Host-Guest Complexation Driven Dynamic Supramolecular Self-Assembly

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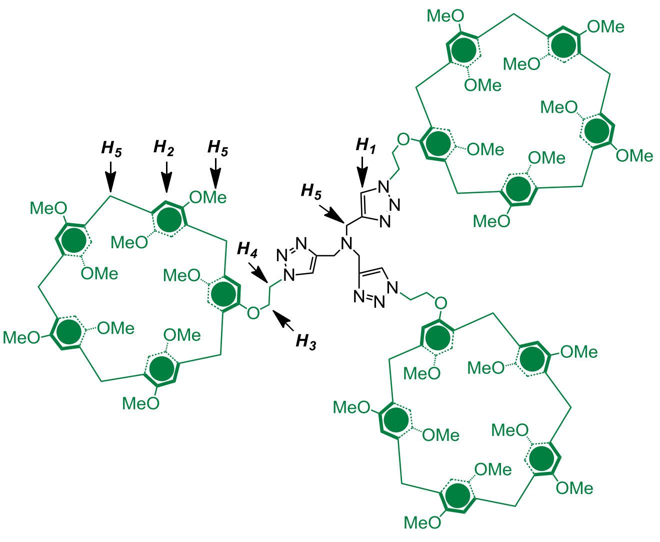
General Methods

Organic reagents were purchased from Aldrich and used without further purification. All the solvents and inorganic reagents were commercially available. Me_2CO was dried with anhydrous $MgSO_4$ before uses. 1,4-Dimethoxypillar[5]arene (Dmpillar)[S1] and azido-pillar[5]arene (**3**)[S2] were synthesized according to the literature procedures. UV-vis spectra were recorded with Shimadzu UV-3600 UV-Vis-NIR spectrophotometer at 298 K. The emission spectra were recorded on a Varian Cary Eclipse fluorescence spectrophotometer (Exited at 488 nm). Cyclic voltammetry (CV) was performed on a GAMRY Reference 600 potentiostat / galvanostat / ZRA system with a three electrode cell in a Me_2CO solution containing tetrabutylammonium hexafluorophosphate ($TBAPF_6$, 0.01 mM) at a scan rate of 200 mV s^{-1}. A Pt disk (d = 2 mm) was used as the working electrode, a Pt wire was used as the counter electrode, and a Ag / AgCl (saturated with KCl) electrode was used as the reference electrode. The stock solutions (10^{-1} mol•L^{-1} and 10^{-3} mol•L^{-1}) of the complexes **1•2** and DMpillar•**2** were prepared with anhydrous Me_2CO. All the sample solutions for the investigation of the critical assembly concentration were freshly prepared by diluting the stock solutions according to literature procedures.[S3]

^1H nuclear magnetic resonance (^1H NMR) spectra were recorded at room temperature on Bruker Avance 300 with working frequencies of 300 MHz for ^1H and 75 MHz for ^{13}C nuclei. Variable temperature ^1H NMR, variable concentration ^1H NMR and ^1H NOESY NMR were recorded on a BBFO 400 spectrometer. Chemical shifts were reported in ppm relative to the signals corresponding to the residual non-deuterated solvent (Me_2CO: δ 2.09 ppm), and coupling constants were recorded in Hertz (Hz). All ^{13}C NMR spectra were recorded with the simultaneous decoupling of ^1H nuclei. The following abbreviations were used to explain the multiplicities: *s*, singlet; *d*, doublet; *t*, triplet; *b*, broad peaks; *m*, multiplet or overlapping peaks. The high resolution time-of-flight mass spectrometry (TOFMS) was performed on a Waters Q-tof Premier MS spectrometer.

Negative-stained TEM images was recorded on a JEM 1400 electron microscope (120 kV) equipped with slow scan CCD and using cold cathode field emission as the gun. The samples for negative-stained TEM were prepared by dropping a droplet of the orange sample solution onto a TEM grid (copper grid, 300 meshes, coated with carbon film), immediately followed by staining with 1% sodium phosphotungstate in H_2O (about 2 μL) and allowing to air-dry. SEM images were obtained on a JSM 6340 scanning electron microscope (0.5−30 kV) equipped with Cold cathode FEG as electron source. Fluorescent microscopy images were recorded by using Nikon confocal microscope. DLS measurements were carried out with a Zetasizer Nano ZS instrument from Malvern Instruments Ltd. at 298 K using a 633 nm ‘red’ laser. The mean hydrodynamic size was calculated with Zetasizer software.

Syntheses of Compounds 1 and 2



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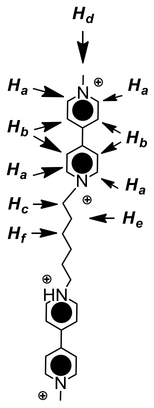

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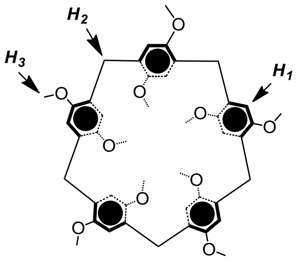
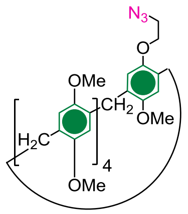


DMpillar



3

1: Tripropargylamine (14.0 mg, 0.11 mmol), **3** (270 mg, 0.33 mmol), tetrakis(acetonitrile) copper(I) hexafluorophosphate (12.3 mg, 0.033 mmol), and tris[(1-benzyl-1H-1,2,3-triazol-4-yl)methyl] amine (TBTA) were dissolved in Me_2CO (20 mL). The mixture solution was stirred under reflux for 2 d. The solution was then poured into H_2O (200 mL). The aqueous phase was extracted (3 × 200 mL) with CH_2Cl_2. The combined organic layers were dried (Mg_2SO_4) and the solvent was removed in vacuum. The mixture was subjected to column chromatography (SiO_2, gradient elution from 2% up to 7% MeOH in CH_2Cl_2) to afford **1** (255.1 mg) in 91% yield. ^{1}H NMR (300 MHz, *d*-acetone): δ = 7.34 (s, 1H), 6.88-6.84 (m, 10H), 4.80 (s, 2H), 4.29 (s, 2H), 3.72 (s, 42H). ^{13}C NMR (75 MHz, *d*-acetone): δ =150.9, 150.4, 148.8, 129.2, 128.5, 128.2, 128.0, 127.9, 120.1, 113.5, 55.0, 52.2, 48.8. HR-MS (ESI): $C_{147}H_{163}N_{10}O_{30}$ calcd for *m/z* = 2549.1507, found *m/z* = 2549.1497 $[M + H]^+$.

2: The compound **2** was synthesized according to the reported method.[S4] ^{1}H NMR (300 MHz, *d*-acetone): δ = 9.38 (t, J = 6 Hz, 8H), 8.81 (d, *J* = 6 Hz, 8H), 4.95 (t, *J* = 6 Hz, 4H), 4.76 (s, 6H), 2.24 (s, 4H), 1.61 (s, 4H). ^{13}C NMR (75 MHz, *d*-acetone): δ = 152.9, 149.8, 149.0 146.6, 145.9

126.9, 62.0, 48.5, 30.7, 25.8. HR-MS (ESI): $C_{28}H_{34}N_4F_{18}P_3$ calcd for *m/z* = 861.1709, found *m/z* = 861.1724 $[M]^+$.

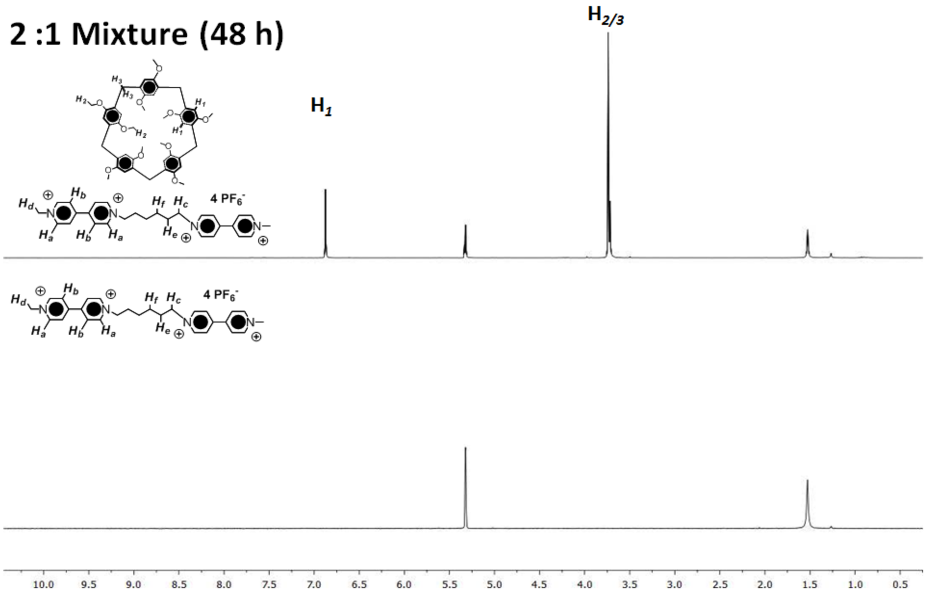


Fig. S1 ^{1}H NMR spectra (400 MHz, room temperature) of (upper) DMpillar[5]arene and **2** with a 2:1 molar ratio (1 mM) and (down) pure **2** in CD_2Cl_2. The compound **2** has a poor solubility in CD_2Cl_2.

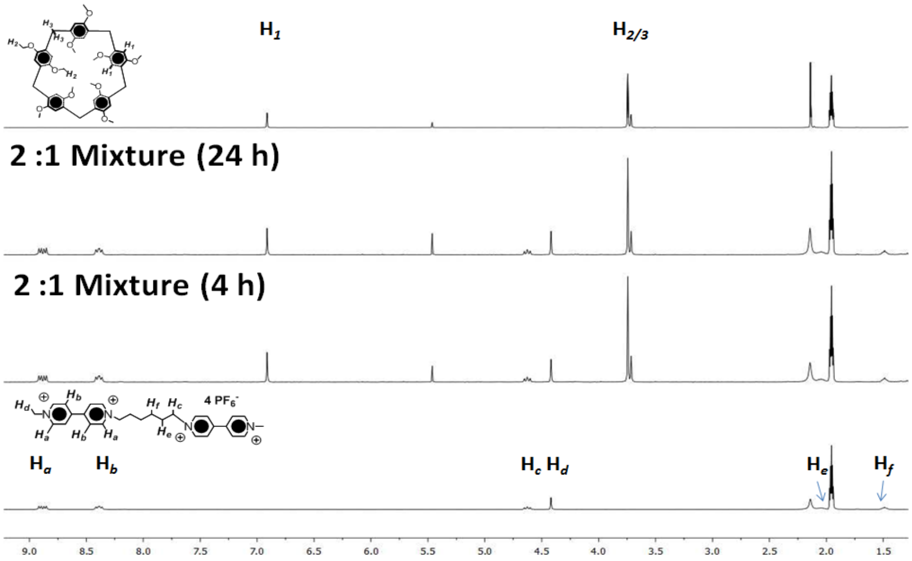


Fig. S2 ^{1}H NMR spectra (400 MHz, room temperature) of DMpillar[5]arene and **2** with a 2:1 molar ratio (1 mM), pure **2**, and pure DMpillar[5]arene in MeCN-d_3. No chemical shifts can be observed in MeCN-d_3 even after 24h.

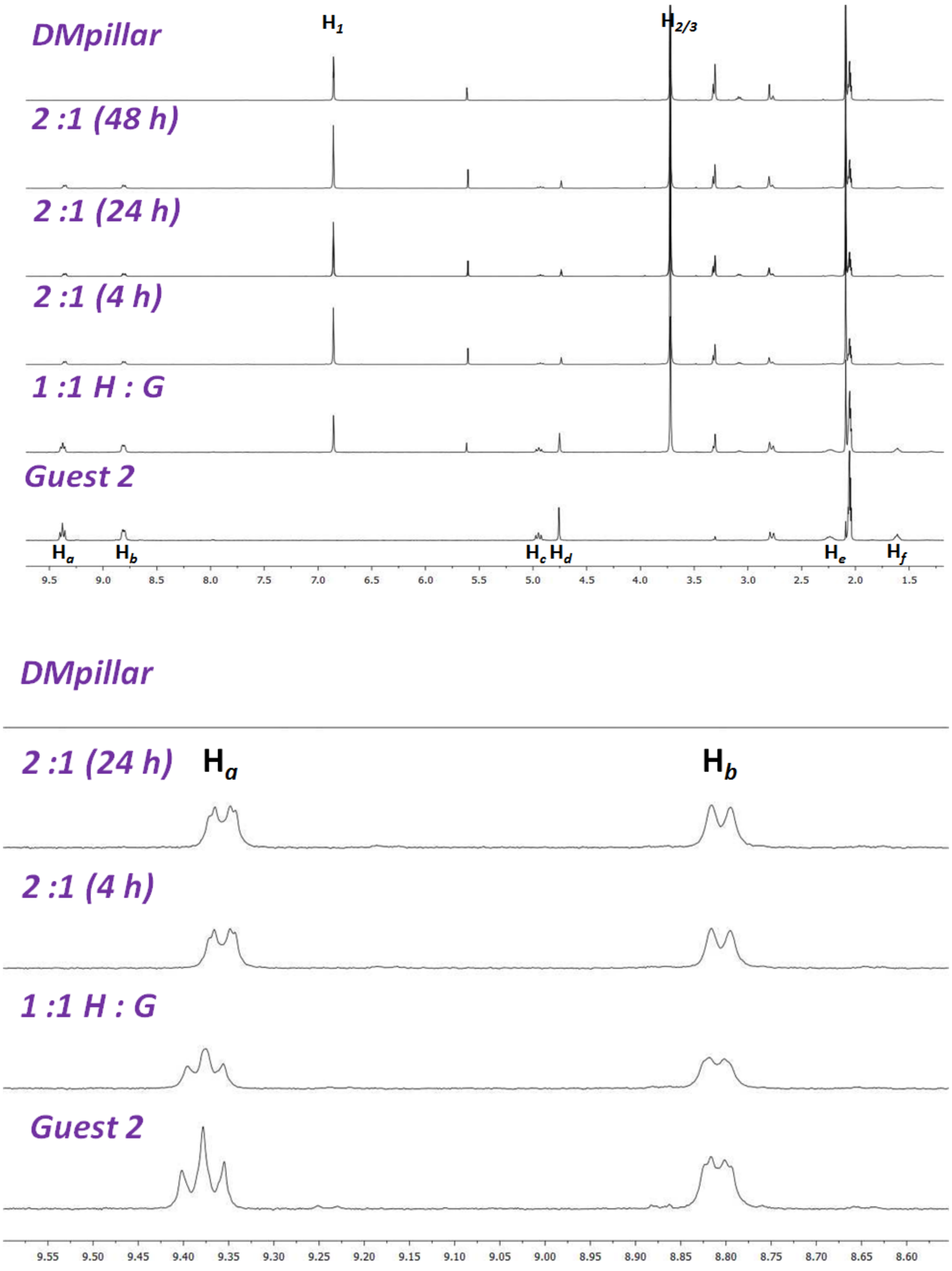


Fig. S3 ^{1}H NMR spectra (400 MHz, room temperature) of compound **2**, DMpillar[5]arene, and the complex of DMpillar[5]arene with **2** in 1:1 or 1:2 molar ratio (1 mM) in Me$_2$CO-d_6 with full (up) and selected area (bottom).

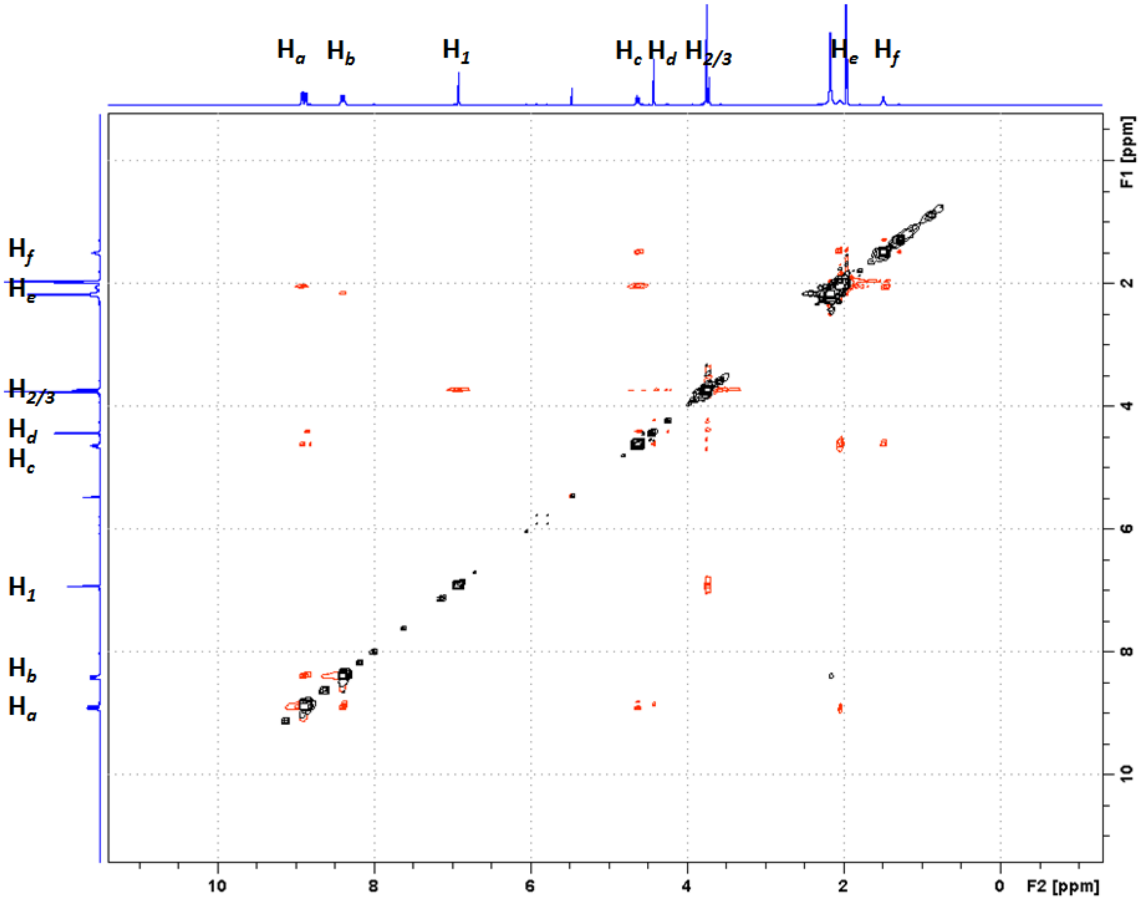
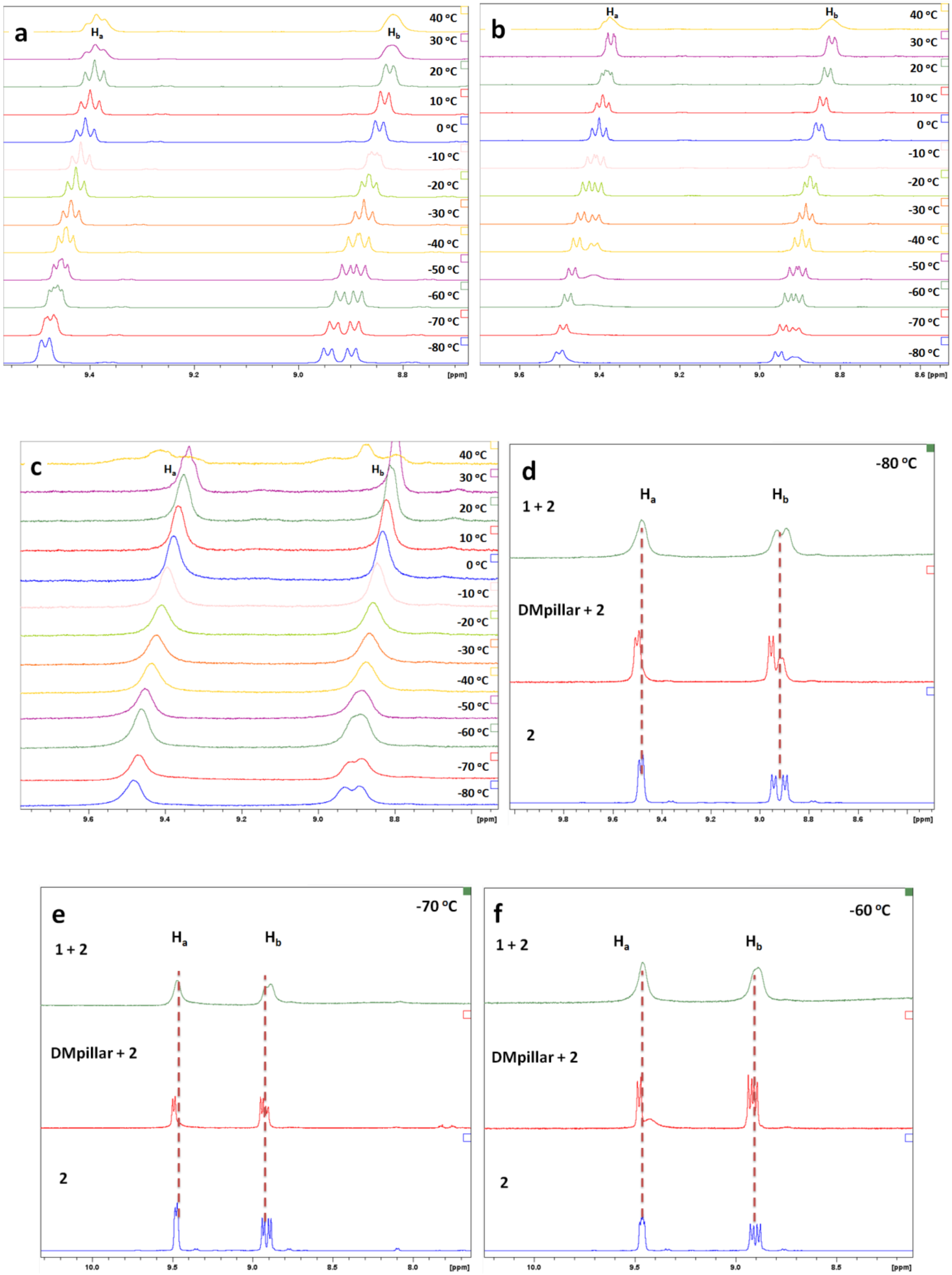


Fig. S4 ^{1}H NOESY NMR spectra (400 MHz) of the mixture of DMpillar with compound **2** in a 2:1 molar ratio (1 mM) in MeCN-d_3 at ambient temperature.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H_a
H_b
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30 °C
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e
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DMpillar + 2
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f
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1 + 2
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DMpillar + 2
2
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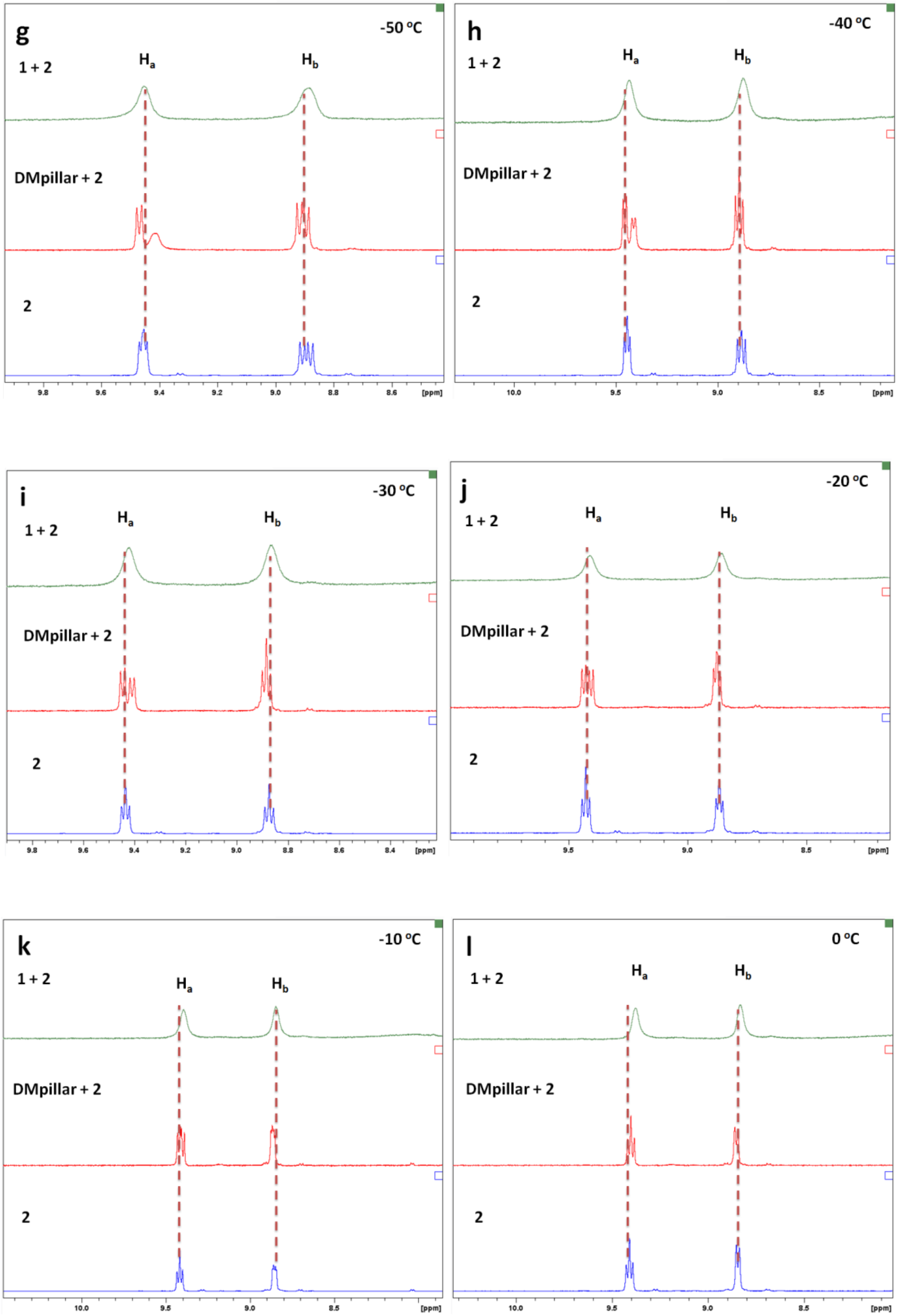
g
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1 + 2
H_a
H_b
DMpillar + 2
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9.6
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h
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1 + 2
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DMpillar + 2
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10.0
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i
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DMpillar + 2
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H_a
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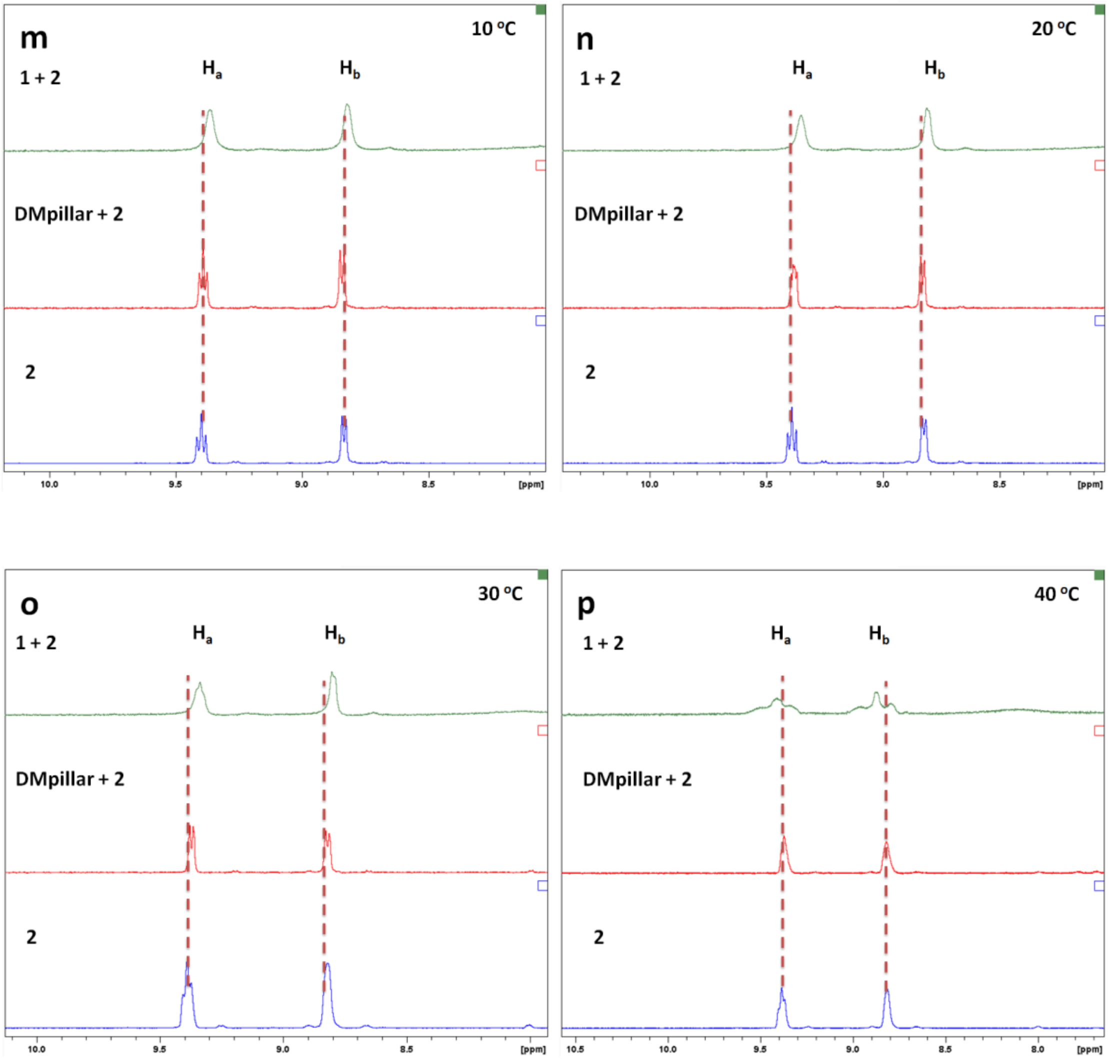


Fig. S5 Partial VT ^{1}H NMR spectra (400 MHz, 1 mM, Me$_2$CO-*d*$_6$) of (a) compound **2**, (b) the complex of DMpillar and **2**, and (c) the complex of **1** and **2**. Partial ^{1}H NMR spectra (400 MHz) of the complex of DMpillar[5]arene and **2** with a 1:2 molar ratio (1 mM), the complex of **1** and **2** with a 2:3 molar ratio (1 mM), and pure **2** (1 mM) in Me$_2$CO-*d*$_6$ at variable temperatures of (d) -80 ^{o}C, (e) -70 ^{o}C, (f) -60 ^{o}C, (g) -50 ^{o}C, (h) -40 ^{o}C, (i) -30 ^{o}C, (j) -20 ^{o}C, (k) -10 ^{o}C, (l) 0 ^{o}C, (m) 10 ^{o}C, (n) 20 ^{o}C, (o) 30 ^{o}C and (p) 40 ^{o}C.

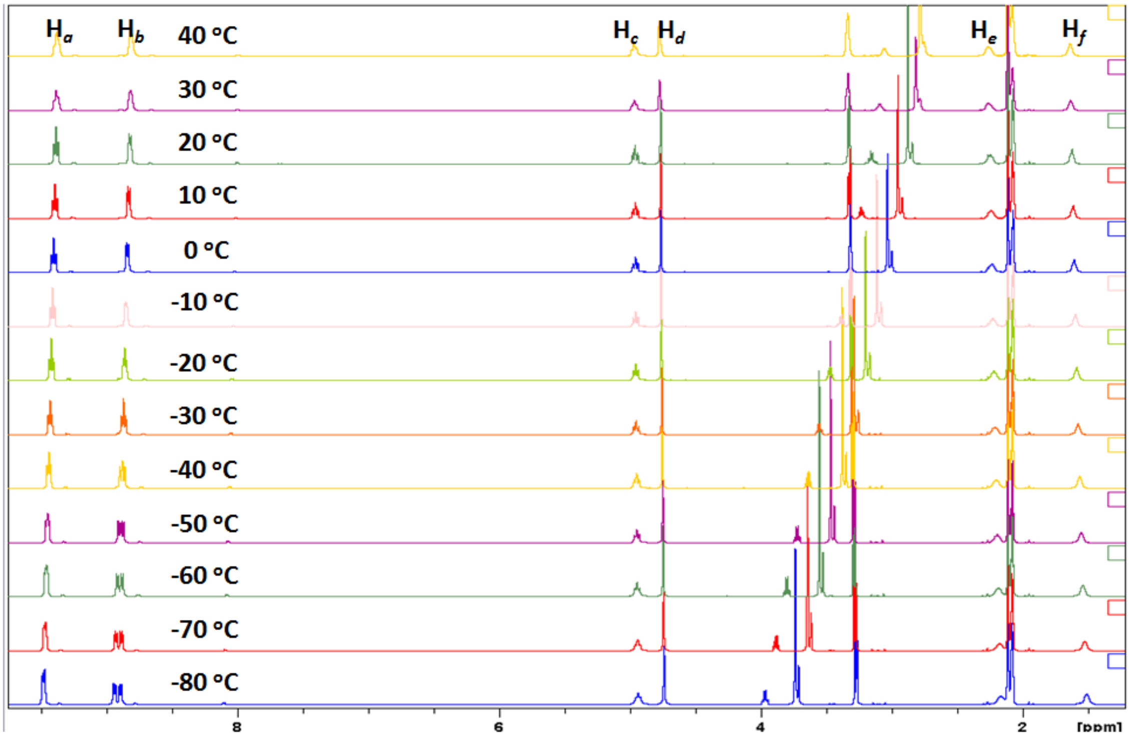


Fig. S6 Full VT ^{1}H NMR spectra (400 MHz) of the compound **2** (1mM) in Me_2CO-d_6 at variable temperatures.

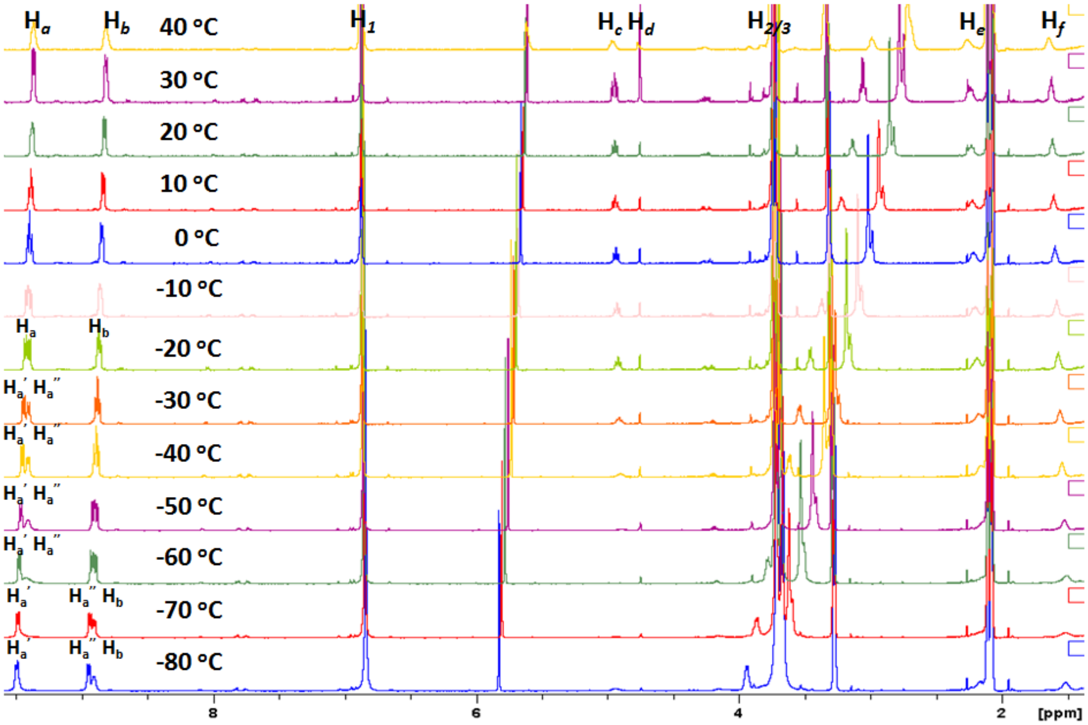


Fig. S7 Full VT ^{1}H NMR spectra (400 MHz) of the complex of DMpillar with compound **2** (1 mM) in a 2:1 molar ratio in Me_2CO-d_6 at variable temperatures.

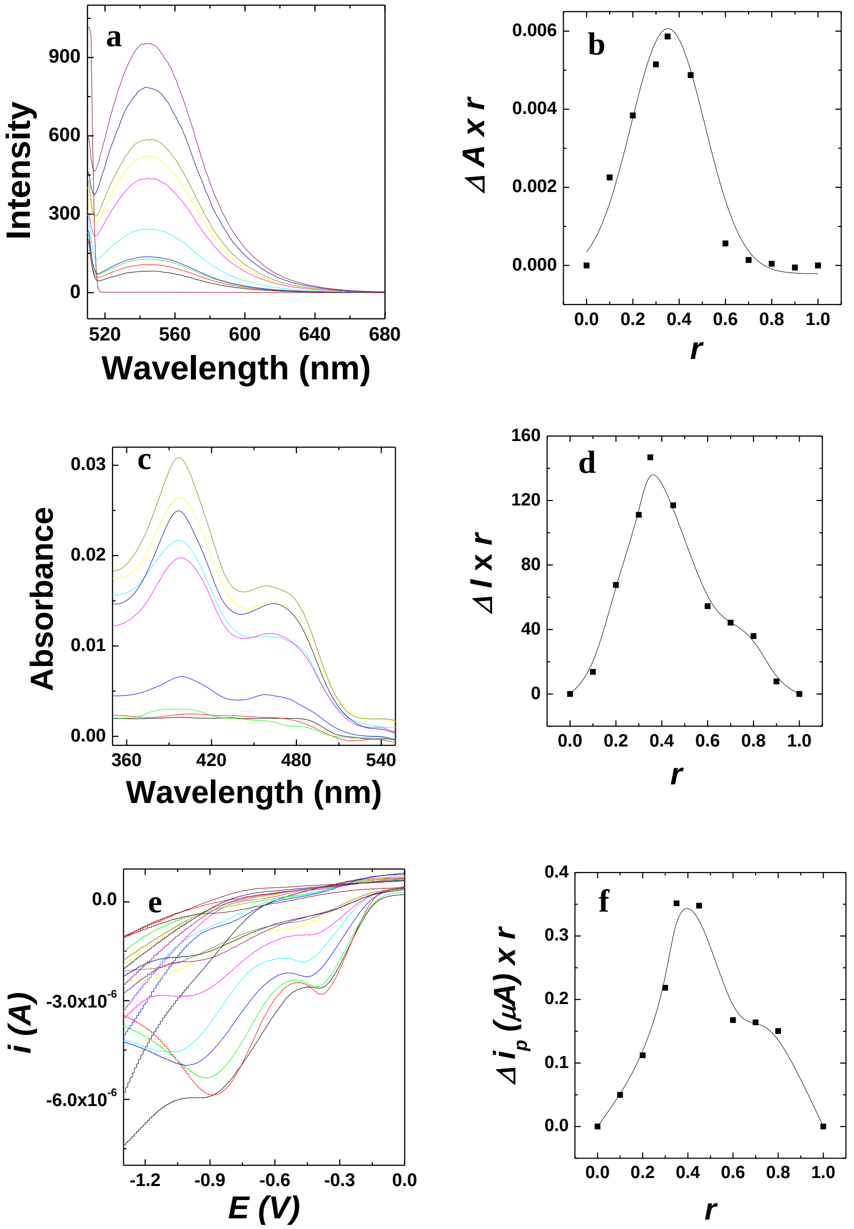


Fig. S8 (a) Fluorescent spectra of the complex of DMpillar and **2** (curves from top to bottom, molar ratios from 0 : 10 to 10 : 0) in Me_2CO solution (0.01 ~ 0.1 mM), excited at 510 nm. (b) Job's plot of *ΔI*×*r* vs *r* detected by fluorescent intensity at 540 nm. (c) UV spectra of the complex of DMpillar and **2** (curves from top to bottom, molar ratios from 0 : 10 to 10 : 0) in Me_2CO solution (0.01 ~ 0.1 mM). (d) Job's plot of *ΔA*×*r* vs *r* detected by UV absorption at 400 nm. (e) Cyclic voltammograms of the complex of DMpillar and **2** with the molar ratios from 0 : 10 to 10 : 0 in Me_2CO (0.01 ~ 0.1 mM) with $TBAPF_6$ (0.01 mM) as the supporting electrolyte, recorded with a Pt disk (*d* = 2 mm) electrode at a scan rate of 200 mVs^{-1}. (f) Job's plot of $\Delta I_p \times r$ vs *r* detected by the peak current (I_p) value. [*r* = [Guest] / ([Host]+[Guest])]

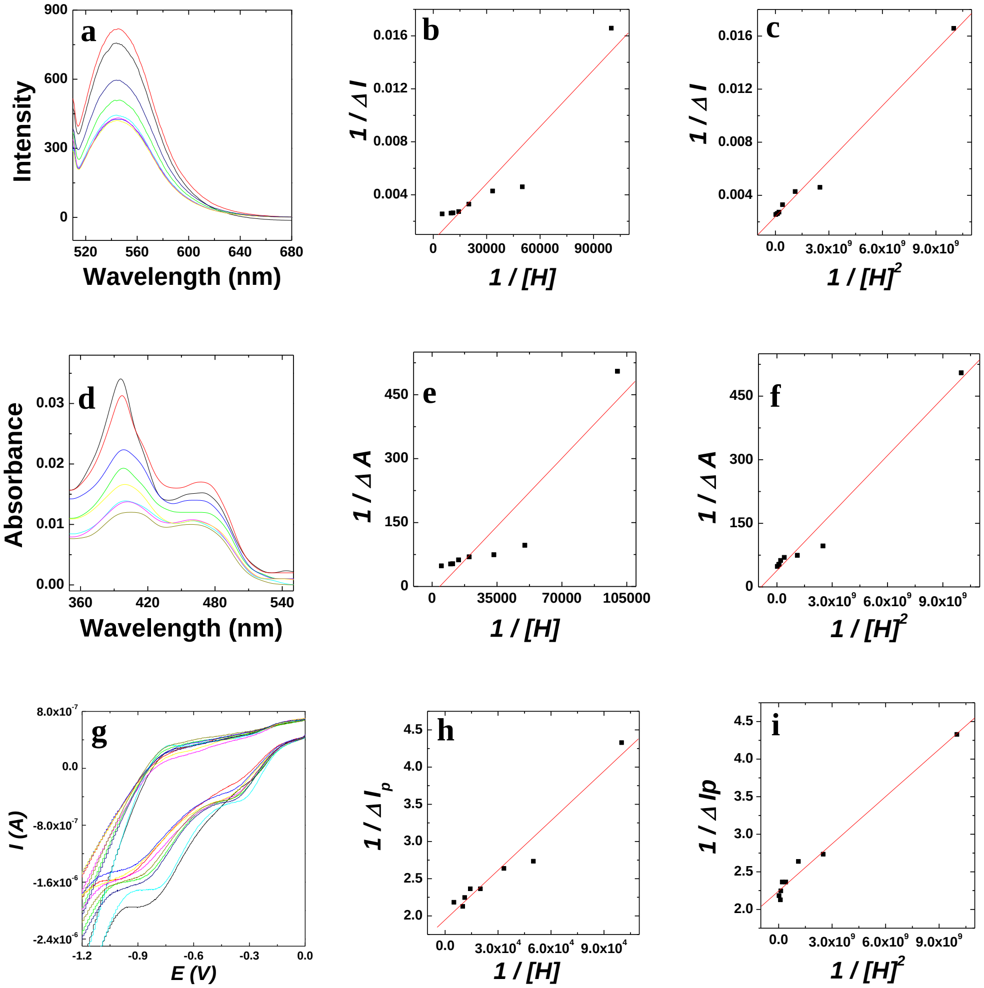


Fig. S9 (a) Fluorescent spectra of the complex of DMpillar and **2** (curves from top to bottom, molar ratios = 0 : 1, 1 : 1, 2 : 1, 3 : 1, 5 : 1, 7 : 1, 9 : 1, 10 : 1, 20 : 1) in Me_2CO solution (~ 10^{-5} mM), excited at 510 nm. (b) The plot of *1 / ΔI* vs *1 / [Host]* detected by fluorescent intensity at 540 nm. $K = 3.86 \times 10^3$ M^{-1}, $R = 0.9486$. (c) The plot of *1 / ΔI* vs $1 / [Host]^2$ detected by fluorescent intensity at 540 nm. $K = 1.71 \times 10^9$ M^{-2}, $R = 0.9939$. (d) UV spectra of the complex of DMpillar and **2** (curves from top to bottom, molar ratios = 0 : 1, 1 : 1, 2 : 1, 3 : 1, 5 : 1, 7 : 1, 9 : 1, 10 : 1, 20 : 1) in Me_2CO solution (~ 10^{-5} mM). (e) The plot of *1 / ΔI* vs *1 / [Host]* detected by UV absorption at 400 nm. $K = 4.1 \times 10^3$ M^{-1}, $R = 0.9268$. (f) The plot of *1 / ΔI* vs $1 / [Host]^2$ detected by UV absorption at 400 nm. $K = 8.52 \times 10^8$ M^{-2}, $R = 0.9880$. (g) Cyclic voltammograms of the complex of DMpillar and **2** (~10^{-5} M, curves from bottom to up, molar ratios = 0 : 1, 1 : 1, 2 : 1, 3 : 1, 5 : 1, 7 : 1, 9 : 1, 10 : 1, 20 : 1) in Me_2CO with $TBAPF_6$ (10^{-5} M) as the supporting electrolyte, recorded with a Pt plate (*d* = 2 mm) electrode at a scan rate of 200 mVs^{-1}. (h) The plot of $1 / \Delta I_p$ vs $1 / [Host]$ detected by the I_p value. $K = 8.7 \times 10^3$ M^{-1}, $R = 0.9772$. (i) The plot of $1 / \Delta I_p$ vs $1 / [Host]^2$ detected by the I_p value. $K = 1.07 \times 10^9$ M^{-2}, $R = 0.9919$.

Table S1 Stoichiometry (n) and apparent binding constant (*K*) were calculated according to Benesi–Hildebrand equation,[S5] $1/\Delta X = 1/\alpha + 1/\alpha K[\mathrm{Host}]^n$ with the plot of $1/\Delta X$ vs $1/[\mathrm{Host}]^n$ determined by UV, fluorescent and CV. The ΔX stands for the changes of absorbance (ΔA), fluorescent emission intensity (ΔI) and peak current (ΔI_p) of **2** in the presence of DMpillar. As shown in Figure S8, the plot of $1/\Delta X$ vs $1/[\mathrm{Host}]^2$ has a good linear least-squares fit with a better correlation coefficient than that of the plot of $1/\Delta X$ vs $1/[\mathrm{Host}]$, indicating that the stoichiometry of the inclusion complex between DMpillar and the compound **2** is 2 : 1. The stoichiometry was also confirmed by the continuous Job's variation method (Job's plot)[S6] as shown in Figure S7. According to previous reports about pillararene-based inclusion complexes,[S7] average binding constant (*K*) for the 1 : 1 complexation between DMpillar and guests is around 10^3 M^{-1}. Stable complexes can be formed and detected with both low *K* (~10 M^{-1}) and high *K* (~10^4 M^{-1}). The *K* of the 2 : 1 inclusion complex between DMpillar and the compound **2** here is around 10^9 M^{-2}. This is reasonable, since the compound **2** has two recognition sites for the complexation and the *K* of a 2 :1 inclusion complex calculated by Benesi–Hildebrand equation is exponentially higher than that of a 1 : 1 inclusion complex.

Method	**H : G (n)**	***K***	***R***
UV	1 : 1	3.86×10^3 M^{-1}	0.9486
	2 : 1	1.71×10^9 M^{-2}	0.9939
Fluorescence	1 : 1	4.1×10^3 M^{-1}	0.9268
	2 : 1	8.52×10^8 M^{-2}	0.9880
CV	1 : 1	8.7×10^3 M^{-1}	0.9772
	2 : 1	1.07×10^9 M^{-2}	0.9919

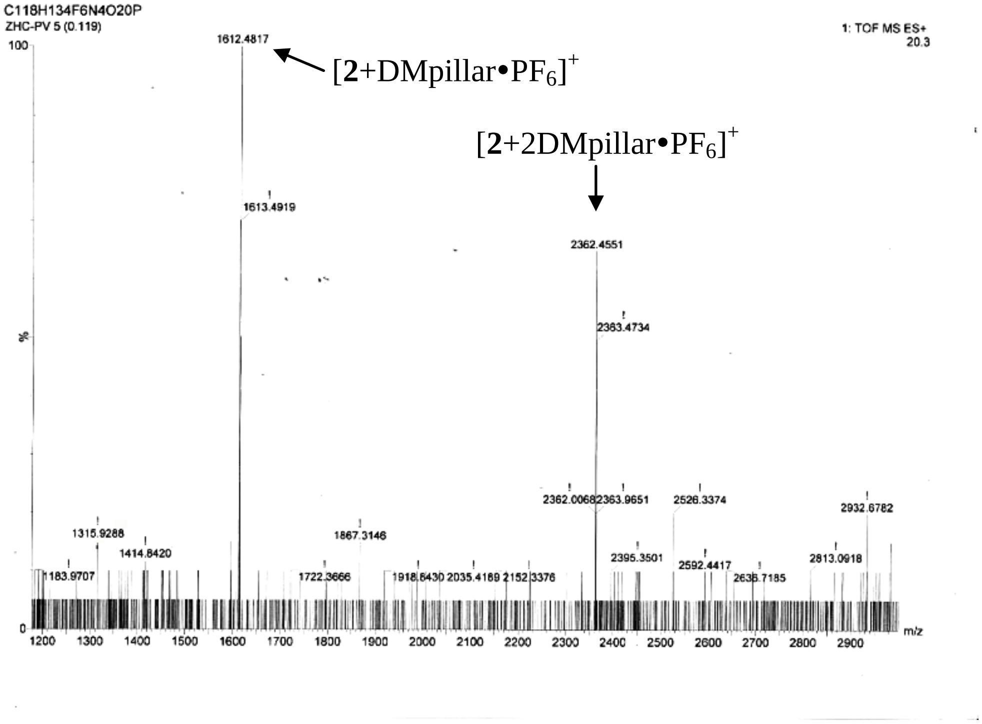
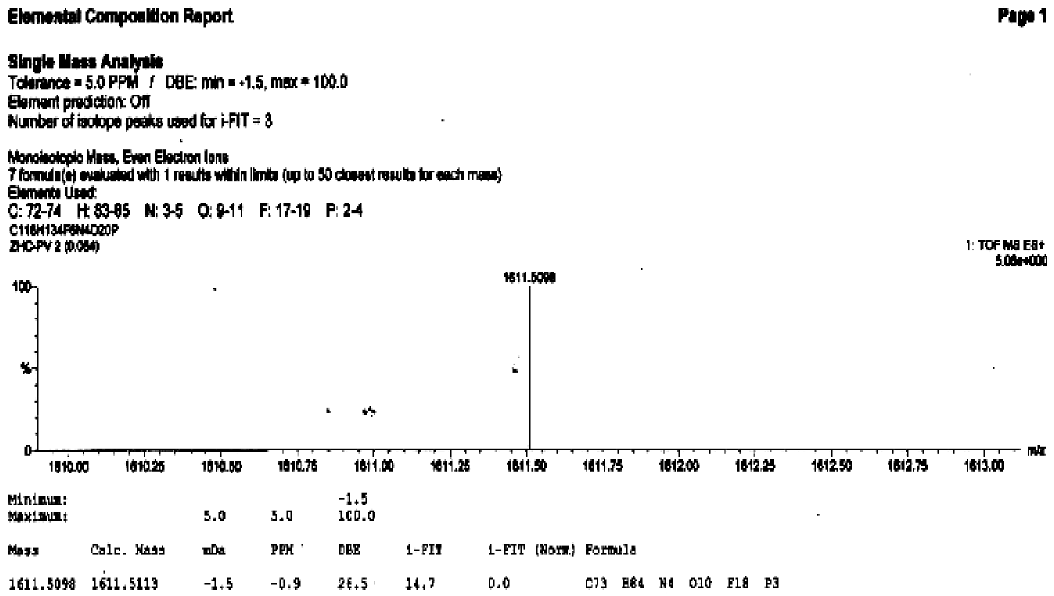


Fig. S10 Mass spectrometry (MS) is a very convenient technique for determining the stoichiometry of the charged pillararene complexes.[S8] Mass spectra of the 2 : 1 complex between DMpillar and **2** in Me_2CO solution is present.



Elemental Composition Report **Page 1**

Single Mass Analysis
Tolerance = 5.0 PPM / DBE: min = -1.5, max = 100.0
Element prediction: Off
Number of isotope peaks used for i-FIT = 3

Monoisotopic Mass, Even Electron Ions
7 formula(e) evaluated with 1 results within limits (up to 50 closest results for each mass)
Elements Used:
C: 72-74 H: 83-85 N: 3-5 O: 9-11 F: 17-19 P: 2-4
C118H134F6N4O20P
ZHC-PV 2 (0.054)

```
Minimum:                                 -1.5
Maximum:                    5.0    5.0   100.0

Mass       Calc. Mass   mDa    PPM    DBE    i-FIT   i-FIT (Norm) Formula

1611.5098  1611.5113    -1.5   -0.9   26.5   14.7    0.0          C73  H84  N4  O10  F18  P3
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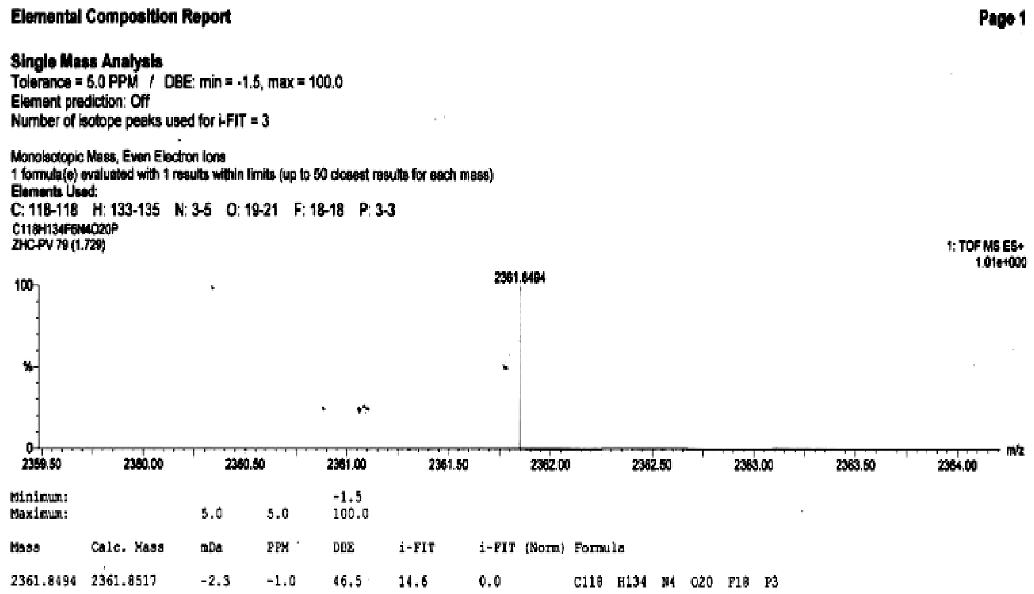

Elemental Composition Report **Page 1**

Single Mass Analysis
Tolerance = 5.0 PPM / DBE: min = -1.5, max = 100.0
Element prediction: Off
Number of isotope peaks used for i-FIT = 3

Monoisotopic Mass, Even Electron Ions
1 formula(e) evaluated with 1 results within limits (up to 50 closest results for each mass)
Elements Used:
C: 118-118 H: 133-135 N: 3-5 O: 19-21 F: 18-18 P: 3-3
C118H134F6N4O20P
ZHC-PV 79 (1.729)

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Minimum:                                 -1.5
Maximum:                    5.0    5.0   100.0

Mass       Calc. Mass   mDa    PPM    DBE    i-FIT   i-FIT (Norm) Formula

2361.8494  2361.8517    -2.3   -1.0   46.5   14.6    0.0          C118  H134  N4  O20  F18  P3
```

Fig. S11 High resolution TOF mass spectra of the 1 : 1 complex of DMpillar with **2** (up) [DMpillar+**2**−PF_6^-]$^+$ *Calc.* 1611.5113, *Found* 1611.5098, and the 2 : 1 complex of DMpillar with **2** (bottom) [2DMpillar+**2**−PF_6^-]$^+$ *Calc.* 2361.8517, *Found* 2361.8494.

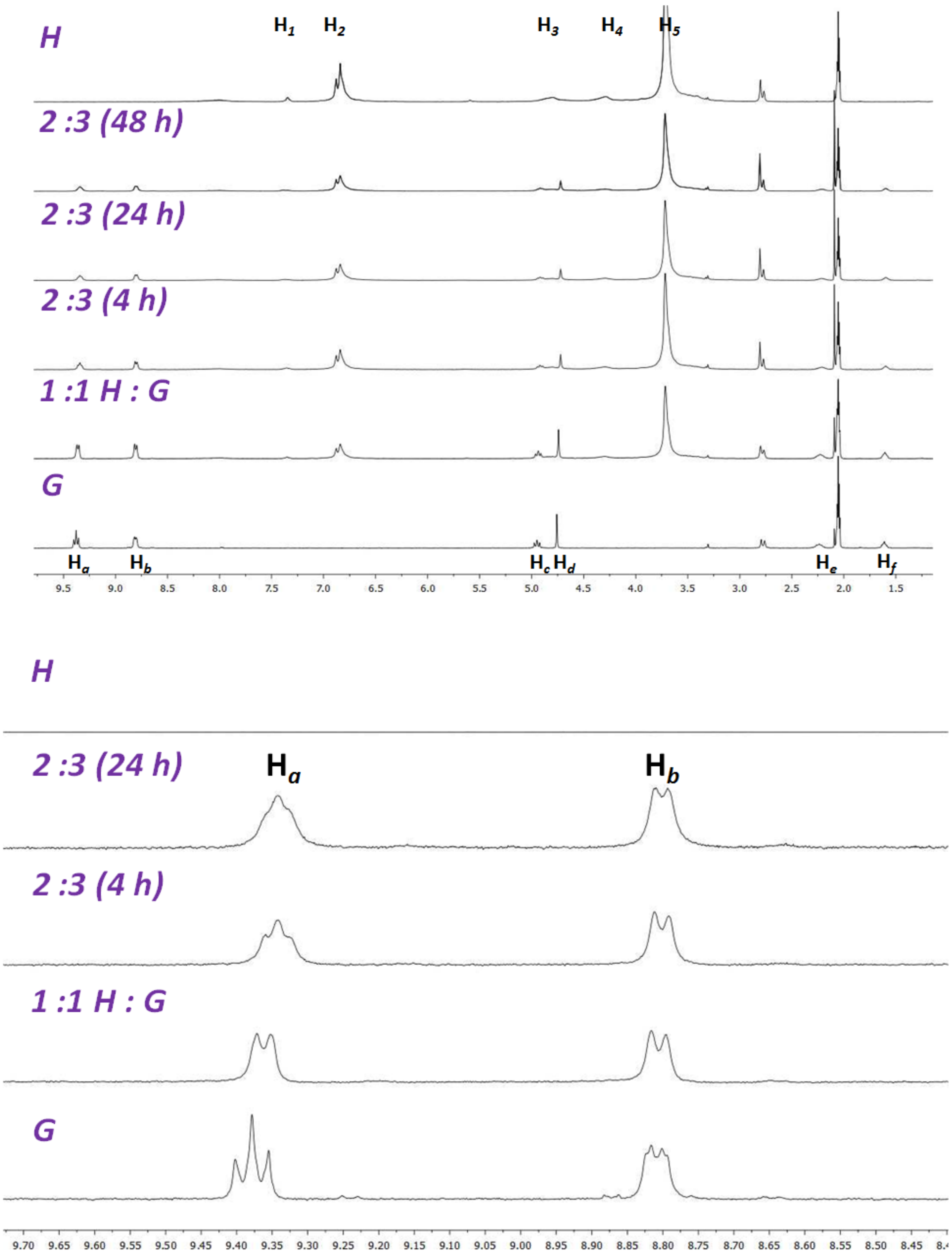

Fig. S12 ^{1}H NMR spectra (400 MHz, room temperature) of compound **1**, compound **2**, and the complex of **1** and **2** (1 mM) with 1:1 or 2:3 molar ratio in Me_2CO-d_6 with full (up) and selected area (bottom).

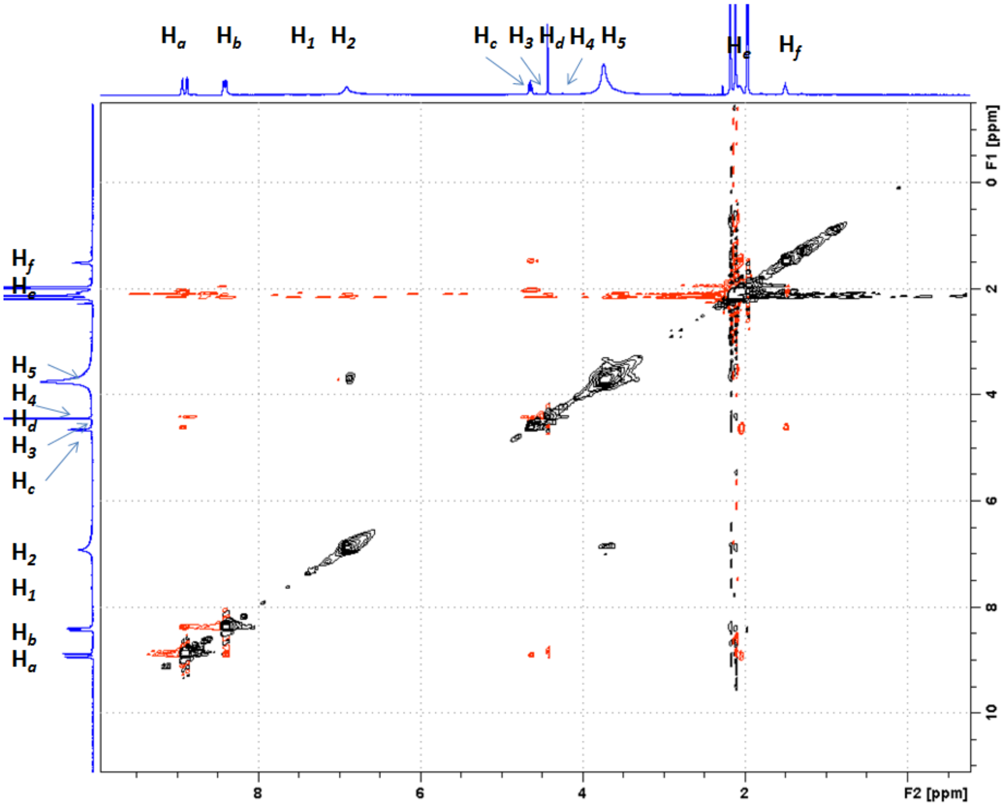

Fig. S13 ^{1}H NOESY NMR spectra (400 MHz) of the mixture of trimer **1** with compound **2** in a 2:3 molar ratio (1 mM) in MeCN-d_3 at ambient temperature.

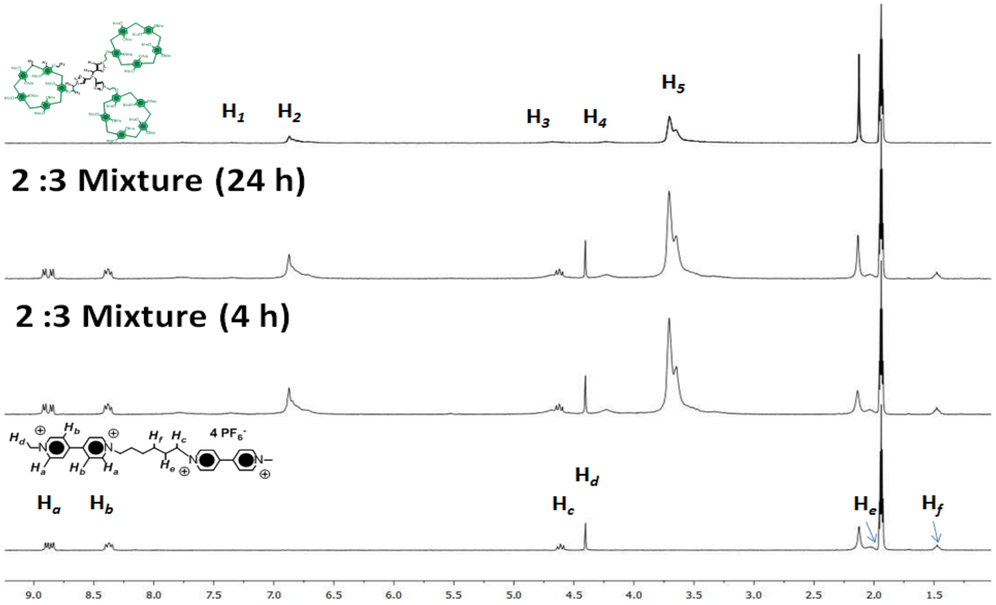

Fig. S14 ^{1}H NMR spectra (400 MHz, room temperature) of compound **1**, compound **2**, and the complex of **1** and **2** (1 mM) with a 2:3 molar ratio in MeCN-d_3. No chemical shifts can be observed.

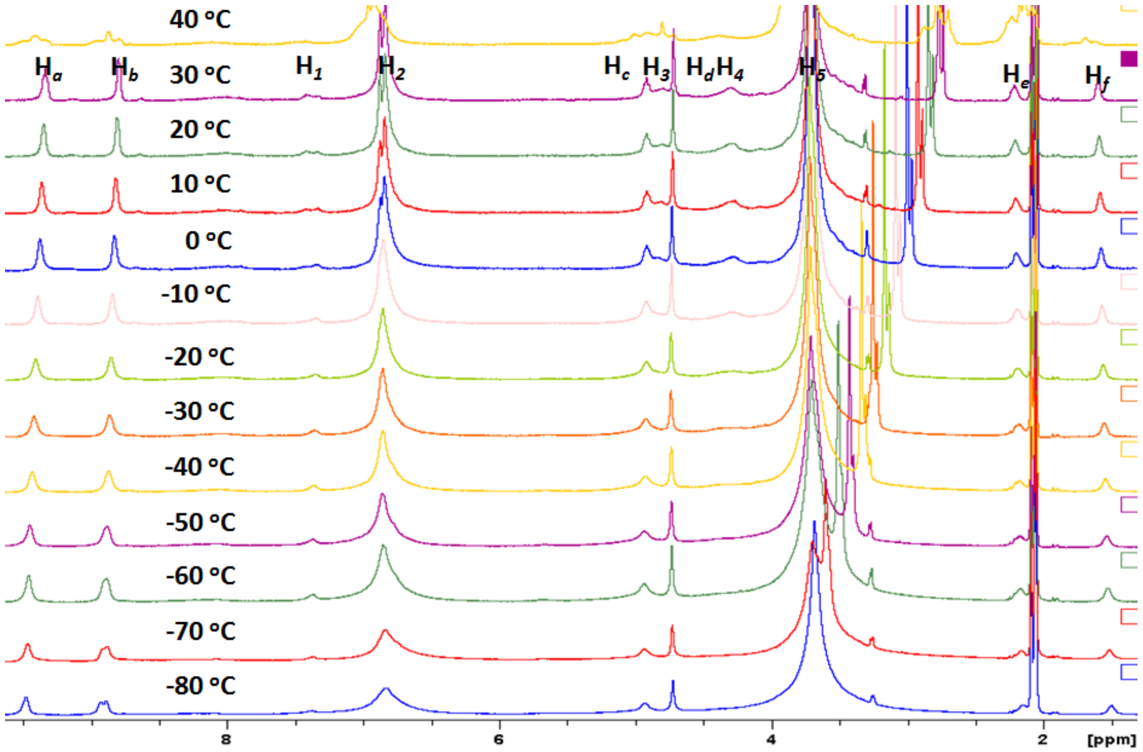

Fig. S15 Full VT ^{1}H NMR spectra (400 MHz) of the complex of **1** with **2** (1mM) with a 2:3 molar ratio in Me_2CO-d_6.

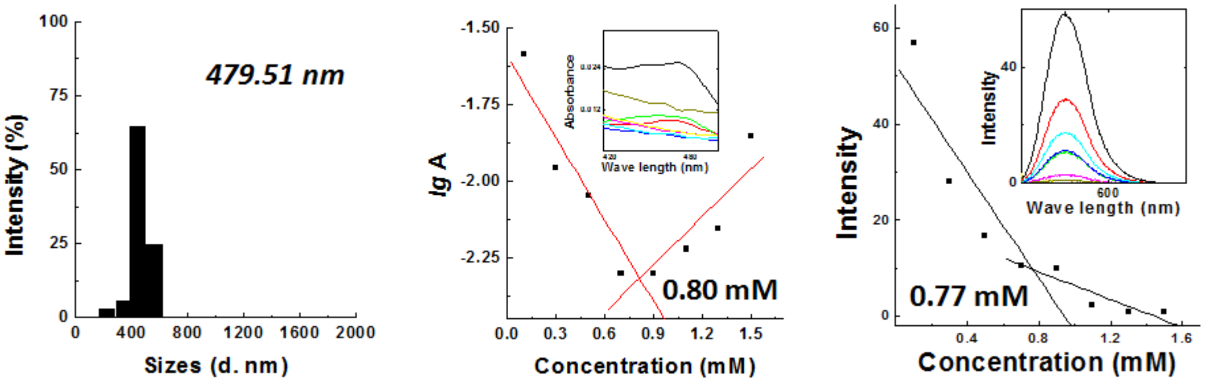

Fig. S16 DLS size distributions of the complex of DMpillar with **2** (1 mM) in a 2:1 molar ratio in Me_2CO. The mean diameter is 479.5 nm (left). The critical assembly concentration of the complex in Me_2CO was determined by (middle) UV-vis and (right) fluorescent spectra.

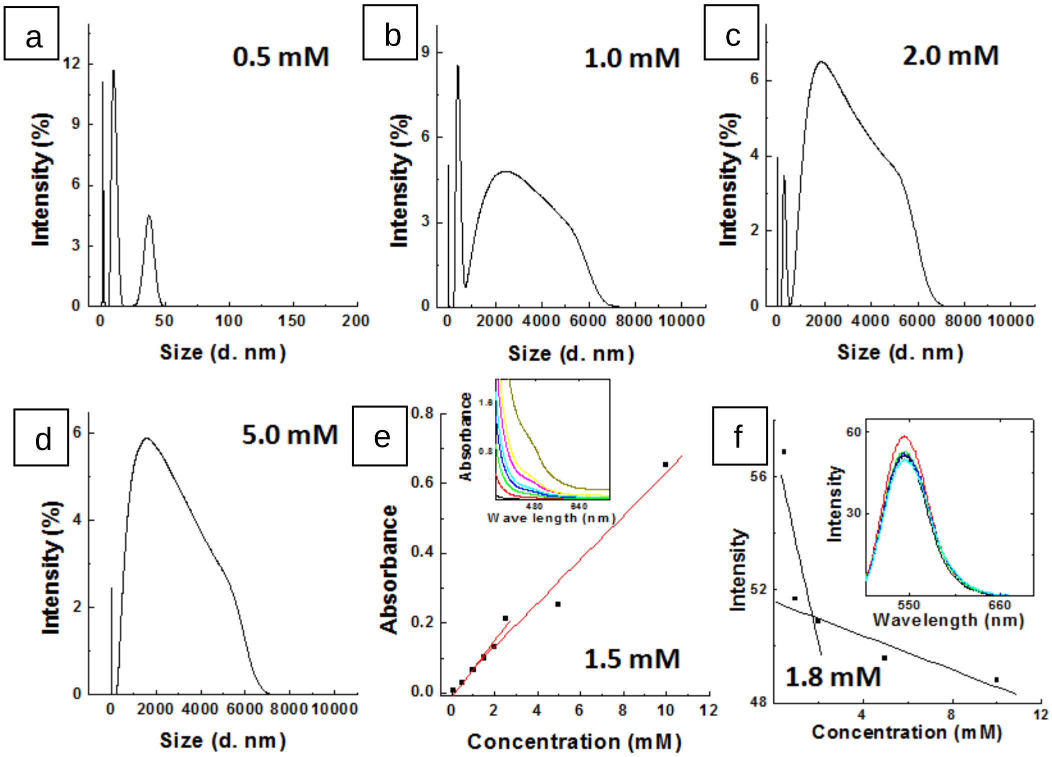

Fig. S17 (a-d) DLS size distributions of the complex of **1** with **2** (1 mM) in a 2:3 molar ratio in Me_2CO under different concentrations. The variable (e) UV-vis and (f) fluorescent spectra of the complex in Me_2CO were recorded.

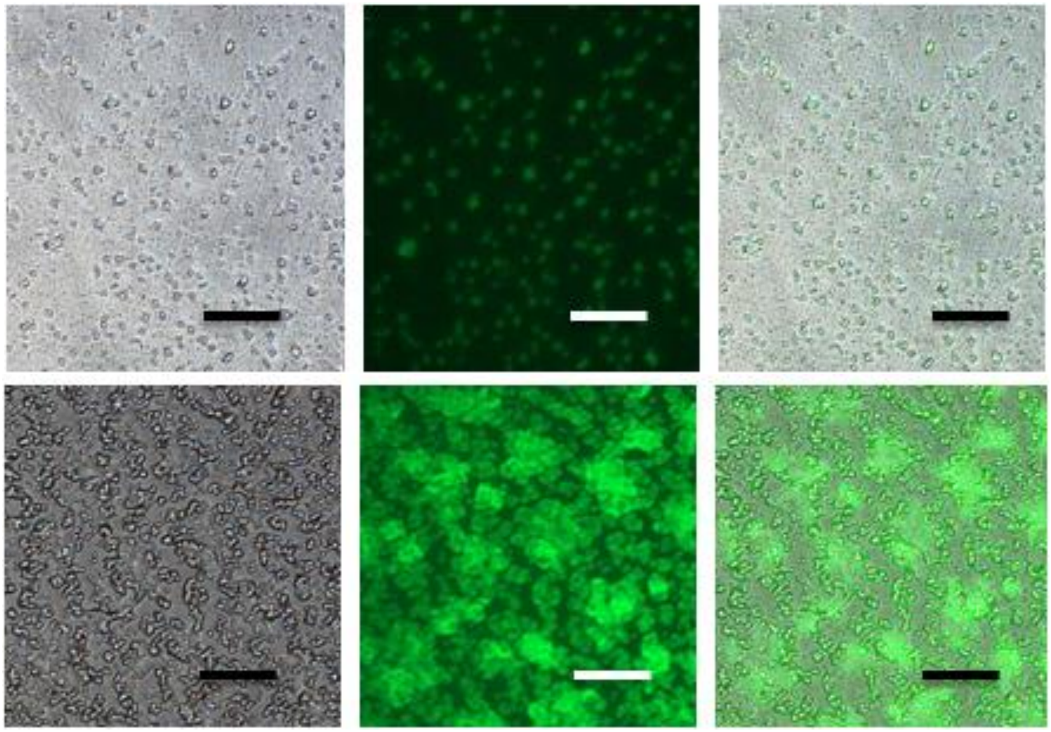

Fig. S18 Fluorescent microscopy images of the complex of **1** with **2** in a 2:3 molar ratio in Me_2CO. Up, 1 mM, from left to right: bright field, the sample excited at 488 nm, and merged figure. Scale bar is 10 μm. Bottom, 5 mM, from left to right: bright field, the sample excited at 488 nm, and merged figure. Scale bar = 10 μm.

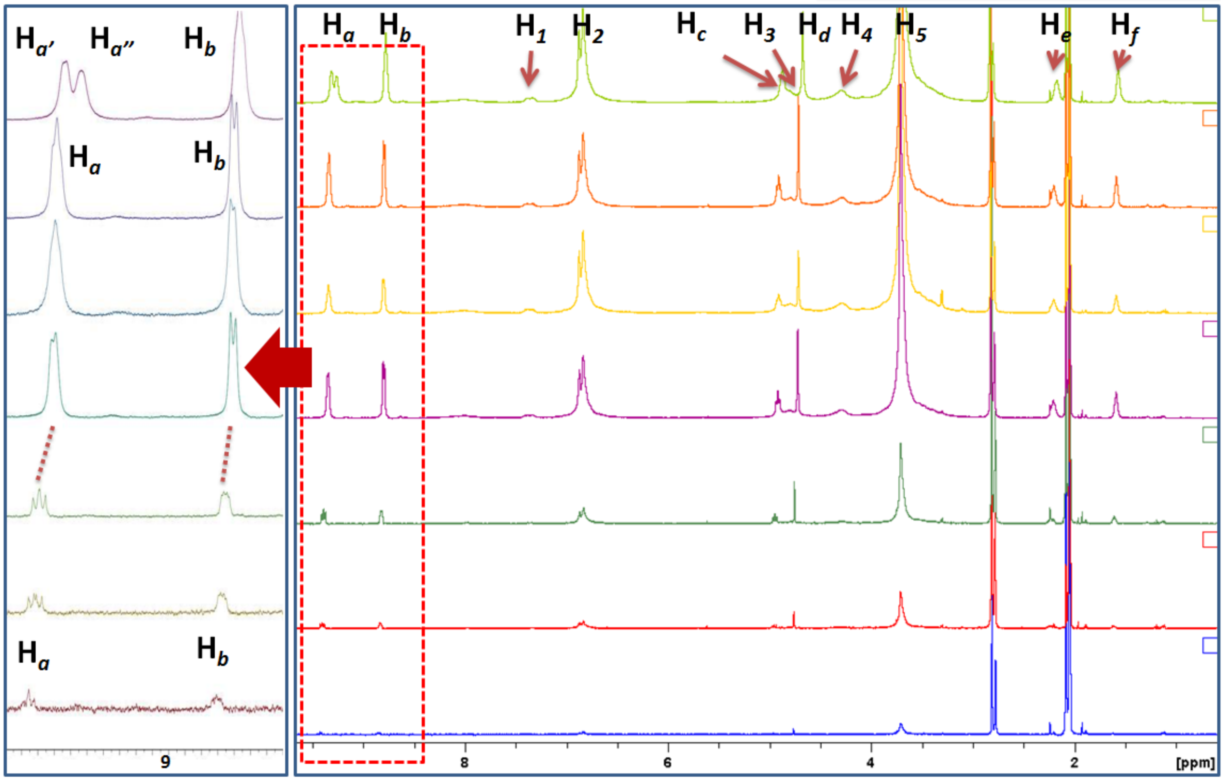

Fig. S19 ^{1}H NMR spectra (400 MHz, room temperature, Me_2CO-d_6) of the complex of **1** and **2** at different concentrations, from top to bottom: 10.0 mM, 5.0 mM, 3.0 mM, 2.0 mM, 1.0 mM, 0.5 mM and 0.1 mM with full scale (right) and selected area (left).

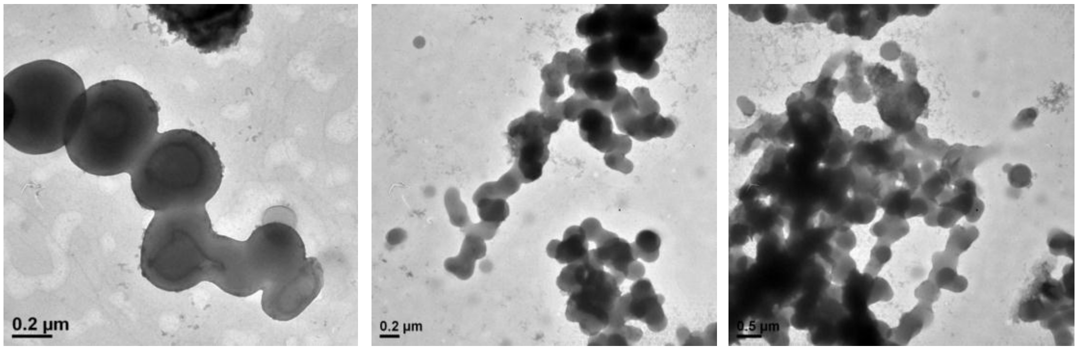

Fig. S20 Negative-stained TEM images of the complex of **1** with **2** under the sample concentration of 1.5 mM with different scale bars.

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