Cyclic dimer of a fused porphyrin zinc complex as a novel host with two π-electronically coupled binding sites†

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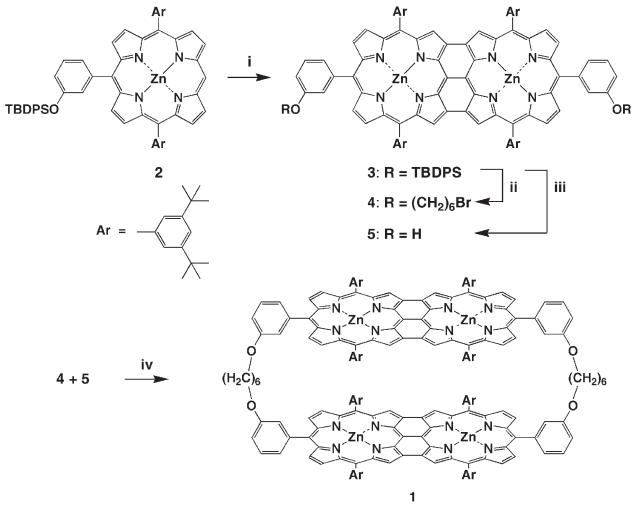
Upon complexation with 4,4′-bipyridine, a cyclic dimer of a fused porphyrin zinc complex, having two π-electronically coupled binding sites, shows a strong negative cooperativity in the second guest binding, to allow stepwise formation of 1 : 1 and 1 : 2 inclusion complexes.

Cyclic host molecules composed of extra large π-conjugated systems are interesting in that their host–guest chemistry can be markedly affected by π-electronic interactions. However, examples of these molecules are only very limited. Müllen *et al.* have synthesized a cyclic dimer of a hexa-*peri*-hexabenzocoronene (HBC) derivative with 42 π-electrons, and reported that the two HBC units strongly interact electronically, thereby making the conformational change dynamics extremely slow.[1] Here we report a novel cyclic dimer of a fused porphyrin bearing 44 π-electrons (**1**). Fused porphyrins[2] are a new class of π-conjugated molecules, whose metal complexes are expected to provide two electronically coupled binding sites for guest molecules. Thus, the first guest binding may electronically affect the second guest binding. Despite numerous examples of steric effects on multiple guest-binding events,[3] cooperative binding phenomena due to such a π-electronic conjugation have never been explored to date. In the present communication, we report results of a coordination interaction between a nitrogenous base such as 4,4′-bipyridine (bpy) and cyclic dimer **1**,[4] along with its monomeric precursor (**3**), and highlight a strong negative cooperativity in the second guest inclusion into the π-electronic cavity of **1**.

Cyclic dimer **1** was obtained according to Scheme 1.[5] Oxidative ring closure of **2** with DDQ/$Sc(OTf)_3$, followed by bromoalkylation at the phenolic functionalities, afforded a zinc complex of fused porphyrin **4**. On the other hand, deprotection of the silyl groups after the oxidative ring closure gave a fused porphyrin zinc complex **5**. Then, alkaline-mediated coupling of **4** with **5** yielded cyclic dimer **1**, which was unambiguously characterized by MALDI-TOF-MS and ^{1}H NMR analyses. The absorption spectrum of **1** was nearly identical to that of its monomeric precursor (**3**), suggesting that the two fused zinc porphyrin units in **1** hardly interact with one another.

Spectroscopic titration of **1** with bpy in toluene at 20 °C clearly displayed a two-step spectral change profile with isosbestic points at 958, 984 and 1072 nm at [bpy]/[**1**] = 0–0.7 (a) and 962, 1015 and 1107 nm at [bpy]/[**1**] = 1.4–2.0 (b) (Fig. 1). When [bpy]/[**1**] exceeded 2.0, no further spectral change took place. Together with the Job's plot profile,[5] these titration characteristics indicate the stepwise formation of highly stable 1 : 1 (**1** ⊃ bpy) and 1 : 2 (**1** ⊃ bpy_2) host–guest complexes. The ^{1}H NMR spectrum of a 1 : 2.5 mixture of **1** and bpy in toluene-d_8 at 20 °C showed at δ 5.58 and 4.93 ppm two



Scheme 1 *Reagents and conditions*: (i) DDQ, $Sc(OTf)_3$, toluene, r.t.; (ii) $Br(CH_2)_6Br$, KF, 18-crown-6, acetone, 50 °C; (iii) TBAF, THF, r.t.; (iv) K_2CO_3, DMF, r.t.

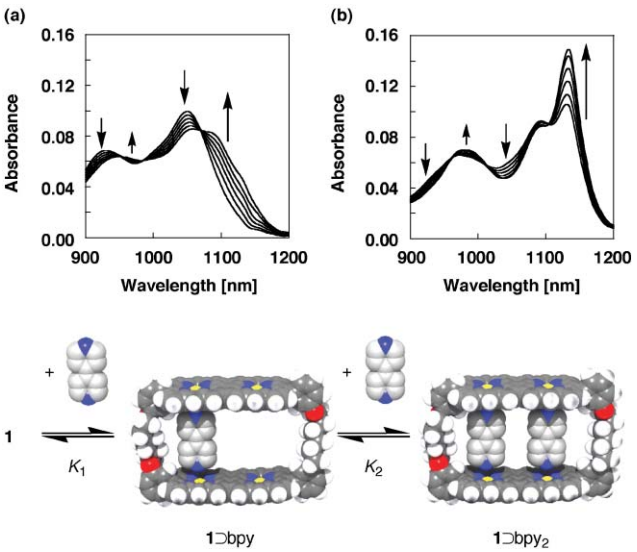


Fig. 1 Spectroscopic titration of **1** with 4,4′-bipyridine (bpy) in toluene at 20 °C. $[\mathbf{1}]_0 = 2.0 \times 10^{-6}$ M; [bpy]/[**1**] = 0–0.7 (a) and 1.4–2.0 (b).

† Electronic supplementary information (ESI) available: synthesis of **2**–**6**, ^{1}H NMR of **1** and **1** ⊃ bpy_2 and spectroscopic titration of **1**/bpy, **3**/py and **6**/py. See http://www.rsc.org/suppdata/cc/b5/b501689d/

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upfield-shifted signals due to included bpy, whose integral ratios to the OCH_2 signal (8H) of **1**, for example, were in excellent agreement with those expected for **1**⊃bpy_2.[5]

The association constants for the first (K_1) and second (K_2) complexation events of **1** with bpy were too large for accurate evaluation by spectroscopic titration methods. However, the relative ratio $K_1/4K_2$, generally used for the evaluation of cooperativity in complexation with two guest molecules,[6] was successfully obtained from the populations of uncomplexed and complexed **1** in toluene. Namely, changes in absorbance of **1** at the isosbestic points for the first (1072 nm) and second (1107 nm) guest binding events, upon titration with bpy, allowed for the evaluation of the populations of **1**, **1**⊃bpy and **1**⊃bpy_2 at [bpy]/[**1**] = 1.0 as 18, 76 and 6%, respectively (Fig. 2). Using the equation $K_1/4K_2 = [\mathbf{1}\supset bpy]^2/4[\mathbf{1}][\mathbf{1}\supset bpy_2]$, the ratio $K_1/4K_2$ was estimated as 12 (Table 1). Since this value is much greater than unity, it is obvious that the binding of **1** with the first bpy molecule results in considerable lowering of the complexation activity of the second binding site (negative cooperativity).

Titration of monomeric fused porphyrin zinc complex **3** with pyridine (py) in toluene at 20 °C displayed a spectral change profile similar to the case with **1**. When the molar ratio [py]/[**3**] became greater than 50, the isosbestic points initially observed at 946, 983 and 1076 nm shifted toward 968, 1017 and 1116 nm, respectively.[5] The association constants K_1 and K_2, as evaluated by a nonlinear curve-fitting method using a program LSPE,[7] were 1.4×10^4 and 2.0×10^3 M^{-1}, respectively (Table 1), and the ratio $K_1/4K_2$ was calculated to be 1.8. This ratio is again larger than unity but much smaller than that observed for the cyclic dimer **1** (12). For comparison, the zinc complex of a phenylene-bridged diporphyrin

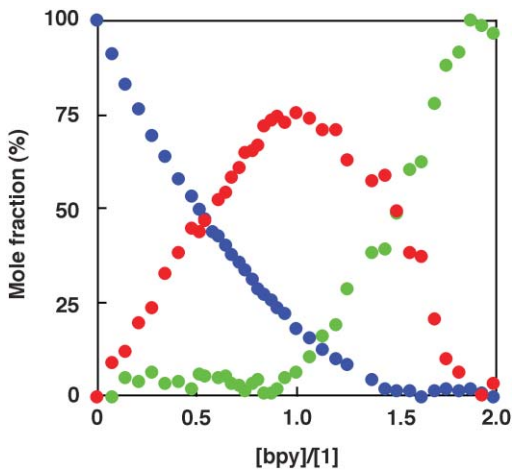
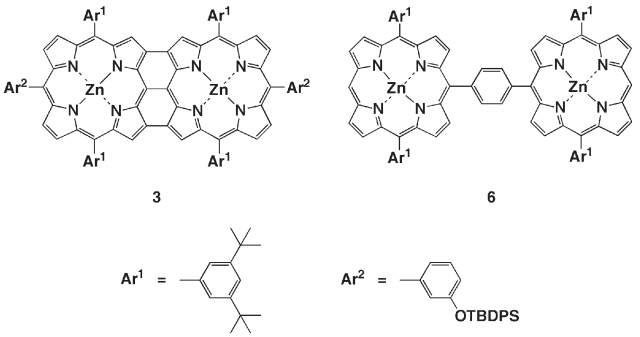


Fig. 2 Mole fractions of **1** (blue), **1**⊃bpy (red) and **1**⊃bpy_2 (green) upon titration of **1** with 4,4′-bipyridine (bpy) in toluene at 20 °C. $[\mathbf{1}]_0 = 2.0 \times 10^{-6}$ M.

Table 1 Association constants (K_1, K_2) for the complexation of **1** with 4,4′-bipyridine (bpy), and **3** and **6** with pyridine (py) in toluene at 20 °C

	K_1/M^{-1}	K_2/M^{-1}	$K_1/4K_2$
1/bpy	$> 10^8$	$> 10^8$	12
3/py	1.4×10^4	2.0×10^3	1.8
6/py	9.3×10^3	2.4×10^3	0.97

(**6**) having two π-electronically separated binding sites was titrated with py under identical conditions to the above.[5] As expected, the ratio $K_1/4K_2$ obtained from the spectral change profile was nearly unity (Table 1), indicating the absence of any cooperativity between the two binding sites. From these observations, it is clear that the negative cooperativity observed for the complexation of **1** with bpy and that of **3** with py, is due to the electronic coupling between the binding sites. The fact that the complexation of **1** ($K_1/4K_2 = 12$) shows a much greater negative cooperative effect than that of **3** ($K_1/4K_2 = 1.8$) is interesting and is understandable in that the first ligand for **1** is very strongly coordinated and its electronic effect on the second binding site can therefore be pronounced.



In conclusion, we have developed the first host molecule having π-electronically coupled binding sites (**1**), by cyclodimerization of a fused porphyrin zinc complex. Although the host molecule can accommodate two molecules of 4,4′-bipyridine in its large π-electronic cavity, it shows a strong negative cooperativity in the complexation events due to an electronic coupling between the two binding sites. The highly enhanced cooperativity of **1**, compared with its monomeric reference (**3**), enables the stepwise guest inclusion to form 1 : 1 and 1 : 2 host–guest complexes selectively. Hybridization of **1**⊃bpy with different guest molecules to form heterodimeric inclusion complexes is an interesting subject worthy of further investigation.‡

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Notes and references

‡ *Cyclic dimer* ***1***: To a DMF suspension (50 mL) of K_2CO_3 (100 mg, 0.72 mmol), being stirred under Ar, was added dropwise a DMF solution (15 mL) of a mixture of **4** (84 mg, 0.042 mmol) and **5** (70 mg, 0.042 mmol) at a rate of 0.4 mL/h using a microfeeder. After the addition was completed, the mixture was stirred for a further 24 h. Then, the reaction mixture was poured into toluene, washed with water, dried over Na_2SO_4 and evaporated to dryness. The residue was subjected to preparative size exclusion chromatography with toluene as an eluent, where the second fraction was collected and evaporated to dryness. The residue was recrystallized from $CHCl_3$/cyclohexane to give **1** as dark purple powder (22 mg, 15%); ^1H NMR ($CDCl_3$, 20 °C, ppm): 7.62 (d, 8H, pyrrole-β-H), 7.60 (d, 8H, pyrrole-β-H), 7.55 (br, 8H, Ar), 7.48 (s, 8H, Ar), 7.42–7.34 (m, 16H, Ar), 7.14 (s, 8H, pyrrole-β-H), 7.10 (br, 4H, Ar), 7.04 (d, 4H, Ar), 3.69 (t, 8H, OCH_2), 2.34–2.32 (m, 8H, OCH_2CH_2), 1.87–1.84 (m, 8H, $OCH_2CH_2CH_2$), 1.37 (s, 72H, *t*-Bu), 1.19 (s, 72H, *t*-Bu); MALDI-TOF-MS *m*/*z* calcd. for $C_{228}H_{232}N_{16}O_4Zn_4$ (M^+) 3520.6, found 3520.9; UV-vis

(toluene, 20 °C): λ_{max} (log ε) 418 (5.50), 461 (5.06), 561 (5.42), 928 (4.64), 1050 (4.80) nm.

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