Authentic contact contributions to the carbon shifts of *exo*-norbornylamine are produced by cobalt and nickel acetylacetonates (Figure 1B) which reflect the trends previously observed.[6,8,9] It will be seen that the deviations from the carbon shifts which we have observed with Eu(DPM) and *exo*-norbornylamine as well as those with borneol and isoborneol and lanthanide chelates[4] fit the idea that the contact contributions for these cases are *opposite in sign* for the α and β carbons, and are larger for the more highly substituted carbon.[6b] Furthermore, the evidence is that the praseodymium contact contributions are *opposite in sign* to the europium contact contributions. This is most clearly seen for the borneol–isoborneol carbon shifts[4] but can also be qualitatively inferred from the difference between the C-1 and C-2 praseodymium-induced shifts shown in Figure 1B.

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[9] The sizable downfield shift of C-6 produced by Ni(AcAc)$_2$, which contrasts to the very small shifts at C-4, C-5, and C-7, may represent a special long-range stereospecific contact contribution; see also S. R. Johns, R. A. Smith, G. E. Hawkes, and J. D. Roberts, *Proc. Nat. Acad. Sci. U. S.*, in press.

[10] NATO Postdoctoral Fellow, 1970–1972.

Geoffrey E. Hawkes,[10] Claude Marzin
S. R. Johns, John D. Roberts*
Contribution No. 4484
Gates and Crellin Laboratories of Chemistry
California Institute of Technology
Pasadena, California 91109
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Dynamics of Axial Ligation in Metalloporphyrins. II. Porphyrin "Inversion" and Halogen Exchange in High-Spin Iron Complexes

Sir:

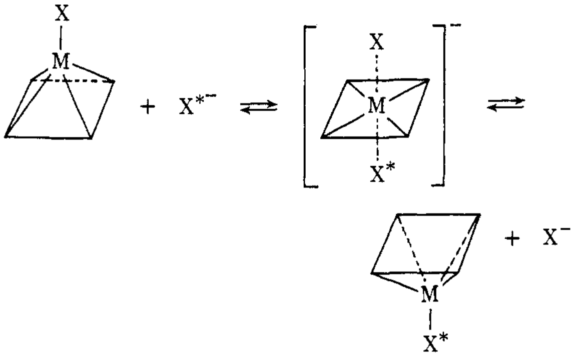
The systematic characterization of the stereochemistry[1] of iron porphyrins has led to the elucidation of the interrelation of a number of their structural and magnetic features which not only describe the behavior of the simple inorganic model compounds but also reflect some important biological functions[2] of various classes of heme proteins. Thus structural[1] and magnetic data[3] have revealed that high-spin, HS, forms of iron porphyrins suffer significant displacements of the iron atom out of the porphyrin plane. These displacements, which should be larger for the ferrous[4] (~0.75 Å) than the ferric[5,6] ion (~0.4–0.5 Å), reflect the inability of the tetrapyrrole "hole" to accommodate[1] these sizable HS ions. Hence five-coordinate geometry is common in the HS complexes. Upon addition of a sixth ligand, the spin multiplicity of the ground state decreases, generally yielding diamagnetic ferrous and spin-doublet ferric species,[1,3] whose reduced ionic radii are easily accommodated within the porphyrin plane.[7,8]

This conversion of iron(II) from an out-of-plane HS to an in-plane diamagnetic, six-coordinate species upon oxygenation is typical of the heme proteins, myoglobin and hemoglobin.[2,4,9,10] The latter tetraheme protein exhibits cooperativity among its subunits with respect to oxygenation, which has been the subject of considerable recent interest.[1,4,5–11] The biochemical trigger[1,4,9,10] which precipitates this cooperativity is thought to originate precisely from the sizable rearrangement imposed on the protein chain of the globin molecule by reducing the distance between the F-8 histidine and the heme plane[4,9] by some ~0.75 Å upon oxygenation of one subunit.

There is, therefore, considerable interest in the thermodynamic and kinetic parameters describing the motion of an iron atom relative to the porphyrin plane. Although calculations[12] have confirmed the stabilizing effect of the out-of-plane displacement of the iron in HS species, little is known about the magnitude of this stabilization. Furthermore, since it has been proposed[10] that iron–heme moieties exist in some form of mobile equilibrium with respect to the position of the iron relative to the porphyrin plane, an estimate of the possible rate constants for such mobility could be of value.

One approach is to monitor the rate of porphyrin "inversion," where the metal moves from one side of the porphyrin plane to the other. The activation energy for such a process would be related to this stabilization energy and would also reflect the "mobility"[10] of the HS iron atom. High-spin, five-coordinate ferrous porphyrin complexes have not been characterized; however, the HS ferric analogs of both natural and synthetic porphyrins are well characterized.[6,13,14]

We report here on the porphyrin "inversion" for the HS complexes of tetra-*p*-tolylporphyrin, *p*-CH$_3$-TPPFeCl, and octaethylporphyrin, OEPFeCl, where the "inversion" is induced by facile halogen exchange according to (A). The *m*-H signal in *p*-CH$_3$TPPFeCl has been shown[14] to be a doublet with a separation of ~110 Hz at 35°, reflecting the magnetic nonequivalence of the two sides of the heme plane and the restricted rotation[15] of the aryl group. Upon addition of in-



(A)

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creasing amounts of Cl$^-$, in the form of $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}$, to a 0.040 *M* p-CH$_3$TPPFeCl solution[16] in CDCl$_3$, the *m*-H doublet broadens by a dynamic process, coalescing into a single peak at a $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}/p\text{-}\mathrm{CH_3TPPFeCl}$ ratio of ~6.5. Simple two-site exchange analysis yields[17] the rate of inversion $\tau_{318}^{-1} \sim 4.5 \times 10^2$ sec^{-1} for this solution. Increasing the temperature of the solution resulted in the expected narrowing of the collapsed line. The increasing *m*-H line widths[18] with added $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}$ and the observed narrowing of the lines upon diluting a given sample containing both complex and $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}$ confirm the bimolecular or associative mechanism.[19] It should be noted that, although Cl$^-$ exchange may simultaneously occur by other mechanisms, the present nmr method succeeds in selecting only the S$_N$2 "inversion" pathway.

Since averaging of the two *m*-H signals could occur *via* phenyl group rotation, which we have shown[15] to occur at higher temperatures in the pure complex, a clear distinction between porphyrin "inversion" *via* (A) and a salt effect on the phenyl rotational barrier cannot be made without resorting to ^{35}Cl nmr. However, convincing evidence for the "inversion" mechanism is obtained by considering the nmr spectrum of OEPFeCl.[15] As shown elsewhere,[15] the displaced iron atom induces diastereotopism in the methylene protons, giving rise to a doublet in the temperature range −60 to +95°; the α-CH$_2$ trace at 75° is shown in Ia of Figure 1. This diastereotopism is similarly averaged by reaction A, with no possible interference from internal alkyl rotation. The traces in Figure 1 exhibit the effect on the line widths of added $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}$ (Ia–c),[20] temperature (IIa–c), and concentrations (IIIa–c), which closely parallel the data for p-CH$_3$TPPFeCl. The trace in IIc is to be contrasted to a well-resolved doublet separated by 230 Hz for the pure complex at 95°.

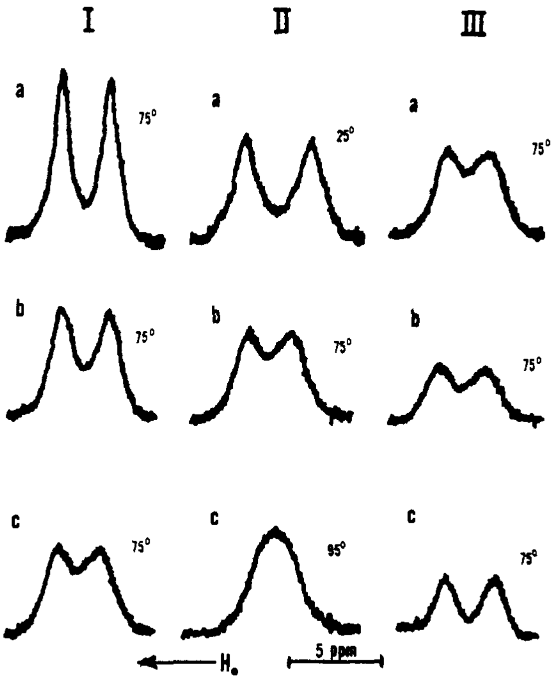

Figure 1. Proton nmr traces of the region of the methylene doublet (~−33 to −37 ppm from TMS) for HS OEPFeCl in CDCl$_3$: I, 75°, 0.040 *M* in OEPFeCl with $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}$ concentration of (a) 0.00, (b) 0.24, and (c) 0.43 *M*; II, 0.040 *M* OEPFeCl, 0.43 *M* $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}$, at (a) 26, (b) 75, and (c) 95°; III, fixed concentration ratio of $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}/\mathrm{OEPCl}$ ~10.7, with OEPFeCl concentration of (a) 0.040, (b) 0.027, and (c) 0.020 *M*.

Collapse of the methylene doublet occurs at a much higher temperature (~90°) and higher $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}/$complex ratio (~10.7) than for p-CH$_3$TPPFeCl, yielding[17] $\tau_{363}^{-1} \sim 10^3$ sec^{-1}. Analysis of a 0.040 *M* solution of OEPFeCl at 35° with a $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}/$OEPFeCl ratio of ~6.5 indicates a line width increase of ≤20 Hz over that of the pure complex, yielding $\tau_{318}^{-1} \leq 60$ sec^{-1}. Hence, the rate of "inversion" is considerably slower for OEP than p-CH$_3$TPP at the same temperature and excess Cl$^-$ concentration,[21] which is in contrast to our previous report[22] on the reverse order of axial ligand labilities in the low-spin bis(imidazole) complexes.[7] This reversal of rates can be understood in terms of the different mechanisms. The more basic OEP ligand weakens[23] the bond to the sixth ligand, stabilizing the five-coordinate intermediates in the dissociative imidazole exchange. For the same reason, the six-coordinate intermediate in the associative halogen exchange is destabilized by OEP relative to p-CH$_3$TPP.

Accurate determination of the activation parameters must await an analysis of the role of ion pairing[16] of $[\mathrm{Bu_4N^+}]\mathrm{Cl^-}$. Since spin conversion is known to be fast in such systems,[24] the activation energy may yield insight as to whether "inversion" proceeds *via* a spin-state change in the intermediate.[24a] The observation of similarly diastereotopic methylene protons in deuteroporphyrin IX dimethyl ester[25] will permit the inclusion of natural porphyrins. Studies to extend these capabilities to aqueous systems, as well to assay the effects of variable axial ligand, solvent, and metal ion, are in progress.

Acknowledgments. The author is indebted to Dr. F. A. Walker for the porphyrin samples and for helpful discussions.

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(26) Fellow of the Alfred P. Sloan Foundation, 1972–1974.

Gerd N. La Mar[26]
Department of Chemistry, University of California
Davis, California 95616

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