Inorg. Chem. **2007**, *46*, 1517–1519

Inorganic Chemistry
Communication

Photochemical Production of a Highly Reactive Porphyrin–Iron–Oxo Species

Zhengzheng Pan,[†] Rui Zhang,*[,‡] Leslie W.-M. Fung,*[,†] and Martin Newcomb*[,†]

Department of Chemistry, University of Illinois at Chicago, 845 West Taylor Street,
Chicago, Illinois 60607, and Department of Chemistry, Western Kentucky University,
Bowling Green, Kentucky 42101

Received October 14, 2006

Oxidation of 5,10,15,20-tetramesitylporphyrinatoiron(III) perchlorate, (TMP)$Fe^{III}(ClO_4)$, with ferric perchlorate in acetonitrile gave a metastable species identified as (TMP)$Fe^{IV}(ClO_4)_2$ that decayed within seconds to the known isomeric species $(TMP^{•+})Fe^{III}(ClO_4)_2$. Irradiation of the metastable species with 355 nm laser light gave a highly reactive transient that reacts with simple organic reductants (alkenes and arylalkanes) 5 orders of magnitude faster than known Compound I analogues, $(TMP^{•+})Fe^{IV}(O)(X^-)$.

Macrocyclic ligand-complexed transition-metal−oxo intermediates are the active species in a variety of biological and laboratory oxidation reactions,[1−3] and porphyrin−iron complexes, mimics of heme-containing peroxidase and cytochrome P450 enzymes, are widely studied. Neutral porphyrin−iron(IV)−oxo derivatives are well-known, relatively stable species.[4−7] More highly oxidized iron(IV)−oxo porphyrin radical cations, often called Compounds I in biological contexts, are the most reactive porphyrin−iron−oxo transients characterized to date.[8−12] Iron(IV)−oxo porphyrin radical cations are postulated to be the oxidants in systems that employ porphyrin−iron(III) salts as catalysts and sacrificial oxidants such as *m*-chloroperoxybenzoic acid or iodosobenzene.[13,14] In biological systems, Compounds I are formed by reactions of peroxidase and catalase enzymes with hydrogen peroxide,[12,15] and Compound I species are thought to be oxidants in cytochrome P450 enzymes.[16−18]

The high reactivity observed in catalytic reactions with iron−porphyrin species is not paralleled in stoichiometric reactions of iron(IV)−oxo porphyrin radical cations, which, for example, oxidize low-energy benzylic C−H bonds only sluggishly.[19,20] The cysteine thiolate ligand to iron in cytochrome P450 enzymes weakens an Fe−O bond and activates a Compound I species, but the Compound I derivative of the cytochrome P450 119 enzyme was found to be a low-reactivity species,[21] and the Compound I derivative of the heme thiolate enzyme chloroperoxidase reacts with organic substrates only 2−3 orders of magnitude faster than simple Compound I models.[22] Neither Compound I species in enzymes nor their model iron(IV)−oxo porphyrin radical cations will oxidize unactivated C−H bonds in hydrocarbons, where the C−H bond dissociation energies are about 10 kcal/mol greater than the benzylic C−H bond dissociation energy

---

* To whom correspondence should be addressed. E-mail: rui.zhang@wku.edu (R.Z.), lfung@uic.edu (L.W.-M.F.), men@uic.edu (M.N.).

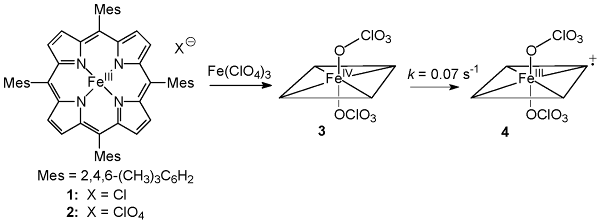
[†] University of Illinois at Chicago.

[‡] Western Kentucky University.

(1) Sheldon, R. A. *Metalloprophyrins in Catalytic Oxidations*; Marcel Dekker: New York, 1994.
(2) Meunier, B. *Metal−Oxo and Metal−Peroxo Species in Catalytic Oxidations*; Springer-Verlag: Berlin, 2000.
(3) Meunier, B. *Chem. Rev.* **1992**, *92*, 1411−1456.
(4) Balch, A. L.; Chan, Y. W.; Cheng, R. J.; La Mar, G. N.; Latos-Grazynski, L.; Renner, M. W. *J. Am. Chem. Soc.* **1984**, *106*, 7779−7785.
(5) Gold, A.; Jayaraj, K.; Doppelt, P.; Weiss, R.; Chottard, G.; Bill, E.; Ding, X.; Trautwein, A. X. *J. Am. Chem. Soc.* **1988**, *110*, 5756−5761.
(6) Bell, S. E. J.; Cooke, P. R.; Inchley, P.; Leanord, D. R.; Lindsay Smith, J. R.; Robbins, A. *J. Chem. Soc., Perkin Trans.* **1991**, *2*, 549−559.
(7) Groves, J. T.; Gross, Z.; Stern, M. K. *Inorg. Chem.* **1994**, *33*, 5065−5072.
(8) Groves, J. T.; Haushalter, R. C.; Nakamura, M.; Nemo, T. E.; Evans, B. J. *J. Am. Chem. Soc.* **1981**, *103*, 2884−2886.
(9) Balch, A. L.; Latos-Grazynski, L.; Renner, M. W. *J. Am. Chem. Soc.* **1985**, *107*, 2983−2985.
(10) Mandon, D.; Weiss, R.; Jayaraj, K.; Gold, A.; Terner, J.; Bill, E.; Trautwein, A. X. *Inorg. Chem.* **1992**, *31*, 4404−4409.
(11) Czarnecki, K.; Nimri, S.; Gross, Z.; Proniewicz, L. M.; Kincaid, J. R. *J. Am. Chem. Soc.* **1996**, *118*, 2929−2935.
(12) Hiner, A. N. P.; Raven, E. L.; Thorneley, R. N. F.; Garcia-Canovas, F.; Rodriguez-Lopez, J. N. *J. Inorg. Biochem.* **2002**, *91*, 27−34.
(13) Groves, J. T.; Watanabe, Y. *J. Am. Chem. Soc.* **1988**, *110*, 8443−8452.
(14) Nam, W.; Jin, S. W.; Lim, M. H.; Ryu, J. Y.; Kim, C. *Inorg. Chem.* **2002**, *41*, 3647−3652.
(15) Dawson, J. H. *Science* **1988**, *240*, 433−439.
(16) Ortiz de Montellano, P. R. *Cytochrome P450 Structure, Mechanism, and Biochemistry*, 3rd ed.; Kluwer: New York, 2005.
(17) Sono, M.; Roach, M. P.; Coulter, E. D.; Dawson, J. H. *Chem. Rev.* **1996**, *96*, 2841−2887.
(18) Denisov, I. G.; Makris, T. M.; Sligar, S. G.; Schlichting, I. *Chem. Rev.* **2005**, *105*, 2253−2277.
(19) Zhang, R.; Chandrasena, R. E. P.; Martinez, E., II; Horner, J. H.; Newcomb, M. *Org. Lett.* **2005**, *7*, 1193−1195.
(20) Pan, Z.; Zhang, R.; Newcomb, M. *J. Inorg. Biochem.* **2006**, *100*, 524−532.
(21) Newcomb, M.; Zhang, R.; Chandrasena, R. E. P.; Halgrimson, J. A.; Horner, J. H.; Makris, T. M.; Sligar, S. G. *J. Am. Chem. Soc.* **2006**, *128*, 4580−4581.
(22) Zhang, R.; Nagraj, N.; Lansakara, P. D. S. P.; Hager, L. P.; Newcomb, M. *Org. Lett.* **2006**, *8*, 2731−2734.

10.1021/ic061972w CCC: $37.00

Scheme 1



in ethylbenzene,[23] but the oxidants in the catalytic processes oxidize hydrocarbons so rapidly that they do not accumulate to detectable levels. One possible explanation presented[24,25] for the dichotomy between the low reactivities of iron(IV)−oxo porphyrin radical cations and the fast oxidation reactions of porphyrin−iron catalysts and P450 enzymes is that the actual oxidants in the catalytic systems are high-energy isomers of Compounds I, possibly porphyrin−iron(V)−oxo species.[26−28]

Our group reported photochemical entries to high-valent macrocyclic ligand manganese(IV)−oxo and manganese(V)−oxo derivatives by ligand cleavage reactions using laser flash photolysis (LFP) methods.[29] Related photochemical ligand cleavage reactions of high-valent iron azides gave iron(V)− and iron(VI)−nitrido species,[30] and photolysis of a corrole−iron(IV) chlorate gave a highly reactive transient tentatively identified as a corrole−iron(V)−oxo species.[31] We report here an extension of our studies to a porphyrin−iron complex, and photochemical production of an apparent iron−oxo species that is 5 orders of magnitude more reactive than the corresponding Compound I derivatives.

5,10,15,20-Tetramesitylporphyrinatoiron(III) chloride, (TMP)Fe^{III}Cl (**1**; Scheme 1), was converted to the known perchlorate salt (TMP)Fe^{III}(ClO$_4$) (**2**). Reaction of **2** with ferric perchlorate in CH$_3$CN gave a metastable species (**3**) that converted to the known derivative (TMP$^{\bullet+}$)Fe^{III}(ClO$_4$)$_2$ (**4**)[32] with a 10 s half-life at 20 °C (k = 0.07 s^{-1}).

Compound **3** was characterized as an iron(IV) species (S = 1) by UV−visible, electron paramagnetic resonance (EPR), and NMR spectroscopies and magnetic susceptibility measurements. It is EPR-silent as required for S = 1, and its magnetic susceptibility measured by the Evans NMR method[33] in CH$_3$CN was $\mu_{\mathrm{eff}} = 2.85\ \mu_{\mathrm{B}}$ (calcd for $S = 1$: $2.83\ \mu_{\mathrm{B}}$). An $S = {}^{3}/_{2}$ iron(III) derivative antiferromagnetically (AF) coupled to a porphyrin radical cation also would be EPR-silent, but the ^{1}H NMR spectrum of **3** (Figure 1) confirmed the former structure because the signals have positive δ values. For all aryl protons in **3**, the $S = 1$ species should have positive δ values, and the iron(III) species ($S = {}^{3}/_{2}$) AF coupled with a porphyrin radical cation should have negative δ values.[34,35]

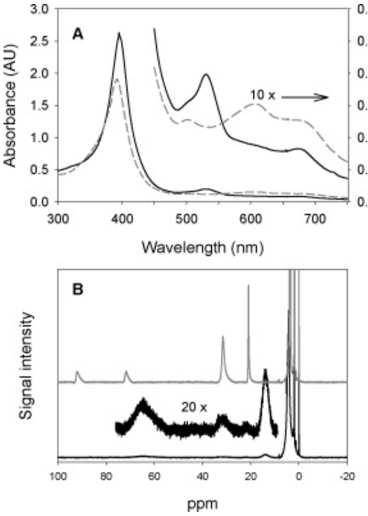


Figure 1. (A) UV−visible spectra. The spectrum of **3** is shown as the solid black lines, and that of **4** is shown as the dashed gray lines. (B) NMR spectra at −40 °C. The spectrum of **3** is the black line and expansion, and the spectrum of **4** is the gray line. See the Supporting Information for NMR spectral details.

The UV−visible spectrum of **3** further supports the assigned structure (Figure 1). The Soret band of **3** is sharp, and the Q band at 530 nm is pronounced, as is expected for a neutral porphyrin. The absorbance of **3** between 600 and 750 nm is too weak for a porphyrin radical cation species and, in fact, is weaker than that for neutral porphyrin 5,10,15,20-tetramesitylporphyrinatoiron(III) salts (Supporting Information). Isomer **4**, containing a porphyrin radical cation, has a UV−visible spectrum that resembles those of Compound I species (TMP$^{\bullet+}$)Fe^{IV}(O)(X) (Supporting Information).

LFP of **3** with 355 nm light in a CH$_3$CN solution gave a highly reactive transient (**5**) that could be monitored by UV−visible spectroscopy. A time-resolved difference spectrum is shown in Figure 2A, where the transient formed photochemically has a positive absorbance and decays with time and its product has a negative absorbance. Transient **5** has a Soret band absorbance that is red-shifted from that of its product with $\lambda_{\max}$ of the Soret band in the range of 395−405 nm and $\lambda_{\max}$ of the Q band at about 530 nm. The UV−visible spectrum of **5** is not similar to that of any known 5,10,15,20-tetramesitylporphyrinatoiron derivative.[7,32,36]

---

(23) Griller, D.; Kanabus-Kaminska, J. M.; Maccoll, A. *THEOCHEM* **1988**, *40*, 125−131.

(24) Watanabe, Y. *J. Biol. Inorg. Chem.* **2001**, *6*, 846−856.

(25) Newcomb, M.; Chandrasena, R. E. P. *Biochem. Biophys. Res. Commun.* **2005**, *338*, 394−403.

(26) Ogliaro, F.; de Visser, S. P.; Groves, J. T.; Shaik, S. *Angew. Chem., Int. Ed.* **2001**, *40*, 2874−2878.

(27) Dey, A.; Ghosh, A. *J. Am. Chem. Soc.* **2002**, *124*, 3206−3207.

(28) A synthetic putative iron(V)−oxo−porphyrin species was reported, but theoretical calculations suggest that the species is not a true iron(V)−oxo species. See: Yamaguchi, K.; Watanabe, Y.; Morishima, I. *J. Chem. Soc., Chem. Commun.* **1992**, 1721−1723 and ref 27.

(29) (a) Newcomb, M.; Zhang, R. *J. Am. Chem. Soc.* **2003**, *125*, 12418−12419. (b) Zhang, R.; Horner, J. H.; Newcomb, M. *J. Am. Chem. Soc.* **2005**, *127*, 6573−6582. (c) Zhang, R.; Harischandra, D.; Newcomb, M. *Chem.−Eur. J.* **2005**, *11*, 5713−5720.

(30) (a) Wagner, W. D.; Nakamoto, K. *J. Am. Chem. Soc.* **1989**, *111*, 1590−1598. (b) Berry, J. F.; Bill, E.; Bothe, E.; George, S. D.; Mienert, B.; Neese, F.; Wieghardt, K. *Science* **2006**, *312*, 1937−1941.

(31) Harischandra, D. N.; Zhang, R.; Newcomb, M. *J. Am. Chem. Soc.* **2005**, *127*, 13776−13777.

(32) Groves, J. T.; Quinn, R.; McMurry, T. J.; Nakamura, M.; Lang, G.; Boso, B. *J. Am. Chem. Soc.* **1985**, *107*, 354−360.

(33) (a) Evans, D. F. *J. Chem. Soc.* **1959**, 2003−2005. (b) Sur, S. *J. Magn. Reson.* **1989**, *82*, 169−173.

(34) Walker, F. A. *Inorg. Chem.* **2003**, *42*, 4526−4544.

(35) The representation of **3** and **4** in Scheme 1 with two perchlorate anions bound to iron is for convenience. One bound perchlorate is required for the photochemistry of **3**, and compound **4** and related species are known to have bound perchlorate (see ref 32).

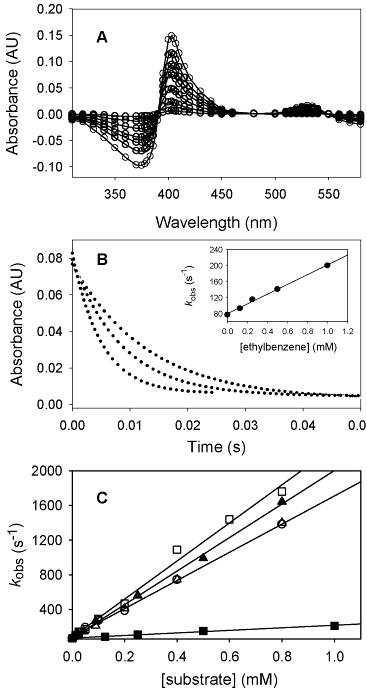


Figure 2. (A) Time-resolved spectrum for 100 ms following 355 nm irradiation of species **3** in CH_3CN at ambient temperature. (B) Representative kinetic traces at 403 nm (gray lines) and fits (dotted lines) from the reactions of **5** with ethylbenzene at (from the top) 0.0, 0.25, and 1.0 mM concentrations in CH_3CN at ambient temperature. Observed rate constants are plotted in the inset of the figure. (C) Observed rate constants for reactions of **5** in CH_3CN at ambient temperature with diphenylmethane (■), *cis*-cyclooctene (○), *trans*-stilbene (△), *cis*-stilbene (▲), and cyclohexene (□). The lines (the slopes of which are the second-order rate constants) are regression solutions.

Transient **5** is a remarkably reactive species. When produced in CH_3CN in the absence of additional organic reductants, **5** decayed with a 10 ms half-life ($k = 77$ s^{-1}) at ambient temperature. When organic reductants were present, the decay of **5** accelerated linearly with the reductant concentration (Figure 2), indicating second-order reactions. From the pseudo-first-order rate constants obtained with various concentrations of reductants (Supporting Information), we obtained the second-order rate constants listed in Table 1. The high reactivity of **5** is apparent by comparison of these rate constants to those for the Compound I derivative $(TMP^{\bullet+})Fe^{IV}(O)(ClO_4)$[20] (**6**) and the 5,10,15,20-tetrakis(pentafluorophenyl)porphyrin−manganese(V)−oxo cation[29] (**7**). Species **7** is the most reactive porphyrin−metal−oxo complex with known rate constants,[29] and transient **5** is comparable in reactivity to **7**.

Table 1. Second-Order Rate Constants for Reactions of **5**−**7** with Organic Reductants[a]

substrate	**5**	**6**[b]	**7**[c]
diphenylmethane	$(1.5 \pm 0.4) \times 10^5$	1.3	1.4×10^5
ethylbenzene	$(1.2 \pm 0.1) \times 10^5$	1.6	1.3×10^5
trans-stilbene	$(1.6 \pm 0.1) \times 10^6$	3.4	
cis-stilbene	$(2.0 \pm 0.2) \times 10^6$	90	6.1×10^5
cis-cyclooctene	$(1.6 \pm 0.1) \times 10^6$	62	
cyclohexene	$(2.2 \pm 0.3) \times 10^6$	68	

[a] Second-order rate constants in units of M^{-1} s^{-1} for reactions in CH_3CN at 20 ± 2 °C; errors in the rate constants for **5** are at 2σ. [b] **6** = $(TMP^{\bullet+})Fe^{IV}(O)(ClO_4)$; kinetics are from ref 20. [c] **7** = 5,10,15,20-tetrakis(pentafluorophenyl)porphyrinatomanganese(V) oxo cation; kinetics are from ref 29b.

The nature of transient **5** was suggested by its reaction with an alkene, which indicated that **5** behaved as an oxygen-transfer metal−oxo species as opposed to a radical-generating species. An acetonitrile solution of **2** and 1.2 equiv of $Fe(ClO_4)_3$ at −40 °C gave **3** in 80% yield, as determined by UV−visible spectroscopy. Addition of excess cyclooctene to this and irradiation with 350 nm light in a photochemical reactor gave cyclooctene oxide (28% based on **3**). Control reactions demonstrated that no epoxide was formed without light, without **2**, without $Fe(ClO_4)_2$, or when **3** was allowed to decay to **4** before irradiation. In the preparative reaction, salt **2** was the major porphyrin compound present by UV−visible spectral analysis after the reactions. This result and the isosbestic behavior at 390 nm in the LFP experiments (Figure 2A) indicate that **5** reacted to give porphyrin−iron(III) salts directly.

Transient **5** cannot be a simple ligand-exchanged derivative of **6**. It reacts 5 orders of magnitude faster than **6** and the chloride salt analogue,[20] and substitution of the axial ligand in **6** by the weak binding solvent CH_3CN would give an even less reactive species.[37] We speculate that **5** is an isomer of **6**, however, possibly one best described as an iron(V)−oxo species.[26,27,31] Electronic excited states of porphyrin−metal complexes relax on the picosecond time scale,[29b] and a porphyrin−iron(V)−oxo species that existed in the millisecond time frame would require a high barrier for internal electron transfer from the porphyrin to the metal.

Transient **5** appears to be a member of a new class of porphyrin−iron−oxo derivatives as deduced by its unique UV−visible spectrum in comparison to known Compound I analogues, the formation of epoxide product in reaction with cyclooctene, and the very high reactivity of **5**. Further characterization of this species will lead to a better understanding of its detailed structure, but it is noteworthy that **5** displays reactivity appropriate for the active oxidants in a catalytic process under turnover conditions and in cytochrome P450 enzymes.

Acknowledgment. This work was supported by NIH Grants GM-48722 and GM-068621.

Supporting Information Available: Experimental details, time-resolved, ^{1}H NMR, and UV−visible spectra, and kinetic traces for reactions of **5**. This material is available free of charge via the Internet at http://pubs.acs.org.

IC061972W

---

(36) Mizutani, Y.; Hashimoto, S.; Tatsuno, Y.; Kitagawa, T. *J. Am. Chem. Soc.* **1990**, *112*, 6809−6814.

(37) (a) Gross, Z.; Nimri, S. *Inorg. Chem.* **1994**, *33*, 1731−1732. (b) Nam, W.; Won, J. S.; Lim, M. H.; Ryu, J. Y.; Kim, C. *Inorg. Chem.* **2002**, *41*, 3647−3652.