Porphyrin Chemistry

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Oxidative Annulation of β-Aminoporphyrins into Pyrazine-Fused Diporphyrins**

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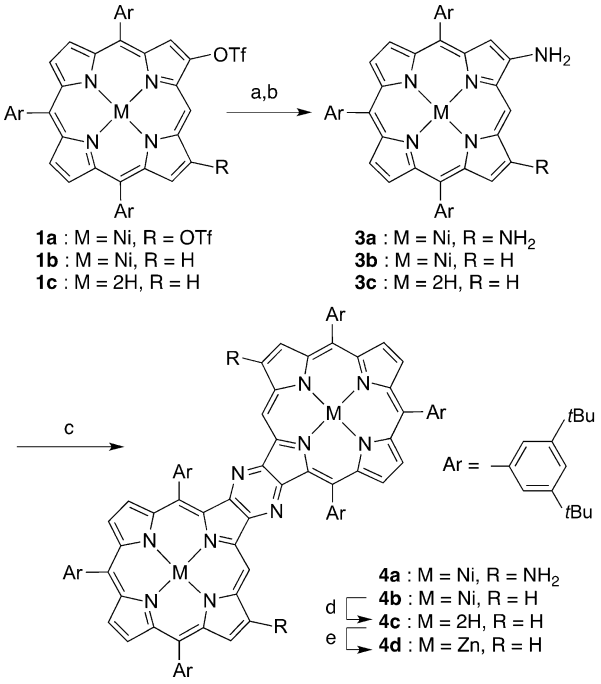
Covalently linked porphyrin arrays have attracted much attention as biomimetic light harvesting systems for photosynthesis, optoelectronic devices, and molecular wires.[1] The construction of covalent linkages between porphyrin units often employs palladium-catalyzed cross-coupling[2] or oxidative coupling reactions.[3] In particular, the oxidative dimerization of porphyrins offers a versatile and reliable method for the construction of multiporphyrin arrays. Treatment of *meso*-unsubstituted porphyrins with strong oxidants, such as $AgPF_6$,[4a,b] 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ)-$Sc(OTf)_3$[4c] (Tf = trifluoromethanesulfonyl), and phenyliodine bis(trifluoroacetate),[4d] yields directly linked porphyrin oligomers with high regioselectivity. These transformations always include bond formation at the *meso* position because of its high reactivity.

Among such oxidative coupling reactions, a fusion reaction allows the connection of two π-electronic systems by two or more bonds in a single step. This strategy is highly useful for constructing rigid and planar structures, which would be effective for π-conjugation and suppression of energetic decay in the photoirradiated excited state. However, such oxidative fusion reactions with porphyrins have been limited to the formation of *meso*–β doubly linked and *meso*–*meso*, β–β, β′–β′ triply linked diporphyrins.[4c] In the course of our research on β-functionalized porphyrins, we serendipitously found an oxidative dimerization of β-aminoporphyrins that efficiently provides pyrazine-fused diporphyrins. Interestingly, the reaction proceeds smoothly at the β positions with perfect regioselectivity to construct two direct linkages in one step.[5]

We examined the oxidation of **3a**, which was prepared through the Pd-catalyzed cross-coupling of porphyrin bistriflate **1a**[7] with benzophenone imine as the key step (Scheme 1). The addition of 4.0 equiv of DDQ into a dilute solution of **3a** in chloroform (1.0 mmol L^{-1}) at room temperature afforded **4a** as a single product in 63% yield. The reaction was sensitive to the reaction media, and no reaction occurred in dichloromethane. The high-resolution mass spectrum of **4a** contained the parent mass-ion peaks at $m/z = 1938.0031$ (calcd for $C_{124}H_{142}N_{12}Ni_2Na$: 1938.0080 $[M+Na^+]$), which suggests the formation of a dimeric species of **3a**. The ^1H NMR spectrum of **4a** has four doublet resonances and one singlet resonance for the β protons, which indicates the presence of unsymmetrical porphyrin units. Relative to **3a**, two signals from the aryl protons were shifted to lower field at $\delta = 8.17$ and 8.14 ppm, probably as a result of a deshielding effect by the neighboring porphyrin ring current. The NOESY spectrum of **4a** (Figure S10 in the Supporting Information) showed correlations between these aryl protons and a *meso* proton of the porphyrin. On the basis of these spectral data, we assigned **4a** as a pyrazine-fused diporphyrin (Scheme 1).[8,9] The oxidation of β-monoaminoporphyrin **3b** also afforded the corresponding pyrazine-fused dimer **4b** in 82% yield. The present reaction also proceeded with free-base β-aminoporphyrin **3c** to produce **4c** in 11% yield (in two steps from **2c**). Furthermore, free-base **4c** was obtained in 84% yield by demetalation of **4b** with H_2SO_4. **4b** was then converted to biszinc complex **4d** in 60% yield upon



Scheme 1. Synthesis and oxidation of β-aminoporphyrins. Reaction conditions: a) $Ph_2C{=}NH$ (3.0 equiv), $[Pd_2(dba)_3]{\cdot}CHCl_3$ (5 mol%), Xantphos (10 mol%), Cs_2CO_3 (2.0 equiv), dioxane, reflux, 24 h; b) Conc. HCl, THF, reflux, 1 h; c) DDQ (4 equiv), $CHCl_3$, RT, 1.5 h for **4a** and 1 h for **4b**; d) H_2SO_4, TFA, RT, 1.5 h; e) $Zn(OAc)_2{\cdot}2H_2O$, MeOH, $CHCl_3$, reflux, 3 h.

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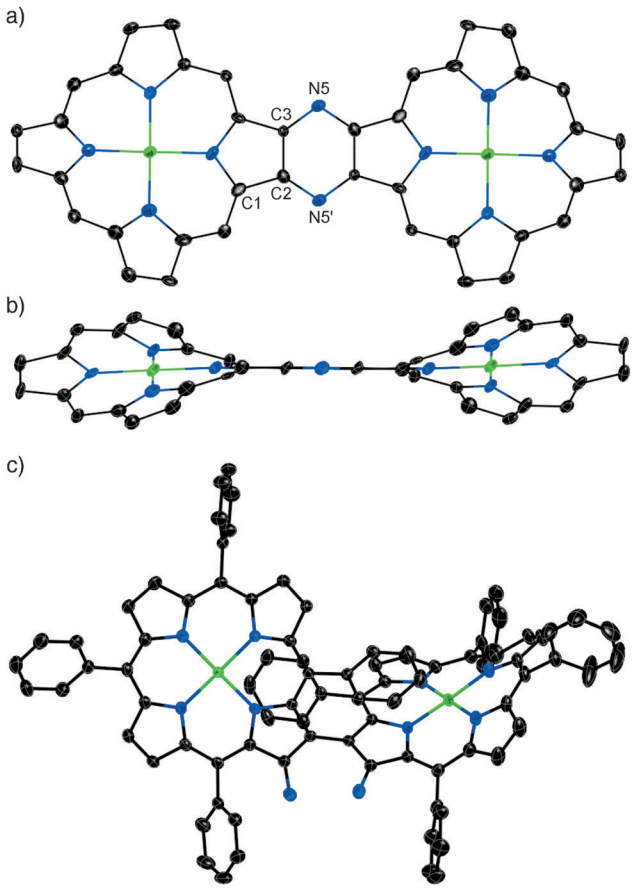


Figure 1. X-ray crystal structures of **4b** and **7**: a) Top view and b) side view of **4b**. c) Top view of **7**. Hydrogen atoms and *meso*-aryl groups of **4b** are omitted for clarity. Thermal ellipsoids are at 50% probability level.

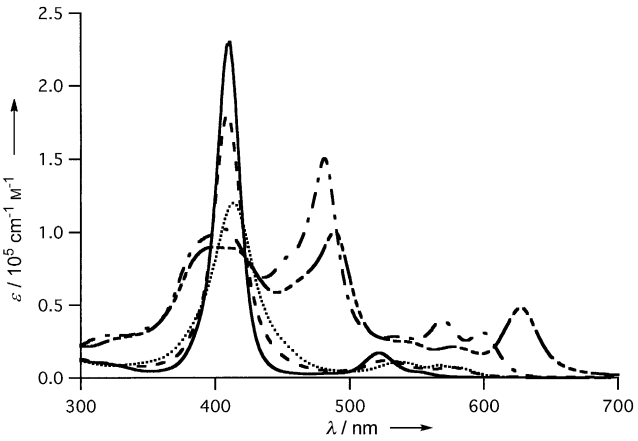


Figure 2. UV/Vis absorption spectra of **3a** (••••), **3b** (– – –), **4a** (——----), **4b** (–•–•), and tris(3,5-di-*tert*-butylphenyl)porphyrin Ni^{II} (**8**, ——) in CH_2Cl_2.

treatment with $Zn(OAc)_2{\cdot}2H_2O$. The structure of **4b** was unambiguously elucidated by X-ray diffraction analysis (Figure 1).[10] A suitable crystal was obtained by vapor diffusion of acetonitrile into a solution of **4b** in carbon tetrachloride. The whole structure of **4b** is twisted as a result of the ruffled nickel(II) porphyrin subunits, in contrast to a quite planar geometry around the central pyrazine ring. The bond length of C1–C2 is 1.45 Å, which is almost equivalent to a standard $C(sp^2)$–$C(sp^2)$ single bond length (ca. 1.47 Å). Furthermore, the bond lengths in the central pyrazine core are 1.40 Å for C2–C3, 1.34 Å for C3–N5, and 1.34 Å for N5′–C2. On the basis of these bond lengths, the harmonic oscillator model of aromaticity (HOMA) value of the pyrazine moiety is calculated to be 0.977, which indicates strong aromaticity in the pyrazine ring.

Figure 2 shows the UV/Vis absorption spectra of **3a** and **4a**, as well as tris(3,5-di-*tert*-butylphenyl)porphyrin nickel(II) (**8**). Aminoporphyrin **3a** has a typical spectrum for a monomeric porphyrin. The red-shifted Q-band of **3a** is a result of electron donation from the amino groups to the porphyrin core. In contrast, **4a** has split Soret bands at 399, 411, and 489 nm.[11] The Q-band has a substantial bathochromic shift owing to effective π-conjugation between the two porphyrin rings. Such intramolecular interactions were investigated by electrochemical analysis. Table 1 summarizes the electrochemical data of **3a**, **3b**, **4a**, and **4b** measured by cyclic voltammetry (Figure S15 in the Supporting Information). The dimers **4a** and **4b** have relatively smaller ΔE values (the gap between the first oxidation and the first reduction potentials

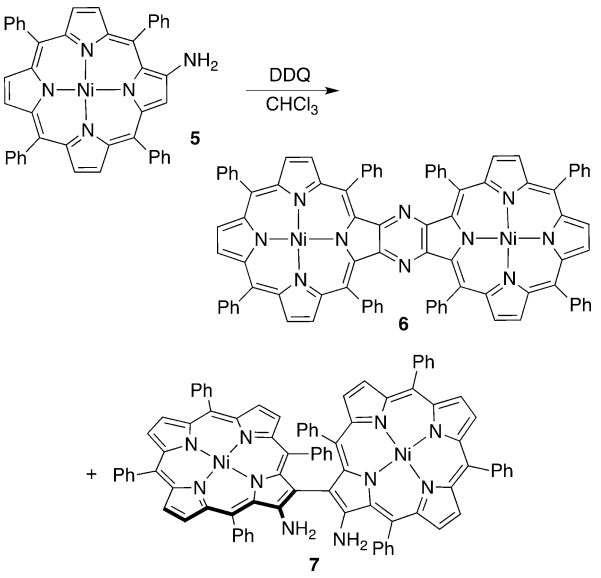
Table 1: Summary of cyclic voltammetry of **3a**, **3b**, **4a**, **4b**, and tris(3,5-di-*tert*-butylphenyl)porphyrin Ni^{II} (**8**).[a]

Compound	E_{ox}^2 [V]	E_{ox}^1 [V]	E_{red} [V]	ΔE [V]
8	–	0.524	−1.84	2.36
3a	–	0.148	−1.88	2.02
3b	–	0.307	−1.84	2.15
4a	0.448	0.270	−1.61	1.88
4b	0.729	0.488	−1.58	2.07

[a] Solvent: CH_2Cl_2; electrolyte: Bu_4NPF_6; working electrode: Pt; counter electrode: Pt; reference electrodte: $Ag/AgClO_4$; scan rate: 0.1 Vs^{-1}; potentials are recorded versus ferrocene/ferrocenium ion couple.

($E_{ox}^1 - E_{red}$)), than the monomers **8** and **3b**, which indicates the decrease in the HOMO–LUMO gaps. Furthermore, splitting of the oxidation potential was detected for both **4a** and **4b**. These results suggest effective electronic interaction between the two porphyrin rings.[12] Notably, the difference in the oxidation potential between **4a** and **3b** is smaller than that for the reduction potential. This trend is also detected for **8** and **4b**. This result implies that the formation of the pyrazine ring mainly affects the LUMOs of porphyrin rings to reduce the HOMO–LUMO gaps.

The oxidative fusion reaction is not limited to 5,10,15-triarylporphyrins **3**, which have one unsubstituted *meso* position. Oxidation of 2-aminotetraarylporphyrins with the Dess–Martin periodinane reagent is known to produce the corresponding porphyrin α-diones in moderate yields.[13] In contrast, we found that treatment of 2-amino-5,10,15,20-tetraphenylporphyrin (**5**) with DDQ in chloroform afforded the pyrazine-fused dimer **6** in 18% yield (Scheme 2). The pyrazine-fused structure was assigned by its highly symmetric ^1H NMR spectrum, which has only three signals for the β protons. Furthermore, the high-resolution mass spectrum,



Scheme 2. Oxidation of β-aminotetraphenylporphyrin.

contained the parent mass-ion peaks at $m/z = 1365.3172$ (calcd for $C_{88}H_{53}N_{10}Ni_2$: 1365.3156 $[M+H^+]$), which also confirmed the formation of **6**. The formation of the pyrazine-fused dimer **6** is rather remarkable, since the dimerization process would be required to endure the steric repulsion between the *meso*-phenyl groups on the two coupling porphyrins.

Interestingly, we could isolate another product **7** in 14% yield from the reaction mixture. The ^{1}H NMR spectrum of **7** has six doublet resonances for β protons and two NH protons. The resonances from one of the phenyl groups were detected in the shielded region at 7.30, 6.46, 5.90, 5.05, and 4.24 ppm. The dimeric structure was confirmed by high-resolution mass spectrometry. On the basis of these data, we characterized **7** as a β–β' singly linked diporphyrin (Scheme 2). The structure of **7** was finally elucidated by X-ray diffraction analysis (Figure 1c).[14] A fine crystal was obtained by vapor diffusion of ethanol into a solution of **7** in chlorobenzene. The two porphyrin units are connected directly at the β position adjacent to the amino group, and the dihedral angle between the two proximal pyrrole units is 54°. The bond length of the linkage between the two porphyrins is 1.46 Å, which is normal for a $C(sp^2)$–$C(sp^2)$ single bond and indicates little π-conjugation between the two porphyrins. The phenyl group on one porphyrin moiety is overlapped with the other porphyrin ring and the average distance between the two moieties is 3.18 Å, which suggests the existence of a π–π interaction. Diporphyrin **7** is a C_2-symmetric diamine and probably has axial chirality as a result of restricted bond rotation similar to that in 1,1′-binaphthyl-2,2′-diamine, which is widely used as a chiral source in asymmetric syntheses. We are currently attempting the optical resolution of **7**.

Figure 3 shows the UV/Vis absorption spectra of **4b**, **6**, and **7** in dichloromethane. The spectrum of **6** has similar features to that of **4b** but with slight red-shifts for both Soret and Q-bands, probably as a result of the distorted conformation of the porphyrin macrocycle. In contrast, the peaks in the

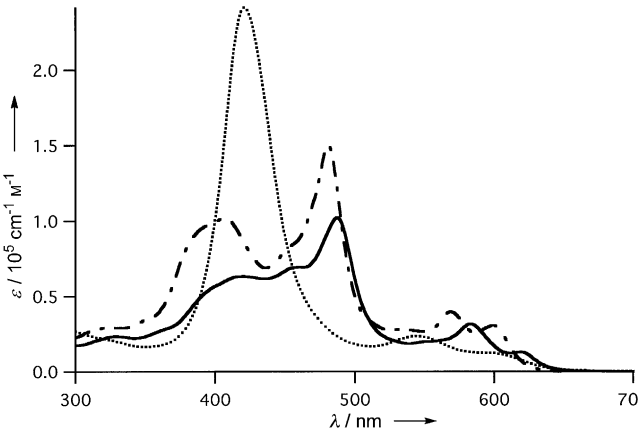


Figure 3. UV/Vis absorption spectra of **4b** (–•–•), **6** (——), and **7** (•••••) in CH_2Cl_2.

spectrum of **7** are not split, which suggests the presence of negligible exciton-coupling interactions between the two porphyrin chromophores. This spectral characteristic of **7** is in line with reported β–β singly linked diporphyrins.[14] The electrochemical properties of **6** were also investigated by cyclic voltammetry (Figure S16 in the Supporting Information). As for **4a** and **4b**, **6** has two reversible oxidation potentials at 0.575 and 0.419 V and two reversible reduction potentials at −1.60 and −1.72 V. These results also support the pyrazine-fused dimeric structure of **6**.

In summary, we have developed an oxidative dimerization of β-aminoporphyrins by the formation of a fused pyrazine ring. The dimer has effective π-conjugation, as shown by the significantly red-shifted absorption spectra. This dimerization protocol is promising for connecting π-conjugated molecules to construct rigid π-systems in a one-pot operation. Furthermore, the oxidation of 2-amino-5,10,15,20-tetraphenylporphyrin with DDQ provides the diamino, β–β linked diporphyrin **7**, which is a route to C_2-symmetric diamines. This porphyrin dimer would be applicable as a chiral ligand or an organocatalyst. Further investigation on oxidative fusion reactions and the application of diporphyrins is ongoing.

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[14] $C_{94}H_{61}ClN_{10}Ni_2$; $M = 1483.40$; triclinic; space group $P\bar{1}$ (No. 2); $a = 13.651(5)$, $b = 14.673(5)$, $c = 17.669(5)$ Å; $\alpha = 96.569(5)$, $\beta = 90.727(5)$, $\gamma = 93.011(5)°$; $V = 3510(2)$ Å^3; $Z = 2$; $T = 90(2)$; $\rho_{calcd} = 1.403$ g cm^{-1}; $R_1 = 0.0636$ ($I > 2\sigma(I)$), $wR_2 = 0.1664$ (all data); GOF = 1.083. CCDC 853874 (**7**) 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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