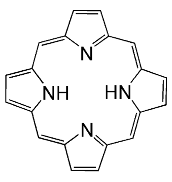
Porphyrin Derivatives

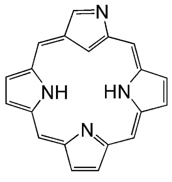
Doubly N-Confused Pentaphyrins

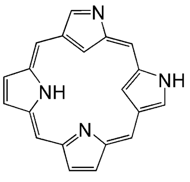
*Alagar Srinivasan, Tomoya Ishizuka, Hiromitsu Maeda, and Hiroyuki Furuta**

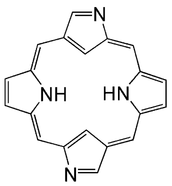
In recent years, research on porphyrin analogues has received increased attention in regard to their structural diversity as well as their functionality.[1] Among such porphyrinoids, N-confused porphyrin (**NCP**), a porphyrin isomer that contains a confused pyrrole ring connected through its α,β′-positions in the macrocycle, exhibits unusual physical and chemical properties which greatly differ from those of normal porphyrins.[2] The further confused isomer, doubly N-confused porphyrin (**N_2CP**, *cis* and *trans*), also displays unusual coordination chemistry and properties, such as stabilization of unusual oxidation states of metals, existence of different tautomeric forms, efficient photosensitization of singlet oxygen, and formation of supramolecular hydrogen-bonding networks.[3] Thus, the introduction of one or more confused pyrrole rings in the porphyrin macrocycles, which we call the confusion approach method, would be a useful strategy to explore the hitherto unknown novel porphyrinoids. In fact, we have successfully demonstrated that the doubly N-confused hexaphyrin (**N_2CH**) and its dioxo (**N_2CO_2H**) derivatives preferably bound bismetal ions in the core.[4] Very recently, we also identified N-confused, doubly N-fused pentaphyrins (**NCF_2P_5**), which contain two fused tripentacyclic rings of confused and normal types in the core, during an attempt to synthesize N-confused pentaphyrin.[5] At this point, it was really a question whether introduction of further confusion into such a macrocycle would lead to a doubly N-confused isomer of **$N_2CF_2P_5$** or a further fused one. Interestingly, the doubly N-confused pentaphyrin obtained was not fused, but existed in an oxo-substituted form similar to **N_2CO_2H**.[4] Herein, we report the syntheses and the structural characterization of the doubly N-confused oxopentaphyrin (**N_2COP_5**) and doubly N-confused dioxopentaphyrin (**$N_2CO_2P_5$**). The mono-oxopentaphyrin forms a self-assembled dimer in the solid state through hydrogen-bonding interactions, while the dioxopentaphyrin exists in a monomeric form as a result of intramolecular hydrogen-bonding interactions within the core.

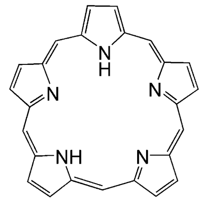
The synthetic method followed here is basically a [3+2] acid-catalyzed condensation, which has already been used for the synthesis of doubly N-fused pentaphyrins (**NCF_2P_5**).[5] Stirring a mixture of a solution of N-confused tripyrrane (**1**)[4,5] and N-confused dipyrromethane dicarbinol (**2**)[6] in the presence of *p*-toluenesulfonic acid (*p*-TSA), followed by oxidation with *p*-chloranil afforded two isomeric, partially oxidized products **3a** and **3b** in yields of 23 and 12%, respectively, together with a trace amount of **4** (Scheme 1a). The FAB mass spectra of both **3a** and **3b** showed a signal for the molecular ion at *m*/*z* 1222, which suggested the presence of the pentaphyrin framework. The ^{1}H NMR spectra of **3a** and **3b** in $CDCl_3$ were similar and the signals appeared between $\delta = 13.00$ and 5.00 ppm. The NH proton of the confused pyrroles (rings A and B) resonated at $\delta = 8.56$ ppm and the α- and β-CH protons resonated at 8.18 and 5.58 ppm, respectively, for **3a**, while those protons appeared at $\delta = 8.62$, 8.17, and 5.75 ppm, respectively, for **3b** (Table 1). In addition, the two *meso*-CH protons were observed as a singlet at $\delta = 5.78$ ppm and a NH proton was observed in a downfield region at $\delta = 12.54$ ppm as a result of the intramolecular hydrogen-bonding interactions. The ^{1}H NMR spectra suggested that **3a** and **3b** were both symmetrical isomers of the pentaphyrin intermediates shown in Scheme 1. Both the compounds were rather unstable and easily oxidized to aromatic **4** in quantitative yield.

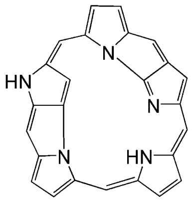

Porphyrin (P)

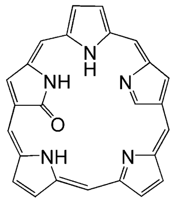

NCP

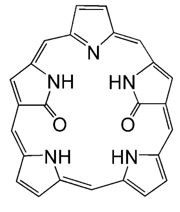

***cis*-N_2CP**

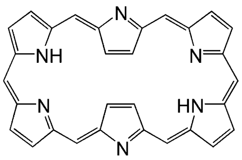

***trans*-N_2CP**

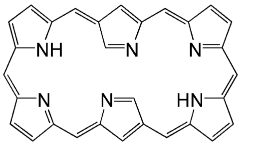

Pentaphyrin (P_5)

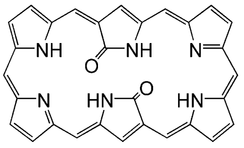

NCF_2P_5


N_2COP_5


$N_2CO_2P_5$


Hexaphyrin (H)


N_2CH


N_2CO_2H

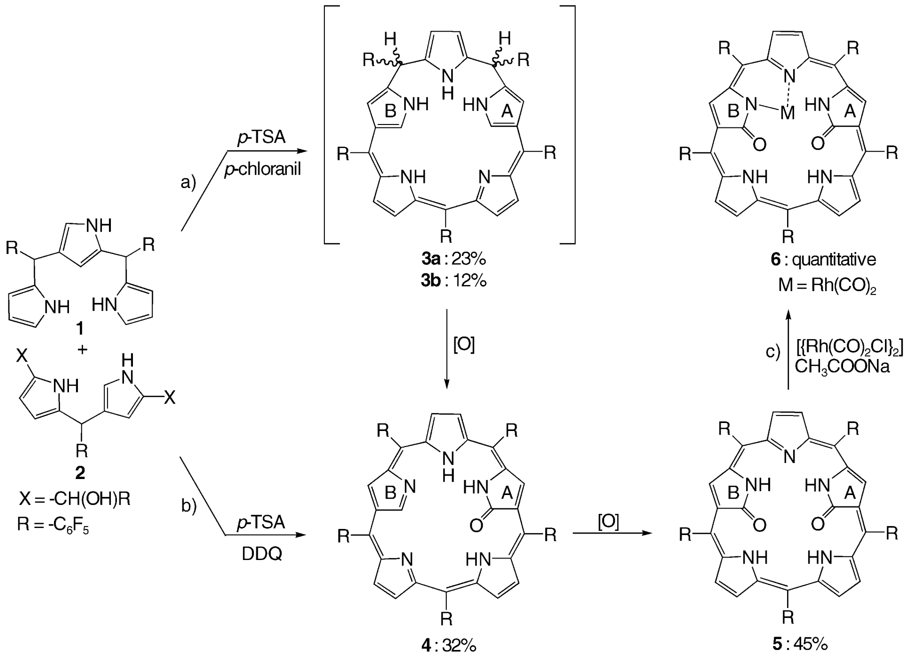
The doubly N-confused oxopentaphyrin (**N_2COP_5**, **4**) was obtained as a greenish solid in 32% yield by changing the

---

[*] Dr. A. Srinivasan, Dr. T. Ishizuka, Dr. H. Maeda, Prof. Dr. H. Furuta
Department of Chemistry and Biochemistry
Graduate School of Engineering
Kyushu University
Fukuoka 812-8581 (Japan)
Fax: (+81) 92-651-5606
E-mail: hfuruta@cstf.kyushu-u.ac.jp
Prof. Dr. H. Furuta
PRESTO, JST

Supporting information for this article is available on the WWW under http://www.angewandte.org or from the author.

DOI: 10.1002/ange.200453732



Scheme 1. Syntheses of doubly N-confused mono- and dioxopentaphyrins (**4**, and **5**) and the Rh^{I} complex (**6**).

Table 1: Selected physical data for **3**–**6**.

3a: m.p. >300 °C (decomp); ^{1}H NMR (CDCl$_3$, 300 MHz): $\delta = 12.54$ (brs, 1H, NH), 8.56 (s, 2H, NH), 8.18 (s, 2H), 7.64 (s, 1H, NH), 6.41 (d, $J = 6$ Hz, 2H), 6.19 (d, $J = 6$ Hz, 2H), 5.82 (d, $J = 3$ Hz, 2H) 5.78 (s, 2H), 5.58 ppm (s, 2H); FABMS: m/z 1222 $[M]^+$; UV/Vis (CH$_2$Cl$_2$): $\lambda_{max} = 349$, 391, 644 nm.

3b: m.p. >300 °C (decomp); ^{1}H NMR (CDCl$_3$, 300 MHz): $\delta = 12.52$ (brs, 1H, NH), 8.62 (s, 2H, NH), 8.17 (s, 2H), 7.46 (s, 1H, NH), 6.41 (d, $J = 6$ Hz, 2H), 6.19 (d, $J = 6$ Hz, 2H), 5.76 ppm (m, 6H); FABMS: m/z 1222 $[M]^+$; UV/Vis (CH$_2$Cl$_2$): $\lambda_{max} = 349$, 390, 492, 643 nm.

4: m.p. >300 °C (decomp); ^{1}H NMR (CDCl$_3$, 300 MHz at −40 °C): $\delta = 9.19$ (s, 1H), 8.78 (s, 1H), 8.38 (d, $J = 6$ Hz, 1H), 8.31 (d, $J = 6$ Hz, 1H), 8.17 (m, 3H), 7.99 (d, $J = 3$ Hz, 1H), 3.65 (s, 1H, NH), 2.44 (s, 1H), 1.42 (s, 1H, NH), 1.10 ppm (s, 1H, NH); FABMS: m/z 1232 $[M]^+$; UV/Vis (CH$_2$Cl$_2$): λ_{max} (ε [mol^{-1}dm^{3}cm^{-1}]) = 388 (31000), 544 (81000), 676 (9600), 723 (6600), 861 nm (2600).

5: m.p. >300 °C (decomp); ^{1}H NMR (CDCl$_3$, 300 MHz at −40 °C): $\delta = 10.04$ (s, 2H), 8.84 (m, 6H), 0.85 (s, 2H, NH), −0.54 ppm (s, 2H, NH); FABMS: m/z 1251 $[M]^+$; UV/Vis (CH$_2$Cl$_2$): λ_{max} (ε [mol^{-1}dm^{3}cm^{-1}]) = 341 (10000), 393 (20000), 446 (8500), 542 (77000), 585 (87000), 716 (7200), 801 (12000), 875 nm (1900).

6: m.p. >300 °C (decomp); ^{1}H NMR (CDCl$_3$, 300 MHz at −40 °C): $\delta = 10.22$ (s, 1H), 9.63 (s, 1H), 8.83 (d, $J = 6$ Hz, 1H), 8.70 (d, $J = 6$ Hz, 2H), 8.57 (d, $J = 3$ Hz, 1H), 8.30 (m, 1H), 8.23 (d, $J = 3$ Hz, 1H), 0.90 (s, 2H, NH), −4.26 ppm (s, 1H, NH); FABMS: m/z 1351 $[M]^+$; UV/Vis (CH$_2$Cl$_2$): λ_{max} (ε [mol^{-1}dm^{3}cm^{-1}]) = 354 (28000), 406 (41000), 582 (96000), 627 (87000), 778 (13000), 818 (14000), 922 nm (9700).

oxidizing agent from p-chloranil to 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) (Scheme 1b). The FAB mass spectrum of **4** showed a molecular ion signal at m/z 1232, which indicated the presence of a pentaphyrin skeleton as well as an oxo group. In fact, the presence of a C=O group was confirmed by the presence of a band at $\tilde{\nu} = 1716$ cm^{-1} in the IR spectrum. The ^{1}H NMR spectrum of **4** recorded in CDCl$_3$ at −40 °C showed the three different NH signals at $\delta = 3.65$, 1.42 (CONH), and 1.10 ppm. The β-CH proton of the inverted oxo-substituted pyrrole (ring A) resonated at $\delta = 9.19$ ppm while the α- and β-CH (ring B) protons of the confused pyrrole were observed at $\delta = 2.44$ and 8.78 ppm, respectively, which proved that the product was a 22π electron aromatic compound (Table 1). Further support for this aromaticity came from the electronic absorption spectrum, which displayed a Soret-like band at 544 nm (Figure 1). However, the compound was relatively unstable and gradually oxidized in CH$_2$Cl$_2$ at room temperature over seven days into doubly N-confused dioxopentaphyrin (**N$_2$CO$_2$P$_5$**, **5**) in 45 % yield.

The FAB mass spectrum of **5** showed the molecular ion signal at m/z 1251, which suggested the presence of two oxo groups in the pentaphyrin skeleton. The presence of a C=O group was confirmed by a band at 1710 cm^{-1} in the IR spectrum. The ^{1}H NMR spectrum of **5** recorded in CDCl$_3$ at −40 °C showed only four signals, thus indicating the symmetrical structure of the aromatic compound **5**. As expected, the α-CH proton of ring B observed in the spectrum of **4** disappeared and a set of two signals for the NH and β-CH groups in ring A and B appeared at $\delta = -0.54$ and 10.04 ppm, respectively, while the remaining two NH signals were observed at $\delta = 0.85$ ppm (Table 1). The aromatic structure of **5** was also suggested from the absorption spectrum, which displayed an intense, split Soret-like band at 542 and 585 nm as well as Q-bands from 700 to 900 nm (Figure 1).

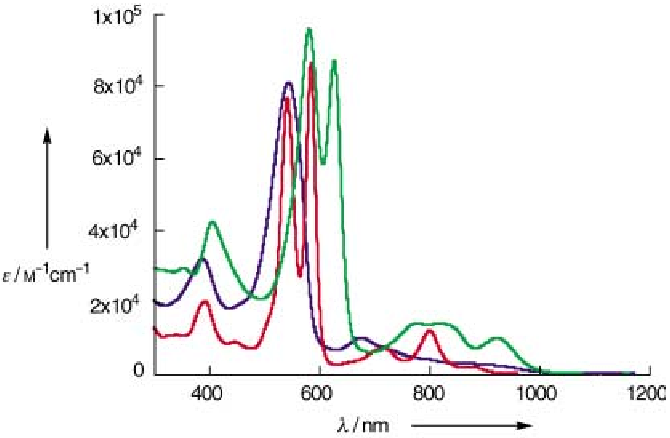


Figure 1. Absorption spectra of **4** (blue), **5** (red), and **6** (green) in CH$_2$Cl$_2$.

The explicit structural details of **4** and **5** were revealed by X-ray single-crystal analyses (Figure 2a and b).[7] Consistent

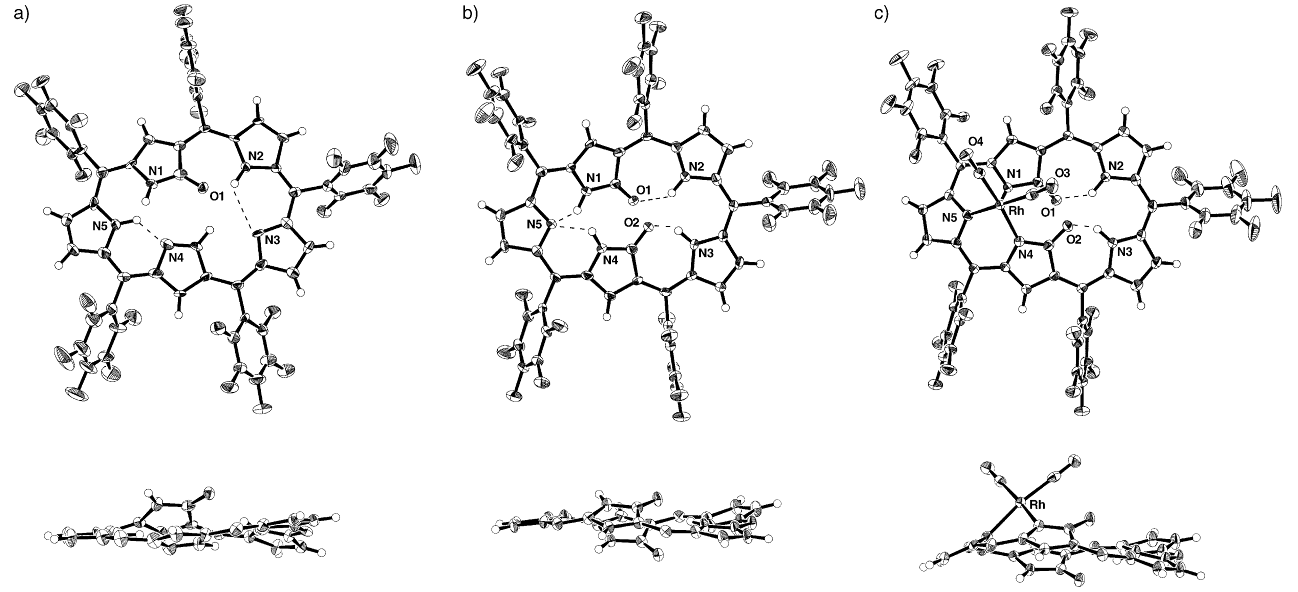


Figure 2. X-ray structures of a) **4**, b) **5**, and c) the Rh^I complex of **5** (**6**), top view (upper) and side view. (lower). *meso*-Aryl groups are omitted for clarity in the side view. Hydrogen-bonding interactions are indicated by broken lines.

with the above observations were the findings that both the confused pyrrole rings are inverted and one oxygen atom (O1) is attached at the inner α-carbon atom in **4**, while two oxygen atoms (O1, O2) are present in **5**. The bond lengths between the carbon and oxygen atoms are in the range of a C−O double bond, that is, 1.25(1) Å for **4**, and 1.224(8) and 1.231(7) Å for **5**. The pentaphyrin structure of **4**, which consists of the core 30 atoms, is highly distorted from the least-square plane, with a mean deviation of 0.32(1) Å and a tilting angle of the oxygen-substituted pyrrole (ring A) from the core plane of 146.0(4)°. The dihedral angles ∠CNC clearly indicate that there are three inner NH protons located at N1, N2, and N5. Namely, these angles are larger than 110°, while those of N3 and N4 are smaller than 106°.[8] Two of the three NH protons (at N2 and N5) form intramolecular hydrogen bonds with the neighbors (N2−H···N3 and N4···H−N5, with lengths of 3.00(1) Å for N2···N3 and 2.55(1) Å for N4···N5), while the remaining N1−H proton forms an intermolecular hydrogen bond with the N1′−H group in another molecule to form a dimer (Figure 3). The distance between the N1 and O1′ atoms in the dimer is 2.84(1) Å and each molecule is arranged in a parallel fashion at an intermolecular distance of 4.3(2) Å.[7a] The CONH units present in **5** do not form such hydrogen-bonding interactions to form a dimer or oligomer, instead, four intramolecular hydrogen bonds are observed between O1···H−N2, O2···H−N3, N1−H···N5, and N4−H···N5 with lengths of 2.639(5), 2.567(6), 2.587(7), and 2.509(7) Å for O1···N2, O2···N3, N1···N5, and N4···N5, respectively. The intramolecular hydrogen-bonding interactions result in the pentaphyrin core of **5** being less distorted (0.270(7) Å) than **4** (Figure 2b).[7b]

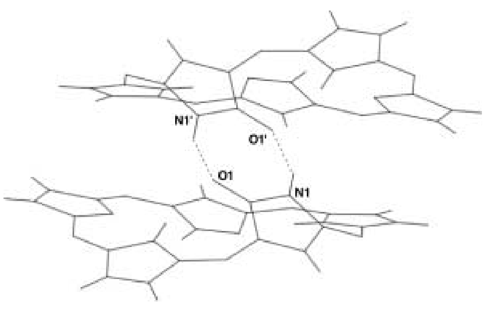


Figure 3. Hydrogen-bonded dimer of **4**. *meso*-Aryl groups are omitted for clarity. Hydrogen-bonding interactions are indicated by broken lines.

The metal coordination chemistry of the stable compound **5** was examined using a Rh^I salt. Treatment of **5** with $[\{Rh(CO)_2Cl\}_2]$in the presence of sodium acetate in refluxing CH_2Cl_2 resulted in the formation of the Rh^I complex **6** in quantitative yield (Scheme 1c).[9] The unsymmetrical structure of the complex was suggested by the appearance of two different pyrrole β-CH (rings A and B) signals at $\delta = 10.22$ and 9.63 ppm in the ^{1}H NMR spectrum of **6**. The remaining pyrrole NH protons and the significantly shielded oxopyrrole NH (ring A) proton resonated at $\delta = 0.90$ and −4.26 ppm, respectively, which confirms that only two pyrrolic nitrogen atoms are coordinated to the Rh^I center in the cavity (Table 1). The electronic absorption spectrum of **6** displayed a split Soret-like band at 582 and 627 nm and the longest wavelength Q-bands appeared at 922 nm, which are 40 to 46 nm (Soret and Q-bands, respectively) bathochromic shifted relative to **5** (Figure 1).[10]

The structure of the Rh^I complex **6** was confirmed by single-crystal X-ray analysis (Figure 2c).[7c] As predicted from the above observations, there is only one Rh atom coordinated to the pentaphyrin skeleton in **6**. One imino (N5) and one amino (N4) nitrogen atom of the macrocycle are coordinated to the Rh^I ion and the other two coordination sites are occupied by the carbonyl ligands. The Rh atom is located above the mean plane of the macrocycle and the geometry around the metal center is close to square-planar (N4-Rh-N5, 80.2(2)°). The angle between the plane containing the Rh center and its coordinated atoms and the pentaphyrin plane is 54.64(9)°. Similar to **5**, intramolecular hydrogen bonds are formed between O1···H–N2 and O2···H–N3 in **6** and the atom distances of O1···N2 and O2···N3 are 2.643(5) and 2.557(6) Å, respectively. The pentaphyrin plane of **6** is highly distorted from the core plane with a mean deviation of 0.362(5) Å, while the intermolecular Rh···Rh distance is 3.3405(5) Å (see Supporting Information), which is considerably longer than a Rh^I–Rh^I single bond (2.617–2.705 Å).[11]

In conclusion, we have synthesized doubly N-confused oxopentaphyrin and doubly N-confused dioxopentaphyrin as well as demonstrating the coordination chemistry of the latter compound. It has been clearly shown that the introduction of one more confused pyrrole ring into the macrocycle framework resulted in the remarkable structural diversity. Although the oxo-substitution mechanism is not clarified yet, the doubly N-confused oxopentaphyrins shown here are the first examples of a stable nonfused, *meso*-aryl-type pentaphyrin.[5,12,13] The present study exploited the interaction of Rh^I ions, but other metal ions are likely to interact with the macrocycle. Similar to doubly N-confused dioxohexaphyrins (**N_2CO_2H**), efforts are currently underway to prepare a variety of bismetal complexes.

Experimental Section

3: A mixture of **1** (150 mg, 0.27 mmol) and **2** (190 mg, 0.27 mmol) in CH_2Cl_2 was stirred in a nitrogen atmosphere for 15 min at room temperature. *p*-TSA (7.7 mg, 0.040 mmol) was then added to the mixture and the solution was stirred for a further 1 h in the dark. The reaction mixture was then passed through a column of silica gel using CH_2Cl_2 (200 mL) as the eluent. *p*-Chloranil (199 mg, 0.81 mmol) was added to the combined solution and the mixture refluxed for a further 1 h, then stirred at room temperature for 2 days. After removal of the solvent, the crude product was purified by column chromatography, first on basic alumina and then on silica gel. A blue fraction was eluted with CH_2Cl_2/hexane (35:65), which gave **3b** (40 mg, 12%) as a blue solid after removal of the solvent. Another blue fraction was eluted with CH_2Cl_2/hexane (50:50) and afforded **3a** (76 mg, 23%) as a blue solid.

4: DDQ (183 mg, 0.81 mmol) instead of *p*-Chloranil was added to the mixture in the synthesis of **3**. The solution was stirred for 1 h at room temperature. After removal of the solvent, the crude product was purified by column chromatography, first on basic alumina and then on silica gel. A pink fraction was eluted with CH_2Cl_2/hexane (45:55), which gave **4** (106 mg, 32%) as a greenish solid after removal of the solvent.

5: Compound **3** (50 mg, 0.041 mmol) was dissolved in CH_2Cl_2 (15 mL) and the solution stirred at room temperature. The reaction was monitored by TLC (silica gel) after every 10 h. The color of the solution gradually changed from pink to purple over 7 days. The solvent was evaporated, and the residue was purified by column chromatography on silica gel. A purple fraction was eluted with CH_2Cl_2/hexane (30:70) which gave **5** (23 mg, 45%) as a greenish solid. The remaining product was identified as starting material **4**.

6: Compound **5** (25 mg, 0.02 mmol) was dissolved in CH_2Cl_2 (50 mL). Anhydrous sodium acetate (16 mg, 0.2 mmol) and $[\{Rh(CO)_2Cl\}_2]$ (16 mg, 0.04 mmol) were added to the solution and the mixture was stirred under reflux for 3 h. After removal of the solvent, the residue was purified by column chromatography on silica gel. A blue fraction was eluted with CH_2Cl_2/hexane (40:60), which gave **6** (quantitative) as a green solid after removal of the solvent.

Received: January 12, 2004 [Z53732]

Keywords: aromaticity · macrocyclic ligands · oxidation · porphyrinoids · rhodium

---

[1] a) *The Porphyrin Handbook*, *Vol. 2* (Eds.: K. M. Kadish, K. M. Smith, R. Guilard), Academic, San Diego, **2000**; b) A. Jasat, D. Dolphin, *Chem. Rev.* **1997**, *97*, 2267–2340; c) J. L. Sessler, S. J. Weghorn, *Expanded, Contracted and Isomeric Porphyrins*, Pergamon, New York, **1997**.

[2] a) H. Furuta, T. Asano, T. Ogawa, *J. Am. Chem. Soc.* **1994**, *116*, 767–768; b) P. J. Chmielewski, L. Latos-Grażyński, K. Rachlewicz, T. Głowiak, *Angew. Chem.* **1994**, *106*, 805–808; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 779–781; c) H. Furuta, H. Maeda, A. Osuka, *Chem. Commun.* **2002**, 1795–1804; d) L. Latos-Grażyński in ref. [1], chap. 14.

[3] a) H. Furuta, H. Maeda, A. Osuka, *J. Am. Chem. Soc.* **2000**, *122*, 803–807; b) H. Furuta, H. Maeda, A. Osuka, *J. Org. Chem.* **2000**, *65*, 4222–4226 (corrigendum: H. Furuta, H. Maeda, A. Osuka, *J. Org. Chem.* **2000**, *65*, 5450); c) H. Furuta, H. Maeda, A. Osuka, *J. Org. Chem.* **2001**, *66*, 8563–8572; d) K. Araki, H. Winnischofer, H. E. Toma, H. Maeda, A. Osuka, H. Furuta, *Inorg. Chem.* **2001**, *40*, 2020–2025; e) H. Furuta, H. Maeda, A. Osuka, M. Yasutake, T. Shinmyozu, Y. Ishikawa, *Chem. Commun.* **2000**, 1143–1144; f) H. Maeda, A. Osuka, H. Furuta, *Supramol. Chem.* **2003**, *15*, 447–450; g) H. Maeda, A. Osuka, H. Furuta, *J. Am. Chem. Soc.* **2003**, *125*, 15690–15691; h) K. Araki, F. N. Engelmann, I. Mayer, H. E. Toma, M. S. Baptista, H. Maeda, A. Osuka, H. Furuta, *Chem. Lett.* **2003**, *32*, 244–245; i) H. Maeda, A. Osuka, H. Furuta, *Tetrahedron* **2004**, *60*, 2427–2432.

[4] A. Srinivasan, T. Ishizuka, A. Osuka, H. Furuta, *J. Am. Chem. Soc.* **2003**, *125*, 878–879.

[5] A. Srinivasan, T. Ishizuka, H. Furuta, *Angew. Chem.* **2004**, *116*, 894–897; *Angew. Chem. Int. Ed.* **2004**, *43*, 876–879.

[6] H. Maeda, A. Osuka, Y. Ishikawa, I. Aritome, Y. Hisaeda, H. Furuta, *Org. Lett.* **2003**, *5*, 1293–1296.

[7] a) Crystal data for **4**: $C_{55}H_{12}N_5OF_{25}\cdot 2.5\,H_2O$, $M_r = 1278.73$, triclinic, space group $P\bar{1}$ (no. 2), $a = 12.49(1)$, $b = 15.31(1)$, $c = 16.04(1)$ Å, $\alpha = 119.09(7)$, $\beta = 97.56(7)$, $\gamma = 94.61(8)°$, $V = 2619(3)$ Å^3, $Z = 2$, $R = 0.085$, $wR = 0.1140$, GOF = 1.174; b) crystal data for **5**: $C_{55}H_{12}N_5O_2F_{25}\cdot C_8H_{18}$, $M_r = 1363.92$, triclinic, space group $P\bar{1}$ (no. 2), $a = 12.2382(8)$, $b = 15.4371(10)$, $c = 16.2425(11)$ Å, $\alpha = 97.9870(10)$, $\beta = 106.6900(10)$, $\gamma = 107.6360(10)°$, $V = 2714.0(3)$ Å^3, $Z = 2$, $R = 0.064$, $wR = 0.058$, GOF = 1.025; c) crystal data for **6**: $C_{57}H_{11}N_5O_4F_{25}Rh\cdot 1.5\,C_6H_{14}$, $M_r = 1536.88$, triclinic, space group $P\bar{1}$ (no. 2), $a = 12.08(1)$, $b = 15.14(1)$, $c = 18.00(2)$ Å, $\alpha = 98.80(8)$, $\beta = 100.48(8)$, $\gamma = 95.13(8)°$, $V = 3212(5)$ Å^3, $Z = 2$, $R = 0.062$, $wR = 0.086$, GOF = 1.030. CCDC-228400–228402 (**4**–**6**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB21EZ, UK; fax: (+44)1223-336-033; or deposit@ccdc.cam.ac.uk).

[8] S. J. Silvers, A. Tulinsky, *J. Am. Chem. Soc.* **1967**, *89*, 3331–3337.

[9] A. Srinivasan, H. Furuta, A. Osuka, *Chem. Commun.* **2001**, 1666–1667.

[10] M. Gouterman in *The Porphyrins*, *Vol. 3* (Ed.: D. Dolphin), Academic, New York, **1978**, pp. 1–165.

[11] a) O. S. Mills, E. F. Paulus, *J. Organomet. Chem.* **1967**, *10*, 331–336; b) O. S. Mills, J. P. Nice, *J. Organomet. Chem.* **1967**, *10*, 337–342.

[12] a) H. Raxhausen, A. Gossauer, *J. Chem. Soc. Chem. Commun.* **1983**, 275; b) C. Brückner, E. D. Sternberg, R. W. Boyle, D. Dolphin, *Chem. Commun.* **1997**, 1689–1690.

[13] J.-Y. Shin, H. Furuta, A. Osuka, *Angew. Chem.* **2001**, *113*, 639–641; *Angew. Chem. Int. Ed.* **2001**, *40*, 619–621.