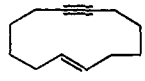
to that of **4** with the exception that the relative peak areas are 2:2:1. The splitting pattern of the symmetrical multiplet centered at 5.30 ppm is identical with that found in *cis,cis*-1,6-cyclodecadienes.[11] In the presence of Adams catalyst in acetic acid **4** consumed 3 molar equiv of hydrogen. Cyclododecane was isolated in 87% yield, mp 61–62°.[12] The nmr spectrum of the cyclododecane shows a single peak at 1.32 ppm, and its mass spectrum shows a parent ion at *m/e* 168.

Direct irradiation of **2** gives only one major product (**5**). This product was isolated as the silver nitrate adduct by treatment with aqueous silver nitrate. Treatment of this adduct with ammonia liberated **5** which was isolated in 42% yield. The nmr spectrum of **5** shows two overlapping broad signals centered at 1.70 and 2.02 ppm and a multiplet centered at 5.70 ppm (relative areas 4:4:1, respectively). The ir spectrum shows a sharp peak at 960 cm^{-1} (s) which is absent in the spectrum of **4**. The Raman spectrum of neat **5** shows bands at 2285, 2232, and 1667 cm^{-1}. The parent ion peak in the mass spectrum is at *m/e* 162.[13] Reduction of **5** over Adams catalyst gave cyclododecane, isolated in 90% yield, which was identical in all respects with the cyclododecane obtained from **4**, mmp 61–62°. On the basis of the above spectral and chemical observations it is concluded that **5** is *trans*-cyclododeca-1-en-7-yne.



5

The photochemistry of **1** and **2** is summarized in eq 1 and 2. In the absence of triphenylene the initial

$$\mathbf{1} \xrightarrow{h\nu} \mathbf{3} + \mathbf{4} \quad (1)$$

$$\mathbf{2} \xrightarrow{h\nu} \mathbf{5} \quad (2)$$

rate of formation of **3** from **1** is at least three times faster than the formation of **4**. No photochemical interconversion of **1** and **2** was detected. Completely stereospecific formation of **4** and **5** from **1** and **2**, respectively, is in accord with the Hoffmann–Woodward selection rule for a concerted photochemical four-electron $2\sigma \rightarrow 2\pi$ process.[14] This result is revealing with respect to a related mechanistic aspect of the reactions. Concerted cleavage of the two σ bonds of the electronically excited cyclobutenes could produce electronically excited **4** and **5**. Since electronic excitation in the double bonds of these products would have led to their interconversion,[4] either the electronic excitation is retained exclusively in the triple bonds, or, more likely, the reactions involve direct reorganization from excited cyclobutenes to ground-state products.[15,16]

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(12) L. Ruzicka, M. Stoll, H. W. Huyser, and H. A. Biekenoogen, *Helv. Chim. Acta*, **13**, 1152 (1930).
(13) Satisfactory carbon and hydrogen analyses were obtained for **4** and **5**.
(14) R. Hoffmann and R. B. Woodward, *J. Amer. Chem. Soc.*, **87**, 2046 (1965).
(15) E. F. Ullman, *Accounts Chem. Res.*, **1**, 353 (1968).
(16) Such reorganization appears to be involved in the photochemical conversion of **3** to **1**.[8,17]
(17) W. Th. A. M. van der Lugt and L. J. Oosterhoff, *Chem. Commun.*, 1235 (1968).

According to orbital symmetry considerations disrotatory ring opening of electronically excited cyclobutenes to dienes is an allowed process.[1] Formation of *cis,cis*-1,1′-bicyclohexenyl (**3**) from **1** was therefore expected. The reverse reaction is known[8] and its disrotatory course has been established experimentally in the case of 2,4-hexadiene.[18] Disrotatory diene formation from excited **2** would lead to the highly strained *cis,trans*-1,1′-bicyclohexenyl (**6**) which has been proposed as the intermediate in the photosensitized conversion of **3** to **1**.[19] If **6** → **1** is a facile thermal reaction, the fact that **1** is not a product of the irradiation of **2** rules out transient formation of **6** in our system. We note that in accord with orbital symmetry considerations which predict conrotatory ring opening of ground-state cyclobutenes to dienes, thermal diene formation is energetically easier from **2** than from **1**.[20] The effect of ring size on reactions 1 and 2 is under investigation.

Acknowledgment. This research was supported in part by National Science Foundation Grant GP-7941 and by the University Science Development Program of the National Science Foundation, Grant GU-2612.

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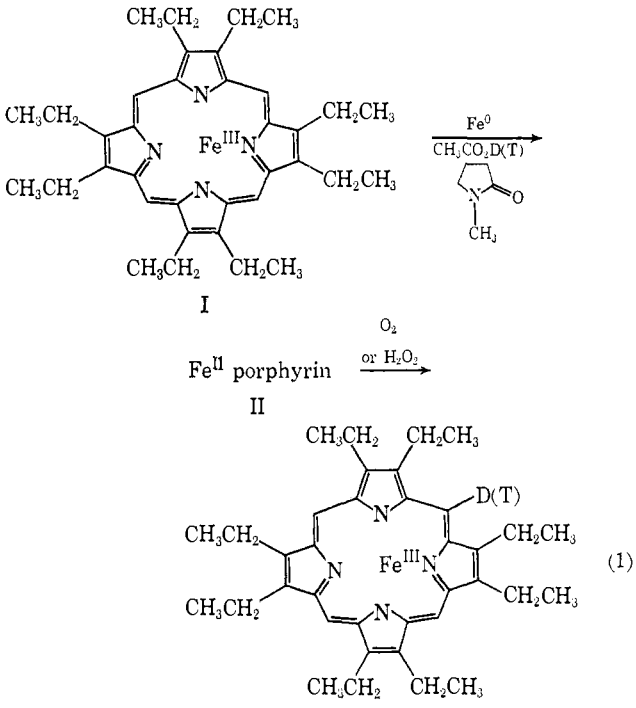
Peripheral Attack in the Reduction and Oxidation of Iron Porphyrins

Sir:

As a part of our study of the electron-transfer chemistry of hemes and hemoproteins we wish to report direct evidence for peripheral attack upon the porphyrin ring during the chemical reduction and oxidation of chloroiron(III) octaethylporphyrin. The system employed is indicated in eq 1. The salient feature of the process is that it is accompanied by hydrogen exchange at the *meso* position.

Thus, dilute solutions of octaethylhemin (I), λ_{max} 628, 532, 504 mμ, were reduced with iron powder in 1:1 N-methylpyrrolidone–CH_3CO_2D under nitrogen[1] to the corresponding heme (II), λ_{max} 566, 532 mμ. The latter was oxidized to the iron(III) state with air or hydrogen peroxide. After removal of iron[2] the purified porphyrin, λ_{max} 611, 560, 529, 495 mμ, was subjected to nmr analysis as the dication in CF_3CO_2D. The spectra of octaethylporphyrin and the porphyrin obtained from Hemin blank runs, that were not subjected to reduction or oxidation, were identical and showed a CH_3 resonance at δ 1.4 (triplet, 24 H), CH_2 at 3.8 (quartet, 16 H), and the vinylic *meso* proton at 10.7 (singlet, 4 H). Hence, neither the hemin nor the porphyrin undergoes skeletal C–H exchange in the reaction solution or upon work-up, and the porphyrin

(1) The method is an adaptation of that previously reported: D. G. Whitten, E. W. Baker, and A. H. Corwin, *J. Org. Chem.*, **28**, 2363 (1963); C. E. Castro, *J. Amer. Chem. Soc.*, **86**, 2310 (1964).
(2) J. E. Falk, "Porphyrins and Metalloporphyrins," Elsevier Publishing Co., New York, N. Y., 1964, p 135.



(1)

does not exchange in CF_3CO_2D.[3] However, the intensity of the vinylic proton resonance in the porphyrin obtained from a hemin that was reduced and oxidized was diminished. Thus, one cycle of reduction and hydrogen peroxide oxidation alters the CH_2–CH intensity ratio from 4 to 6 ± 1. At the same time, the area of CH_3–CH_2 signals remains constant at 1.5. In no case was there a change in the absolute or relative intensities of the ethyl protons.

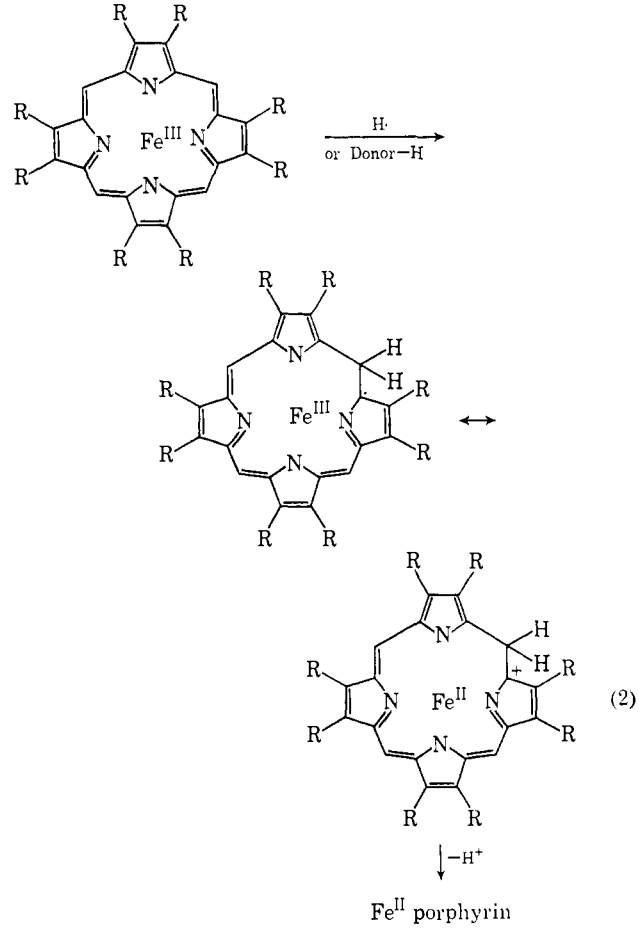
As an independent and more sensitive assessment of exchange during the redox cycle, parallel experiments were performed with a solvent system composed of 1:1 N-methylpyrrolidone–CH_3CO_2T (sp act. 1.77 mCi/mmol). Purified porphyrins[4] obtained from hemin blanks in this system contained no appreciable tritium (<0.2%). On the other hand, solutions that were reduced and air oxidized a single time show a 5% incorporation of tritium, assuming no isotope effect for the process.[5]

These results indicate that peripheral attack must be an important aspect of electron transfer in hemoproteins, and they cast an alternate perspective upon an array of biochemical phenomena in which porphyrin or porphyrin-like biometallics are involved. A brief exposition of the concordance of peripheral, "outer-sphere," electron transfer with the properties of hemoglobin and some of the cytochromes are noted here. An amplified presentation of these views will be made later.

Hemoglobin. Upon oxygenation, oxygen enters the coordination sphere of iron in hemoglobin to form a low-spin complex of iron(II) protoporphyrin. The other axial ligand is an imidazole moiety of a histidine residue.[6] Clearly, rapid electron transfer to oxygen *does not* ensue from this arrangement of molecules. However, a slow oxidation of hemoglobin does occur. The slow oxidation can be rationalized by the lack of easy access to a suitably exposed peripheral site for oxygen or a species derived from it. Thus, hemoglobin is the classic example of no reaction in a metalloporphyrin even though the oxidant has become a ligand of the metal. The lethargy to oxidation in this state bespeaks an alternate path for electron transfer.

Cytochrome *b*. Some of the *b* cytochromes possess the unusual capacity to be oxidized yet not inhibited by either carbon monoxide or cyanide.[7] An explanation for these observations must take the form that either (a) oxygen can approach reactive loci (presumably iron) that CN^- and CO cannot or (b) as we infer from this study, none of these entities approach iron and the oxidation results from a peripheral outer-sphere process. This view posits that, for these cytochromes, binding to iron is "blocked" by the protein matrix, but the periphery of the porphyrin ring must be exposed.

Cytochrome *c*. The X-ray analysis of cytochrome *c*[8] is wholly consistent with the foregoing argument. The heme is held to the protein by juncture through the axial positions of iron in axle-like fashion. There is a



(2)

(3) This finding is in accord with the lethargy of octaethylporphyrin toward deuteration; *cf.* R. Bonnet and G. F. Stephenson, *Proc. Chem. Soc.*, 291 (1964).

(4) As an added precaution, to eliminate N–H background exchange, after alumina chromatography, the purified porphyrin was thrice dissolved in CF_3CO_2H and evaporated to dryness at room temperature before it was transferred to a counting vial.

(5) It is not possible at this time to indicate the stoichiometry of the exchange process because the system is not calibrated for an isotope effect and we do not know the precise nature of the process. Certainly the amount of exchange that occurs exceeds the amount of tritium incorporated.

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(7) H. R. Mahler and E. H. Cordes, "Biological Chemistry," Harper and Row, Inc., New York, N. Y., 1966, pp 594–595.

(8) R. E. Dickerson, M. L. Kopka, J. Weinzerl, J. Varnum, D. Eisenberg, and E. Margoliash, *J. Biol. Chem.*, **242**, 3015 (1967).

considerable exposure of the porphyrin periphery. In light of this structure and the results of the present work the iron–imidazole–iron "inner-sphere" electron-transfer model for the cytochromes[9] would seem to require an inordinate amount of conformational change. That is to say, the minimum series of movements for electron transfer would require the iron porphyrins of two cytochromes to face out, transfer a ligand, and tuck back into the protein. In contrast, a peripheral interaction of the porphyrin rings of two cytochromes need not involve a conformation change for electron transfer to occur. The latter interaction is consonant with the fast electron-transfer properties of these units. The recently noted reduction of imidazole-bound cytochrome *c* by ascorbic acid[10] is consistent with these views.

The simplest mechanism for exchange upon reduction in our system might be formulated as a hydrogen-atom transfer, eq 2. A complementary formulation could be written for exchange upon oxidation. This sequence is in harmony with the converse generation of magnesium porphyrin radical cations upon one-electron oxidation.[11,12] The implications of peripheral attack in the redox chemistry of metalloporphyrins and hemoproteins is being investigated at all levels.

Acknowledgment. This work was supported by the National Science Foundation and by a predoctoral National Institutes of Health Environmental Science Traineeship to H. F. D. for which the authors are grateful.

(9) D. W. Urry and H. Eyring, *J. Theor. Biol.*, **8**, 198 (1965).
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(11) J. H. Fuhrhop and D. Mauzerall, *J. Amer. Chem. Soc.*, **90**, 3875 (1968).
(12) R. H. Felton, D. Dolphin, D. C. Borg, and J. Fajer, *ibid.*, **91**, 198 (1969).

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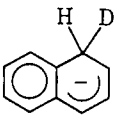
Reactions of Aromatic Radical Anions. IV. Evidence for an Addition Mechanism in the Reaction of Sodium Naphthalene and Hydrogen

Sir:

Recent work has shown that tetrahydrofuran solutions of sodium naphthalene absorb molecular hydrogen and that sodium hydride and naphthalene are stoichiometric reaction products.[1,2] No definitive experiments with regard to the mechanism of this interesting reaction have been reported.

We now wish to report evidence that sodium naphthalene is involved as more than just an electron-transfer agent, and to propose a mechanism for this reaction. Further evidence is proposed by Tamaru and coworkers for an anion intermediate.[3]

Two reasonable mechanisms[4] for the reaction are shown (eq 1–5). While both schemes involve initial electron transfer to molecular hydrogen to give hydride and a hydrogen (H) atom; they differ in the subsequent steps. Mechanism I involves reduction of the H radical to hydride which is expected to be facile based on several analogous reactions,[5–7] whereas mechanism II involves addition of the H radical to the radical anion which also finds analogy,[8,9] followed by loss of hydride to give the observed products. In order to differentiate between these schemes, we have studied the reaction using deuterium (D_2) gas. If mechanism I prevails, the products of reaction with D_2 are NaD and unlabeled naphthalene. If mechanism II prevails, however, the species formed in the addition step has a deuterium atom incorporated in the aromatic nucleus, *viz.*



Unless an unusually large inverse isotope effect operates for step 5, loss of hydride yields naphthalene containing deuterium.

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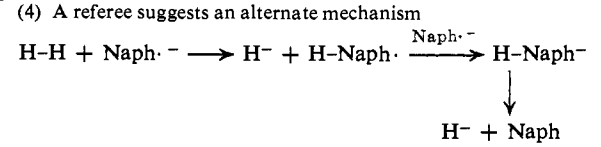
(3) M. Ichikawa, M. Soma, T. Onishi, and K. Tamaru, *ibid.*, in press.
(4) A referee suggests an alternate mechanism



The consequences of this mechanism, insofar as the present experiments are concerned, are identical with those of mechanism II. However, we consider this less likely since it involves nucleophilic attack of an extremely soft base on a very hard acid.
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