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Remarkable Effects of P-Perfluorophenyl Group on the Synthesis of Core-Modified Phosphaporphyrinoids and Phosphadithiasapphyrin

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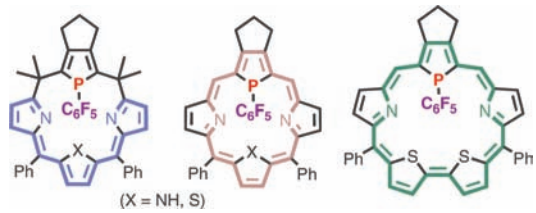
ABSTRACT



P,X,N_2-type phosphaporphyrins and phosphacalixphyrins (X = N, S) bearing a perfluorophenyl (C_6F_5) group at the core phosphorus atom were prepared in high overall yield from 1-perfluorophenyl-2,5-di(ethoxycarbonyl)phosphole as a common starting material. In addition, P−C_6F_5 P,S_2,N_2-type sapphyrin was successfully prepared as the first example of ring-expanded phosphorus-containing porphyrin.

Core modification of porphyrins, namely, replacement of the core pyrrolic nitrogen atom by another heteroatom or carbon, has been known as a powerful tool to alter their optical/electrochemical properties and coordinating ability drastically.[1] Recently, we prepared the first examples of phosphorus-containing core-modified porphyrins **1X**[2−4] and calixphyrins **2X**[5] (Figure 1) and disclosed their characteristic optical and electrochemical properties, coordinating behavior, and reactivity. For instance, P,X,N_2-porphyrins **1X** were found to possess considerably small HOMO−LUMO gaps as compared with N_4- and S,X,N_2-porphyrins (X = N, S),[2a,b,d] and the 18π-systems of **1X** were easily reconstructed by complexation with zerovalent group 10 metals[2c] and

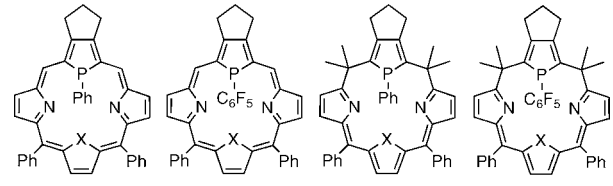


Figure 1. P,X,N_2-Porphyrins **1X**, **1X$_F$** and P,X,N_2-Porphyrins **2X**, **2X$_F$** (X = N, S).

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(1) For reviews on core-modified porphyrins, see: (a) Latos-Grażyński, L. In *The Porphyrin Handbook*; Kadish, K. M., Smith, K. M., Guilard, R., Eds.; Academic Press: San Diego, 2000; Vol *2*, Chapter 14. (b) Jasat, A.; Dolphin, D. *Chem. Rev.* **1997**, *97*, 2267–2340. (c) Furuta, H.; Maeda, H.; Osuka, A. *Chem. Commun.* **2002**, 1795–1804. (d) Gupta, I.; Ravikanth, M. *Coord. Chem. Rev.* **2006**, *250*, 468–518. (e) Lash, T. D. *Eur. J. Org. Chem.* **2007**, 5461–5481. (f) Misra, R.; Chandrashekar, T. K. *Acc. Chem. Res.* **2008**, *41*, 265–279. (g) Matano, Y.; Imahori, H. *Acc. Chem. Res.* **2009**, *42*, 1193–1204.

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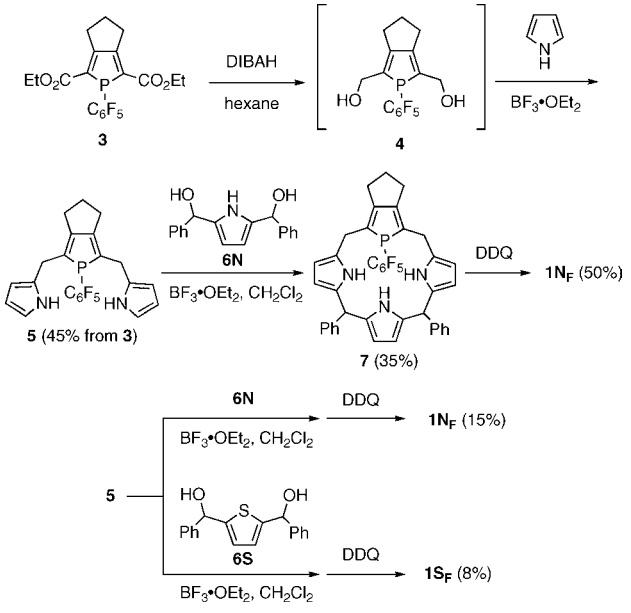
P-oxidation with H_2O_2,[2d] affording unique 20π and/or 22π systems. While these properties and reactivities of phosphaporphyrins are of interest, there were distinct drawbacks for the synthesis due to the high reactivity of a σ^3-phosphorus atom. First, P-masking/demasking steps are necessary in the synthesis of **1X** and **2X**, which increases the number of reaction steps. Second, P-oxidation inevitably occurs in the ring oxidation of σ^3-P porphyrinogens to give significant amounts of P-oxo side products, which severely reduces the yield of target porphyrins **1X**.[2d,6] A possible solution to these drawbacks is to improve the durability of the σ^3-phosphorus center under acidic and oxidizing conditions. In this regard, attachment of an electron-withdrawing group onto the phosphorus atom is a highly promising approach. Here we report the synthesis of P,X,N_2-porphyrins $\mathbf{1X_F}$ and P,X,N_2-calixphyrins $\mathbf{2X_F}$ (X = N, S) bearing a perfluorophenyl (C_6F_5) group at the core phosphorus atom. Notably, the introduction of C_6F_5 group improves the chemical stability of the σ^3-phosphorus center dramatically, and both $\mathbf{1X_F}$ and $\mathbf{2X_F}$ are readily available in high overall yield from a common starting material. Moreover, P,S_2,N_2-sapphyrin, the first example of P-containing expanded porphyrin, was successfully prepared by taking advantage of the electron-withdrawing nature of the C_6F_5 group.

The P−C_6F_5-type P,X,N_2-porphyrins $\mathbf{1X_F}$ (X = N, S) were prepared starting from 1-perfluorophenyl-2,5-di(ethoxycarbonyl)phosphole **3**[7] by a similar method used for the synthesis of **1X**[2a,b,d] (Scheme 1). Reaction of **3** with

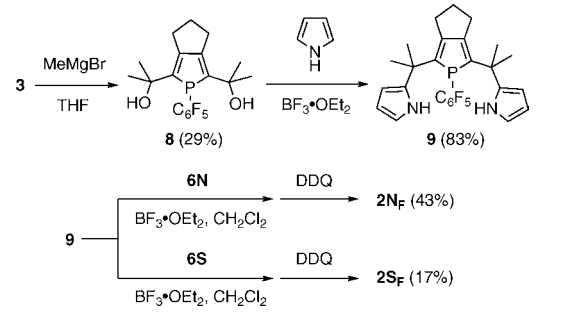
Scheme 1. Synthesis of C_6F_5-Type P,X,N_2-Porphyrins $\mathbf{1X_F}$



diisobutylaluminium hydride (DIBAH) in hexane gave 2,5-di(hydroxymethyl)phosphole **4**, which was then treated with excess pyrrole in the presence of BF_3•OEt_2 to afford phosphatripyrrane **5** in 45% yield based on **3**.[8] The BF_3-promoted dehydrative condensation of **5** with 2,5-bis[hydroxy(phenyl)methyl]pyrrole **6N**[9] gave σ^3-P,N_3-porphyrinogen **7** in 35% yield as a mixture of three diastereomers. In sharp contrast to the corresponding P−Ph analogues, diol **4** and phosphatripyrrane **5** are sufficiently stable against air and acids. Therefore, it is not necessary to protect the σ^3-phosphorus center throughout the sequential BF_3-promoted dehydrative condensation reactions from **4** to **7**. Finally, the ring oxidation of the porphyrinogen **7** with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) afforded target porphyrin $\mathbf{1N_F}$. In the present synthesis, only trace amounts of P-oxo byproducts were found in the crude reaction mixture, and the yield of $\mathbf{1N_F}$ from **7** (50%) was almost three times larger than that of **1N** from the P−Ph-type porphyrinogen (17%).[2b,d] Alternatively, $\mathbf{1N_F}$ can be prepared in a one-pot procedure from **5** and **6N** in 15% yield (18% yield for stepwise synthesis). According to a similar procedure, P,S,N_2-porphyrin $\mathbf{1S_F}$ was prepared from **5** and 2,5-di[hydroxy(phenyl)methyl]thiophene **6S**[10] in 8% yield (based on **5**).

The P−C_6F_5-type P,X,N_2-calixphyrins $\mathbf{2X_F}$ (X = N, S) were also prepared starting from **3** without P-masking (Scheme 2). Treatment of **3** with excess MeMgBr gave

Scheme 2. Synthesis of C_6F_5-Type P,X,N_2-Calixphyrins $\mathbf{2X_F}$



tertiary diol **8** in 29% yield. Dehydrative condensation of **8** with excess pyrrole afforded phosphatripyrrane **9** in 83% yield. The BF_3-promoted dehydrative condensation of **9** with **6X** (X = N, S) followed by DDQ oxidation afforded P,X,N_2-calixphyrins $\mathbf{2N_F}$ and $\mathbf{2S_F}$ in 43% and 17% yields, respectively.

Notably, the overall yields of P−C_6F_5-type P,X,N_2-porphyrins $\mathbf{1X_F}$ and P,X,N_2-calixphyrins $\mathbf{2X_F}$ from **3** are increased by 1.5−10 times as compared with those of P−Ph analogues **1X** and **2X**. In addition, the number of reaction processes is reduced by 1−2 steps.

Compounds $\mathbf{1X_F}$ and $\mathbf{2X_F}$ were isolated as purple and red solids, respectively, and fully characterized by standard spectroscopic techniques. In the ^{19}F NMR spectra of $\mathbf{1X_F}$ and $\mathbf{2X_F}$, the *ortho*, *meta*, and *para* ^{19}F signals of the P−C_6F_5 group were observed at δ_F −165.9 to −163.0, −132.7 to −126.4, and −156.8 to −154.3, respectively. The ^{1}H NMR spectra of $\mathbf{1X_F}$ and $\mathbf{2X_F}$ essentially resemble those of P−Ph counterparts **1X** and **2X**. For instance, the pyrrole-β protons of $\mathbf{1N_F}$ appeared at the downfield region (δ 8.38−8.69) relative to the corresponding protons of $\mathbf{2N_F}$ (δ 5.93−6.60). Figure 2 summarizes differences in chemical shifts ($\Delta\delta$) of the peripheral (heterole-β) protons between $\mathbf{1X_F}$ and $\mathbf{2X_F}$.

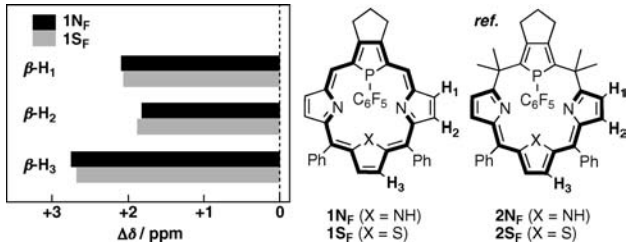


Figure 2. Downfield shifts ($\Delta\delta$) of the β protons of $\mathbf{1N_F}$ (black) and $\mathbf{1S_F}$ (gray) from those of $\mathbf{2N_F}$ and $\mathbf{2S_F}$.

Significant diatropic ring current effects ($\Delta\delta = 1.82-2.75$) stemming from the 18π annulene circuit are clearly observed for $\mathbf{1X_F}$. The ring current effects in $\mathbf{1X_F}$ also emerged as upfield resonances of ^{31}P nucleus ($\mathbf{1N_F}$, δ_p −30.7 vs $\mathbf{2N_F}$, δ_p −15.9; $\mathbf{1S_F}$, δ_p −22.5 vs $\mathbf{2S_F}$, δ_p −15.8). It seems that introduction of the electron-withdrawing C_6F_5 group at the core phosphorus atom perturbs the aromaticity of P,X,N_2-porphyrin π-circuits only slightly.

The UV−vis absorption spectrum of P,N_3-porphyrin $\mathbf{1N_F}$ is similar to that of the P−Ph counterpart **1N** (Table 1; Figure S1 in Supporting Information), whereas both Soret and Q bands of P,S,N_2-porphyrin $\mathbf{1S_F}$ were broadened and the Q_{0-0} band was red-shifted by ca. 60 nm as compared to that of **1S** (Table 1 and Figure 3).[11] The electrochemical properties of $\mathbf{1X_F}$ were examined by cyclic voltammetry (CV) and differential pulse voltammetry (DPV) (Figure S3 in Supporting Information). The first oxidation potential ($E_{ox,1}$) and the first and second reduction potentials ($E_{red,1}$ and $E_{red,2}$) of $\mathbf{1N_F}$ and $\mathbf{1S_F}$ determined by DPV are shifted to the negative side compared to the respective potentials of the P−Ph analogues **1X** ($\Delta E_{ox,1} = 0.05-0.15$ V; $\Delta E_{red,1} = 0.01-0.06$ V; $\Delta E_{red,2} = 0.08-0.10$ V). The replacement of the P-phenyl group with the P-perfluorophenyl group has proven to enhance the electron-accepting ability of the phosphaporphyrin π-systems slightly.

Table 1. UV−Vis Absorption Maxima and Redox Potentials (vs Fc/Fc^+)[a,b] of **1X**, $\mathbf{1X_F}$, and **11** in CH_2Cl_2

compd	λ_{max} (Soret; Q), nm	$E_{ox,1}$, V	$E_{red,1}$;$E_{red,2}$, V
1N[c]	431; 486, 522, 555, 636, 698	+0.38 (ir)	−1.51 (r); −1.74 (q-r)
1S[c]	440; 492, 518, 547, 647, 718	+0.45 (ir)	−1.36 (r); −1.56 (q-r)
$\mathbf{1N_F}$	433; 528, 560, 640, 704	+0.53 (ir)	−1.50 (r); −1.66 (ir)
$\mathbf{1S_F}$	441; 544, 780	+0.50 (ir)	−1.30 (ir); −1.46 (ir)
11	500; 599, 740, 835	+0.43 (ir)	−1.39 (ir); −1.59 (ir)

[a] Reference electrode: Ag/Ag^+ [0.01 M $AgNO_3$, 0.1 M n-Bu_4NPF_6 (MeCN)]. [b] "r", "q-r", and "ir" in parentheses indicate that the processes occur reversibly, quasi-reversibly, and irreversibly. [c] Data from ref 2d.

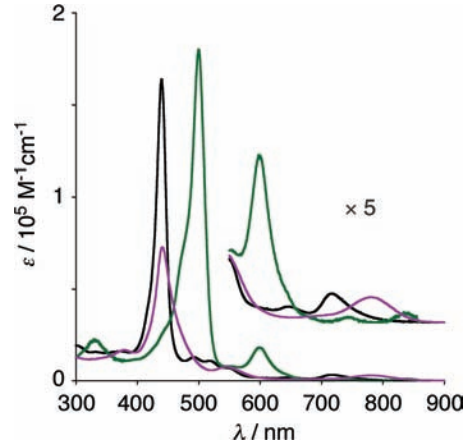


Figure 3. UV−vis absorption spectra of **1S** (black; data from ref 2d), $\mathbf{1S_F}$ (purple), and **11** (green) in CH_2Cl_2.

Considering rich coordination chemistry of expanded porphyrins,[12] the synthesis of phosphorus-containing expanded porphyrins is a challenging subject.[13] However, all attempts to prepare expanded phosphaporphyrins from the P−Ph-type phosphatripyrrane have been unsuccessful so far. In this context, the successful result on the synthesis of $\mathbf{1X_F}$ was quite encouraging, and we decided to use P−C_6F_5-type phosphatripyrrane **5** as a key precursor for the synthesis of expanded phosphaporphyrins. The first target, P−C_6F_5-type phosphadithiasapphyrin **11**,[14,15] was successfully prepared by the BF_3-promoted [3 + 2] dehydrative condensation between **5** and 5,5′- bis[hydroxy(phenyl)methyl]bithiophene **10**[16] followed by in situ DDQ oxidation (eq 1). It should be emphasized again that P-masking is not involved in the condensation/oxidation steps. The sapphyrin **11** was isolated as an air-stable shiny green solid. The diagnostic spectral

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(6) Ring oxidation of P-masked P,X,N_2-porphyrinogens (X = N, S, O) did not afford 18π P,X,N_2-porphyrins. See ref 2b,d.

(7) Compound **3** was prepared via Ti^{II}-mediated cyclization of 1,7-bis(ethoxycarbonyl)hepta-1,6-diyne followed by treatment with $C_6F_5PCl_2$ according to the reported procedure for the synthesis of 1-phenyl-2,5-di(ethoxycarbonyl)phosphole: Matano, Y.; Miyajima, T.; Nakabuchi, T.; Matsutani, Y.; Imahori, H. *J. Org. Chem.* **2006**, *71*, 5792–5795.

(8) It was convenient to use **4** in a semi-purified state for the subsequent reaction with pyrrole, although **4** is isolable as a colorless solid in 61% yield. For details, see Supporting Information.

features of **11** are as follows. In the ^{19}F and ^{31}P NMR spectra, **11** showed three ^{19}F signals at δ_F −165.2 (*ortho*), −128.5 (*meta*), and −155.2 (*para*), and one ^{31}P signal at δ_P −28.4. In the ^1H NMR spectrum of **11**, peripheral (*meso*, pyrrole-β, and thiophene-β) protons resonate significantly downfield (δ 8.49−10.11), which corroborates the 22-π aromaticity of **11** (Figure 4). The relatively downfield appearance (δ 2.90−4.58) of the peripherally fused trimethylene protons of **11** originates from the 22-π diatropic ring current effect. It is therefore likely that the phosphole ring in **11** takes on a noninverted conformation as represented schematically in eq 1. This structural feature is in marked contrast to that of previously reported X,S_2,N_2-sapphyrins (X = N, O, S, Se), where the heterocyclic rings opposite to the bithiophene unit take on an inverted conformation.[15a,b] Presumably, in P,S_2,N_2-sapphyrin **11**, the trimethylene substituents at the phosphole ring disturb its inversion sterically.[17,18] The UV−vis absorption spectrum of **11** shows an intense Soret band at λ_{max} 500 nm and weak Q bands at λ_{max} 599−835 nm (Figure 3), both of which are close to the values reported for the inverted X,S_2,N_2-sapphyrins (Soret: λ_{max} 490−510 nm, Q: λ_{max} 600−880 nm).[15a,b] The redox potentials of **11** determined by DPV were more cathodic in comparison with the respective values of $\mathbf{1S_F}$ (Table 1; Figures S3c in Supporting Information).

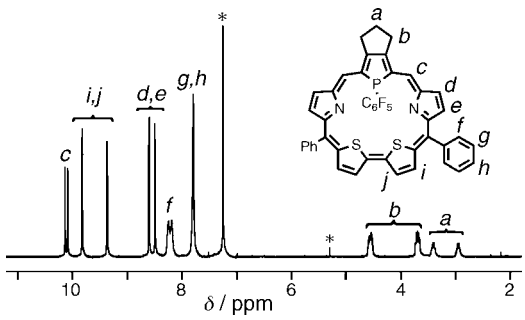
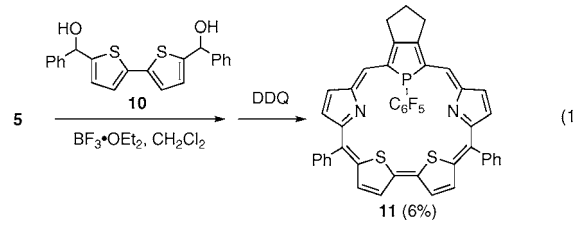


Figure 4. ^1H NMR spectrum of **11** in $CDCl_3$. Asterisks (*) inidicate residual solvents.



In summary, we have revealed that the P−C_6F_5-type P,X,N_2- porphyrins and P,X,N_2-calixphyrins (X = N, S) can be prepared more easily than their P−Ph analogues. In addition, the first example of phosphorus-containing core-modified sapphyrin was successfully prepared from P−C_6F_5 phosphatripyrrane as the key precursor. The present results exemplify that the functionalization at the phosphorus atom is a highly promising strategy to bring chemical stability to the phosphaporphyrin skeleton. Studies on the coordination chemistry of this new series of core-modified porphyrin ligands are now in progress.

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Supporting Information Available: Experimental details and characterization data, ^1H and ^{13}C NMR spectra for new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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(11) The broadening and bathochromic shift of $\mathbf{1S_F}$ may be due to electronic repulsion between the core sulfur atom and the P−C_6F_5 fluorine atoms in $\mathbf{1S_F}$.
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(17) In the variable temperature ^1H NMR spectra of **11** (−100 °C to +80 °C: CD_2Cl_2 or $CDCl_2CDCl_2$), the signals due to the peripheral (*meso*, pyrrole-β, thiophene-β, and trimethylene) protons show negligible changes ($\Delta\delta$ < 0.5 ppm). This implies that the structure of π-system in **11** is not flexible in solution.
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