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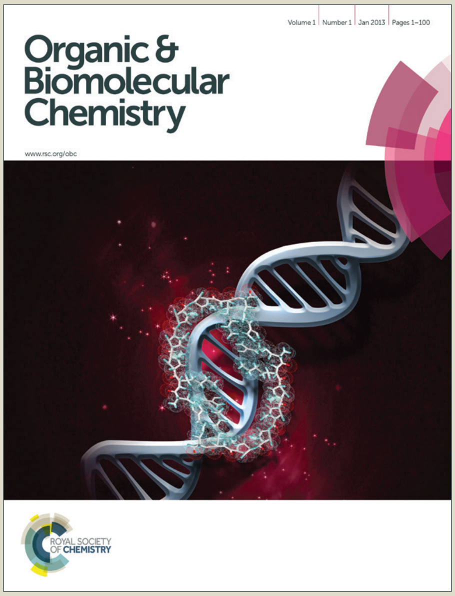

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Synthesis of directly fused porphyrin dimers through $Fe(OTf)_3$-mediated oxidative coupling

Chuan-Mi Feng, Yi-Zhou Zhu,* Shao-Chun Zhang, Yun Zang and Jian-Yu Zheng*

An efficient and general $Fe(OTf)_3$-mediated oxidative coupling method was developed for the synthesis of doubly or triply linked porphyrin dimers. Besides the central metal and peripheral substituent, regioselectivity of the oxidative coupling was found to be closely relevant to the onset oxidation potential of porphyrin substrate, and reactant with higher $E_{onset(ox)}$ tends to generate *meso-β* doubly fused porphyrin dimer.

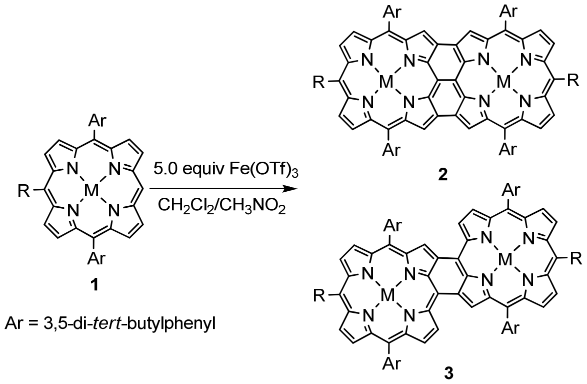
Directly linked porphyrin arrays are of particular interest because of their remarkable electrochemical, photochemical, and photophysical properties due to the strong interaction between two closely adjacent porphyrin moieties.[1] Amongst those, *meso-meso* and *meso-β* directly linked porphyrins have attracted special attention for their extended π-electron conjugation, extremely low HOMO-LUMO gaps, and the lowest energy absorption bands that reach into the near-infrared region.[2] Numerous molecules with such structure have, therefore, been synthesized and subsequently applied in molecular wires,[3] photoelectric conversion devices,[4] functional supramolecular systems,[5] and nonlinear optical materials.[6]

As a matter of fact, great efforts have been devoted to the convenient synthetic method of directly fused porphyrin arrays, and one-electron oxidative coupling was considered to be more attractive due to its high efficiency and simplicity.[7] With the continuous attention in this area, professor Osuka and coworkers have successfully developed several reagent systems such as $AgPF_6$,[7a] BAHA,[7b,7c] DDQ-$Sc(OTf)_3$,[1b,7d] and $AuCl_3$-AgOTf.[7e] Other useful methods based on Cu(II)[7f,7g] and iodine(III)[7i,7j,8a-d] have also been achieved. The reactivity and selectivity of such methods have been found to depend largely on the central metal and the peripheral substituent of porphyrin precursors. Though this phenomenon has existed for a long time, a clear explanation for that is still pursued and switching method is commonly needed to prepare different types of porphyrin dimers.

Many studies on the mechanism of such one-electron oxidative coupling of porphyrin have been done. The position of the generation of the radical cation was considered as the crucial reason for the regioselectivity of product.[8] If the precursor tends to form *meso*-radical cation first, it would give *meso-meso* directly linked structure as major product. While *β*-radical cation was preferable, *meso-β* type compound would finally achieve. Since the ability for the generation of radical cation was straightforward affected by the nature of HOMO orbital (either a_{1u} or a_{2u}),[8g] and the relationship between HOMO and onset oxidation potential can be described as E_{HOMO} = -e $E_{onset(ox)}$ - 4.8 eV ($E_{onset(ox)}$ *vs.* Fc/Fc^+),[9] the electrochemical potential may be used as an indicative character to predict the product regioselectivity.

Iron is the cheapest and most abundant element on earth, comprising nearly 5.6% of the earth's crust and the predominant component of the earth's core. Thus the Fe(III)-mediated coupling reactions were widely used to fuse aromatic moieties into the porphyrins. With these methods, porphyrins fused with azulene,[10] anthracene,[1d,2c] pyrene,[11] triphenylene,[12] boron dipyrromethene (BODIPY),[13] naphthalene,[14] diarylamine,[15] and dibenzo[*a,g*]corannulene[16] have been achieved. However, the additional fragments were needed to be conjugated to porphyrin monomer first before being applied in the Fe(III)-promoted reactions.

Table 1 Oxidative coupling of porphyrin **1** with $Fe(OTf)_3$



Ar = 3,5-di-*tert*-butylphenyl

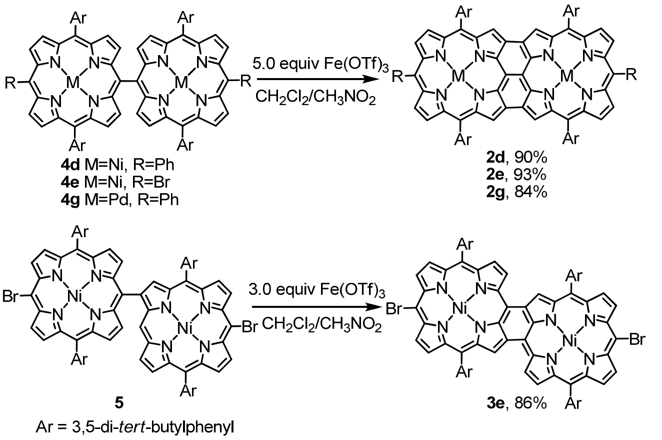
Entry	Reactant	M	R	$E_{onset(ox)}$[a]	Yield[b] (%)	
1	**1a**	Cu	Ph	0.54	**2a** 52	**3a** 30
2	**1b**	Cu	Br	0.57	**2b** 23	**3b** 56
3	**1c**	Cu	NO_2	0.72	0	**3c** 63
4	**1d**	Ni	Ph	0.61	**2d** 49	**3d** 43
5	**1e**	Ni	Br	0.65	**2e** 40	**3e** 46
6	**1f**	Ni	NO_2	0.77	0	**3f** 82
7	**1g**	Pd	Ph	0.68	0	**3g** 76
8	**1h**	Pd	NO_2	0.83	0	**3h** 78

[a] Experimental conditions: values for $E_{onset(ox)}$ in V versus Fc/Fc^+ in CH_2Cl_2

with n-Bu_4NPF_6 (0.1 M) as the supporting electrolyte and Ag/Ag^+ electrode as the reference electrode. [b]Isolated yield (time: 2 h).

$FeCl_3$ is the most used species of those Fe(III) reagents, but sometimes it will result in chlorinated by-products. Alternatives such as $Fe(ClO_4)_3$ and $Fe(OTf)_3$ have, therefore, been utilized in oxidative coupling reaction.[14] Herein, we report a facile Fe(III)-mediated intermolecular oxidative coupling of porphyrin substrates with one *meso*-H. Porphyrin derivatives with significantly different oxidation potential were prepared through inner metal- and peripheral substituent-varying. Substrates with *meso*-aryl, bromo and nitro group, as well as different metals were all smoothly transformed into fused porphyrin dimers. Notably, the product regioselectivity was observed to be closely relevant to the $E_{\mathrm{onset(ox)}}$ value of starting material, and the ratio of *meso-β* product rises with the increase of $E_{\mathrm{onset(ox)}}$ value of reactants.

After the general reaction condition screening, the procedure for $Fe(OTf)_3$-mediated oxidation was optimized as: to a solution of metalloporphyrin monomer in the mixture of dry CH_2Cl_2 and CH_3NO_2 was added 5.0 equiv of $Fe(OTf)_3$ at room temperature, and the resulting mixture was allowed to stir 2 h before being terminated by saturated sodium bicarbonate solution. Representative substituents such as aryl, bromo, and nitro group, as well as Cu(II), Ni(II), and Pd(II) metal were selected to investigate this oxidative coupling reaction. As shown in Table 1, 5,10,15-triarylporphyrin **1a** gave mixed products of *β-β,meso-meso,β'-β'* triply linked porphyrin dimer **2a** in 52% yield and *meso-β* doubly linked porphyrin dimer **3a** in 30% yield (entry 1). Similar to that, a mixture of product was obtained for substrate **1b** with *meso*-Br, but the yield of *meso-β* doubly linked compound rose up to become the major component (entry 2). Precursor with strong electron-withdrawing nitro group also performed well in this condition, and only *meso-β* doubly linked porphyrin dimer can be observed (entry 3). All the results indicate that peripheral substituents do have significant influence on the regioselectivity of this oxidative coupling of porphyrin. With respect to Ni(II) porphyrin, a similar tendency was observed (entries 4-6), the ratio of *meso-β* doubly linked porphyrin dimer rose with the increase of the electron-withdrawing ability of the substituents. From the data of entries 1, 4 and 7, it is reasonable to conclude that the inner metal also heavily influences the regioselectivity. As compared to the Cu(II) porphyrin **1a**, the ratio of *meso-β* product for porphyrin **1d** obviously increased and got close to that of *β-β,meso-meso,β'-β'* triply linked product. When it further comes to Pd(II) porphyrin, only one product was obtained either for aryl substituent or nitro group (entries 7 and 8).[7b,7d] It is worthy to point out, porphyrins with bromo and nitro group are powerful building blocks and can be easily further transformed into other function groups through transition-metal-catalyzed coupling reaction[7e,17] or substitution reaction[8d,18] to achieve porphyrin-based functional molecules. This is also the first oxidative coupling case of the porphyrin with strong electron-withdrawing nitro group at *meso* position.



Scheme 1 $Fe(OTf)_3$ mediated fusion of the singly linked porphyrin dimers.

Meso-meso directly linked porphyrin dimers[8b] and *meso-β* singly linked porphyrins[8d] were subsequently used in such $Fe(OTf)_3$-promoted oxidative coupling. Treated with 5.0 equiv of $Fe(OTf)_3$, *meso-meso* singly linked dimers **4d** and **4e** gave triply linked compounds **2d** and **2e** in 90% and 93% yield, respectively. The Pd(II) porphyrin precursor **4g** also produce the same triply linked porphyrin structure **2g** with 84% yield. When *meso-β* linked porphyrin **5** was used, *meso-β* fused dimer **3e** was finally obtained in 86% yield. Notably, all these reactions show much higher yield than the reactions using porphyrin monomer as reactants, and the reactions completed within 30 min. For no side-product occurring in the reaction, the workup procedure is quite simple and time-saving.

ESR spectrum of the reaction mixture was measured to understand the mechanism for the $Fe(OTf)_3$-mediated cross-coupling reaction (Fig. S17).[19] No radical signal was detected for the measurement of the reaction mixture without $Fe(OTf)_3$ at −50 °C. After introducing the $Fe(OTf)_3$, a sharp signal was observed at $g = 2.0082$, which can be assigned to the radical species generated from **1f** because the value of g is similar to the reported Zn(II) and Pd(II) porphyrin ($g = 2.0024$ and 1.9966, respectively).[7d] The spectrum exhibited no splitting due to the coupling with the nitrogens, indicating that one electron was removed from the a_{1u} orbital of **1f**.

To better comprehend the regioselectivity of this kind of reaction, cyclic voltammetry (CV) has been employed,[9] and the data was summarized in Table 1. From the onset oxidation potentials in the cyclic voltammogram, the HOMO can be readily estimated. The onset oxidation potentials ($E_{\mathrm{onset(ox)}}$ *vs.* Fc/Fc^+) of Cu(II) porphyrins increase in the order of **1a** < **1b** < **1c** (entries 1-3), from which their HOMO levels are estimated to be -5.34, -5.37 and -5.52 eV respectively, according to the equation $E_{\mathrm{HOMO}} = -e\, E_{\mathrm{onset(ox)}} - 4.8$ eV. The yields of *meso-β* fused Cu(II) porphyrins were also found to increase in the same order of **3a** < **3b** < **3c**. That can be attributed to the increase of the electron-withdrawing ability of the peripheral substituents, which has been proved to not only lower the energy of a_{2u} relative to that of a_{1u} but also raise the oxidation potential.[8g] As a result, the radical cation shows a trend of forming at *β* position. Similar tendency has been found in the Ni(II) porphyrin substrates. As for Pd(II) porphyrin reactants, since the increased electronegativity of metal should decrease the energy of a_{2u} relative to that of a_{1u}, they gave only *meso-β* fused dimers.[8g] Meantime, they show higher oxidation potentials than the corresponding Cu(II)- and Ni(II)-porphyrins. Accordingly, besides the central metal and peripheral substituent, regioselectivity of the oxidative coupling was closely relevant to the onset oxidation potential of porphyrin substrate. The greater the value is, much more *meso-β* doubly linked product forms.

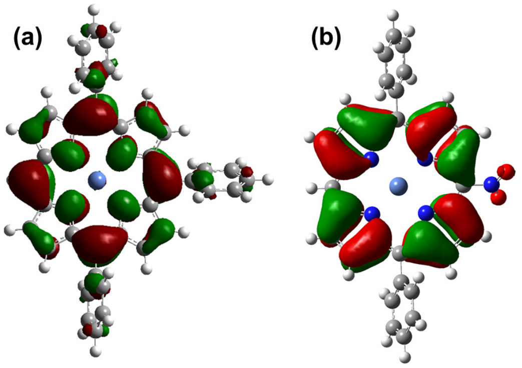


Fig. 1. HOMO of **1d** (a) and **1f** (b) derived by calculations at the B3LYP/6-31G(d) level, using the LANL2DZ effective core potential for nickel. 3,5-Di-*tert*-butylphenyl groups were replaced by phenyl to simplify calculations.

Density functional theory (DFT) calculations were further conducted with the Gaussian 03 program at the B3LYP/6-31G(d) level using the LANL2DZ effective core potential for the investigation of the molecular configuration and frontier molecular orbitals. *tert*-Butyl groups have been removed to simplify the calculation. The optimized geometries and electron distributions of the HOMOs of the dyes are shown in Fig. 1. As shown in Fig. 1a, the electron density of the HOMOs of Ni(II) porphyrin **1d** mainly localize at its *meso*-carbons, and little at β-carbons and nitrogen atoms, showing potential to yield radical cation in the order of meso-position > β-position. That is consistent with the result of entry 4 in Table 1. As for porphyrin **1f**, the electron density distributes mainly at β-carbons, and nearly blank at the *meso*-carbons, which also agrees with the fact that only *meso-β* doubly linked product was observed in entry 6, Table 1.

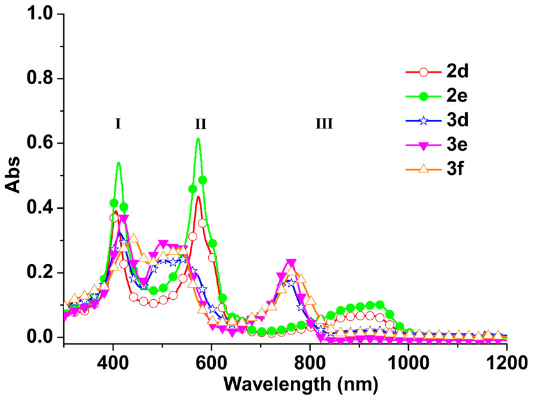


Fig. 2. Ultraviolet-visible-infrared absorption spectra of porphyrins **2d** (red line), **2e** (green line), **3d** (blue line), **3e** (pink line) and **3f** (yellow line) in $CHCl_3$.

The distinctive absorption of the porphyrin derivatives is of great significance for developing the porphyrin-based photoelectric conversion materials and sensors. As shown in Fig. 2, all spectra consist of three major broad and red-shifted bands (I, II and III), and the absorption maximum of band III for meso-β fused dimers **3d**, **3e** and **3f** appeared at 754, 756 and 765 nm, respectively. While the absorption maximum of triply linked species appeared at 932 and 937 nm, respectively, which is largely red-shifted in comparison to that of doubly linked one due to the larger electronic π-conjugation. In contrast to the spectra of **3d** and **3e**, about 10 nm red shift of the lowest energy absorption band of NO_2-Ni(II) dimer **3f** can be clearly observed.

In conclusion, we have developed a general and efficient Fe(III)-mediated oxidative coupling method to synthesize fused porphyrin dimers. Substrates with strong electron-withdrawing nitro group at *meso* position were also successfully used to complete this transformation. Besides the central metal and peripheral substituent, regioselectivity of the oxidative coupling was further found to be closely relevant to the onset oxidation potential of porphyrin substrate. The ratio of meso-β doubly linked species in product increases accompanying the enhancement of the $E_{\text{onset(ox)}}$ of starting material.

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Notes and references

State Key Laboratory and Institute of Elemento-Organic Chemistry, Collaborative Innovation Center of Chemical Science and Engineering (Tianjin) Nankai University, Tianjin, China. Tel.: +86-022-2350-5572; fax: +86-022-2350-5572; e-mail: zhuyizhou@nankai.edu.cn, jyzheng@nankai.edu.cn

† Electronic Supplementary Information (ESI) available: Synthetic procedures, ESR, CV and NMR data are avaliable. See DOI: 10.1039/b000000x/

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