# Notes

## Three Isoelectronic Structures of One-Electron-Oxidized Nickel Porphyrins

**Hiroshi Tsurumaki, Yoshihito Watanabe,* and Isao Morishima***

Division of Molecular Engineering, Graduate School of Engineering, Kyoto University, Kyoto 606-01, Japan

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### Introduction

Heme enzymes such as peroxidases, catalases, and P-450's catalyze many types of oxidations and oxygenations by the use of higher valent oxo–iron complexes, so-called compound I.[1] The biological utilization of two-electron-oxidized equivalents at the active sites is made possible by employing iron porphyrin complexes. We recently showed that several complexes isoelectronic with two-electron-oxidized iron porphyrin complexes, i.e., the O=$Fe^{IV}$TMP π-cation radical,[2] O=$Fe^{V}$TDCPP,[3] $Fe^{III}$TMP-*N*-O,[4] and the $Fe^{III}$TMP dication,[5] can be prepared by synthetic heme models. These complexes are formally two-electron-oxidized from the parent $Fe^{III}$TMP; i.e., $Fe^{III}$TMP is able to maintain its two-electron-oxidized state in various electronic structures.

In this study, we have extended our efforts to the interconversion of electronic structures of oxidized metalloporphyrin complexes in the reactions of $Ni^{II}$TMP-*N*-O and $Ni^{II}$TPP-*N*-O with acids.

### Experimental Section

**Preparation of $H_2$TMP-*N*-O and $H_2$TPP-*N*-O.** $H_2$TMP and $H_2$TPP were prepared by literature methods.[6,7] $H_2$TMP-*N*-O and $H_2$TPP-*N*-O were prepared by using maleic peracid as an oxidant according to the procedure of Bonnett and co-workers.[8] Products were purified by column chromatography ($SiO_2$) with benzene–AcOEt (10:1). The yields of $H_2$TMP-*N*-O and $H_2$TPP-*N*-O were 43.6% and 14.5%, respectively. Data for $H_2$TPP-*N*-O are as follows. UV–vis, log ϵ ($\lambda_{max}$, nm): 5.11 (416), 3.78 (544), 3.84 (593), 3.41 (681). $^1$H NMR (ppm) in $CD_2Cl_2$: pyrr H 9.01 (2H, d, *J* = 5.0 Hz), 8.86 (2H, d, *J* = 5.0 Hz), 8.67 (2H, s), 7.82 (2H, s); Ph H 8.21–8.29, 7.75–7.82, 7.55 (20H, m); NH 1.07 (2H, s). FAB mass: *m*/*z* 631 ($M^+$), 615 ($M^+$ – O).

**Preparation of $Ni^{II}$TMP-*N*-O and $Ni^{II}$TPP-*N*-O.** $(CH_3CO_2)_2Ni{\cdot}4H_2O$ (200 mg) was added to a DMF solution (30 mL) of $H_2$TMP-*N*-O (15 mg). The mixture was heated at 110 °C under an argon atmosphere for 1.5 h. The solution was cooled to room temperature and added to 300 mL of water. After filtration at reduced pressure, the solid residue was dissolved in 10 mL of hexane–$CH_2Cl_2$ (1:1), and the solution was applied to a silica gel column. The column was eluted with hexane–$CH_2Cl_2$ (1:1) to give a red-yellow fraction which contained $Ni^{II}$TMP. Further elution with $CH_2Cl_2$ gave a red fraction. Evaporation of the solvent and recrystallization from $CH_2Cl_2$–methanol gave 11 mg (67%) of Ni(II)-TMP-*N*-O. UV–vis, log ϵ ($\lambda_{max}$, nm) in $CH_2Cl_2$: 5.08 (417), 3.98 (569). $^1$H NMR (ppm) in $CD_2Cl_2$: pyrr H 8.61 (2H, d, *J* = 5.0 Hz), 8.38 (2H, s), 8.36 (2H, d, *J* = 5.0 Hz), 7.10 (2H, s); *m*-H 7.31 (2H, s), 7.29 (2H, s), 7.17 (2H, s), 7.15 (2H, s); *p*-Me 2.56 (12H, d); *o*-Me 2.30 (6H, s), 2.16 (4H, s), 1.50 (4H, s), 1.44 (4H, s). FAB mass: *m*/*z* 854 ($M^+$), 838 ($M^+$ – O).

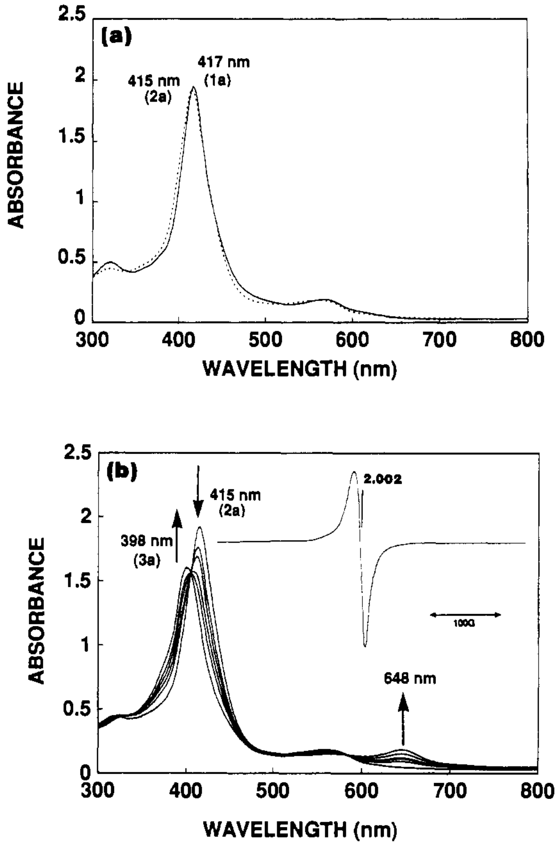
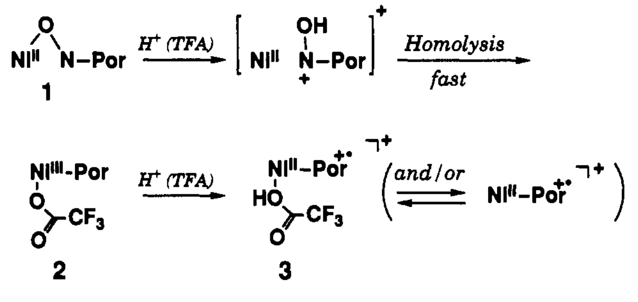


**Figure 1.** UV–vis spectral changes for the reaction of **1a** with TFA in $CH_2Cl_2$ at –25 °C. Panel a: solid line, **1a** ($1.2 \times 10^{-5}$ M); dotted line, 20 molar equiv of TFA added. Panel b: changes upon addition of 10 molar equiv aliquots of TFA; inset, EPR spectrum of **3a** in $CH_2Cl_2$ at 77 K.

**Scheme 1**



$Ni^{II}$TPP-*N*-O was obtained in 57.5% yield by the same method. UV–vis, log ϵ ($\lambda_{max}$, nm) in $CH_2Cl_2$: 5.05 (418), 3.92 (569). $^1$H NMR (ppm) in $CD_2Cl_2$: pyrr H 8.95 (2H, d, *J* = 5.0 Hz), 8.68 (2H, s), 8.67 (2H, d, *J* = 5.0 Hz), 7.17 (2H, s); Ph H 8.49–7.67 (20H, m). FAB mass: *m*/*z* 686 ($M^+$), 670 ($M^+$ – O)

**Deuterated Porphyrin.** Mesithylene was treated twice with 10M sulfuric acid-$d_2$ at 50 °C for 1 h to afford 60%-enriched mesitylene-$d_3$ as estimated from the $^1$H NMR spectrum.[9] Conversion of mesitylene-$d_3$ to mesitaldehyde-$d_2$ was accomplished by a literature method.[10] Pyrrole-

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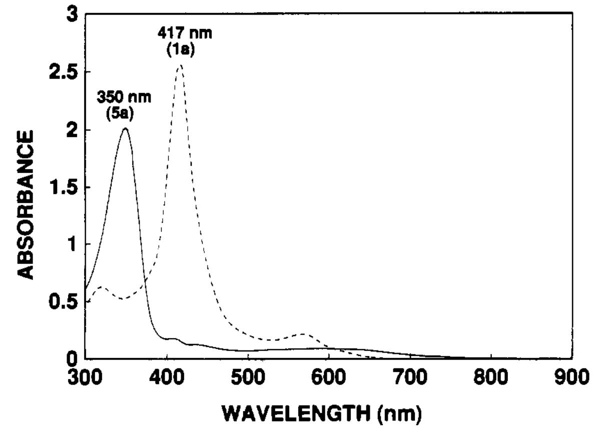

**Figure 2.** UV–vis spectral change for the reaction of **1a** with TFMS in $CH_2Cl_2$–ethyl acetate (1:1) at −25 °C: solid line, **1a** ($2.2 \times 10^{-5}$ M); dotted line, 100 molar equiv of TFMS added.

$d_5$ was prepared by acetic acid-$d_1$ exchange as described by Fajar et al.[11] Pyrrole-$d_8$ and meta-$d_8$ of HzTMP were prepared from pyrrole-$d_5$ and mesitaldehyde-$d_2$, respectively, in the usual manner.[6]

**Physical Measurements.** $^1$H NMR spectra were recorded at 500 MHz using a GE Omega 500 spectrometer, and $^2$H NMR were recorded at 46.1 MHz on a Nicolet NT-300 spectrometer. Chemical shifts were reported relative to residual solvent resonances ($CH_2Cl_2$, δ 5.3; AcOEt, δ 4.1, 1.2). The sample concentrations for $^1$H and $^2$H NMR measurements were 3–5 mM. EPR spectra were obtained with a JEOL PE-2X spectrometer. UV–vis spectra were recorded on a Shimadzu UV 2200 or Hitachi U-3210 spectrophotometer equipped with thermoelectric cold cells.

## Results and Discussion

**Reaction of 1 with TFA.** The reaction of **1a** with 20 molar equiv of TFA in $CH_2Cl_2$ at −25 °C causes an instantaneous spectral change to yield **2a**, whose Soret band appears at 415 nm (Figure 1a). The EPR spectrum of **2a** indicates the structure of **2a** to be that of low-spin Ni$^{III}$TMP ($g$ = 2.40, 2.12, 2.04). Introduction of a large excess amount of TFA to a $CH_2Cl_2$ solution of **2a** causes a further isosbestic spectral change, giving **3a** (Figure 1b). Appearance of a broad band at 600–700 nm for **3a** suggests the formation of a porphyrin π-cation radical.[12-14] Conclusive evidence for the porphyrin π-cation radical formation was obtained by the EPR measurement of **3a**. As shown in Figure 1b (inset), the absorbance at $g$ = 2.002 is an indication of free radical formation on the porphyrin ring, while the central nickel is diamagnetic.[12] The UV–vis and EPR spectra of **3a** allow us to assign its electronic structure to the Ni$^{II}$TMP π-cation radical. The transformation of Ni$^{III}$TMP to the Ni$^{II}$TMP π-cation radical by the introduction of a large amount of TFA could be caused by the change of the ligand from $^-OCOCF_3$ to $HOCOCF_3$ to weaken the ligand field. Similar reactions were also observed when **1b** was employed. While the formation of one-electron-oxidized nickel porphyrins (**2**, **3**) in the reactions of **1** with TFA suggests a homolytic N–O bond cleavage mechanism, an alternative heterolytic bond cleavage followed by rapid one-electron reduction also explains the observation of **2** and **3**. Especially, the formation of Fe(III) porphyrin dication complexes in the reaction of Fe(III) porphyrin *N*-oxides and TFA[5] is suggestive of the transient production of the dication complexes of Ni$^{II}$TMP and Ni$^{II}$TPP. The Ni$^{II}$TPP dication is known to react with methanol to afford the corresponding nickel(II) isoporphyrin.[12] Thus, the reaction of **1b** and TFA was examined in $CH_2Cl_2$–MeOH (40:1), and exclusive formation of Ni$^{III}$TPP was observed. The result supports the direct formation of **2** due to homolytic N–O bond cleavage. The reaction sequence is summarized in Scheme 1.

The reaction of **1** with TFA was also examined in ethyl acetate,

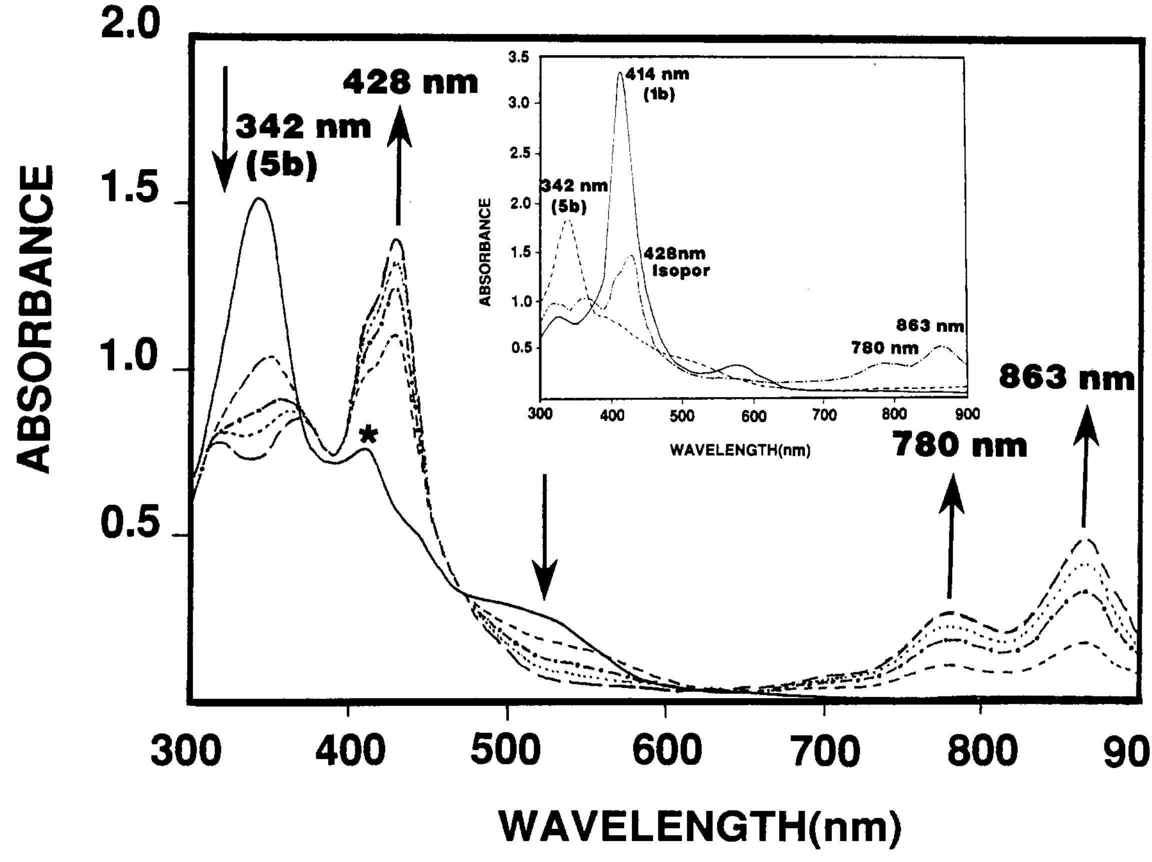

**Figure 3.** UV–vis spectral changes for the reaction of **5b** with MeOH in ethyl acetate at −20 °C ($2.4 \times 10^{-5}$ M). The inset shows a comparison of **1b**, **5b**, and isoporphyrin: solid line, **1b**; dotted line, **5b**; dashed line, isoporphyrin. The asterisked shoulder is due to Ni$^{III}$TPP(TFMS) as a byproduct in the reaction of **1b** with TFMS.

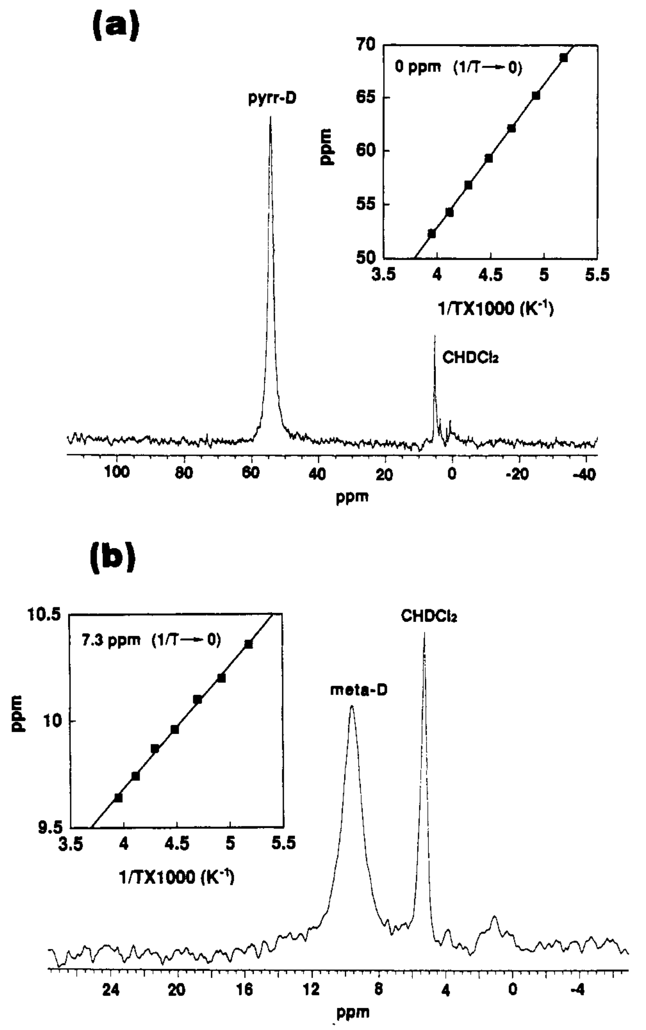

**Figure 4.** $^2$H NMR spectra of **5a** in $CH_2Cl_2$ at -30 °C: (a) pyrrole deuterium signal; inset, Curie plot; (b) meta deuterium signal; inset, Curie plot.

since polar solvents would favor the heterolytic N–O bond cleavage process over homolysis. The reaction profile is biphasic, i.e., instantaneous formation of **2a** followed by the production of **4a**.[15] The EPR spectrum of **4a** gives three absorptions at $g$ = 2.31, 2.27, 2.04 indicative of **4a** being a Ni(III) porphyrin. Thus, both **2a** and **4a** are Ni$^{III}$TMP complexes. We have tentatively assigned **2a** and **4a** to Ni$^{III}$TMP(TFA) and Ni$^{III}$TMP(TFA)$_2$, respectively.

**Reaction of 1 with TFMS.** Alteration of the acid from TFA to TFMS in the reaction with **1a** was found to give a new product (**5a**). The UV–vis spectrum of **5a** shows a less intense blue-shifted Soret band and disappearance of the Q band (Figure 2). The disappearance of the Q band in the UV–vis spectrum is suggestive of the porphyrin dication formation, since the loss of two electrons from the HOMO of the porphyrin ring will diminish the transition from the $A_{2u}$ to the $e_g$* orbital.[14] The reactions of TPP dication complexes of Zn(II), Mg(II), and Ni(II) with methanol readily afford isoporphyrins.[12,16] Thus, the reaction of **5b** with methanol was monitored directly by UV–vis spectroscopy at -20 °C. Introduction of MeOH to an ethyl acetate solution of **5b** causes the spectral changes shown in Figure 3. Two intense bands in the near-IR region are characteristic of isoporphyrin complexes.[16] Figure 3 (inset) shows the comparison of UV–vis spectra of **1b**, **5b**, and isoporphyrin in ethyl acetate at -20 °C. The formation of isoporphyrin provides further evidence for the dication structure of **5**.

The addition of 1 molar equiv of iodide to a solution of **5a** afforded Ni$^{II}$TMP, indicating that **5a** is a complex one-electron-oxidized from Ni$^{II}$TMP and isoelectronic structures for Ni$^{II}$-TMP$^{+\bullet}$ and Ni$^{III}$TMP. Therefore, the interconversion between **5a** and the Ni(III) porphyrin upon changing of the ligand field was examined. The addition of an excess of TFMS to an ethyl acetate solution of **4a** at -25 °C causes isosbestic UV–vis spectral changes to afford **5a**. Further, the addition of excess pyridine to an ethyl acetate solution of **5a** at -25 °C gives **6a**. The EPR spectrum of **6a** in ethyl acetate at 77 K shows two sets of five signals due to hyperfine coupling ($A_\perp$ = 16.6 G, $A_\parallel$ = 22.9 G) for the nitrogens of two pyridines around $g_\perp$ = 2.17 and $g_\parallel$ = 2.02, respectively, indicative of **6a** being Ni$^{III}$TMP(Py)$_2$. The reversible formation of **5a** from Ni$^{III}$TMP[17] implies that **5a** should be formulated as the Ni$^{I}$TMP dication.

In order to confirm the electronic structure of **5a**, $^2$H NMR spectra were examined. Figure 4 shows $^2$H NMR spectra of pyrrole-$d_8$ and *meta*-$d_8$ samples of **5a**. The resonances obey the Curie law in the temperature range -80 to -20 °C. Observation of the *meta* deuterium of the mesityl groups at ca. 9.8 ppm at -30 °C readily eliminates an $A_{2u}$ type porphyrin $\pi$-cation radical structure, since greater spin density of the radical orbital ($A_{2u}$) located at the *meso* carbons should induce large $\pi$-spin density at the phenyl carbons of the mesityl groups to result in large shifts of the phenyl proton signals (Figure 4b).[18] In addition, the formation of the Ni(I) porphyrin dication complex, for which an unpaired electron should be located in the $d_{x^2-y^2}$ orbital, explains a large downfield shift of the pyrrole deuterium of **5a** (Figure 4a).[19] An EPR measurement of **5a** was also performed. Though the EPR spectrum is expected to be very similar to that of nickel(I) octaethylisobacteriochlorin (d$^9$, $S$ = $^1/_2$),[20] no EPR signals of **5a** were observed even at 5 K in ethyl acetate. However, this could be explained by the rapid relaxation and broadness of the EPR signals, consistent with the observation of the sharp pyrrole deuterium signal for **5a**. The spectroscopic evidence described above demonstrates the first examples of Ni(I) porphyrin dication complexes.

In conclusion, we have shown the three isoelectronic structures of one-electron-oxidized nickel porphyrins (**3**–**5**) obtained in the reactions of Ni(II) porphyrin *N*-oxides (**1a**, **1b**) with acids. Especially, **5** is concluded to be an unusual Ni(I) porphyrin dication complex. In addition, reversible interconversion between a Ni(III) porphyrin and **5** was observed.

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