# ChemComm

## Formation of ring-in-ring complexes between crown ethers and rigid TVBox<sup>8+</sup>

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## **1. General Methods**

All reagents were purchased from commercial suppliers (Aldrich or VWR) and used without further purification. Compound 3•Cl<sup>S1</sup> was prepared according to literature procedures. Thin layer chromatography (TLC) was performed on silica gel 60 F254 (E. Merck). Column chromatography was carried out on silica gel 60F (Merck 9385, 0.040-0.063 mm). Nuclear magnetic resonance (NMR) spectra were recorded on Agilent DD2 600 MHz or 500 MHz or Bruker Avance III 500 spectrometers, with working frequencies of 600 and 500 MHz for <sup>1</sup>H, and 150 and 125 MHz for <sup>13</sup>C nuclei, respectively. Chemical shifts are reported in ppm relative to the signals corresponding to the residual non-deuterated solvents (CD<sub>2</sub>HCN:  $\delta$  =1.94 ppm). Highresolution mass spectra were measured on a Finnigan LCQ iontrap mass spectrometer (HR-ESI). Cyclic voltammetry (CV) experiments were carried out at room temperature in argon-purged solutions in DMF with a Gamry Multipurpose instrument (Reference 600) interfaced to a PC. CV Experiments were performed using a glassy carbon working electrode (0.071 cm<sup>2</sup>). The electrode 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 Ag/AgCl electrode. The concentration of supporting electrolyte (tetrabutylammonium hexafluorophosphate) was 0.1 M. Single crystal X-ray data were collected on a Bruker Kappa Apex II CCD diffractometer using Cu-Ka radiation. Data collection and structure refinement details can be found in the CIF files. CCDC depositions 1021673-1021675 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data request/cif.

## 2. Synthetic Protocols



Scheme S1: Synthesis of 4•2PF<sub>6</sub>

**4·2PF**<sub>6</sub>: Compound **3·**Cl (1.3 g, 3.62 mmol) and 1,4-phenylenediamine (0.1 g, 0.93 mmol) were added to *abs* EtOH (10 mL) in a round-bottom flask. The reaction mixture was heated under reflux for 48 h, during which a brown precipitate was formed. After cooling down to room temperature, the precipitate was filtered and collected. Then, it was suspended in H<sub>2</sub>O (30 mL) and the insoluble solid was filtered off. NH<sub>4</sub>PF<sub>6</sub> was added to the filtrate until no more precipitate was formed. The precipitate was collected and washed with MeOH and Et<sub>2</sub>O, giving pure **4·**2PF<sub>6</sub> (320 mg, 44 %) as a yellow solid. <sup>1</sup>H NMR (500 MHz, CD<sub>3</sub>CN, 298 K):  $\delta_H = 9.10$  (d, J = 5 Hz, 4H), 8.92 (d, J = 5 Hz, 4H), 8.58 (d, J = 5 Hz, 4H), 8.11 (s, 4H), 7.94 (d, J = 5 Hz, 4H). <sup>13</sup>C NMR (125 MHz, CD<sub>3</sub>CN, 298 K):  $\delta_C = 156.8$ , 152.0, 146.1, 145.2, 142.0, 127.9, 127.2, 123.1. ESI-HRMS for **4·**2PF<sub>6</sub>; Calcd for C<sub>26</sub>H<sub>20</sub>F<sub>12</sub>N<sub>4</sub>P<sub>2</sub>: m/z = 533.1324 [ $M - PF_6$ ]<sup>+</sup>; found: 533.1334.



Scheme S2: Synthesis of DB-4PF<sub>6</sub>.

**DB-4PF**<sub>6</sub>: α,α'-Dibromo-*p*-xylene (1.95 mg, 7.39 mmol) was added to MeCN (50 mL) in a threenecked round-bottom flask. The solution of **4**•2PF<sub>6</sub> (1 g, 1.48 mmol) in MeCN (50 mL) was added to the above solution using a syringe pump over 20 h under reflux. After heating under reflux for additional 3 days, the reaction mixture was cooled to room temperature. The yellow precipitate was collected by filtration and re-dissolved in H<sub>2</sub>O, followed by the addition of excess of NH<sub>4</sub>PF<sub>6</sub>. The resulting precipitate was collected by filtration, washed with MeOH and Et<sub>2</sub>O and dried in air, giving pure **DB**•4PF<sub>6</sub> (0.9 g, 53 %) as an orange solid. <sup>1</sup>H NMR (500 MHz, CD<sub>3</sub>CN, 298 K):  $\delta_H$  = 9.23 (d, *J* = 5 Hz, 4H), 9.04 (d, *J* = 10 Hz, 4H), 8.63 (d, *J* = 10 Hz, 4H), 8.50 (d, *J* = 10 Hz, 4H), 8.15 (s, 4H), 7.58 (d, *J* = 10 Hz, 4H), 7.52 (d, *J* = 10 Hz, 4H), 5.86 (s, 4H), 4.62 (s, 4H). <sup>13</sup>C NMR (125 MHz, CD<sub>3</sub>CN, 298 K):  $\delta_C$ =152.6, 150.9, 146.8, 146.7, 145.4, 141.4, 133.7, 131.2, 130.8, 128.7, 128.5, 128.2, 65.3, 33.5. ESI-HRMS for **DB**•4PF<sub>6</sub>; Calcd for C<sub>42</sub>H<sub>36</sub>Br<sub>2</sub>F<sub>24</sub>N<sub>4</sub>P<sub>4</sub>: *m/z* = 1191.0206 [*M* – PF<sub>6</sub>]<sup>+</sup>; found: 1191.0210.



Scheme S3: Synthesis of TVBox•8PF<sub>6</sub>.

**TVBox-8PF**<sub>6</sub>: Compound **DB**•4PF<sub>6</sub> (500 mg, 0.37 mmol), **4**•2PF<sub>6</sub> (254 mg, 0.37 mmol) and tetrabutylammonium iodide (15 mg, 0.075 mmol) were added to MeCN (100 mL) in a round-bottom flask. After heating under reflux for 72 h, the reaction mixture was cooled to room temperature. The precipitate was collected and subjected to RP-HPLC. The pure fractions were collected and concentrated in vacuum. The residue was dissolved in H<sub>2</sub>O, followed by the addition of NH<sub>4</sub>PF<sub>6</sub>, to yield **TVBox**•8PF<sub>6</sub> (80 mg, 10 %) as a white solid. <sup>1</sup>H NMR (500 MHz, CD<sub>3</sub>CN, 298 K):  $\delta_H = 9.09$  (d, J = 5 Hz, 8H), 8.99 (d, J = 5 Hz, 8H), 8.48 (d, J = 10 Hz, 8H), 8.37 (d, J = 10 Hz, 8H), 8.01 (s, 8H), 7.68 (s, 8H), 5.86 (s, 8H). <sup>13</sup>C NMR (125 MHz, CD<sub>3</sub>CN, 298 K):  $\delta_C = 152.2$ , 150.2, 146.6, 146.5, 145.3, 136.4, 131.8, 128.6, 128.3, 128.0, 65.6. ESI-HRMS for **TVBox**•8PF<sub>6</sub>; Calcd for C<sub>58</sub>H<sub>56</sub>F<sub>48</sub>N<sub>8</sub>P<sub>8</sub>: m/z = 927.1234 [ $M - 2PF_6$ ]<sup>2+</sup>; found: 927.1253.

## 3. NMR Spectroscopic Studies

### 3.1 NMR Spectroscopic Characterisation

NMR spectroscopies were used to characterize  $4 \cdot 2PF_6$ , **DB**  $\cdot 4PF_6$  and **TVBox**  $\cdot 8PF_6$  in CD<sub>3</sub>CN at 298 K. The resonances, assignment and integration are labeled in the NMR spectra. In the case of **TVBox**  $\cdot 8PF_6$ , the assignment has been made based on  $^1H^{-1}H$  COSY and NOESY (Figure S4). The correlation peaks are labeled in the spectra.

9.11 9.11 8.93 8.93 8.92 8.57 8.57 8.57 7.94 7.93



**Figure S1**: <sup>1</sup>H (500 MHz, CD<sub>3</sub>CN, 298 K) and <sup>13</sup>C (125 MHz, CD<sub>3</sub>CN, 298 K) NMR spectra of **4**•2PF<sub>6</sub>.



Figure S2: <sup>1</sup>H (500 MHz, CD<sub>3</sub>CN, 298 K) and <sup>13</sup>C (125 MHz, CD<sub>3</sub>CN, 298 K) NMR spectra of DB•4PF<sub>6</sub>.



Figure S3: <sup>1</sup>H (500 MHz, CD<sub>3</sub>CN, 298 K) and <sup>13</sup>C (125 MHz, CD<sub>3</sub>CN, 298 K) NMR spectra of TVBox-8PF<sub>6</sub>.



Figure S4: <sup>1</sup>H-<sup>1</sup>H TOCSY and NOESY NMR spectra (500 MHz,  $CD_3CN$ , 298 K) of TVBox-8PF<sub>6</sub>.

## 3.2 Determination of Binding Constants between TVBox<sup>8+</sup> and Crown Ethers and Observation of Temperature Dependent Chemical Shift of Complexes.

In order to determine the binding ratios between **TVBox**<sup>8</sup> and crown ethers, Job plots were performed by carrying out the <sup>1</sup>H NMR investigations of **TVBox**<sup>8</sup> with varying amount of crown ethers in CD<sub>3</sub>CN (In the cases of **DN38C10** and **DN50C14**, 10% CDCl<sub>3</sub> was added to improve the solubility.). Ten samples were prepared with different proportions of **TVBox**•8PF<sub>6</sub> and crown ethers and a constant total concentration of 0.2 mM ([**TVBox**<sup>8</sup>] + [crown ethers] = 0.2 mM). NMR spectra were recorded for all the samples, showing the shift of signals of **TVBox**•8PF<sub>6</sub>. Job plots (Figure S5), which were obtained by plotting  $\Delta\delta\chi$  against  $\chi$ , where  $\chi =$ [**TVBox**<sup>8</sup>] / ([**TVBox**<sup>8</sup>] + [crown ethers]), indicating that crown ethers form 1:1 complexes with of **TVBox**•8PF<sub>6</sub>. <sup>1</sup>H NMR titrations were performed by adding small volumes of a concentrated guest solution in CDCl<sub>3</sub> to a solution of **TVBox**•8PF<sub>6</sub> in CD<sub>3</sub>CN. The shifts of the proton resonances for the host molecule were observed (Figure S6, S8, and S10) and used to determine the binding constants (*K*<sub>a</sub>). The *K*<sub>a</sub> values were calculated using a software program Dynafit<sup>\$2</sup> by employing a 1:1 binding model.

VT <sup>1</sup>H NMR Spectra (Figure S7, S9, and S11) were used to investigate the dynamics of complex formation. It was found that as the temperature decreases, signals corresponding to crown ethers are upfield shifted, illustrating that at lower temperatures, the 'ring-in-ring' complexes are more stable.



**Figure S5**: Job plot for complexes between **TVBox**<sup>8+</sup> and (A) **DB24C8**, (B) **DN38C10** and (C) **DN50C14**. ([**TVBox**<sup>8+</sup>] + [crown ether]) = 0.2 mM.





**Figure S6**: Partial <sup>1</sup>H NMR spectra (600 MHz, CD<sub>3</sub>CN, 298 K, [**TVBox**<sup>8+</sup>]<sub>0</sub> = 0.1 mM) of **TVBox**<sup>8+</sup> with varying amount of **DB24C8**. From a) – k), the amount of **DB24C8** is 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 equivalents per **TVBox**<sup>8+</sup>.





**Figure S7**: Partial <sup>1</sup>H NMR spectra (500 MHz, CD<sub>3</sub>CN, [**TVBox**<sup>8+</sup>] = 0.2 mM) of 1:1 mixture of **TVBox**<sup>8+</sup> and **DB24C8** at different temperatures.







**Figure S8**: Partial <sup>1</sup>H NMR spectra (600 MHz, CD<sub>3</sub>CN, 298 K, [**TVBox**<sup>8+</sup>]<sub>0</sub> = 0.1 mM) of **TVBox**<sup>8+</sup> with varying amount of **DN34C10**. From a) – k), the amount of **DN34C10** is 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 equivalents per **TVBox**<sup>8+</sup>. The cross denotes CHCl<sub>3</sub>.







**Figure S9**: Partial <sup>1</sup>H NMR spectra (500 MHz,  $CD_3CN$ , [**TVBox**<sup>8+</sup>] = 0.2 mM) of 1:1 mixture of **TVBox**<sup>8+</sup> and **DN34C10** at different temperatures. The cross denotes  $CHCl_3$ .







**Figure S10**: Partial <sup>1</sup>H NMR spectra (600 MHz, CD<sub>3</sub>CN, 298 K, [**TVBox**<sup>8+</sup>]<sub>0</sub> = 0.1 mM) of **TVBox**<sup>8+</sup> with varying amount of **DN50C14**. From a) – k), the amount of **DN50C14** is 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10 equivalents per **TVBox**<sup>8+</sup>. The cross denotes CHCl<sub>3</sub>.







**Figure S11**: Partial <sup>1</sup>H NMR spectra (500 MHz,  $CD_3CN$ , [**TVBox**<sup>8+</sup>] = 0.2 mM) of 1:1 mixture of **TVBox**<sup>8+</sup> and **DN50C14** at different temperatures. The cross denotes  $CHCl_3$ .

## 3.3 Geometry of the complex between TVBox<sup>8+</sup> and DN50C14

The geometry of the complex has been analysed by 2D NOESY spectroscopy. Cross peaks, which are observed (Figure S12) between the  $H_{\alpha}/H_{\delta}$  protons of **TVBox**<sup>8+</sup> and the DNP protons of **DN50C14**, indicate that both DNP rings are located close to the bipyridinium units at both ends of **TVBox**<sup>8+</sup>. In addition, cross peaks between protons on polyether loops and those on both the bipyridinium units and the central *p*-phenylene ring indicate that the polyether loops of **DN50C14** are folded along the long sides of **TVBox**<sup>8+</sup>, probably stabilised by [C–H…O] interactions, as noted previously in the literature.<sup>S5</sup>



**Figure S12**: <sup>1</sup>H-<sup>1</sup>H NOESY NMR Spectrum (500 MHz, CD<sub>3</sub>CN, 298 K) of the 1:1 complex between **TVBox**<sup>8+</sup> and **DN50C14**.

## 4. Crystallographic Characterisation

All crystallographic data are available free of charge from the Cambridge Crystallographic Data Centre (CCDC) via www.ccdc.cam.ac.uk/data\_request/cif.

## TVBox•8PF<sub>6</sub>

(a) Method: Single crystals of **TVBox**•8PF<sub>6</sub> were grown by slow vapour diffusion of *i*Pr<sub>2</sub>O to a solution of **TVBox**•8PF<sub>6</sub> in MeCN at room temperature. A suitable crystal was selected and mounted in inert oil and transferred to the cold gas stream of a Kappa Apex 2 diffractometer. The crystal was kept at 100 K during data collection. Using Olex2,<sup>S3</sup> the structure was solved with the XS<sup>S4</sup> structure solution program using Direct Methods and refined with the ShelXL<sup>S4</sup> refinement package using Least Squares minimization.

(b) Crystal data: monoclinic, space group *c*2/c (no. 15), a = 53.047(3), b = 13.8933(7), c = 23.3837(11) Å,  $\beta = 107.888(3)^{\circ}$ , V = 16400.7(14) Å<sup>3</sup>, Z = 4, T = 100.09 K,  $\mu$ (CuK $\alpha$ ) = 3.056 mm<sup>-1</sup>,  $D_{calc} = 1.754$  g/mm<sup>3</sup>, 71652 reflections measured (7.946  $\leq 2\Theta \leq 128.928$ ), 13549 unique ( $R_{int} = 0.0462$ ,  $R_{sigma} = 0.0377$ ) which were used in all calculations. The final  $R_1$  was 0.0656 ( $I > 2\sigma(I)$ ) and  $wR_2$  was 0.1964 (all data).

Distance restraints were imposed on the disordered  $PF_6^-$  anions and the disordered rings. Rigid bond restraints were imposed on the displacement parameters as well as restraints on similar amplitudes separated by less than 1.7 Ang. on the disordered fluorine and carbon atoms. CCDC number: 1021673.



**Figure S13**: Stick representation of the extended superstructures of **TVBox**<sup>8+</sup>. The central *p*-phenylene bridges are disordered. The  $PF_6^-$  counterions and solvent molecules were removed for the sake of clarity.

### PhCI\_TVBox•8PF<sub>6</sub>

(a) Method: Single crystals of **PhCl** $\subset$ **TVBox**•8PF<sub>6</sub> were grown by slow vapour diffusion of *i*Pr<sub>2</sub>O to a MeCN solution containing PhCl and **TVBox**•8PF<sub>6</sub> (molar ratio, 50:1) at room temperature. A suitable crystal was selected and mounted in inert oil and transferred to the cold gas stream of a Kappa Apex 2 diffractometer. The crystal was kept at 100 K during data collection. Using Olex2, the structure was solved with the XS structure solution program using Direct Methods and refined with the ShelXL refinement package using Least Squares minimization.

(b) Crystal data: monoclinic, space group  $p2_1/n$  (no. 14), a = 13.8603(4), b = 16.2006(5), c = 27.9776(8) Å,  $\beta = 102.9615(16)^\circ$ , V = 6122.2(3) Å<sup>3</sup>, Z = 2, T = 99.98 K,  $\mu$ (CuK $\alpha$ ) = 3.020 mm<sup>-1</sup>,  $D_{calc} = 1.586$  g/mm<sup>3</sup>, 35631 reflections measured ( $8.476 \le 2\Theta \le 130.114$ ), 10353 unique ( $R_{int} = 0.0236$ ,  $R_{sigma} = 0.0229$ ) which were used in all calculations. The final  $R_1$  was 0.0493 ( $I > 2\sigma(I)$ ) and  $wR_2$  was 0.1413 (all data).

Rigid bond restraints were imposed on the displacement parameters as well as restraints on similar amplitudes separated by less than 1.7 Ang. on the disordered fluorine atoms. CCDC number: 1021675.



**Figure S14**: Stick representation of the extended superstructures of **PhCI** $\subset$ **TVBox**<sup>8+</sup>. The PF<sub>6</sub><sup>-</sup> counterions and solvent molecules were removed for the sake of clarity.

## PhMe<sub>C</sub>TVBox•8PF<sub>6</sub>

(a) Method: Single crystals of **PhMe** $\subset$ **TVBox**•8PF<sub>6</sub> were grown by slow vapour diffusion of iPr<sub>2</sub>O to a MeCN solution containing PhMe and **TVBox**•8PF<sub>6</sub> (molar ratio, 50:1) at room temperature. A suitable crystal was selected and mounted in inert oil and transferred to the cold gas stream of a Kappa Apex 2 diffractometer. The crystal was kept at 100 K during data collection. Using Olex2, the structure was solved with the XM structure solution program using Direct Methods and refined with the ShelXL refinement package using Least Squares minimization.

(b) Crystal data: monoclinic, space group  $p2_1/c$  (no. 14), a = 13.978(8), b = 16.440(10), c = 27.093(19) Å,  $\beta = 102.00(3)^\circ$ , V = 6090(7) Å<sup>3</sup>, Z = 2, T = 99.99 K,  $\mu$ (CuK $\alpha$ ) = 2.182 mm<sup>-1</sup>,  $D_{calc} = 1.460$  g/mm<sup>3</sup>, 18959 reflections measured ( $6.326 \le 2\Theta \le 100.768$ ), 6343 unique ( $R_{int} = 0.1053$ ,  $R_{sigma} = 0.1094$ ) which were used in all calculations. The final  $R_1$  was 0.1931 ( $I > 2\sigma(I)$ ) and  $wR_2$  was 0.4898 (all data).

Rigid bond restraints were imposed on the displacement parameters as well as restraints on similar amplitudes separated by less than 1.7 Ang. were refined globally. Distance restraints were imposed on the disordered  $PF_6^-$ .

The solvent masking procedure as implemented in Olex2 was used to remove the electronic contribution of solvent molecules from the refinement. As the exact solvent content is not known, only the atoms used in the refinement model are reported in the formula here. Total solvent accessible volume / cell = 239.4 Å<sup>3</sup> [3.9%] Total electron count / cell = 41.0. CCDC number: 1021674.



**Figure S15**: Stick representation of the extended superstructures of  $PhMe_TVBox^{8+}$ . The  $PF_6^-$  counterions and solvent molecules were removed for the sake of clarity.

## 5. Reference

- S1 M. Freitag and E. Galoppini, *Langmuir*, 2010, **26**, 8262.
- S2 P. Kuzmič, Anal. Chem., 1996, 237, 260.
- S3 O. V. Dolomanov, L. J. Bourhis, R. J. Gildea, J. A. K. Howard, H. Puschmann, J. Appl. Crystallogr. 2009, 42, 339.
- S4 G. Sheldrick, *Acta Cryst.* 2008, A64, 112.
- S5 M. Juríček, J. C. Barnes, E. J. Dale, W.-G. Liu, N. L. Strutt, C. J. Bruns, N. A. Vermeulen, K. C. Ghooray, A. A. Sarjeant, C. L. Stern, Y. Y. Botros, W. A. Goddard and J. F. Stoddart, J. Am. Chem. Soc., 2013, 135, 12736.