DOI: 10.1002/ange.201408307

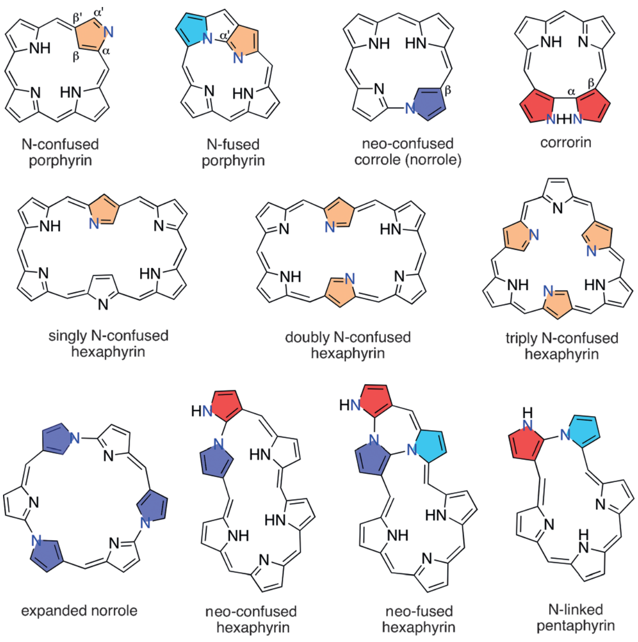
Porphyrinoids

Neo-Fused Hexaphyrin: A Molecular Puzzle Containing an N-Linked Pentaphyrin**

Pingchun Wei, Kai Zhang, Xin Li, Deying Meng, Hans Ågren, Zhongping Ou, Seikweng Ng, Hiroyuki Furuta, and Yongshu Xie**

Abstract: *The first neo-confused hexaphyrin(1.1.1.1.1.0) was synthesized by oxidative ring closure of a hexapyrrane bearing two terminal "confused" pyrroles. The new compound displays a folded conformation with a short interpyrrolic C⋯N distance of 3.102 Å, and thus it readily underwent ring fusion to afford a neo-fused hexaphyrin with an unprecedented 5,5,5,7-tetracyclic ring structure. Furthermore, coordination of* Cu^{II} *triggered a ring opening/contracting reaction to afford a* Cu^{II} *complex of an N-linked pentaphyrin derivative. The roles of reactive N−C bonds in the porphyrinoid macrocycles were demonstrated.*

In recent years, porphyrin analogues have received increasing interest due to their rich structural diversity, properties, and functions that cannot be realized by regular porphyrins.[1] Expanding the macrocycle size is an important approach for developing novel porphyrin analogues. For example, hexaphyrins are one of the representative expanded porphyrins, which have demonstrated various conformations due to the large flexible skeletons.[2] Another important approach is changing the linking modes between the pyrrole units. In this respect, by incorporation of "mislinked" pyrrole rings, in what we call the "confusion approach",[3] a variety of novel porphyrin analogues have been developed with unique properties.[4–10] Typical examples include N-confused porphyrin,[4] N-fused porphyrin,[5] corrorin,[6] neo-confused corrole (norrole),[8] neo-confused porphyrin,[9] and expanded norrole (Scheme 1).[10] In these compounds, the confused pyrrole units are linked in the α,β′-mode (confused*)* or N,β-mode (*n*eo-confused). By applying the confusion approach to hexaphyrins, we have synthesized singly, doubly, and triply N-confused hexaphyrins with rectanglular and triangular conformations, respectively.[2f,11]



Scheme 1. Structures of N-confused porphyrin and related porphyrin analogues.

Recently, we reported that the pentaphyrin (**P₅**) with two confused pyrroles at both ends exhibited a unique ring closure reaction and subsequent ring contraction/expansion reactions with neo-confused linkage.[12] The unexpected transformation of the confused oligopyrroles as well as the unique structures of the macrocycles tempted us to explore the reactions for a series of related oligomers. Herein we report a hexapyrrane (**P₆**) with two terminal N-confused pyrroles, which underwent an oxidative ring closure reaction to yield an unprecedented neo-confused hexaphyrin (**1**) with two confused pyrroles directly linked, and further oxidation induced an intramolec-

---

[*] P. C. Wei, K. Zhang, D. Y. Meng, Prof. Dr. Y. S. Xie
Key Laboratory for Advanced Materials and Institute of Fine Chemicals, East China University of Science & Technology
Shanghai 200237 (P. R. China)
E-mail: yshxie@ecust.edu.cn

Prof. Dr. H. Furuta
Center for Molecular Systems, Department of Chemistry and Biochemistry, Graduate School of Engineering
Kyushu University, Fukuoka 819-0395 (Japan)
E-mail: hfuruta@cstf.kyushu-u.ac.jp

Dr. X. Li, Prof. Dr. H. Ågren
Department of Theoretical Chemistry and Biology
School of Biotechnology
KTH Royal Institute of Technology, SE-10691 Stockholm (Sweden)

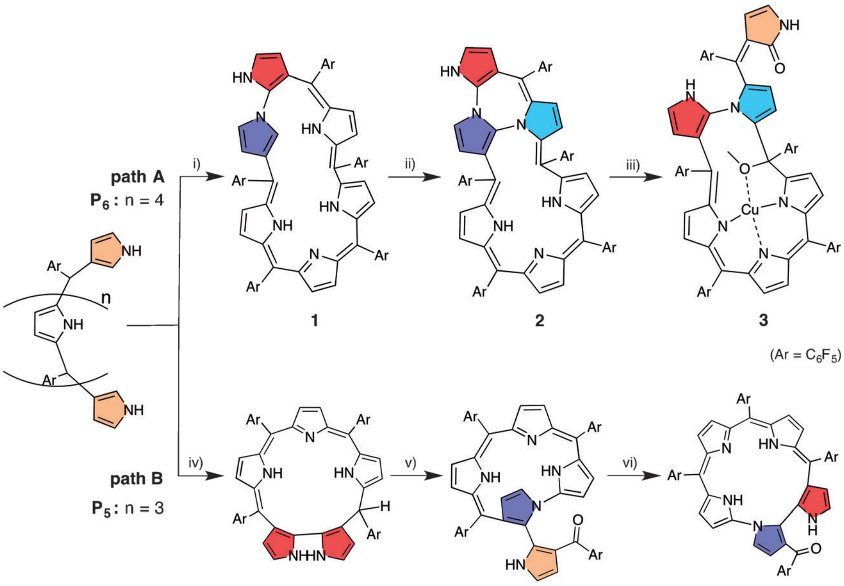
Prof. Dr. Z. P. Ou
School of Chemistry & Chemical Engineering
Jiangsu University, Zhenjiang 212013 (P. R. China)

Prof. Dr. S. W. Ng
Department of Chemistry, University of Malaya, Kuala Lumpur and Chemistry Department, King Abdulaziz University (Saudi Arabia)

[**] This work was supported by NSFC/China (21472047, 91227201), National Basic Research 973 Program (2013CB733700), the Science Fund for Creative Research Groups (21421004), the Oriental Scholarship, NCET-11-0638, the Fundamental Research Funds for the Central Universities (WK1013002), JSPS Grant-in-Aid for Scientific Research (25248039), and the University of Malaya (UM.C/625/1/HIR/247).

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.201408307.

ular ring fusion reaction to afford a neo-fused hexaphyrin (**2**) containing a 5,5,5,7-tetracyclic ring in the skeleton. Furthermore, the coordination of **2** with Cu^{II} afforded a complex (**3**) with an N-linked pentaphyrin framework appending a pyrrolyl moiety. In brief, the oxidative ring closure reaction of $\mathbf{P_6}$ afforded a neo-confused hexaphyrin (**1**), which was eventually transformed to an N-linked pentaphyrin (**3**) through the formation and cleavage of reactive C–N bonds.



Scheme 2. Reactions of oligopyrroles $\mathbf{P_6}$ (path A) and $\mathbf{P_5}$ (path B).[12] i) DDQ, CH_2Cl_2, 14%; ii) DDQ, CH_2Cl_2, 87%; iii) $Cu(OAc)_2{\cdot}H_2O$, MeOH, air, 6%; iv) DDQ, CH_2Cl_2, 70%; v) Et_3N, CH_3CN, air, 90%; vi) DDQ, CH_2Cl_2, 20%.

Details of the syntheses are outlined in Scheme 2 (path A). For comparison, the reactions observed with pentapyrrane $\mathbf{P_5}$ are also shown (path B).[12] The key precursor, the doubly terminal-confused hexapyrrane ($\mathbf{P_6}$), was synthesized by the acid condensation of bilane with *N*-triisopropylsilyl β-pyrrole carbinol, followed by deprotection with Bu_4NF.[13] Then $\mathbf{P_6}$ was oxidized with 4 equiv of 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ). In contrast to the ring closure at both the α-positions of the confused pyrroles observed with $\mathbf{P_5}$,[12] the cyclization proceeded with a β,*N*-α,β linking mode, affording neo-confused hexaphyrin (**1**) and neo-fused hexaphyrin (**2**) in yields of 14% and 2%, respectively. The ratio of **1** and **2** is highly dependent on the amount of DDQ used. When 5.5 equiv of DDQ was applied, **2** was obtained as the main product with a yield of 12%, and almost no **1** was obtained, indicating that **1** was further oxidized to afford **2**. Supporting this, the oxidation of **1** with equimolar DDQ afforded **2** in a yield of 87%.

The ^1H NMR spectrum of **1** in $CDCl_3$ exhibits four NH peaks and 13 CH signals (Figure S11), and the number of pyrrolic CH signals is one less than that of the hexapyrrane, indicative of macrocycle formation through the generation of a C–N bond, which is consistent with the crystal structure (vide infra). Two inner NH groups ($\delta = 12.30$ and 10.70 ppm) may be involved in intramolecular hydrogen bonds. The signal of an outer NH group ($\delta = 8.32$ ppm) is highly dependent on the solvent (Figure 1), which may be ascribed to the formation of an intermolecular hydrogen bond. Another NH signal at a relatively high field of $\delta = 6.40$ ppm is slightly dependent on the solvent, which indicates the difficulty in forming either intramolecular or intermolecular hydrogen bonds. Upon further oxidation to **2**, the number of NH and CH signals was each reduced by 1 (Figures S4 and S12), indicating the formation of an additional C–N bond, which is consistent with the ring fusion structure of **2** (vide infra).

The best evidence for the formation of C–N bonds in the macrocyclic structures of **1** and **2** came from the crystal structures[14] (Figure 2). Interestingly, the bipyrrole rings in **1** are directly linked in a unique β,*N*-*α*,β mode, which bears similarity to the bonding mode in neo-confused corrole (norrole)[8] and corrorin,[6] and thus **1** is named neo-confused hexaphyrin(1.1.1.1.1.0).

The internal ring pathway of **1** contains a minimum of 22 atoms, and the molecule contains one imino and five amino N atoms, whose positions were assigned based on the bond lengths and C-N-C bond angles (Figure S13). The highly distorted molecule contains six interconnected pyrrole units A–F, with successive interplane angles of 18.8°, 24.7°, 19.0°, 47.9°, 39.9, and 46.5°, respectively. Finally, **1** exhibits a figure-eight-type, V-shaped folded conformation (Figure 2b). Within the macrocycle, N3 is intramolecularly hydrogen-bonded to H2 and H4 with N3···N2 and N3···N4 distances of 2.727(4) and 2.654(4) Å, respectively. The N6–H moiety points out of the macrocycle and may be involved in intermolecular hydrogen bonds. In contrast, N5–H is hidden in the folded macrocycle, which hampers the formation of either inter- or

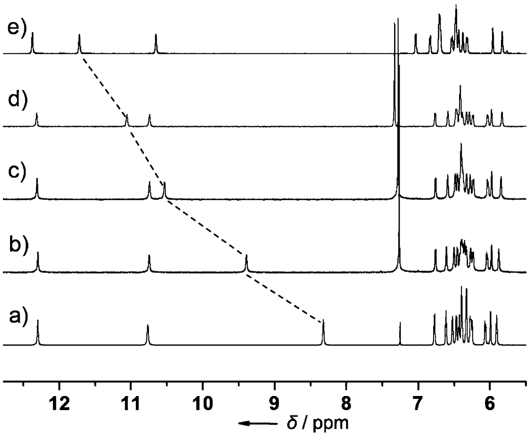


Figure 1. 400 MHz ^1H NMR spectra of **1** in different solvents: a) 0.5 mL $CDCl_3$, b)–d) 0.5 mL $CDCl_3$ + 1, 5, 20 μL $[D_6]DMSO$, e) 0.5 mL $[D_6]DMSO$.

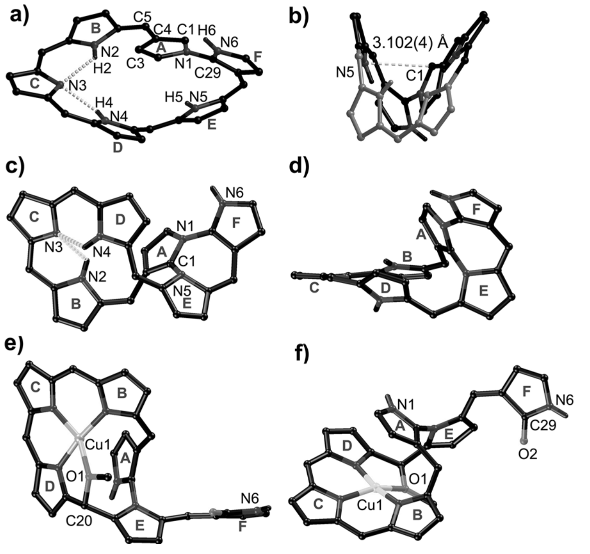


Figure 2. Complementary views of the molecular structures of **1** (a, b), **2** (c, d), and **3** (e, f). C_6F_5 and hydrogen atoms attached to carbons are omitted for clarity.

intramolecular hydrogen bonds. These observations perfectly agree with the ^{1}H NMR results (vide supra). It is noteworthy that the folded conformation results in a rather short distance of 3.102(4) Å between C1 of ring A and N5 of ring E, which may facilitate the formation of a covalent bond between them. This inference was indeed confirmed in the crystal structure of **2** (vide infra).

Hexaphyrin **2** was obtained by further oxidation of **1** with DDQ. Interestingly, in the crystal structure of **2** (Figure 2 c,d), the formation of a new C−N bond was observed between the N5 atom of ring E and the C1 atom of ring A as expected. Thus, an additional seven-membered C_5N_2 ring was generated and two new interpyrrolic C−N bonds were formed in the oxidative ring fusion reaction. In fact, ring fusion reactions between two pyrrolic rings in N-confused porphyrinoids have been commonly observed and the formed N-fused porphyrinoids involve a 5,5,5-tricyclic structure.[5,7,8b] In contrast, **2** exhibits an unprecedented 5,5,5,7-tetracyclic structure involving a seven-membered ring with the pyrroles E, A, and F linked in an unprecedented α,*N*-α,*N*-α,β mode. Thus, **2** may be named neo-fused hexaphyrin(1.1.1.1.1.0). Similar to **1**, **2** also exhibits a folded conformation and the seven-membered ring adopts a boat conformation with the A/E, E/F, and F/A interplane angles of 61.5°, 35.5°, and 39.6°, respectively.

Considering the macrocyclic structures of **1** and **2** with inner NH and CH moieties available for metal coordination, we continued to check their metal coordination behavior. The addition of zinc acetate to solutions of **1** and **2** did not induce any obvious reactions. However, the color of a solution of **2** in methanol gradually changed from brown to light yellow upon addition of $Cu(OAc)_2$ under aerobic condition (Scheme 2).[14] Thus, **3** was isolated as a dark yellow solid in about 6% yield. The low yield was mainly due to decomposition during the purification on a silica gel column. The ^{1}H NMR spectrum of **3** showed only weak unresolved signals, indicative of the coordination of a paramagnetic Cu^{II} ion. The mass spectrum showed a molecular ion peak at 1392, roughly corresponding to the adduct of **2**, Cu, and a methoxy moiety, which is consistent with the crystal structure.

The crystal structure of **3**[15] revealed that the seven-membered ring in **2** has been opened through the cleavage of the N1−C29 bond between rings A and F (Scheme 2 and Figure 2 e,f). Accompanying the interpyrrolic bond cleavage, an O atom was attached to the α-position of ring F with the C29−O2 distance of 1.234(9) Å, indicative of a C=O bond. Interestingly, a methoxy group was attached to one of the *meso*-carbon atoms with the C20−O1 bond length of 1.464(9) Å, typical for a C−O single bond, which may be formed by the addition of a methanol solvent molecule. Thus, C20 exists as an sp^3-hybridized carbon center, which interrupts the conjugation of the macrocycle. The dicationic Cu1 atom is coordinated to three N atoms in the roughly planar tripyrrin moiety formed by rings B, C, and D. In addition, Cu1 is further coordinated to the methoxy O1 atom with an Cu−O bond length of 2.142(5) Å, thus affording a distorted tetrahedral coordination environment. The macrocycle also adopts a folded conformation, with ring A stacked over the tripyrrin moiety formed by rings B, C, and D. Finally ring E links these two parts with the D/E and A/E interplane angles of 80.6° and 82.2°, respectively.

As described above, the coordination of **2** with Cu^{II} led to oxidative cleavage with concomitant formation of C=O and C−O bonds. Similar oxidative cleavage reactions have been reported for porphyrins and porphyrinoids to afford linear oligopyrroles.[16] The generation of **3** is unique in that successive ring fusion and regioselective oxidative cleavage reactions of a porphyrinoid result in a macrocycle having a different size[17] and connection mode. The details of the reaction mechanism are unclear yet. However, it is likely that coordination of Cu^{II} triggers the dioxygen attack at the C_α−N bond, followed by the addition of methanol at the *meso*-position (Scheme S1).

The electrochemical properties of compounds **1**–**3** were examined in CH_2Cl_2 containing 0.1 M tetra-*n*-butylammonium perchlorate and the cyclic voltammograms are illustrated in Figure S15. Porphyrinoids **1**–**3** are robust against electrochemical oxidation and reduction, exhibiting two reversible one-electron oxidations and one reversible one-electron reduction. The measured half-wave potentials ($E_{1/2}$) for the first oxidation are 0.53 V for **1**, 0.62 V for **2**, and 0.58 V for **3**, while the $E_{1/2}$ values for the first reduction of these compounds are −0.98, −1.00, and −0.88 V, respectively. Thus, the HOMO–LUMO gaps were estimated to be 1.51, 1.62, and 1.46 eV for **1**–**3** under the given experimental conditions.

The absorption spectra of **1**–**3** exhibit broad Soret-like and Q-like bands in the ranges of 397–441 and 721–786 nm, respectively (Figure 3 a; Figure S16). Both **1** and **2** display emission around 900 nm with quantum yields (Φ_F) of 0.06% and 0.3%, respectively (Figure 3 b).[18] The higher latter value may be ascribed to the better rigidity of **2** due to the presence of an additional seven-membered ring. The emission wavelengths are shorter than those observed for reported regular and confused hexaphyrins,[2a,f,11b,19] which may be explained

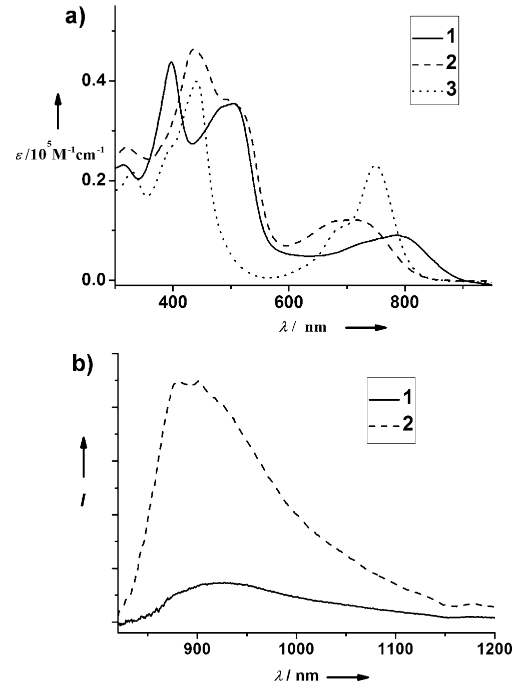


Figure 3. a) Absorption spectra of **1**–**3** and b) emission spectra of **1** and **2** in CH_2Cl_2.

by the poorer conjugation owing to the nonplanar folded conformations.

Density functional theory (DFT) calculations were carried out for compounds **1**–**3** using the Gaussian 09 program package (Figures S17–S21).[20] The HOMO–LUMO gaps of **1**–**3** were calculated to be 1.90, 2.00, and 1.76 eV (Figure S17),[21] respectively, which is in good agreement with the electrochemical data. Time-dependent (TD) DFT calculations were employed to understand the optical features of **1** and **2**, which gave the expected wavelengths (Figure S21). Compared to the MO energy levels of **1**, the HOMO of **2** is slightly stabilized, which may be ascribed to the newly formed C−N bond. Thus, a larger HOMO–LUMO gap was observed, leading to blue shift of the lowest energy absorption band. Accordingly, the lowest energy bands of **1** and **2** are centered at 786 and 712 nm, respectively. The open-shell electronic structure associated with the Cu^{II} ion in **3** results in a smaller HOMO–LUMO gap relative to those of **1** and **2**. The TD-DFT calculations for compound **3** indicate that the absorption band at 749 nm arises from a combination of electronic transitions mainly among the α-spin orbitals, where in particular the SOMO(α)→LUMO+2(α) transition contributes a large fraction (Figure S20).

In summary, we have synthesized three novel hexapyrrolic porphyrinoids **1**–**3**. A unique β,*N*-α,β bonding mode between the two confused pyrroles and a folded conformation were observed for **1** with a short interpyrrolic C⋅⋅⋅N distance of 3.102(4) Å, and thus it readily underwent further ring fusion to afford the neo-fused hexaphyrin **2** with an unprecedented 5,5,5,7-tetracyclic structure. Furthermore, the coordination of Cu^{II} triggered a ring-opening reaction to afford **3**, which contains an N-linked pentaphyrin framework. Both **1** and **2** exhibit fluorescence emission around 900 nm, and thus they may find applications as near-infrared luminescent dyes. In conclusion, by the confusion approach, directly linked confused pyrrole rings in hexaphyrins result in folded structures and unique reactivity to afford novel macrocycles with interesting properties.

Received: August 15, 2014

Keywords: fused-ring systems · hexaphyrins · macrocycles · pentaphyrins · porphyrinoids

---

[1] a) M. Stępień, N. Sprutta, L. Latos-Grażyński, *Angew. Chem. Int. Ed.* **2011**, *50*, 4288–4340; *Angew. Chem.* **2011**, *123*, 4376–4430; b) S. Saito, A. Osuka, *Angew. Chem. Int. Ed.* **2011**, *50*, 4342–4373; *Angew. Chem.* **2011**, *123*, 4432–4464.

[2] a) M. G. P. M. S. Neves, R. M. Martins, A. C. Tome, A. J. D. Silvestre, A. M. S. Silva, V. Felix, J. A. S. Cavaleiro, M. G. B. Drew, *Chem. Commun.* **1999**, 385–386; b) J.-Y. Shin, H. Furuta, K. Yoza, S. Igarashi, A. Osuka, *J. Am. Chem. Soc.* **2001**, *123*, 7190–7191; c) M. Suzuki, A. Osuka, *Org. Lett.* **2003**, *5*, 3943–3946; d) S. Shimizu, J. Y. Shin, H. Furuta, *Angew. Chem. Int. Ed.* **2003**, *42*, 78–82; *Angew. Chem.* **2003**, *115*, 82–86; e) M. Suzuki, A. Osuka, *Chem. Eur. J.* **2007**, *13*, 196–202; f) Y. S. Xie, K. Yamaguchi, M. Toganoh, H. Uno, M. Suzuki, S. Mori, S. Saito, A. Osuka, H. Furuta, *Angew. Chem. Int. Ed.* **2009**, *48*, 5496–5499; *Angew. Chem.* **2009**, *121*, 5604–5607.

[3] a) H. Furuta, H. Maeda, A. Osuka, *Chem. Commun.* **2002**, 1795–1804; b) A. Srinivasan, H. Furuta, *Acc. Chem. Res.* **2005**, *38*, 10–20.

[4] a) H. Furuta, T. Ogawa, T. Asano, *J. Am. Chem. Soc.* **1994**, *116*, 767–768; b) P. J. Chmielewski, L. Latos-Grażyński, K. Rachlewicz, T. Głowiak, *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 779–781; *Angew. Chem.* **1994**, *106*, 805–808; c) T. Morimoto, S. Taniguchi, A. Osuka, H. Furuta, *Eur. J. Org. Chem.* **2005**, 3887–3890.

[5] a) H. Furuta, T. Ishizuka, A. Osuka, *J. Am. Chem. Soc.* **2000**, *122*, 5748–5757; b) M. Toganoh, T. Kimura, H. Uno, H. Furuta, *Angew. Chem. Int. Ed.* **2008**, *47*, 8913–8916; *Angew. Chem.* **2008**, *120*, 9045–9048; c) M. Toganoh, A. Sato, H. Furuta, M. Toganoh, A. Sato, H. Furuta, *Angew. Chem. Int. Ed.* **2011**, *50*, 2752–2755; *Angew. Chem.* **2011**, *123*, 2804–2807.

[6] a) H. Furuta, H. Maeda, A. Osuka, *J. Am. Chem. Soc.* **2001**, *123*, 6435–6436; b) M. Toganoh, S. Gokulnath, Y. Kawabe, H. Furuta, *Chem. Eur. J.* **2012**, *18*, 4380–4391.

[7] a) I. Gupta, A. Srinivasan, T. Morimoto, M. Toganoh, H. Furuta, *Angew. Chem. Int. Ed.* **2008**, *47*, 4563–4567; *Angew. Chem.* **2008**, *120*, 4639–4643; b) A. Srinivasan, T. Ishizuka, H. Furuta, *Angew. Chem. Int. Ed.* **2004**, *43*, 876–879; *Angew. Chem.* **2004**, *116*, 894–897.

[8] a) K. Fujino, Y. Hirata, Y. Kawabe, T. Morimoto, A. Srinivasan, M. Toganoh, Y. Miseki, A. Kudo, H. Furuta, *Angew. Chem. Int. Ed.* **2011**, *50*, 6855–6859; *Angew. Chem.* **2011**, *123*, 6987–6991; b) M. Toganoh, Y. Kawabe, H. Furuta, *J. Org. Chem.* **2011**, *76*, 7618–7622.

[9] a) T. D. Lash, A. D. Lammer, G. M. Ferrence, *Angew. Chem. Int. Ed.* **2011**, *50*, 9718–9721; *Angew. Chem.* **2011**, *123*, 9892–9895; b) R. Li, G. M. Ferrence, T. D. Lash, *Chem. Commun.* **2013**, *49*, 7537–7539; c) R. Li, A. D. Lammer, G. M. Ferrence, T. D. Lash, *J. Org. Chem.* **2014**, *79*, 4078–4093.

[10] S. C. Gadekar, B. K. Reddy, V. G. Anand, *Angew. Chem. Int. Ed.* **2013**, *52*, 7164–7167; *Angew. Chem.* **2013**, *125*, 7305–7308.

[11] a) S. Gokulnath, K. Yamaguchi, M. Toganoh, S. Mori, H. Uno, H. Furuta, *Angew. Chem. Int. Ed.* **2011**, *50*, 2302–2306; *Angew.*

Chem. **2011**, *123*, 2350 – 2354; b) A. Srinivasan, T. Ishizuka, A. Osuka, H. Furuta, *J. Am. Chem. Soc.* **2003**, *125*, 878 – 879.

[12] Y. S. Xie, P. C. Wei, X. Li, T. Hong, K. Zhang, H. Furuta, *J. Am. Chem. Soc.* **2013**, *135*, 19119 – 19122.

[13] Synthetic details are shown in Supporting Information.

[14] When the reaction was performed under air or using THF instead of MeOH, only complicated and unidentified mixtures were obtained.

[15] CCDC 1013756 (**1**), 1013757 (**2**), 1013757 (**3**) contain 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..

[16] a) H. Furuta, H. Maeda, A. Osuka, *Org. Lett.* **2002**, *4*, 181 – 184; b) S. Saito, K. Furukawa, A. Osuka, *J. Am. Chem. Soc.* **2010**, *132*, 2128 – 2129.

[17] R. Paolesse, S. Licoccia, G. Bandoli, A. Dolmella, T. Boschi, *Inorg. Chem.* **1994**, *33*, 1171 – 1176.

[18] Related to Zn-N_2C-hexaphyrin. J. H. Kwon, T. H. Ahn, M. C. Yoon, D. Y. Kim, M. Y. Koh, D. Kim, H. Furuta, M. Suzuki, A. Osuka, *J. Phys. Chem. B* **2006**, *110*, 11683 – 11690.

[19] a) X. J. Zhu, S. T. Fu, W. K. Wong, J. P. Guo, W. Y. Wong, *Angew. Chem. Int. Ed.* **2006**, *45*, 3150 – 3154; *Angew. Chem.* **2006**, *118*, 3222 – 3226.

[20] All the calculations were achieved with Gaussian09 program package at the B3LYP/6-31G* level. See Supporting Information for calculation details.

[21] Since compound **3** has an unpaired electron, its HOMO is defined as the highest occupied molecular orbital with α-spin, or the so-called SOMO (singly occupied molecular orbital).