manner similar to that used previously for ring-substituted styrenes.[20] The amounts of benzophenone formed during the methanolic ozonolyses of triphenylethylene were also measured by infrared spectroscopy. The acetaldehyde formed during the ozonolysis of the β-methylstyrenes did not interfere with the spectroscopic measurements of the intensities of the carbonyl bands in the region of 1700–1712 cm^{-1}, since this aldehyde is very rapidly transformed to its hemiacetal by the methanol present in the solvent. The formation of hemiacetal of the aromatic aldehydes was checked using standard solutions of the aldehydes in the presence of 1.0 *M* CH_3OH. No appreciable effect on the intensity of the carbonyl band was observed and hence the formation of hemiacetal was negligible under these experimental conditions. The aromatic aldehydes used for the infrared calibration curves were dissolved in CCl_4, in the presence of 1.0 *M* CH_3OH. The results obtained in this way were compared with the proportions of aldehyde formed as determined by gas chromatography.

The gas chromatographic analyses were performed using a 5750 F & M gas chromatograph, using a flame detector. Six-foot columns of 10% Hyprose on Chromosorb P, or of Silicone Rubber UC W 98 were used. After the ozonization, the solvent loss due to evaporation during the ozonolysis was carefully compensated and 5-μl samples were injected in the gas chromatograph. The chromatograms were integrated by means of a planimeter and the area under the peak corresponding to the olefin which did not react and also to the aldehydes which were formed were compared to the areas under the peaks obtained under the same conditions using standard samples of the appropriate substances. The analyses were repeated a minimum of five times. The reproducibility is illustrated by the following example, which gives the areas measured for five different injections of a 0.05 *M* benzaldehyde solution in CCl_4, in the presence of 1.0 *M* CH_3OH: 15.19, 15.36, 15.74, 15.15, and 15.37 cm^2. For each substance five to ten experiments were carried out to determine the proportion of cleavage; two different oven temperatures were used with no effect on the results. The results reported in Table VII have been calculated with a confidence limit ≥95%.

Acknowledgment. The authors express their gratitude to Professor D. Gravel for helpful discussions and to Mr. J. Grignon for assistance in performing the experimental work. The financial support given by the National Research Council of Canada is gratefully acknowledged.

Unusual Metalloporphyrins. III. Induced Oxidation of Cobalt(II) and Iron(II) Porphyrins by Unsaturated Hydrocarbons[1]

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Abstract: The induced oxidations of cobalt(II) and iron(II) porphyrins by unsaturated hydrocarbons are described. The oxidation reactions were characterized experimentally and by wavelength-absorption shifts in the visible spectra. Metal–olefin interactions were shown by *cis*- to *trans*-2-butene isomerizations. Unsaturated hydrocarbons are classified into two categories: class I, which cause immediate oxidation, include unsaturated hydrocarbons with isolated double or triple bonds; class II, which cause slower oxidation, include unsaturated hydrocarbons with conjugated double or triple bonds. The reversible solvent caused oxidation of the cobalt porphyrins is discussed.

Metalloporphyrins play an important role in many chemical processes which are essential to life. Cellular respiration, an important biological process, is dependent upon these pyrrole pigments. Only in the last 20 years, however, has the important fundamental role of hematin compounds in the process of cellular respiration become evident. In cellular respiration, the chemical energy of the organic substances is made available for a variety of different energy requirements of the living cell.

In addition to the respiratory enzyme (cytochrome oxidase) and a variety of cytochromes, other hematin enzymes such as catalase and peroxidase are found in the cells of aerobic organisms. It is proposed[2] that these enzymes interact with ligands by π bonding. In these biological compounds, it is the metal in the metalloporphyrin moiety which would π bond to the ligand. An investigation of the reactions of π-bonding ligands such as olefins[3] with metalloporphyrins was undertaken to elucidate the mechanism of π interaction. In addition, information determined from this investigation might provide insight into the controversial bonding mode of oxygen in oxyhemoglobin and myoglobin which is thought to be of the π-bonding type.[4]

During this investigation, it was discovered that addition of unsaturated hydrocarbons to cobalt(II) porphyrins caused immediate oxidation of the Co(II) to Co(III) followed by degradation.[1b] This reaction was applied to the biologically important iron(II) porphyrin systems and these results in addition to those of the cobalt oxidation are presented in this paper.

Experimental Section

Reagents and Solvents. All solvents used were reagent grade and were further purified by distillation under nitrogen from respective

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(1) (a) Supported by National Science Foundation Grant GB-5732. (b) Preliminary results of this work were reported: M. Tsutsui, R. A. Velapoldi, K. Suzuki, and A. Ferrari, *J. Am. Chem. Soc.*, **90**, 2723 (1968).

(2) Conference of Prospectives of π-Interactions in Biological Systems, New York Academy of Sciences, New York, N. Y., March 28, 1967.

(3) It has been proposed that olefins are plant hormones since they appear to regulate certain growth functions in plants: J. D. Goeschl, H. K. Pratt, and B. A. Bonner, *Plant Physiol.*, **42**, 1077 (1967); J. D. Goeschl, L. Rappaport, and H. K. Pratt, *ibid.*, **41**, 877 (1966); S. P. Burg and E. A. Burg, *Proc. Natl. Acad. Sci. U. S.*, **55**, 262 (1966).

(4) Original reference which proposed π bonding: L. Pauling and C. D. Coryell, *ibid.*, **22**, 159 (1936).

drying agents.[5] Olefins used were obtained from Matheson Coleman and Bell and J. T. Baker and were purified by refluxing over lithium aluminum hydride under nitrogen followed by distillation just prior to use. Electronic grade nitrogen (Air Reduction Inc.) was further purified by passing the nitrogen through a sodium–potassium amalgam reducing the oxygen content to less than 0.1 ppm. The solvents and olefins were distilled under this purified nitrogen, and thus have approximately the same oxygen concentration as the nitrogen.

Spectra. Ultraviolet and visible spectra were obtained on a Cary Model 15 recording spectrophotometer using 1 and 10 cm matched silica cells. A silica cell was also used which had Schlenk tube connections for obtaining spectra of solutions under purified nitrogen with the exclusion of air. Infrared spectra were obtained as mulls, KBr disks or in solution on a Perkin-Elmer Model 337 spectrophotometer.

Magnetic Susceptibilities. Magnetic susceptibilities were measured by the Guoy method. Solid and solution susceptibilities were determined. Cobalt(II) mesoporphyrin IX dimethyl ester (Co^{II}MPIXDME) was dissolved in pyridine ($\sim 2 \times 10^{-2}$ *M*) and the magnetic susceptibility of the solution was determined as soon as possible and at various times thereafter. The diamagnetism due to the pyridine and tube were measured and taken into account in the final magnetic susceptibility calculations.

Gas Chromatography. *cis*- and *trans*-2-butene (1 ml of liquid) in 2 ml of chloroform solutions of Co^{II}MPIXDME and in 2 ml of chloroform were allowed to stand for several hours at 23° in sealed Pyrex capsules which were then opened and the butenes were distilled into a Dry Ice–acetone trap. Butene analyses were carried out using a Perkin-Elmer Model 54 gas chromatograph with an ethyl malonate on Chromosorb P column. *cis*- and *trans*-2-butenes were also reacted in a similar manner using the usual 10% pyridine–benzene solution of iron(II) bis(pyridine) mesoporphyrin IX dimethyl ester ($Fe^{II}Py_2$PPIX). The butenes were analyzed on an F & M Model 810 gas chromatograph using a silver nitrate–ethyl malonate on Chromosorb P column.

Procedures. Metalloporphyrins were dissolved in various solvents and excess ($\sim 10^3$ times metalloporphyrin concentration) unsaturated hydrocarbons were added with shaking in the silica cell. Spectra were taken immediately (within 1 min) and for varying times after addition of the unsaturated hydrocarbons. This procedure was done under purified, dry nitrogen and in the atmosphere. Oxygen and air were bubbled through the solutions of the metalloporphyrins to determine air stability.

Various ratios of pyridine–benzene were prepared and used as solvents for Fe^{II}MPIXDME and Fe^{II}PPIX to determine the pyridine concentration needed to stabilize the Fe(II) and inhibit air oxidation. Oxygen and air were bubbled through these solutions to determine stability.

Preparations. Mesoporphyrin IX dimethyl ester, MPIXDME, was prepared by literature procedures.[6]

Mesoporphyrin IX, MPIX, was prepared by the acid hydrolysis of MPIXDME.[6a]

Cobalt(II) mesoporphyrin IX dimethyl ester, Co^{II}MPIXDME, was prepared by the method of Taylor.[7]

Cobalt(II) mesoporphyrin IX, Co^{II}MPIX, was also prepared by the method of Taylor.[7]

Cobalt(III) mesoporphyrin IX hydroxide, Co^{III}OHMPIX, was prepared by the oxidation of Co^{II}MPIX.[8]

Iron(III) mesoporphyrin IX dimethyl ester chloride, Fe^{III}-ClMPIXDME, was prepared by a variation of the method of Erdman and Corwin.[9] MPIXDME (0.205 g), $Fe(OAc)_2$ (0.50 g), and NaCl (0.50 g) were refluxed in 30 ml of glacial acetic acid for 2 hr. The red-violet reaction mixture turned brown during refluxing. The acetic acid was removed under reduced pressure; the residue was stirred with 30 ml of distilled water, filtered, washed with several 5-ml portions of distilled water, and then with 10 ml of methanol. The product was recrystallized from methanol–petroleum ether (bp 30–60°).

Iron(II) bis(pyridine)mesoporphyrin IX dimethyl ester, Fe^{II}-Py_2MPIXDME, was prepared by the method of Fleischer,[10] *et al.*

Iron(II) bis(pyridine)protoporphyrin IX, $Fe^{II}Py_2$PPIX, was prepared in the same manner as the mesoporphyrin compound, starting with Hemin.

Results and Discussion

Addition of unsaturated hydrocarbons to a solution of Co^{II}MPIXDME in various solvents results in an immediate shift of the Soret band from 393 to 411 mμ which are due to Co(II) and Co(III) respectively.[7,8,11] The β and α bands also shift from 518 and 553 mμ to 528 and 558 mμ. The spectral dependence of cobalt oxidation state has also been experimentally proven. Co^{II}MPIX and Co^{III}OHMPIX were prepared and expected values for the magnetic susceptibilities were obtained [2.73 BM[12] for Co(II) and diamagnetism for Co(III)]. The visible spectra, included in Table I which is a summary of the spectra of compounds used in this study, show the same absorptions for the respective cobalt species as observed in the oxidation followed by spectral shifts.

Table I. Visible Spectra of Various Metalloporphyrins

Porphyrin	Soret band, mμ	β band, mμ	α band, mμ
Co^{II}MPIX	392	516	551
[Co^{III}MPIX]OH	412	529	559
Co^{II}MPIXDME	393	518	553
[Co^{III}MPIXDME]OH	411	528	558
$Fe^{II}Py_2$PPIX[a]	418	526	557
[Fe^{III}PPIX]OH[a]	405	570	595
$Fe^{II}Py_2$MPIXDME[a]	409	517	546
[Fe^{III}MPIXDME]OH[a]	398	510	535

[a] In 10% pyridine–benzene solution.

In addition, Co^{II}MPIXDME dissolved in pyridine, showed a decrease in magnetic susceptibility from an initial value of 0.92 BM to 0 BM at time infinity (24 hr). Visible spectra of the pyridine solution, taken simultaneously with the magnetic susceptibility measurements, showed approximately 50% oxidation initially and total oxidation at time infinity, thus proving metal oxidation.

Oxidation of the Co(II) porphyrin occurs under different reaction conditions: upon addition of unsaturated hydrocarbons to solutions of the Co^{II}-MPIXDME in various solvents and in solvents of high dielectric constants or strong coordinating ability.

The addition of unsaturated hydrocarbons to solutions of Co(II) causes immediate oxidation (less than 2 min) and a disappearance of the spectrum due to Co(III). Table II summarizes the oxidation of Co^{II}-MPIXDME in various solvents upon cyclohexene addition and the relative stability of the Co(II) species in various solvents.

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(5) L. F. Fieser, "Experiments in Organic Chemistry," D. C. Heath and Co., Boston, Mass., 1957; L. F. Fieser and M. Fieser, "Reagents for Organic Synthesis," John Wiley & Sons, Inc., New York, N. Y., 1967.

(6) (a) J. E. Falk, "Porphyrins and Metalloporphyrins," Elsevier Publishing Co., New York, N. Y., 1964; (b) H. Fischer and H. Orth, "Die Chemie des Pyrrols," Vol. 2, Part 1, Akad, Verlagsgesellschaft, Leipzig, 1937.

(7) J. R. Taylor, *J. Biol. Chem.*, **135**, 569 (1940).

(8) D. G. Whitten, E. W. Baker, and A. H. Corwin, *J. Org. Chem.*, **28**, 2363 (1963).

(9) A. H. Corwin and J. G. Erdman, *J. Am. Chem. Soc.*, **78**, 2437 (1956).

(10) J. H. Wang, A. Nakahara, and E. B. Fleischer, *ibid.*, **80**, 1109 (1958).

(11) V. Caglioti, P. Silvestroni, and C. Furlani, *J. Inorg. Nucl. Chem.*, **13**, 95 (1960).

(12) The high magnetic susceptibility for Co(II) with one unpaired electron has been explained by placing the electron in the $d_z{}^2$ orbital, thus enhancing orbital contribution to the magnetic moment: B. N. Figgis and R. S. Nyholm, *J. Chem. Soc.*, 12 (1954).

Table II. The Effect of Solvents and Cyclohexene Addition to Solutions of Co^{II}MPIXDME

		Oxidation	
Solvent	Dielectric constant[a]	Solvent only	Cyclohexene addition
n-Hexane	1.89	No	No
1,4-Dioxane	2.20	No	No
Cyclohexene	2.22	No	No
Carbon tetrachloride	2.24	No	Yes
Benzene	2.28	No	Yes
Thiophene	2.76	No	Yes
Chloroform	4.81	No	Yes
Ethyl acetate	6.02	No	Yes
Pyridine	12.30	Yes	Yes
Ethanol	24.30	Yes	Yes
Methanol	32.63	Yes	Yes

[a] "Handbook of Chemistry and Physics," R. C. Weast, S. M. Selby, and C. D. Hodgman, Ed., The Chemical Rubber Publishing Co., Cleveland, Ohio, 1965, p E30.

It is seen from Table II that oxidation occurs if the dielectric constant of the solvent is higher than the dielectric constant of the cyclohexene suggesting that the solvent has to be more polar than the olefin, probably to aid in electron transfer. In fact, Co(II) is stable in cyclohexene proving that oxidation does not occur due to peroxides or other species present in the olefin.[13] The olefin bonds to the coordinately unsaturated Co^{II}MPIXDME along the z axis as evidenced by *cis*- to *trans*-2-butene isomerization, but not with metal oxidation.[14] No *trans* to *cis* isomerizations were observed due probably to steric hindrance of the *trans* isomer which would make initial π coordination difficult. Spectral shifts showing oxidation also occurred in the *cis–trans* isomerization.

The unsaturated hydrocarbon is a strong π-bonding ligand[15] and would π bond to the cobalt replacing a coordinated solvent to form a d^7 square-pyramidal structure. This coordination decreases the electron density in the negative z direction, which creates stronger dipole–dipole interactions between the Co(II) and the remaining coordinated solvent molecule. Octahedral symmetry is more closely approximated resulting in the immediate oxidation of the d^7 octahedral Co(II) porphyrin to the more stable d^6 octahedral Co(III) species. Square-planar to octahedral structural conversions are common and oxidation is enhanced by crystal field stabilization energies.[16] This observation is also borne out by the fact that ligands, such as pyridine and cyanide which coordinate strongly along the z axis of square-planar cobalt(II) species, lower the oxidation potential of the cobalt by more than 2 V.[11,17]

The unsaturated hydrocarbons added to chloroform solutions of the Co^{II}MPIXDME causing oxidation are categorized into two classes. Class I hydrocarbons, which cause an immediate spectral shift (less than 2 min) consist of unsaturated hydrocarbons with an isolated double or triple bond such as cyclohexene, 1-pentene, 2-pentene, 1-hexyne, 1-hexene, 1-octyne, and 1,5- and 1,3-cyclooctadienes. Class II hydrocarbons, which cause a slow spectral shift (~3–5 hr), consist of unsaturated hydrocarbons with a conjugated double or triple bond such as diphenylacetylene, phenylacetylene, *cis*- and *trans*-stilbenes, 1,4-diphenyl-1,3-butadiene, acrylonitrile, and fumaric and maleic acids. The conjugated systems are less reactive probably due to bond stability caused by conjugation; formation of π and eventually σ bonds with the metal would necessarily require added energy.

Class II hydrocarbons may be further broken down into two subcategories. *cis* isomers oxidize the Co(II) species more rapidly than *trans* isomers. *cis*-Stilbene gave 25% oxidation and *trans*-stilbene gave 5% oxidation of the Co(II) after 2.5 hr. Maleic and fumaric acids showed 70 and 15% oxidation, respectively, at the end of this same time period. In the *trans*-stilbene, increased resonance and lower energy considerations[18] are consistent with the observations that increased resonance decreases reactivity. The *cis*-stilbene is in a higher energy state and would be expected to isomerize upon coordination. The *cis* isomer is not as sterically hindered from complexing with the metalloporphyrin as the *trans* isomer, and the coordination of the *trans* isomer would thus require higher energy due to steric repulsions. Similar considerations are pertinent for maleic and fumaric acids.

In solvent caused oxidation of the Co^{II}MPIXDME, an isobestic point is observed at 402 mμ, Figure 1. Considering the spectral changes [Co(II) → Co(III)] and the absence of additional peaks at other wavelengths during these changes, this observation would suggest that only the two species, Co(II) and Co(III), are present in solution.

Approximately 25 hr are needed for complete oxidation to occur and the Co(III) species formed is stable as evidenced by no further spectral changes after total oxidation. This reaction is reversible. Removal of methanol by vacuum and heating (~60°) yields the original Co^{II}MPIXDME. A similar study using pyridine as the solvent necessitates higher temperatures for total solvent removal, Table III. These results are also in accord with Corwin, *et al.*[8,19] and Taylor[7] who reported that the interconversion of Co(II) to Co(III) was solvent and temperature dependent and was also facile.

The stability of the Co(II) species in solvents of low dielectric constants, Table II, shows that the solvent molecules do not coordinate strongly enough to force the electron in the d_{z^2} orbital into the porphyrin ring or to remove it altogether, resulting in oxidation. Thus, strongly coordinating ligands and ligands with high

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(13) Air independence of the oxidation was shown by varying the reaction conditions (see Experimental Section) with the results that even bubbling oxygen did not cause cobalt oxidation.

(14) Examples of this type of nonoxidative coordination are well known: E. O. Fischer and H. Werner, "Metal π Complexes," Vol. 1, Elsevier Publishing Co., New York, N. Y., 1966; M. A. Bennet, *Chem. Rev.*, **62**, 611 (1962); J. Halpern, *Ann. Rev. Phys. Chem.*, **16**, 103 (1965); J. A. Gibson and G. Wilkinson, *J. Chem. Soc., A*, 1733 (1966).

(15) C. H. Langford and H. B. Gray, "Ligand Substitution Processes," W. A. Benjamin, Inc., New York, N. Y., 1965; J. P. Collman, M. Kubota, and J. W. Hosking, *J. Am. Chem. Soc.*, **89**, 4809 (1967).

(16) F. Basolo and R. G. Pearson, "Mechanisms of Inorganic Reactions," John Wiley & Sons, Inc., New York, N. Y., 1958, pp 57, 203; J. M. Pratt and R. J. P. Williams, *J. Chem. Soc., A*, 1291 (1967); A. E. Martell and M. Calvin, "Chemistry of the Metal Chelate Compounds," Prentice-Hall, Inc., Englewood Cliffs, N. J., 1956.

(17) (a) J. E. Falk and J. N. Phillips, "Chelating Agents and Metal Chelates," F. P. Dwyer and D. P. Mellor, Ed., Academic Press, New York, N. Y., 1964, p 470; F. A. Cotton and G. Wilkinson, "Advanced Inorganic Chemistry," Interscience Publishers, New York, N. Y., 1966, p 867; (b) L. Pauling, "The Nature of the Chemical Bond," Cornell University Press, Ithaca, N. Y., 1960, p 148.

(18) H. H. Jaffé and M. Orchin, "Theory and Applications of Ultraviolet Spectroscopy," John Wiley & Sons, New York, N. Y., 1962.

(19) A. H. Corwin, D. G. Whitten, E. W. Baker, and C. G. Kleinspehn, *J. Am. Chem. Soc.*, **85**, 3621 (1963).

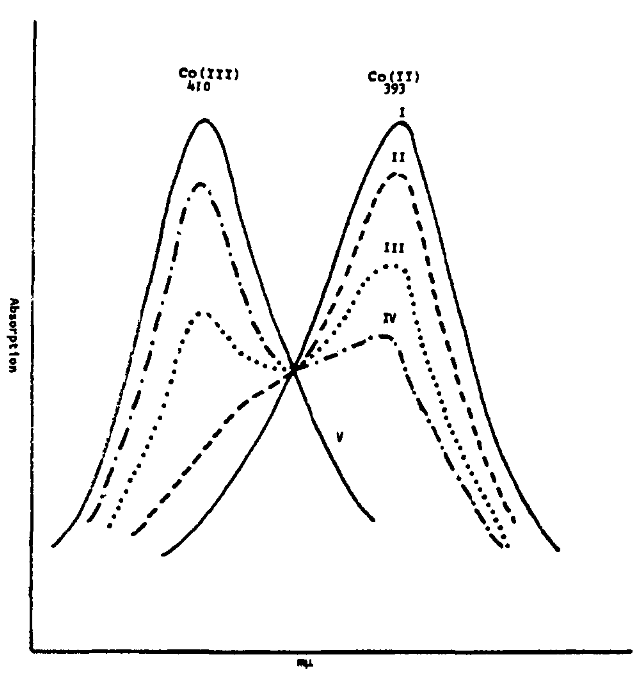

Figure 1. The spectral change of $\mathrm{Co^{II}MPIXDME}$ in MeOH. Spectra I–V taken at 5-hr intervals.

dielectric constants (a measure of the dipolar nature of the ligand and therefore a measure of σ-type bonding) decrease tetragonal distortion of the square planar d^7 Co(II) species. Approach to octahedral symmetry and the resulting decrease in oxidation potential facilitate cobalt oxidation.[17]

Table III. Reversibility of Pyridine-Caused Oxidation

Species	Heating temp, °C[a]	Absorption,[c] mμ
Co(III)[b]	Room temperature	417
Co(III) and Co(II)	50	417, 395 (s)
Co(III) and Co(II)	100	417, 393
Co(III) and Co(II)	150	417 (s), 393

[a] For 1 hr under vacuum. [b] In pyridine. [c] s = shoulder.

A contrast between olefin-induced and solvent-caused oxidation is necessary. No isosbestic point was observed in olefin-induced oxidation. The Co(III) species formed in the olefin-induced oxidation reacts further as evidenced by the disappearance of the Co(III) spectrum, and the change in color of the solution from pink to yellow. Once the reaction has reached the point where no Co(III) spectrum is observable the process is not reversible. This is in contrast to solvent-caused oxidation which is reversible. It is evident, then, that the further reaction which occurs, must be between the Co(III) species and either the coordinated olefin or excess olefin in solution.

It is possible that the olefin π coordinates to the Co(II) and then adds to the inorganic free radical Co(II) with its unpaired electron in the d_{z^2} orbital forming essentially a σ bond. The organic free radical could then react with the porphyrin to destroy conjugation, causing the disappearance of the Co(III) spectrum. These types of metal oxidative olefin addition are well known.[20] Reactions with labeled olefins would determine if the olefin were incorporated into the porphyrin structure.

Addition of unsaturated hydrocarbons to iron(II) porphyrins also results in the oxidation of Fe(II) to Fe(III) followed by a disappearance of the Fe(III) spectrum. The oxidation may be followed by typical spectral shifts:[8] 418–405 mμ for $\mathrm{Fe^{II}Py_2PPIX}$ and 409–398 mμ for $\mathrm{Fe^{II}Py_2MPIXDME}$ as summarized in Table I.

Strongly coordinating ligands such as pyridine are needed to maintain the stable d^6 Fe(II) oxidation state. The oxidation reaction was not due to air oxidation since solutions of the Fe(II) porphyrins are stable in the 10% pyridine–benzene solvent used in this study. A 1% pyridine–benzene solution of the Fe(II) porphyrins is oxidized slowly upon standing in air or within 1 hr if oxygen is bubbled through the solution. The spectral shifts observed upon olefin addition and upon air oxidation of the pyridine–benzene solutions were identical, showing that the spectral shift is due to oxidation. The spectral assignments for the Fe(II) and Fe(III) species are also well documented in the literature.[6a,8]

Olefin coordination was shown by *cis*- to *trans*-2-butene isomerizations, but not the reverse isomerization, *trans* to *cis*. This is in agreement with the findings for the cobalt porphyrin, substantiating the steric and electronic considerations which were discussed.

A large excess of olefin is needed (10^3 times the metalloporphyrin concentration), undoubtedly due to an equilibrium which is present in the pyridine solution, eq 1. Kinetic factors which dictate the positional

$$\mathrm{Fe^{II}Py_2L + olefin \rightleftharpoons Fe^{II}olefinPyL + Py} \qquad (1)$$

approach of the olefin to the metal porphyrins would also contribute to the need for excess olefin.

In addition, the unsaturated hydrocarbons fall into the same categories as discussed previously, conjugated and nonconjugated systems. Slow oxidation of the iron(II) porphyrins (1 hr for total oxidation) occurs upon addition of the conjugated system, 2-vinylpyridine. Replacement of a pyridine ligand by the 2-vinyl pyridine along the z axis by σ bonding with the d_{z^2} orbital occurs. The vinyl group in the 2 position is in close contact with the coordination sphere along one of the π-bonding t_{2g} orbital axes (d_{xz} or d_{yz} but not d_{xy}) and π bonding to the iron is facilitated. As σ overlap decreases, π overlap increases until the iron changes to a high-spin d^6 configuration since the energy supplied by π bonding does not force electron pairing resulting in a low-spin configuration. Iron may then be oxidized to the d^5 electron configuration which is more stable in the high-spin state.[21]

Replacement of the pyridine by unsaturated hydrocarbons would also induce oxidation by a change of low-spin Fe(II) to the high-spin state for the reasons mentioned above.

The addition of 4-vinylpyridine gives an immediate 1-mμ shift of the hemochromogen spectra indicating pyridine replacement; but no oxidation occurs. The

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(20) J. P. Collman, *Trans. N. Y. Acad. Sci.*, 30, 479 (1968); J. P. Collman, K. W. Kang, W. F. Little, and M. F. Sullivan, Abstracts, 3rd International Symposium on Organometallic Chemistry, Munich, Aug 1967, p 334; similar reaction involving H· radical from the solvent is also feasible: J. Halpern, *Chem. Eng. News*, **46**, 68 (Oct 31, 1966).

(21) J. E. Falk and D. D. Perrin, "Haematin Enzymes," J. E. Falk, R. Lemberg, and R. K. Morton, Ed., Pergamon Press, New York, N. Y., 1961, p 65.

shift with 4-vinylpyridine suggests that it is a stronger σ-bonding ligand than pyridine and lack of oxidation shows that it is sterically unfavorable for the vinyl group in the 4 position to π bond with the iron. Intramolecular oxidation would also be unfavorable.

It is interesting to note that the spectral shift indicative of the Fe(II) oxidation is to the blue while for Co(II) oxidation, it is to the red. These shifts have been explained by electronic[22] and steric factors[8,19] and more recently by stereoelectronic factors,[23] but the main assignments of the spectra as to Co(II), Co(III), Fe(II), or Fe(III) remain unchanged.

(22) M. Gouterman, *J. Chem. Phys.*, **30**, 1139 (1959).

(23) A. H. Corwin, A. B. Chivvis, R. W. Poor, D. G. Whitten, and E. W. Baker, *J. Am. Chem. Soc.*, **90**, 6577 (1968).

Reactions of Cobalt(I) Supernucleophiles. The Alkylation of Vitamin B_{12s}, Cobaloximes(I), and Related Compounds[1]

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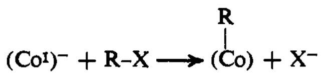
Abstract: Results of kinetic measurements are presented which indicate that the reactions of alkyl halides with vitamin B_{12s}, cobaloximes(I), and other Co(I) chelates proceed by a classical S_N2 mechanism, the Co(I) centers being some of the most powerful nucleophiles known. The evidence for this mechanism providing the dominant reaction pathway is based mainly on the analysis of substrate structural effects on the substitution rates. Although the *absolute* reactivities of the Co(I) nucleophiles are up to 10^7 times greater than those, *e.g.*, of iodide ion, the relative reactivities with various substrates are very similar. Surprisingly, the rates of reactions of the alkyl halides studied are no more sensitive to steric effects of the corrin ligand system than to those of the cobaloxime moiety. Steric hindrance by out-of-plane corrin ligands appear in later stages of the Co–C bond formation process, as evidenced by the instability of secondary alkyl cobalamins in contrast to the corresponding cobaloxime derivatives. The factors influencing the nucleophilicity of the Co(I) chelates, in particular, the effects of axial bases, ligand structure, and possible mechanistic alternatives of the alkylation reactions are discussed. The presence of the coordinated 5,6-dimethylbenzimidazole does not cause a substantial change of the Co(I) nucleophilicity of vitamin B_{12s}.

The reaction of vitamin B_{12s} with alkylating agents is of fundamental biochemical importance and constitutes the most versatile method of synthesizing organocobalamins (eq 1).[3] We have recently[4] presented



$$(Co^{I})^- + R\text{–}X \longrightarrow \overset{R}{\overset{|}{(Co)}} + X^- \qquad (1)$$

evidence indicating that this reaction (where RX is an alkyl halide) follows an S_N2 mechanism involving the powerfully nucleophilic Co(I) derivative of vitamin B_{12} (vitamin B_{12s}). It was also indicated that cobaloxime(I) derivatives react with alkyl halides by the same mechanism, thus providing the basis for a systematic quantitative comparison of the alkylation reactions of vitamin B_{12s} with those of simple, well-defined vitamin B_{12} model compounds. In the present paper we describe the results of detailed kinetic and mechanistic studies on the reactions of vitamin B_{12s} and "cobaloximes" with alkyl halides.

The Nature and Reactions of Co(I) Nucleophiles

Vitamin B_{12} and other strong field planar cobalt chelates form spin-paired Co(I) (d^8) derivatives on reduction. The Co(II)/Co(I) reduction potentials of vitamin B_{12} and of several other cobalt chelates have been estimated[4,5] to be in the order of -0.59 to -0.80 V (at equilibrium with 1 atm of H_2 and a platinum catalyst) and were found to depend on the effective coordinating power of the in-plane ligands and the donor–acceptor bonding properties of the axial ligands. The highest occupied orbital in the reduced cobalt species is the weakly antibonding d_{z^2} orbital,[4,6] whose directional characteristics and high charge density are responsible for the high nucleophilicity perpendicular to the plane of the molecule. The occurrence of the macrocyclic "loop" in the molecule of vitamin B_{12} implies that the coordination of the Co(I) ion by the axial base (*i.e.*, 5,6-dimethylbenzimidazole) could serve the specific purpose of increasing the nucleophilicity of the Co(I) ion. To answer this question we have therefore studied the effect of axial bases on the reactivity of the Co(I) nucleophiles. The alkylation reac-

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