New Optically Active Diporphyrin Having a Chiral Cyclophane as a Spacer

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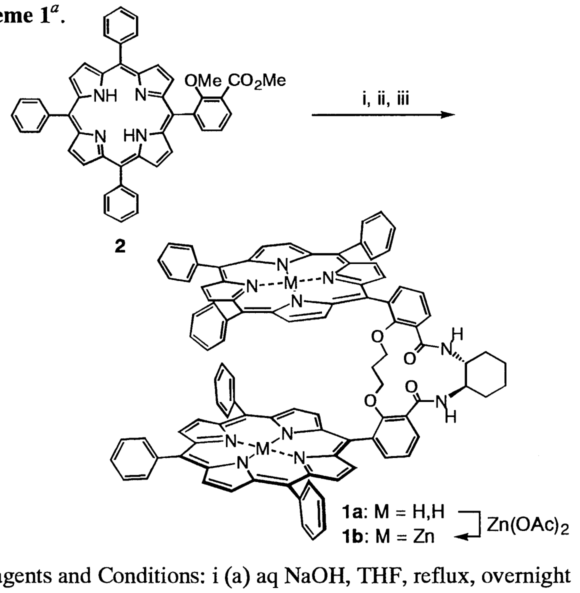
Optically active dimeric porphyrin covalently linked by a chiral cyclophane was synthesized; the two porphyrin chromophores were disposed in a slipped cofacial fashion, which was found to be tunable by cooperative coordination of diamines with various chain lengths.

Synthetic diporphyrins[1] have attracted considerable attention as models for naturally-occurring supramolecular assemblies of porphyrin derivatives including chlorophylls, such as the photosynthetic reaction center complex,[2] the light-harvesting complex[3] and cytochrome *c* oxidase. Although a large number of variants of covalently-linked porphyrin dimers have been reported,[1] the biomimetic multi-pigment system with a specific spatial arrangement[2,3] is still an important target of synthesis and physicochemical studies.[1,4,5] Here we report a new optically active diporphyrin **1** having a chiral cyclophane as a spacer. By using the chiral spacer, (i) unique *offset* geometry of the two porphyrins as observed in nature[2,3] can be constructed; the significance of such a specific geometry has not been extensively investigated, and (ii) the circular dichroic (CD) spectroscopy becomes available and will be useful for the model study as well as the conformational analysis.

The synthesis of diporphyrin **1a** was achieved as shown in Scheme 1. The monomeric porphyrin **2** was prepared by condensation of methyl 2-methoxy-3-formylbenzoate, benzaldehyde and pyrrole in propionic acid.[6] After hydrolysis and treatment with $SOCl_2$, the resultant acid chloride was coupled with (1*R*,2*R*)-1,2-cyclohexanediamine to afford diporphyrin **3**. Demethylation of **3** with BBr_3 and subsequent intramolecular bridging alkylation with 1,3-dibromopropane gave the target diporphyrin **1a** in a good yield.

The conformation of diporphyrin **1a** was analyzed by means of the NMR measurements and the computational calculations. The assignments of the 1D proton resonances of **1a** on the basis of 2D-NMR (COSY, EXSY) experiments revealed a ring current effect arising from the neighboring porphyrin(s). A set of resonances corresponding to the protons of one of the three phenyl groups at the *meso*-positions ($\Delta\delta$ = 0.2–0.9 ppm) as well as a set of resonances corresponding to the β-protons of a pyrrole ring ($\Delta\delta$ = 0.8–1.0 ppm) were upfield-shifted in comparison with those of monomer **2**, indicating that these moieties are disposed above the adjacent porphyrin. Larger upfield-shifts ($\Delta\delta$ = 1.5–2.0 ppm) were observed for the protons of the bridging trimethylene chain. A combination of molecular mechanics calculations and molecular dynamics (MD) simulations yielded the optimized structure shown in Figure 1.[7] The intramolecular hydrogen bonds in the cyclophane cavity contribute to the conformational stability of **1a**, and as a result, the two porphyrin planes are nearly parallel and offset each other (Figure 1); the center-to-center distance is *ca.* 7 Å and the shortest interplanar distance is *ca.* 3 Å. Although the conformation shown in Figure 1 deviates from C_2 symmetry, the C_2-symmetric NMR signal pattern and the MD simulations at 300 K suggested that the conformation of **1a** fluctuates to a

Scheme 1[a].



[a]Reagents and Conditions: i (a) aq NaOH, THF, reflux, overnight (b) $SOCl_2$, benzene, reflux, 3 h (c) (1*R*,2*R*)-cyclohexanediamine, benzene, pyridine, 2 d (59%); ii BBr_3, CH_2Cl_2, –40 °C, 2.5 h (92%); iii $Br(CH_2)_3Br$, K_2CO_3, acetone, reflux, 8 d (62%).

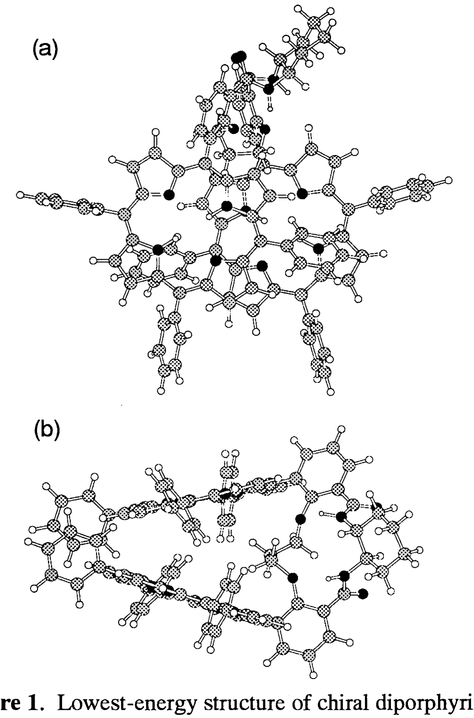


Figure 1. Lowest-energy structure of chiral diporphyrin **1a** (CAChe system/MM2 force field) (a) Top view. (b) Side view.

considerable degree in solution. Nevertheless, the optimized structure shown in Figure 1 is qualitatively consistent with the aforementioned NMR spectral features. Importantly, the slipped cofacial geometry of **1a** is similar to that observed in the naturally-occurring chlorophyll assemblies.[2,3]

The CD spectrum of **1a** (Figure 2a) shows the intense and split Cotton effects with the opposite signs at the Soret region, which are qualitatively similar to those reported previously[5d] and are attributable to the chiral exciton coupling[8] between the two porphyrin chromophores.[5] The exciton interaction was detected by the CD spectroscopy much more clearly than by the UV–vis absorption spectroscopy; the UV–vis measurements indicated that the Soret band of **1a** in $CHCl_3$ was blue-shifted only by 2 nm as compared with that of monomer **2**. The result that the Cotton effect of **1a** is stronger than that of dimethoxyporphyrin **3** (Figure 2a) supports the well-defined chiral conformation of **1a** as shown in Figure 1.

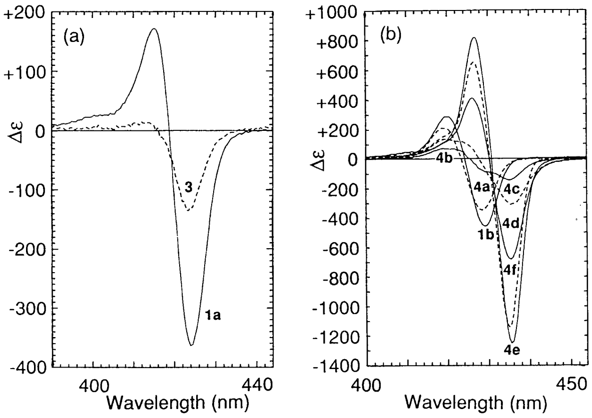


Figure 2. CD spectra of (a) **1a** and **3** and (b) **1b** in the absence and presence of the diamine **4a–f** (*ca*. 1 equiv.) in CH_2Cl_2.

Finally, the binding of zinc complex **1b** to a series of diamines $NH_2(CH_2)_nNH_2$ **4a–f** (n = 2–7) was examined to further fix the conformation of the diporphyrin. ^1H NMR titrations indicated that the diamine was bound between the two porphyrins (in the cavity) *via* the double coordinations. The binding constants (K_a) of **1b** for diamines in CH_2Cl_2 at 25 °C as determined by the UV–vis spectrophotometric titration[5c,9] were found to be $>10^7$ M^{-1} for all cases. Clear exciton splitting of the Soret band was observed only for the complexes of **1b** with **4e–f** (Table 1). The CD spectra of the complexes **1b•••4a–f** showed the split Cotton effect with various intensities at the Soret region, depending upon the chain length of the diamine (Figure 2b). These results clearly indicate that both the distance and the orientation between the two porphyrin chromophores are tuned by the cooperative coordination of the diamines without any appreciable loss of the binding energy, which will be useful for the study on the physicochemical property of a series of conformationally isomeric diporphyrins with specific spatial arrangement.

Table 1. Comparison of the absorption spectra (Soret band)

	λ_{max} /nm	Half-bandwidth /nm
1b	418	17
1b•••4a	424	9
1b•••4b	425	10
1b•••4c	426	10
1b•••4d	426	11
1b•••4e	426 437	*ca*. 18
1b•••4f	426 437	*ca*. 19

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7 The MM2 force field with augmented parameters implemented in the CAChe system (ver. 3.8, Sony /Tektronix) was used. The sequential search was adopted for the four dihedral angles in the cyclophane moiety. Each structure obtained was further optimized with the above dihedral angles unrestrained to yield several stable conformers.

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