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Porphyrinoids

A 20π-Electron Heteroporphyrin Containing a Thienopyrrole Unit**

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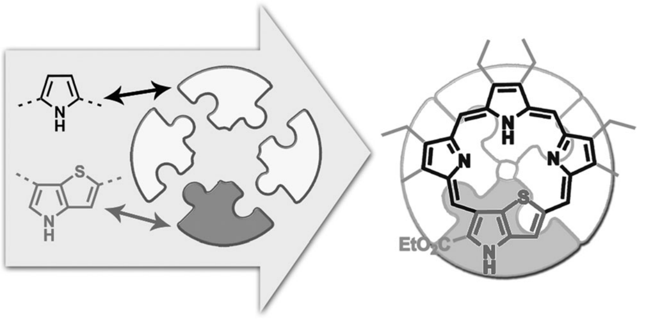
Dedicated to Professor Noboru Ono on the occasion of his 70th birthday

Porphyrins have been the focus of intense research interest owing to their pivotal role in many important biochemical processes and their suitability for diverse applications in medicine, material science, and catalysis, based on the properties associated with their heteroaromatic 18π-electron conjugation systems.[1] The synthesis of many structural analogues, such as core-modified porphyrins,[2] N-confused porphyrins,[3] corroles,[4] porphycenes,[5] contracted porphyrins,[6] and expanded porphyrins,[7] have been investigated in conjunction with their diverse applications and the wider study of macroaromaticity.[8] Typically, synthetic work has focused on increasing or decreasing the number of the pyrrolic (or other heteocyclic) subunits within the macrocyclic ring and on varying the relative connectivity between the pyrrolic constituents or adjusting the number of bridging *meso*-carbon atoms. The synthesis of functionalized pyrrole subunits is challenging, and there has been comparatively little research on core-modified porphyrins, in which pyrrolic nitrogens are replaced by other heteroatoms such as O, S, Se, and Te.[9] Herein, we report the first example of the synthesis and characterization of a core-modified porphyrinoid containing a thienopyrrole moiety (**1**; Scheme 1).



Scheme 1. Heteroporphyrin containing one thienopyrrole unit.

The incorporation of the fused heteropyrrole ring of thienopyrrole creates a very stable nonaromatic macrocycle with a 27 atom 30π-electron system. The optical and redox properties differ markedly from those of conventional 18π-electron heteroaromatic tetrapyrrolic porphyrinoids. Although a 17 atom 20π-electron inner perimeter would be anticipated for tautomers with two inner protonated pyrroles, the π system is nearly planar. Highly distorted structures have recently been reported for (4*n*)π-electron porphyrinoids such as oxidized 16π-electron and reduced 20π-electron (isophlorins) porphyrins, which have inner perimeters consisting of 16 rather than 17 atoms.[10] The π system can be readily transformed into a transient radical species, through chemical and electrochemical methods.

The thienopyrrole-containing porphyrin **1** was prepared from thienopyrrole dialdehyde **2** and tripyrrane diacid **3b**[12] by using the acid-catalyzed “3+1” MacDonald method[11] (40% yield, the experimental details are provided in the Supporting Information). Compound **2** was prepared from 2-formylthiophene and ethylazidacetate. The initial reaction provided ethyl 2-azido-3-(thiophen-2-yl)acrylate, which upon cyclization gave ethyl 4*H*-thieno[3,2-b]pyrrole-5-carboxylate **4**[13] and then subsequent formylation provided **2** (Scheme 2).

The structure of **1** was unambiguously elucidated by single-crystal X-ray diffraction analysis (Figure 1).[14] Suitable crystals were obtained by slow diffusion of hexane into a dichloromethane solution. The macrocycle adopts a near planar conformation, which differs markedly from the distorted structures that have been reported for porphyrins with (4*n*)π-electron systems.[10] Planar conformations are normally expected to lead to a destabilization of the π system for porphyrins with (4*n*)π-electron systems. The average displacement of the β-carbon atoms from the least-square plane of the *meso*-carbon atoms was 0.093 Å, which is in marked contrast with the 1.36 Å value for [20]isophlorin.[13a] It is also noteworthy that the thienopyrrole ring is tilted out of the least-square plane by only 2.695°, whereas the other three pyrrole rings are tilted by 3.012°, 3.092°, and 7.040°. In a similar manner to the [20]isophlorins, however, clear alternation is observed in the C−C bond lengths around the

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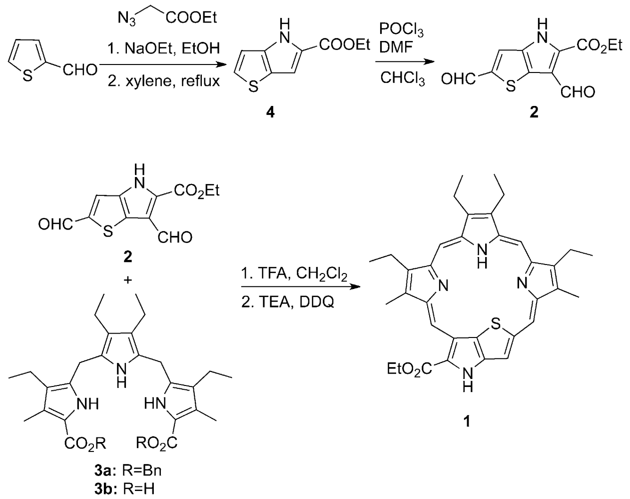


Scheme 2. Synthesis of heteroporphyrin **1**.

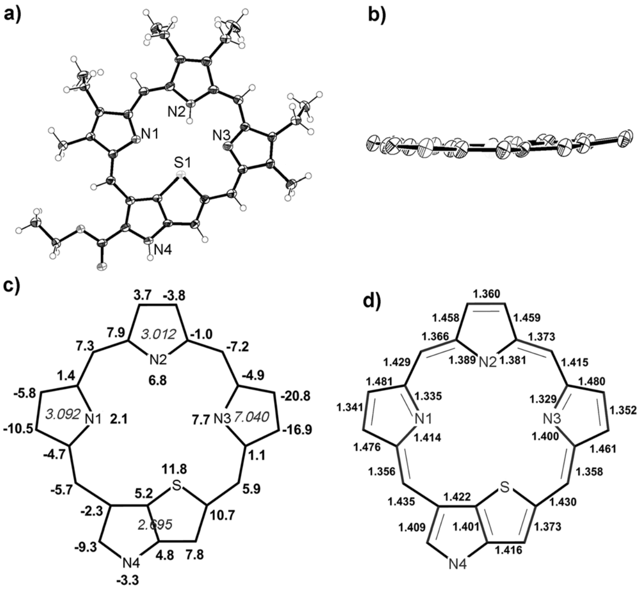


Figure 1. The X-ray crystal structure of **1**: a) Top view, solvent molecules have been omitted for clarity; b) side view, the solvent molecules, hydrogen atoms, and peripheral groups are omitted for clarity. c) Displacement (in 0.01 Å units) of the core atoms from the least-square plane of the *meso*-carbon atoms (black values) and torsion angles between heterocyclic ring and the mean plane (values in italics). d) Bond lengths (in Å units) in the core.

periphery of the macrocycle. Half of the C_{meso}–C_{α} bonds are elongated, with an average bond distance of 1.427 Å, whereas the others have an average value of 1.363 Å. Compound **1** therefore has a localized bond structure with discrete single and double bonds, in marked contrast with the π-electron delocalization on the inner perimeter of heteroaromatic porphyrinoid π systems. B3LYP geometry optimizations carried out on an unsubstituted model structure with 6-31G* basis set (see the Supporting Information, Table S1) predict that the X-ray structure corresponds to the most stable of six possible tautomers for the π system. When the nitrogen on the outer perimeter is protonated there is no conjugation circuit available so the molecule can be viewed as being nonaromatic.

The NMR signals of protons attached to porphyrinoid rings provide a precise indication of the aromatic character of the molecule, and are of particular value when comparisons can be made between structurally related systems.[15] Therefore, the ^{1}H NMR spectra of **1** and an aromatic 18π-electron thiaporphyrin analogue (**5**) were measured in $CDCl_3$ (Figure 2), so that a comparison could be made. The peripheral proton signals of heteroaromatic porphyrinoids experience marked downfield shifts as a result of the shielding effect of the macrocyclic ring current, whereas the inner protons are deshielded, and are often found at negative δ values. In the spectrum of the *meso*-unsubstituted thiaporphyrin (**5**) the *meso*-C–H signals are located at 10.14 and 10.13 ppm. In contrast, the signals of the four *meso*-protons of **1** appeared at higher field as four sharp singlets (Figure 2b, signals b–e) at 6.57, 6.20, 4.97 and 4.82 ppm, thus reflecting not only the lower symmetry, but also the nonaromaticity of this macrocycle. The singlet at 7.16 ppm (signal a) can be assigned to the thiophene ring proton, which lies significantly upfield relative to the analogous signal (10.72 ppm) in the [18]thiaporphyrin (**5**) spectrum. It is noteworthy that three separate signals corresponding to nonequivalent N–H protons have been confirmed by deuteroxide exchange experiments to lie in the range of 9–17 ppm (see the Supporting Information, Figure S12). These signals represent a significant downfield shift relative to the negative δ value for the signal corresponding to the N–H of [18]thiaporphyrin. In contrast to the signals of the peripheral protons, the signals for N–H have been observed to exchange rapidly between measurements

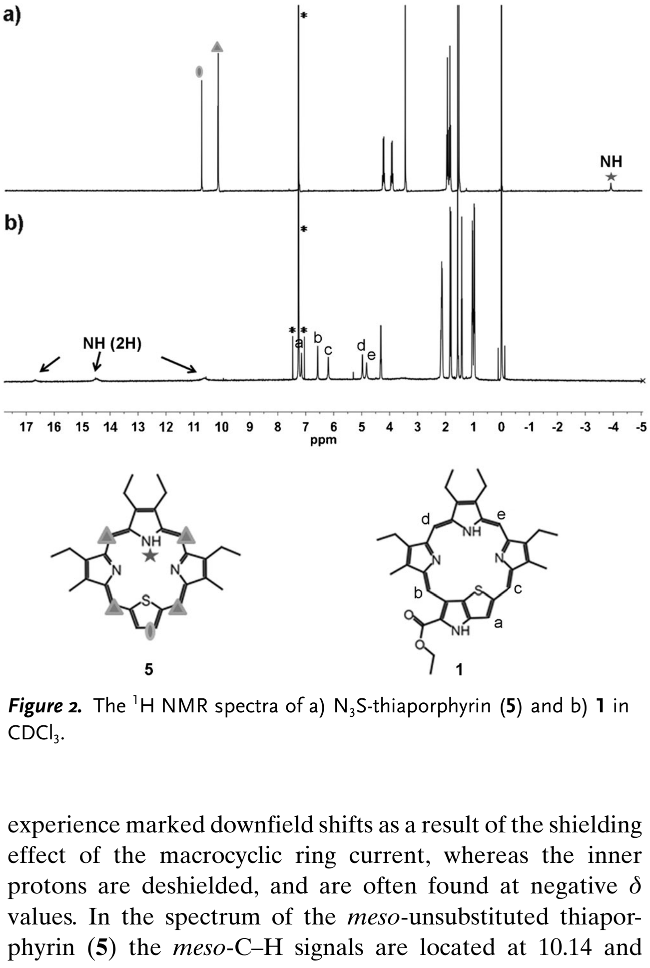
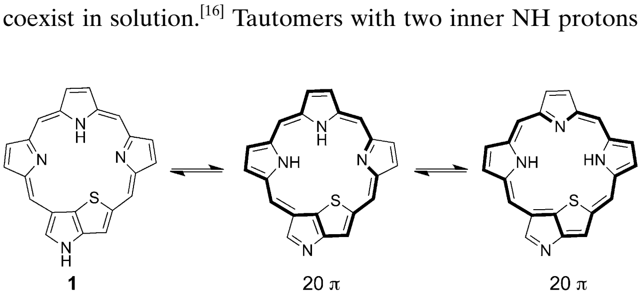


Figure 2. The ^{1}H NMR spectra of a) N_3S-thiaporphyrin (**5**) and b) **1** in $CDCl_3$.

made at room temperature. This phenomenon can be interpreted as being due to N–H tautomerism (Scheme 3) and as evidence that other more-antiaromatic tautomers coexist in solution.[16] Tautomers with two inner NH protons arranged in *cis* and *trans* alignments are predicted to be 3–6 kcal mol^{-1} less stable than the tautomer that has a protonation pattern corresponding to that of the X-ray structure (see the Supporting Information, Table S1).



Scheme 3. The three most stable prototropic tautomers of **1** based on B3LYP geometry optimizations with 6-31G(d) basis sets for an unsubstituted model compound.

The anisotropy of the induced current density (ACID) of **1** was calculated (Figure 3). ACID calculations have been used in the analysis of various planar and nonplanar porphyrinoids (in closed-shell forms),[17] because they reveal, through numerous point vectors, the induced ring current density expected when an external magnetic field is applied. The conjugation pathways can be estimated by adjusting the isosurface values. The ACID isosurface plot for the most stable tautomer of **1** predicts relatively poor electron conjugation, as there is a disrupted pattern within the electronic current. This finding is consistent with a weak ring current and a poorly delocalized topology, as would be expected for a nonaromatic π system. The current density vectors mapped onto the ACID isosurface plot exhibit a paramagnetic (counterclockwise) current around the macrocycle and diamagnetic ring currents within the pyrrole and thienopyrrole rings. In addition, the critical isosurface value (CIV) is very low at several bonds and high within the heterocyclic ring. Interestingly, the ACID plot of one of the possible tautomers that has two inner N–H protons contains counterclockwise currents (Figure 3b and the Supporting Information Figure S17); this result suggests that a stronger antiaromatic ring current is generated in the tautomers that have a 20π-electron conjugation system. The nucleus-independent chemical shift (NICS) method[18] was also used to evaluate the aromatic properties of **1**. A relatively small positive NICS(1) value was calculated for the most stable tautomer of **1** (see the Supporting Information, Table S2), compared with the large negative NICS(1) value for an 18π-electron porphyrin. Larger positive values are calculated for the tautomers having two inner NH protons.

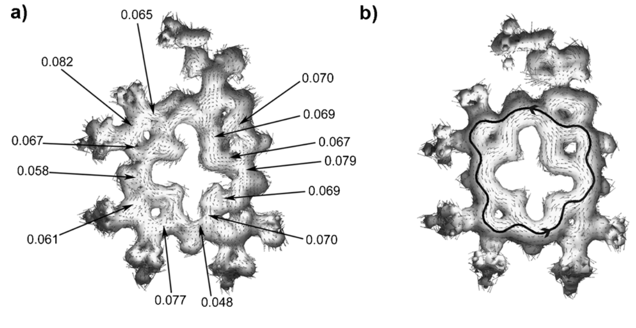


Figure 3. ACID plots of a) **1** and b) a tautomer with two inner NH protons at an isosurface value of 0.03. The external magnetic field is applied orthogonal to the macrocycle plane with its vector pointing towards the viewer. Current density vectors (lines and conics) are plotted onto the ACID isosurface. The critical isosurface values (CIV) for compound **1** are provided.

Molecular orbital calculations have been carried out for **1** (Figure 4a). Notably, the nodal patterns of the HOMO and LUMO of **1** are similar to what would be anticipated for the doubly degenerate LUMO of a 20π-electron porphyrinoid, as the number of angular nodes is the same. Michl and coworkers have demonstrated that this is the pattern that would normally be anticipated for what they termed an antiaromatic (4*n*)π-electron system.[19] This (4*n*)π-electron system lacks biradical character as a result of a large splitting between the HOMO and the LUMO. MO calculations carried out for the six tautomers of an unsubstituted model compound (see the Supporting Information, Figure S15) clearly demonstrate that the angular nodal patterns of the HOMO and LUMO are retained in each case. The UV/Vis absorption spectrum of **1** contains two intense bands at 356 nm and 455 nm (Figure 4b). The optical properties of **1** can be readily interpreted based on Michl's 4*n* perimeter model.[19] As the HOMO and LUMO of **1** have an equal number of angular nodes, the HOMO→LUMO transition is predicted to be electric-dipole forbidden. The weak absorption bands observed between 700–1000 nm can be assigned to the HOMO→LUMO transition, which is referred to as the S transition in Michl's 4*n* perimeter model.[19] Thus, the spectrum is similar to those reported recently for nonaromatic porphyrinoids with (4*n*)π-electron systems.[10,20]

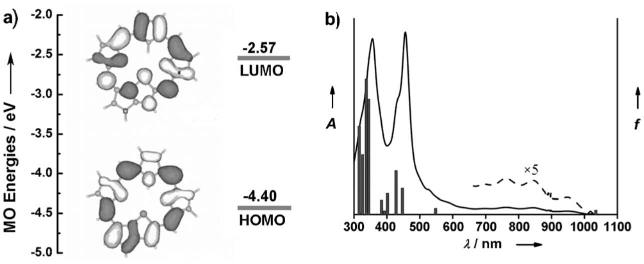


Figure 4. a) Frontier π-MO energies and nodal patterns for **1**. b) The observed electronic absorption spectrum of **1** and the calculated TD-DFT (black bars) oscillator strengths (right axis) at the B3LYP/6-31G* level of theory.

Spectroelectrochemistry has been used to explore the redox properties of **1**. During reduction at a controlled potential of -1.35 V (the first reduction peak in CV is shown in the Supporting Information, Figure S10) in a thin-layer cell, the intensity of the two main peaks at 356 and 455 nm decreases, while a new band appears at 400 nm together with broad, featureless peaks in the 500–800 nm region (Figure 5 a). Well-defined isosbestic points are observed at 380, 420, 480, and 767 nm, which indicates that a single reduced species (a radical anion) is being formed. When **1** was treated with $NaBH_4$ for 10 min at room temperature in CH_2Cl_2, the color of the solution changed dramatically from brown to green. The absorption spectrum changed to show an intense peak at approximately 410 nm and several weaker bands in the long-wavelength region between 500–800 nm (Figure 5 b), a pattern that closely resembles that of the spectroelectrochemically reduced species. The reduced species is EPR active with a g factor of 2.002 (see the Supporting Information, Figure S13).[21,22] The ^1H NMR signals corresponding to **1** disappeared after the addition of $NaBD_4$ in $CDCl_3$ (see the Supporting Information, Figure S14), as would be expected upon the generation of a radical species. The MALDI-TOF mass spectrum is consistent with the proposed structure (see the Supporting Information, Figure S15).

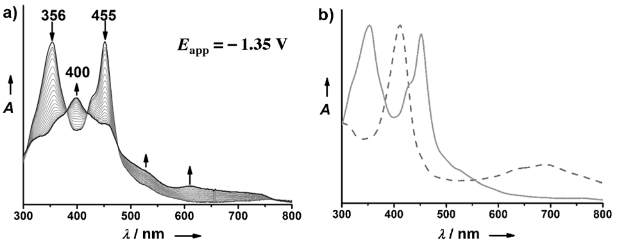


Figure 5. a) Spectral changes in the UV/Vis absorption spectrum of **1** upon reduction at a controlled potential $E_{app} = -1.35$ V, in a CH_2Cl_2 solution containing 0.1 M of $TBAPF_6$. b) The absorption spectrum of **1** (solid line) and of **1** in the presence of $NaBH_4$ (dotted line).

In summary, a nonaromatic heteroporphyrin bearing one thienopyrrole moiety has been successfully synthesized and characterized for the first time. The stable nonaromatic system can be transformed into a radical species by a chemical or spectroelectrochemical reduction. We believe that the use of thienopyrrole as a building block offers a new perspective for the design of porphyrins with novel photophysical properties. Efforts to introduce additional thienopyrrole moieties into the porphyrin macrocycle are currently underway.

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[14] Crystallographic data for **1**: $C_{71}H_{78}Cl_2N_8S_2$, $M_r = 1242.47$, crystal dimensions: $0.200 > 0.040 > 0.010$ mm^3, triclinic $P\bar{1}$ (# 2), $a = 8.5350(5)$, $b = 13.3574(9)$, $c = 14.685(1)$ Å, $V = 1567.0(2)$ Å^3, $Z = 1$, $D_{calcd} = 1.317$ g cm^{-3}, $T = 100$ K, 12901 measured reflections, 5735 reflections with[$I > 2\sigma(I)$]. $R = 0.0723$, RW = 0.2109, GOF = 1.020. CCDC 875597 (**1**) contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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