

Solution Conformations of Hydroporphyrin Complexes. Synthesis and Properties of *cis*- and *trans*-Octaethylchlorin Complexes

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The free-base and Cu(II), Mg(II), Ni(II), Sn(IV), and Zn(II) complexes of *cis*- and *trans*-octaethylchlorin (OEC) have been synthesized. UV-vis, ^1H NMR, ^{13}C NMR, and electrochemical data are presented. The properties of *cis*-OEC complexes generally resemble those of *trans*-OEC, excepting small red shifts and reduced intensities in the UV-vis spectra, greater shielding in the ^1H NMR spectra, and markedly reduced stabilities of *cis*-OEC cation radicals and dications. In general, the properties of the Ni(II) complexes differ substantially from those of larger metal ions. Vicinal coupling constants for the 2,3-H atoms of the *cis* and *trans* free base and Ni(II) complexes were obtained from analysis of ^{13}C satellite peaks. The data establish that in solution the pyrroline rings of these complexes adopt half-chair or envelope conformations, that pyrroline rings of defined stereochemistry can adopt different conformations and that metalation with Ni(II) can induce major conformation changes in the pyrroline ring if not the entire macrocycle. The homonuclear 2D *J*-resolved ^1H NMR spectrum of *trans*-Ni(OEC) strongly suggests that the complex has an S_4 -ruffled structure. A considerable body of evidence is consistent with structures of this type for both *cis*- and *trans*-Ni(OEC). The greatly enhanced stability of the *cis*-Ni(OEC) cation radical and dication (on the cyclic voltammetric time scale) establishes that chemical reactivity can be significantly affected by macrocycle conformation.

Introduction

Recent discoveries¹⁻⁸ have increased greatly the known biological roles of hydroporphyrin⁹ complexes and have stimulated intense interest in these systems.¹⁰⁻²⁷ A major goal of previous studies

was to develop the comparative chemistry of metalloporphyrins and metallohydroporphyrins. Significant differences could be suggestive of properties intrinsic to hydroporphyrins and their metal complexes that could make them better suited to serve as prosthetic groups in specific enzymatic reactions than the corresponding complexes of other tetrapyrroles.¹²

One striking difference is the greater ease of oxidation of hydroporphyrin complexes.¹⁰⁻¹⁷ Unlike corresponding porphyrin complexes, the CO and NO complexes of $\text{Fe}^{\text{II}}(\text{iBC})^{28}$ are oxidized at the ligand rather than at the metal.^{14,17} No current evidence

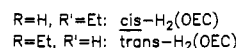
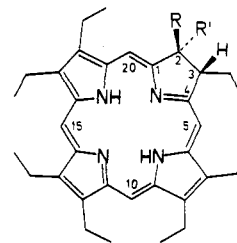
- (1) Siroheme in nitrite and sulfite reduction: Murphy, M. J.; Siegel, L. M.; Kamin, H.; Rosenthal, D. *J. Biol. Chem.* **1973**, *248*, 2801. Murphy, M. J.; Siegel, L. M. *J. Biol. Chem.* **1973**, *248*, 6911. Vega, J. M.; Garrett, R. H.; Siegel, L. M. *J. Biol. Chem.* **1975**, *250*, 7980. Vega, J. M.; Kamin, H. *J. Biol. Chem.* **1977**, *252*, 896. Scott, A. I.; Irwin, A. J.; Siegel, L. M.; Shoolery, J. N. *J. Am. Chem. Soc.* **1978**, *100*, 316, 7987.
- (2) Corrin biosynthesis: Battersby, A. R. *Experientia* **1978**, *34*, 1. Battersby, A. R.; McDonald, E. *Bioorg. Chem.* **1978**, *7*, 161. Scott, A. I. *Acc. Chem. Res.* **1978**, *11*, 29. Deeg, R.; Kriemler, H.-P.; Bergmann, K.-H.; Muller, G. *Hoppe-Seyler's Z. Physiol. Chem.* **1977**, *358*, 339. Battersby, A. R.; McDonald, E. In *Vitamin B₁₂*; Dolphin, D., Ed.; Wiley: New York, 1982; p 455.
- (3) Factor F430: Pfalz, A.; Livingston, D. A.; Juan, B.; Diekert, G.; Thauer, R. K.; Eschenmoser, A. *Helv. Chim. Acta* **1985**, *68*, 1338. Pfalz, A.; Juan, B.; Fassler, A.; Eschenmoser, A.; Jaenchen, R.; Gilles, H. H.; Diekert, G.; Thauer, R. K. *Helv. Chim. Acta* **1982**, *65*, 828. Ellefson, W. L.; Wolfe, R. S. *J. Biol. Chem.* **1981**, *256*, 4259.
- (4) Bonellin: Ballantine, J. A.; Psaila, A. F.; Peter, A.; Murray-Rust, P.; Ferrito, V.; Schembri, F.; Jaccarini, V. *J. Chem. Soc., Perkin Trans. 1* **1980**, 1080.
- (5) Heme d nitrite reductases: Gudat, J. C.; Singh, J.; Wharton, D. C. *Biochim. Biophys. Acta* **1973**, *292*, 376. Horie, S.; Watanabe, T.; Nakamura, S. *J. Biochem.* **1976**, *80*, 579. Le Gall, J.; Payne, W. J.; Morgan, T. V.; DerVartanian, D. V. *Biochem. Biophys. Res. Commun.* **1979**, *87*, 355.
- (6) *Neurospora crassa* catalase: Jacob, G. S.; Orme-Johnson, W. H. *Biochemistry* **1979**, *18*, 2967, 2975.
- (7) Myeloperoxidase: Bakkenist, A. R. J.; Wever, R.; Vulsma, T.; Plat, H.; van Gelder, B. F. *Biochem. Biophys. Acta* **1978**, *524*, 45. Davis, J. C.; Averill, B. A. *J. Biol. Chem.* **1981**, *256*, 5992. Sibbet, S. S.; Hurst, J. K. *Biochemistry* **1984**, *23*, 3007.
- (8) Sulfhemoglobin and sulfmyoglobin: Brittain, T.; Greenwood, C.; Barber, D. *Biochem. Biophys. Acta* **1982**, *705*, 26. Andersson, L. A.; Loehr, T. M.; Lim, A. R.; Mauk, A. G. *J. Biol. Chem.* **1984**, *259*, 15340.
- (9) (a) Scheer, H. In *The Porphyrins*; Dolphin, D., Ed.; Academic: New York, 1978; Vol. 2, pp 1-44. (b) Scheer, H.; Inhoffen, H. H. *Ibid.*, pp 45-90.
- (10) Stolzenberg, A. M.; Spreer, L. O.; Holm, R. H. *J. Chem. Soc., Chem. Commun.* **1979**, 1077.
- (11) Stolzenberg, A. M.; Spreer, L. O.; Holm, R. H. *J. Am. Chem. Soc.* **1980**, *102*, 364.
- (12) Stolzenberg, A. M.; Strauss, S. H.; Holm, R. H. *J. Am. Chem. Soc.* **1981**, *103*, 4763.
- (13) (a) Richardson, P. F.; Chang, C. K.; Hanson, L. K.; Spaulding, L. D.; Fajer, J. *J. Phys. Chem.* **1979**, 3420. (b) Richardson, P. F.; Chang, C. K.; Spaulding, L. D.; Fajer, J. *J. Am. Chem. Soc.* **1979**, *101*, 7736. (c) Chang, C. K. *Biochemistry*, **1980**, *19*, 1971.
- (14) (a) Chang, C. K.; Fajer, J. *J. Am. Chem. Soc.* **1980**, *102*, 848. (b) Chang, C. K.; Hanson, L. K.; Richardson, P. F.; Young, R.; Fajer, J. *Proc. Natl. Acad. Sci. U.S.A.* **1981**, *78*, 2652.
- (15) (a) Fujita, E.; Fajer, J. *J. Am. Chem. Soc.* **1983**, *105*, 6743. (b) Fujita, E.; Chang, C. K.; Fajer, J. *J. Am. Chem. Soc.* **1985**, *107*, 7665.
- (16) Chang, D.; Malinski, T.; Ulman, A.; Kadish, K. M. *Inorg. Chem.* **1984**, *23*, 817.
- (17) (a) Feng, D.; Ting, Y.-S.; Ryan, M. D. *Inorg. Chem.* **1985**, *24*, 612. (b) Fernandes, J. B.; Feng, D.; Chang, A.; Keyser, A.; Ryan, M. D. *Inorg. Chem.* **1986**, *25*, 2606.
- (18) Strauss, S. H.; Holm, R. H. *Inorg. Chem.* **1982**, *21*, 863.
- (19) Strauss, S. H.; Silver, M. E.; Ibers, J. A. *J. Am. Chem. Soc.* **1983**, *105*, 4108.
- (20) Strauss, S. H.; Silver, M. E.; Long, K. M.; Thompson, R. G.; Hudgens, R. A.; Spartalian, K.; Ibers, J. A. *J. Am. Chem. Soc.* **1985**, *107*, 4207.
- (21) (a) Monforts, F.-P.; Ofner, S.; Rasetti, V.; Eschenmoser, A.; Woggon, W.-D.; Jones, K.; Battersby, A. R. *Angew. Chem., Int. Ed. Engl.* **1979**, *18*, 675. (b) Angst, C.; Kajiwara, M.; Zass, E.; Eschenmoser, A. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 140. (c) Johansen, J. E.; Angst, C.; Kratky, C.; Eschenmoser, A. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 141. (d) Naab, P.; Lattmann, R.; Angst, C.; Eschenmoser, A. *Angew. Chem., Int. Ed. Engl.* **1980**, *19*, 143. (e) Waditschatka, R.; Eschenmoser, A. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 630. (f) Waditschatka, R.; Diener, E.; Eschenmoser, A. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 631.
- (22) (a) Cruse, W. B. T.; Harrison, P. J.; Kennard, O. *J. Am. Chem. Soc.* **1982**, *104*, 2376. (b) Barkigia, K. M.; Fajer, J.; Spaulding, L. D.; Williams, G. J. B. *J. Am. Chem. Soc.* **1981**, *103*, 176. (c) Barkigia, K. M.; Fajer, J.; Chang, C. K.; Williams, G. J. B. *J. Am. Chem. Soc.* **1982**, *104*, 315.
- (23) Kratky, C.; Angst, C.; Johansen, J. E. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 211.
- (24) (a) Ulman, A.; Fisher, D.; Ibers, J. A. *J. Heterocycl. Chem.* **1982**, *19*, 409. (b) Gallucci, J. C.; Swepston, P. N.; Ibers, J. A. *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.* **1982**, *B38*, 2134. (c) Suh, M. P.; Swepston, P. N.; Ibers, J. A. *J. Am. Chem. Soc.* **1984**, *106*, 5164.
- (25) (a) Kratky, C.; Waditschatka, R.; Angst, C.; Johansen, J. E.; Plaquevent, J. C.; Schreiber, J.; Eschenmoser, A. *Helv. Chim. Acta* **1985**, *68*, 1312. (b) Waditschatka, R.; Kratky, C.; Juan, B.; Heinzer, J.; Eschenmoser, A. *J. Chem. Soc., Chem. Commun.* **1985**, 1604.
- (26) (a) Ogoshi, H.; Watanabe, E.; Yoshida, Z.; Kincaid, J.; Nakamoto, K. *Inorg. Chem.* **1975**, *14*, 1344. (b) Ozaki, Y.; Kitagawa, T.; Ogoshi, H. *Inorg. Chem.* **1979**, *18*, 1772.
- (27) (a) Andersson, L. A.; Loehr, T. M.; Chang, C. K.; Mauk, A. G. *J. Am. Chem. Soc.* **1985**, *107*, 182. (b) Andersson, L. A.; Loehr, T. M.; Sotiriou, C.; Wu, W.; Chang, C. K. *J. Am. Chem. Soc.* **1986**, *108*, 2908.
- (28) Abbreviations: OEP, 2,3,7,8,12,13,17,18-octaethylporphyrin dianion; OEC, 2,3-dihydro-2,3,7,8,12,13,17,18-octaethylporphyrin dianion (chlorin); OEiBC, mixture of *ttt*- and *tct*-2,3,7,8-tetrahydro-2,3,7,8,12,13,17,18-octaethylporphyrin dianion (isobacteriochlorin); TPP, 5,10,15,20-tetraphenylporphyrin dianion; TMC, 2,3-dihydro-5,10,15,20-tetramethylporphyrin dianion; TPC, 2,3-dihydro-5,10,15,20-tetraphenylporphyrin dianion; iBC, generic isobacteriochlorin dianion. The IUPAC numbering scheme has been employed here; see drawing in text.

necessitates or even implies that oxidations of the iBC π -system are biologically relevant, however. Magnetic properties and ligand affinities of iron complexes also were demonstrated to be somewhat macrocycle-dependent,¹⁸⁻²⁰ but the relevance of these differences to enzyme function is not immediately obvious.

A potentially significant difference has emerged from structural studies of Ni(II) and Fe(II) hydrophorphyrin complexes. Structures of Ni(II)²⁹ and Fe(II)^{20,30} porphyrins are planar or somewhat distorted. In contrast, the corresponding hydrophorphyrin complexes experience a marked S_4 ruffle and are saddle-shaped.^{19,20,23-25} The steepness of the saddle increases with the degree of saturation of the macrocycle π -system.^{24c,25} Planar porphyrin and hydrophorphyrin complexes have core sizes that result in Ni-N bond lengths that are longer than optimal for a square-planar Ni(II) ion.^{24c,25a} Metal-nitrogen bond lengths are shorter in an S_4 -ruffled conformation.³¹ The greater extent of ruffling in hydrophorphyrin complexes was attributed to their increased flexibility (decreased aromaticity)^{19,20,24c,25a} and was taken as evidence for greater structural compliance of hydrophorphyrins compared with that of porphyrins.^{19,20} One possible consequence of this conclusion is that the details of the structure of iron hydrophorphyrin complexes in various ligation and spin states could be less different than those of corresponding porphyrin complexes. Hydrophorphyrin complexes could also have greater conformational lability. Both factors could lower activation barriers and result in more rapid rates of reaction in hydrophorphyrin-containing systems. A similar suggestion had been made previously, based upon preliminary observations of increased rates of metalation and rates of reduction for certain iBC complexes.¹²

The importance of ruffling to the solution chemistry of nickel hydrophorphyrins has not been fully demonstrated. Evidence for the generality of ruffling in nickel hydrophorphyrin complexes rests primarily upon data from X-ray diffraction studies. Solution equilibria involving nickel octaethylhexahydrophorphyrin stereoisomers were rationalized by analysis of the expected conformations for ruffled complexes.^{25a} In addition, ¹H NMR data have established that nickel(II) *cccc*-octaethylpyrrocorphinato is ruffled and that a 12 kcal/mol inversion barrier exists between the two enantiomorphically ruffled conformers.^{25b} Unfortunately, demonstration of ruffled conformers of nickel(II) *cccc*-octaethylpyrrocorphinato in solution does little to establish the existence of ruffling in the solution chemistry of chlorins, bacteriochlorins, or isobacteriochlorins. The structure of the *cccc*-pyrrocorphinato exhibits the steepest ruffling of a tetrapyrrole macrocycle observed to date for any hydrophorphyrin characterized by X-ray crystallography.²⁵ Thus, it is the complex most likely to exhibit ruffling in solution. In contrast, structures of nickel chlorin complexes are ruffled to a lesser extent than any other class of hydrophorphyrin.^{24,25} Evidence for ruffled conformers of chlorin complexes would suggest that ruffling is important in the solution chemistry of all hydrophorphyrins. Chlorins have the smallest number of possible stereoisomers of all hydrophorphyrins. Comparison of the properties of cis and trans diastereomers could establish whether the details of the conformations of the macrocycle in solution are strongly influenced by the stereochemistry of the substituents.

We report here the results of our investigations of the solution physicochemical properties of two series of chlorin complexes of known stereochemistry, *cis*- and *trans*-M(OEC) (where M = H₂, Cu, Mg, Ni, Sn(Cl)₂, and Zn). The *cis*-metallochlorins are reported here for the first time. Our data establish that the conformation of these hydrophorphyrin complexes depends upon the stereochemistry of the substituents and the identity of the coordinated metal, suggest that nickel chlorins are S_4 -ruffled in solution, and, most importantly, demonstrate that conformational changes can result in differences in chemical reactivity.



Experimental Section

General Comments. Manipulations were carried out under a nitrogen atmosphere by use of Schlenk techniques or in a Vacuum/Atmospheres Co. drybox. All chromatographic procedures involving *cis*-OEC complexes were performed in the drybox. Reagents and solvents were treated as previously reported³² and were thoroughly degassed prior to use. Absorption spectra were recorded on a Perkin-Elmer Lambda 4C spectrophotometer. Other spectroscopic and electrochemical measurements were obtained as before.³²

Preparation of Complexes. H₂(OEP),³³ *trans*-H₂(OEC),³⁴ *trans*-Zn(OEC),³⁵ and *trans*-Cu(OEC)³⁶ were prepared by published methods. The phosphoric acid extraction procedure reported in the workup of *trans*-H₂(OEC) was found to be unnecessary and was omitted.

***cis*-Octaethylchlorin.** The procedure is a modification of the *p*-toluenesulfonohydrazide reduction of H₂(OEP).³⁴ A 200-mL three-neck flask equipped with a condenser, stirrer, and addition funnel was charged with 0.75 g of H₂(OEP), 5.62 g of potassium carbonate, and 40 mL of freshly distilled β -picoline. The mixture was thoroughly degassed, placed under a nitrogen atmosphere, and brought to reflux. A solution of 7.50 g of *p*-toluenesulfonohydrazide in 23 mL of β -picoline was degassed, placed in the addition funnel, and added dropwise over a 2-h period. The reaction mixture was refluxed for an additional 2 h, cooled to room temperature, and added to 300 mL of a 1:1 benzene/water mixture. The benzene layer was separated and was washed with cold 10% HCl (2 \times 75 mL), water (100 mL), saturated sodium bicarbonate solution (2 \times 75 mL), and finally water (2 \times 100 mL) again. Evaporation of the solvent afforded a purple powder, which was a mixture of porphyrin (major component), chlorin, and degradation products. The soluble portion of this powder was redissolved in a minimal quantity of 7:3 cyclohexane/benzene and was applied to a 2 \times 18 cm column of grade 3 alumina. The desired product eluted first with the same solvent mixture. Recrystallization from chloroform/hexane afforded 50 mg of *cis*-H₂(OEC) (7% yield from starting H₂(OEP)). The column was removed from the drybox, and unreacted porphyrin was stripped from the column with 80:20 chloroform/methanol. Crude porphyrin was recrystallized by extraction with toluene in a Soxhlet extractor.³⁷ Recovery of crystalline H₂(OEP) was about 65%.

***cis*-Cu(OEC).** A solution of 50 mg of *cis*-H₂(OEC) and 50 mg of Cu(C₂H₃O₂)₂·2H₂O in 20 mL of DMF was refluxed under nitrogen for 1 h. After the mixture was cooled to room temperature, 30 mL of water was added. The product precipitated. The mixture was extracted with several portions of chloroform. The combined extracts were evaporated to dryness. The crude product was purified by chromatography on grade 3 alumina. Elution was with 99:1 benzene/methanol. Recrystallization from chloroform/hexane afforded *cis*-Cu(OEC) in 85% yield.

***cis*- or *trans*-Mg(OEC).** A 50-mg sample of the chlorin was dissolved in 20 mL of dry benzene. The resulting solution was placed in a Schlenk flask under a nitrogen atmosphere. A 150- μ L aliquot of a 0.5 M solution of methylmagnesium bromide in diethyl ether (excess) was added by syringe. The solution was stirred at room temperature for 30 min and was then heated at reflux for an additional 30 min. After the mixture was cooled, 10 mL of water was added. The benzene layer was transferred by cannula to another Schlenk flask, and the solvent was removed. The residue was purified by chromatography on a grade 3 alumina column eluted with 99:1 benzene/methanol. Evaporation of the solvent

- (29) (a) Cullen, D. L.; Meyer, E. F., Jr. *J. Am. Chem. Soc.* **1974**, *96*, 2095.
(b) Meyer, E. F., Jr. *Acta Crystallogr., Sect. B: Struct. Crystallogr. Cryst. Chem.* **1972**, *B28*, 2162.
(30) Collman, J. P.; Hoard, J. L.; Kim, N.; Lang, G.; Reed, C. A. *J. Am. Chem. Soc.* **1975**, *97*, 2676.
(31) Hoard, J. L. *Ann. N.Y. Acad. Sci.* **1973**, *206*, 18.

- (32) Stolzenberg, A. M.; Glazer, P. A.; Foxman, B. M. *Inorg. Chem.* **1986**, *25*, 983.
(33) Wang, C.-B.; Chang, C. K. *Synthesis* **1979**, 548.
(34) Whitlock, H. W., Jr.; Hanauer, R.; Oester, M. Y.; Bower, B. K. *J. Am. Chem. Soc.* **1969**, *91*, 7485.
(35) Furhop, J.-H. Z. *Naturforsch., B: Anorg. Chem., Org. Chem., Biochem., Biophys., Biol.* **1970**, *25B*, 255.
(36) Eisner, U.; Lichtarowicz, A.; Linstead, R. P. *J. Chem. Soc.* **1956**, 733.
(37) Paine, J. B., III; Kirshner, W. B.; Moskowitz, D. W.; Dolphin, D. *J. Org. Chem.* **1976**, *41*, 3857.

Table I. Quantitative Absorption Spectral Data for M(OEC) Complexes^a

complex	λ_{max} , nm (ϵ , mM) ^b						
<i>c</i> -Cu(OEC)	389.5 (89.8)	400.6 (135)	495.6 (6.1)	531.0 (5.6)	575.2 (9.3)		619.0 (46.7)
<i>t</i> -Cu(OEC)	388.7 (83.2)	399.2 (155)	494.7 (5.5)	529.0 (6.5)	563.2 (10.5)		613.8 (40.8)
<i>c</i> -Mg(OEC)	387.8 (54.8)	408.2 (192)		511.9 (5.3)	579.3 (8.5)	595.7 (6.5)	624.3 (62.0)
<i>t</i> -Mg(OEC)	386.0 (66.7)	406.9 (215)		511.3 (7.1)	576.0 (9.3)	592.2 (7.9)	620.3 (70.2)
<i>c</i> -Ni(OEC)	388.0 (68.5)	399.8 (89.8)	490.8 (5.2)	523.3 (4.2)	579.3 (8.8)	594.7 (11.0)	619.0 (50.4)
<i>t</i> -Ni(OEC)	387.0 (57.2)	396.7 (73.2)	489.3 (4.7)	522.2 (4.7)	575.1 (7.2)	592.2 (8.3)	614.9 (40.6)
<i>c</i> -Sn(OEC)Cl ₂	385.3 (48.9)	404.4 (167)		513.9 (6.9)	578.4 (10.5)	600.0 (7.0)	627.3 (60.1)
<i>t</i> -Sn(OEC)Cl ₂	382.5 (51.3)	403.2 (190)		512.0 (7.5)	575.9 (9.2)	595.0 (7.5)	622.1 (72.3)
<i>c</i> -Zn(OEC)		402.2 (162)	502.0 (6.3)	535.5 (5.8)	570.0 (9.4)	593.8 (6.1)	621.0 (51.0)
<i>t</i> -Zn(OEC)		400.1 (164)	501.3 (6.5)	537.7 (5.3)	571.4 (9.2)	589.7 (9.4)	616.8 (76.5)

^a(2–6) × 10⁻⁴ M benzene solution. ^bRelative values are known to the precision indicated; absolute values are accurate only to several percent.

from the eluate afforded the product as a blue solid. MS (trans; EI): *m/e* 558 (M⁺), 556.

***cis*- or *trans*-Ni(OEC).** A solution of 50 mg of the chlorin and 70 mg of NiCl₂·6H₂O in 25 mL of DMF was refluxed under nitrogen for 1 h. The blue solution was cooled to room temperature, and 50 mL of water was added. The product precipitated. The mixture was extracted with several portions of chloroform. Combined extracts were taken to dryness, and the residue was purified by chromatography on a grade 3 alumina column. Elution was with benzene. The solid obtained from the eluate was recrystallized from chloroform/methanol to afford the product in 80–90% yield.

***cis*- or *trans*-Sn(OEC)Cl₂.** Chlorins were metalated by the literature method.³⁸ These reactions were run aerobically to permit oxidation of the intermediate Sn(II) metalochlorin to Sn(IV). Crude products were purified by recrystallization from chloroform/hexane. MS (cis and trans; EI): *m/e* 724 (M⁺ peak with greatest intensity, intensities of 720–730 region similar to those predicted from isotopic abundances), 689, 654, 629, 558, 362 (M²⁺).

***cis*-Zn(OEC).** A methanol solution of Zn(C₂H₃O₂)₂ was added to a solution of the chlorin in chloroform. The solution was refluxed for 30 min and was then evaporated to dryness. The crude product was purified by chromatography on a grade 3 alumina column eluted with 99:1 benzene/methanol. The solid recovered from the eluate was recrystallized from chloroform/hexane.

Results and Discussion

Several syntheses of *cis*-H₂(OEC) have been reported.^{21b,34,39} Diborane reduction of H₂(OEP) gave a 5:1 mixture of *cis*- and *trans*-H₂(OEC) in about 10% yield.³⁹ Chromatographic separation of the isomers and unreacted porphyrin resulted in extensive loss of material. The isolated yield of pure *cis* isomer was only 1.5%. *cis*-H₂(OEC) was obtained in 10% yield from a mixture of chlorins and diastereomeric isobacteriochlorins produced by reaction of dilute solutions of octaethylporphyrinogen with cobalt chloride.^{21b} Two procedures are selective for the *cis* isomer. Reduction of H₂(OEP) by *p*-toluenesulfonylhydrazide followed by a series of phosphoric acid extractions to separate the product from unreacted porphyrin afforded *cis*-H₂(OEC) in 11% yield.³⁴ Catalytic hydrogenation of Zn(OEP) under vigorous conditions (180 atm, 90 °C, 90 h) gave an 8% yield of the *cis* isomer.³⁹

None of these procedures as reported represent a practical route to *cis*-H₂(OEC). The *p*-toluenesulfonylhydrazide reduction would appear to be the method of choice given its stereoselectivity and the mild conditions employed. Unfortunately, the phosphoric acid extractions in our hands resulted in loss of all the air- and light-sensitive *cis*-H₂(OEC) that was present in the crude product. However, we found that chromatographic purification of the crude product, when carried out in a drybox, permitted isolation of the desired chlorin from the mixture with little loss. (In contrast, chromatographic workup performed under an argon atmosphere outside the drybox resulted in significant loss of product.) The *cis*-H₂(OEC) prepared in this manner was free of contamination by either *trans*-H₂(OEC) or H₂(OEP). The yield was 7% based upon the quantity of porphyrin initially present but was 20% based upon the quantity of porphyrin consumed. Unreacted H₂(OEP) was readily recovered and recycled.

cis- and *trans*-H₂(OEC) were metalated by standard methods. Both reacted more readily under milder conditions than H₂(OEP). Metalation of *cis*-H₂(OEC) invariably led to slight formation of OEP complexes by oxidative dehydrogenation. *trans*-H₂(OEC) was not oxidized under these conditions.

Absorption Spectra. Spectral data for *cis*- and *trans*-M(OEC) complexes are collected in Table I. Our data are similar to those reported earlier for *trans*-M(OEC) (M = Cu, Mg, Ni, SnCl₂, and Zn)^{26a,35,36,40} when allowances are made for the differences in solvent systems employed. Spectra of the previously unreported *cis*-M(OEC) complexes resemble the spectra of the corresponding *trans*-M(OEC) complexes. The absorption bands of the *cis* complexes were somewhat red shifted (1–7 nm), and most but not all had diminished extinctions relative to the *trans* complexes. The same trends were noted in the spectra of the free-base complexes.³⁹

A decrease in the ratio of the intensity of the Soret band to the α (Q or visible) band is a characteristic feature of the UV–vis spectra of hydroporphyrins.^{36,41} This ratio is on the order of 10–40 for OEP complexes,⁴¹ 3–4 for OEC complexes,^{26a,35,36,40} and about 1–2 for OEiBC complexes.^{11,40,42} The decrease was attributed to the reduced symmetry and aromaticity of the π -system of the hydroporphyrins.⁴⁰ The ratio of the bands (1.8) in the spectra of both *cis*- and *trans*-Ni(OEC) was substantially lower than expected for a chlorin. This could be suggestive of a further lowering of symmetry and overlap caused by ruffling.

¹H NMR Spectra. Spectral data for *cis*- and *trans*-H₂(OEC) and *cis*- and *trans*-M(OEC) complexes are collected in Table II. The spectra of both free-base complexes were recorded at lower field and analyzed in some detail.^{34,39,43} The chemical shifts of the meso protons of several *trans*-M(OEC) complexes³⁵ and complete spectra of *trans*-Sn(OEC)Cl₂⁴⁴ and -Zn(OEC)²⁰ also have been reported. Our results were in substantial agreement with the literature data.

The spectra of *cis*- and *trans*-OEC complexes were similar with the exception that most peaks in the spectra of the *cis* complexes experienced slight (0.1 ppm) upfield shifts. Exceptions to the upfield shift in *cis* complexes included the pyrroline methylene and β -protons and the NH protons. These effects were noted previously for the free-base complexes.^{34,39,43}

The ABX multiplet pattern that is assigned to the pyrroline ring methylene and β protons (2, 3) is a distinctive feature of the spectra of OEC complexes. (The A and B protons of the multiplet are also coupled to methyl protons.) These patterns differed in the *cis* and *trans* complexes. In the former, J_{AX} and J_{BX} were equal and the shift difference between A and B protons was small.⁴³ In the latter complex, J_{AX} and J_{BX} were inequivalent and the shift difference between the A and B protons was large.^{11,43} The AB multiplet patterns of M(OEC) complexes closely resembled the patterns of their respective free bases with the ex-

(38) Corwin, A. H.; Collins, O. D., III. *J. Org. Chem.* **1962**, *27*, 3060.

(39) Inhoffen, H. H.; Buchler, J. W.; Thomas, R. *Tetrahedron Lett.* **1969**, 1145.

(40) Gradyushko, A. T.; Solovov, K. N.; Tsvirko, M. P. *Opt. Spektrosk.* **1978**, *44*, 1123.

(41) Gouterman, M. In *The Porphyrins*; Dolphin, D., Ed.; Academic: New York, **1978**; Vol. 3, pp 1–165.

(42) Stolzenberg, A. M. Ph.D. Thesis, Stanford University, 1980.

(43) Wolf, H.; Scheer, H. *Justus Liebigs Ann. Chem.* **1973**, 1710.

(44) Whitten, D. G.; Yau, J. C.; Carroll, F. A. *J. Am. Chem. Soc.* **1971**, *93*, 2291.

Table II. ^1H NMR Data for $\text{M}(\text{OEC})$ Complexes^a

position ^b	complex									
	<i>c</i> -H ₂	<i>t</i> -H ₂	<i>c</i> -Mg	<i>t</i> -Mg	<i>c</i> -Ni	<i>t</i> -Ni	<i>c</i> -SnCl ₂	<i>t</i> -SnCl ₂	<i>c</i> -Zn	<i>t</i> -Zn
15,10-H	9.67	9.75	9.08	9.48	9.06	9.11	9.74	9.80	9.45	9.55
5,20-H	8.84	8.90	8.18	8.51	8.04	8.16	8.79	8.85	8.49	8.64
2,3-H ^c	4.73	4.58	4.34	4.43	4.11	4.07	4.88	4.65	4.53	4.43
7,18-CH ₂ ^d	3.99	4.05	3.63	3.85	3.53		3.88	3.92	3.81	3.87
8,17-CH ₂ ^d	3.90	3.95	3.62	3.84	3.52	3.57 ^e	3.86	3.90	3.81	3.86
12,13-CH ₂ ^d	3.86	3.93	3.55	3.74	3.41		3.75	3.77	3.69	3.76
2,3-CH ₂ ^f	2.42 ^g	2.44	2.18 ^g	2.35	2.07	1.85 ^g	2.51 ^g	2.44	2.33	2.33 ^g
		2.20		2.13	1.90			2.33	2.14	
7,18-CH ₃ ^h	1.83	1.88	1.55	1.77	1.59	1.68	1.84	1.86	1.76	1.80
8,17-CH ₃ ^h	1.79	1.85	1.54	1.75	1.55	1.64	1.82	1.83	1.75	1.78
12,13-CH ₃ ^h	1.79	1.84	1.47	1.75	1.50	1.59	1.79	1.80	1.72	1.77
2,3-CH ₃ ^h	1.08	1.11	0.99	1.04	0.95	1.02	1.19	1.07	1.10	1.09
N-H ⁱ	-2.27	-2.41								

^a δ relative to internal Me₄Si; 5 mM in CDCl₃ at 20 °C. ^b Numbering follows IUPAC convention. ^c X part of ABX multiplet. ^d Quartet; typical $J = 7$ Hz. ^e Center position of multiplet—does not resolve to three quartets in homonuclear 2D J -resolved spectra (see text). ^f A and B parts of ABX multiplet; typical $J_{AB} = 14$ Hz. ^g A and B too close to determine individual chemical shifts. ^h Triplet; typical $J = 7$ Hz. ⁱ Broad.

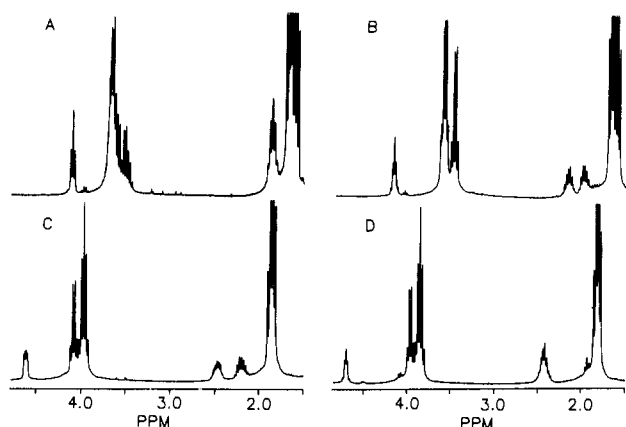


Figure 1. ^1H NMR spectra (300 MHz) of 1 mM (A) *t*-Ni(OEC), (B) *c*-Ni(OEC), (C) *t*-H₂(OEC), and (D) *c*-H₂(OEC) in CDCl₃ solution. The 7,8,12,13,17,18-CH₃ peaks have been truncated.

ception of the nickel complexes. For the nickel complexes, the multiplet patterns resembled the pattern of the free base with the opposite stereochemistry (Figure 1). Thus, metalation with nickel must have caused substantial changes in the conformations available to the pyrroline ethyl groups and consequently to chemical shifts and coupling constants. Further evidence for conformational changes in the nickel complexes is presented below.

Porphyrin meso protons are strongly deshielded by the porphyrin ring current. Progressive saturation of double bonds in hydro-porphyrins decreases the aromaticity of the macrocycle π -system and the magnitude of the effect of the ring current. The chemical shift(s) of the meso protons change from 10.4 ppm for H₂(OEP)³⁷ to 8.9–9.8 ppm for *trans*-H₂(OEC) to 6.8–8.5 ppm for H₂(OEiBC).¹¹ Metalation of *cis*- and *trans*-H₂(OEC) with nickel resulted in upfield shifts of 0.6–0.8 ppm in the positions of the meso protons, considerably in excess of the upfield shifts that resulted upon metalation with the other metal ions considered here. (*cis*-Mg(OEC) was an exception.) Other positions experience similar but smaller upfield shifts in the nickel complexes (Figure 1). Thus, the data establish that, consistent with a ruffled conformation, metalation with nickel caused marked reduction in the macrocycle ring current.

Pyrroline Ring Conformations. The β protons (2, 3) of *cis*- and *trans*-H₂(OEC) are magnetically inequivalent by the coupling constant criterion. Vicinal coupling of the B protons was not discussed in earlier reports of the ^1H NMR spectra of these complexes.^{11,43} The magnitude of the vicinal coupling constant of the β protons, $^3J_{2,3}$, is a function of their dihedral angle,⁴⁵ which in turn depends upon the conformation of the pyrroline ring. The

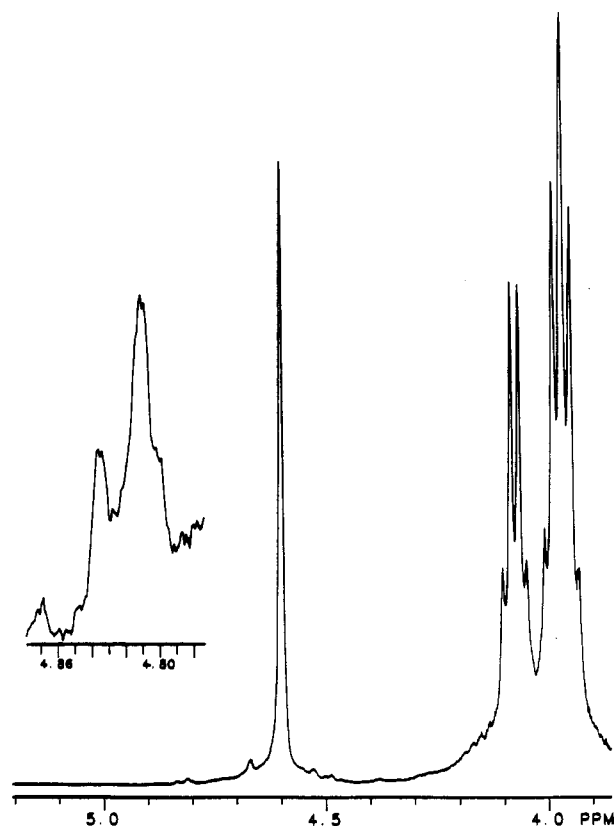


Figure 2. ^1H NMR spectrum (300 MHz) of 10 mM *t*-H₂(OEC) in CDCl₃. The 2,3-H peak at 4.58 ppm is a singlet due to irradiation of the 2,3-CH₂ multiplet. The inset is an expansion of the downfield ^{13}C satellite peaks.

magnitudes of these coupling constants were determined in an effort to obtain information about the conformations of the complexes.

Attempts to simulate the spectrum of the spin systems of interest in *cis*- and *trans*-H₂(OEC) complexes (β protons and pyrroline ring ethyl group methylene protons decoupled from the adjacent methyl protons) established that the spectrum was not sensitive to the value of $^3J_{2,3}$. The desired data were obtained from an analysis of the ^{13}C satellites of the β proton peak.⁴⁶ The adjacent methylene protons were decoupled to simplify the 2- ^{13}C , 2-H, 3-H spin system to an ABX system. A representative spectrum of the region of interest is shown in Figure 2 for *trans*-H₂(OEC). The intensity of the satellite lines was quite small owing to the low relative intensity of the β -proton peak and the low natural

(45) Karplus, M. *J. Chem. Phys.* **1959**, *30*, 11. Karplus, M. *J. Am. Chem. Soc.* **1963**, *85*, 2870.

(46) Becker, E. D. *High Resolution NMR, Theory and Chemical Applications*, 2nd ed.; Academic: New York, **1980**; p 174.

abundance of ^{13}C . Typically, 2000 transients were acquired to obtain an adequate signal to noise ratio with moderately concentrated samples (5–10 mM).⁴⁷ Satellites are approximately symmetrically placed about the central peak at a frequency separation of one-half the carbon–hydrogen coupling constant, $^1J_{\text{CH}}$.⁴⁶ Upfield satellites often were obscured under the larger downfield satellites of the pyrrole ring methylene protons, as in Figure 2. Trace impurities and spinning sidebands can mask or be mistaken for the satellites. Hence, the assignment of satellites was confirmed by direct measurement of $^1J_{\text{CH}}$ from coupled ^{13}C NMR spectra. The 2,3-carbon peaks were identified in turn by single-resonance decoupling of the β protons.⁴⁸ Further confirmation of the assignment of satellites was obtained by acquiring the spectrum without decoupling of the adjacent methylene protons. The additional coupling to these protons reduced the intensity of the ^{13}C satellite peaks sufficiently that they were not observed.

The magnitudes of $^3J_{2,3}$ observed for *cis*- and *trans*- $\text{H}_2(\text{OEC})$ were the *reverse* of those expected for a flat pyrroline ring with eclipsed substituents. The unexpectedly large value of 7.8 Hz observed for *trans*- $\text{H}_2(\text{OEC})$ requires that the dihedral angle between the 2- and 3-protons approach either 0 or 180°. The former is consistent with a half-chair conformation of the five-membered pyrroline ring that places the ethyl groups in a pseudodiaxial relationship. Precisely this type of conformation was observed in the X-ray structures of two diastereomers of $\text{H}_2(\text{OEiBC})$, both of which have *trans* reduced pyrroline rings.²³ The ^{13}C satellites for *cis*- $\text{H}_2(\text{OEC})$ were single broad peaks rather than doublets. On the basis of the full width at half-height of the peak, $^3J_{2,3}$ is at most 3.3 Hz. This value is substantially smaller than expected and requires that the dihedral angle approach 90°. An axial–equatorial half-chair or an envelope conformation is suggested for the pyrroline ring. For both complexes, deformation from a planar pyrroline ring serves to decrease unfavorable steric interaction of ethyl groups with each other.

The ^{13}C satellites of the β protons of the *cis*- and *trans*- $\text{M}(\text{OEC})$ complexes were also investigated. With the exception of the nickel complexes, the signal to noise ratio of the satellites was too small to be clearly observed. The magnitudes of $^3J_{2,3}$ in the nickel complexes, 8.0 Hz for *cis*-Ni(OEC) and 3.0 Hz for *trans*-Ni(OEC), were the opposite of those found for *cis*- and *trans*- $\text{H}_2(\text{OEC})$. The change in $^3J_{2,3}$ was a consequence of conformational changes and not of isomerization during metalation. Isomerically pure *trans*- $\text{H}_2(\text{OEC})$ was recovered quantitatively upon demetalation of the nickel complex prepared from *trans*- $\text{H}_2(\text{OEC})$.⁴⁹ The observed $^3J_{2,3}$ value for *trans*-Ni(OEC) is consistent with a conformation in solution similar to that in crystalline *trans*-Ni(OEiBC)²³ and in crystalline *trans*-Fe(OEC).²⁰ The pyrroline rings of these complexes adopt shallow half-chair conformations with diequatorial ethyl groups. In addition, the entire *trans*-Ni(OEiBC) macrocycle is markedly ruffled in an S_4 fashion. Ruffling increases the distances between groups on adjacent pyrrole rings, relieving the steric congestion about the periphery of the macrocycle.⁵⁰ Similar, but less pronounced, ruffling was noted for *trans*-Fe(OEC).²⁰ Remarkably, the value of $^3J_{2,3}$ observed for *cis*-Ni(OEC) requires that the pyrroline ring substituents become nearly eclipsed. Shorter Ni–N distances must result in a stabilization sufficiently large to overcome the destabilizations that result from eclipsed pyrroline ring substituents and reduction of overlap in the macrocycle π -system.

No change was noted in the number or line widths of the ^{13}C satellites of the nickel complexes in variable-temperature experiments over the range –50 to +30 °C. Thus, the observed $^3J_{2,3}$ value did not appear to represent an average over a population of conformers that have substantially different $^3J_{2,3}$ values and

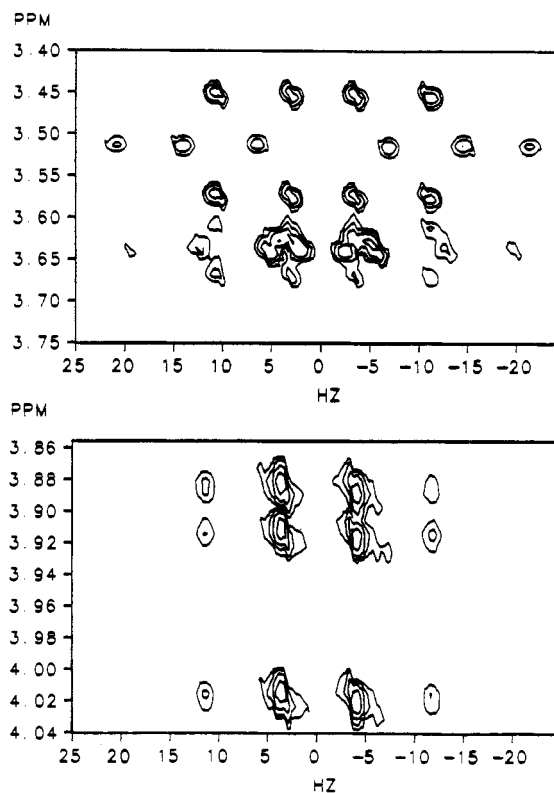


Figure 3. Contour plots of the homonuclear 2D J -resolved spectra (300 MHz) of *c*- $\text{H}_2(\text{OEC})$ (lower) and *t*-Ni(OEC) (upper).

that have relatively large barriers to interconversion.

Several workers have attempted to use the magnitude of the $^3J_{2,3}$ coupling constant and the Karplus relationship for vicinal coupling constants⁴⁵ to assign the pyrroline ring stereochemistry of unsymmetrically substituted chlorins and isobacteriochlorins.^{51,52} The method, as applied, is predicted on implicit assumptions that the pyrroline ring, if not the entire macrocycle, is planar and that the β substituents are eclipsed. Our results establish that the pyrroline rings of chlorins of defined stereochemistry can have several different conformations in solution. The exact conformation adopted reflects a balance of energetic contributions arising from substituent stereochemistry and metal coordination among other factors. The magnitude of the β -proton coupling constant does not necessarily convey any information about the stereochemistry of a hydroporphyrin. Thus, stereochemical assignments based solely upon the magnitude of this coupling constant must be regarded as suspect.⁵³

2D Homonuclear J -Resolved Spectra. It has been suggested that metallohydroporphyrin complexes will be significantly S_4 -ruffled if the optimal M–N distance in complexes of the metal with unidentate ligands is less than 1.99 Å.^{24c} The metal ions included in this study span a range of radii such that optimal M–N distances are above and below 1.99 Å. We have sought evidence of ruffling to test the above suggestion.

The ^1H NMR spectra of the diastereotopic pyrrole ring methylene protons could be quite sensitive to the effects of a ruffled conformation. S_4 -ruffling distortions destroy the local mirror plane of a planar macrocycle. If the environments of two diastereotopic methylene protons are sufficiently different on the NMR time scale, a discernible AB multiplet will result.⁵⁴ In addition, ruffling

(47) Satisfactory proton spectra can be obtained with four transients at this concentration.

(48) Stolzenberg, A. M.; Stershic, M. T. *Magn. Reson. Chem.* **1987**, *25*, 256.

(49) Battersby, A. R.; Jones, K.; Snow, R. J. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 734. Lewis, N. J.; Pfaltz, A.; Eschenmoser, A. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 735.

(50) Woodward, R. B. *Angew. Chem.* **1960**, *72*, 651.

(51) Closs, G. L.; Katz, J. J.; Pennington, F. C.; Thomas, M. R.; Strain, H. H. *J. Am. Chem. Soc.* **1963**, *85*, 3809.

(52) Smith, K. M.; Goff, D. A. *J. Am. Chem. Soc.* **1985**, *107*, 4954.

(53) The assigned stereochemistry is one of the nickel isobacteriochlorins in ref 52 was confirmed by an X-ray structure: Barkigia, K. M.; Fajer, J.; Goff, D. A.; Smith, K. M., unpublished observations.

(54) AB multiplets can also result from out-of-plane metal ions or unsymmetric coordination of axial ligands. The metal ions included in this study are either four- or six-coordinate and in plane or exchange axial ligands under the conditions of the study.

Table III. ^{13}C NMR Data for M(OEC) Complexes^a

position ^b	complex									
	c-H ₂	t-H ₂	c-Mg	t-Mg	c-Ni	t-Ni	c-SnCl ₂	t-SnCl ₂	c-Zn	t-Zn
2,3-CH ₃ ^c	12.65	10.92	12.46	10.68	12.00	11.19	12.16	10.09	12.49	10.73
7,18-CH ₃ ^c	17.92	17.98	18.00	18.15	17.50	17.54	17.58	17.70	17.92	18.02
8,17-CH ₃ ^c	18.29	18.30	18.45	18.60	18.11	18.14	18.05	18.10	18.46	18.48
12,13-CH ₃ ^c	18.69	18.70	18.59	18.72	18.18	18.21	18.19	18.22	18.57	18.60
2,3-CH ₂ ^d	22.50	31.00	21.90	31.09	20.25	28.49	22.14	31.08	21.93	30.98
7,18-CH ₂ ^d	19.29	19.30	19.20	19.44	19.14	19.12	19.35	19.36	19.30	19.36
8,17-CH ₂ ^d	19.51	19.51	19.28	19.60	19.28	19.30	19.55	19.60	19.45	19.50
12,13-CH ₂ ^d	19.74	19.76	19.37	19.62	19.35	19.38	19.59	19.70	19.54	19.58
1,4-C	166.86	167.72	161.92	163.39	153.76	155.55	160.27	161.10	163.04	164.13
2,3-C ^e	51.98	54.58	50.88	53.43	51.70	54.04	50.63	52.51	50.65	53.06
5,20-C ^f	92.10	92.77	91.59	92.75	92.00	93.08	91.69	92.33	92.27	93.15
10,15-C ^f	98.93	98.71	101.25	101.54	101.08	100.56	101.04	100.65	101.25	101.00
unassigned	132.20	132.20	137.37	137.53	136.15	136.11	138.54	138.48	137.39	137.37
macrocycle	134.23	134.14	139.83	139.49	137.69	137.53	139.17	139.78	139.44	139.52
carbons	137.40	137.54	142.62	142.96	137.84	137.71	140.20	140.15	143.05	143.06
	139.14	139.04	142.74	143.26	139.38	139.31	141.04	141.04	143.42	143.47
	142.30	142.31	143.09	143.71	143.52	143.28	144.56	144.41	143.99	144.01
	149.39	149.40	150.44	151.04	144.00	144.28	148.35	148.21	151.17	151.21

^a δ relative to internal Me₄Si; 5 mM in CDCl₃ at 20 °C. ^b Numbering follows IUPAC convention. ^c Proton-coupled spectrum: ^e Quartet, typical $^1J_{\text{CH}} = 127$ Hz. ^d Triplet, typical $^1J_{\text{CH}} = 127$ Hz. ^e Doublet, typical $^1J_{\text{CH}} = 130$ Hz. ^f Doublet, typical $^1J_{\text{CH}} = 158$ Hz.

distortions have two possible enantiomerically related senses.²⁵ *trans*-M(OEC) can potentially form a mixture of two enantiomeric pairs (*R,S*,eq,eq and *R,S*,ax,ax) when ruffled. The equilibrium populations of the two enantiomeric pairs will be determined by the difference in energy caused by the different orientations of the substituents. In contrast, *cis*-M(OEC) complexes can form only an enantiomeric pair (*R,R*,ax,eq) of product complexes from the two senses of ruffling, owing to the meso symmetry of the *cis* complex.

The pyrrole ring methylene proton region of spectra of chlorin complexes consisted of several overlapping multiplets. We obtained homonuclear 2D *J*-resolved ¹H spectra to clarify this region of the spectra. A representative 2D spectrum is shown in the lower part of Figure 3. Three individual quartet spin multiplets were observed, suggesting the macrocycle is either planar in a static sense or by averaging on the NMR time scale. The one anomalous complex was *trans*-Ni(OEC), whose 2D spectrum is shown in the upper part of Figure 3. The pyrrole ring methylene proton region consisted of six different peaks, which appeared to be second-order patterns. The complexity of this region of the spectrum was also apparent in the conventional ¹H NMR spectrum (Figure 1). These observations are consistent with a ruffled conformation for this complex. The absence of second-order patterns in *cis*-Ni(OEC) could suggest that the barrier to inversion of the sense of ruffling is small.

¹³C NMR Spectra. Spectral data for *cis*- and *trans*-H₂(OEC) and *cis*- and *trans*-M(OEC) complexes are collected in Table III. Our data agree with those reported for *trans*-H₂(OEC),⁵⁵ the only complex of the series that has been characterized by ¹³C NMR. Assignments of carbons with attached protons were made with the aid of APT, proton-coupled, and single-frequency proton-decoupled spectra. The assignments of the pyrroline α -carbons (1, 4) of *trans*-H₂(OEC) were based upon direct evidence from a 2D ¹³C-¹³C INADEQUATE experiment and the enhancements observed in single-frequency decoupling experiments.⁴⁸ Pyrroline α -carbons of the other complexes were assigned by analogy. The remaining quaternary carbons were not assigned.

As expected, the methylene carbons (2a, 3a) of the pyrroline ring ethyl substituents and the pyrroline β -carbons (2, 3) in *cis*-H₂(OEC) were 8.50 and 2.6 ppm upfield, respectively, of the corresponding carbons in the *trans* complex. The observed shifts are attributable to the γ -gauche effect⁵⁶ and confirm the original assignment of the stereochemistry of the two OEC isomers, which was based upon oxidative degradation of the *trans* isomer to

racemic 2,3-diethylsuccinic acid.³⁴ Comparisons of the chemical shifts of analogous carbons in other hydroporphyrins should provide a method for establishing the stereochemistry when both isomers are accessible. Smaller upfield shifts were also noted for the pyrroline α -carbons (1, 4) and pyrroline-ring-adjacent meso carbons (5, 20) in the *cis* isomer relative to those in the *trans* isomer. With the exception of the methyl carbons of the pyrroline ring ethyl substituents, the chemical shifts of all other positions were nearly identical in the two isomers. The ¹³C NMR spectra of the metallochlorins are similar to the spectra of the free bases for the most part. The differences between *cis* and *trans* isomers discussed above were preserved upon metalation.

Two features of the spectra of the nickel complexes are noteworthy. The chemical shifts of the 2,3-CH₂ carbons in the nickel complexes were significantly upfield (*cis*, 1.9 ppm; *trans*, 2.5 ppm) of the corresponding carbons in any of the other complexes (range: *cis*, 0.6 ppm; *trans*, 0.11 ppm). This shielding could reflect the increased steric interactions of these carbons that result from the change in the conformation of the pyrroline ring ethyl groups from diaxial (free base) to diequatorial (Ni). Even larger shielding (7–8 ppm) was observed for the pyrroline α -carbons (1, 4) of the nickel chlorins. It is precisely these carbons that should experience the greatest change in geometry (pyramidalization) and hybridization upon ruffling of the macrocycle.^{25a} Thus, the shielding observed for the Ni complexes could be consistent with a ruffled structure for these complexes.

Voltammetry. Several investigations of the redox properties of chlorin free base and metal complexes have been reported.^{10-17,35,57} The chlorins investigated in these studies either lacked β substituents or had *trans* stereochemistry. We report here the first data for *cis*-OEC complexes and data for several *trans*-M(OEC) complexes that have not been investigated by cyclic voltammetry (Table IV). Data for Zn(OEC) and H₂(OEC) were included to permit comparisons with the other complexes under closely similar experimental conditions (acetonitrile solution, 0.1 M TBAP).

The cyclic voltammograms of *cis*-H₂(OEC) (Figure 4) and *trans*-H₂(OEC)⁵⁸ were superficially alike. Both consisted of two one-electron oxidations and two one-electron reductions. The potentials of corresponding processes for these complexes were nearly identical.⁵⁹ Reduction processes of *cis*-H₂(OEC) and *trans*-H₂(OEC) were reversible. Substantial differences existed in the stability of the cation radicals and dication of the *cis* and

(57) Cloutour, C.; Debaig-Valade, C.; Pommier, J.-C. *J. Organomet. Chem.* **1981**, *220*, 21.

(58) See Figure 5 of ref 11.

(59) This result establishes that the increased tendency of the *cis* isomer to undergo oxidative dehydrogenation is a kinetic phenomenon.

(55) Smith, K. M.; Unsworth, J. F. *Tetrahedron* **1975**, *31*, 367.

(56) Wehrli, F. W.; Wirthlin, T. *Interpretation of Carbon-13 NMR Spectra*; Heyden: London, 1978; pp 22–47.

Table IV. Potentials of Free-Base OEC and Metal-OEC Complexes

complex	$E_{1/2}$, ^a V ^b				other
	2+/1+	1+/0	0/1-	1-/2-	
<i>c</i> -H ₂ (OEC)	1.12 ^{c,d}	0.58 ^e	-1.43	-1.89	1.63 ^{c,d,f}
<i>t</i> -H ₂ (OEC) ^g	1.10 ^e	0.59	-1.44	-1.89	
<i>c</i> -Cu(OEC) ^h	1.12 ^{c,d}	0.46	-1.51	-2.11 ⁱ	
<i>t</i> -Cu(OEC) ^h	1.09	0.47	-1.52	-2.15 ⁱ	
<i>c</i> -Mg(OEC)	0.66 ^{c,d}	0.27	-1.69		
<i>t</i> -Mg(OEC)	0.64	0.27	-1.71		
<i>c</i> -Ni(OEC)	0.85	0.49	-1.48		
<i>t</i> -Ni(OEC)	0.82	0.48	-1.46		
<i>c</i> -Sn(OEC)Cl ₂	1.52 ^{c,d,j}	1.03 ^e	-0.97		-1.37, ^{f,i} (-1.31 ^{c,k}), -1.78
<i>t</i> -Sn(OEC)Cl ₂	1.59 ^{c,d,j}	1.04	-0.98		-1.39, ^{f,i} (-1.31 ^{c,k}), -1.78
<i>c</i> -Zn(OEC)	0.84 ^{c,d}	0.34 ^e	-1.61	-2.05 ⁱ	
<i>t</i> -Zn(OEC) ^l	0.83	0.36	-1.61	-1.99	

^a $E_{1/2} = 1/2(E_{p,a} + E_{p,c})$. ^b Vs. SCE at 25 °C in acetonitrile solution 0.1 M in TBAP, unless noted otherwise. ^c $E_{p,a}$ (irreversible). ^d Peak position at 100 mV/s scan rate. ^e $i_{p,c} < i_{p,a}$. ^f Two-electron process. ^g Lit.¹¹ data: 1.11, 0.59, -1.46, \sim -1.9 V. ^h CH₂Cl₂ solution. ⁱ $E_{p,c}$ (irreversible). ^j More than one-electron process. ^k One-electron process. ^l Lit.¹¹ data: 0.83, 0.35 V.

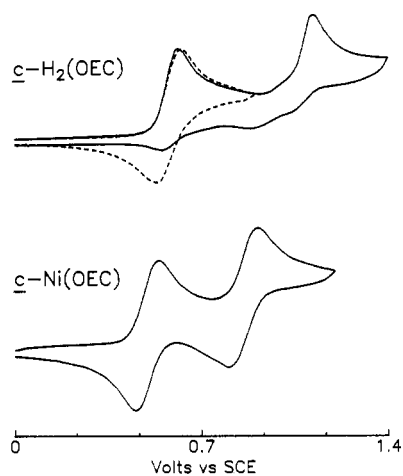


Figure 4. Cyclic voltammograms of the 1+/0 and 2+/1+ processes of *c*-H₂(OEC) and *c*-Ni(OEC) recorded at 100 mV/s in acetonitrile solution. The dashed line is the voltammogram of the 1+/0 process of *c*-H₂(OEC) scanned separately at 200 mV/s.

trans isomers. The first oxidation of *trans*-H₂(OEC) was electrochemically reversible.¹¹ Some loss of the *trans*-H₂(OEC) dication occurred on the cyclic voltammogram time scale at a scan rate of 100 mV/s.¹¹ In contrast, the first oxidation of *cis*-H₂(OEC) was not chemically reversible ($i_{p,a}/i_{p,c} > 1$). Less than 80% of the cation radical could be rereduced at a scan rate of 1000 mV/s. The second oxidation was totally irreversible; no reverse wave was observed at scan rates as great as 2000 mV/s. Although small anodic waves were detected at slow scan rates at potentials corresponding to the first and second oxidations of H₂(OEP), the latter does not appear to be the principal decomposition product. An oxidation that had an anodic current equivalent to approximately two electrons was observed at 1.63 V, a potential close to that reported for H₄(OEP)²⁺.⁶⁰ Formation of an N-protonated product upon oxidative dehydrogenation of a hydroporphyrin was reported previously.¹¹

Metalation of *cis*- or *trans*-H₂(OEC) with redox-innocent metal ions changed the potentials of the redox processes and generally enhanced the stability of cation-radical and dication species, a phenomenon noted previously for H₂(OEtBC).¹¹ The sign and magnitude of the shifts in potential were identical for the *cis* and *trans* isomers, depended on the electronegativity of the metal ion,⁶⁰ and were similar to those observed upon metalation of both

H₂(OEP)⁶⁰ and octaethylporphyrin-2-one.³² For *trans*-OEC, metalation with Mg or Zn led to a reversible second oxidation process (cation radical \rightarrow dication). Similarly, formation of the *cis*-Mg(OEC) cation-radical species became chemically reversible on the cyclic voltammogram time scale. For *cis*-Cu(OEC), formation of the cation radical was nearly chemically reversible. In contrast, metalation of *cis*-OEC with zinc afforded little increase in stability. A substantial portion of the cation radical of *cis*-Zn(OEC) decomposed to Zn(OEP) on the cyclic voltammogram time scale. The second oxidations of all *cis*-OEC complexes remained totally irreversible. The appearance in the cyclic voltammograms of these complexes of two oxidation waves (one for Mg) and two reduction waves, all at potentials corresponding to processes of the respective M(OEP) complexes, and the enhancement of these waves by momentary electrolysis beyond the potential of the first *cis*-M(OEC) oxidation (second for Mg) established that the cation radicals and/or dications underwent oxidative dehydrogenation to the porphyrin complexes.

Interpretations of the cyclic voltammograms of *cis*- and *trans*-Ni(OEC) were complicated by the possibility of the oxidation of Ni^{II} to Ni^{III}. Ni^{III}(TPP)⁺ species were observed upon direct oxidation of Ni^{II}(TPP) in benzonitrile⁶¹ or upon cooling of solutions of Ni^{II}(TPP)⁺⁺ in CH₂Cl₂ in the presence of particular anions.^{16,62-64} Thus, the nickel ion can be oxidized at potentials comparable to those of the oxidation of a porphyrin π -system. Ni(OEC) complexes could therefore be oxidizable by as many as three electrons. Only two one-electron oxidation processes were observed for *cis*- or *trans*-Ni(OEC) out to the limit of solvent or electrolyte breakdown (in excess of 2 V vs. SCE). The cation radical *trans*-Ni^{II}(OEC)⁺⁺ was prepared by ferric ion oxidation of *trans*-Ni(OEC).³⁵ Consistent with this assignment, we observed a 300-mV negative shift of the first oxidations of the isomeric Ni(OEC) complexes relative to those of Ni(OEP)⁶⁵ in the same solvent. This was comparable to the observed potential differences between the first oxidations of M(OEP) and M(OEC) when M was a redox-innocent metal.^{11,35} The second oxidation could correspond to oxidation of the nickel ion, but it is not obvious why the second macrocycle oxidation should then be inaccessible. It is more probable that both processes involve oxidation of the π -system as in Ni(TMC).¹⁶ In any event, what truly is remarkable is that both oxidations of *cis*-Ni(OEC) were reversible on the cyclic voltammogram time scale (scan rate of 100 mV/s; Figure 4).

A single one-electron reduction was found for *cis*- and *trans*-Ni(OEC) out to the limit of solvent breakdown (in excess of -2.2 V vs. SCE). Although two one-electron reductions were reported for Ni(TPP),⁶⁶ no other second reduction of a nickel porphyrin complex has been reported.⁶⁷ The reductions of Ni^{III} porphyrins generally have been thought to form Ni^{II} anion radicals.^{16,61,66,67} Were Ni(OEC) to react identically, it would not be obvious why the reduction to a dianion should be inaccessible. The potential of the reduction of Ni(OEC) is such that the second reduction should be positive of the solvent limit, provided that the normal difference of 0.42 ± 0.05 V⁶⁸ between the first and second ring reductions is maintained. On the other hand, the observed reduction could represent reduction of Ni^{II} to Ni^I. Several Ni^I tetraazamacrocyclic complexes were prepared from Ni^{II} complexes at potentials positive of the reduction of Ni(OEC).^{69,70} Correct assignments of the oxidized and reduced Ni(OEC) complexes will require characterization by spectroelectrochemical and EPR

(60) Furhop, J.-H.; Kadish, K. M.; Davis, D. G. *J. Am. Chem. Soc.* **1973**, *95*, 5140.

- (61) Wolberg, A.; Manassen, J. *J. Am. Chem. Soc.* **1970**, *92*, 2982. Wolberg, A.; Manassen, J. *Inorg. Chem.* **1970**, *9*, 2365.
 (62) Dolphin, D.; Niemi, T.; Felton, R. H.; Fajita, S. *J. Am. Chem. Soc.* **1975**, *97*, 5288.
 (63) Johnson, E. E.; Niemi, T.; Dolphin, D. *Can. J. Chem.* **1978**, *56*, 1381.
 (64) Kim, D.; Miller, L. A.; Spiro, T. G. *Inorg. Chem.* **1986**, *25*, 2468.
 (65) Stolzenberg, A. M.; Stershic, M. T., unpublished observations.
 (66) Felton, R. H.; Linschitz, H. *J. Am. Chem. Soc.* **1966**, *88*, 1113.
 (67) Kadish, K. M. *Prog. Inorg. Chem.* **1986**, *34*, 525.
 (68) Kadish, K.; Davis, D. G.; Furhop, J. H. *Angew. Chem., Int. Ed. Engl.* **1972**, *11*, 1014.
 (69) Lovecchio, F. V.; Gore, E. S.; Busch, D. H. *J. Am. Chem. Soc.* **1974**, *96*, 3109.
 (70) Gagne, R. R.; Ingle, D. M. *Inorg. Chem.* **1981**, *20*, 420.

spectroscopic methods. The results of such studies will be reported elsewhere.⁶⁵

The electrochemical behavior of the Sn(OEC)Cl₂ complexes was distinctly different from that of the other OEC complexes. As expected, the highly electropositive Sn^{IV} ion shifted the potential of the first oxidation some 450 mV positive of the potential of the free bases.^{35,57,60} In addition, an irreversible second oxidation process with a peak height greater than that of a one-electron process was observed. The instability of the cis cation radicals was evidenced as before by the presence of an oxidation wave at a potential corresponding to the first oxidation of Sn(OEP)Cl₂.⁶⁵ Three reduction processes were observed for *trans*-Sn(OEC)Cl₂. The first at -0.98 V was a simple reversible one-electron process when scanned separately. The second reduction at -1.37 V was a two-electron process. Reversal of the scan direction just negative of the second reduction wave permitted observation of a one-electron oxidation at -1.31 V. No significant oxidation current was observed at a potential corresponding to the first one-electron process. Finally, a reversible one-electron reduction was observed at -1.78 V. *cis*-Sn(OEC)Cl₂ behaved identically except for the lesser stability of the reduced species formed in these processes. The 2.02-V potential difference between the first reduction and the first oxidation was nearly identical with the difference in potentials between ring oxidation and reduction processes in OEC complexes lacking a redox-active metal. On this basis,⁶⁰ the first reduction product was the Sn^{IV}(OEC)Cl₂⁻ anion radical. Subsequent reductions could involve formation of ring-protonated or Sn(II) complexes. The nature of the species formed in these reductions is currently under investigation.

Summary and Conclusions. Properties of *cis*- and *trans*-Ni(OEC) deviated significantly from those of complexes with larger metal ions. Anomalous features of the nickel complexes included (i) the low ratio of the extinction of the Soret band to that of the α band, (ii) the changes in the difference in the chemical shifts of the A and B portions of the ABX multiplet, (iii) significantly greater shielding of protons (reduced ring currents), (iv) the major changes in the pyrroline ring conformation upon metalation with nickel as evidenced by the ³J_{2,3} vicinal coupling constant, (v) the second-order spectrum of the pyrrole ring methylene protons of the *trans* isomer, (vi) the substantially greater shielding of the pyrroline α -carbons, and (vii) the greatly enhanced stability of the *cis*-Ni(OEC) cation radical and dication. Each anomaly could be consistent with a ruffled conformation for the Ni(OEC) complexes. Although no single observation by itself unequivocally establishes that these complexes are ruffled, taken as a whole they make a compelling case.

Structures of nickel chlorin complexes are ruffled to a lesser extent than any other class of hroporphyrin.^{24,25} Chlorins might therefore be expected to have a lesser tendency to undergo deformations in solution. Our results provide evidence for ruffled conformations of Ni(OEC) complexes and suggest that ruffled conformations are of potential significance to the solution chemistry of hroporphyrins at all levels of saturation. Additionally, the results lend credibility to the proposed greater flexibility and structural compliance of hroporphyrin macrocycles.

Our evidence demonstrates that the stereochemistry of the β substituents can modulate conformational features of hroporphyrin complexes. The homonuclear 2D *J*-resolved spectra of the Ni(OEC) complexes require that the barrier to inversion of the sense of ruffling for the *cis* complex is significantly smaller

than for the *trans* complex. (Alternatively, the *cis* complex is not ruffled at all.) The magnitude of the ³J_{2,3} coupling constant for the *cis* complex demonstrated that the pyrroline ring ethyl groups were nearly eclipsed. This unfavorable substituent group interaction may serve to limit the extent of an otherwise favorable conformational change (ruffling). Thus, it appears that the tail can wag the dog to some extent.

Arguments presented above suggested that the greater flexibility and structural compliance of hroporphyrin macrocycles could result in increased rates of reaction. The observation of barriers to inversion for nickel(II) *cccc*-octaethylpyrrocorphin^{25b} and *trans*-Ni(OEC) suggests that the opposite may also be true. The flexibility of hroporphyrin macrocycles dictates that the energy required to distort the macrocycle is small. On the other hand, the contraction of the nickel-nitrogen distances that accompanies ruffling will be exothermic. Thus, the net stabilization energy of the ruffled conformation could be substantial. The stabilization energy will contribute to the activation energy and to the free energy change of any process that requires the macrocycle to flatten.

In light of the above, substituent modulation of conformation must also be viewed as substituent modulation of reactivity. It is interesting to note that native F430, which is not the thermodynamically preferred epimer of F430, has a greater affinity for axial ligands than the stable epimer.⁷¹ The stereochemistry of native F430 may limit the extent of ruffling of this complex and thereby decrease the free energy change associated with the flattening of the macrocycle that is required to accommodate a high-spin Ni(II) ion.

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Note Added in Proof. It has been reported⁷² that metalation of chlorophyll derivatives with nickel results in profound variations in side-chain conformation, presumably reflecting conformational changes in the pyrroline ring.

Registry No. *c*-H₂(OEC), 27341-05-5; H₂(OEP), 2683-82-1; *c*-Cu(OEC), 108101-90-2; *t*-Cu(OEC), 54676-27-6; *c*-Mg(OEC), 108101-91-3; *t*-Mg(OEC), 108101-92-4; *c*-Ni(OEC), 108101-93-5; *t*-Ni(OEC), 54676-28-7; *c*-Sn(OEC)Cl₂, 108036-71-1; *t*-Sn(OEC)Cl₂, 108101-94-6; *c*-Zn(OEC), 108101-95-7; *t*-Zn(OEC), 54676-27-6; *c*-H₂(OEC)²⁺, 108101-96-8; *c*-Cu(OEC)²⁺, 108036-72-2; *t*-Cu(OEC)²⁺, 108101-97-9; *c*-Mg(OEC)²⁺, 108036-73-3; *t*-Mg(OEC)²⁺, 108101-98-0; *c*-Ni(OEC)²⁺, 108036-74-4; *t*-Ni(OEC)²⁺, 108101-99-1; *c*-Sn(OEC)Cl₂²⁺, 108036-75-5; *t*-Sn(OEC)Cl₂²⁺, 108102-00-7; *c*-Zn(OEC)²⁺, 108036-76-6; *c*-H₂(OEC)⁺, 108102-01-8; *c*-Cu(OEC)⁺, 108036-77-7; *t*-Cu(OEC)⁺, 108102-02-9; *c*-Mg(OEC)⁺, 108036-78-8; *t*-Mg(OEC)⁺, 108102-03-0; *c*-Ni(OEC)⁺, 108036-79-9; *t*-Ni(OEC)⁺, 108102-04-1; *c*-Sn(OEC)Cl₂⁺, 108036-80-2; *t*-Sn(OEC)Cl₂⁺, 108102-05-2; *c*-Zn(OEC)⁺, 108102-06-3; *c*-H₂(OEC)⁻, 108102-07-4; *c*-Cu(OEC)⁻, 108036-81-3; *t*-Cu(OEC)⁻, 108102-08-5; *c*-Mg(OEC)⁻, 108036-82-4; *t*-Mg(OEC)⁻, 108102-09-6; *c*-Ni(OEC)⁻, 108036-83-5; *t*-Ni(OEC)⁻, 108102-10-9; *c*-Sn(OEC)Cl₂⁻, 108036-84-6; *t*-Sn(OEC)Cl₂⁻, 108146-29-8; *c*-Zn(OEC)⁻, 108036-85-7; *c*-H₂(OEC)²⁻, 108102-11-0; *c*-Cu(OEC)²⁻, 108036-86-8; *t*-Cu(OEC)²⁻, 108102-12-1; *c*-Zn(OEC)²⁻, 108102-13-2; *p*-toluenesulfonohydrazide, 1576-35-8.

(71) Pfaltz, A.; Livingston, D. A.; Juan, B.; Diekert, G.; Thauer, R. K.; Eschenmoser, A. *Helv. Chim. Acta* **1985**, *68*, 1338.

(72) Smith, K. M.; Goff, D. A.; Abraham, R. J. *J. Org. Chem.* **1987**, *52*, 176.