# Four constitutional isomers of BMpillar[5]arene: synthesis, crystal structures and complexation with *n*-octyltrimethyl ammonium hexafluorophosphate

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1. Materials and methods

4-Methoxyphenol, boron trifluoride ethyl ether complex, 1-bromobutane and 1,2-dichloroethane were reagent grade and used as received. The 1-butoxy-4-methoxybenzene,<sup>S1</sup> EMpillar[5]arenas,<sup>S2</sup> and noctyltrimethyl ammonium hexafluorophosphate  $5^{S3}$  were synthesized according to literature procedures. Solvents were either employed as purchased or dried according to procedures described in the literature. <sup>1</sup>H NMR spectra were collected on a Varian Unity INOVA-400 spectrometer with internal standard TMS. <sup>13</sup>C NMR spectra were recorded on a Varian Unity INOVA-400 spectrometry at 100 MHz. Mass spectra were performed on a Bruker Esquire 3000 plus mass spectrometer (Bruker-Franzen Analytik GmbH Bremen, Germany) equipped with an ESI interface and an ion trap analyzer. HRMS were obtained on a Bruker 7-Tesla FT-ICRMS equipped with an electrospray source (Billerica, MA, USA). The melting points were collected on a SHPSIC WRS-2 automatic melting point apparatus. The energy-minimized structure of complex **4**⊃**5** in Figure S29 was calculated using the GAUSSIAN 03 software, based on the arithmetic method B3LYP/6-31G(D) (Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Montgomery, J. A., Jr.; Vreven, T.; Kudin, K. N.; Burant, J. C.; Millam, J. M.; Iyengar, S. S.; Tomasi, J.; Barone, V.; Mennucci, B.; Cossi, M.; Scalmani, G.; Rega, N.; Petersson, G. A.; Nakatsuji, H.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Klene, M.; Li, X.; Knox, J. E.; Hratchian, H. P.; Cross, J. B.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Ayala, P. Y.; Morokuma, K.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Zakrzewski, V. G.; Dapprich, S.; Daniels, A. D.; Strain, M. C.; Farkas, O.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Ortiz, J. V.; Cui, Q.; Baboul, A. G.; Clifford, S.; Cioslowski, J.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Challacombe, M.; Gill, P. M. W.; Johnson, B.; Chen, W.; Wong, M. W.; Gonzalez, C.; Pople, J. A. Gaussian 03, revision D.01; Gaussian, Inc.: Wallingford, CT, 2005).

2. Synthesis of constitutional isomers 1, 2, 3 and 4



To a solution of 1-butoxy-4-methoxybenzene (12.8 g, 71.1 mmol) in 1,2-dichloroethane (100 mL), paraformaldehyde (2.20 g, 71.1 mmol) was added under nitrogen atmosphere. Then, boron trifluoride diethyl etherate (9.4 mL, 75 mmol) was added to the solution and the mixture was stirred at room temperature for 4 h and concentrated by rotary evaporation. The resulting oil was dissolved in  $CH_2Cl_2$  (250 mL) and washed twice with  $H_2O$  (100 mL). The organic layer was dried over anhydrous  $Na_2SO_4$  and evaporated to afford the mixture of constitutional isomers **1**, **2**, **3** and **4** which were isolated by flash column chromatography using petroleum ether/ethyl acetate from 500:1 to 50:1 ( $\nu/\nu$ ). The fractions containing the four products were combined and concentrated, respectively, under vacuum to give **1** (1.97 g, 14%, mp 130.5–131.3 °C), **2** (2.02 g, 15%, mp 121.0–122.0 °C), **3** (2.77 g, 20%, mp 123.1–123.8 °C) and **4** (0.87 g, 6%, mp 149.7–150.5 °C) as white solids.

The proton NMR spectrum of **1** is shown in Figure S1. <sup>1</sup>H NMR (400 MHz, chloroform-*d*, room temperature)  $\delta$  (ppm): 6.81–6.77 (m, 10H), 3.86–3.81 (m, 10H), 3.70–3.74 (m, 10H), 3.67–3.65 (m, 15H), 1.77–1.71 (m, 10H), 1.54–1.47 (m, 10H), 0.97–0.93 (m, 15H). The <sup>13</sup>C NMR spectrum of BMpillar[5]arene **1** is shown in Figure S2. The <sup>13</sup>C NMR (100 MHz, chloroform-*d*, room temperature)  $\delta$  (ppm): 150.43, 150.06, 128.16, 127.96, 114.98, 114.05, 68.09, 55.53, 31.71, 29.38, 19.52, 13.89. LRESIMS is shown in Figure S3: *m/z* 983.8 [M + Na]<sup>+</sup> (100%). HRESIMS: *m/z* calcd for [M + Na]<sup>+</sup> C<sub>60</sub>H<sub>80</sub>O<sub>10</sub>Na, 983.5649, found 983.5682, error 3.4 ppm.









*Figure S3.* Electrospray ionization mass spectrum of **1** in a mixture of chloroform and methanol. Assignment of the main peak: m/z 983.8 [M + Na]<sup>+</sup> (100%).

The proton NMR spectrum of **2** is shown in Figure S4. <sup>1</sup>H NMR (400 MHz, chloroform-*d*, room temperature)  $\delta$  (ppm): 6.83–6.78 (m, 10H), 3.86–3.82 (m, 3.9 Hz, 10H), 3.80–3.74 (m, 10H), 3.69–3.67 (m, 15H), 1.79–1.74 (m, 10H), 1.59–1.45 (m, 10H), 0.98–0.94 (m, 15H). The <sup>13</sup>C NMR spectrum of BMpillar[5]arene **2** is shown in Figure S5. <sup>13</sup>C NMR (100 MHz, chloroform-*d*, room temperature)  $\delta$  (ppm): 150.14, 149.65, 128.46, 128.26, 114.29, 113.37, 67.83, 55.50, 32.04, 29.12, 19.41, 14.02. LRESIMS is shown in Figure S6: *m/z* 983.7 [M + Na]<sup>+</sup> (100%). HRESIMS: *m/z* calcd for [M + Na]<sup>+</sup> C<sub>60</sub>H<sub>80</sub>O<sub>10</sub>Na, 983.5649, found 983.5686, error 3.8 ppm.



*Figure S4.* <sup>1</sup>H NMR spectrum (400 MHz, chloroform-d, 25 °C) of 2.





*Figure S6.* Electrospray ionization mass spectrum of 2 in a mixture of chloroform and methanol. Assignment of the main peak: m/z 983.7 [M + Na]<sup>+</sup> (100%).

The proton NMR spectrum of **3** is shown in Figure S7. <sup>1</sup>H NMR (400 MHz, chloroform-*d*, room temperature)  $\delta$  (ppm): 6.94–6.80 (m, 10H), 3.94–3.81 (m, 10H), 3.80–3.65 (m, 25H), 1.84–1.73 (m, 10H), 1.57–1.48 (m, 10H), 0.99–0.96 (m, 15H). The <sup>13</sup>C NMR spectrum of BMpillar[5]arene **3** is shown in Figure S8. <sup>13</sup>C NMR (100 MHz, chloroform-*d*, room temperature)  $\delta$  (ppm): 150.34, 149.88, 128.33, 128.12, 114.74, 113.87, 67.91, 55.59, 32.01, 29.46, 19.53, 13.99. The LRESIMS is shown in Figure S9: *m/z* 983.7 [M + Na]<sup>+</sup> (100%). HRESIMS: *m/z* calcd for [M + Na]<sup>+</sup> C<sub>60</sub>H<sub>80</sub>O<sub>10</sub>Na, 983.5649, found 983.5603, error –4.7 ppm.



*Figure S8.* <sup>13</sup>C NMR spectrum (100 MHz, chloroform-*d*, 25 °C) of **3**.



*Figure S9.* Electrospray ionization mass spectrum of **3** in a mixture of chloroform and methanol. Assignment of the main peak: m/z 983.7 [M + Na]<sup>+</sup> (100%).

The proton NMR spectrum of **4** is shown in Figure S10. <sup>1</sup>H NMR (400 MHz, chloroform-*d*, room temperature)  $\delta$  (ppm): 6.91 (s, 5H), 6.83 (s, 5H), 3.87 (t, J = 6.5 Hz, 10H), 3.79 (s, 10H), 3.74 (s, 15H), 1.86–1.76 (m, 10H), 1.63–1.50 (m, 10H), 1.01 (t, J = 7.4 Hz, 15H). The <sup>13</sup>C NMR spectrum of BMpillar[5]arene **4** is shown in Figure S11. <sup>13</sup>C NMR (100 MHz, chloroform-*d*, room temperature)  $\delta$  (ppm): 150.38, 149.90, 128.21, 128.16, 114.57, 113.75, 67.93, 55.58, 32.03, 29.12, 19.54, 14.04. LRESIMS is shown in Figure S12: m/z 983.4 [M + Na]<sup>+</sup> (100%). HRESIMS: m/z calcd for [M + Na]<sup>+</sup> C<sub>60</sub>H<sub>80</sub>O<sub>10</sub>Na, 983.5649, found 983.5636, error –1.3 ppm.



*Figure S10.* <sup>1</sup>H NMR spectrum (400 MHz, chloroform-*d*, 25 °C) of 4.





*Figure S12.* Electrospray ionization mass spectrum of **4** in a mixture of chloroform and methanol. Assignment of the main peak: m/z 983.4 [M + Na]<sup>+</sup> (100%).

### 3. NOESY spectrum of 4



Figure S13. NOESY spectrum (400 MHz, chloroform-d, 25 °C) of 4.

4. Partial COSY spectrum of a chloroform solution of 15 mM 4 and 10 mM 5





Figure S14. Partial COSY spectrum of a chloroform solution of 15 mM 4 and 10 mM 5.

5. ESI-MS of solutions of each of 1, 2, 3 and 4 with 5



*Figure S15.* Electrospray ionization mass spectrum of a mixture of **1** and **5** in a mixture of chloroform and methanol. Assignment of main peaks: m/z 1131.5  $[\mathbf{1} + \mathbf{5} - \text{HPF}_6]^+$  (18%) and 172.1  $[\mathbf{5} - \text{PF}_6]^+$  (100%).



*Figure S16.* Electrospray ionization mass spectrum of a mixture of 2 and 5 in a mixture of chloroform and methanol. Assignment of main peaks: m/z 1130.9 [2 + 5 – HPF<sub>6</sub>]<sup>+</sup> (29%) and 172.1 [5 – PF<sub>6</sub>]<sup>+</sup> (100%).



*Figure S17.* Electrospray ionization mass spectrum of a mixture of **3** and **5** in a mixture of chloroform and methanol. Assignment of main peaks: m/z 1131.7 [**3** + **5** – HPF<sub>6</sub>]<sup>+</sup> (17%) and 172.1 [**5** – PF<sub>6</sub>]<sup>+</sup> (100%).



*Figure S18.* Electrospray ionization mass spectrum of a mixture of **4** and **5** in a mixture of chloroform and methanol. Assignment of main peaks: m/z 1131.9 [**4** + **5** – HPF<sub>6</sub>]<sup>+</sup> (32%) and 172.1 [**5** – PF<sub>6</sub>]<sup>+</sup> (100%).

#### 6. Stacking styles of 1, 2, 3 and 4 in the solid state

The four isomers stack in two patterns (A and B), and form channels composed of the pillar cavities in the solid state. 1 and 3 stack in pattern A: edge to edge in register. 2 and 4 stack in pattern B: corner to edge,  $72^{\circ}$  rotated with respect to each other.



*Figure S19.* Presentation of the two stacking patterns (only the rigid equilateral pillar parts are shown for clarity).



*Figure S20.* The stacking patterns of 1, 2, 3 and 4 (only the rigid equilateral pillar parts are shown for clarity): (a) 1; (b) 2; (c) 3; (d) 4.

7. Variable-temperature <sup>1</sup>H NMR spectra of **1** 



*Figure S21.* <sup>1</sup>H variable-temperature <sup>1</sup>H NMR spectra (500 MHz) of **1** (5.00 mM) in toluene- $d_8$ .

# 8. Variable-temperature ${}^{1}HNMR$ spectra of 2



*Figure S22.* <sup>1</sup>H variable-temperature <sup>1</sup>H NMR spectra (500 MHz) of **2** (5.00 mM) in toluene- $d_8$ .

9. Variable-temperature <sup>1</sup>H NMR spectra of **3** 



*Figure S23.* <sup>1</sup>H variable-temperature <sup>1</sup>H NMR spectra (500 MHz) of **3** (5.00 mM) in toluene- $d_8$ .

10. Variable-temperature  ${}^{1}HNMR$  spectra of **4** 



*Figure S24.* <sup>1</sup>H variable-temperature <sup>1</sup>H NMR spectra (500 MHz) of 4 (5.00 mM) in toluene- $d_8$ .

11. Full <sup>1</sup>H NMR spectrum of a chloroform solution of 10 mM 5



*Figure S25.* <sup>1</sup>H NMR spectrum (400 MHz, chloroform-d, 25 °C) of 10 mM 5.

12. Full <sup>1</sup>H NMR spectrum of a chloroform solution of 15 mM 4 and 10 mM 5



*Figure S26.* <sup>1</sup>H NMR spectrum (400 MHz, chloroform-d, 25 °C) of 15 mM 4 and 10 mM 5.

#### 13. The crystal structure of EMpillar[5]arene

At first, we tried to synthesize an asymmetric pillar[5]arene using 1-ethoxy-4-methoxybenzene as the monomer. A mixture of 1-ethoxy-4-methoxybenzene (10 mM), paraformaldehyde (10 mM) and  $BF_3 \cdot O(C_2H_5)_2$  (10 mM) was stirred in 1,2-dichloroethane (40 mL) under nitrogen atmosphere at room temperature for 4 h. Only one spot was detected using TLC analysis. The <sup>1</sup>H NMR and ESI-MS showed that it was a cyclic pentamer. However, when we got its crystal structure (Figure S27), we surprisingly

found that it was composed of two constitutional isomers. Consequently, there should be another explanation for the observation of one spot in the TLC analysis: the product we got was a mixture which could not be separated.



*Figure S27.* The crystal structure of EMpillar[5]arene. Hydrogens and three CH<sub>3</sub>CN solvent molecules were omitted for clarity. Carbons are red, oxygens are green. Methyl groups are magenta and ethyl groups are blue.

## 14. Partial<sup>1</sup>H NMR spectra of the four constitutional isomers

It is well known that four conformers of calix[4]arene can be easily distinguished by the characteristic 1H NMR patterns of the bridging methylene protons.<sup>S4</sup> They will appear as a pair of doublets, two pairs of doublets, one singlet and a pair of doublets, and one singlet for the cone, partial cone, 1,2-alternate, and 1,3-alternate conformers, respectively. The yields of the four conformers of calix[4]arene can be estimated directly from the <sup>1</sup>H NMR spectrum of the crude product. However, since the corresponding protons of 1, 2, 3 and 4 have almost the same chemical shifts, it is impossible to estimate the molar ratio of these four constitutional isomers of BMpillar[5]arene from the <sup>1</sup>H NMR spectrum of the crude product. However, the <sup>1</sup>H NMR spectrum of each of them still has its own features. The aromatic protons  $(H_1)$  of  $C_5$  4 appear as a pair of singlets, and the phenyl protons on the butoxy side appear at higher field (NOESY of 4 in Figure S13), since the butoxy group is a better electron-donating group than the methoxy group. The bridging methylene protons  $H_2$  of 4 display only a singlet. From the integrations of  $H_2$  and  $H_1$ , we can distinguish isomers 1, 2 and 3. The ten bridging methylene protons  $H_2$  of 1 appear as three peaks with an integration ratio of 4:2:4. The bridging methylene protons  $H_2$  of 2 and 3 both produce three peaks, and the integration ratio of these three peaks for both 2 and 3 is 2:6:2. However, the aromatic protons  $H_1$ of **3** appear as two parts with equal integrations. Therefore, from their <sup>1</sup>H NMR spectra, the four isomers can be distinguished. Especially 4 could be easily determined.



*Figure S28.* Partial <sup>1</sup>H NMR spectra (400 MHz, chloroform-d, 25 °C) of the four isomers: (a) **1**; (b) **2**; (c) **3**; (d) **4**.

15. The energy-minimized structure of complex  $4 \supset 5$ 



*Figure S29.* The energy-minimized structure of complex  $4 \supset 5$ : (a) side view, (b) top view, (c) bottom view. 5 is blue in a space-filling model. 4 is red in a ball-and-stick model. All hydrogens were omitted for clarity.

16. The Job plots of complexes  $1 \supset 5$ ,  $2 \supset 5$ ,  $3 \supset 5$  and  $4 \supset 5$ 



*Figure S30.* Job plot: the stoichiometry of the complex between 1 and 5 in chloroform-*d* solution using proton NMR data for H<sub>1</sub> of 5. [1]<sub>c</sub> is the concentration of complexed 1.  $[1]_0 + [5]_0 = 10.0$  mM.



*Figure S31.* Job plot: the stoichiometry of the complex between 2 and 5 in chloroform-*d* solution using proton NMR data for H<sub>1</sub> of 5. [2]<sub>c</sub> is the concentration of complexed 2.  $[2]_0 + [5]_0 = 10.0$  mM.



*Figure S32.* Job plot: the stoichiometry of the complex between 3 and 5 in chloroform-*d* solution using proton NMR data for H<sub>1</sub> of 5. [3]<sub>c</sub> is the concentration of complexed 3.  $[3]_0 + [5]_0 = 10.0$  mM.



*Figure S33.* Job plot: the stoichiometry of the complex between **4** and **5** in chloroform-*d* solution using proton NMR data for H<sub>1</sub> of **5**. [**4**]<sub>c</sub> is the concentration of complexed **4**. [**4**]<sub>0</sub> + [**5**]<sub>0</sub> = 10.0 mM.

17. The two most stable conformations of DMPillar[5]arene



Figure S34. The two most stable conformations of DMPillar[5]arene.

Up to now, all of the symmetric pillar[n]arenes (n = 5,6) have two equivalent most stable conformations in their crystal structures. Here is an easy example to explain the relationship between the two conformations of dimethoxypillar[5]arene. They are mirror images to each other, no matter they are conformationally fixed or flexible.



*Figure S35.* Theoretical analyses of products of the condensation reaction.

# 19. The Conformations of 4



*Figure S36.* a) The two most stable conformations of **4**, b) the six unstable conformations of **4** (caused by the steric interactions between the two near alkoxy groups).

20. Partial <sup>1</sup>H NMR spectra of mixtures of **5** and **4** 



*Figure S37.* Partial <sup>1</sup>H NMR spectra (400 MHz, chloroform-*d*, 25 °C) of **5** (a); 2 mM **5** and 0.5 mM **4** (b); 2 mM **5** and 1 mM **4** (c); 2 mM **5** and 2 mM **4** (d); 2 mM **5** and 5 mM **4** (e); 2 mM **5** and 8 mM **4** (f); 2 mM **5** and 15 mM **4** (g); **4** (h).

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