Demetalation of (5,10,15,20-Tetraphenylporphyrinato)iron Complexes: Effect of Substituents at the *o*-Positions of Phenyl Groups

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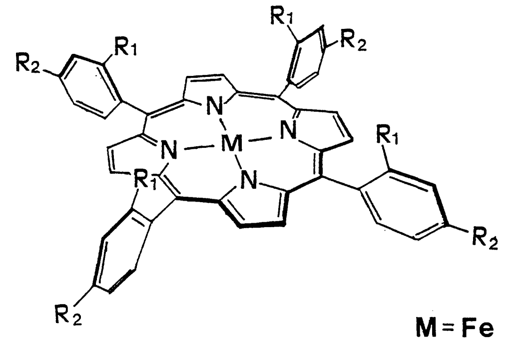
Synopsis. The demetalation of a series of (5,10,15,20-tetraphenylporphyrinato)iron(III) complexes having bulky substituents at the *o*-positions of phenyl rings was studied in acetic acid in the presence of iron(II) chloride and HCl. The reaction occurred simultaneously with the reduction of Fe(III) porphyrin to Fe(II) porphyrin, since no demetalation was observed without iron(II) chloride. The pseudo-first-order rate constants, which were determined spectrophotometrically, decreased with an increase in the bulkiness of the *o*-substituents on the phenyl rings. The atropisomeric structures of the products were determined by high-resolution NMR measurements.

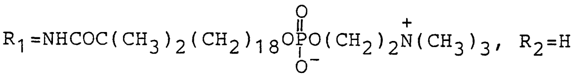


1 R_1=H, R_2=H

2 R_1=H, R_2=NHCOC(CH$_3$)$_3$

3 R_1=NHCOC(CH)$_3$, R_2=H

4 R_1=NHCOC(CH$_3$)$_2$(CH$_2$)$_{18}$OH, R_2=H

5 

R_1=NHCOC(CH$_3$)$_2$(CH$_2$)$_{18}$O$\overset{O}{\overset{\|}{\underset{O^-}{P}}}$O(CH$_2$)$_2\overset{+}{N}$(CH$_3$)$_3$, R_2=H

The metal insertion reaction was studied kinetically and thermodynamically in order to understand the mechanism of how porhyrins form the metalloporphyrin complexes in nature.[1,2] An intermediate complex (sitting-atop model) was proposed.[3] Still, less attention has been pain to the demetalation process, although the reaction is closely related to metalation.[4] It is expected that the introduction of bulky substituents to a porphyrin induces not only a decrease in intermolecular metal-metal interaction (dimerization), but also affects the reactivities of the porphyrin group. A preliminary report appeared concerning the effect of such bulky substituents on copper incorporation into tetraphenylporphyrins.[5]

In this paper we describe the demetalation of a series of (5,10,15,20-tetraphenylporphyrinato)iron(III) complexes with bulky ortho-substituents at the phenyl groups in a FeCl$_2$–HCl–acetic acid system at 20 °C and the rate of demetalation in order to discuss the effect of the ortho-substituents on the intramolecular reaction. In addition, a method to determine the atropisomeric structure was established by the use of high-resolution ^{1}H NMR measurements on the demetalated products prepared by the present method.

Experimental

Materials. Reagent-grade iron(II) chloride, concd HCl and acetic acid were purchased from Wako Chem. Co. and used without further purification. (5,10,15,20-Tetrapheylporphyrinato)iron(II) chloride (**1**) was purchased from Aldrich Chemical Co. and purified by silicagel column chromatography. [5,10,15,20-*Tetrakis*(*α*,*α*,*α*,*α*-*o*-pivalamidophenyl)porphyrinato] iron(III) chloride (**3**) was prepared according to methods described in the literature.[6,7] Fe(III) porphyrin chloride (**4**) and Fe(III) porphyrin chloride (**5**) were prepared according to previous papers.[8,9][5,10,15,20-*Tetrakis*(*p*-pivalamidophenyl)porphyrinato]iron(III) chloride (**2**) was propared by the reaction of pivaloyl chloride with 5,10,15,20-tetrakis (*p*-aminophenyl)porphyrin.[10]

Kinetic Measurements. The rate constants of demetalation were determined spectrophotometrically by measuring the UV and VIS adsorption spectra of a porphyrin. A double-beam UV and VIS absorption spectrophotometer (Shimadzu MPS-2000) was used. The kinetic runs were conducted under pseudo-first-order conditions, i.e. in the presence of a large excess of HCl and FeCl$_2$ over porphyrinatoiron(III). The reaction temperature was 20 °C. A solution of a Fe(III) porphyrin (20 μmol dm^{-3}) in acetic acid (5 cm^3) was mixed under argon with 0.02 ml of concd HCl. The reaction was started by adding a FeCl$_2$-saturated aqueous solution under an argon atmosphere in a sealed quartz cell (path length: 10 mm). The final concentrations of HCl, FeCl$_2$, and water were 0.33 mol dm^{-3}, 3.9 mmol dm^{-3}, and 1.8 mol dm^{-3}, respectively.

Preparative Demetalation for ^{1}H NMR Spectral Measurements. Measurements of the ^{1}H NMR spectra of demetalated products were carried out with derivatives **3** and **5**. Sample preparations were as follows. Fe(III) porphyrin **3** (30 mg, 26 μmol) was dissolved in a mixed solution of acetic acid (150 ml) and concd HCl (30 ml). To the porphyrin solution was added solid FeCl$_2$ (30 mg, 0.42 mmol) under an argon atmosphere at 20 °C. After 1 h of stirring, the solvent was removed under reduced pressure. The residue dissolved in chloroform was washed with 5% NaHCO$_3$, dried over Na$_2$SO$_4$ and then evaporated to dryness. The residue was chromatographed on silica gel eluted with benzene–diethyl ether (4/3 by volume) to give the metal-free porphyrin **3′**. The yield was 23 mg (87%). Anal. Found: C, 74.27; H, 7.28; N, 9.23%. Calcd for $C_{64}H_{66}N_8O_4 \cdot 1H_2O$: C, 74.68; H, 6.54; N, 9.89%. IR (KBr) 1690 and 1580 cm^{-1}. VIS (CHCl$_3$) λ_{max} 643, 587, 545, 511, 480(sh), and 418 nm.

Fe(III) porphyrin **5** (100 mg, 35 μmol) was demetalated by the same procedure described for **3**. The product, however, was purified by column chromatography on Toyopearl HW-40F (Tosoh Co.) eluted with methanol. During column purifivation, porphyrin dication was spontaneously converted to the correponding porphyrin. The yield was 76 mg (80%). Anal. Found: C, 61.76; H, 9.35; N, 5.23; P, 3.97%. Calcd for $C_{152}H_{248}N_{12}O_{20}P_4 \cdot 15H_2O$: C, 61.69; H, 9.53; N, 5.68; P, 4.19%. IR (KBr) 1690, 1580, 1240, 1080, and 960 cm^{-1}. VIS (MeOH) λ_{max} 644, 589, 547, 513, 480(sh), and 418 nm.

The ^{1}H NMR spectra of the products were obtained by JEOL GSX-400 FTNMR spectrometer in $CDCl_3$ or CD_3OD with Me_4Si used as an internal standard.

Results and Discussion

It is well-known that the metalloporphyrins can be divided into five 'stability classes' which indicate their resitance towards protic acids.[11] A porphyrinatoiron(III) complex belongs to class-III in demetalation,[12] and the reduced one (porphyrinatoiron(II)) is much more susceptible to demetalation. From this view a demetalation reaction of an iron(III) porphyrin was studied with the concomitant reduction to iron(II) by various reductants.[13] The mechanism of iron(III) demetalation in the presence of iron(II) chloride and HCl as a 'catalytic' reductant has been studied kinetically and the following mechanism was postulated:[13]

$$\mathrm{ClFe(III)P} + \mathrm{Fe(II)} + \mathrm{HCl} \rightleftarrows \mathrm{HFe(III)Cl_4} + \mathrm{Fe(II)P} \tag{1}$$

and

$$\mathrm{Fe(II)P} + n\,\mathrm{HCl} \rightarrow \mathrm{Fe(II)} + \mathrm{H_4P^{2+}}, \tag{2}$$

where P indicates a porphyrinato ligand. The reaction follows pseudo-first-order kinetics:

$$-\mathrm{d[ClFe(III)P]}/\mathrm{d}t = k_{\mathrm{obsd}}\,\mathrm{[ClFe(III)P]}, \tag{3}$$

where k_{obsd} indicates a pseudo-first-order rate constant for demetalation.

In the present paper, the demetalation of a series of iron(III) porphyrins was conducted in acetic acid containing concd HCl in the presence of an excess amount of iron(II) chloride, as described in the Experimental section. For example, the original spectrum of **5** (absorption maxima at 506, 589, and 645 nm) disappeared and changed to that of the metal-free porphyrin dication (absorption maxima at 585 and 636 nm). The isosbestic points (472, 560, and 661 nm) were maintained during the reaction. This indicates that the reaction is apparently from Fe(III)P to H_4P^{2+}. No demetalation reaction occurred in the absence of iron(II) chloride under the HCl concentration employed in the present study; in the absence of HCl no reaction could be induced by iron(II) chloride. This fact indicates that the demetalation is caused by a concurrent reaction accompanying both a reduction process and a removal process of an iron ion, shown by the ternary reaction (1). Other iron(III) porphyrins also showed the same reaction behavior.

The pseudo-first-order rate constants (k_{obsd}) were determined by pseudo-first order plots. The linearity of the plots revealed the first-order kinetics, and the determined rate constants were independent of employed wavelength (480—680 nm). Table 1 summarizes the rate constants, under the same experimental conditions, for the demetalation reactions of a series of (5,10,15,20-tetraphenylporphyrinato)iron(III) having different substituents at the ortho positions of phenyl rings (complexes **1**—**5**). Table 1 clearly shows that the rate constants are remarkably dependent on the substituents at ortho-positions.

Table 1. Values of Pseudo-First-Order Rate Constants (k_{obsd}) of Demetalation Reactions

Compound	$k_{\mathrm{obsd}}/\mathrm{s}^{-1}$[a]
1	1.5×10^{-2}
2	1.0×10^{-2}
3 (α_4)[b]	1.4×10^{-3}
3 ($\alpha_n\beta_{4-n}$)[b]	1.3×10^{-3}
4	3.1×10^{-4}
5 (α_4)[b]	1.8×10^{-4}
5 ($\alpha_n\beta_{4-n}$)[b]	4.3×10^{-4}

a) Pseudo-first-order rate constants at 20 °C, in acetic acid–H_2O. [Fe(III)porphyrin]=20 μmol dm^{-3}, [HCl]=0.33 mol dm^{-3}, [$FeCl_2$]=3.9 mmol dm^{-3}. b) α_4 and $\alpha_n\beta_{4-n}$ (n=4, 3, 2) mean a $\alpha,\alpha,\alpha,\alpha$-atropisomer and a mixture of four atropisomers, respectively.

The rate of a demetalation reaction is considered to be affected largely by the following three factors: (1) the basicity of a porphyrinato ligand, (2) the deformability of a porphyrin ring plane, and (3) the solvation on a porphyrin ring plane.

The basicity of these tetraphenylporphyrin ligands having various ortho-substituents is considered to be almost the same, since the Hammet sigma coefficient of the alkanamido groups is practically zero.[14]

An X-ray diffraction analysis revealed that the porphyrin dications (diacids), that is, products of demetalation, form a domed structure by a van der Waals repulsion of the inner hydrogen atoms of the porphyrin ring.[15] During a demetalation reaction, it can be postulated that an intermediate complex having a domed structure of a porphyrin ring, like a sitting-atop model,[3] is formed. It has been reported concerning a kinetic study of the thermal atropisomerization and photomerization study of [5,10,15,20-*tetrakis*($\alpha,\alpha,\alpha,\alpha$-*o*-substituted phenyl)porphyrinato]metal complexes that the planality of a porphyrin ring is closely related to the steric repulsion of the bulky groups and regulates the rotation of the phenyl rings.[16] That is, the bulky substituents restrict the tilting of pyrrole rings, resulting in less deformability of a porphyrin ring. The fact that the bulky groups (pivalamido groups) at the para positions, as in the case of the complex **2**, showed a rate constant similar to that of **1** also suggests that a steric interation of the bulky groups at the ortho positions is important. Our results are consistant with the conclusion that the ruffling of the porphyrin may results in an enhancement of the reactivity on the electrophilic meso-substitution in metalloporphyrins.[17]

The porphyrin ring is considered to be less solvated on the side of bulky ortho-substituents and desolvated irons are expected to be more easily removed. However, this is inconsistent with the experimental results.

The demetalation of **3** and **5** was carried out in preparative scales in order to give the corresponding

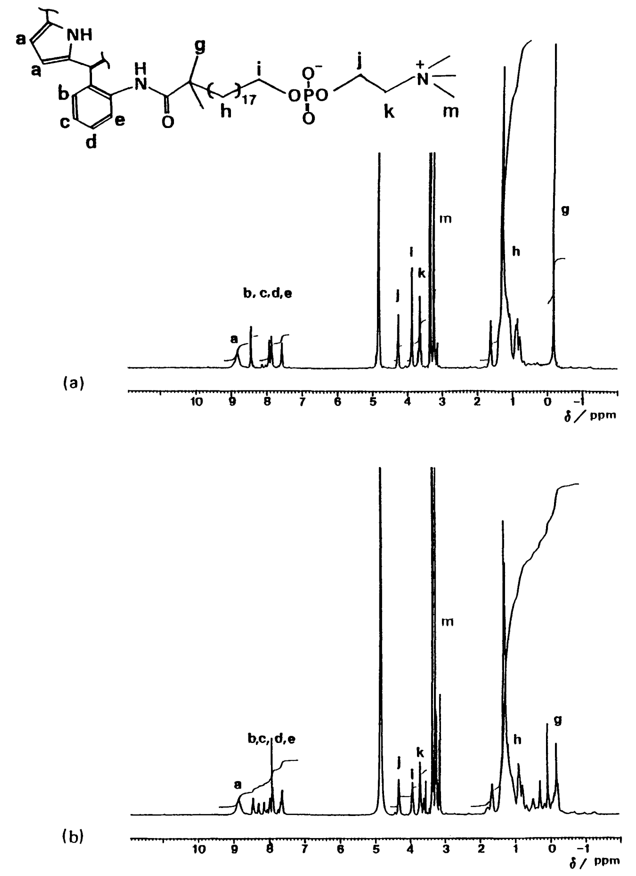


Fig. 1. 400 MHz ^{1}H NMR spectra of the demetalated products of $5(\alpha_4)$ (a) and a mixture of four atropisomers ($5(\alpha_n\beta_{4-n})$) (b) in CD_3OD.

demetalated products in high yields (>80%). The structures of the products were confimed by various analyses, as described in the experimental section. Figure 1 shows the 400 MHz ^{1}H NMR spectra of the demetalated products of $5(\alpha_4)$ and a mixture of four atropisomers $5(\alpha_n\beta_{4-n})$. The structure of the α_4 atropisomer of 5 was supported by the single peak at $\delta=-0.2$ ppm due to the methyl protons of the 2,2-position of the acyl chains of the same chemical environment (Fig. 1(a)), while the Fe(III) porphyrin comprising of a mixture of four atropisomers,$5(\alpha_n\beta_{4-n})$, gave a product having multiple signals near $\delta=0.0$ ppm due to the multiple methyl protons of chemically different environments (Fig. 1(b)). It is therefore obvious that no atropisomerization was induced during the demetalation reaction under the conditions used in the present study.

References

1) J. H. Buchler, "Porphyrins and Metalloporphyrins," ed by K. M. Smith, Elsevier Publ., Amsterdam (1975), p. 157; *idem.*, "The Porphyrins," ed by D. Dolphin, Academic Press, New York (1978), Vol. IA, p. 389.

2) D. K. Lavallee, *Comments Inorg. Chem.*, **5**, 155 (1986).

3) E. B. Fleisher and J. H. Wang, *J. Am. Chem. Soc.*, **82**, 3498 (1960).

4) P. Hambright, "Porphyrins and Metalloporphyrins," ed by K. M. Simth, Elsvier Publ., Amstendam (1975), p. 233.

5) J. Turay and P. Hambright, *Inorg. Chim. Acta,* **53**, L147 (1981).

6) J. P. Collman, R. R. Gagne, C. A. Reed, T. R. Halbert, G. Lang, and W. T. Robinson, *J. Am. Chem. Soc.*, **93**, 1247 (1975).

7) T. H. Sorrell, *Inorg. Synth.*, **20**, 161 (1980).

8) Y. Matsushita, E. Hasegawa, K. Eshima, and E. Tsuchida, *Chem Lett.*, **1983**, 1387; E. Tsuchida, H. Nishide, M. Yuasa, E. Hasegawa, Y. Matsushita, and K. Eshima, *J. Chem. Soc., Dalton Trans.*, **1985**, 275.

9) E. Tsuchida and H. Nishide, *Top. Curr. Chem.*, **132**, 64 (1986).

10) A. Bettelheim, B. A. White, S. A. Raybuck, and R. W. Murray, *Inorg. Chem.*, **26**, 1009 (1987).

11) J. W. Buchler, L. Puppe, K. Rohbok, and H. H. Schneehage, *Ann. N. Y. Acad. Sci.*, **206**, 116 (1973).

12) J. N. Phillips, *Rev. Pure Appl. Chem.*, **10**, 35 (1960).

13) J. H. Espenson and R. J. Christensen, *Inorg. Chem.*, **16**, 2561 (1977).

14) P. Zuman, "Substituent Effects in Organic Polarography," Plenum Press, New York (1967), p. 46.

15) A. Stone and E. B. Fleisher, *J. Am. Chem. Soc.*, **90**, 2735 (1968).

16) R. A. Fritag and D. G. Whitten, *J. Phys. Chem.*, **87**, 3918 (1983).

17) E. Watanabe, S. Nishimura, H. Ogoshi, and Z. Yoshida, *Tetrahedron,* **31**, 1385 (1975).