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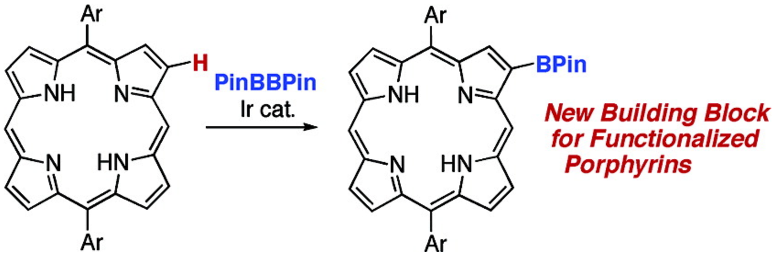

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Highly Regioselective Ir-Catalyzed β-Borylation of Porphyrins via C−H Bond Activation and Construction of β−β-Linked Diporphyrin

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Directly linked multiporphyrinic molecules have received much attention because of their unique properties.[1] We have developed an efficient route to *meso*-*meso*-linked porphyrins via Ag(I)-mediated coupling of *meso*-unsubstituted porphyrins.[1d,e] The cross-coupling reaction between bromo- and borylporphyrins is also a powerful tool.[2] Consequently, borylated porphyrins that can be available via borylation of *meso*-bromoporphyrins are highly useful building blocks.[3]

Recently, organoboron chemistry has been booming in fruitful combination with transition metal catalysis. The Suzuki−Miyaura reaction has become the most frequently used procedure for cross-coupling reactions.[4] Furthermore, iridium-catalyzed direct borylation of aromatic compounds via C−H bond activation clearly demonstrates the power of transition metal catalysis and has opened up a new stage of organoboron chemistry.[5]

In connection with the synthesis of porphyrin arrays, we have attempted the synthesis of borylated porphyrins via the iridium-catalyzed direct borylation. We found that treatment of 5,15-bis(3,5-di-*tert*-butylphenyl)porphyrin (**1a**) with bis(pinacolato)diborane in the presence of a catalytic amount of $[Ir(cod)OMe]_2$ and 4,4′-di-*tert*-butyl-2,2′-bipyridyl (tbbpy) in 1,4-dioxane provided monoborylated porphyrin in 43% yield. Bisborylated porphyrins were also obtained in 14% combined yield as a mixture of two regioisomers (1:1). The reaction proceeded very cleanly without any byproducts with recovery of **1a** (37%). To our surprise, the ^{1}H NMR spectra of the borylporphyrin products **2a**, **3a**, and **4a** indicated that borylation took place at the β-position adjacent to the unsubstituted *meso*-position. Typically, in the case of **2a**, substantial downfield shifts due to the introduced boryl group were observed for two singlet signals, *meso*-H^4 ($\delta = 11.01$) and β-H^5 ($\delta = 9.68$), while the ^{1}H NMR spectrum of **1a** exhibits *meso*-H^1, β-H^2, and β-H^3 at 10.32, 9.41, and 9.13 ppm, respectively. On the basis of these results, we concluded that β-H^2 in **1a** was selectively replaced with the boryl group to provide **2a**. This has been confirmed by the X-ray diffraction analysis (vide infra). To our knowledge, this is the first example of peripheral metalation of porphyrins via C−H bond activation that proceeds with unprecedented regioselectivity of β- over *meso*-position.

Scheme 1

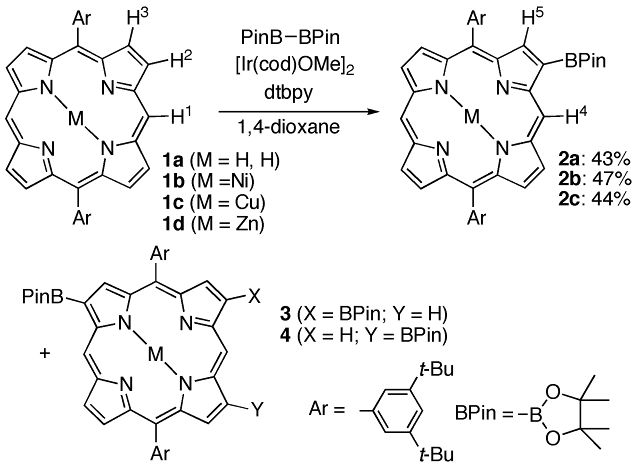
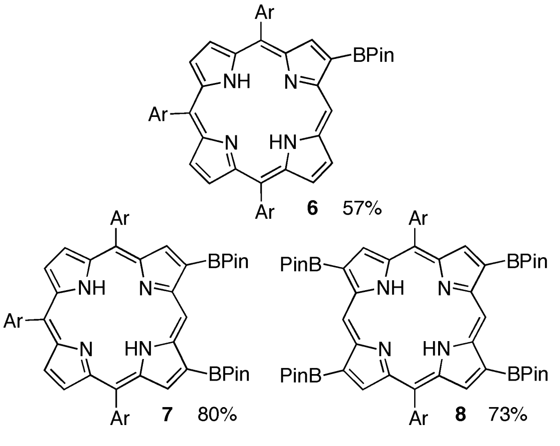


Chart 1



With regard to the regioselectivity, most of known electrophilic reactions toward 5,15-disubstituted porphyrins, such as halogenation, nitration, and Vilsmeier reactions, occur selectively at the *meso*-position.[6,7] Nucleophiles, such as alkyllithiums, also attack exclusively at the *meso*-position of *meso*-unsubstituted porphyrins.[8] It is worthy to note that the most reactive *meso*-position remained untouched during this process. Consequently, the present direct β-borylation offers a unique method for regioselective modification of relatively simple porphyrins to functionalized ones. We assume that the observed regioselectivity is mainly determined by steric factors. Thus, tetrakis(3,5-di-*tert*-butylphenyl)porphyrin, which has only congested β-pyrrolic protons, was recovered unchanged. The borylation of Ni- and Cu-porphyrins **1b** and **1c** can be also carried out to provide the monoborylated porphyrins **2b** and **2c** in 47 and 44% yields, in a manner similar to the free base **1a**. Unfortunately, the reaction was sluggish with Zn-porphyrin **1d** because of its low solubility in dioxane. Borylation of 5,10,15-tris(3,5-di-*tert*-butylphenyl)porphyrin (**5**) provided the desired 2-borylporphyrin **6** in 57% yield.

Furthermore, exhaustive borylation of 5,10,15-triarylporphyrin **5** and 5,15-diarylporphyrin **1a** with excess diborane for a prolonged reaction period furnished 2,18-bis- and 2,8,12,18-tetraborylated porphyrins **7** and **8** in 80 and 73% yields, respectively (Chart 1). The structure of tetraborylated porphyrin **8** has been clearly elucidated by the X-ray crystallographic analysis (Figure 1).[9] Obviously, the sterically less hindered β-position was borylated with high regioselectivity. Introduction of four boryl groups does not result in any distortion of the flat porphyrin structure. Interestingly,

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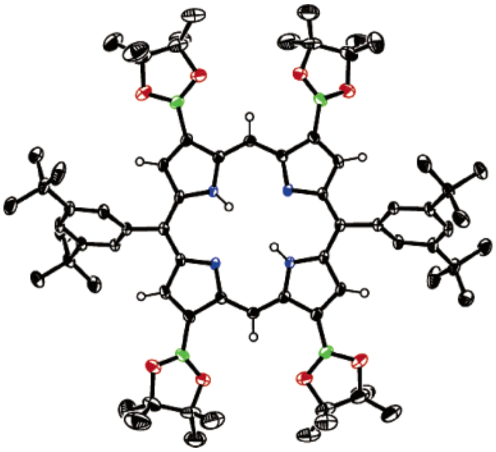
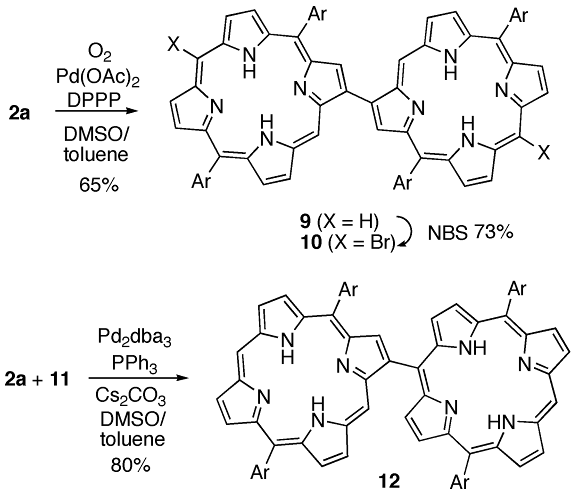


Figure 1. X-ray structure of 2,8,12,18-tetraborylated porphyrin **8**. Hydrogen atoms on the aryl and dioxaborolanyl groups are omitted for clarity.

Scheme 2



the dioxaborolane rings are kept rather coplanar to the porphyrin ring, which is favorable for the electronic interaction between the vacant orbital of boron and the π-orbital of the porphyrin. In contrast, the dioxaborolane plane is tilted at 52.0° to the porphyrin plane in the *meso*-borylporphyrin synthesized by Therien et al. The B−C bond lengths (1.544 and 1.555 Å) were somewhat shortened as compared with that of *meso*-borylporphyrin (ca 1.57 Å). The Soret bands as well as the Q-bands of **2a** and **8** are red-shifted compared to that of **1a** along with broadening of the Soret band (Supporting Information). This is probably due to the lowering of one of the degenerate LUMOs by the electron-withdrawing boryl group, which is in line with the DFT calculations at the B3LYP/6-31G* level (Supporting Information). The fluorescence spectra of **2a** and **8** are also red-shifted (Supporting Information).

β-Borylated porphyrin **2** is a highly useful building block for the synthesis of porphyrin-containing molecules.[2a,10] Palladium-catalyzed oxidative dimerization of **2a** can be successfully applied to the synthesis of $\beta-\beta$-linked diporphyrin **9** in good yield (Scheme 2).[11] In addition, construction of *meso*-β-linked diporphyrin **12** was accomplished effectively via the Suzuki−Miyaura coupling between **2a** and *meso*-bromoporphyrin **11**. Importantly, these *meso*-aryl β-linked porphyrin dimers, the $\beta-\beta$-linked one in particular, are quite difficult to synthesize due to limited availability of proper β-functionalized porphyrin precursors. Diporphyrin products **9** and **12** have unsubstituted *meso*-positions, which allow further functionalization via conventional transformations, such as regioselective dibromination with NBS from **9** to **10** in good yield. The product is also useful for further fabrications of porphyrin arrays.

In summary, we have achieved highly regioselective borylation of *meso*-arylporphyrins via C−H bond activation under iridium catalysis. This protocol offers an effective method for β-functionalization of porphyrins, which is otherwise inaccessible or entails multistep synthesis. One key feature is that the reaction does not hurt the usually reactive *meso*-positions. Functionalization of β-borylated porphyrins by taking advantage of rich organoboron chemistry and exploitation of them for fabrication of multiporphyrinic compounds are currently underway in our laboratory.

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Supporting Information Available: General procedures, spectral data for compounds, absorption and fluorescence spectra, and calculated MOs by the DFT method. CIF file for the X-ray analysis of **8**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(9) Crystal data for **8**: $C_{72}H_{98}B_4N_4O_8$, $M_w = 1190.78$, tetragonal, space group $I4_1/a$ (No. 88), $a = 33.417(2)$ Å, $b = 33.417(2)$ Å, $c = 12.6691(18)$ Å, $V = 14148(2)$ Å^3, $Z = 8$, $D_{calcd} = 1.118$ g/cm^3, $T = 90$ K, 68 905 measured reflections, 6490 unique reflections, $R = 0.0723$, $R_w = 0.2142$ (all data) GOF = 1.041 ($I > 2.0\sigma(I)$).

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