

## Supplementary Information

### Dynamic behavior of macrocycle-based organic frameworks in single-crystal to single-crystal guest exchanges

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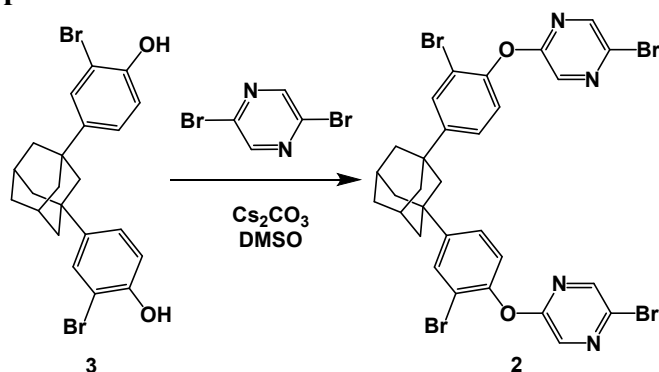
#### Table of Contents

• General Information	S2
• Synthesis of <b>1</b> and <b>2</b>	S3
• <sup>1</sup> H and <sup>13</sup> C NMR spectra of <b>1</b> and <b>2</b>	S5
• Calculated voids of crystals <b>1a–1e</b> (Fig. S1)	S7
• Single crystal X-ray diffraction experiment for crystal <b>1a</b> (Fig. S2)	S8
• Single crystal X-ray diffraction experiment for crystal <b>1b</b> (Fig. S3, 4)	S10
• Single crystal X-ray diffraction experiment for crystal <b>1c</b> (Fig. S5)	S12
• Single crystal X-ray diffraction experiment for crystal <b>1d</b> (Fig. S6, 7)	S14
• Single crystal X-ray diffraction experiment for crystal <b>1e</b> (Fig. S8, 9)	S16
• References	S18

## General Information

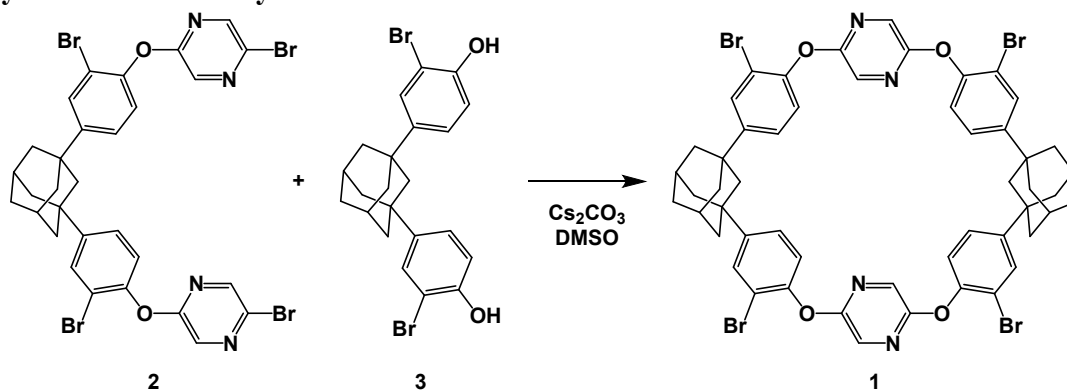
All solvents and reagents involved in this work were obtained from commercial suppliers including TCI Co., Ltd., Wako Pure Chemical Industries Ltd., Sigma-Aldrich Co., and Cambridge Isotope Laboratories, Inc. and were used without further purification. 1,3-Bis(3-bromo-4-hydroxyphenyl)adamantane (**3**) was synthesized according to the previous literature.<sup>1</sup> All air-sensitive reactions were carried out under an argon atmosphere. IR spectra were recorded on a Jasco FT/IR-6300. <sup>1</sup>H and <sup>13</sup>C NMR spectra were recorded on a Bruker AV400 spectrometer at room temperature in CDCl<sub>3</sub>. Chemical shifts are reported in ppm with tetramethylsilane as the reference standard. X-ray crystallographic data were collected using a Bruker D8 VENTURE diffractometer with CuK $\alpha$  radiation. Column chromatography was performed by using Wakogel C-200, and thin-layer chromatography was carried out on 2.0 mm Merck precoated silica gel glass plates. Gel permeation chromatography was performed using recycling preparative HPLC (LC-9204, Japan Analytical Industry Co., Ltd.) and a JAIGEL H series column (Japan Analytical Industry Co., Ltd.). HRMS measurements of **1** and **2** were conducted on Exactive (Thermo Fisher Scientific), which consists of an Orbitrap analyzer and an atmospheric pressure chemical ionization (APCI) source. The void volumes were calculated by using the Mercury software.

## Synthesis of compound 2



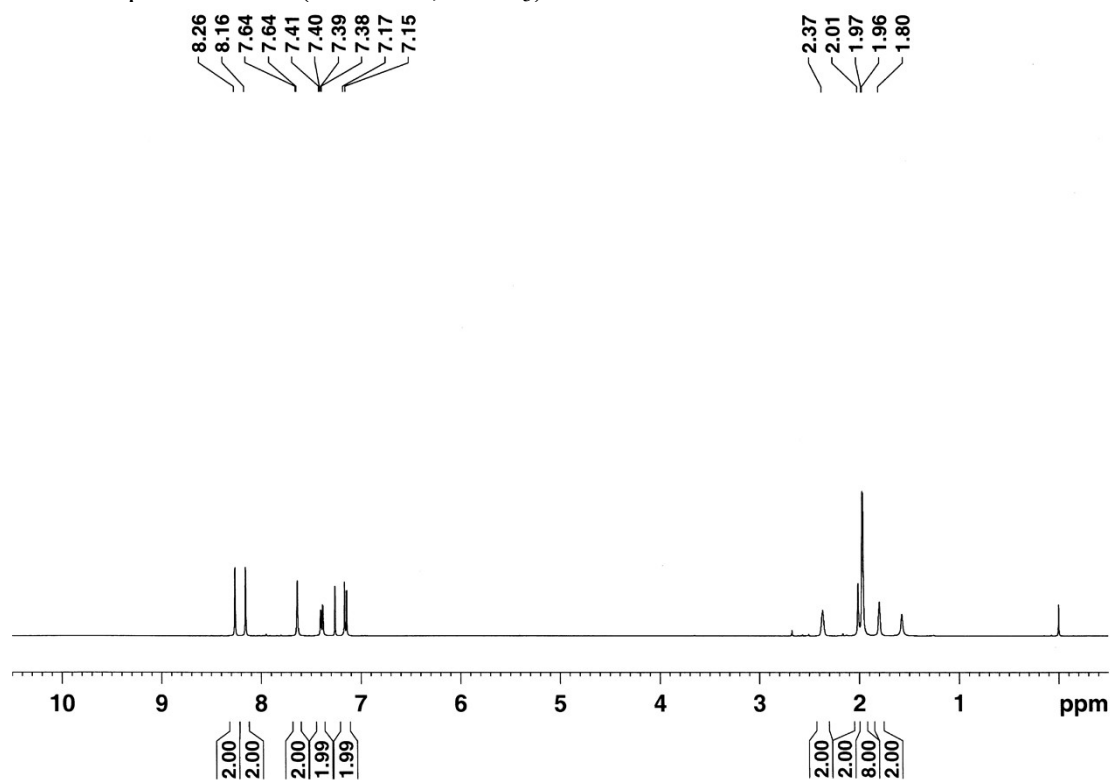
A mixture of 1,3-bis(3-bromo-4-hydroxyphenyl)adamantane (1.91 g, 4.00 mmol), 2,5-dibromopyrazine (2.85 g, 12.0 mmol), and cesium carbonate (3.91 g, 12.0 mmol) in dried dimethyl sulfoxide (50.0 mL) was stirred for 3 h at room temperature, and then for 16 h at 120 °C under an argon atmosphere. The reaction mixture was evaporated under reduced pressure. The residue was suspended in chloroform and washed with H<sub>2</sub>O, brine, dried over anhydrous sodium sulfate, and filtered. Evaporation of the solvent followed by silica gel column chromatography (eluent: CHCl<sub>3</sub>) and gel permeation chromatography (eluent: CHCl<sub>3</sub>) gave the title compound as a white solid (1.96 g, 2.47 mmol) in 62% yield. M.p. 129–130 °C. FT-IR (ATR, cm<sup>-1</sup>): 2910, 2847, 1558, 1486, 1444, 1329, 1270, 1164, 1106, 1012, 905, 831, 806. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ 8.26 (s, 2H), 8.16 (s, 2H), 7.64 (sd, *J* = 2.0 Hz, 2H), 7.39 (dd, *J* = 8.4, 2.0 Hz, 2H), 7.16 (d, *J* = 8.4 Hz, 2H), 2.37 (br s, 2H), 2.01 (br s, 2H), 1.97–1.96 (m, 8H), 1.80 (br s, 2H). <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>) δ 158.9, 149.9, 147.8, 143.5, 135.2, 132.3, 130.6, 125.5, 123.1, 116.1, 49.0, 42.0, 37.3, 35.5, 29.3. HRMS (APCI, *m/z*) Calcd for C<sub>30</sub>H<sub>25</sub>Br<sub>4</sub>N<sub>4</sub>O<sub>2</sub> [M + H]<sup>+</sup> 788.8706, found 788.8701.

### Synthesis of macrocycle 1

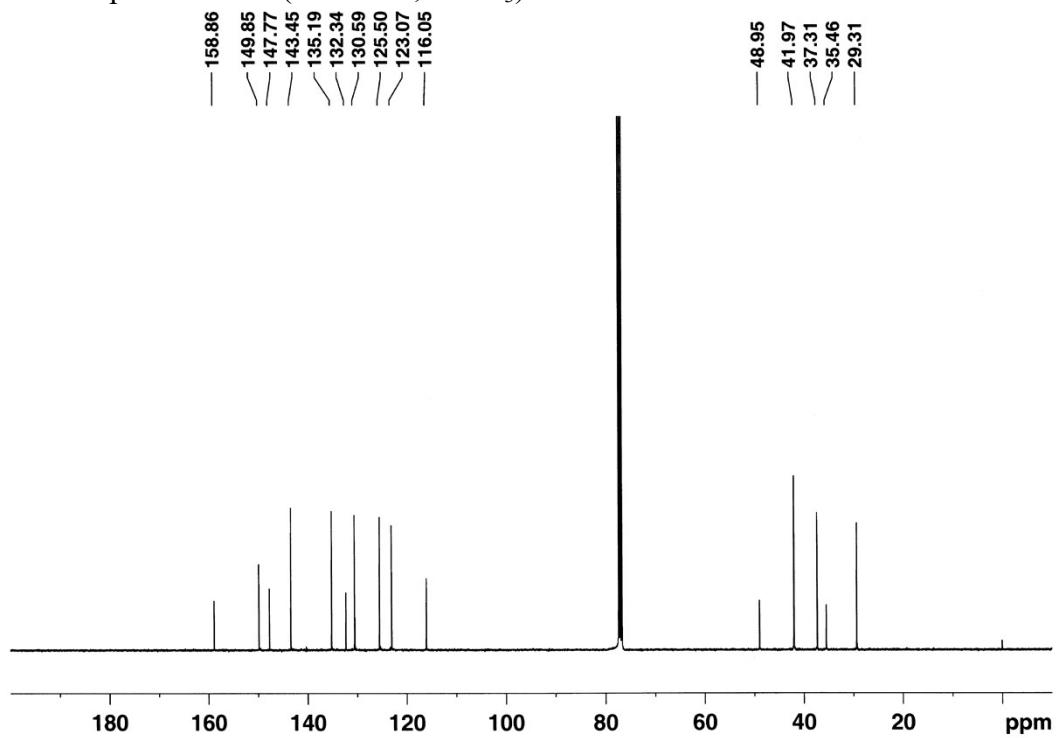


A mixture of **2** (158 mg, 0.20 mmol), **3** (95.6 mg, 0.20 mmol), and cesium carbonate (0.20 g, 0.60 mmol) in dried dimethyl sulfoxide (20.0 mL) was stirred for 3 h at room temperature, and then 16 h at 120 °C under an argon atmosphere. The reaction mixture was evaporated under reduced pressure. The residue was suspended in chloroform and washed with  $\text{H}_2\text{O}$ , brine, dried over anhydrous sodium sulfate, and filtered. Evaporation of the solvent followed by silica gel column chromatography (eluent:  $\text{CHCl}_3$ ) and gel permeation chromatography (eluent:  $\text{CHCl}_3$ ) gave the title compound as a white solid (28.0 mg, 0.025 mmol) in 25% yield. M.p. > 300 °C (decomposed). FT-IR (ATR,  $\text{cm}^{-1}$ ): 2909, 2848, 1558, 1487, 1444, 1330, 1270, 1164, 1106, 1012, 904, 831, 806.  $^1\text{H}$  NMR (400 MHz,  $\text{CDCl}_3$ )  $\delta$  7.66 (s, 4H), 7.56 (sd,  $J = 2.4$  Hz, 4H), 7.29 (dd,  $J = 8.8, 2.4$  Hz, 4H), 7.08 (d,  $J = 8.4$  Hz, 4H), 2.38 (br s, 4H), 2.07 (br d,  $J = 12.0$  Hz, 8H), 1.86 (br d,  $J = 11.6$  Hz, 8H), 1.74 (br s, 4H), 1.71 (br s, 4H).  $^{13}\text{C}$  NMR (100 MHz,  $\text{CDCl}_3$ )  $\delta$  156.0, 149.4, 148.6, 130.5, 129.3, 125.5, 122.8, 116.0, 51.9, 41.2, 37.2, 35.4, 29.2. HRMS (APCI,  $m/z$ ) Calcd for  $\text{C}_{52}\text{H}_{45}\text{Br}_4\text{N}_4\text{O}_4$  [ $\text{M} + \text{H}$ ] $^+$  1105.0169, found 1105.0180.

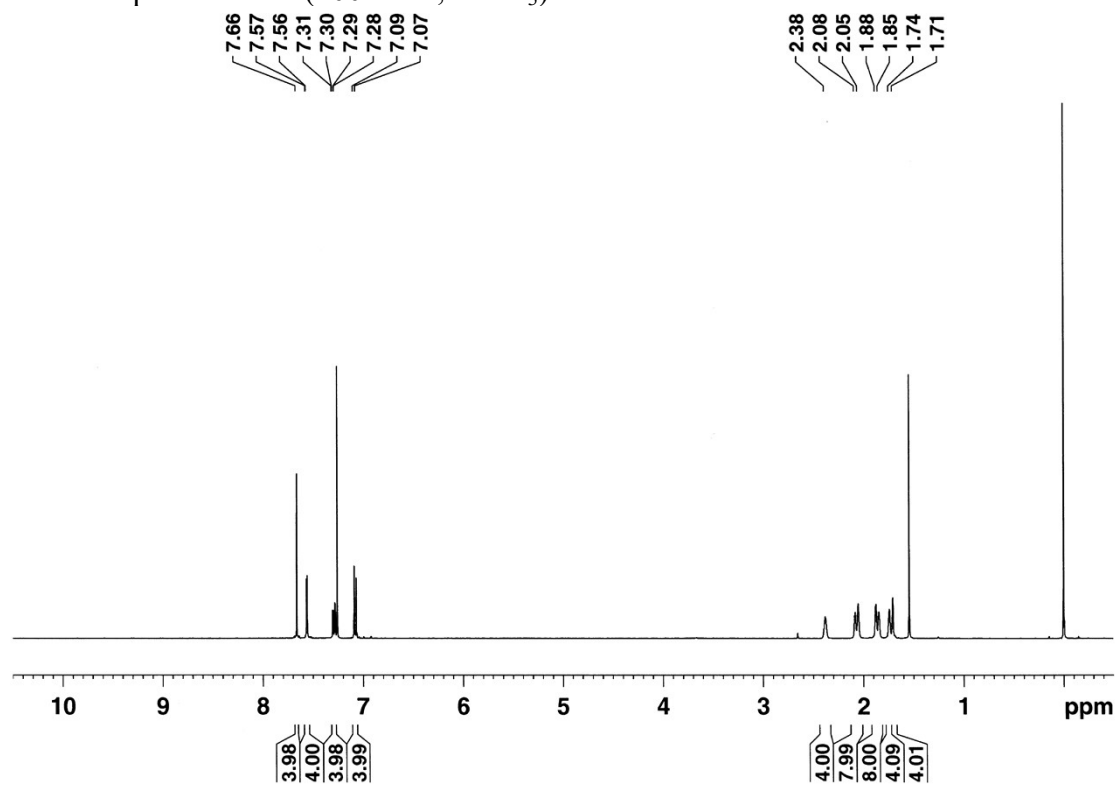
$^1\text{H}$  NMR spectrum of **2** (400 MHz,  $\text{CDCl}_3$ )



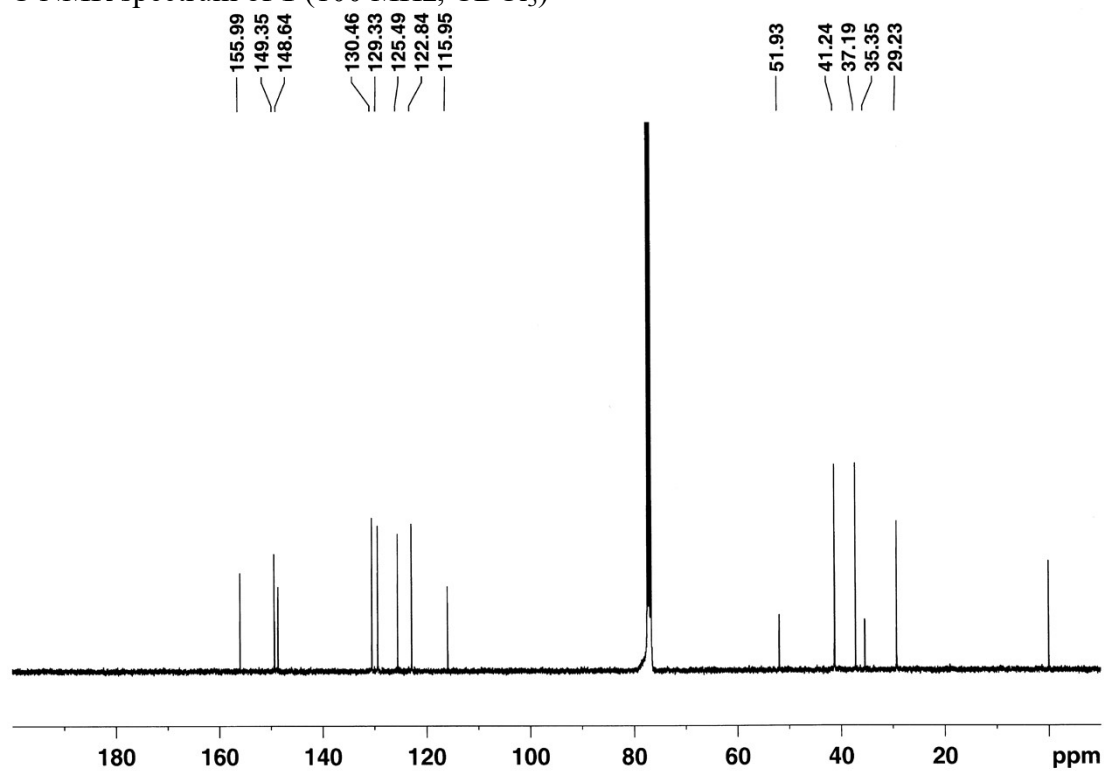
$^{13}\text{C}$  NMR spectrum of **2** (100 MHz,  $\text{CDCl}_3$ )

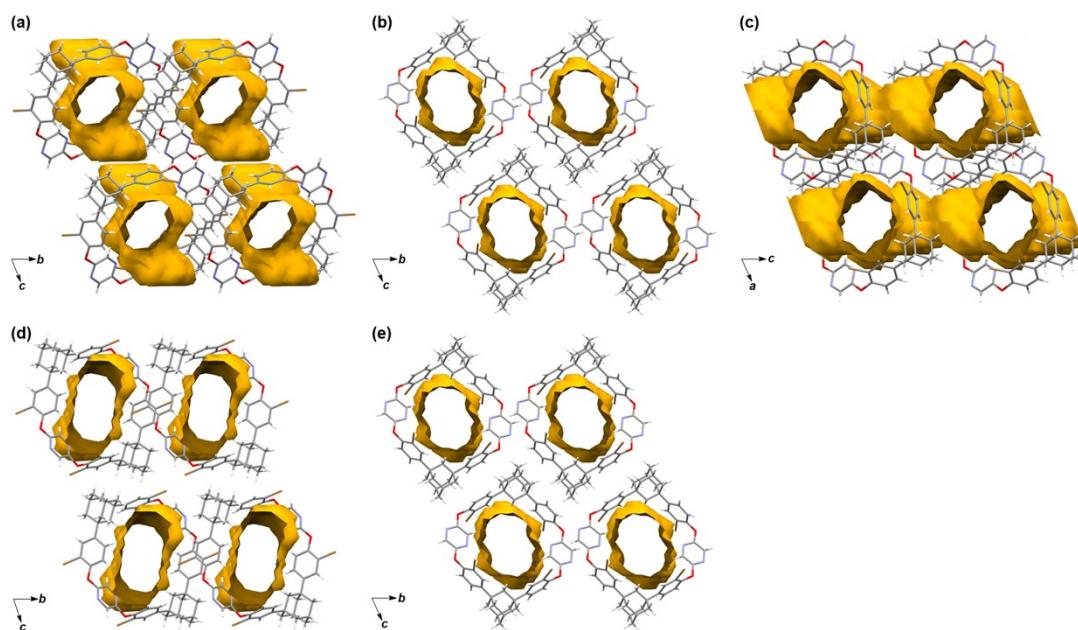


$^1\text{H}$  NMR spectrum of **1** (400 MHz,  $\text{CDCl}_3$ )



$^{13}\text{C}$  NMR spectrum of **1** (100 MHz,  $\text{CDCl}_3$ )





**Fig. S1** Calculated voids of crystals (a) **1a**, (b) **1b**, (c) **1c**, (d) **1d**, and (e) **1e** with top views.

### Single crystal X-ray diffraction experiment for crystal 1a

A colorless prismatic crystal ( $0.180 \times 0.150 \times 0.120 \text{ mm}^3$ ), obtained from acetone/dichloromethane, was immersed in Paraton-N oil and placed in the  $\text{N}_2$  cold stream at 100 K. Data were collected using diffractometer with CMOS detector (Bruker D8 VENTURE,  $\text{CuK}\alpha$ :  $\lambda = 1.54178 \text{ \AA}$ ). Absorption correction was performed by an empirical method implemented in SADABS.<sup>2</sup> Structure solution and refinement were performed by using SHELXT-2014/5<sup>3</sup> and SHELXL-2018/3<sup>4</sup>.

$\text{C}_{55}\text{H}_{50}\text{Br}_4\text{Cl}_6\text{N}_4\text{O}_4$ ,  $M_r = 1363.33$ ; triclinic, space group  $P-1$ ,  $Z = 1$ ,  $D_{\text{calc}} = 1.644 \text{ g}\cdot\text{cm}^{-3}$ ,  $a = 10.6218(8)$ ,  $b = 11.3383(8)$ ,  $c = 12.3181(9) \text{ \AA}$ ,  $\alpha = 68.588(2)$ ,  $\beta = 88.724(2)$ ,  $\gamma = 85.755(2)^\circ$ ,  $V = 1377.31(18) \text{ \AA}^3$ , 19021 measured and 5346 independent [ $I > 2\sigma(I)$ ] reflections, 374 parameters, final  $R_1 = 0.0517$ ,  $wR_2 = 0.2067$ ,  $S = 1.075$  [ $I > 2\sigma(I)$ ] and  $R_1 = 0.0522$ ,  $wR_2 = 0.2071$ ,  $S = 1.075$  [all data]. CCDC 2099489

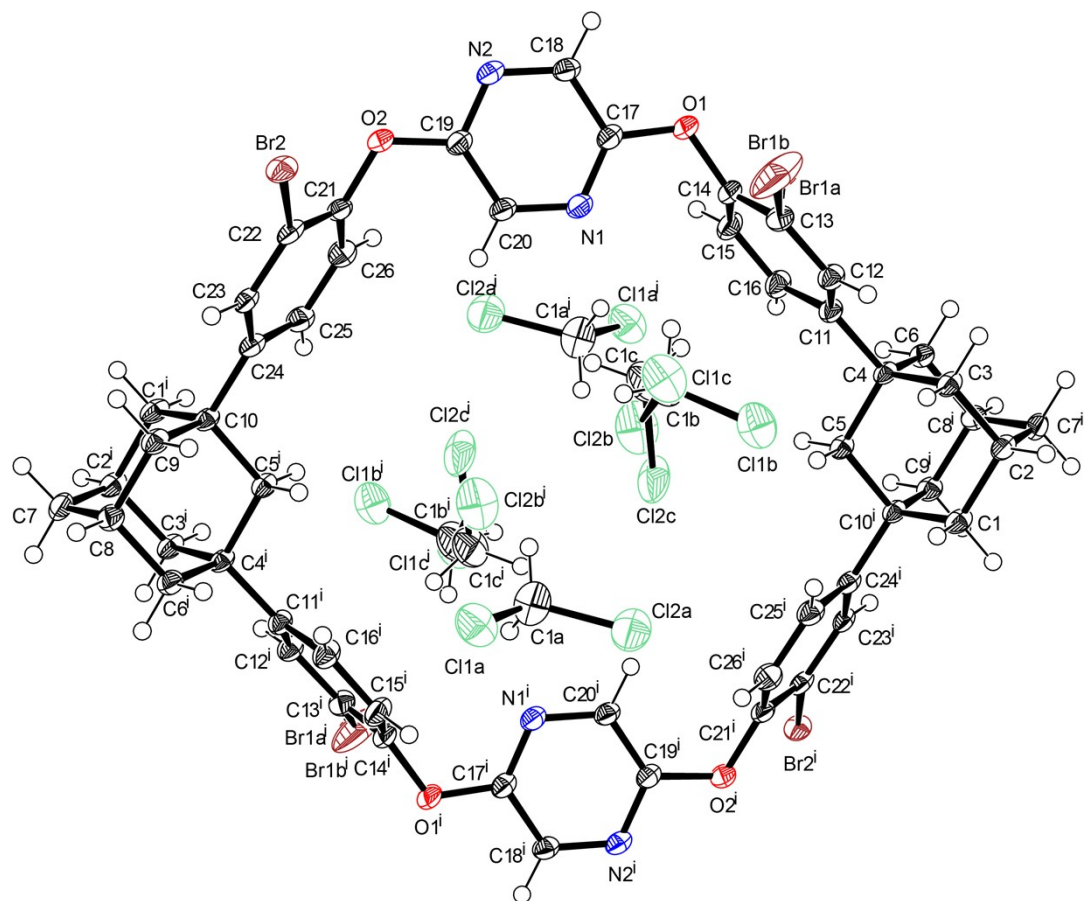
All non-hydrogen atoms were refined anisotropically. The hydrogen atoms were geometrically placed on the calculated positions using a riding model (AFIX 13, 23 and 43) with  $U_{\text{iso}}$  values constrained to 1.2/1.5  $U_{\text{eq}}$  of their parent atoms.

One bromine atom in the host molecule is disordered to two positions (Br1a and Br1b). The occupancies of the disordered atoms are refined to be 0.80 and 0.20.

Three dichloromethane molecules found were refined as follows. The dichloromethane molecule (C1a, C11a, Cl2a and C1c, C11c, Cl2c) was normally refined with the occupancies of 0.70 and 0.30, respectively. Half the dichloromethane molecule (C1b, C11b, Cl2b) lied on a symmetric center was firstly refined with the free variable and finally fixed with the site occupancy factor of 0.5 (combination with PART -n). A total of three guest molecules was included in the unit cell.

To calculate the guest accessible void volume and residual electron density, PLATON/SQUEEZE<sup>5</sup> analysis was applied to the guest removed crystal structure. The result showed 167 electrons and  $397 \text{ \AA}^3$  of potential solvent accessible void volume in the unit cell. One dichloromethane molecule contains 42 electrons.





**Fig. S2** Ortep drawing of **1** and dichloromethane in crystal **1a** (50% probability).

### Single crystal X-ray diffraction experiment for crystal 1b

A colorless prismatic crystal ( $0.150 \times 0.120 \times 0.100$  mm<sup>3</sup>), obtained from hexane/1-chloropropane, was immersed in Paraton-N oil and placed in the N<sub>2</sub> cold stream at 100 K. Data were collected using diffractometer with CMOS detector (Bruker D8 VENTURE, CuK $\alpha$ :  $\lambda = 1.54178$  Å). Absorption correction was performed by an empirical method implemented in SADABS.<sup>2</sup> Structure solution and refinement were performed by using SHELXT-2014/5<sup>3</sup> and SHELXL-2018/3<sup>4</sup>.

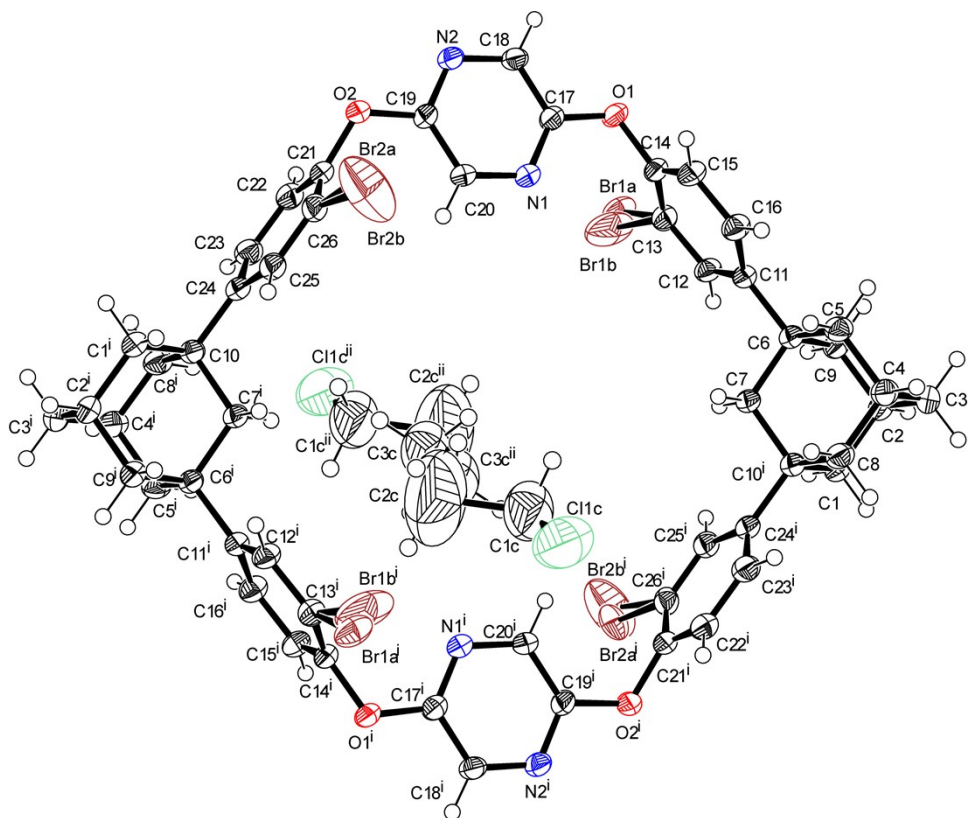
C<sub>55</sub>H<sub>51</sub>Br<sub>4</sub>ClN<sub>4</sub>O<sub>4</sub>,  $M_r = 1187.08$ ; triclinic, space group  $P-1$ ,  $Z = 1$ ,  $D_{\text{calc}} = 1.551$  g·cm<sup>-3</sup>,  $a = 6.5880(3)$ ,  $b = 14.1875(7)$ ,  $c = 15.2526(7)$  Å,  $\alpha = 64.022(2)$ ,  $\beta = 82.732(2)$ ,  $\gamma = 85.997(2)^\circ$ ,  $V = 1271.11(11)$  Å<sup>3</sup>, 18323 measured and 4856 independent [ $I > 2\sigma(I)$ ] reflections, 340 parameters, 26 restraints, final  $R_1 = 0.0410$ ,  $wR_2 = 0.1215$ ,  $S = 1.068$  [ $I > 2\sigma(I)$ ] and  $R_1 = 0.0431$ ,  $wR_2 = 0.1233$ ,  $S = 1.084$  [all data]. CCDC 2099490

All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were refined isotropically on the calculated positions using a riding model (AFIX 13, 137, 23 and 43) with  $U_{\text{iso}}$  values constrained to 1.2/1.5  $U_{\text{eq}}$  of their parent atoms.

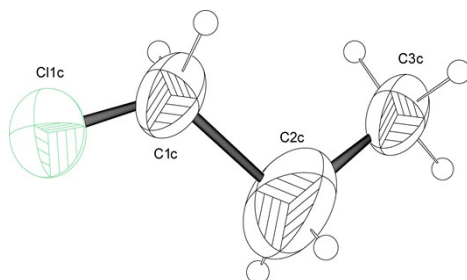
The bromine atoms in the host molecule were disordered to two positions (Br1a, Br1b and Br2a, Br2b) with the occupancies of 0.90, 0.10, and 0.85, 0.15, respectively.

The 1-chloropropane molecules found were refined as follows. The 1-chloropropane molecule (C1c, C2c, C3c and Cl1c) was normally refined with the occupancy to be 0.5. The overlapped and disordered 1-chloropropane (C1c<sup>ii</sup>, C2c<sup>ii</sup>, C3c<sup>ii</sup> and Cl1c<sup>ii</sup>) placed by closely located symmetry center was refined by PART applying with DANG, DELU, DFIX, EADP and, SIMU with the occupancy of 0.5.

To calculate the guest accessible void volume and residual electron density, PLATON/SQUEEZE<sup>5</sup> analysis was applied to the guest removed crystal structure. The result showed 58 electrons and 234 Å<sup>3</sup> of potential solvent accessible void volume in the unit cell. One 1-chloropropane molecule contains 42 electrons.



**Fig. S3** Ortep drawing of **1** and 1-chloropropane in crystal **1b** (50% probability).



**Fig. S4** Ortep drawing of 1-chloropropane in crystal **1b** (50% probability).

### Single crystal X-ray diffraction experiment for crystal 1c

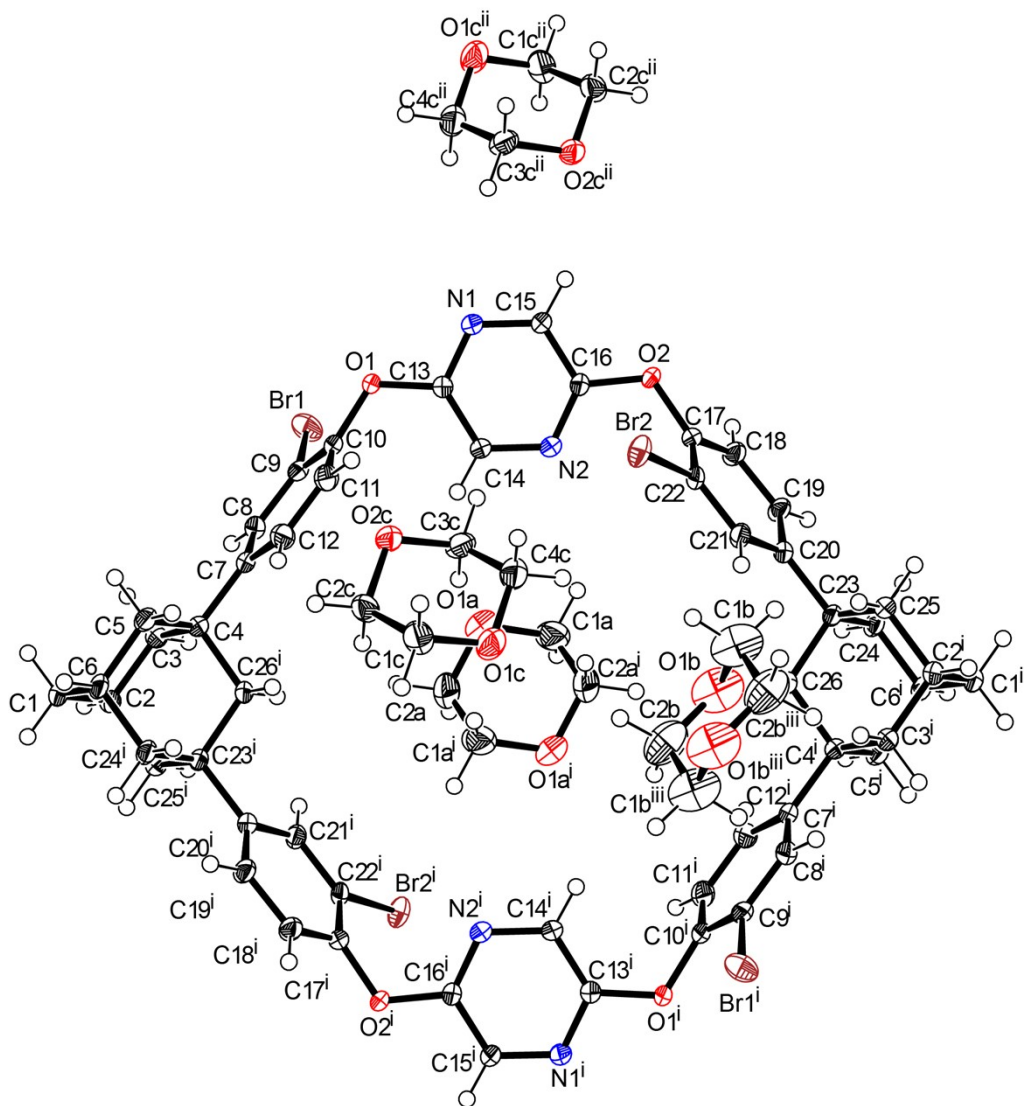
A colorless prismatic crystal ( $0.120 \times 0.050 \times 0.050 \text{ mm}^3$ ), obtained from 1,4-dioxane/dichloromethane, was immersed in Paraton-N oil and placed in the  $\text{N}_2$  cold stream at 100 K. Data were collected using diffractometer with CMOS detector (Bruker D8 VENTURE,  $\text{CuK}\alpha$ :  $\lambda = 1.54178 \text{ \AA}$ ). Absorption correction was performed by an empirical method implemented in SADABS.<sup>2</sup> Structure solution and refinement were performed by using SHELXT-2014/5<sup>3</sup> and SHELXL-2018/3<sup>4</sup>.

$\text{C}_{68}\text{H}_{76}\text{Br}_4\text{N}_4\text{O}_{12}$ ,  $M_r = 1460.96$ ; triclinic, space group  $P-1$ ,  $Z = 1$ ,  $D_{\text{calc}} = 1.527 \text{ g}\cdot\text{cm}^{-3}$ ,  $a = 11.3807(8)$ ,  $b = 11.6442(8)$ ,  $c = 13.1925(9) \text{ \AA}$ ,  $\alpha = 83.978(3)$ ,  $\beta = 66.041(3)$ ,  $\gamma = 86.807(3)^\circ$ ,  $V = 1588.64(19) \text{ \AA}^3$ , 23153 measured and 5401 independent [ $I > 2\sigma(I)$ ] reflections, 397 parameters, final  $R_1 = 0.0378$ ,  $wR_2 = 0.0939$ ,  $S = 1.036$  [ $I > 2\sigma(I)$ ] and  $R_1 = 0.0458$ ,  $wR_2 = 0.0976$ ,  $S = 1.036$  [all data]. CCDC 2099491

All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were refined isotropically on the calculated positions using a riding model (AFIX 13, 23 and 43) with  $U_{\text{iso}}$  values constrained to 1.2/1.5  $U_{\text{eq}}$  of their parent atoms.

One 1,4-dioxane molecule (O1c, O2c, C1c, C2c, C3c and C4c) was normally refined. Other two 1,4-dioxane molecules (O1a, C1a, C2a and O1b, C1b, C2b) in which the centroid of each molecule was riding on the symmetry center were firstly refined with the free variable and finally fixed with the site occupancy factor of 1.0. A total of four guest molecules were included in the unit cell.

To calculate the guest accessible void volume and residual electron density, PLATON/SQUEEZE<sup>5</sup> analysis was applied to the guest removed crystal structure. The result showed 185 electrons and  $604 \text{ \AA}^3$  of potential solvent accessible void volume in the unit cell. One 1,4-dioxane molecule contains 48 electrons.



**Fig. S5** Ortep drawing of 1 and 1,4-dioxane in crystal 1c (50% probability).

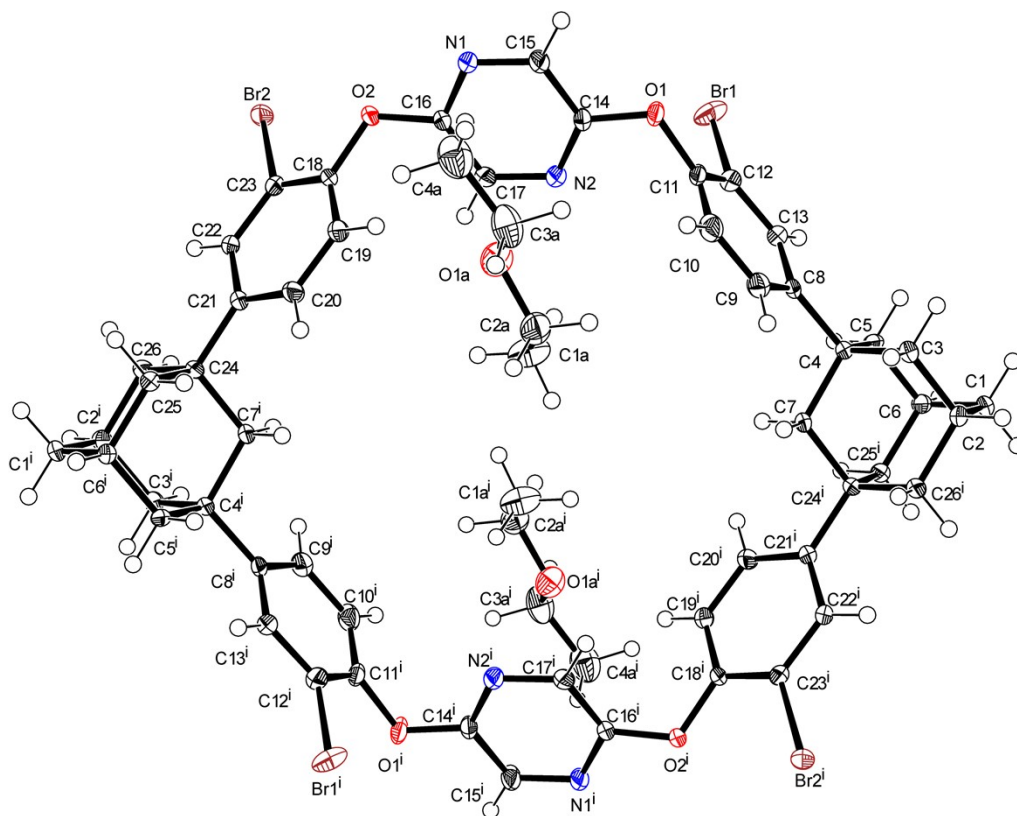
### Single crystal X-ray diffraction experiment for crystal 1d

A colorless prismatic crystal ( $0.120 \times 0.100 \times 0.100 \text{ mm}^3$ ), obtained from the crystal **1a** soaked with diethyl ether for 24 h at room temperature, was immersed in Paraton-N oil and placed in the  $\text{N}_2$  cold stream at 100 K. Data were collected using diffractometer with CMOS detector (Bruker D8 VENTURE,  $\text{CuK}\alpha$ :  $\lambda = 1.54178 \text{ \AA}$ ). Absorption correction was performed by an empirical method implemented in SADABS.<sup>2</sup> Structure solution and refinement were performed by using SHELXT-2014/5<sup>3</sup> and SHELXL-2018/3<sup>4</sup>.

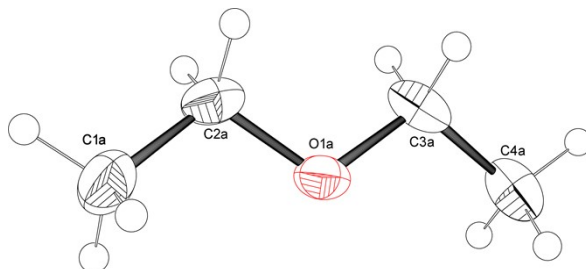
$\text{C}_{60}\text{H}_{64}\text{Br}_4\text{N}_4\text{O}_6$ ,  $M_r = 1256.79$ ; triclinic, space group  $P-1$ ,  $Z = 1$ ,  $D_{\text{calc}} = 1.552 \text{ g}\cdot\text{cm}^{-3}$ ,  $a = 7.803(2)$ ,  $b = 11.554(3)$ ,  $c = 15.741(4) \text{ \AA}$ ,  $\alpha = 72.604(5)$ ,  $\beta = 89.478(5)$ ,  $\gamma = 83.484(5)^\circ$ ,  $V = 1345.0(6) \text{ \AA}^3$ , 16698 measured and 5180 independent [ $I > 2\sigma(I)$ ] reflections, 336 parameters, final  $R_1 = 0.0334$ ,  $wR_2 = 0.1002$ ,  $S = 1.049$  [ $I > 2\sigma(I)$ ] and  $R_1 = 0.0402$ ,  $wR_2 = 0.1356$ ,  $S = 1.049$  [all data]. CCDC 2099492

All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were refined isotropically on the calculated positions using a riding model (AFIX 13, 137, 23 and 43) with  $U_{\text{iso}}$  values constrained to 1.2/1.5  $U_{\text{eq}}$  of their parent atoms.

To calculate the guest accessible void volume and residual electron density, PLATON/SQUEEZE<sup>5</sup> analysis was applied to the guest removed crystal structure. The result showed 169 electrons and  $307 \text{ \AA}^3$  of potential solvent accessible void volume in the unit cell. One diethyl ether molecule contains 42 electrons.



**Fig. S6** Ortep drawing of **1** and diethyl ether in crystal **1d** (50% probability).



**Fig. S7** Ortep drawing of diethyl ether in crystal **1d** (50% probability).

### Single crystal X-ray diffraction experiment for crystal 1e

A colorless prismatic crystal ( $0.100 \times 0.100 \times 0.050$  mm<sup>3</sup>), obtained from the crystal **1b** soaked with diethyl ether for 24 h at room temperature, was immersed in Paraton-N oil and placed in the N<sub>2</sub> cold stream at 100 K. Data were collected using diffractometer with CMOS detector (Bruker D8 VENTURE, CuK $\alpha$ :  $\lambda = 1.54178$  Å). Absorption correction was performed by an empirical method implemented in SADABS.<sup>2</sup> Structure solution and refinement were performed by using SHELXT-2014/5<sup>3</sup> and SHELXL-2018/3<sup>4</sup>.

C<sub>56</sub>H<sub>54</sub>Br<sub>4</sub>N<sub>4</sub>O<sub>5</sub>,  $M_r = 1182.67$ ; triclinic, space group  $P-1$ ,  $Z = 1$ ,  $D_{\text{calc}} = 1.541$  g·cm<sup>-3</sup>,  $a = 6.5928(11)$ ,  $b = 14.239(2)$ ,  $c = 15.231(3)$  Å,  $\alpha = 63.995(5)$ ,  $\beta = 82.597(5)$ ,  $\gamma = 85.988(5)^\circ$ ,  $V = 1274.2(4)$  Å<sup>3</sup>, 18012 measured and 4868 independent [ $I > 2\sigma(I)$ ] reflections, 344 parameters, 29 restraints, final  $R_1 = 0.0508$ ,  $wR_2 = 0.1525$ ,  $S = 1.082$  [ $I > 2\sigma(I)$ ] and  $R_1 = 0.0538$ ,  $wR_2 = 0.1582$ ,  $S = 1.092$  [all data]. CCDC 2099493

All non-hydrogen atoms including two chloroform molecules were refined anisotropically. Hydrogen atoms were refined isotropically on the calculated positions using a riding model (AFIX 13, 137, 23 and 43) with  $U_{\text{iso}}$  values constrained to 1.2/1.5  $U_{\text{eq}}$  of their parent atoms.

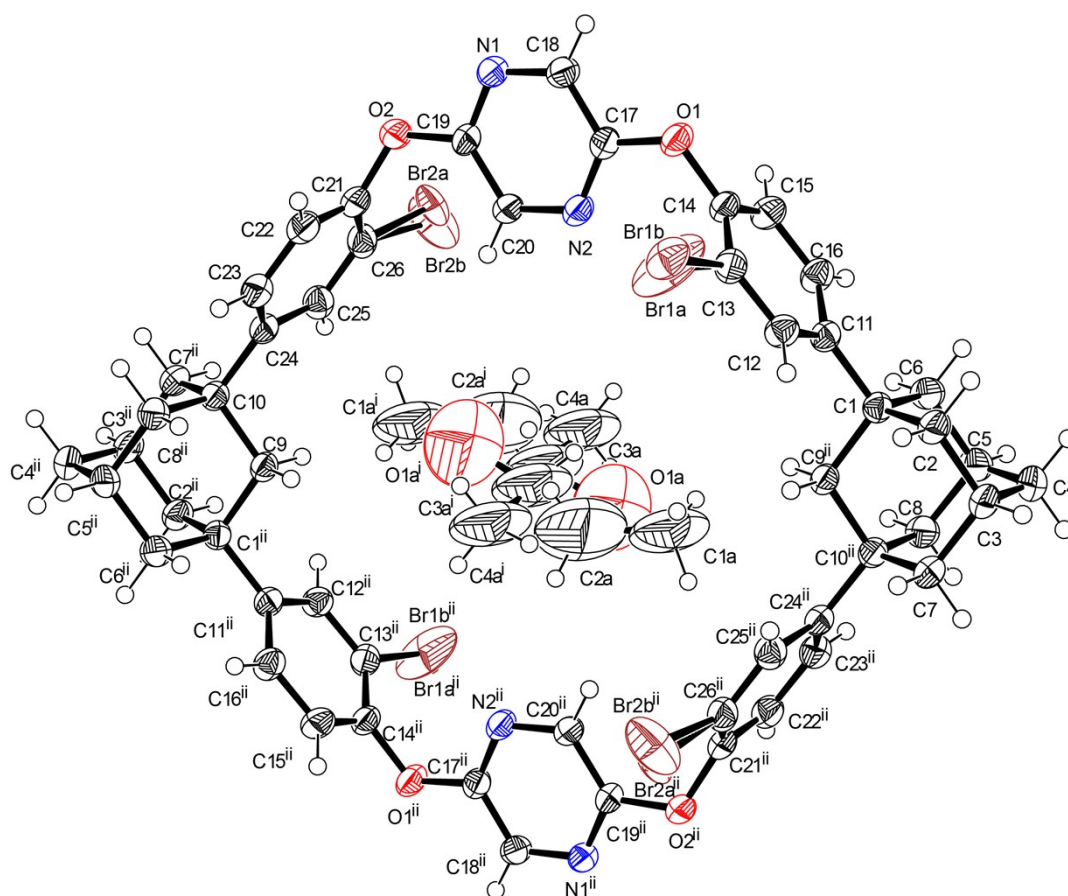
The bromine atoms in the host molecule were disordered to two positions (Br1a, Br1b and Br2a, Br2b) with the occupancies of 0.88, 0.12, and 0.67,0.33, respectively.

The diethyl ether molecules found were refined as follows. The diethyl ether molecule (C1a, C2a, C3a, C4a and O1a) was normally refined with the occupancy to be 0.5. The overlapped and disordered diethyl ether molecule (C1a<sup>i</sup>, C2a<sup>i</sup>, C3a<sup>i</sup>, C4a<sup>i</sup> and O1a<sup>i</sup>) placed by closely located symmetry center was firstly refined with the free variable and finally fixed with the site occupancy factor of 0.5 (combination with PART -n).

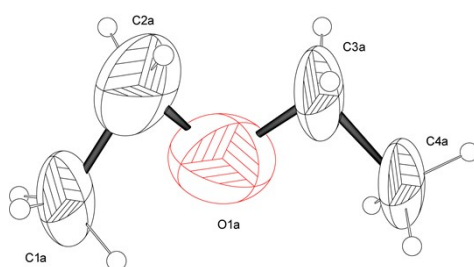
To calculate the guest accessible void volume and residual electron density, PLATON/SQUEEZE<sup>5</sup> analysis was applied to the guest removed crystal structure. The result showed 73 electrons and 242 Å<sup>3</sup> of potential solvent accessible void volume in the



unit cell. One diethyl ether molecule contains 42 electrons.



**Fig. S8** Ortepe drawing of **1** and diethyl ether in crystal **1e** (50% probability).



**Fig. S9** Ortepe drawing of diethyl ether in crystal **1e** (30% probability).

## References

- (1) M. Tominaga, H. Masu and I. Azumaya, *Cryst. Growth Des.*, 2011, **11**, 542–546.
- (2) G. M. Sheldrick, *SADABS*. University of Göttingen, Germany, 1996.
- (3) G. M. Sheldrick, *Acta Crystallogr., Sect. A: Found. Adv.*, 2015, **71**, 3–8.
- (4) G. M. Sheldrick, *Acta Crystallogr., Sect. C: Struct. Chem.*, 2015, **71**, 3–8.
- (5) A. L. Spek, *Acta Crystallogr., Sect. C: Struct. Chem.*, 2015, **71**, 9–18.