Self-assembly of a Bisporphyrin Supramolecular Cage Induced by Molecular Recognition Between Complementary Hydrogen Bonding Sites

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Addition of an alkyl substituted triaminopyrimidine, TAP, to a solution of porphyrin **2** bearing two rigidly attached complementary hydrogen bonding moieties of the uracil type, leads to the self-assembly of a bisporphyrin supramolecular cage structure **1** from the *syn* rotamer and probably a zig-zag strand from the *anti* rotamer.

The self-assembly of well-defined supramolecular architectures rests on the design of molecular components containing the appropriate information and interacting through the correct recognition algorithm.[1,2] The process is inorganic when it involves metal ion coordination as in the spontaneous generation of double helical complexes, the helicates.[1,3] The designed use of suitable hydrogen bonding patterns[4] yields organic supramolecular structures of various types such as extended arrays,[5–7] ribbons,[6] tapes[7] and cyclic[5,7b–9] species.

With photoactive, electroactive for ionoactive components, functional supramolecular devices may result.[1] Energy and electron transfer processes have been investigated mainly between covalently linked components;[10] systems assembled through hydrogen bonding have also been reported.[11] We now describe the self-assembly of the bisporphyrin supramolecular cage entity **1** and its Zn^{II} derivative, structures that are both closed and functional.

The synthesis of the porphyrin component **2** was accomplished by the coupling of two substituted dipyrrolylmethanes **3**,‡ under equilibrium conditions[12]§ (Fig. 1). Alternatively, the statistical mixture of the 5; 5, 10; 5, 15; 5, 10, 15 and 5, 10, 15, 20 *meso* substituted uracyl porphyrins with phenyl groups in the remaining positions, can be synthesized under standard literature conditions[13] from 4 equiv. of pyrrole, 2 equiv. of 1-decyl-5-formyluracil and 2 equiv. of benzaldehyde, followed by separation of the different compounds. This is the first example of a non-aromatic nitrogen heterocycle directly attached to the porphyrin ring.[14]

The uracil recognition groups are rigidly linked to the porphyrin macrocycle **2** and rotation about the connecting bond is hindered by the ethyl substituents on the porphyrin pyrroles. Thus **2** has two rotameric forms, *syn* and *anti* with respect to the relative orientation of the two uracil groups. Assembly was performed by interacting compound **2** or its Zn^{II} derivative with 5-alkyl-2,4,6-triaminopyrimidines (alkyl-TAP) as complementary hydrogen bonding components. One would expect the *syn* rotamer of **2** to give the 2 porphyrin + 2 alkyl-TAP (2 + 2) cage structure **1**, and the *anti* rotamer to yield a zig-zag strand species.

Evidence for self-assembly was provided by a variety of experimental data: ^{1}H NMR, molecular mass determinations by electrospray mass spectrometry and by vapour phase osmometry (VPO), fluorescence quenching and enhancement, as well as substrate binding. Addition of the alkyl-TAP increased the solubility of porphyrin **2** by five- to seven-fold in aprotic solvents.¶

The presence of two rotamers in **2** was indicated by the observation of signal doubling in the ^{1}H NMR spectrum (CD_2Cl_2) for the porphyrin methine (δ 10.23, 10.19), the uracil NH (δ 9.05, 8.95), and the uracil CH (δ 7.83, 7.75) protons [Fig. 2(*b*)]. Upon addition of 1 equiv. of octyl-TAP [Fig. 2(*a*)] marked downfield shifts were found for the uracil NH signal (to a broad absorption between δ 13–14) as well as for the 2-NH_2 (from δ 4.28 to 5.0) and the 4,6 NH_2 (from δ 4.24 to 5.5) signals of the octyl-TAP [Fig. 2(*c*)]. These shifts showed that hydrogen bonding was taking place between the complementary recognition sites, as found for TAP–barbituric acid associates;[6a] however, both isomers were still observed.|| After three days at room temperature the amount of the *anti* rotamer had decreased to 15–20%.** We interpret this to indicate that the self-assembly of the cage **1** through 12 hydrogen bonds shifted the *syn–anti* equilibrium towards the *syn* rotamer.

The electrospray mass spectra of the self-assembled species containing the zinc porphyrin **2**–Zn (in CH_2Cl_2; 5 : 1 acetonitrile–water at pH 6 eluent) showed an M^{++} parent ion at 1336.2 (calc. for **1**–2Zn + $2H^+$ m/z^{++} = 1336). No significant peaks were found at masses greater than a (2 + 2) species, and the mass peaks for (2 + 1) and (1 + 1) species had intensities similar to or lower than that of **1**. While these results are consistent with both the self-assembled cage **1** and a (2 + 2) strand, the fact that no higher order associates were observed suggests that the predominant form under these conditions was indeed the former.†† When the Fe^{III} complex of **2** was

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† URA422 of the CNRS.

‡ All compounds gave satisfactory spectral (^{1}H NMR, ^{13}C NMR, mass, UV–VIS) and microanalytical data. 5-[bis(5-benzyloxycarbonyl-3,4-diethyl-2-pyrrolyl)methyl]-1-decyluracil was synthesized (76% yield) by the condensation of 1-decyl-5-formyluracil and 2-benzyloxycarbonyl-3,4-diethylpyrrole in ethanol solution containing BF_3–Et_2O at reflux for 5 h. After purification by column chromatography using silica gel and hexane–ethyl acetate (3:1) the benzyl groups were removed by catalytic hydrogenation in tetrahydrofuran (THF) with 10% Pd/C at room temp. for 1 h. The resulting orange–yellow solid, **3**, (90% yield) was used without further purification.

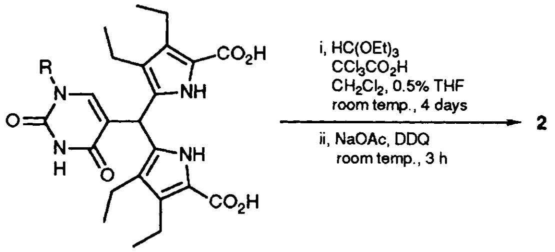
§ Synthesis of **2**: dichloromethane, trichloroacetic acid and triethyl orthoformate were added in the order given to a solution of **3** in THF.[14] After stirring for 4 days in the dark, sodium acetate and 2,3-dichloro-5,6-dicyano-1,4-benzoquinone, DDQ, were added and the mixture stirred for 3 h. The residue was placed on top of a short silica gel column and eluted with 4 : 1 toluene–ethyl acetate where only the product moves; 11.6% yield based on **3**.

¶ Upon mixing the two components at 2 mmol dm^{-3} the solution becomes thixotropic after about 30 min at room temp., but the apparent viscosity decreases over the next 24–48 h.

|| The chemical shifts differ depending on the solvent, thus in chloroform the uracil NH signal shifts from δ 8.7 to a broad signal at 11.2 and in THF from δ 8.9 to 10.7. The *syn–anti* equilibrium is also somewhat solvent dependent.

** The ^{13}C NMR also shows that the concentration of one of the rotamers is significantly diminished. The two rotamers are separable by preparative TLC, but upon removing the compound with the greater R_F, which is assumed to be the *anti* rotamer, with acetone and redissolving it in $CDCl_3$, the ^{1}H NMR shows that both rotamers are present, one enriched over the other. However, variable temperature ^{1}H NMR studies do not show a significant change in the spectra up to 30 °C in $CDCl_3$; thus the rotamerization could be facilitated by binding on a surface, by polarity of the solvent, or by formation of hydrogen bonded species.

†† No useful electrospray mass spectra could be obtained when **2** was used in the self-assembled complex under a wide variety of instrumental, sample solution and eluent conditions probably owing to the acidic eluent required to positively charge the complex; the FAB mass spectra in a tetraglyme matrix were unsuccessful for all self-assembled complex.



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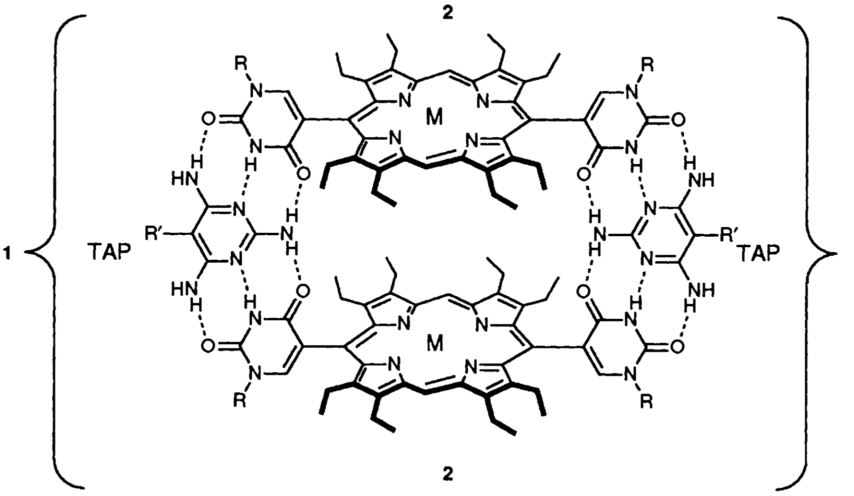

Fig. 1 Supramolecular cage-like structure, **1**, formed by the self-assembly of two porphyrins containing 5-alkyluracil recognition groups, **2** and two alkyltriaminopyrimidine (TAP) units. R = decyl, R′ = octyl or decyl, M = $2H^+$, $Fe^{III}Cl$ or Zn^{II}

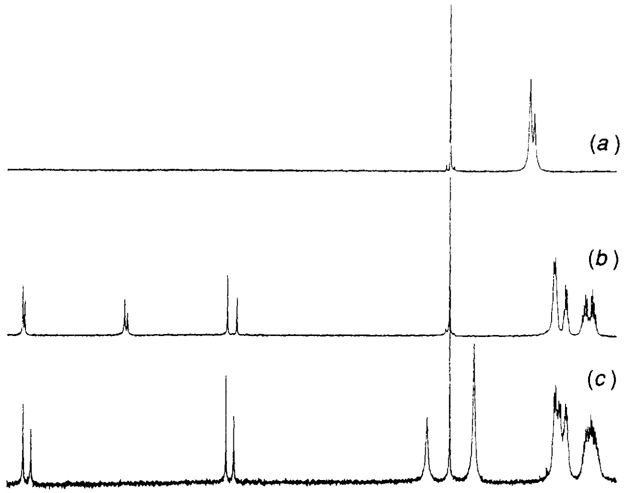

Fig. 2 400 MHz ^1H NMR spectra in CD_2Cl_2 (*a*) of octyl-TAP; (*b*) the porphyrin free base, **2**; (*c*) 15 min after the addition of a stoichiometric amount of octyl-TAP to **2**, forming the supramolecular cage **1**; the broad uracil NH signal at δ 13–14 is not shown

used, the mass spectral data were also compatible with the formation of **1** (M = FeCl).

VPO determinations yielded a molecular weight of 2714 ± 120 for the self-assembled complex using **2** and decyl-TAP in dry CH_2Cl_2 at 26 °C (calc. 2602). In CH_2Cl_2 + 5% ethanol the molecular weight was found to be 2813 ± 214, but when the solution contained 10% ethanol and 0.1% HCl the value obtained from VPO was 583 ± 42, and in dimethylformamide (DMF) at 90 °C with 0.1% water it was 664 ± 104. These values are in the range of the 'average' molecular weight of 650 [(1035 + 265)/2] for the two individual components of the system.

Marked changes were observed in the luminescence properties of **2** upon self-assembly. Complex **2** itself exhibited a typical fluorescence at 636.8 and 699.6 nm (excitation at 415 nm), and the normal quenching with increasing concentration due to aggregation *via* π-stacking (Fig. 3).§§ In contrast, the self-assembled complex showed a remarkably (almost) constant fluorescence from 5 to 1 mmol dm^{-3} (Fig. 3) retaining 50–60% of the maximum intensity of **2** at ~10 mmol dm^{-3}. When ethanol containing 0.1% HCl was added to the solution (10% v/v), the emission reverted to that of the unassembled protonated porphyrin at the same concentration. These results indicate that a specific assembled complex was formed. The quenching at low concentrations upon the addition of octyl-TAP agrees with the positioning of two prophyrins in a cofacial arrangement with about 1 nm separation, rather than with a strand structure. At much higher concentrations, the octyl-TAP units act as spacer preventing closer than 1 nm π-stacking interactions on one face while the decyl groups on **2** may protect the outer face; thus the fluorescence at 0.175 mmol is 20-fold greater for the assembled complex than for the individual porphyrin at the same concentration.¶¶

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§§ The UV–VIS spectrum of the assembled complex is essentially the same as that of the individual porphyrin for both the free base **2** and the Zn porphyrin.

¶¶ The formation of **1** may be unfavourable at low concentrations for thermodynamic and entropic reasons. The fluorescence results argue against the presence of large amounts of a strand structure which would leave some of the porphyrin faces exposed for π-stacking and a sharper decrease in the fluorescence relative intensity with concentration would be expected. The slight decrease in the fluorescence intensity with increasing concentration could be due to stacking between *anti* rotamers in a fraction of uncharacterized chain stucture, consistent with the observed equilibrium in the NMR spectrum, as well as some fluctuating interactions between the cage species **1**.

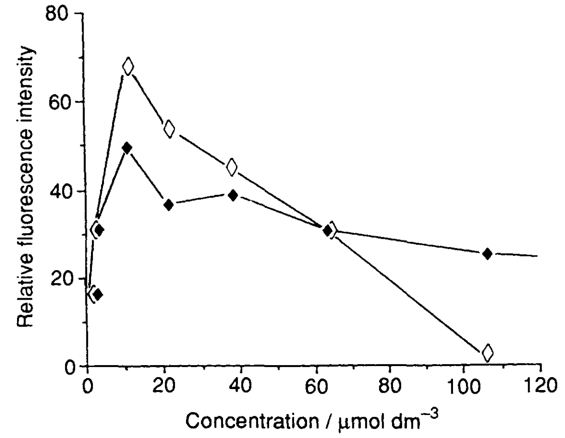

Fig. 3 Relative intensity of the fluorescence emission at 636.8 nm of the porphyrin free base, **2**◊, and the self-assembled complex, **1**♦, plotted *vs.* concentration in dry CH_2Cl_2. The solutions were allowed to stand for 36 to 48 h before fluorescence measurements were performed. The emission at 699.6 nm showed the same characteristics.

Complex **1**–Zn binds 4,4′-bipyridine (bpy) more strongly than Zn tetraphenylporphyrin or Zn octaethyl-porphyrin or **2**–Zn as measured by the exchange of this ligand by ^{1}H NMR. Titration of 1.2 equiv. of bpy into a solution of **1**–Zn resulted in four broadened resonances for this ligand: two for the bpy enclosed in the self-assembled cage and two for the bpy bound by the open strand structures in exchange with the excess unbound ppy.[15][‖‖]

The accumulated evidence suggests that the self-assembly of the porphyrin **2** or its Zn^{II} complex and TAP yields mainly the closed bisporphyrin species **1** through hydrogen bonding recognition; however, a certain amount of open ended chain structures may also be present. The entity **1** represents a self-assembled supramolecular analogue of covalently linked bisporphyrin cage compounds.[16,17] These results are a first step in the controlled formation of organized multimeric and polymeric porphyrin arrays of supramolecular nature. Metallation of one of the two porphyrins would create a self-assembled donor–acceptor system; alternatively, various acceptors such as quinones may be incorporated into the arrays. A variety of electron and energy transfer processes may result.

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[‖‖] These bpy peaks are readily identified by their large upfield shifts upon binding to Zn porphyrins, thus the signals of the 3,3′ and 2,2′ protons of bpy are at δ 2.4 and ~5.3 in the assembled cage complex. As the concentration of bpy increases, exchange of bpy bound by the open chain structure with free bpy moves the chemical shift towards its normal value, similar to what is observed for Zn tetraphenyl- and octaethyl-porphyrins.