_2, ppm): δ 52.8, 60.1, 61.5, 67.7, 67.8, 69.3, 69.6, 70.1, 70.8, 72.3, 105.5, 106.3, 107.7, 114.2, 125.0, 126.5, 132.0, 154.2, 159.7, 166.8. MS (HR-MALDI): Calcd for $C_{36}H_{51}O_{14}$ $[M + H]^+$ *m*/*z* = 707.328, found *m*/*z* = 707.319.

6: A solution of TsCl (0.84 g, 4.40 mmol) in CH_2Cl_2 (20 mL) was added dropwise to a solution of **5** (1.40 g, 1.98 mmol), Et_3N (1 mL, 7.17 mmol), and DMAP (10.0 mg, 0.08 mmol) in CH_2Cl_2 (50 mL) at 0 °C under an atmosphere of Ar. The reaction mixture was warmed up to room temperature over the course of stirring for 16 h. After the precipitated salts were filtered and the solvent had been evaporated under reduced pressure, the residue was purified by column chromatography (SiO_2, EtOAc : Hexane =

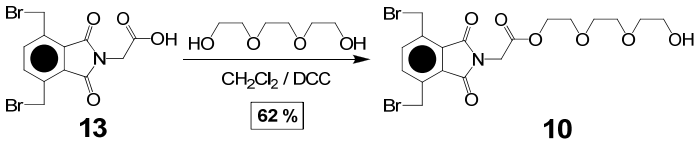
70:30) to give a tosylate. ^{1}H NMR (500 MHz, CD_2Cl_2, ppm): δ 2.44 (s, 6H, OTs-CH_3), 3.63–3.89 (m, 23H, OCH_2CH_2O and CO_2CH_3), 3.96–4.02 (m, 4H, OCH_2CH_2O), 4.13–4.17 (m, 8H, OCH_2CH_2O), 4.29–4.32 (m, 4H, OCH_2CH_2O), 6.72 (s, 1H, Ar-H), 6.90–6.91 (d, J = 5.2 Hz, 2H, Ar-H), 7.20 (s, 2H, Ar-H), 7.36–7.39 (m, 6H, Ar-H and OTs-H), 7.79–7.89 (m, 6H, Ar-H and OTs-H).

The tosylate and LiBr (1.94 g, 20.0 mmol) were dissolved in dry Me_2CO (50 mL) and the reaction mixture was heated under reflux for 30 h. After cooling down to room temperature, the solution was filtered and the residue washed with Me_2CO. The combined organic solution was concentrated and the residue was purified by column chromatography (SiO_2, EtOAc) to give compound **6** (1.34 g, 81 %) as a brown oil. ^{1}H NMR (500 MHz, CD_2Cl_2, ppm): δ 3.58–3.60 (m, 4H, OCH_2CH_2O), 3.72–3.91 (m, 19H, OCH_2CH_2O and CO_2CH_3), 4.00–4.32 (m, 16H, OCH_2CH_2O), 6.73 (s, 1H, Ar-H), 6.90 (s, 2H, Ar-H), 7.21 (s, 2H, Ar-H), 7.37–7.39 (d, J = 7.2 Hz, 2H, Ar-H), 7.87 (s, 2H, Ar-H). ^{13}C NMR (125 MHz, CD_2Cl_2, ppm): δ 31.4, 52.2, 69.7, 70.4, 71.1, 105.2, 105.8, 107.7, 115.3, 125.4, 127.9, 132.1, 144.8, 154.3, 166.3. MS (HR-MALDI): Calcd for $C_{36}H_{49}Br_2O_{12}$ $[M + H]^+$ m/z = 831.159, found m/z = 831.151.

8: The TTF diol **7** (0.26 g, 1.00 mmol) and **6** (0.83 g, 1.00 mmol) in dry THF (200 mL) were added dropwise to a solution of NaH (0.10 g) and Cs_2CO_3 (0.70 g) in dry THF (100 mL) under an atmosphere of Ar. The reaction mixture was heated under reflux for 2 days. After cooling down to room temperature, NaH was quenched by adding a solution of Me_2CO/H_2O (9:1, 1 mL) to the reaction mixture. The solid residue was removed by filtration. The solvent in the filtrate was removed under reduced pressure and the residue was purified by column chromatography (SiO_2, EtOAc) to give **8** (0.19 g, 20 %) as a yellow oil. ^{1}H NMR (500 MHz, CD_2Cl_2, ppm): δ 3.65–3.90 (m, 23H, OCH_2CH_2O and CO_2CH_3), 4.00–4.32 (m, 20H, OCH_2CH_2O and TTF-CH_2), 6.27–6.29 (m, 2H, TTF-H), 6.74 (s, 1H, Ar-H), 6.90–6.91 (d, J = 7.2 Hz, 2H, Ar-H), 7.22 (s, 2H, Ar-H), 7.37–7.39 (d, J = 7.2 Hz, 2H, Ar-H), 7.87–7.89 (d, J = 7.2 Hz, 2H, Ar-H). ^{13}C NMR (125 MHz, CD_2Cl_2, ppm): δ 52.1, 69.8, 70.5, 70.9, 71.2,

73.3, 79.2, 105.0, 105.8, 107.9, 115.5, 118.1, 125.4, 128.6, 130.2, 131.9, 139.4, 144.9, 154.1, 166.2. MS (HR-MALDI): Calcd for $C_{44}H_{55}O_{14}S_4$ $[M + H]^+$ m/z = 935.248, found m/z = 935.235.

9: Crown ether **8** (0.19 g, 0.20 mmol) was dissolved in MeOH (20 mL), then MeONa (0.05 g, 1.00 mmol) was added and the resulting solution was heated under reflux and an atmosphere of Ar for 8 h. The solution was cooled down to room temperature and then poured into H_2O (40 mL) and acidified with diluted HCl (0.1 M). The solution was extracted with CH_2Cl_2 (5 × 40 mL). The organic layers were combined, dried ($MgSO_4$), filtered, and evaporated to give the compound **9** (0.17 g, 90 %). ^{1}H NMR (500 MHz, CD_3CN, ppm): δ 3.63–3.89 (m, 20H, OCH_2CH_2O), 3.99–4.32 (m, 20H, OCH_2CH_2O and TTF-CH_2), 6.25–6.27 (m, 2H, TTF-H), 6.72 (s, 1H, Ar-H), 6.90–6.92 (d, J = 7.4 Hz, 2H, Ar-H), 7.34 (s, 2H, Ar-H), 7.36–7.38 (d, J = 7.4 Hz, 2H, Ar-H), 7.85–7.87 (d, J = 7.4 Hz, 2H, Ar-H), 11.13 (s, 1H, CO_2H). ^{13}C NMR (125 MHz, CD_3CN, ppm): δ 70.7, 71.1, 71.4, 73.6, 79.0, 106.1, 106.6, 108.2, 115.7, 118.0, 125.3, 128.5, 130.4, 131.6, 139.3, 144.8, 153.9, 169.7. MS (HR-MALDI): Calcd for $C_{43}H_{52}O_{14}S_4$ [M] m/z = 920.224, found m/z = 920.217.



Scheme S3 Synthesis of **10**.

10: See **Scheme S3**. A solution of **13** (1.95 g, 5.00 mmol) in CH_2Cl_2 (30 mL) was added dropwise to a solution of triethylene glycol (1.05 g, 7.00 mmol), DCC (1.24 g, 6.00 mmol), and DMAP (15.0 mg) in CH_2Cl_2 (70 mL) at room temperature under an atmosphere of Ar. After the mixture had been stirred for 6 h, the resulting suspension was filtered, the filtrate was evaporated, and the residue was subjected to column chromatography (SiO_2, EtOAc : MeOH = 99:1) to give compound **10** (1.62 g, 62 %) as an oil. ^{1}H NMR (500 MHz, CD_2Cl_2, ppm): δ 3.56–3.58 (m, 2H, OCH_2CH_2O), 3.65–3.68 (m, 8H, OCH_2CH_2O),

4.16–4.18 (m, 2H, OCH_2CH_2O), 4.43 (s, 2H, NCH_2), 5.01 (s, 4H, CH_2Br), 7.88 (s, 2H, Ar-H). ^{13}C NMR (125 MHz, CD_2Cl_2, ppm): δ 28.9, 44.1, 61.8, 67.3, 70.2, 70.6, 133.0, 137.4, 147.8, 166.9, 167.7.

11: A mixture of **9** (0.18 g, 0.20 mmol), **10** (0.10 g, 0.20 mmol), DCC (0.05 g, 0.25 mmol), and DMAP (5.00 mg) in CH_2Cl_2 (30 mL) was stirred at room temperature under an atmosphere of Ar for 6 h. The solution was then evaporated under reduced pressure, and the residue was subjected to column chromatography (SiO_2, EtOAc : Hexane = 90:10) to give compound **11** (0.24 g, 85 %). ^1H NMR (500 MHz, CD_2Cl_2, ppm): δ 3.65–3.92 (m, 28H, OCH_2CH_2O), 4.01–4.33 (m, 24H, OCH_2CH_2O and TTF-CH_2), 4.44 (s, 2H, NCH_2CO_2), 4.99 (s, 4H, CH_2Br), 6.27–6.29 (m, 2H, TTF-H), 6.73 (s, 1H, Ar-H), 6.90–6.92 (d, J = 7.2 Hz, 2H, Ar-H), 7.22 (s, 2H, Ar-H), 7.37–7.39 (d, J = 7.2 Hz, 2H, Ar-H), 7.88–7.90 (m, 4H, Ar-H). ^{13}C NMR (125 MHz, CD_2Cl_2, ppm): δ 31.4, 44.2, 65.8, 70.7, 71.3, 73.5, 78.9, 105.5, 106.2, 108.3, 115.8, 118.2, 125.6, 128.4, 130.3, 133.3, 137.5, 139.0, 144.8, 148.2, 153.9, 165.8, 167.6. MS (HR-MALDI): Calcd for $C_{61}H_{72}O_{20}S_4Br_2N$ $[M + H]^+$ m/z = 1424.190, found m/z = 1424.173.

1•$4PF_6$: A mixture solution of **11** (0.14 g, 0.10 mmol) and dicationic salt **12**•$2PF_6$ (0.11 g, 0.15 mmol) in DMF (10 mL) was stirred at room temperature for 5 days. Et_2O (100 mL) was added to the mixture solution to precipitate the crude product. The precipitate was isolated by filtration and then subjected to column chromatography (SiO_2, MeOH : aqueous NH_4Cl (2 M) : $MeNO_2$ = 7:2:1). Green fractions containing the product were combined and concentrated under reduced pressure. Solid NH_4PF_6 was then added to the concentrated solution to precipitate **1**·$4PF_6$ (0.04 g, 16 %) as a dark green solid. ^1H NMR (500 MHz, CD_3CN, ppm): δ 3.70–4.34 (m, 52H, OCH_2CH_2O and TTF-CH_2), 4.46 (s, 2H, NCH_2CO_2), 5.43–5.63 (m, 8H, **CBPQT**$^{4+}$-CH_2), 5.96–6.18 (m, 2H, TTF-H), 6.59 (s, 1H, Ar-H), 6.92–7.58 (m, 12H, Ar-H, DNP-H, and Xylylene-H in **CBPQT**$^{4+}$), 7.94–8.22 (m, 10H, DNP-H and Pyridium-H_β in **CBPQT**$^{4+}$), 8.79–8.98 (m, 8H, Pyridium-H_α in **CBPQT**$^{4+}$). MS (ESI): Calcd for $C_{89}H_{95}F_{18}N_5O_{20}P_3S_4$

$[M - PF_6]^+$ m/z = 2116.4, found m/z = 2116.3; Calcd for $C_{89}H_{95}F_{12}N_5O_{20}P_2S_4$ $[M - 2PF_6]^{2+}$ m/z = 985.7, found m/z = 985.5.

Characterization. The switching behavior of the $CBPQT^{4+}$ ring in **1**•$4PF_6$ was investigated using cyclic voltammetry (CV), differential pulse voltammetry (DPV), UV-vis spectroelectrochemistry (SEC), and ^{1}H NMR spectroscopy. In the DPV analysis (Fig. S1), the first and second TTF oxidation peaks are found around +0.81 V, potentials which correspond to the first oxidation of the TTF unit encircled by the $CBPQT^{4+}$ ring and/or the second oxidation of the TTF unit once the ring has migrated from the TTF unit to the DNP unit. The cathodic scan of the DPV analysis reveals the related peaks at +0.45 and +0.78 V. Fig. S2 displays a fitted first-order decay profile for this relaxation process obtained from the CV data of **1**•$4PF_6$ in Ar-purged MeCN at 298K with scan rates in the range of 50–700 mV s^{-1}. The values for the decay time (τ_{298}), kinetic constant (k_{298}), and free energy of activation ($\Delta G^{\ddagger}_{298}$) are 0.65 ± 0.03 s, 1.52 ± 0.07 s^{-1}, and 17.0 ± 0.8 kcal mol^{-1}, respectively.

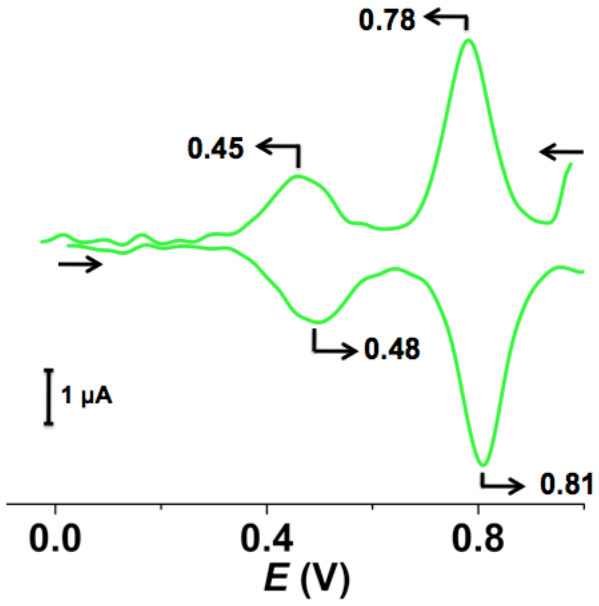


Fig. S1 DPV measurements for **1**•$4PF_6$. The data were recorded in Ar-purged MeCN at 298 K. The concentrations of the sample and supporting electrolyte were 1.0 mM and 0.1 M, respectively.

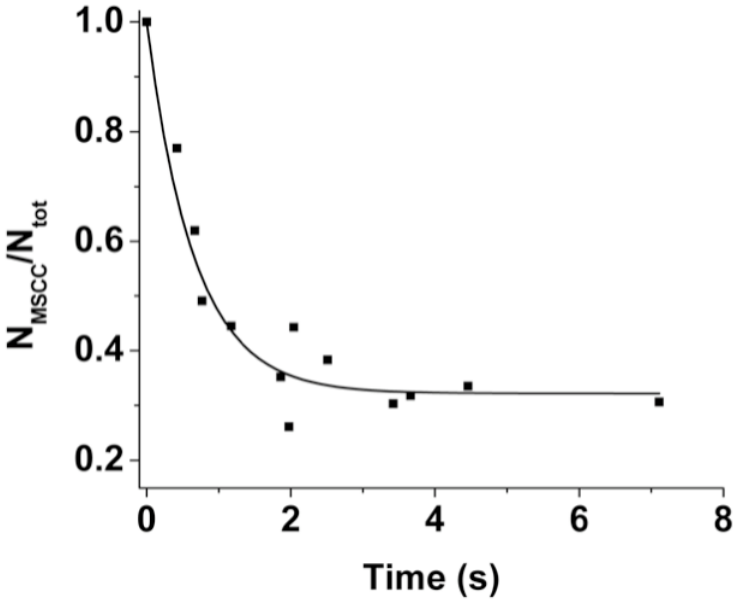


Fig. S2 The matching first order decay profile for the relaxation from the MSCC to the GSCC, and time constants obtained from the CV data measured for **1**•4PF_6 in Ar-purged MeCN at 298 K with different scan rates (50 – 700 mV s^{-1}). The concentrations of the sample and supporting electrolyte were 1.0 mM and 0.1 M, respectively.

References

S1 P.-L. Anelli, P. R. Ashton, R. Ballardini, V. Balzani, M. Delgado, M. T. Gandolfi, T. T. Goodnow, A. E. Kaifer, D. Philp, M. Pietraszkiewicz, L. Prodi, M. V. Reddington, A. M. Z. Slawin, N. Spencer, J. F. Stoddart, C. Vicent and D. J. Williams, *J. Am. Chem. Soc.*, 1992, **114**, 193–218.

S2 Y. Liu, A. H. Flood and J. F. Stoddart, *J. Am. Chem. Soc.*, 2004, **126**, 9150–9151.