Electronic Supplementary Information

Pillar[5]arene-Based Supramolecular Polypseudorotaxanes Constructed from Quadruple Hydrogen Bonding

Xiao-Yu Hu, Pingyuan Zhang, Xuan Wu, Wei Xia, Tangxin Xiao, Juli Jiang, Chen Lin and Leyong Wang*

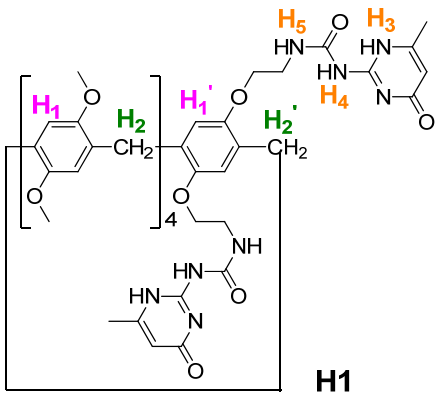
Key Laboratory of Mesoscopic Chemistry of MOE, Center for Organic Molecular Chemistry, School of Chemistry and Chemical Engineering, Nanjing University, Nanjing 210093 (China).

Table of Contents

1. General information.

All reactions were performed in atmosphere unlessotherwise stated. The commercially available reagents and solvents were either employed as purchased or dried according to procedures described in the literature. Column chromatography was performed with silica gel (200-300 mesh) produced by Qingdao Marine Chemical Factory, Qingdao (China). All yields were given as isolated yields. NMR spectra were recorded on a Bruker DPX 300 MHz spectrometer (or Bruker DPX 400 MHz spectrometer) with internal standard tetramethylsilane (TMS) and solvent signals as internal references at room temperature, and the chemical shifts (δ) were expressed in ppm and J values were given in Hz. Low-resolution electrospray ionization mass spectra (LR-ESI-MS) were obtained on Finnigan Mat TSQ 7000 instruments. High-resolution electrospray ionization mass spectra (HR-ESI-MS) were recorded on an Agilent 6540Q-TOF LCMS equipped with an electrospray ionization (ESI) probe operating in positive-ion mode with direct infusion. Viscosity measurements were carried out with Ubbelohde micro viscometers (Shanghai Liangjing Glass Instrument Factory, 0.40 mm inner diameter) at 298K in chloroform. Scanning electron microscopy (SEM) investigations were carried out on a Shimadzu SSX-550 instrument. Dynamic light scattering (DLS) measurements were carried out on a Brookhaven BI-9000AT system (Brookhaven Instruments Corporation, USA), using a 200-mW polarized laser source (λ= 532 nm). Melting points (M.p.) were determined using a Focus X-4 apparatus (made in China) and were not corrected.

2. ^{1}H NMR spectra of difunctionalized pillar[5]arene host (H1) in the different concentrations.



H1

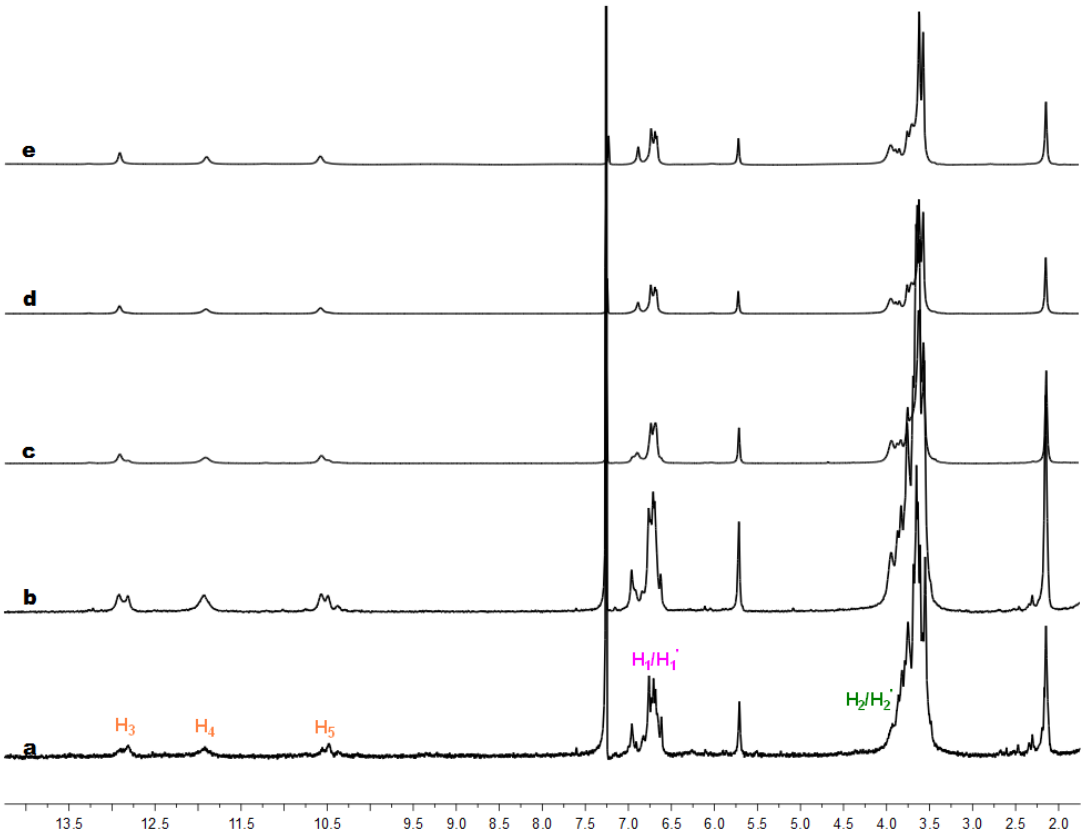


Fig. S1. ^{1}H NMR spectra ($CDCl_3$, 298 K, 300 MHz) of **H1** at different concentrations (mM): (a) 2.0, (b) 10.0, (c) 30.0, (d) 75.0, (e) 150.0.

In order to study the assembly behavior of **H1**, we performed the ^{1}H NMR experiments in chloroform. From the spectra above (Fig S1), we found that the **Upy** N–H signals showed large downfield shifts (H_3, H_4 and H_5, between 10 and 13.5 ppm) compared with the corresponding monomer in DMSO-D_6, which was consistent with the four DDAA hydrogen bonds present in the dimer and gave direct evidence for the dimerization of **UPy** units. Moreover, the Upy N-H signals also showed lower intensity and became broad. The above evidences indicated the linear polymer formation at relatively high concentrations.

3. 2D NOESY analysis of H1 with G.

The 2D NOESY NMR spectrum (Figure S2) of the solution of **H1–G** (the concentration of **H1** and **G** are 30.0 and 10.0 mM, respectively) showed the protons H_a and H_b on the diamine was correlated with the pillar[5]arene benzene-ring protons (H_1) and methylene protons (H_2). This confirmed the complexation of **H1** and **G**.

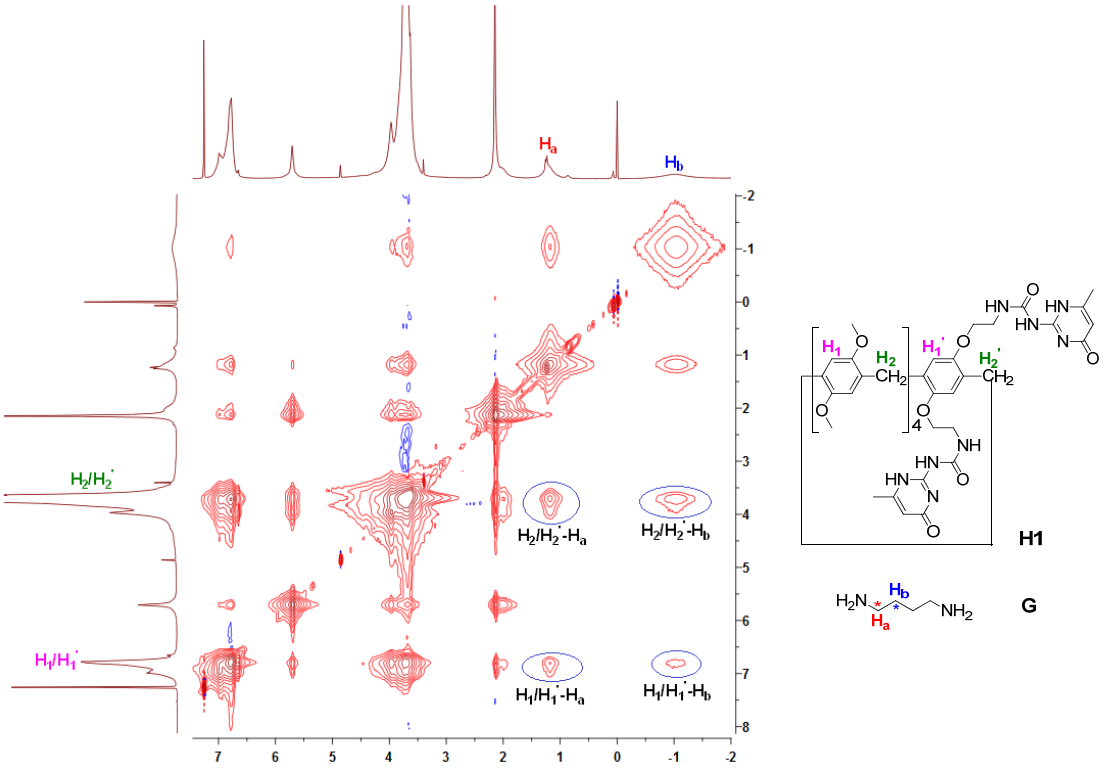


Figure S2. 2D NOESY analysis of **H1** with **G** in $CDCl_3$ with a mixing time of 300 ms. (400 MHz, 298 K, The concentrations of host and guest are 30.0 and 10.0 mM, respectively)

4. ESI-MS and Job plots experiments.

Electrospray ionization mass spectrometry (ESI-MS) is a very convenient technique for determining the stoichiometry of the charged host–guest complexes. As shown in Fig. S3, the ESI mass spectrum of1:1mixture of **G** and **H1** in chloroform solution showed peaks for both 1:1 [**H1**–**G** + **H**]$^+$ (1199.60). Moreover, we also performed a Job plot experiment (Fig. S4). Job plots also showed the 1:1 complexation stoichiometry based on the proton NMR data, which is in accordance with the above-mentioned results of ESI-MS.

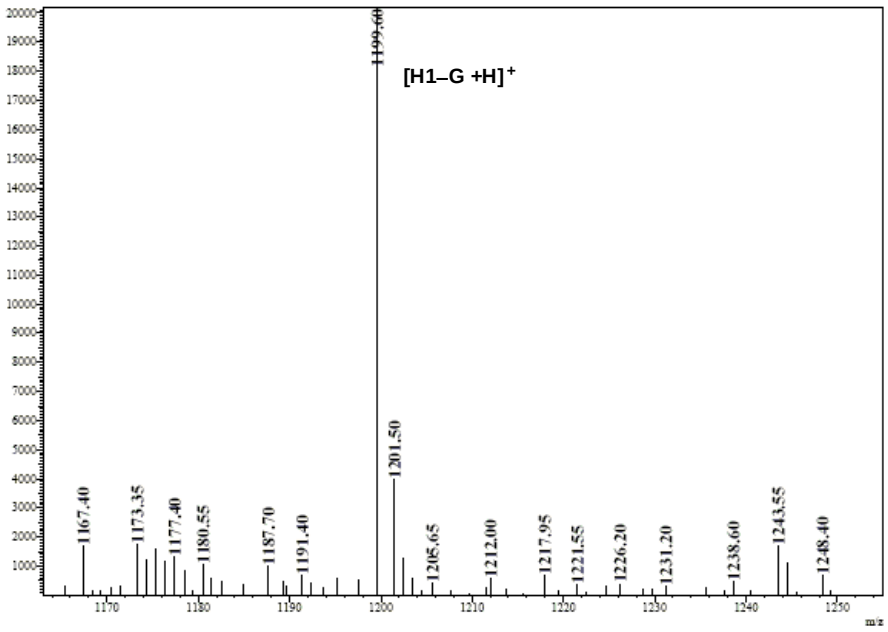


Fig. S3. Electrospray ionization mass spectrum of a solution of **H1**and **G**. Assignment of the main peak: 1199.60 [**H1**–**G**+ H]$^{+}$.

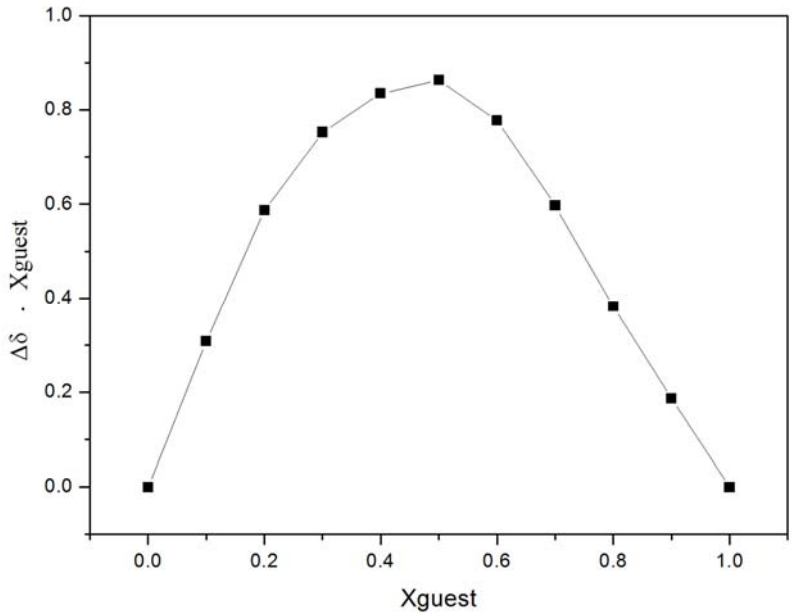


Fig. S4. Job plots experiment: Job plot showing the 1:1 stoichiometry of the complex between **H1** and **G** in $CDCl_3$ by plotting the $\Delta\delta$ in chemical shift of the guest's methylene proton H_b (for proton designations, see Fig. S5) observed by ^{1}H NMR spectroscopy against the molefraction of dimer (X_{host}). ([host] + [guest] = 20.0 mM).

5. Association constant determination for the complexation of H1 and G.

To determine the association constant between **H1**and 1,4-diamine (**G**), ^{1}H NMR titrations were done insolutions which had a constant concentration of **G** (10 mM) and varying concentrations of **H1**. By a non-linear curve-fitting method, the association constant between the guest and **H1** was calculated.[S1]

The non-linear curve-fitting was based on the equation: $\Delta\delta = (\Delta\delta_\infty/[G]_0)\ (0.5[H]_0 + 0.5([G]_0+1/K_a) - (0.5\ ([H]_0\ 2 + (2[H]_0(1/K_a - [G]_0)) + (1/K_a + [G]_0)2)\ 0.5))$ (Eq. S1). Where $\Delta\delta$ is the chemical shift change of H_a on **G** at $[H]_0$, $\Delta\delta_\infty$ is the chemical shift change of H_a when the guest is completely complexed, $[G]_0$ is the fixed initial concentration of the guest, and $[H]_0$ is the varying concentrations of **H1**.

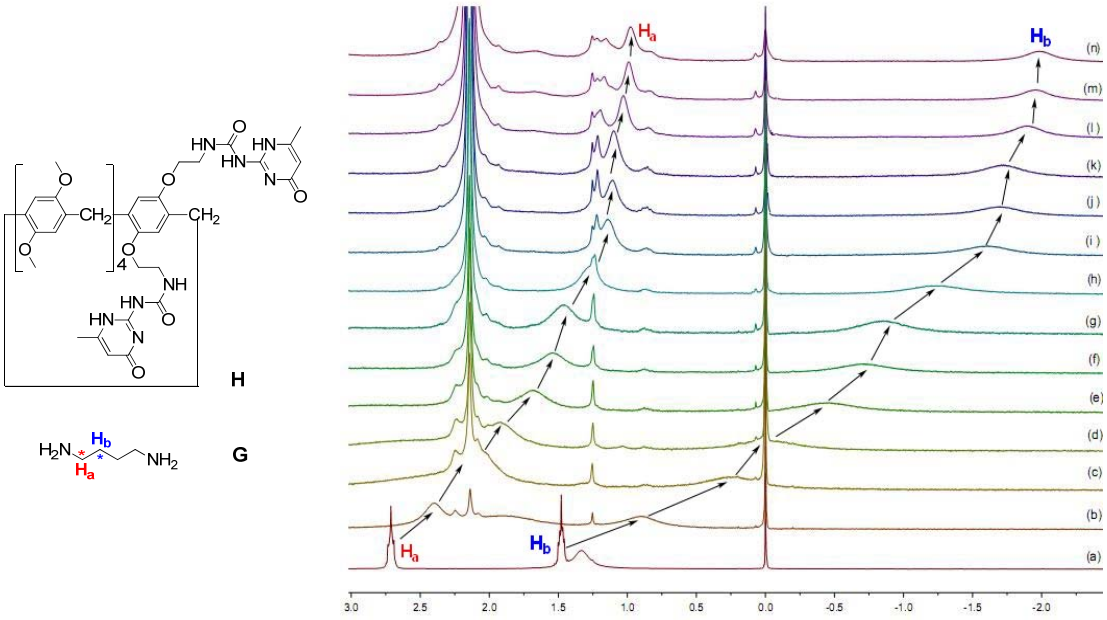
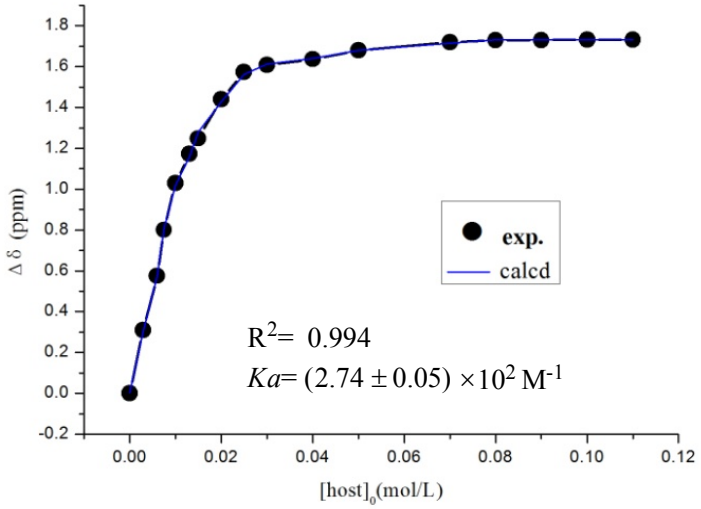


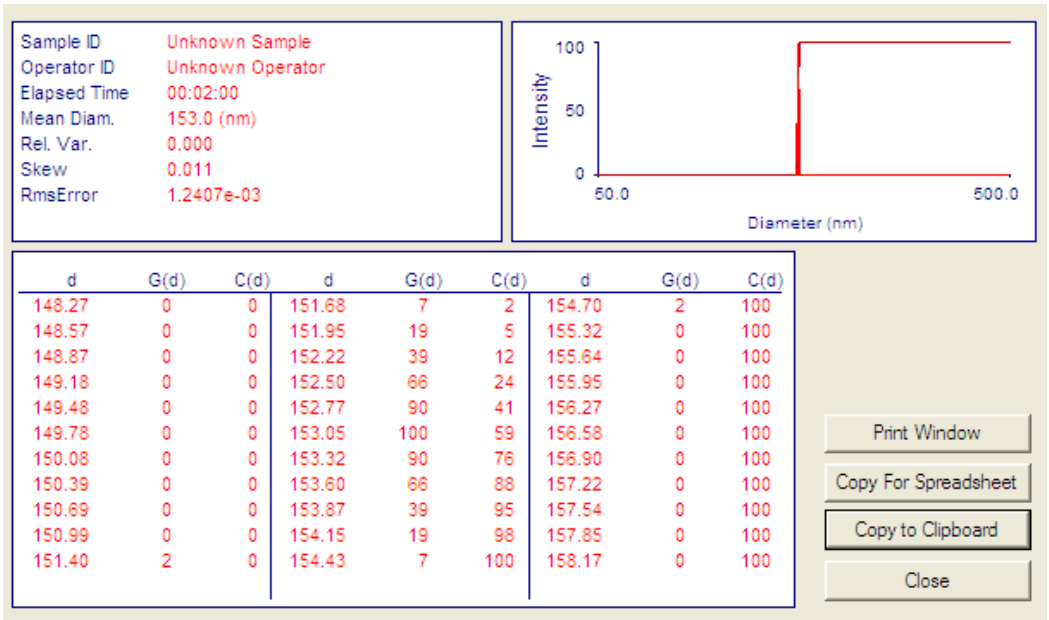
Fig. S5. ^{1}H NMR spectra ($CDCl_3$, 298 K, 300 MHz) of **G** at a concentration of 10 mM with different concentrations (mM) of **H1**: (a) 0.0, (b) 3.0, (c) 6.0, (d) 7.5, (e) 10.0, (f) 13.0, (g) 15.0, (h) 20.0, (i) 25.0, (j) 30.0, (k) 35.0, (l) 50.0, (m) 70.0, (n) 80.0.



6. DLS of the supramolecular polymers.

The solutions were filtrated, prior to use, through a filter (pore size: 0.45μm). Solutions of **H1** and **G** at concentration of 40 mM have average R_h values of 153 nm, which indicated the formation of large supramolecular polymers.

40 mM solution:



d	G(d)	C(d)	d	G(d)	C(d)	d	G(d)	C(d)
148.27	0	0	151.68	7	2	154.70	2	100
148.57	0	0	151.95	19	5	155.32	0	100
148.87	0	0	152.22	39	12	155.64	0	100
149.18	0	0	152.50	66	24	155.95	0	100
149.48	0	0	152.77	90	41	156.27	0	100
149.78	0	0	153.05	100	59	156.58	0	100
150.08	0	0	153.32	90	76	156.90	0	100
150.39	0	0	153.60	66	88	157.22	0	100
150.69	0	0	153.87	39	95	157.54	0	100
150.99	0	0	154.15	19	98	157.85	0	100
151.40	2	0	154.43	7	100	158.17	0	100

Fig. S6. Distribution of the hydrodynamic diameter of a 40 mM equimolar solution of **H1** and **G** in chloroform at 298 K.

7. The average degree of polymerization

In our manuscript, the supramolecular polypseudorotaxane backbone was constructed by the quadruple hydrogen bonding. Therefore, according to the reference,[S2] based on the K_{dim} value of the UPy groups of 5.7×10^7 M^{-1}, the average degree of polymerization (DP) was estimated using the following equation: $DP = 4*K_{dim}*([UPy_{tot}]-[UPy_{cyclic}])/ \{sqrt(1+8*K_{dim}[UPy_{tot}])-1\}$, whereas at 298 K, $[UPy_{cyclic}] = 2*$Critical Concentration.

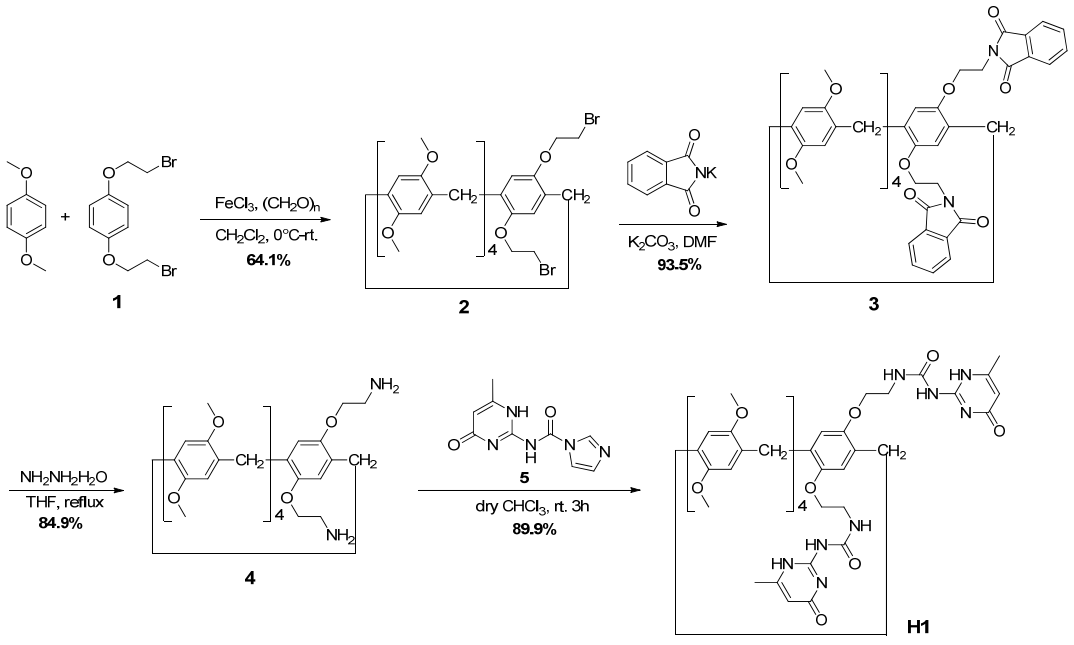
The average degree of polymerization (DP) for **H1** as well as in the presence of the diamine guest (**G**) were eatimated as following:

Concentration of H1 (mM)	DP	Concentration H1–G (mM)	DP
40	1435	40	755
60	2404	60	1850
80	3150	80	2670

8. Synthesis of the difunctionalized pillar[5]arene host (H1).

General procedure:

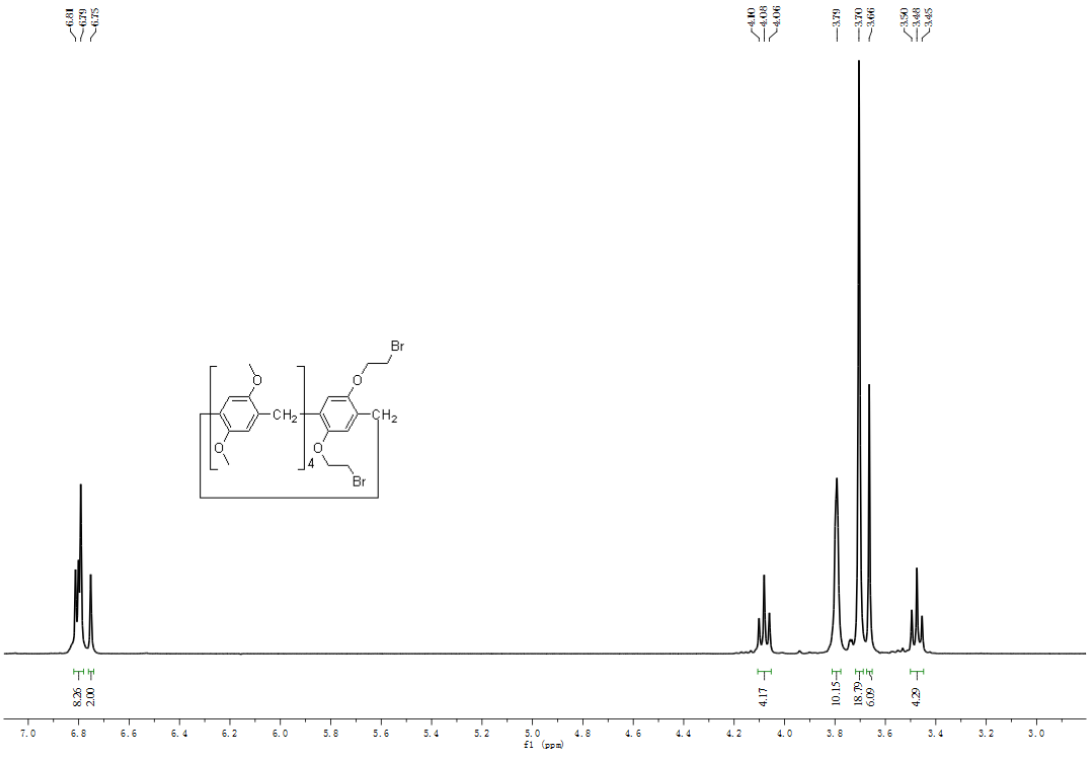
Compounds **1**[S3] and **5**[S4] were prepared according to the previously reported method.

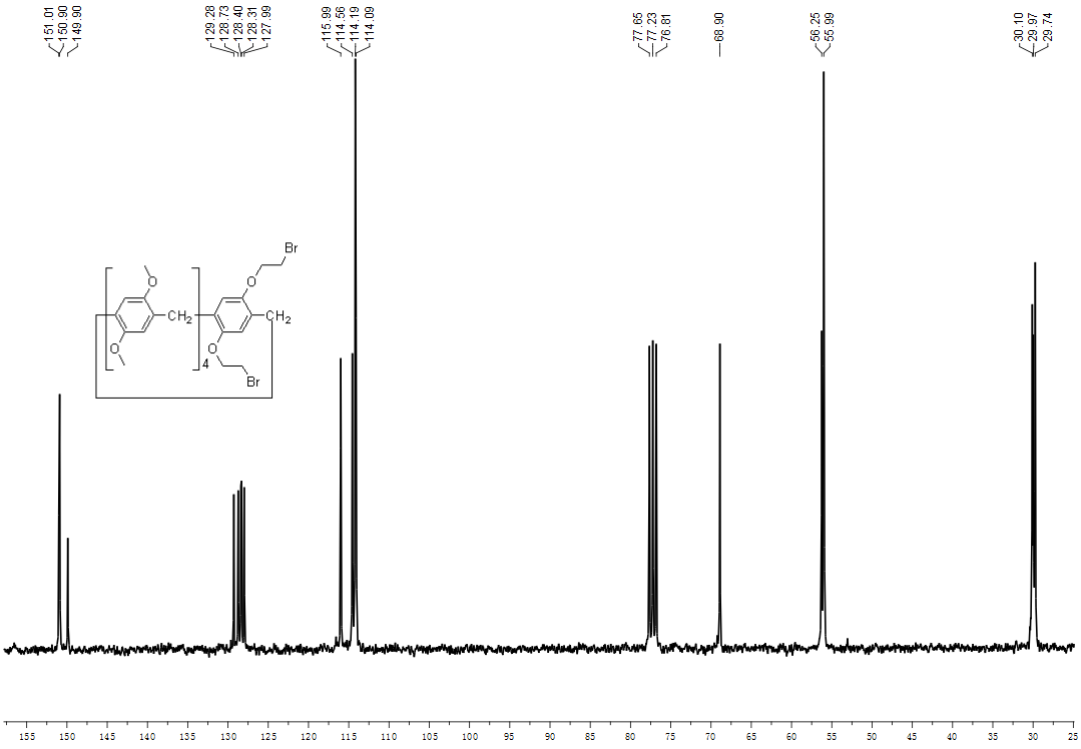


Scheme S1. Synthesis of the **UPy**-difunctionalized pillar[5]arene host **H1**.

Preparation of compound 2[S5]

1,4-dimethoxybenzene (8.84 g, 64 mmol), **1** (1.3 g, 4 mmol), paraformaldehyde (5.77 g, 192 mmol) were dissolved in CH_2Cl_2 (350 mL). After cooling to 0°C, $FeCl_3$ (1.6 g, 10 mmol) was added under argon atmosphere, then the mixture was stirred at 0 ºC for 1 h and then it was rose to room temperature for 4 h. After the reaction was completed, water (50 mL) was added and the organic layer was washed with water (100 mL), saturated brine (100 mL) and dried over Na_2SO_4. Then, the solvent was removed under vacuum and the residue was purified by silica-gel flash column chromatography using petroleum ether/CH_2Cl_2/EtOAc (100:200:1) as the eluent. The desired product **2** was obtained as a white solid (2.4 g, 64.1%). ^{1}H NMR spectra for **2** was shown as following: ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 6.80 (d, J = 6.3 Hz, 8H), 6.75 (s, 2H), 4.08 (t, J = 6.2 Hz, 4H), 3.79 (s, 10H), 3.70 (br s, 18H), 3.66 (s, 6H), 3.48 (t, J = 6.2 Hz, 4H). ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 151.01, 150.90, 149.90, 129.28, 128.73, 128.40, 128.31, 127.99, 115.99, 114.56, 114.19, 114.09, 68.90, 56.25, 55.99, 30.10, 29.97, 29.74. ESI-MS (m/z): 959.10 $[M + Na]^+$.

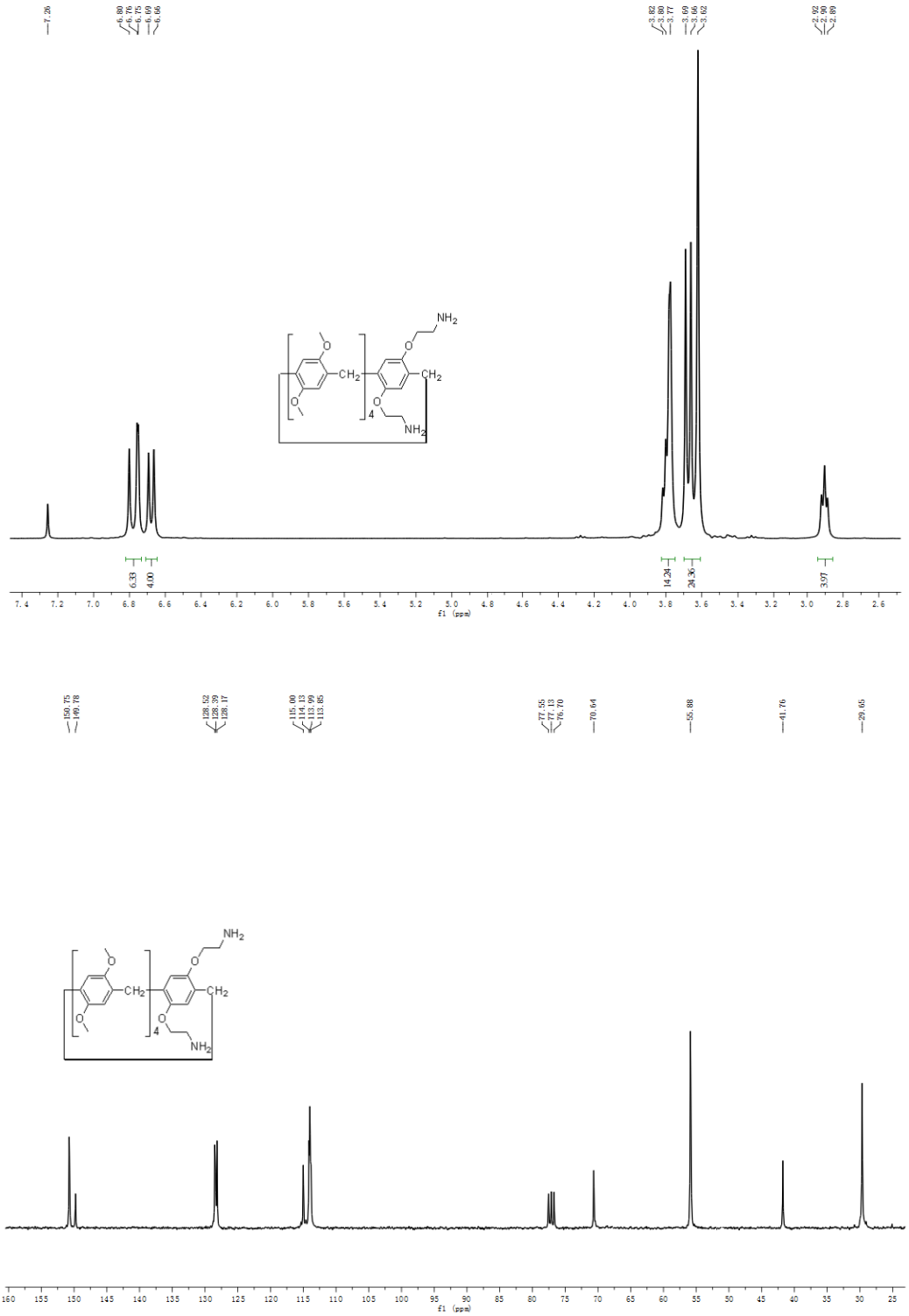




Preparation of compound 4

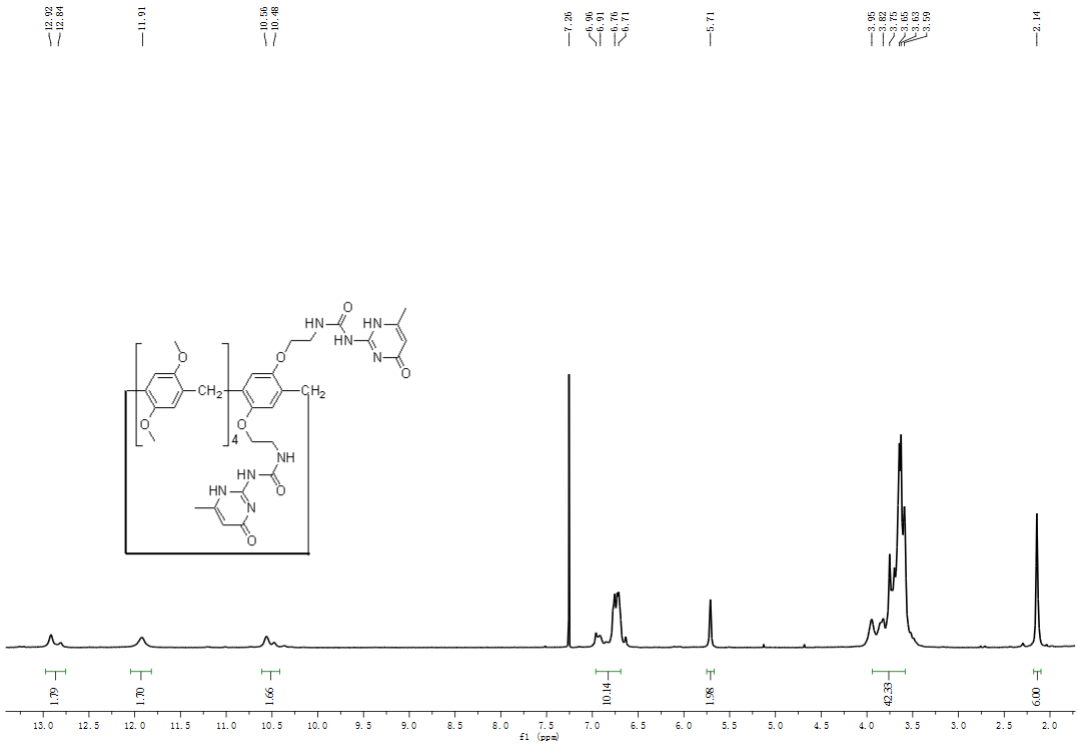
A solution of **2** (2.0 g, 2.14 mmol) and potassium phthalimide (0.95 g, 5.13 mmol) were heated in DMF (50 mL) at 40 °C overnight. Then, removed the solvent and added water (50 mL), extracted with DCM (50 mL × 5 times), dried over Na_2SO_4. Then, the solvent was removed under vacuum and the desired product **3** was obtained as a light yellow solid (1.5 g, 93.5%), which was used to next step without further purification. Then, compound **3** (1.5 g, 1.4 mmol) was dissolved in THF (100 mL) and hydrazine monohydrate (1 mL) was added in. The reaction mixture was refluxed for 24 h, and then concentrated HCl (1 mL) was added dropwise and the mixture was refluxed for a further 1h. Removal of the solvent gave the hydrochloride salt as a white solid. Water (100 mL) was added into above mixture, and the solution was neutralized with NaOH (10%), extracted with DCM (50 mL×5), and washed with saturated salt water (50 mL × 2), dried over Na_2SO_4. Then, the solvent was removed under vacuum and the residue was purified by silica-gel flash column chromatography using CH_2Cl_2/MeOH (3:1) as the eluent. The desired product **4** was obtained as a white solid (0.95 g, 84.9%). ^{1}H NMR and ^{13}C NMR spectra for **4** was shown as following: ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm): 6.82-6.73 (m, 6H), 6.68 (d, J = 8.9 Hz, 4H), 3.82-3.75 (m, 14H), 3.70-3.61 (m, 24H), 2.90 (t, J = 5.0 Hz, 4H). ^{13}C NMR (75 MHz, $CDCl_3$)

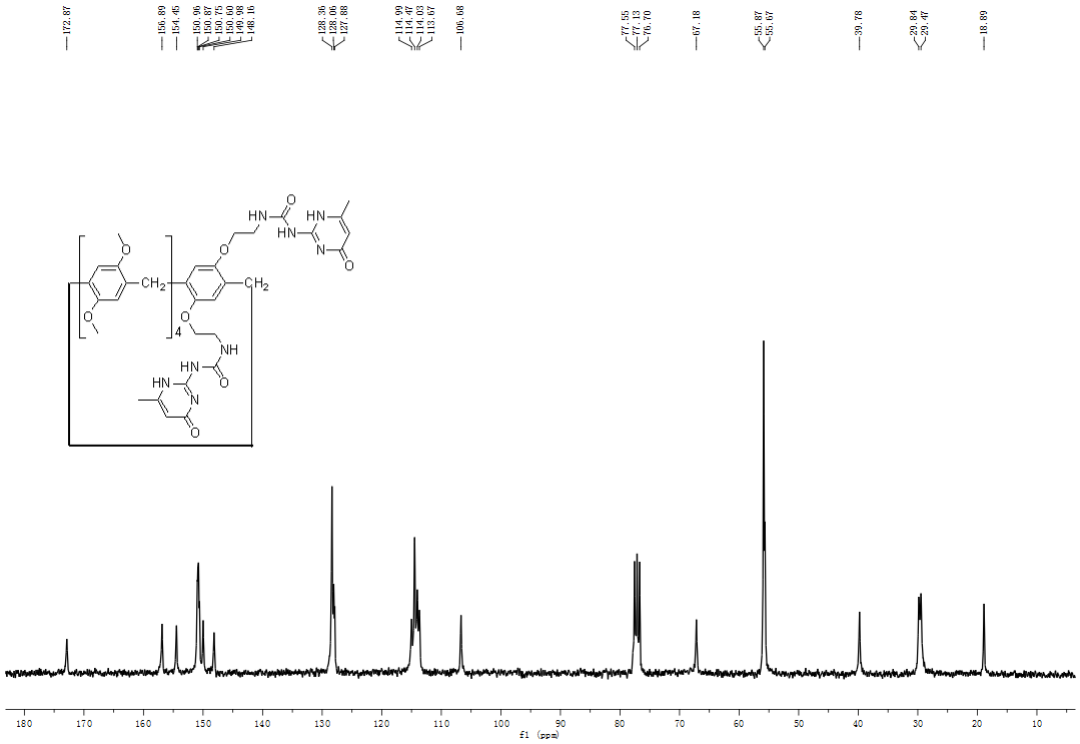
δ (ppm): 150.75, 149.78, 128.52, 128.39, 128.17, 115.00, 114.13, 113.99, 113.85, 70.64, 55.88, 41.76, 29.65. ESI-MS (m/z): 809.35 $[M + H]^+$. M.p. 141-142 °C.



Preparation of compound H1

Compound **4** (0.41 g, 0.5 mmol) and **5** (0.44 g, 2.0 mmol) were dissolved in dry $CHCl_3$ (10 mL) and this solution was stirred under nitrogen at 60 °C overnight. To the reaction mixture 50 mL of dry $CHCl_3$ was added and the organic layer was washed with 1N HCl (30 mL), saturated $NaHCO_3$ (30 mL), brine (30 mL), and dried over Na_2SO_4. After the solvent was removed, the resulting residue was subjected to column chromatography CH_2Cl_2/MeOH 100:1 (*v*/*v*), to give **H1** (0.5 g, 89.9%) as white powder. ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm): 12.88 (br s, 2H), 11.91 (s, 2H), 10.52 (br s, 2H), 6.96-6.71 (m, 10H), 5.71 (s, 2H), 3.95-3.59 (m, 42H), 2.14 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$) δ (ppm): 172.87, 156.89, 154.45, 150.96, 150.87, 150.75, 150.60, 149.98, 148.16, 128.36, 128.06, 127.88, 114.99, 114.47, 114.03, 113.67, 106.68, 67.18, 55.87, 55.67, 39.78, 29.84, 29.47, 18.89. ESI-MS (m/z): 1111.25 $[M + H]^+$. HR-ESI-MS: *m*/*z* calcd for $[M+H]^+$ $C_{47}H_{70}N_8O_{14}$, 1111.4777; Found 1111.4782. M.p. 201-202 °C.





References:

S1. P. R. Ashton, R. Ballardini, V. Balzani, M. Belohradsky, M. T. Gandolfi, D. Philp, L. Prodi, F. M. Raymo, M. V. Reddington, N. Spencer, J. F. Stoddart, M.Venturi and D. J. Williams, *J. Am. Chem. Soc.,* 1996, **118**, 4931−4951.

S2. B. J. B. Folmer, R. P. Sijbesma, E. W. Meijer, *J. Am. Chem. Soc.*, 2001, **123**, 2093–2904; S.-L. Li, T. Xiao, W. Xia, X. Ding, Y. Yu, J. Jiang and L. Wang, *Chem. Eur. J.*, 2011, **17**, 10716–10723.

S3. J. Lee, S. Y. Kim, S. Park, J.-O. Lim, J.-M. Kim, M. Kang, J. Lee, S.-U. Kang, H.-K. Choi, M.-K. Jin, J. D. Welter, T. Szabo, R. Tran, L. V. Pearce, A. Toth and P. M. Blumberg, *Bioorg. Med. Chem.* 2004, **12**, 1055−1069.

S4. (a) F. H. Beijer, R. P. Sijbesma, H. Kooijman, A. L. Spek, E. W. Meijer, *J. Am. Chem. Soc.*, 1998, **120,** 6761−6769; (b) H. M. Keizer, R. P. Sijbesma and E. W. Meijer, *Eur. J. Org. Chem.*, 2004, 2553−2555.

S5. L. Liu, D. Cao, Y. Jin, H. Tao, Y. Kou and H. Meier, *Org. Biomol. Chem.*, 2011, **9**, 7007−7010.