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β,β′-Linked cofacial bis-porphyrins

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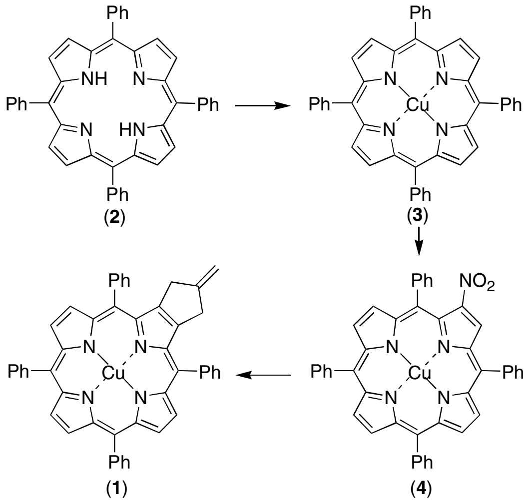
Abstract—The copper(II) porphyrin **1**, bearing a fused methylenepropano ring, undergoes an unusual self-sensitized photo-oxygenation reaction in the presence of DBU to give a high yield of a cofacial bis-porphyrin **7** under very mild conditions. The structures of compounds **1** and **7** were confirmed by X-ray crystallography.

Multiporphyrin arrays[1] have attracted much recent interest because they play important roles in many areas such as in light harvesting,[2] energy and electron transfer,[3] and multielectron redox catalysis.[4] Among the many examples, the covalently linked porphyrin arrays, especially cofacial porphyrins[5,6] have been widely studied in the past two decades because of their unique photo-electronic properties, and particularly for their potential applications as electron-energy transfer moieties in molecular wires.[1,7] To date, several fused bis-porphyrins and oligoporphyrins have been synthesized.[8] Among these, the most successful cofacial porphyrins are the so-called Pacman systems consisting of two octa-alkylporphyrins linked by a single rigid bridge.[5] However, the synthesis of cofacial porphyrins has been, and will remain, a challenge.[9]

The development of new methods for carbon–carbon bond formation is at the heart of organic synthesis. The most desirable methods are those that are easily accomplished in large scale, operate near ambient temperature, and do not require drastic reaction conditions. Usually, the construction of carbocyclic rings requires the preparation of highly functionalized intermediates. The reactions of atomic oxygen with unsaturated organic compounds have demonstrated that the primary reactive intermediates can undergo extensive rearrangement before forming isolable oxygenated products.[10,11] The reaction of oxygen (^3P) atoms with olefins,[12] methylenecycloalkanes,[11] and phenylethylenes[13] have been reported.



We have previously synthesized several fused metallocenoporphyrin derivatives and bis-porphyrin-metallocenes.[14] Herein we report an unexpectedly efficient synthesis of a cofacial metallo-bis-porphyrin through a simple DBU catalyzed carbon–carbon bond formation reaction following a self-sensitized oxygenation reaction. Our substrate for the cofacial bis-porphyrin formation is the β,β′-fused methylenepropanoporphyrin **1**, which is a key precursor in our metallocenoporphyrin syntheses.[14] In particular, we make use of literature observations in which methylene cycloalkanes can be oxygenated to give very useful intermediates for further modification,[11] and in this particular case, formation of cofacial bis-porphyrin systems.

Keywords: Cofacial bis-porphyrins; Copper(II) porphyrins; Methylenecycloalkenes; Methylenepropanoporphyrins; Porphyrin photo-oxygenation.

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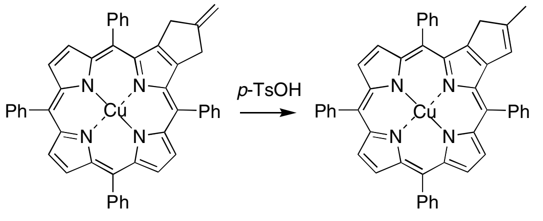
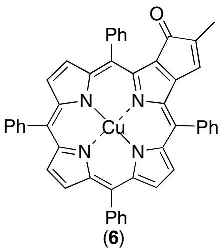


(1) (5)

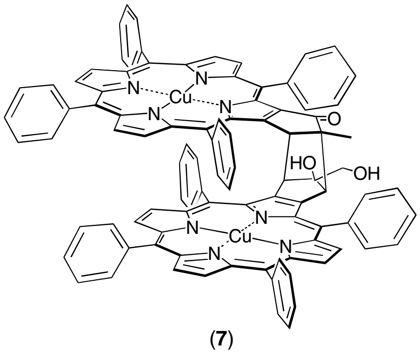
Insertion of copper into 5,10,15,20-tetraphenylporphyrin (H_2TPP; **2**) was achieved using $Cu(OAc)_2$ in $MeOH/CHCl_3$. 2-Nitro-CuTPP (**4**) was synthesized by treatment of CuTPP (**3**) with $LiNO_3$. As previously reported,[14] a palladium catalyzed [3+2] cycloaddition reaction between **4** and 2-[(trimethylsilyl)methyl]-2-propen-1-yl acetate gave the copper(II) porphyrin adduct **1**. Under strictly air-free conditions compound **1** was obtained in 85% yield. The structure of **1**[15] was confirmed by X-ray crystallography (Fig. 1).[†] The 24-atom porphyrin ring system has a flattened saddle conformation, with mean out-of-plane deviation 0.18 Å and maximum 0.417(9) Å. The Cu atom lies 0.017(1) Å from this plane and forms Cu–N distances in the range 1.975(7)–2.006(6) Å. The five-membered ring carrying the exocyclic C=C bond is nearly planar, with mean deviation 0.03 Å, and is coplanar with the pyrrole ring fused to it.

An acid catalyst (*p*-TsOH) was used to successfully migrate the double bond in **1** into the thermodynamically preferred *endo*-position, to give **5**[16] in 90% yield. Both **1** and **5** were stable in the solid state. However, while handling their solutions in air it became apparent from TLC and mass spectrometry that they were being transformed into oxygenated side products. In the dark, under argon, porphyrins **1** and **5** were perfectly stable; in the separate presence of either air or light, both were again stable, but once exposed to both light and air, they were rapidly transformed into oxygenated by-products. The conjugated endocyclic alkene porphyrin **5** was the more unstable in the presence of both light and air, and its major oxygenation product (52% isolated yield) was the α,β-unsaturated ketone **6**.[17]



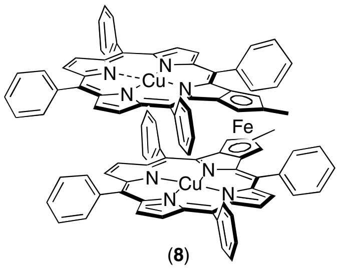
(6)

A literature search revealed numerous examples of photo-oxygenation of organic molecules bearing *exo*-cyclic alkenes. Of particular relevance was the work of Havel[11] who showed that methylenecycloalkanes react with ground state oxygen atoms. Methylenecycloalkanes were shown to yield epoxides, and alkenones among other oxygenated products. In other work, alkenyl-linked [60]fullerene derivatives have been shown to self-photo-oxygenate to give allylic alcohols,[18] and Saracoglu et al.[19] have shown, for example, that cycloheptatriene derivatives can be photo-oxygenated in the presence of H_2TPP (**2**) as a singlet oxygen sensitizer to give the norcaradiene endoperoxides and bis-epoxide derivatives. The relevance of this literature became apparent when upon treatment with DBU, porphyrin **1** afforded a 60% yield of the oxygenated bis-porphyrin **7**.[20] Figure 2 shows the X-ray structure of the bis-porphyrin **7**.[‡] The bis-porphyrin is folded, with the two porphyrin planes approximately parallel [dihedral angle 4.1(5)°], and a perpendicular distance between coordination planes of approximately 4.2 Å. The Cu–Cu distance is 5.290(4) Å, and Cu–N distances fall within the range 1.942(8)–2.002(8) Å.



(7)

The optical spectrum of bis-porphyrin **7** is shown in Figure 3 and, with its red-shifted Q-bands, is fairly characteristic of a π-stacked bis-porphyrin (compared with the monomeric species **1**). This contrasts dramatically with the optical spectrum of the corresponding, conjugated fused bis-ferrocenoporphyrin **8** (Fig. 3) that demonstrates direct electronic interactions between the two porphyrin systems associated with the ferrocene. Compound **8** was obtained in 7.5% yield from **5** by treatment with LDA followed by $FeCl_2$.[21]



(8)

[†] Compound **1**, $C_{48}H_{32}CuN_4{\cdot}CHCl_3$, triclinic space group *P*-1, $a = 12.940(4)$, $b = 13.185(5)$, $c = 13.694(7)$ Å, $\alpha = 108.12(2)$, $\beta = 117.71(2)$, $\gamma = 90.22(2)°$, $V = 1935.0(14)$ Å^3, $T = 110$ K, $Z = 2$, $R = 0.094$ ($F^2 > 2\sigma$), $Rw = 0.271$ (all F^2) for 5879 unique data and 514 refined parameters. CCDC 280898.

[‡] Compound **7**, $C_{96}H_{60}Cu_2N_8O_3$, triclinic space group *P*-1, $a = 14.174(6)$, $b = 16.881(8)$, $c = 17.876(10)$ Å, $\alpha = 99.97(3)$, $\beta = 101.23(3)$, $\gamma = 99.171(17)°$, $V = 4048(3)$ Å^3, $T = 110$ K, $Z = 2$, $R = 0.101$ ($F^2 > 2\sigma$), $Rw = 0.278$ (all F^2) for 100,38 unique data and 448 refined parameters. CCDC 280897.

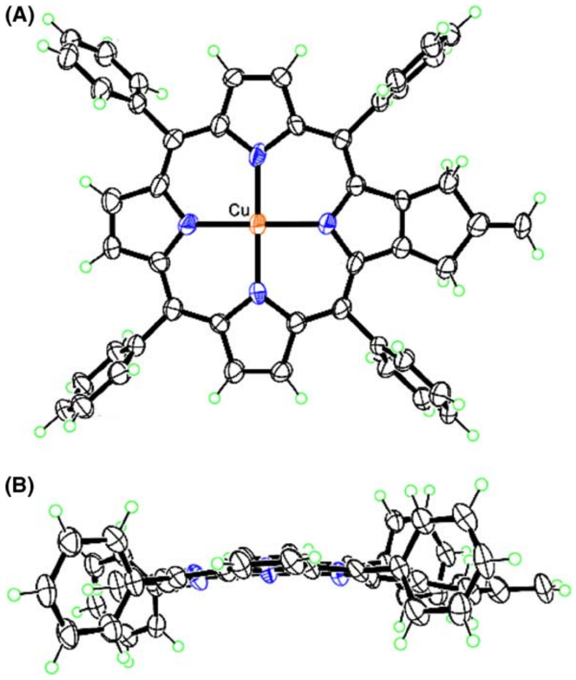


Figure 1. X-ray structure of compound **1**; A, top-view; B, side-view.

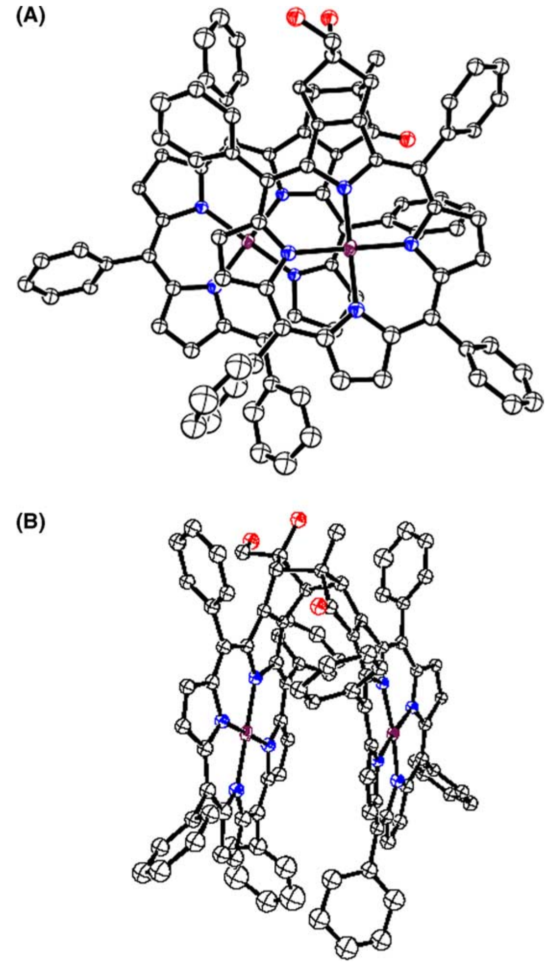


Figure 2. X-ray structure of bis-porphyrin **7**; A, top-view; B, side-view.

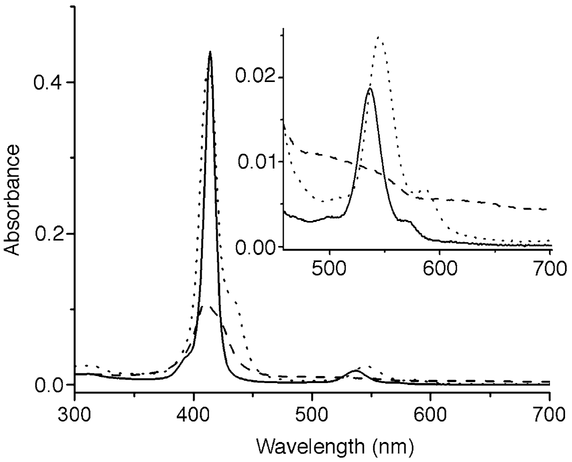


Figure 3. UV–vis spectra, in dichloromethane at 1×10^{-6} M, of bis-porphyrin **7** (dotted line); porphyrin **1** (solid line); and bis-porphyrinylferrocene **8** (dashed line).

Apart from the identification of intermediate porphyrin **6**, there is other preliminary evidence to support an oxygenation–dimerization mechanistic sequence to give **7**. A small amount of the bis-porphyrin **7** was also detected by refluxing compound **1** in THF for 2 days in the presence of a weak Lewis acid (silica gel). Under these conditions the yield of **7** was admittedly low, but two additional porphyrins were isolated as major products. MALDI-TOF showed a molecular weight peak at *m*/*z* 743.341 for the less polar unknown, and for the more polar unknown product, the molecular weight peak appeared at *m*/*z* 758.101. These measurements indicate one or two oxygen atoms have been added to the starting material **1**. For the latter, another peak at *m*/*z* 742.2 was also apparent in the MALDI-TOF spectrum, indicating that the more polar unknown product undergoes a facile loss of one oxygen atom. We believe that the DBU and silica gel reactions follow similar reaction pathways and that oxygenated porphyrin monomers are precursors of the bis-porphyrin **7** in both cases.

The reactive oxygen species responsible for production of the oxygenated porphyrins is probably generated by the photoactivation of dioxygen in situ by the metalloporphyrin **1**. Photosensitization by *paramagnetic* copper(II) porphyrins is unusual, but not unique. Skalkos and co-workers have shown that some copper(II) porphyrins can be used in photodynamic therapy,[22] and Chandrasekhar et al. have shown that a copper(II) porphyrin can be used to promote cleavage of DNA.[23]

Acknowledgment

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15. *Selected data for* **1**: MALDI-TOF: calcd *m*/*z* for $C_{48}H_{32}CuN_4$ 728.3; found 728.1; Anal. Calcd for $C_{48}H_{32}CuN_4{\cdot}C_6H_{14}$: C, 79.62; H, 5.69; N, 6.88. Found: C, 79.22; H, 5.72; N, 7.05. UV/vis: λ_{max} CH_2Cl_2 (log ε) 414 nm (5.64), 536 (4.27), 568 (3.49).
16. *Selected data for* **5**: MALDI-TOF: calcd *m*/*z* for $C_{48}H_{32}CuN_4$ 728.3; found 727.9; UV/vis λ_{max} CH_2Cl_2 (log ε) 411 nm (5.51), 540 (4.36).
17. *Procedure for synthesis of porphyrin* **6**: A mixture of endocyclic alkene porphyrin **5** (100 mg, 0.14 mmol) and DBU (100 μL, 0.67 mmol) in CH_2Cl_2 (20 mL) was stirred at room temperature under air for 5 h. The mixture was purified by column chromatography on silica gel using CH_2Cl_2/hexane (v/v = 1/2) as eluent, giving the green porphyrin **6** in 52% yield (54 mg, 0.072 mmol). UV/vis: λ_{max} CH_2Cl_2 (log ε) 338 nm (4.72), 399 (5.22), 454 (5.47), 549 (4.25), 584 (4.30), 637 (4.65); MALDI-TOF $C_{48}H_{30}CuN_4O$ (M+H): calcd *m*/*z* for 742.2; found 742.5.
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20. *Procedure for synthesis of* **7**: A mixture of β,β′-fused copper(II) methylenepropanoporphyrin **1** (100 mg, 0.14 mmol) and DBU (100 μL, 0.67 mmol) in CH_2Cl_2 (20 mL) was stirred at room temperature in air for 52 h. The mixture was purified by column chromatography on silica gel using CH_2Cl_2 as eluent, giving the title porphyrin **7** in 60% yield (63 mg, 0.042 mmol). UV/vis: λ_{max} CH_2Cl_2 (log ε) 413 nm (5.62), 545 (4.40), 585 (3.83); MS (HR-MALDI-TOF) $C_{96}H_{62}Cu_2N_8O_3$ (M^+): calcd *m*/*z* for 1502.3553; found 1502.1324. The crystal of **7** (Fig. 2) was grown by slow diffusion of hexane into dichloromethane solution.
21. *Selected data for* **8**: MALDI-TOF: calcd *m*/*z* for $C_{96}H_{62}Cu_2FeN_8$ 1510.5; found 1510.1; UV/vis: λ_{max} CH_2Cl_2 (log ε) 410 nm (5.04).
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