

Synthesis of a Phosphorus-Containing Hybrid Porphyrin

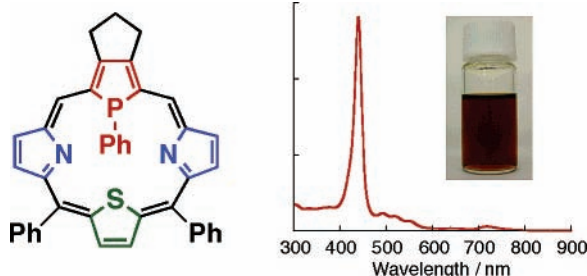
Yoshihiro Matano,^{*,†} Takashi Nakabuchi,[†] Tooru Miyajima,[†] Hiroshi Imahori,[†] and Haruyuki Nakano[‡]

Department of Molecular Engineering, Graduate School of Engineering, Kyoto University, Nishikyo-ku, Kyoto 615-8510, Japan, and Department of Chemistry, Graduate School of Sciences, Kyushu University, Fukuoka 812-8581, Japan

matano@scl.kyoto-u.ac.jp

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ABSTRACT



A phosphorus-containing hybrid porphyrin was successfully prepared via the BF_3 -promoted dehydrative condensation between σ^4 -phosphatripyrrane and 2,5-bis[hydroxy(phenyl)methyl]thiophene. The NMR and UV–vis absorption spectra, electrochemical measurements, and DFT calculations revealed that the σ^3 -P,N₂S-hybrid porphyrin exhibits high aromaticity as an 18 π -electron system in terms of both geometric and magnetic criteria.

Porphyrins are one of the most widely studied aromatic macrocycles because of their important roles in biological, materials, and coordination chemistry. Chemical modification of the core of porphyrins is a highly promising approach to developing new classes of dyes and catalysts, as the electronic structures and coordination environments of the porphyrin ring can be changed dramatically.¹ In this respect, much attention has been paid to the chemistry of core-modified porphyrins, such as carbaporphyrins,² N-confused porphyrins,³ chalcogen-containing porphyrins,⁴ and pypyrrporphyrins.⁵

Incorporating a phosphorus atom at the core of the porphyrin ring, namely, replacing a pyrrole ring with phosphole, seems a quite promising strategy for altering significantly the optical, electrochemical, and coordinating properties of the porphyrin macrocycle. In 2003, Delaere and Nguyen predicted the ground state electronic structures of unsubstituted monophospha- and diphosphaporphyrins based on density functional theory (DFT) calculations and concluded that these porphyrins would exhibit reasonable aromaticity.⁶ Experimentally, however, phosphorus-containing porphyrins have long been untouched.⁷ Recently, we

[†] Kyoto University.

[‡] Kyushu University.

(1) (a) Latos-Grażyński, L. In *The Porphyrin Handbook*; Kadish, K. M., Smith, K. M., Guillard, R., Eds.; Academic Press: San Diego, 2000. Vol. 2, Chapter 14. (b) Chandrashekar, T. K.; Venkatraman, S. *Acc. Chem. Res.* **2003**, *36*, 676. (c) Sessler, J. L.; Seidel, D. *Angew. Chem., Int. Ed.* **2003**, *42*, 5134. (d) Furuta, H.; Maeda, H.; Osuka, A. *Chem. Commun.* **2002**, 1795. (e) Srinivasan, A.; Furuta, H. *Acc. Chem. Res.* **2005**, *38*, 10. (f) Chmielewski, P. J.; Latos-Grażyński, L. *Coord. Chem. Rev.* **2005**, *249*, 2510. (g) Stepień, M.; Latos-Grażyński, L. *Acc. Chem. Res.* **2005**, *38*, 88. (h) Gupta, I.; Ravikanth, M. *Coord. Chem. Rev.* **2006**, *250*, 468 and references therein.

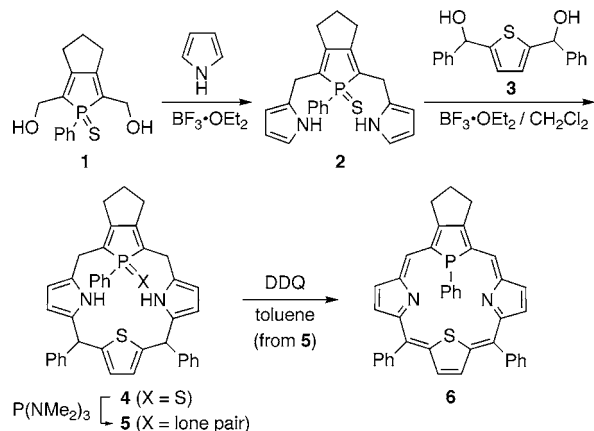
(2) For example, see: (a) Lash, T. D. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 2533. (b) Berlin, K. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 1820. (c) Liu, D.; Ferrence, G. M.; Lash, T. D. *J. Org. Chem.* **2004**, *69*, 6079. (d) Stepień, M.; Latos-Grażyński, L.; Sztterenber, L.; Panek, J.; Latajka, Z. *J. Am. Chem. Soc.* **2004**, *126*, 4566. (e) Sprutta, N.; Swiderska, M.; Latos-Grażyński, L. *J. Am. Chem. Soc.* **2005**, *127*, 13108.

(3) For example, see: (a) Furuta, H.; Asano, T.; Ogawa, T. *J. Am. Chem. Soc.* **1994**, *116*, 767. (b) Chmielewski, P. J.; Latos-Grażyński, L.; Rachlewicz, K.; Glowiak, T. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 779. (c) Furuta, H.; Maeda, H.; Osuka, A. *J. Am. Chem. Soc.* **2000**, *122*, 803. (d) Rachlewicz, K.; Wang, S.-L.; Ko, J.-L.; Hung, C.-H.; Latos-Grażyński, L. *J. Am. Chem. Soc.* **2004**, *126*, 4420.

established a convenient method for the preparation of 2,5-difunctionalized phospholes,⁸ which have proven to be reliable starting materials for phosphorus-containing hybrid calixpyrroles⁹ and calixphyrins.¹⁰ Here, we report the first example of a phosphorus-containing hybrid porphyrin as a new family of core-modified porphyrins. Both experimental and theoretical results clearly demonstrate that the σ^3 -P,N₂,S-hybrid porphyrin possesses high aromaticity with a relatively narrow HOMO–LUMO gap.

Scheme 1 illustrates the synthesis of σ^3 -P,N₂,S-hybrid porphyrin **6**. Treatment of 2,5-bis(hydroxymethyl)-1-phenyl-

Scheme 1. Synthesis of σ^3 -P,N₂,S-Hybrid Porphyrin **6**



1-thiophosphole (**1**)⁸ with excess pyrrole in the presence of $\text{BF}_3 \cdot \text{OEt}_2$ afforded σ^4 -phosphatripyrrane (**2**) in 14% yield. The BF_3 -promoted dehydrative condensation of **2** with 2,5-bis[hydroxy(phenyl)methyl]thiophene (**3**)¹¹ in CH_2Cl_2 gave σ^4 -P,N₂,S-porphyrinogen (**4**) in 36% yield as a mixture of diastereomers.¹² Desulfurization of **4** with excess $\text{P(NMe}_2)_3$ in refluxing toluene yielded σ^3 -P,N₂,S-porphyrinogen (**5**), which was subsequently oxidized by 2,3-dichloro-5,6-

(4) For example, see: (a) Broadhurst, M. J.; Grigg, R.; Johnson, A. W. *J. Chem. Soc. C* **1971**, 3681. (b) Ulman, A.; Manassen, J. *J. Am. Chem. Soc.* **1975**, *97*, 6540. (c) Latos-Grażyński, L.; Lisowski, J.; Olmstead, M. M.; Balch, A. L. *J. Am. Chem. Soc.* **1987**, *109*, 4428. (d) Sessler, J. L.; Cyr, M.; Burrell, A. K. *Tetrahedron* **1992**, *48*, 9661. (e) Lee, C.-H.; Kim, H.-J. *Tetrahedron Lett.* **1997**, *38*, 3935. (f) Narayanan, S. J.; Sridevi, B.; Chandrashekar, T. K.; Ashwani, V.; Roy, R. *J. Am. Chem. Soc.* **1999**, *121*, 9053. (g) Abe, M.; Hilmey, D. G.; Stilts, C. E.; Sukumaran, D. K.; Detty, M. R. *Organometallics* **2002**, *21*, 2986.

(5) (a) Mysliborski, R.; Latos-Grażyński, L.; Sztrenberg, L. *Eur. J. Org. Chem.* **2006**, 3064. (b) Sim, E.-K.; Jeong, S.-D.; Yoon, D.-W.; Hong, S.-J.; Kang, Y.; Lee, C.-H. *Org. Lett.* **2006**, *8*, 3355.

(6) Delaere, D.; Nguyen, M. T. *Chem. Phys. Lett.* **2003**, *376*, 329.

(7) Quite recently, Mathey reported the synthesis of a phosphaporphyrin analog that contains a σ^4 -phosphorus atom at the peripheral position. Mathey, F. Abstract for the JSPS Second Core-to-Core Symposium on Main Group Element Chemistry, Tokyo, 2006, p. 27.

(8) Matano, Y.; Miyajima, T.; Nakabuchi, T.; Matsutani, Y.; Imahori, H. *J. Org. Chem.* **2006**, *71*, 5792.

(9) Matano, Y.; Nakabuchi, T.; Miyajima, T.; Imahori, H. *Organometallics* **2006**, *25*, 3105.

(10) Matano, Y.; Miyajima, T.; Nakabuchi, T.; Imahori, H.; Ochi, N.; Sakaki, S. *J. Am. Chem. Soc.* **2006**, *128*, 11760.

(11) (a) Chadwick, D. J.; Willbe, C. *J. Chem. Soc., Perkin Trans. 1* **1977**, 887. (b) Jang, Y.-S.; Kim, H.-J.; Lee, P.-H.; Lee, C.-H. *Tetrahedron Lett.* **2000**, *41*, 2919.

(12) The ¹H and ³¹P NMR spectra of **4** and **5** indicated that three diastereomers were present. For details, see Supporting Information.

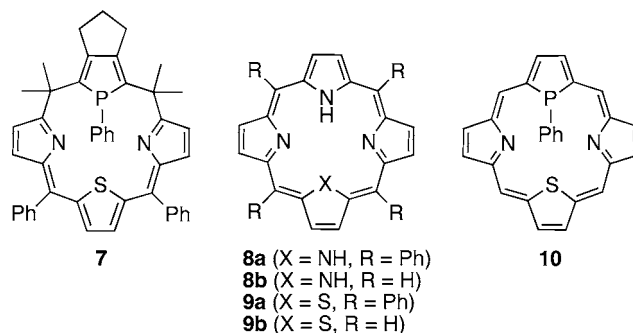


Figure 1. σ^3 -P,N₂,S-Hybrid calixphyrin **7**, porphyrins **8a,b**, 21-thiaporphyrins **9a,b**, and σ^3 -P,N₂,S-hybrid porphyrin **10**.

dicyanobenzoquinone (DDQ) to afford the target compound **6** in 14% yield (from **4**) as an air- and heat-stable reddish purple solid.

The structure of σ^3 -P,N₂,S-hybrid porphyrin **6** was fully characterized by mass spectrometry and NMR spectroscopy. In the HR-FAB-MS spectrum, the parent ion peak (M^+) was observed at m/z 612.1788 (calcd for $\text{C}_{41}\text{H}_{29}\text{N}_2\text{PS}$, 612.1789). In the ¹H NMR spectrum, the *meso*, pyrrole- β , and thiophene- β protons of **6** appeared at δ 10.44 (d, ³ $J_{\text{P-H}}$ = 18.8 Hz), 8.67 and 8.93, and 9.22, respectively, whereas the *P*-phenyl *ortho*-, *meta*-, and *para*-protons appeared at δ 2.29, 5.27, and 5.66, respectively (Figure 2). The significant downfield and upfield

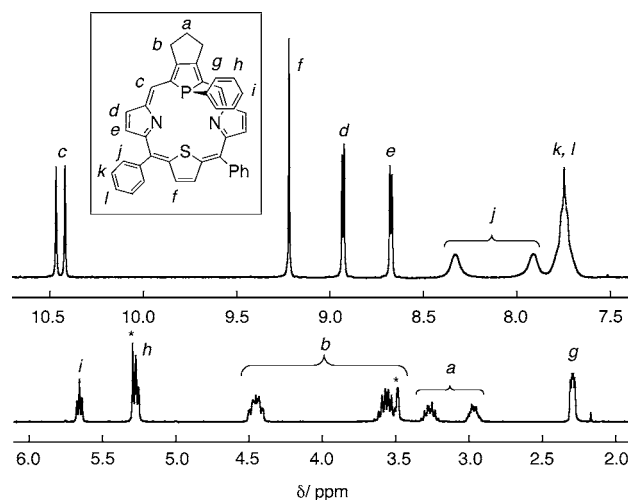


Figure 2. ¹H NMR spectrum of **6** in CDCl_3 at 25 °C. Asterisks (*) indicate the residual solvent peaks.

appearances of these peaks are indicative of a ring current effect derived from the porphyrin π -circuit. The ³¹P peak of **6** (δ 18.6) was also very shielded as compared to that (δ 26.7) of σ^3 -P,N₂,S-calixphyrin **7**¹⁰ and those (δ 32.0–36.0) of 2,5-disubstituted 1-phenylphospholes bearing

the same 3,4-C₃ bridge.^{8,13} Thus, the hybrid porphyrin **6** is likely to possess high aromatic character. It should be noted here that the upfield shift ($\Delta\delta/\text{ppm}$) of the *P*-phenyl protons of **6** relative to the corresponding protons of **7** increases in the order *para* (1.61) < *meta* (2.01) < *ortho* (5.27). This implies that the *P*-phenyl group in **6** stands above the porphyrin π -plane like the *N*-methyl group in *N*-methylporphyrins.¹⁴ As a consequence, the *ortho* protons of the *meso*-phenyl groups, which would be oriented at a slant against the porphyrin plane, were differentiated at 25 °C.¹⁵ In the UV–vis absorption spectrum of **6** in CH₂Cl₂, the Soret band appeared at λ_{max} 440 nm (Figure 3a), which was red-

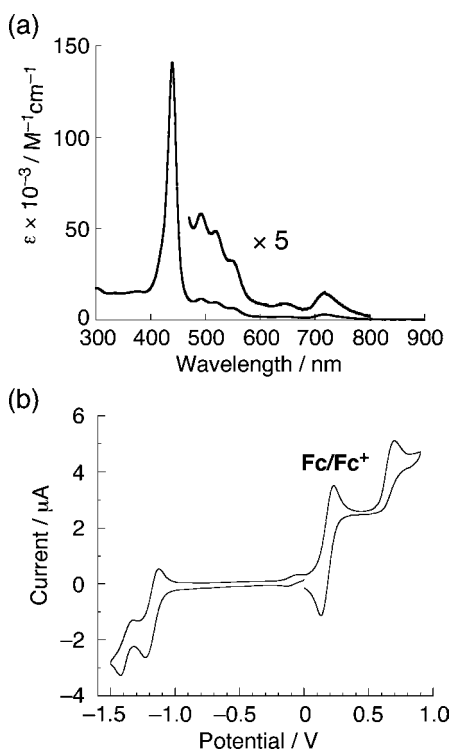


Figure 3. (a) UV–vis absorption spectra of **6** in CH₂Cl₂. (b) Cyclic voltammogram of **6**; 0.1 M *n*Bu₄NPF₆, Ag⁺/Ag (0.01 M AgNO₃). Scan rate 20 mV s⁻¹.

shifted as compared to those of 5,10,15,20-tetraphenylporphyrin (TPP) **8a** (λ_{max} 411 nm) and 21-thia-5,10,15,20-tetraphenylporphyrin **9a** (λ_{max} 425 nm). The Q-type transitions of **6** were also observed at longer wavelengths, λ_{max} 492, 518, 547, 647, and 718 nm. In contrast to **8a**, σ^3 -P,N₂,S-hybrid **6** was not fluorescent.

All attempts to grow single crystals of **6** suitable for X-ray diffraction analysis were unsuccessful. Thus, we carried out

(13) Hay, C.; Hissler, M.; Fischmeister, C.; Rault-Berthelot, J.; Toupet, L.; Nyulász, L.; Réau, R. *Chem. Eur. J.* **2001**, *7*, 4222.

(14) It is known that the *N*-methyl protons in *N*-methylporphyrins are significantly shielded as a result of the ring current effect. For example, see: (a) Lavallee, D. K.; Gebala, A. E. *Inorg. Chem.* **1974**, *13*, 2004. (b) Lavallee, D. K.; Anderson, O. P. *J. Am. Chem. Soc.* **1982**, *104*, 4707.

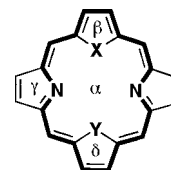
(15) These *ortho* protons (indicated as *j* in Figure 2) coalesced at 60 °C in Cl₂CDCDCl₂.

DFT calculations to reveal the optimized structures of σ^3 -P,N₂,S-hybrid **10**, parent porphyrin **8b**, and 21-thiaporphyrin **9b** as models for **6**, **8a**, and **9a**, respectively.¹⁶ As shown in Figure S5 in Supporting Information, the porphyrin planes of **8b** and **9b** are completely planar, whereas that of **10** is nonplanar. Thus, replacement of the NH unit of thiaporphyrin with the PPh unit (from **9b** to **10**) induces a distortion of the porphyrin plane, where all the heterole subunits are slightly tilted to make a dish-like macrocyclic platform. Such a deviation is presumably caused by electrostatic repulsion between the phosphorus and sulfur atoms in **10**.¹⁷

The phosphorus center in **10** adopts a trigonal pyramidal geometry ($\Sigma_{\text{C-P-C}} = 299.5^\circ$), which prevents effective interaction between the phosphorus lone pair and the porphyrin 18 π -circuit. Similar geometries at the phosphorus center ($\Sigma_{\text{C-P-X}} = 292.4\text{--}296.1^\circ$; X = C, H) were reported for the 21-phospha- and 21,23-diphosphaporphyrins bearing P–H bonds,⁶ suggesting that the phosphorus lone pair in σ^3 -P-containing porphyrins essentially has an s character irrespective of the P substituents. The geometry of the *P*-phenyl group in **10** explains the ¹H NMR observation for **6** as well.

With the optimized structures in hand, we evaluated the aromaticity of **10** by comparing it with those of **8b** and **9b**. Despite the nonplanarity, the P,N₂,S-hybrid **10** keeps high aromaticity in terms of a geometric criterion. The mean HOMA¹⁸ values for all 28 bonds of the porphyrin ring of **8b**, **9b**, and **10** were calculated to be 0.680, 0.645, and 0.550, respectively (Table 1). The rather low value of **10** as

Table 1. HOMA and NICS Values for Model Compounds



porphyrin (X, Y)	8b (NH, NH)	9b (NH, S)	10 (PPh, S)
HOMA			
total ^a	0.680	0.645	0.550
18 π ^b	0.853	0.887	0.879
NICS (ppm)			
α	-16.5	-16.2	-15.6
β	-15.3	-15.9	-16.7
γ	-4.49	-2.54	-1.96
δ		-19.0	-19.8

^a Calculated using all 28 bonds of the porphyrin ring. ^b Calculated using 18 bonds of the [18]annulene circuit.

compared to those of **8b** and **9b** may be ascribed to distortion of the phosphole subunit.¹⁹ On the other hand, the HOMA values for the 18 π -circuit (18 bonds consisting of C and N atoms) of **8b**, **9b**, and **10** are 0.853, 0.877, and 0.879, respectively, implying high aromaticity of **10** as a bridged annulene derivative. To evaluate the degree of aromaticity

of **10** on the basis of a magnetic criterion, we also calculated NICS²⁰ values at the porphyrin ring and heterole ring centers (Table 1). The NICS values at the center of the core atoms of **8b**, **9b**, and **10** are -16.5 , -16.2 , and -15.6 ppm, respectively,²¹ indicating that the aromaticity of the P,N₂,S-hybrid **10** is slightly weaker than those of **8b** and **9b**. Interestingly, the NICS value at the phosphole ring center (β) in **10** (-16.7 ppm) is much higher than that of the parent 1-phenylphosphole (-4.31 ppm).²² This reflects that the cyclic 1,3-diene unit of the phosphole ring is included in an 18π -electron system. Namely, the considerable ring current effect derived from the 18π -circuit was detected at the β position. By contrast, the NICS value at the γ position in **10** (-1.96 ppm) is much lower than the respective value of pyrrole, reflecting the strong 2-azafulvene character of the N-heterole rings.

(16) The structures were optimized by the DFT method at the level of B3LYP/6-311G(d,p). In the optimized structure of **10**, the P-phenyl ring is vertical to the P-S axis. However, the difference in energy between the optimized structure and the structure in which the P-phenyl ring is rotated by 90° (i.e., the P-phenyl ring is parallel to the P-S axis) is very small (1.87 kcal mol⁻¹). Thus, the binding for the P-phenyl ring rotation is considered to be very weak.

(17) It has been reported that substitution of an NH unit of **8b** by a PH unit does not distort the carbon skeleton of the porphyrin ring. See ref 6.

(18) HOMA: Harmonic Oscillator Model of Aromaticity. (a) Kruszewski, J.; Krygowski, T. M. *Tetrahedron Lett.* **1972**, 3839. (b) Krygowski, T. M. *J. Chem. Inf. Comput. Sci.* **1993**, *33*, 70. (c) Krygowski, T. M.; Ciesielski, A.; Bird, C. W.; Kotschy, A. *J. Chem. Inf. Comput. Sci.* **1995**, *35*, 203. (d) Cyrański, M. K.; Krygowski, T. M.; Wisiorowski, M.; van Eikema Hommes, N. J. R.; Schleyer, P. von R. *Angew. Chem., Int. Ed.* **1998**, *37*, 177. In this paper, the HOMA value of **8b** was reported to be 0.666 at the level of B3LYP/6-31G(d).

(19) In the phosphole ring of **10**, the phosphorus atom is slightly deviated from the 1,3-diene unit with a dihedral angle of 2.4° .

(20) NICS: Nuclear Independent Chemical Shift. The NICS values were calculated at the level of GIAO-RHF/6-31+G(d) at the optimized geometries. For details, see Supporting Information.

(21) For the NICS values of porphyrins, see ref 18d. See, also: Furuta, H.; Maeda, H.; Osuka, A. *J. Org. Chem.* **2001**, *66*, 8563.

(22) At the same level of calculations, the NICS values of pyrrole, thiophene, and 1-phenylphosphole were determined as -15.0 , -13.2 , and -4.31 , respectively. For the reported NICS values of these heteroles, see: (a) Dransfeld, A.; Nyulaszi, L.; Schleyer, P. von R. *Inorg. Chem.* **1998**, *37*, 4413. (b) Delaere, D.; Dransfeld, A.; Nguyen, M. T.; Vanquickenborne, L. G. *J. Org. Chem.* **2000**, *65*, 2631. (c) Cyrański, M. K.; Krygowski, T. M.; Katritzky, A. R.; Schleyer, P. von R. *J. Org. Chem.* **2002**, *67*, 1333.

To gain insight into the HOMO and LUMO energies of the P,N₂,S-hybrid porphyrin **6**, redox potentials were measured by cyclic voltammetry (CV) and/or differential pulse voltammetry (DPV). As shown in Figure 3b, the electrochemical oxidation process of **6** is irreversible, and the first oxidation potential of **6** was determined by the DPV measurement to be $+0.45$ V (vs Fc/Fc⁺),²³ which is more cathodic than the reported values for **8a** ($E_{1/2} +0.58$ V) and **9a** ($E_{1/2} +0.62$ V). On the other hand, electrochemical reduction of **6** occurred quasireversibly, and the first and second reduction potentials ($E_{1/2}$) were determined as -1.36 and -1.56 V (vs Fc/Fc⁺), respectively, which are more anodic than those of **8a** (-1.73 and -2.06 V) and **9a** (-1.55 and -1.82 V). These data suggest that modification of the core of the porphyrin from an NH to a PPh unit basically narrows the HOMO-LUMO energy gap.²⁴

In summary, we successfully prepared a phosphorus-containing core-modified porphyrin for the first time. We found that the σ^3 -P,N₂,S-hybrid porphyrin is composed of a bridged [18]annulene π -system and displays high aromaticity in terms of both geometric and magnetic criteria. This class of compounds is expected to behave as macrocyclic, multi-dentate phosphorus ligands with characteristic optical properties. In this context, the coordination chemistry of phosphorus-containing porphyrins is worthy of further study.

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Supporting Information Available: Experimental details, ¹H NMR spectra, and DFT computational results. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(23) The second oxidation potential of **6** was determined to be 0.97 V (vs Fc/Fc⁺) by the DPV measurement.

(24) The HOMO-LUMO energy gaps (eV) of **8b**, **9b**, and **10** were computed by the DFT method to be 2.94, 2.83, and 2.59, respectively.