bond. This formulation is also consistent with the proposed synergistic π-base effect on oxygenations.[5b,6d]

These results indicate that the heme–oxygen complexes are more stable and more easily prepared than has been suspected. While minimal requirements for reversible oxygenation remain to be established, some factors which contribute to optimal binding are now apparent. Current results suggest that an ideal oxyheme would have a single "proximal" imidazole (or other equally good π and/or σ base) having the "distal" side protected from other hemes or from protic solvents and a polar aprotic "solvent" environment.[14,15]

The effect of local environment on the reactivity of coordinated O_2 in oxyheme proteins is apparently more complex than has been previously indicated. Our results agree with the suggestion of Cole, Curthoys, and Magnusson[19] that the distinctions among oxygen carriers and oxidases might be due in part to subtle differences in the polarity as well as protic environment in the immediate vicinity of the heme group.

(14) The "picket fence" iron porphyrin of Collman, et al.,[7] has amide groups near the Fe–OO bond and possibly owes some of its oxygen binding ability to a local "polar solvent" environment.

(15) Previously reported heme–oxygen complexes[5-8,16,17] incorporated some of these properties but none has yet incorporated all of them. The previously synthesized heme cyclophane[18] should incorporate most of these effects.

(16) J. A. Wang, J. Amer. Chem. Soc., 80, 3168 (1958).

(17) A. H. Corwin and S. D. Bruck, J. Amer. Chem. Soc., 80, 4736 (1958).

(18) H. Diekmann, C. K. Chang, and T. G. Traylor, J. Amer. Chem. Soc., 93, 4068 (1971).

(19) S. J. Cole, G. C. Curthoys, and E. A. Magnusson, J. Amer. Chem. Soc., 93, 2153 (1971).

(20) On leave from the Department of Chemistry, Temple University, Philadelphia, Pa.

W. S. Brinigar,[20] C. K. Chang, J. Geibel, T. G. Traylor*

Department of Chemistry, University of California, San Diego
La Jolla, California 92037
Received March 18, 1974

Reversible Reaction of Simple Ferrous Porphyrins with Molecular Oxygen at Low Temperatures

Sir:

Currently there is great interest in studying model compounds of myoglobin and hemoglobin. In recent years this has led to the preparation of cobalt oxygen carriers whose properties have been extensively studied.[1,2] However, when similar iron compounds, such as porphyrins and Schiff bases, are allowed to react with oxygen under analogous conditions, irreversible oxidation to a μ-oxo dimer results.[3,4] In order to prevent dimer formation, sterically hindered iron complexes have been prepared, which react reversibly with oxygen.[5,6] Traylor and Chang have prepared a section of the myoglobin active site which also reacts reversibly with oxygen.[7] This is attributed to the neighboring

(1) R. G. Wilkins, Advan. Chem. Ser., No. 100, 111 (1971).

(2) (a) F. A. Walker, J. Amer. Chem. Soc., 95, 1154 (1973); (b) D. V. Stynes, H. C. Stynes, B. R. James, and J. A. Ibers, ibid., 95, 1796 (1973); (c) M. J. Carter, D. P. Rillema, and F. Basolo, ibid., 96, 392 (1974).

(3) J. P. Collman and C. A. Reed, J. Amer. Chem. Soc., 95, 2048 (1973).

(4) F. Calderazzo, C. Floriani, R. Henzi, and F. L'Eplattenier, J. Chem. Soc. A, 1378 (1969).

(5) J. E. Baldwin and J. Huff, J. Amer. Chem. Soc., 95, 5757 (1973).

(6) J. P. Collman, R. R. Gagne, T. R. Halbert, J.-C. Marchon, and C. Reed, J. Amer. Chem. Soc., 95, 7868 (1973).

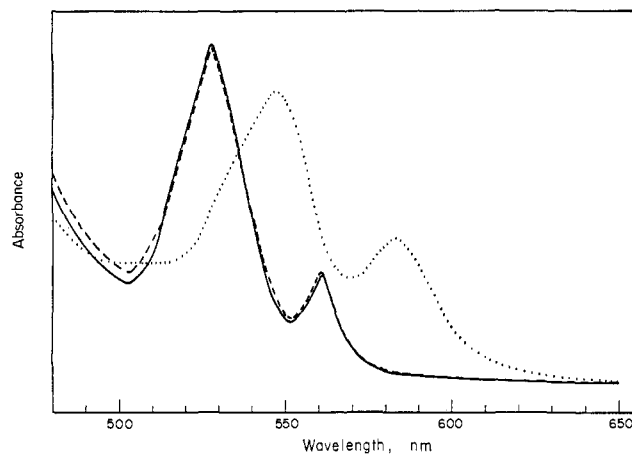(7) C. K. Chang and T. G. Traylor, J. Amer. Chem. Soc., 95, 5810 (1973).

Figure 1. Visible spectrum of $\sim 1 \times 10^{-4}$ F Fe(py)$_2$TPP in methylene chloride at $-78°$: (—) under nitrogen, (····) under oxygen, (- - - -) under nitrogen after one oxygenation–deoxygenation cycle.

group effect of an attached imidazole and to the low temperature $(-45°)$ retardation of irreversible oxidation.

We have preliminary evidence that at low temperatures simple ferrous porphyrins also react reversibly with molecular oxygen. The complexes examined in this work are meso-tetraphenylporphyrinbis(pyridine)iron(II), Fe(py)$_2$TPP,[8] meso-tetraphenylporphyrinbis(1-methylimidazole)iron(II), Fe(1-Me(imid))$_2$TPP,[9] and meso-tetraphenylporphyrinbis(piperidine)iron(II), Fe(pip)$_2$TPP.[10] A water free methylene chloride solution of Fe(py)$_2$TPP, prepared under nitrogen without any added pyridine, is exposed to oxygen at $-78°$. Over a period of 20 min the visible spectrum[11] is shifted into the red region (Figure 1). Removal of oxygen (effected by bubbling rigorously dried and deoxygenated nitrogen through the solution) returns the spectrum to that characteristic of Fe(py)$_2$TPP. Three oxygenation–deoxygenation cycles can be accomplished with less than 10% irreversible oxidation occurring. The spectrum of the solution in the presence of oxygen is very similar to that reported by Collman, et al.,[6] for 1:1 binding of dioxygen by iron(II) in Fe(O$_2$)(1-Me(imid))-($\alpha,\alpha,\alpha,\alpha$-TpivPP) in benzene. This compound is a substituted iron meso-tetraphenylporphyrin whose spectral changes should be similar to those of the unsubstituted complex. Oxygen uptake of Fe(py)$_2$TPP–methylene chloride solutions indicates that 0.96 ± 0.10 mol of O$_2$ are taken up per mole of Fe(py)$_2$TPP initially present.[12] Hence we formulate the observed oxygen adduct as Fe(O$_2$)(py)TPP. Similar spectral changes and reversible behavior are observed for Fe(1-Me(imid))$_2$TPP and Fe(pip)$_2$TPP in methylene chloride at $-78°$.

(8) H. Kabayashi and Y. Yanagawa, Bull. Chem. Soc. Jap. 45, 450 (1972). The preparative procedure followed involves direct reaction of the porphyrin with ferrous acetate. Hence the observed reversibility cannot be ascribed to incomplete removal of a reductant.

(9) Reference 3. Our sincere thanks to Professor J. P. Collman and Dr. R. R. Gagne for generously providing us with a sample of this complex.

(10) L. M. Epstein, D. K. Straub, and C. Maricondi, Inorg. Chem., 6, 1970 (1967).

(11) Spectral measurements were made using a Pyrex cell mounted in a dewar. See ref 2c.

(12) Determined using a 2-cm^{-3} gas buret at constant temperature (solution at $-45°$) and pressure (1 atm); complex contained in a glass ampoule prior to measurement. We are grateful to Professor J. E. Baldwin for helpful suggestions regarding this technique.

This reaction is extremely sensitive to temperature. At room temperature, Fe(py)₂TPP in methylene chloride irreversibly oxidizes with no detectable spectral evidence of adduct formation. At −45°, after 9 min of exposure to oxygen, the spectrum shows that the primary species present is the oxygen adduct. Upon purging with nitrogen, the final spectrum indicates that only about 70% of the initial ferrous complex can be regenerated. However, at −78°, after 17 hr of exposure to oxygen, 85% of the dioxygen complex could still be reversed to the iron(II) state.

In the case of cobalt oxygen carriers, as the dielectric constant of the solvent increases (provided that the solvent is noncoordinating), the equilibrium constant for the formation of the oxygen adduct likewise increases.[13,14] A similar relationship has been found for Fe(py)₂TPP in various solvents at −78°. Under 1 atm of oxygen, complete adduct formation occurs in methylene chloride; only a small amount of adduct is formed in toluene, whereas the degree of adduct formation in ethyl ether lies in between these extremes. This is consistent with the dielectric constants of these solvents; at 20° the values for methylene chloride, ethyl ether, and toluene are[15] respectively 9.08, 4.34, and 2.39. At −78°, these constants are larger, but the same relative order applies. It should be emphasized that in all three solvents, despite varying degrees of adduct formation, the reaction with molecular oxygen is completely reversible at −78°.

(13) H. C. Stynes and J. A. Ibers, *J. Amer. Chem. Soc.*, **94**, 5125 (1972).

(14) M. J. Carter, Ph.D. Thesis, Northwestern University, Evanston, Ill., 1973.

(15) "Handbook of Chemistry and Physics," 43rd ed, The Chemical Rubber Publishing Co., Cleveland, Ohio, 1961, pp 2552–2557.

(16) Subsequent to our observations, Professor Baldwin has found similar reversible oxygen behavior with mesoporphyrin IX bis(1-methylimidazole)iron(II) in methylene chloride at −52°. See J. Almog, J. E. Baldwin, R. L. Dyer, J. Huff, and C. J. Wilkerson, *J. Amer. Chem. Soc.*, **96**, 5600 (1974).

David L. Anderson, Charles J. Weschler, Fred Basolo*

*Department of Chemistry, Northwestern University
Evanston, Illinois 60201*
Received May 1, 1974

Reversible Binding of Dioxygen to Mesoporphyrin IX Derivatives at Low Temperatures

Sir:

The reversible formation of dioxygen complexes with iron(II) derivatives, initially at low temperatures[1–3] and subsequently at 25°,[4,5] has recently been reported. The factors influencing the stability of such complexes

(1) J. E. Baldwin and J. Huff, *J. Amer. Chem. Soc.*, **95**, 5757 (1973).

(2) (a) C. K. Chang and T. G. Traylor, *J. Amer. Chem. Soc.*, **95**, 5810 (1973); (b) *ibid.*, **95**, 8475 (1973); (c) *ibid.*, **95**, 8477 (1973).

(3) Professor F. Basolo has kindly informed us of the observed reversible behavior of *meso*-tetraphenylporphyriniron(II) derivatives at −78°. The apical ligands used in these experiments were pyridine, 1-methylimidazole, and piperidine.

(4) (a) J. P. Collman, R. R. Gagné, T. R. Halbert, J.-C. Mardion, and C. Reed, *J. Amer. Chem. Soc.*, **95**, 7868 (1973); (b) J. P. Collman, R. R. Gagné, and C. A. Reed, *ibid.*, **96**, 2629 (1974).

(5) J. Almog, J. E. Baldwin and J. Huff, in preparation.

toward irreversible oxidation to iron(III) species are becoming clear. Thus in the original octaazamacrocyclic iron complex it was shown that steric hindrance protected the bound oxygen molecule,[1] and subsequently[4,5] the same influence was found to stabilize porphyrin derived iron(II) dioxygen complexes at room temperature. The current explanation of this phenomenon is found in a reduction, by steric hindrance, of the rate of the bimolecular redox process, eq 1. Re-

$$Fe^{II}O_2 + Fe(II) \rightarrow Fe^{II}-O-O-Fe^{II} \rightarrow Fe(III) \qquad (1)$$
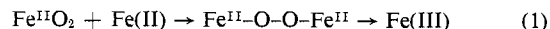
cently an unhindered pentacoordinate porphyrin iron-(II) complex (1) was reported[2a] to reversibly bind oxygen at −45° and the successful binding was attributed to "the neighboring group effect of the covalently attached imidazole" as well as to the temperature effect on process 1. Since the iron(II) species was produced *in situ* by sodium dithionite reduction of the iron(III) species, we felt initially that reversibility could be attributed to residual traces of reductant.[6] Consequently we synthesized the mixture (1:1) of the mesoporphyrin IX derivative **2a** and **2b**[7,8] and converted this through the iron(III) bromo derivative to the iron(II) species by reduction with chromous bis(acetylacetonate) in benzene.[4a] On dissolution of the iron(II) species from **2** in precooled (−50°) dichloromethane[10] at low concentrations (*ca.* 10⁻⁴ M), reversible oxygenation was observed spectrally, confirming *in toto* the previous report[2a] and excluding thereby any possibility of residual reductant. The dioxygen adduct is stable at −50°, showing no deterioration after 45 min. Addition of excess cold pyridine to this adduct solution results in the typical hemochrome spectrum, Figure 1, thus confirming unambiguously the presence of the iron(II) porphyrin.

To investigate the possibility that the neighboring group effect is not important in stabilizing the oxygen adduct of **2**, we synthesized mesoporphyrin IX bis(1-methylimidazole)iron(II) (**3a**) from the mesoporphyrin dimethyl ester by the method described above. A dilute solution of compound **3a** in dichloromethane, (10⁻⁴ M, −50°) reacts reversibly with oxygen as shown by regeneration of the hemochrome spectrum on addition of pyridine, Figure 1. The spectral changes observed were identical with those we have recorded for compound **2**.[11] Furthermore we have measured the stoichiometry of oxygen binding of **3a** by our earlier described volumetric procedure[1] and found a value of O_2:Fe of 1.00 ± 0.04 at −50° and 10⁻³ M. These experiments prove that contrary to the earlier report,[2a,b]

(6) The spectral solutions are dilute [10⁻⁴ M], consequently the amount of residual reductant required would be very low. A previous example of this phenomenon in experiments alleged to describe reversible oxygenation has been recorded; *cf.* M. J. Cowan, J. M. F. Drake, and R. J. P. Williams, *Discuss. Faraday Soc.*, **27**, 217 (1959); Thesis of R. C. Davies, Wadham College, Oxford, 1963.

(7) A mixture (1:1) of the two monoesters of mesoporphyrin IX was obtained by partial esterification with diazomethane. This mixture was coupled with 1-(3-aminopropyl)imidazole,[9] through the mixed pivaloyl anhydride to yield the amide **2a, b**.

(8) All new substances have been characterized by spectroscopic and where possible analytical data.

(9) J. J. Schwan, *J. Heterocycl. Chem.*, **4**, 633 (1967).

(10) These iron(II) complexes, from **2** and **3**, react at room temperature with dichloromethane to yield the iron(III) species. At −50° this reaction is very slow.

(11) We have also repeated the earlier report[2a] by reducing the iron-(III) bromo derivative of **2a, b** with aqueous sodium dithionite solution and then filtering at −45° under argon. The reversible spectral changes are identical with those previously recorded[2a] for this solution and are identical with those observed for **3a**.