At least initially the 1-oxatetramethylene **3** must be created as a singlet and the lifetime of this species might be enhanced by efficient intersystem crossing to its triplet. In this respect our 1,4-diradical may reflect the behavior of the 2-oxatetramethylene **2**.[15] However, our present data cannot shed light on this mechanistically relevant point.

An alternative mechanism which considers fast and reversible simple homolysis of the O–O bond, followed by a rate-determining decarboxylation and/or deketonation is unlikely in view of the appreciable secondary isotope effect and the lack of production of β-lactone **11**. Such a mechanism would require that fragmentation and not generation of the intermediary 1,6-diradical is rate-determining, analogous to the thermal isomerization of cyclopropane into propene for which rearrangement and not generation of the trimethylene diradical is rate determining.[2b] Although the fragmentation of diradicals can exhibit small secondary isotope effects, *e.g.*, the concerted double deketonation of the 1,6-dioxahexamethylene diradical produced in the thermolysis of 1,2-dioxanes,[16] the isotope effect is expected to be negligible for the considerably more exothermic decarboxylation compared to ketonation.[17] However, it seems pertinent to prove this question rigorously by determining the secondary isotope effects separately for α- and β-deuteration. Also chemical trapping experiments of the 1-oxatrimethylene **3** seem feasible in view of their lifetime.[4a] Both mechanistic questions are currently under scrutiny.

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(18) A. P. Sloan Fellow 1968–1972; J. S. Guggenheim Fellow 1972–1973.
(19) Western Fher Fellow 1971–1972; taken in part from the doctoral dissertation.

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Dynamics and Thermodynamics of Axial Ligation in Metalloporphyrins. III. Effects of Molecular Interaction of Ferric Porphyrins with an Aromatic Acceptor

Sir:

The presently available X-ray crystallographic data on a variety of homoproteins[1,2] provide strong evidence for the ubiquitous nature of molecular interaction between porphyrin π system[3] and certain aromatic side chains of the protein. The importance of these aromatic interactions is evidenced by the invariance with genetic origin of the participating aromatic amino acids.[1] Similar π complexes between chlorophyll and quinones[4] have been postulated in the initial stages of the photosynthetic process.

In the myoglobins and hemoglobins[1] the prominent function of these molecular interactions appears to be to position the noncovalently held protoporphyrin in the heme cavity. In the cytochromes, in addition, changes in the molecular interactions[2] are tied to the structural changes accompanying the redox process.

Although it has been demonstrated[5–7] that model porphyrin complexes may interact with a variety of aromatic residues, ostensibly yielding π complexes, previous studies have shed little light on the effect of molecular interactions on the function of the iron in the heme group.

We report here on a proton nmr investigation of the molecular interaction between ferric complexes of tetraphenylporphine, TPP, or octaethylporphyrin, OEP, with the organic π acceptor trinitrobenzene, TNB, in $CDCl_3$, with the objective of determining the effects of this interaction on the thermodynamics and kinetics[8] of axial ligation in both high-spin, HS, and low-spin, LS, porphyrins. We explored the effect of TNB on the following two recently characterized reactions[9,10]

$$\text{TPPFeCl} + 2\text{L} \rightleftharpoons \text{TPPFeL}_2^+\text{Cl}^- \quad (1)$$

$$\text{OEPFeCl} + \text{Cl}^{-*} \rightleftharpoons \text{OEPFeCl}^* + \text{Cl}^- \quad (2)$$

(where L = *N*-methylimidazole).

K_{eq} for reaction 1 is given by $K_{eq} = [\text{TPPFeL}_2^+\text{Cl}^-]/(\text{TPPFeCl})[\text{L}]^2$, and can be conveniently determined[11] by integration of the nmr spectrum. Table I illustrates the effect on the apparent K_{eq} in eq 1 upon the addition of TNB; the decrease in K_{eq} indicates that

Table I. Effect of Trinitrobenzene on the Apparent Equilibrium Constant for the Axial Coordination of *N*-Methylimidazole to Ferric Porphyrins[a]

$[\text{TNB}]^b/[\text{Fe}]_{total}$	$K_{eq} \times 10^{-3}$	$[\text{TNB}]^b/[\text{Fe}]_{total}$	$K_{eq} \times 10^{-3}$
0.00	1.43	1.95	0.38
0.23	0.91	3.28	0.27
0.44	0.77	5.82	0.17
0.98	0.55	7.80	0.14

[a] $K = [\text{TPPFeL}_2^+\text{Cl}^-]/(\text{TPPFeCl})[\text{L}]^2$, when L = *N*-methylimidazole; $CDCl_3$ solvent at 25°. [b] Mole ratio of TNB to total ferric porphyrin complex.

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(11) ^{1}H nmr spectra were run on a Jeol PS-100 FT spectrometer using a Digilab nmr-3 data system; solutions were ~0.02 *M* in complex.

the interaction favors the five-coordinate, HS form. The TNB signal is broadened and shifted upfield considerably,[12] confirming a specific interaction with at least one of the porphyrin species. In a solution containing only the LS form, the diamagnetic TNB signal is unaffected, as is the rate of ligand exchange[9] in reaction 1. In the presence of only the HS form, the TNB peak is again broadened past detection by paramagnetic relaxation[13] and shifted upfield by the porphyrin ring current; the shifts and line width of TPPFeCl are unaffected. This clearly demonstrates that TNB interacts only with, and stabilizes, TPPFeCl.

The kinetics of chloride exchange[10] in eq 2 were monitored by the collapse of the α-CH_2 doublet of OEPFeCl upon addition of excess Cl^- in the form of $Bu_4N^+Cl^-$. The second-order exchange rate ([OEPFeCl] = 0.04 *M*, [Bu_4NCl] = 0.65 *M*) was 600 sec^{-1} for the HS complex at 76°, decreasing to 400 sec^{-1} in the presence of an equimolar amount of TNB. Since chloride exchange has been demonstrated[10] to proceed *via* a six-coordinated intermediate, the results again indicate that formation of the molecular complex stabilizes the five-coordinate, HS species. The effect of TNB on the thermodynamics of eq 1 and the kinetics of eq 2 must reflect a specific interaction with the HS form and not just a solvent effect, since numerous other, similar molecules failed to produce detectable changes at comparable concentrations.[14]

Preliminary analysis suggests that the reduced affinity for axial ligands originates in an electronic effect due to porphyrin–TNB interaction which is transmitted to the metal, rather than from a steric blocking of the axial site by TNB. Hence the TPPFeCl–TNB interaction is envisaged to occur at the periphery of the porphyrin involving a single pyrrole. The basis of this conclusion is that molecular models[15] indicate that, due to the perpendicular phenyl rings, planar π complexes can occur either directly over the metal, or at the periphery with a single pyrrole at a time. The former configuration is considered unlikely since the TPPFeCl line widths are unaffected by TNB interaction. Previous work had shown[16] that the line width is a very sensitive indicator of the axial field strength, such that a TNB over the metal should lead to a significant increase in line width.[17] Similar peripheral interactions have been characterized for LS biscyano hemins.[18]

Previous analyses of iron–porphyrin π bonding have indicated[19,20] the dominance of Fe → P π^* and P → Fe π charge transfer in the HS and LS forms, respectively. Hence the preferred interaction of TNB is consistent with the larger ligand charge density in the HS form. The reduced affinity for additional axial ligand in the HS form is suggested to be the result of the stabilization of the Fe–P bond as a result of interaction with TNB.

The demonstrated reduced affinity for a sixth ligand due to the molecular interaction with an acceptor may be relevant to the action of oxygen binding hemoproteins. In such proteins, the aromatic amino acid residues are generally donors, which would be expected to increase the affinity for the axial ligand over that of the free porphyrin. We have failed to observe effects with a strong donor, probably due to unfavorable free energy considerations.[21] In the protein, however, such interactions could occur due to steric constraints imposed by the folding of the polypeptide backbone.

Current work is aimed at a more detailed description of the molecular interaction with iron as well as other metalloproteins with respect to changes in the axial ligation and redox properties of the metal ion.

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(12) At the ratio [TNB]/[TPPFeCl] ~ 8, the TNB shift is 2.6 ppm upfield from its diamagnetic position, and the line width is ~80 Hz. At lower ratios the line width is so great that the TNB peak cannot be resolved under the TPP phenyl resonances.

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(14) The organic molecules hexamethylbenzene, phenanthrene, phenazine, perylene, acridine, and dimethylaniline produced little changes even at concentrations much greater than for TNB. Furthermore, TNB unlike the other ligands above, causes changes in the optical spectrum of TPPFeCl. The changes in K_{eq} due to TNB are larger than predicted by any 1:1 interaction of TNB with *N*-methylimidazole.

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(17) The lack of changes in the TPPFeCl line widths upon addition of TNB argues strongly against direct coordination of TNB. ^{13}C T_1 measurements on TNB in the presence of TPPFeCl reveal that the two carbons have very similar relaxation times, which is also inconsistent with direct coordination of the TNB *via* the NO_2 group.

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(21) An effect on the equilibrium in eq 1 due to the presence of a donor (*o*-phenanthroline) has been detected (E. H. Abbott, private communication) by monitoring the optical absorption bands of the HS and LS species. The presence of the donor has the effect of *increasing* the apparent K_{eq}, suggesting that the six-coordinate, LS form is stabilized.

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Generation and Reactivity of α-Carbethoxyvinylcuprate

Sir:

While the search for new syntheses of prostaglandins has generated considerable interest and development in the area of terminal vinyl cuprate reagents,[1] the applications of functionalized nonterminal vinyl copper reagents are few indeed.[2] α-Carbalkoxy- and α-carboxyvinylic cuprates have been generated *in situ* from conjugate addition of organocopper reagents to acetylenic esters and acids.[3-5] Whereas oxidation, protonation, and iodination of these intermediates have

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