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FEATURE ARTICLE

Oligomeric porphyrin arrays

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The field of synthesis and physical characterization of oligomeric porphyrin arrays has been the subject of intense research in recent years. Some of these systems present unique physical and optical properties which reflect the extent of electronic interaction between the monomers in the array, and determines their potential applications in chemistry, physics, and biology. General synthetic approaches to a multitude of porphyrin arrays, including directly linked *meso-meso*, *meso*-β, and β-β compounds, oligoporphyrins with fused π-systems, and arrays bearing rigid or flexible spacers, developed by us and by others, are described. X-Ray structures of representative compounds are presented.

Introduction

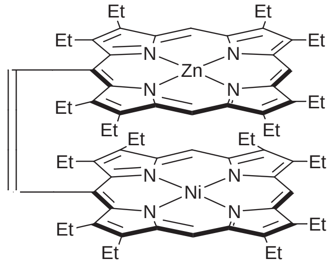
Procedures for the synthesis and functionalization of monomeric porphyrin molecules have advanced to the stage that almost any porphyrin can be obtained using available methodology.[1] Many research groups have now moved to the development of syntheses of porphyrin analogues and to the construction of multiporphyrin arrays which can either mimic natural systems, or can be used as molecular-level devices for advanced technological tasks. Interest in porphyrin arrays as model systems to mimic the vital functions of photosynthetic reaction centers and antenna systems has increased significantly in recent years. Considerable work has been reported in the field of oligoporphyrins, and we will illustrate the most general approaches by discussing some recent developments to which our own group has contributed.

Porphyrin arrays are potential precursors in building electron- and energy-transfer molecular devices; they are also robust and efficient catalysts for the multielectron redox transformations of small molecules and for the oxidation of organic substrates.[2] For all of the uses mentioned above it is important that the individual molecules within an array communicate with each other, otherwise the whole will be no better than the sum of the components and the array cannot behave with enhanced effectiveness. For effective electronic communication between adjacent porphyrins, the geometry, distance, and orientation between components of rigid porphyrin arrays are usually to be considered, though, in the area of molecular recognition such rigidity is not essential.[3] The nature of the bridges between porphyrin components, the extent of steric interactions (if any), and the connectivity of the porphyrin components directly affect the photophysical properties of covalently linked systems. The present Feature Article reports on recent work carried out in our UC Davis laboratories, and places this within the context of related research from other groups.

In the first part of this Article we concentrate on methodology we have developed to use the so-called McMurry reaction for construction of dimeric porphyrin arrays. These include cofacial bisporphyrins and bischlorins, symmetrical and unsymmetrical systems linked by ethene, stilbene, styryl, and hexatriene linkages, as well as planar fully congugated systems, and directly *meso-meso* linked dimers. After that, we discuss porphyrin oligomers derived from other synthetic approaches, leading to structures containing fused π-systems, orthogonal π-systems and supramolecular arrays.

Bridged and cofacial porphyrin oligomers

It seems clear that, at least for the reaction center in bacterial photosynthesis,[4a] cofacial π–π interacting tetrapyrrole chromophores are essential for charge separation, the first step in photosynthesis. Likewise, such interactions are vital in light-harvesting systems.[4b] A simple model of the special pair in such reaction centers would be two cofacially disposed porphyrins with a *meso-meso* alkene tether possessing a *cis* orientation (*e.g.* **1**). Prior to our work, two approaches had been investigated to provide such face-to-face dimers: (1) compounds linked on one side by a rigid aromatic spacer [the PacMan porphyrins of C. K. Chang (*vide infra*)], and (2) compounds with two or more flexible strapping units. Synthetic routes to these kinds of compounds are usually laborious, requiring multiple steps, and provide only low yields of the targeted compounds. Our methodology for the synthesis of cofacial bisporphyrins is based on the low-valent titanium-induced reductive coupling [$TiCl_3(DME)_{1.5}$/Zn-Cu couple] of *meso*-formyl-metalloporphyrins, which are conveniently prepared by Vilsmeier formylation of metalloporphyrins.[5] In the McMurry reaction a mixture of both the *cis*- and the *trans*-bisporphyrins is generally produced.[6,7] That the *cis* compound (presumably the least stable geometrical isomer) is produced at all is something of a surprise; presumably the strong intramolecular face-to-face π-stacking of the metalloporphyrin pinacol intermediate results in the formation of the kinetic cofacial *cis*-dimers, which can be converted into the stable thermodynamic extended *trans*-dimers by heating (to 120 °C for several hours) or photochemically. *Cis-trans* isomerization of ethene-linked bisporphyrins is also observed in acidic conditions and occurs more readily for the metal-free compounds.[7,8] The nature of the central metal ion is a determinant of the relative amounts of the *cis*- and *trans*-bisporphyrins obtained in this reaction, since it significantly affects the extent of macrocyclic π–π stacking prior to the formation of the ethene bond. In the cofacial arrangement (Fig. 1) the two macrocycles are almost parallel, the distance between the two metal centers is 5.36 Å (for the Ni/Zn heterodimer), and substantial macrocyclic overlap occurs as a result of the π–π interaction between the two macrocycles. The ^1H NMR spectra of diamagnetic *cis*-bisporphyrins typically show downfield shifts for the ethylenic protons (between 9.0 and 9.5 ppm), diastereotopic methylene proton signals, and substantial upfield shifts of the *meso* protons adjacent to the ethylene bridge; this supports a similar stacking of the porphyrin units in solution as in the solid state. In contradistinction, the extended *trans*-bisporphyrins (*e.g.* **2**) display a simplified ^1H NMR spectrum with the ethylene protons at 7.7 ppm, and the *meso* protons at 9.5 ppm; the X-ray structure of a bis-Ni *trans*-dimer **2** is shown in Fig. 2. In the optical spectrum the Soret band of the *cis*-porphyrins typically appears blue-shifted relative to the Soret of the corresponding extended *trans*-isomers. The *cis*- and *trans*-isomers also display distinct solubility differences; the *cis*-bisporphyrins are generally more soluble in organic solvents than are the *trans*-compounds, which facilitates their chromato-



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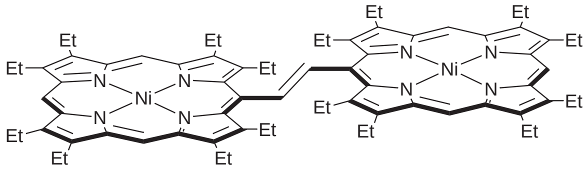

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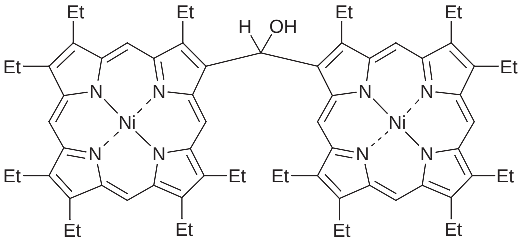

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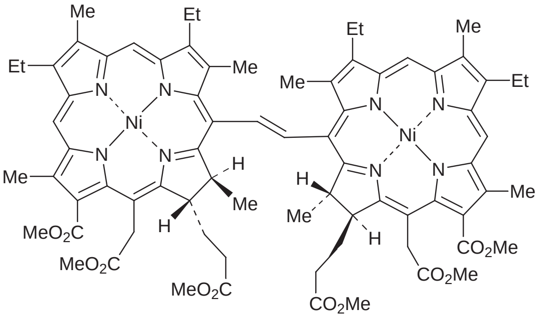

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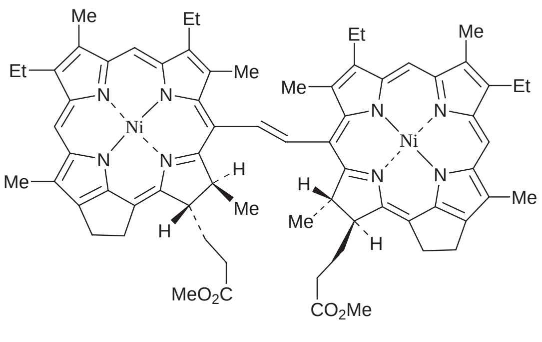

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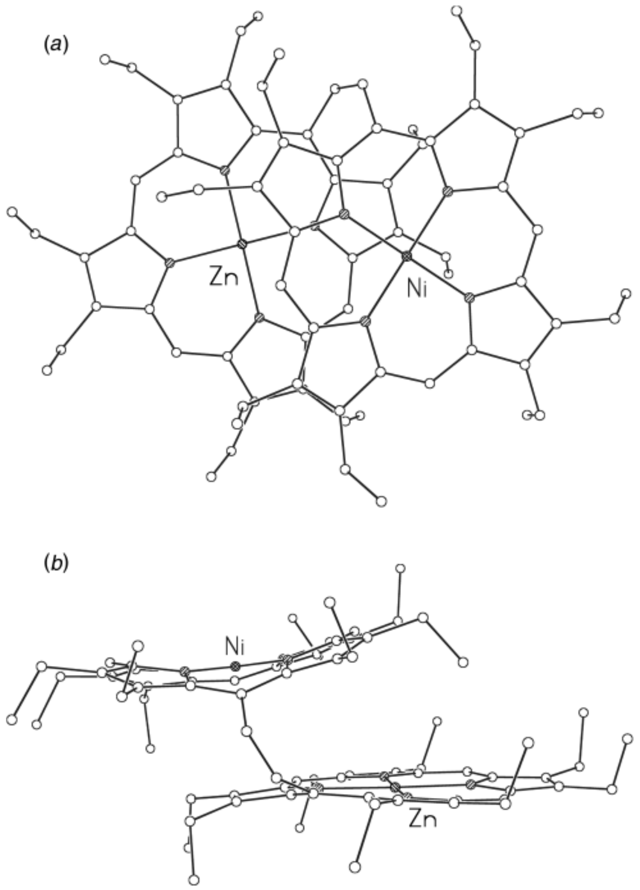


Fig. 1 Molecular structure of heterobimetallic [Ni^{II}][Zn^{II}] *cis*-ethene dimer **1** (hydrogen atoms not shown); (*a*) top view, (*b*) side view.

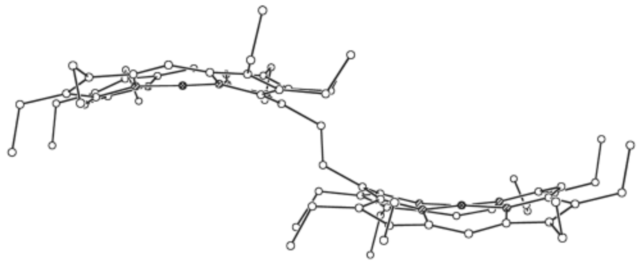


Fig. 2 Molecular structure of bis-Ni^{II} *trans*-ethene dimer **2** (hydrogen atoms not shown).

graphic separation. Pure metal-free *trans*-ethene-1,2-bisporphyrins have also been obtained by oxidation of the corresponding ethanebisporphyrins in refluxing acetic acid.[9] The free-base dimer can be selectively metalated to afford a series of monometallic, and homo- and hetero-bimetallic bisporphyrins.[10] The reductive coupling of *meso*-(2-formylvinyl)metalloporphyrins and metallochlorins analogously produces the corresponding dimers, linked by three conjugated carbon–carbon double bonds.[5]

Under the same reductive coupling conditions, a β-formylmetalloporphyrin produced a hydroxymethylene-bridged dimer **3** by loss of one of the formyl groups,[6] although a β-formylmetallochlorin formed the expected ethene-linked bischlorin. The crystal structure of **3** (Fig. 3) displays a skewed arrangement of the two macrocycles, the two planes of the four nitrogens form an angle of 77.3°, and the distance between the two metal centers is 8.08 Å. The reductive coupling of *meso*-formylmetallochlorins containing bulky propionate ester substituents resulted in the selective formation of the *trans*-bischlorins (such as **4**), which because of steric interactions did not significantly isomerize to the corresponding *cis*-products even upon heating in acetic acid.[11] Aerial oxidation of **4** in refluxing toluene–acetic acid led to the formation of the corresponding *trans*-bisporphyrin, as well as a porphyrin-chlorin hetero-dimer; under the same conditions bischlorin **5** selectively produced the corresponding *cis*-bisporphyrin.

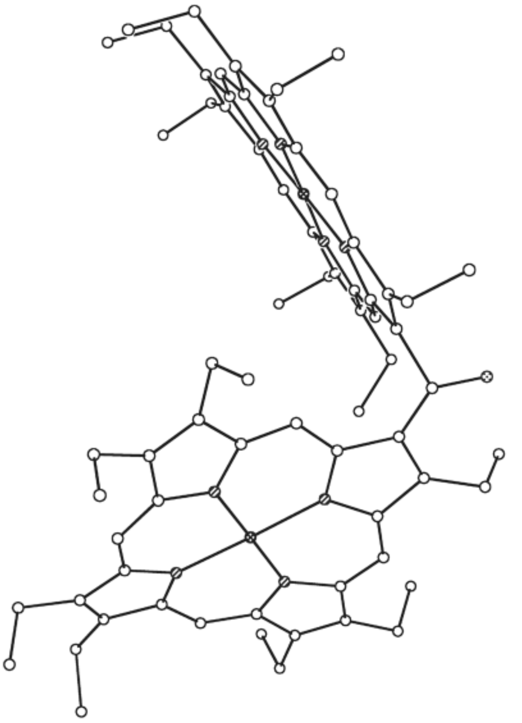


Fig. 3 Molecular structure of bis-Ni^{II} porphyrinyl alcohol **3** (hydrogen atoms not shown).

Syntheses of symmetrical cofacial bisporphyrins containing rigid aromatic bridges, such as 1,2-phenylene, biphenylene and anthracene (the so-called PacMan series), have been accomplished by stepwise condensation of aromatic dialdehydes with a 2-unsubstituted pyrrole, followed by reaction of the α-unsubstituted aromatic-linked bis(dipyrromethane) with a 1,9-diformyldipyrromethane.[12,13] Both symmetrical and unsymmetrical cofacial bisporphyrins are most conveniently prepared by initial monoprotection of the dialdehyde bridge, followed by condensation with pyrrole and an aromatic aldehyde to afford an aldehyde-protected porphyrin. This, upon deprotection and a second cyclization, produces homo- and hetero-bisporphyrins.[14,15] The syntheses of cofacial bisporphyrins bearing two amide bridges,[16] and larger host cavities with four strapping units,[17] have also been reported.

Another successful application of the McMurry methodology involves the synthesis of symmetric stilbene-linked bisporphyrins (*e.g.* **6**). The key intermediate is a stilbene-linked bis(dipyrromethane), produced by reductive dimerization of a 5-(*p*-formylphenyl)dipyrromethane, which upon MacDonald-type condensation with a 1,9-diformyldipyrromethane affords symmetric bisporphyrins such as **6**.[18,19] In yet another approach, these systems were obtained, albeit in lower yield, by reductive coupling of metalloporphyrins bearing a *meso*-(*p*-formylphenyl) substituent.[18,20] The latter methodology yielded both *cis*- and *trans*-stilbene-linked systems.

The synthesis of symmetrical bisporphyrins linked at the *meso* positions by an aryl group usually involves a stepwise

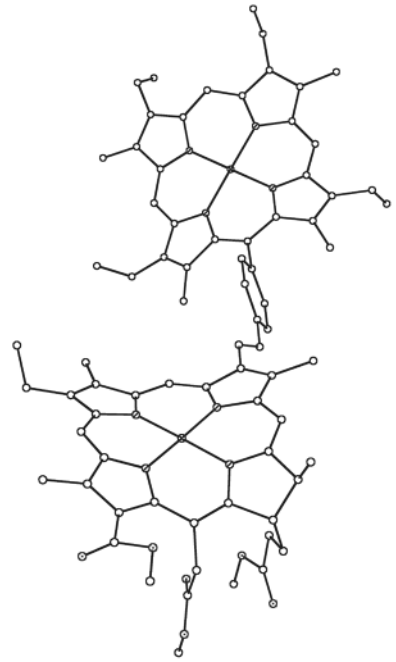
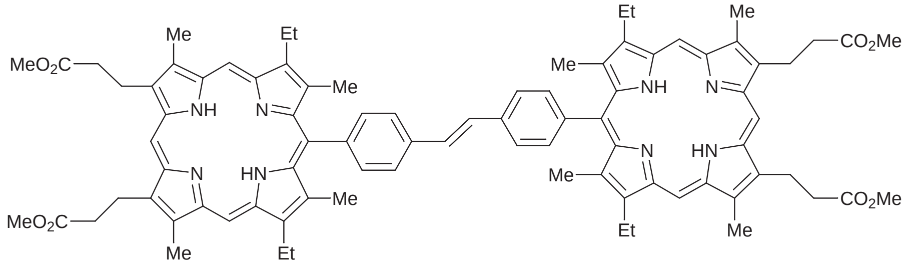


Fig. 4 Molecular structure of Ni^{II} porphyrin–Ni^{II} chlorin heterodimer **7** (hydrogen atoms not shown).



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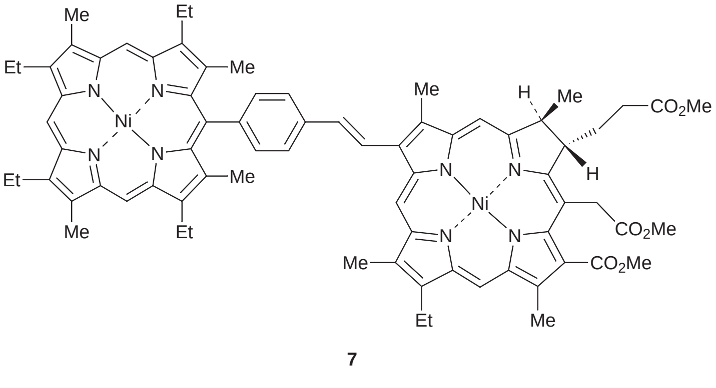

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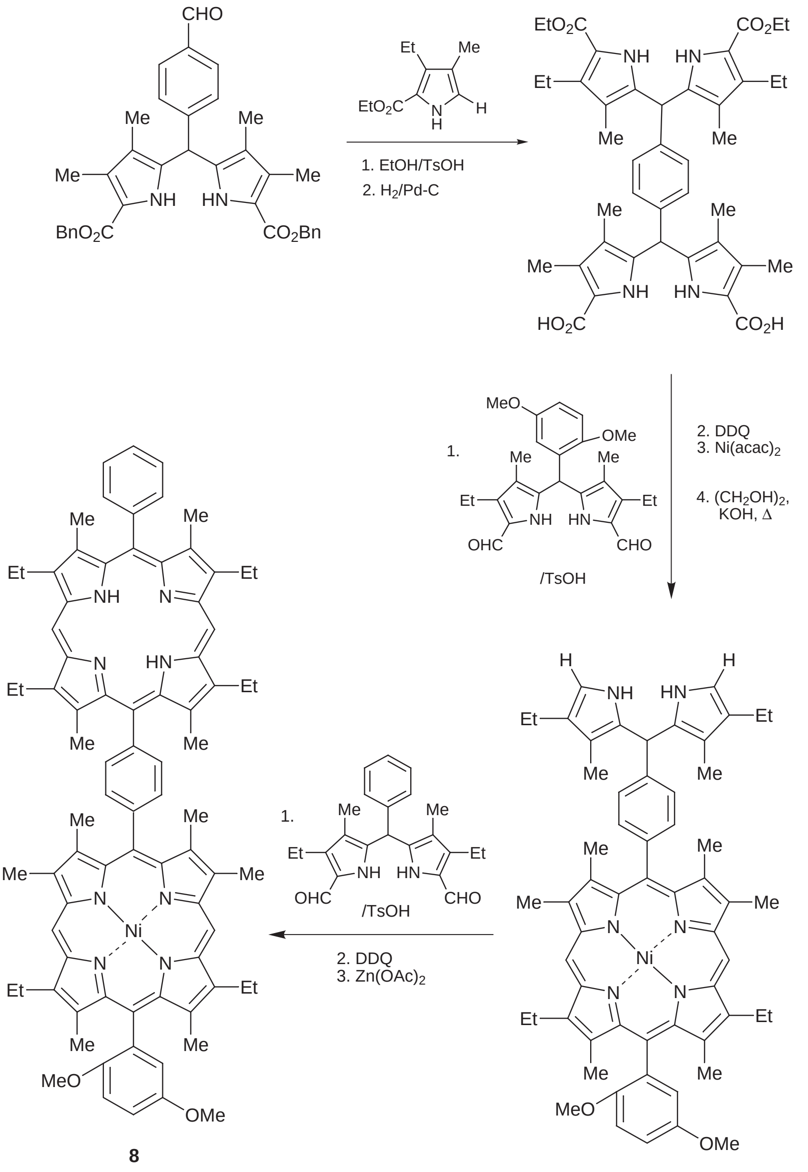
methodology, from intermediate aryl-linked α-unsubstituted bis(dipyrromethanes), which are in turn obtained from the condensation of formyl-substituted aromatic units with 2-unsubstituted pyrroles.[21,22] The preparation of symmetrical phenyl-linked bisporphyrins has also been accomplished, by acid-catalyzed condensation of a porphyrin bearing a *meso*-formylphenyl substituent with an excess of pyrrole and benzaldehyde;[23,24] in the presence of a large excess of pyrrole, a *meso*-[(*p*-formylphenyl)triphenyl]porphyrin was reported to produce a pentaporphyrin in 1% yield.[24] Unsymmetrical dimers and porphyrin-chlorin systems can be obtained from low-valent titanium-promoted heterocouplings of formyl-substituted porphyrins and chlorins, although a statistical mixture of all possible homo- and hetero-dimers is generally produced. When a 2 : 1 mixture of nickel(II) 3-formylchlorin-e_6 trimethyl ester and a *meso*-(*p*-formylphenyl)porphyrin was coupled under the McMurry conditions, the corresponding bisporphyrin and bischlorin were obtained in 6 and 42% yields, respectively, along with the porphyrin-chlorin dimer **7**, in 41% yield.[18] The crystal structure of **7** (Fig. 4) shows the *trans* arrangement of the two macrocycles, and a bow-shaped structure for this molecule with an angle between the two N_4 planes of 35.7°. Unsymmetrical bisporphyrins, such as **8**, linked at the *meso* positions by aromatic groups are generally synthesized as shown in Scheme 1;[18] the key intermediate is an unsymmetrical bis(dipyrromethane) bearing both benzyl and ethyl ester groups which are selectively cleaved and reacted with a dipyrromethane, in a stepwise manner. Phenyl-linked unsymmetrical dimers have been synthesized by reaction of a *meso*-(formylphenyl)porphyrin with a 2-unsubstituted pyrrole, followed by condensation with a dipyrromethane,[25] or by mixed condensation.[26] Bisporphyrins bound by several *trans*-stilbene linkages have also been synthesized from the corresponding poly(benzyl sulfone)-linked bisporphyrins *via* the Ramberg–Bäcklund reaction.[27] A β-substituted porphyrin methylphosphonium salt has been used as a building block for the synthesis of porphyrin arrays, linked by butadiene, styryl, and diethenylphenylene bridges, and consisting of up to nine porphyrin units.[28]

Other syntheses of *meso*-*meso*, *meso*-β or β-β linked porphyrin arrays take advantage of metal-mediated cross-coupling methodologies and the ease with which β- or *meso*-haloporphyrins are prepared. Alkynyl-bridged porphyrin arrays, obtained *via* the Pd^0 cross-coupling of a small set of ethynyl- and halo-porphyrin building blocks display large porphyrin–porphyrin excitonic and electronic couplings far exceeding those of other porphyrin-to-porphyrin aromatic, aliphatic or vinylic linkages.[29] *meso*-Ethynyl bridges are most efficient to conjugatively connect porphyrins. Glazer–Hay oxidative coupling of 5,15-diethynylporphyrin afforded polymeric materials absorbing in the near IR region and exhibiting strong third-order non-linear optical behavior.[30] Construction of *meso*-alkynylaryl



Scheme 1

linked oligoporphyrins relied also on a small set of (halo- and ethynyl-phenyl)porphyrin building blocks and iterative cross-coupling reactions. A variety of molecular structures have been obtained, as exemplified by the preparation of a square macrocyclic array of four mutually coplanar porphyrins from the palladium catalyzed reaction of zinc(II) 5,10-di(*p*-ethynylphenyl)-15,20-dimesitylporphyrin with 5,10-di(*p*-iodophenyl)-15,20-dimesitylporphyrin in the presence of $As(Ph)_3$.[31] Positive coupling of linear *m*-ethynylaryl functionalized porphyrins with copper(I) chloride/air in the presence of pyridine-based templates yielded butadiyne bridged dimeric or tetrameric cyclic species.[32]

Porphyrin oligomers with orthogonal π-systems

The low-valent titanium coupling reaction provides a synthetic route to directly linked *meso*-*meso* bisporphyrins (*e.g.* **9**). Dipyrrol-2-yl ketone smoothly undergoes reductive coupling in the presence of pyridine, affording tetra(pyrrol-2-yl)ethene, which upon tetraformylation under the Vilsmeier conditions, followed by MacDonald-type condensation with a 1,9-di-unsubstituted dipyrromethane, produced bisporphyrin **9** (Scheme 2).[33] The crystal structure of **9** (Fig. 5) shows an orthogonal arrangement of the two directly linked macrocycles; the dihedral angle between the two porphyrin planes was found to be 83.9° (crystallization from CH_2Cl_2–methanol) or 64.3° (crystallization from THF–hexane), the difference probably due to variable lattice packing. The optical spectrum of **9** exhibits a large splitting of the Soret band ($\Delta\lambda$ = 36 nm) which reveals excitonic coupling[34] indicating substantial electronic interaction between the two macrocycles, despite their orthogonal arrangement. Directly *meso*-*meso* linked bisporphyrins and trisporphyrins have also been obtained by reaction of a *meso*-formyl β-unsubstituted porphyrin with a 1,9-di-unsubstituted dipyrromethane,[35] and by electrochemical or Ag^I-promoted oxidative coupling of 5,15-diarylporphyrins.[36] The latter approach also produced higher oligomers, which can be separated by size exclusion chromatography. The one-electron oxidations are usually performed on the Zn^{II} complexes, which readily form the π-cation radical intermediates, and the reaction mechanism probably involves subsequent nucleophilic attack by a neutral zinc(II) porphyrin. The chemical oxidation is usually accomplished with $AgPF_6$ at room temperature, and addition of iodine was reported to accelerate the coupling reaction. The electrochemical oxidation generally uses a platinum net as the working electrode;[37] electrochemical oxidations performed on the free-base porphyrin, and on the Cu^{II}, Pd^{II} and Ni^{II} complexes regioselectively produced *meso*-β linked bisporphyrins.[38] The electrochemical oxidation of zinc(II)octaethylporphyrin in the presence of an excess of 4,4′-bipyridine led to the production of a pentaporphyrin, *via* a *meso*-tetra(4,4′-bipyridinium)porphyrin intermediate.[39]

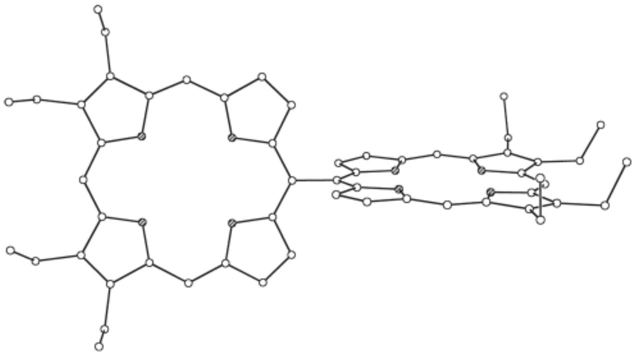
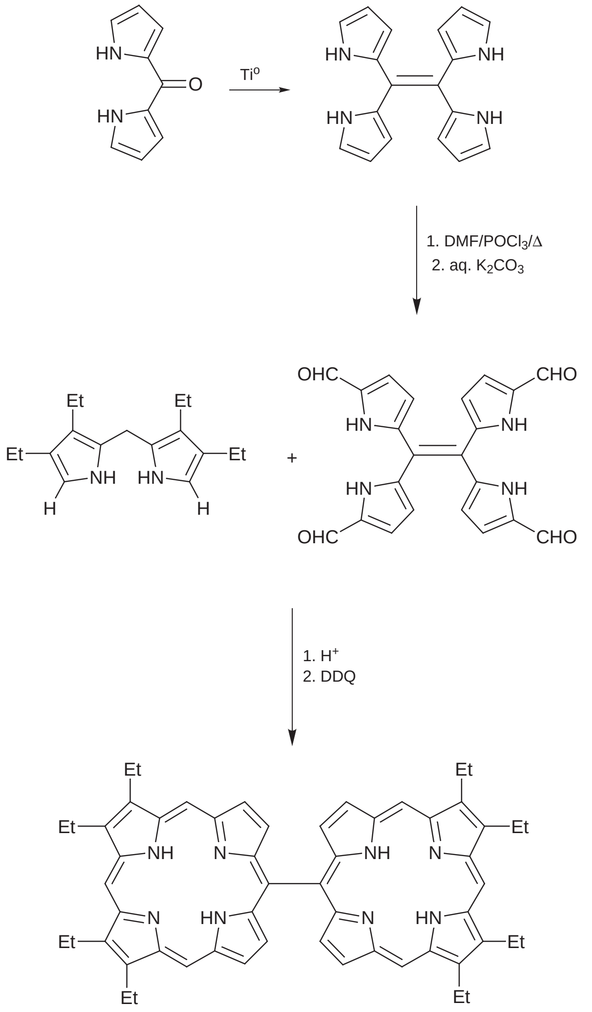


Fig. 5 Molecular structure of free-base *meso-meso* linked dimer **9** (hydrogen atoms not shown). Dihedral angle is 83.9°.



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Scheme 2

Directly *meso*-β linked porphyrin-chlorin dimers have been obtained by mixed condensation of methyl pyropheophorbide *d*, *o*-methylbenzaldehyde, and a 1,9-di-unsubstituted dipyrromethane.[40] We have developed a related synthetic route to porphyrin-chlorin dimers by stepwise condensation of a β-formylchlorin with a 2-unsubstituted pyrrole, *via* a chlorin-dipyrromethane intermediate.[41] Dimer **10** was produced from the condensation of a pyropheophorbide *a*-dipyrromethane with a 1,9-diformyldipyrromethane, whereas trimer **11** resulted from condensation of β-formylpyropheophorbide *a* with a 1,9-di-unsubstituted dipyrromethane. A dimer was also produced from the latter reaction, presumably by cleavage of the strained C_β–C_{meso} bridge at the pyropheophorbide *a*-porphodimethene oxidation step.

Porphyrin oligomers with fused π-systems

Relatively few oligoporphyrin arrays in which individual porphyrin rings are bridged by coplanar aromatic bridges have been prepared. Such rigid coplanar arrays should display pronounced electronic interactions between metal centers *via* overlap of their d(π) orbitals with the conjugated π-system of the porphyrins. The McMurry reaction, applied to chlorophyll derivatives containing an exocyclic cyclopentanone ring, produces fully conjugated bischlorins.[42] The metal-free compound **12** was obtained from the zinc complex monomer by performing the McMurry reaction in the presence of pyridine, followed by demetalation with TFA. The crystal structure of **12** (Fig. 6) shows that the molecule is essentially planar, forming an angle of 2.2° between the two planes of the N_4 atoms. These bischlorin systems show substantial hyperchromic and bathochromic shifts ($\Delta\lambda$ *ca.* 90–100 nm) of the long-wavelength absorption band in their optical spectra when compared with the precursor monomers, a result of their extended π-electronic delocalization (Fig. 7).

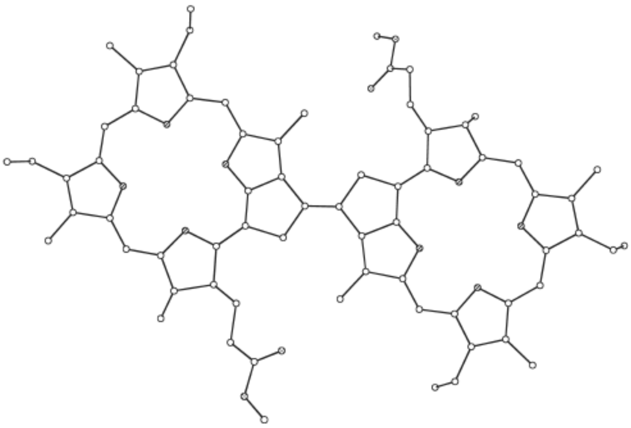
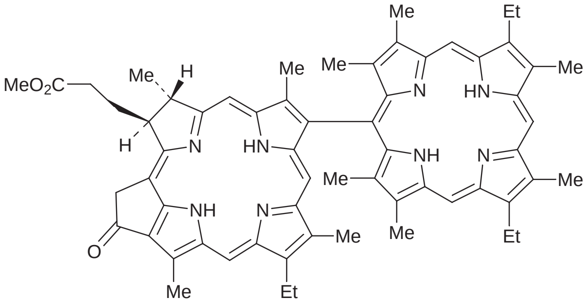


Fig. 6 Molecular structure of planar free-base bis-chlorin **12** (hydrogen atoms not shown).

Crossley and co-workers developed an approach to laterally extended oligoporphyrins sharing up to three 1,4,5,8-tetraazaanthracene units.[43] Linear and bent tris-porphyrins and a tetrakis-porphyrin were prepared by condensing porphyrin-2,3-diones and porphyrin-2,3,12,13- or -2,3,7,8-tetraones with aromatic *ortho*-diamines or 1,2,4,5-tetraamines in refluxing toluene. A bis-tetrabenzoporphyrin in which two benzoporphyrins share a fused benzene ring has been obtained by cross-condensation of pyromellitic dipotassium diimide and potassium *tert*-butylphthalimide at 320 °C.[44] Our approach to related arrays sharing a common benzene ring was based on the participation of *meso*-tetraarylporphyrins as dienophiles in Diels–Alder type reactions with highly activated dienes, such as those generated *in situ* by thermal extrusion of SO_2 from fused aromatic sulfones. Refluxing a solution of *meso*-tetraphenylporphyrin and excess ethyl 1,1-sulfolano[3,4-*c*]pyrrole-2-carboxylate in 1,2,4-trichlorobenzene gave tetraphenylchlorin **13** as an enantiomeric mixture.[45] Oxidation with DDQ and subsequent zinc(II) insertion afforded the corresponding zinc(II) 2*H*-isoindoloporphyrin. Reduction of the ester group of this porphyrin with $LiAlH_4$ produced the alcohol which, upon acid-catalyzed tetramerization and oxidation with *p*-chloranil, gave a cyclohexadiene annulated pentaporphyrin. This pentamer could be further aromatized with excess DDQ to afford a conjugated



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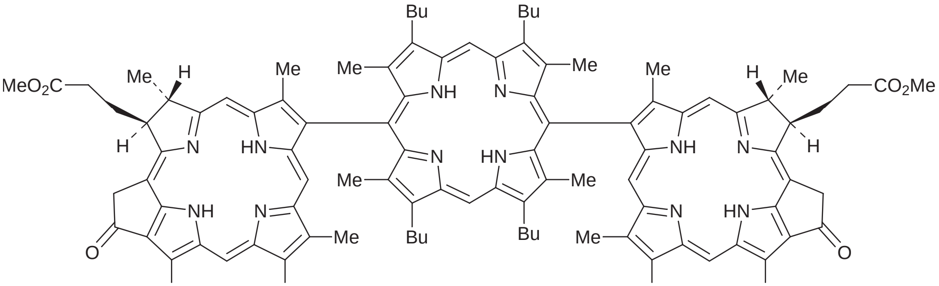

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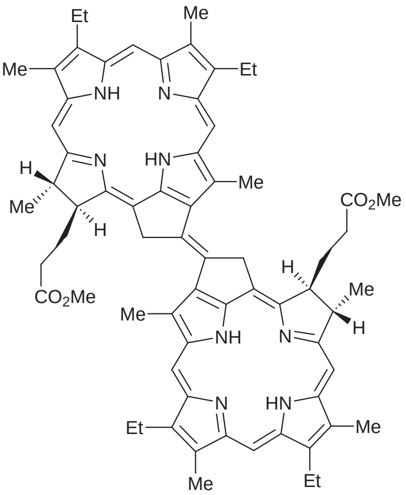

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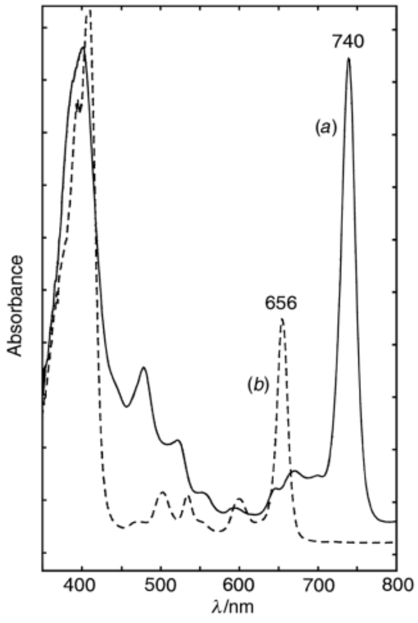
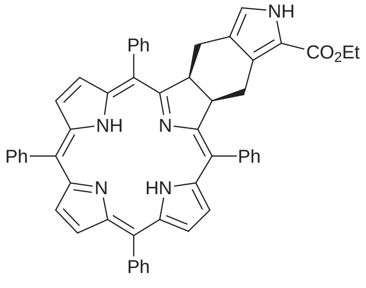


Fig. 7 Optical spectrum, in CH_2Cl_2, of (*a*) bis-chlorin **12** and (*b*) its monomeric pyropheophorbide precursor.

pentaporphyrin **14**, displaying a long-wavelength absorption band at 774 nm. In order to further enhance the interporphyrin communication, we prepared a novel modular β-β′ building block, *i.e.* pyrrolo[3,4-*b*]porphyrin, by applying the [3 + 2] cycloaddition of nitroalkenes with isocyanoacetates[46] to metallo-2-nitrotetraphenylporphyrins ($2\text{-}NO_2TPPs$). We took advantage of the strong ability of the nitro group to activate a tetraarylporphyrin towards Michael addition and its propensity to act as leaving group. Thus, refluxing $Ni(2\text{-}NO_2TPP)$ with methyl isocyanoacetate and two equiv. of DBU in THF–Pr^iOH led, as a result of an *in situ* transesterification reaction with Pr^iOH, to the formation of the first β-fused pyrroloporphyrin, as its isopropyl ester **15**. Fig. 8 shows the X-ray structure of pyrroloporphyrin **15**. Use of benzyl alcohol in place of Pr^iOH yielded advantageously the pyrroloporphyrin benzyl ester **16**. Reaction of $Ni(2\text{-}NO_2TPP)$ with *tert*-butyl isocyanoacetate (in THF–Bu^tOH) gave (in addition to pyrroloporphyrin *tert*-butyl ester) naphthochlorin **17**. Attempted crystallization of **17** afforded a β-β′ naphthochlorin dimer (**18**).[47] Despite the direct β-β′ bond, the macrocycles were nearly coplanar, exhibiting an interplanar angle of 30.1° (Fig. 9). The macrocyclic overlap was limited to one pyrrolic subunit of each naphthochlorin monomer, displaying a marked similarity to the special pair in the bacterial photosynthetic reaction center. The π-radical dimerization of **17** could be promoted by benzoyl peroxide in refluxing benzene to afford **18** in higher yield. When Zn(2-NO_2TPP) was subjected to the Barton–Zard conditions



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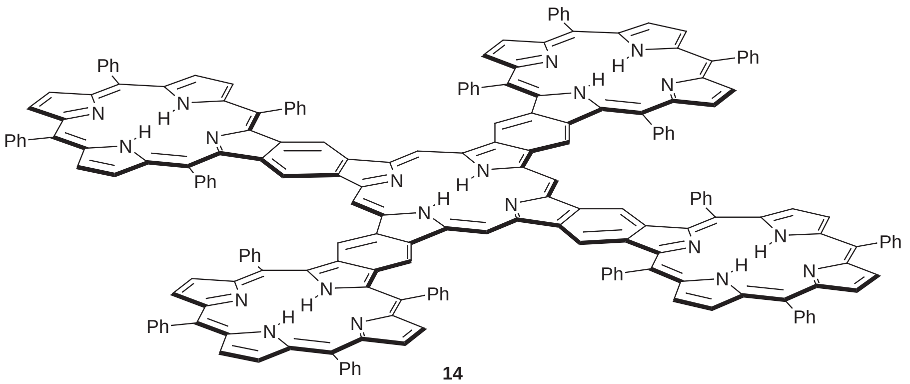

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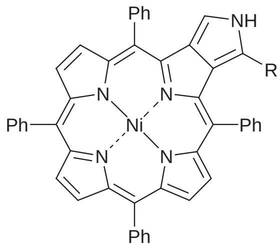
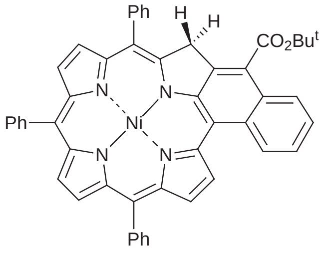


15 R = CO_2Pr^i
16 R = CO_2Bz
20 R = H



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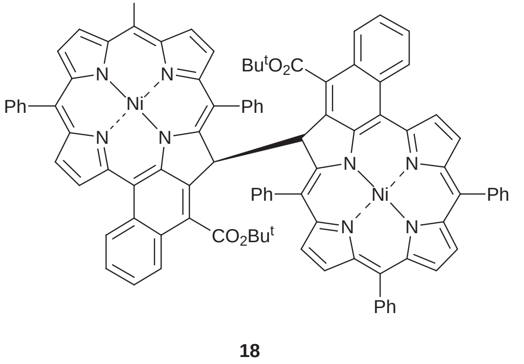

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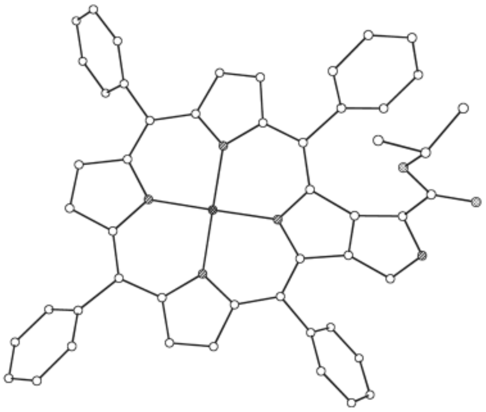


Fig. 8 Molecular structure of Ni^{II} pyrroloporphyrin **15** (hydrogen atoms not shown).

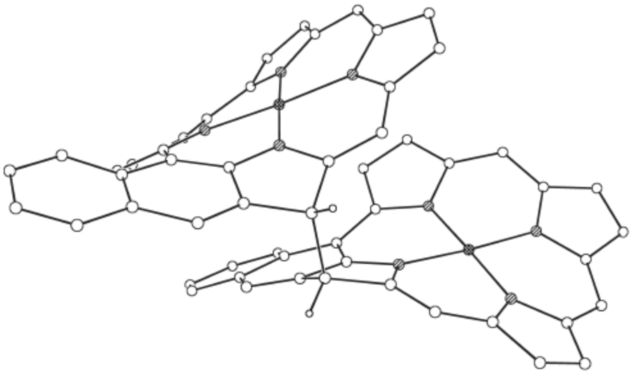


Fig. 9 Molecular structure of Ni^{II} naphthochlorin dimer **18**; ester functions, non-fused phenyl rings, and hydrogen atoms (with the exception of those associated with the direct dimer link) have been omitted for clarity.

Fig. 10 Molecular structure of aggregated Zn^{II} cyclopropyl-annulated chlorin **19** (hydrogen atoms not shown).

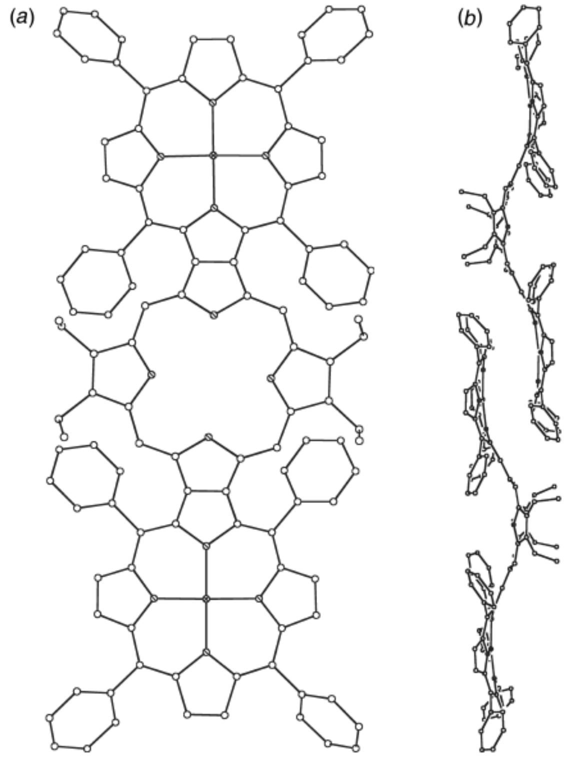
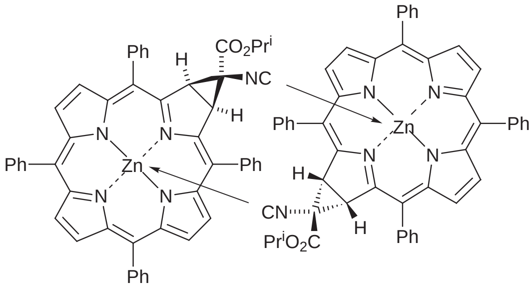


Fig. 11 Molecular structure of $[Ni^{II}][H_4^{2+}][Ni^{II}]$ fused trimer **21**·$(HCl)_2$ (hydrogen atoms not shown); (*a*) top view, (*b*) side view of two molecules illustrating the π–π interactions observed in the crystal packing.

($NCCH_2CO_2Et$, Pr^iOHTHF, DBU), no pyrroloporphyrin was formed; instead a cyclopropyl-annulated chlorin was isolated with an *endo* configuration with regard to the isocyanide group.[48] This zinc(II) chlorin self-assembled with isocyanide axially coordinated to the central zinc(II) ions, affording **19** (crystal structure shown in Fig. 10). Isolation of this cyclopropylchlorin prompted our development of a new methodology for dihydroporphyrin synthesis based on the Michael addition of active methylene compounds to 2-NO_2TPPs.[49] A Diels–Alder cycloaddition of di(2-phenylethyl) acetylenedicarboxylate with an *N*-(*tert*-butoxycarbonyl)pyrrolo[3,4-*b*]porphyrin gave, after cleavage of the Boc group and subsequent zinc(II) insertion, the corresponding zinc(II) 7-azabicyclo[2.2.1]heptadiene porphyrin.[50] In the solid state, a non-covalent cyclic hexameric array was obtained wherein each zinc(II) porphyrin was coordinated to the fused azabicyclo group of an adjoining porphyrin unit. Hydrogenolysis of pyrroloporphyrin benzyl ester **16** using 20% palladium(II) hydroxide on carbon and cyclohexene as the hydrogen donor afforded the green di-α-unsubstituted pyrroloporphyrin **20**.[51] Under non-acidic conditions, 2,5-bis(trimethylammoniomethyl)-3,4-diethylpyrrole reacted with **20** in refluxing methanol–THF in the presence of $K_3Fe(CN)_6$/air to afford the first β-β′-directly-fused porphyrin trimer **21**.[52] This novel compound possesses a large fully-delocalized aromatic network which could possibly give rise to metallic type conduction. The molecular structure of **21**·$(HCl)_2$ was confirmed by X-ray crystallography (Fig. 11). Protonation of the central porphyrin facilitated the crystal packing by enabling intermolecular π–π stacking to occur only between terminal porphyrins, thus giving rise to independent linear rods of fused porphyrins. The porphyrin trimer has an edge-to-edge span of 27.0 Å and an intramolecular distance between metals of 16.16 Å. The most notable feature in the absorption spectra of **21** and a related β-β′ fused dimer [obtained from cross condensation of **20**, pyrrole and 2,5-bis(trimethylammoniomethyl)-3,4-diethylpyrrole] is an intense Q band at 715 nm or at 652 nm for the fused dimer, reminiscent of a bacteriochlorin (or chlorin) type visible spectrum [see optical spectrum of **21**·$(HCl)_2$ on the cover of this Issue]. Demetalation of **21** gave a stable metal-free porphyrin trimer which undergoes two reversible, spectroscopically distinct protonation steps. As shown by X-ray crystallography, protonation takes place first on the two bookend moieties to yield a green tetraprotonated species.[53] The two inner hydrogen atoms of the central porphyrin were located on the non-fused diethylpyrrolic moieties. Upon addition of excess acid a red hexaprotonated species was obtained which featured a split Soret band (429, 510 nm) and two broad Q bands (664, 820 nm). The metal free trimeric fused porphyrin shows a very intense fluorescence band with a maximum at 775 nm. The very short Stokes shift observed could lead, by analogy with the monomeric porphyrin, to the attribution of this band to the lowest π–π* transition. Such an intense band is quite rare in the 750–900 nm range, so



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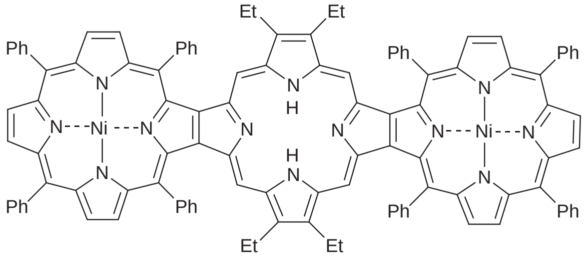

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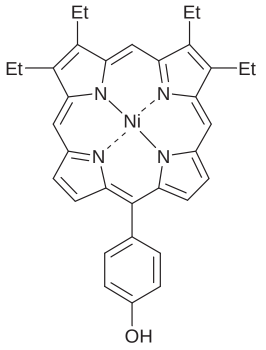

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the fused trimer could be a good reference for measuring quantum yields in this spectral region.[53]

Supramolecular arrays

Spontaneous generation of higher order structures is a major goal in supramolecular chemistry, and self-assembly concepts have been widely applied to rigid polynucleating porphyrin-based ligands in order to mimic light harvesting and electron transport systems. Many photoactive supramolecular assemblies are based upon the peripheral coordination of *meso*-pyridyl groups to transition metals[54] or on their coordination to the central metal ion of a porphyrin.[55] As a recent example, a palladium mediated peripheral assembly of twenty one components [*i.e.* four di(4-pyridyl)porphyrins, four tri(4-pyridyl)porphyrins, one tetra(4-pyridyl)porphyrin and twelve $PdCl_2$ units] resulted in a nonameric square planar porphyrin array.[54] Self-assembled arrays occur through the coordination of the central metal ion by a β-functional group afforded head-to-tail dimeric,[48,56] trimeric,[57] hexameric[50] or polymeric species.[56] Other supramolecular analogues of the photosynthetic special pair have been prepared by inducing the intermolecular aggregation of two tetra(alkylammonio)porphyrins *via* binding their ammonium moieties within the cavities of four ditopic crown ethers.[58] Multiple hydrogen bonding has been employed in the construction of organized porphyrin arrays,[59] but their low kinetic stability ultimately limit their study as well as their use. In the case of double decker or triple decker metalloporphyrinoids, the coordinated metal ions, usually from the lanthanide series, act as the bridging units.[60]

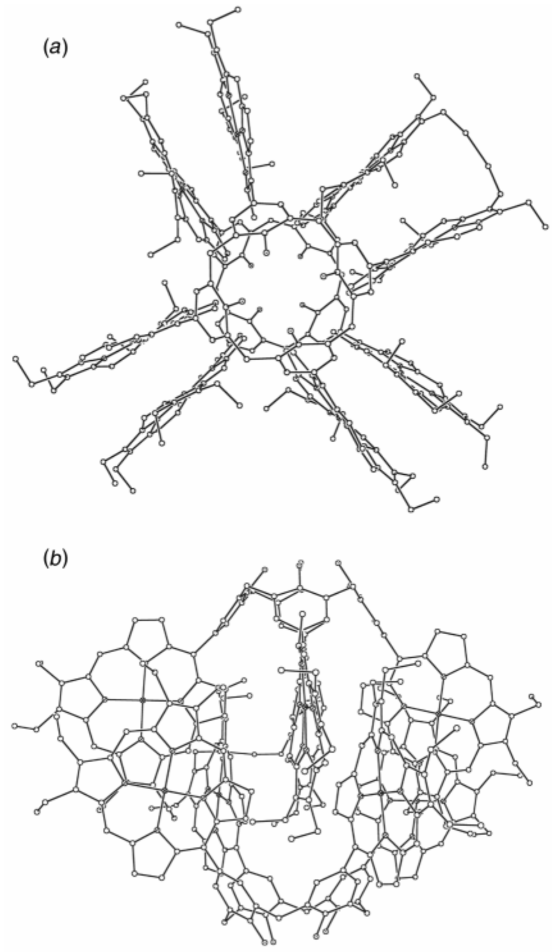
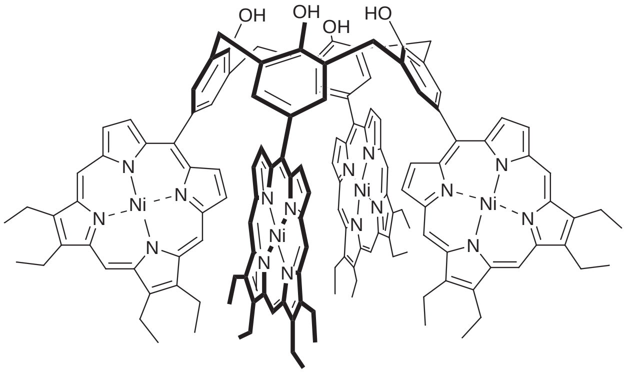


Fig. 12 Molecular structure of aggregated Ni^{II} calix[4]arenoporphyrin (**23**) dimer (hydrogen atoms not shown); (*a*) top view, (*b*) side view.

The design of complex three dimensional arrays *via* the use of building blocks displaying electronic and structural information enticing a covalent self-assembly process is less common. We felt that applying known macrocylization reactions to suitably functionalized porphyrinoids could lead to covalent supramolecular assemblies which are stable, both thermodynamically and kinetically. Our approach to the construction of such arrays with highly organized cavities was based on the redox reactivity of 15-substituted oxophlorins,[61] or the use of a *covalent template* strategy (since up to eight new covalent bonds could be formed in a predefined manner) based on the condensation of phenolic porphyrins into a calix[*n*]arene molecular platform.[62]

Combination of calix[4]arenes, which possess strong ion binding properties, with an organized array of pH-dependent photoactive chromophores can lead to the development of efficient sensor agents. Condensation of a *meso*-(*p*-hydroxyphenyl)porphyrin with formaldehyde under selective alkaline conditions may potentially afford calix[4], [6] or [8]arenoporphyrins. We first targeted a calix[4]arenoporphyrin and adopted the Zinke–Cornforth procedure with minor modifications. To minimize steric congestion among adjacent porphyrins and to increase the solubility of the final product, a porphyrin with unsubstituted β-positions on its upper half and β-ethyl groups on its lower half was targeted. Vilsmeier bisformylation of 5-(*p*-methoxyphenyl)dipyrromethane in refluxing CH_2Cl_2 gave the corresponding 1,9-diformyldipyrromethane, which upon acidic condensation with 2,3,7,8-tetraethyldipyrromethane afforded *p*-(12,13,17,18-tetraethylporphyrin-5-yl)anisole in moderate yield. This MacDonald-type (*i.e.* '2 + 2') condensation was successful only when the β-unsubstituted upper moiety bore the bridging formyl groups. After BBr_3 demethylation and metalation of the nitrogen core, *p*-substituted phenol **22** was obtained



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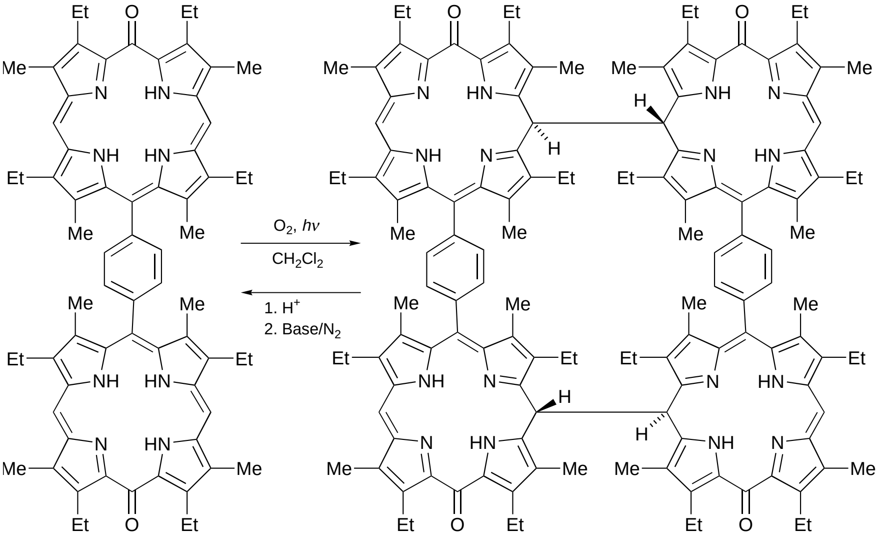
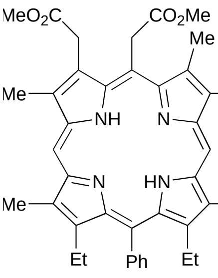
and refluxed in dioxane in the presence of NaOH and formaldehyde, affording mono- and di-benzyl alcohol porphyrins. The crude mixture was then refluxed in diphenyl ether to give the calix[4]arenoporphyrin **23** (purified on Sephadex). The calix[4]arenoporphyrin adopted the cone conformation, a motif prevalent in calix[4]arenes which is stabilized by a cyclic array of intramolecular hydrogen bonds among OH groups. For the solid state, this was shown by X-ray diffraction studies. Figure 12 shows the interactions which exist between two neighboring molecules of calix[4]arenoporphyrin and fully explains the preferential cone conformation over other possible conformations such as the 1,2- or 1,3-alternate. It is apparent that the preference for the cone conformation is related more to a unique π-stabilized dimerization process rather than intramolecular hydrogen bonding at the phenolic head of the molecule; very strong π-stacking interactions are the key feature in the molecular recognition of two calix[4]arenoporphyrin molecules leading to a unique non-covalent cogwheeled array of eight porphyrins. Although an AB type pattern for the benzylic methylene protons characteristic of a fixed cone conformation was not clearly identified, the broad NMR signals, which were only marginally temperature dependent, attest of the persistence of such an aggregated dimeric form in solution. Functionalization of the upper rim and a decrease in hydrogen bonding could favor an aggregation network based on a 1,3-alternate conformation.

Our second strategy toward the synthesis of covalent supramolecular arrays relied on the propensity of oxophlorins (5-oxyporphyrins) to form, upon light induced aerial oxidation, fairly stable π-neutral radicals in which dimerization results in the formation of a carbon–carbon bond between two sp^3 *meso* carbons, sited opposite to the carbonyl group (*i.e.* at the 15-position).[63] In order to alter the oxidation potential, the spin distribution of the π-neutral radical, and the dimerization process, we synthesized 15-substituted oxophlorins, *via* a '2 + 2' condensation of 1,9-diformyldipyrroketones with 5-substituted (ethyl, aryl, porphyrin-5-yl, corrol-10-yl) dipyrromethanes in acid.[61] The ethyl substituent induced a steric stabilization of a novel non-aromatic, non-redox active tautomeric species of oxophlorins (*i.e.* 15-iso-oxophlorin) because the resulting loss in aromatic stabilization is largely overcome by a decrease in the steric congestion at the 15-position introduced by a sp^3 hybridized carbon atom.[61] Upon complexation with zinc(II), these 15-iso-oxophlorins formed a doubly oxo-bridged head to tail dimer, placing the two macrocycles within π–π contact. Formation of the π-neutral radical of 15-substituted oxophlorins with air occurred spontaneously in solution in the case of electron-donating substituents and led to the formation of dimeric species. The presence of two



24 **25**



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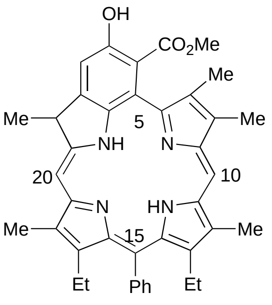

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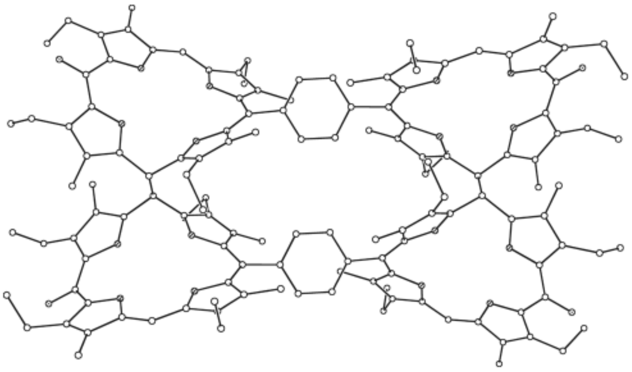

Fig. 13 Molecular structure of dimerized bis-oxophlorin **25** (hydrogen atoms not shown).

regioisomers (with regard to the orientation of the carbonyl groups) resulting from the dimerization demonstrated that 15-substituted oxophlorins dimerize at the 10,10′-positions. Although no attempts were made to separate these regioisomers, spontaneous resolution occurred during the growth of individual single crystals, as shown by the molecular structures of ethyl and phenyl 15-substituted dimers. Introduction of electron-withdrawing groups such as a pentafluorophenyl efficiently minimizes the spontaneous formation of oxophlorin π-radicals. Radical formation could be mediated with a mild oxidant such as $K_3Fe(CN)_6$ in THF, and 15-(pentafluorophenyl)oxophlorins were shown to dimerize with this kind of encouragement, in high yield.

Having established the redox activity of 15-substituted oxophlorins, we used their self-assembly to prepare various tetrameric arrays of chromophores.[61] Bis-oxophlorin **24** was prepared by condensation of 1,9-diformyldipyrroketone with a symmetrical 1,4-bis(dipyrromethan-5-yl)benzene in TFA. A daylight-induced oxidative coupling of bis-oxophlorin **24** afforded, in very high yield, a cyclic macromolecule **25** consisting of four iso-oxophlorin-like subunits arranged in a stereochemically unique *trans*,*trans*,*trans* fashion at the bridging 10,10′-positions (Fig. 13). The molecular structure of **25** showed an overall helical structure with disordered molecules of *n*-hexane fitting into the groove of the helix (not shown). The stereochemistry of the self-assembly process of the achiral components can be controlled by the insertion of a methoxy group at the 10-position of the bis-oxophlorin precursor (when prepared in MeOH–CH_2Cl_2, TsOH) resulting in a tetrameric array possessing a “stepped” structure with a *trans*,*cis*,*trans* orientation at the 10,10’-bridges. Whereas aromatic porphyrins display extremely shielded central nitrogen protons, these iso-oxophlorin species have an interrupted conjugation pathway and feature ^{1}H NMR peaks characteristic of a non-aromatic chromophore, with D_2O/Et_3N exchangeable NH peaks around 13 ppm. Addition of acid (TFA) to all these dimeric and tetrameric species reverses quantitatively the oligomerization process to form the oxophlorin dications as shown by the clean isosbestic points in spectrophotometric studies and by X-ray crystallography. Neutralization drives again the oxidative self-assembly. This overall process involves a very facile redox couple. Owing to the reversible, high yielding self-assembly behaviour of these oxophlorin species, we term this strategy *radical capture* and stress that it represents a unique approach towards the design and synthesis of covalently linked supramolecular assemblies. To further explore radical processes as a generic strategy, we turned our attention to adjacent *meso*,β-bis(methoxycarbonylmethyl)porphyrins.[64] Such porphyrins (*e.g.* **26**) when adsorbed on CH_2Cl_2-moistened silica gel gave the Dieckmann-like cyclized β-keto ester **27** which dimerized at the 20-position *via* the intermediacy of a delocalized π-radical. Any porphyrinoid system that possesses structural features which can efficiently form a stabilized π-radical (*e.g.* the carbonyl oxygen in oxophlorins, or the phenolic moiety in **27**) should undergo oxidative chemistry leading potentially to oligoporphyrin arrays.

Conclusions

It seems clear, from the work of our group and others, that past dramatic advances in the synthesis of monomeric porphyrin systems have brought us to the point where combination strategies for preparation of oligomeric porphyrin arrays are now not only possible, but are being actively exploited. When one combines the unparalleled redox, photochemical, spectroscopic, metal chelation/ligand binding, and catalytic properties of our favorite chromophore with the potential for assembling these molecules to give interactive arrays, one can only conclude that the future for research in this area is unbounded.

Acknowledgements

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