F430 Model Chemistry. Mechanistic Investigation of the Reduction, Coupling, and Dehydrohalogenation of Alkyl Halides by the Nickel(I) Octaethylisobacteriochlorin Anion

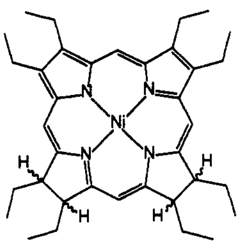
Goutam K. Lahiri, Leonard J. Schussel, and Alan M. Stolzenberg*

Department of Chemistry, West Virginia University, Morgantown, West Virginia 26506-6045

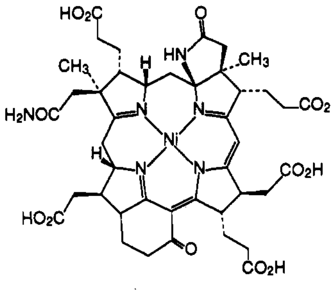
Received August 7, 1992

The reactions of Ni^{I}(OEiBC)$^-$ with alkyl halides and *p*-toluenesulfonates and with hydrogen atom and proton donors were investigated in a wide range of solvents. The ease of reduction of Ni^{II}(OEiBC) by sodium amalgam and the stability of the Ni^{I}(OEiBC)$^-$ generated was greater in more polar solvents. Ni^{I}(OEiBC)$^-$ was not obtained in solvents with weakly acidic protons like *N*-methylformamide. Ni^{I}(OEiBC)$^-$ is oxidized by weak acids like water, alcohols, and thiols to afford H_2 in a reaction with an apparent stoichiometry of 2:1 Ni(I):H_2. Reaction with CH_3X, X = I and OTs, afforded neutral Ni^{II}(OEiBC) in quantitative yield and CH_4 and C_2H_6. Trace quantities of C_2H_4 were also observed. The mass balance of the reaction was essentially complete in THF, but the yield of volatile products was less than expected in other solvents. Reaction with C_2H_5X afforded hydrocarbons C_2H_6, C_2H_4, and C_4H_{10} and trace quantities of C_4H_8. The relative yields of products in both reactions was strongly dependent on the solvent. Coupling (C_2H_6 from CH_3X and C_4H_{10} from C_2H_5X) and elimination products (C_2H_4 from C_2H_5X) increased in more polar solvents. More coupling was observed when X = I than OTs. Isotopic labeling experiments established that the source of the fourth hydrogen in CH_4 is solvent and a pool of protons that is probably residual water. Simultaneous addition of alkyl halides and weak acids led to competitive production of H_2 and alkanes. The proportion of coupled alkyl products decreased greatly in the presence of the weak acid. These observations and other evidence rule out free-radical processes as all but minor contributors to the mechanism and suggest that the reduction, coupling, and dehydrohalogenation of alkyl halides occur at the nickel atom. A mechanism that involves transient alkyl–Ni(OEiBC) and H–Ni(OEiBC) intermediates is proposed. It explains adequately the distributions of products and the production of the trace products and suggests that the unusual structural preferences of Ni(I) could be of functional significance. The apparent failure of Ni^{I}(OEiBC)$^-$ and of Ni^{I}F430M to react with thioethers, including methyl coenzyme M, is discussed in light of the mechanism.

The reactions of the nickel(I) octaethylisobacteriochlorin anion, Ni^{I}(OEiBC)$^-$,[1] with alkyl halides and other electrophiles model many features of the reactions of F430.[2] F430 is the nickel hydrocorphinoid prosthetic group of the enzyme methyl coenzyme M reductase,[3] which in the final step in methanogenesis catalyzes the reductive cleavage of the thioether methyl coenzyme M in the presence of the thiol cofactor (7-mercaptoheptanoyl)threonine phosphate (HS–HTP) to afford methane and a mixed disulfide, eq 1. The enzyme may also be involved in the reductive dehalogenation of chlorinated hydrocarbons by methanogenic bacteria.[4,5] The nickel atom of F430 undergoes oxidation state changes during catalysis by the intact, active enzyme.[6] With the exception of F430,[7] nickel isobacteriochlorin complexes[8,9] are the only tetrapyrrolic compounds that afford isolable nickel(I) complexes when reduced. The nickel(I) forms of F430[10] and of OEiBC[2,8a] react rapidly with methyl iodide to afford significant quantities of methane.



Ni(OEiBC)



F430

$$CH_3\text{–S–CoM} + \text{HS–HTP} \rightarrow CH_4 + \text{CoM–S–S–HTP} \quad (1)$$

Our initial study of the reactivity of Ni^{I}(OEiBC)$^-$ revealed some important features.[2] The anion reacts with methyl iodide in a 2:1 stoichiometry to afford neutral Ni^{II}(OEiBC) in quantitative yield and methane in lesser yield. It also reacts with methyl *p*-toluenesulfonate, MeOTs, but the amount of methane produced is smaller than with methyl iodide. Ni(OEiBC) mediates the electrocatalytic reduction of alkyl halides and *p*-toluenesulfonates at the potential of the Ni(II)/Ni(I) couple. We analyzed the current vs potential curves of the electrocatalytic reductions to obtain relative second-order rate constants for a

---

(1) Abbreviations: OEP, 2,3,7,8,12,13,17,18-octaethylporphyrin dianion; OEC, *trans*-2,3-dihydro-2,3,7,8,12,13,17,18-octaethylporphyrin dianion; OEiBC, mixture of *ttt*- and *tct*-2,3,7,8-tetrahydro-2,3,7,8,12,13,17,18-octaethylporphyrin dianion; F430M, the pentamethyl ester of F430; TPP, 5,10,15,20-tetraphenylporphyrin dianion; tmc, *R,R,S,S* or *R,S,R,S* isomer of 1,4,8,11-tetramethyl-1,4,8,11-tetraazacyclotetradecane; teta, 5,5,7,12,12,14-hexamethyl-1,4,8,11-tetraazacyclotetradecane; dmg, dimethylglyoximato.

(2) Stolzenberg, A. M.; Stershic, M. T. *J. Am. Chem. Soc.* **1988**, *110*, 5397.

(3) (a) Ellefson, W. L.; Whitman, W. B.; Wolfe, R. S. *Proc. Natl. Acad. Sci. U.S.A.* **1982**, *79*, 3707. (b) Rouvière, P. E.; Wolfe, R. S. *J. Biol. Chem.* **1988**, *263*, 7913. (c) Friedmann, H. C.; Klein, A.; Thauer, R. K. *FEMS Microbiol. Rev.* **1990**, *87*, 339.

(4) Krone, U. E.; Laufer, K.; Thauer, R. K.; Hogenkamp, H. P. C. *Biochemistry* **1989**, *28*, 10061.

(5) Fathepure, B. Z.; Boyd, S. A. *FEMS Microbiol. Lett.* **1988**, *49*, 149.

(6) (a) Albracht, S. P. J.; Ankel-Fuchs, D.; van der Zwaan, J. W.; Fontjin, R. D.; Thauer, R. K. *Biochim. Biophys. Acta* **1986**, *870*, 50. (b) Albracht, S. P. J.; Ankel-Fuchs, D.; Böcher, R.; Ellerman, J.; Moll, J.; van der Zwaan, J. W.; Thauer, R. K. *Biochim. Biophys. Acta* **1988**, *955*, 86.

(7) Jaun, B.; Pfaltz, A. *J. Chem. Soc., Chem. Commun.* **1986**, 1327.

(8) (a) Stolzenberg, A. M.; Stershic, M. T. *Inorg. Chem.* **1987**, *26*, 3082. (b) Stolzenberg, A. M.; Stershic, M. T. *J. Am. Chem. Soc.* **1988**, *110*, 6391.

(9) (a) Renner, M. W.; Furenlid, L. R.; Barkigia, K. M.; Forman, A.; Shim, H.-K.; Simpson, D. J.; Smith, K. M.; Fajer, J. *J. Am. Chem. Soc.* **1991**, *113*, 6891. (b) Furenlid, L. R.; Renner, M. W.; Smith, K. M.; Fajer, J. *J. Am. Chem. Soc.* **1990**, *112*, 1634. (c) Renner, M. W.; Forman, A.; Fajer, J.; Simpson, D.; Smith, K. M.; Barkigia, K. M. *Biophys. J.* **1988**, *53*, 277.

(10) Jaun, B.; Pfaltz, A. *J. Chem. Soc., Chem. Commun.* **1988**, 293.

0020-1669/92/1331-4991$03.00/0

series of substrates. The reactivity trends I > Br > OTs > Cl and CH_3 > *n*-C_4H_9 > *sec*-C_4H_9 > *tert*-C_4H_9 are consistent with a two-electron nucleophilic mechanism. This is remarkable because the reduction potential of Ni(OEiBC) is considerably negative of nickel tetraazamacrocyclic complexes, yet the nickel(I) forms of the latter react via electron-transfer and/or radical-based mechanisms.[11-13] The evidence led us to propose that a transient alkyl–Ni(OEiBC) complex is an intermediate in the reaction.[2]

Several important issues were not resolved by the initial study. The mass balance of the reaction was incomplete. The source of the fourth hydrogen in methane was not determined. Direct evidence for an alkyl–nickel intermediate was not obtained. The distribution of products appeared to depend on the choice of substrate and solvent and perhaps on other unidentified variables. It was not clear whether the course of the reaction is affected by the manner in which it is run. Reductions of substrates by $Ni^I(OEiBC)^-$ can be conducted in batch or in catalytic reactions. The latter can be driven either chemically or electrochemically. Finally, the observation that 1-hexene and lesser amounts of methylcyclopentane were produced upon reduction of the radical clock probe 1-bromo-5-hexene raised the possibility that radical species could play a role in the reaction mechanism following the rate-determining step.

The work in this paper addresses the questions of product mass balance and solvent effects on the reactivity. The investigation focuses on electrophiles that contain the two simplest alkyl groups—ethyl, which has a β-hydrogen, and methyl, which does not. We also examine the reactions of $Ni^I(OEiBC)^-$ with hydrogen atom and proton donors. A thorough appreciation of the factors that can affect product distributions with these simple substrates is essential if experiments with stereochemical and radical-trap probes are to be properly executed and interpreted.

Our results establish that reactions of $Ni^I(OEiBC)^-$ proceed by several competing pathways. These include reduction of alkyl halides to alkanes, coupling of alkyl halides to form new carbon–carbon bonds, reaction with proton donors to afford H_2, and the dehydrohalogenation of alkyl halides that have a β-hydrogen. The relative yields of these competing processes are senitive to the identities of the alkyl group and leaving group in the electrophilic reagent, the polarity of the solvent, and the level of residual proton donor (typically water) in the solvent. The evidence rules out free-radical processes as all but minor contributors to the mechanism and implies that carbon–hydrogen and carbon-carbon bond formation and dehydrohalogenation occur at nickel. Many of these processes formally require the availability of cis coordination sites on a metal. In this light, we suggest that the unusual structural preference of Ni(I) for two sets of different Ni–N distances could be functionally significant. The apparent failure of $Ni^I(OEiBC)^-$ and Ni^IF430M to react with thioethers, including methyl coenzyme M, is discussed in light of our results.

Experimental Section

Owing to the extreme sensitivity of $Ni^I(OEiBC)^-$, the following procedures were employed. All distillations were carried out under a nitrogen or argon atmosphere. Reductions and subsequent reactions were performed under nitrogen inside a Vacuum/Atmospheres Co. drybox. The drybox was used exclusively for experiments with nickel(I) to prevent cross-contamination by volatile compounds released into the box atmosphere during unrelated experiments. All glassware was thoroughly cleaned, dried in a 120 °C oven overnight, and placed in the drybox antechamber while still hot. Spectrophotometric cells and serum bottles were treated with aqua regia prior to cleaning to prevent carry over of any traces of mercury from previous experiments.

Materials. Ni(OEiBC)[8] and ammonium 2-(methylthio)ethanesulfonate[14] (*S*-methyl coenzyme M) were prepared by literature methods. The tetraphenylphosphonium salt of the latter compound was obtained by metathesis of aqueous solutions of the ammonium salt and tetraphenylphosphonium chloride. The precipitate was recrystallized from hot acetone and dried under vacuum for 3 days. Tributylammonium perchlorate was prepared by reaction of perchloric acid with tri-*n*-butylamine. It was recrystallized three times from hot anhydrous methanol and thoroughly dried under vacuum at 100 °C. The resulting white, hygroscopic solid was stored in a dry environment.

Reagents and solvents used in this study were HPLC or reagent grade. Alkyl halides and other reagents were examined for purity and were repurified by appropriate means if impurities were detected. Triphenylmethane was recrystallized from benzene and dried under vacuum at 60 °C. Tetrahydrofuran (THF) and diethyl ether were distilled from sodium benzophenone ketyl. *N,N,N',N'*-tetramethylethylenediamine (TMEDA) was purified by refluxing over KOH pellets followed by distillation. *N*-methylformamide (NMF) was dried over activated molecular sieves. 1-Methyl-2-pyrrolidinone (NMP) and propylene carbonate (anhydrous, under nitrogen) were used as received from Aldrich. Methanol was dried by refluxing over magnesium turnings that were activated with a crystal of I_2 and was then distilled. Other solvents were refluxed over CaH_2 and then distilled. All liquids and solvents were degassed by a minimum of three freeze–pump–thaw cycles. Five cycles were used for water and methanol. The water was treated previously by flushing with nitrogen gas overnight.

General Procedure for Reductions and Reactions. Solutions of $Ni^I(OEiBC)^-$ were prepared by reduction of solutions of Ni^{II}(OEiBC) with excess 1% sodium mercury amalgam. The Ni^{II}(OEiBC) solution contained a known weight of complex dissolved in a known volume of solvent that had been pretreated by stirring for 1 h with amalgam. The concentration of complex was typically 5×10^{-5} M for experiments that were intended to monitor $Ni^I(OEiBC)^-$ by UV–vis spectroscopy and 2×10^{-3} M for experiments intended to measure the quantities of substrate-derived products. The solution and amalgam were stirred vigorously, and the progress of the reduction was followed spectroscopically by monitoring the decrease of the Ni^{II}(OEiBC) visible band near 592 nm. An aliquot of the solution was taken periodically and placed in a tightly stoppered cuvette. The cuvette was removed from the drybox and the spectrum was recorded. The time required for reduction and the stability of the reduced species depended on the solvent. With experience, it became possible to judge the completion of the reduction by eye. When reduction was complete, stirring was stopped and the finely divided amalgam was permitted to settle.

Experiments intended to measure reaction products were typically run simultaneously in duplicate or triplicate. A calibrated to-deliver style pipet was used to dispense 5.00-mL aliquots of clear $Ni^I(OEiBC)^-$ solution into several "10-mL" Wheaton serum bottles. (The total volume contained in a capped "10-mL" Wheaton serum bottle is 15.0 mL.) Care was taken not to include any visible mercury. Consequently, a small volume of solution was not used. A Teflon-faced silicone septum (Wheaton no. 224173) and aluminum seal were placed on the mouth of each serum bottle, and the seal was crimped in place. A volume of liquid reagent that typically represented a 100–800-fold molar excess compared to nickel(I) was introduced by microliter syringe. Solid reagents, such as the alkyl *p*-toluenesulfonates, were dissolved in a minimal amount of pretreated solvent, and the resulting solution was added. The volume of added reagent did not significantly alter the volume of the reaction solution or head-space. The serum bottle was then shaken to assist equilibration of gases between solution and head-space and removed from the drybox. The products were promptly analyzed. The variation of results from duplicate serum bottles was small. Most experiments were repeated several times. Agreement between replicate experiments was good.

Catalytic reactions were performed in the following manner. A known quantity of sodium amalgam, 5.00 mL of a solution of Ni(OEiBC) in pretreated solvent, and a small magnetic stir bar were sealed in a serum

---

(11) (a) Gosden, C.; Healy, K. P.; Pletcher, D. *J. Chem. Soc., Dalton Trans.* **1978**, 972. (b) Healy, K. P.; Pletcher, D. *J. Organomet. Chem.* **1978**, *161*, 109. (c) Gosden, C.; Pletcher, D. *J. Organomet. Chem.* **1980**, *186*, 401. (d) Becker, J. Y.; Kerr, J. B.; Pletcher, D.; Rosas, R. *J. Electroanal. Chem. Interfacial Electrochem.* **1981**, *117*, 87. (e) Gosden, C.; Kerr, J. B.; Pletcher, D.; Rosas, R. *J. Electroanal. Chem. Interfacial Electrochem.* **1981**, *117*, 101.

(12) (a) Bakac, A.; Espenson, J. H. *J. Am. Chem. Soc.* **1986**, *108*, 713. (b) Bakac, A.; Espenson, J. H. *J. Am. Chem. Soc.* **1986**, *108*, 719. (c) Ram, M. S.; Bakac, S.; Espenson, J. H. *Inorg. Chem.* **1986**, *25*, 3267.

(13) The authors of ref 11 suggest a different mechanism. See footnote 26 of ref 2.

(14) Gunsalus, R. P.; Romesser, J. A.; Wolfe, R. S. *Biochemistry* **1978**, *17*, 2374.

bottle. The required quantity of the reagent of interest was added by syringe. The serum bottle was agitated to mix the contents and was immediately removed from the drybox. The sampling needle (see below) was then inserted through the septum of the serum bottle, and magnetic stirring was started. Head-space gases were sampled and analyzed immediately and at appropriate intervals thereafter.

Product Analysis. Head-space gases and organic products were analyzed by gas chromatography or by GC/MS. A Hewlett-Packard 5890A gas chromatograph and 3396A integrator were used in these experiments. Separations were typically performed at temperatures between 35 to 40 °C. Compounds were identified by comparison of their retention times to thoses of pure compounds and mixtures of known composition. Low molecular weight hydrocarbons (C_1–C_4) were separated on a 6-ft Poropak Q column. Methylcyclopentane, 1-hexane, and 1-bromo-5-hexene were separated on a 6-ft 10% OV-17 on chromosorb column. A flame ionization detector was used in both of the above cases. Hydrogen was separated on a 6-ft type 5-Å molecular sieve column and measured with a thermal conductivity detector. Argon was used as the carrier gas in hydrogen analyses to eliminate peak inversion or folding, which can result if helium is used as the carrier gas.[15] The sensitivity of the detector to other components is greatly reduced by argon carrier gas. Methane and ethane could be separated and detected during hydrogen analyses, but the accuracy of the analyses for these gases was unsatisfactory. Thus, hydrogen and hydrocarbon products for a given reaction were determined separately using two sets of identically prepared solutions. The GC/MS analysis of deuteriated methanes and ethanes were conducted on a Hewlett-Packard Model 5990A that was fitted with a Poropak Q packed column.

All columns were thoroughly conditioned prior to use and regenerated after each run by holding the oven temperature at 200 °C until the solvent vapor peak came off the column. Absorption of solvent alters the properties of the column and increases the retention time of the hydrocarbon gases. This effect was responsible for our failure to detect ethane in the initial study.

The precision of sampling head-space gases by gastight microliter syringe is too low to permit adequate determination of the mass balance of reactions at this scale. We used a gas sample valve system, whose design and operation are described in supplementary material, to improve the precision of sampling head-space gases. The system enabled us to expand head-space gases into an evacuated, fixed-volume sample loop and then inject the sample onto the column. The reproducibility of injection of gas standards at constant pressure was ±1%.

The measured integrated peak area of each compound of interest in head-space gases was converted to a concentration by use of calibration curves that had been determined using analyzed gas mixtures purchased from Scott Specialty Gases, Inc. This method corrects for the unequal area response of flame ionization detectors for equal numbers of moles of different compounds.[15c] The number of moles of each compound that were present in the head-space was calculated from the concentration and the head-space, sample loop, and injector dead-space volumes. The error in the calculated moles of products is estimated at 5%, ignoring any loss of products through leakage or oxidation of Ni(I) during handling. The relative number of moles of different products within a single sample is known to a much higher precision. Detection limits are estimated to be roughly 10^{-11} mol for hydrocarbon gases and 10^{-10} mol for H_2.

Extensive series of control experiments were performed to ensure that our results were not complicated by other factors. The septum material affected the recovery of products. Product recovery was highest when Teflon-faced silicone septa were used. Incident light had no effect on product yields provided that samples did not sit for an extended period of time (hours) before analysis. Direct reduction of substrates by sodium amalgam was much slower than the reaction with $Ni^I(OEiBC)^-$, with the exception of ethyl iodide. Carryover of amalgam or metallic mercury and their effect on product yields were both negligible. Direct sampling of reaction solutions suggested that slow equilibration between solution and head-space was not a problem. For the products analyzed here, the amount of product that remained in solution was small compared with the amount in the head-space. Finally, analysis of known quantitites of product gases produced in independent reactions showed that our anaytical and calibration methods gave reasonable results. Some control experiments are described in greater detail in the supplementary material.

Results

Reduction of Ni(OEiBC) in Different Solvents. We investigated the reduction of Ni(OEiBC) by sodium amalgam in a range of solvents, as a preliminary to an examination of solvent effects on the reactivity of $Ni^I(OEiBC)^-$. The anion is rapidly formed and is stable to further reduction for an extended time (>48 h) in 1,2-dimethoxyethane (DME), *N*,*N*-dimethylformamide (DMF), hexamethylphosphoramide (HMPA), and NMP. It is also stable in these solvents to reoxidation to Ni(II) when separated from amalgam. In other solvents, the stability of the anion to reoxidation is somewhat less. In addition, $Ni^I(OEiBC)^-$ undergoes further reduction in these solvents to afford a reddish-brown colored, macrocycle reduced complex. The characterization of this complex will be reported elsewhere.[16] Reduction to Ni(I) is complete well before the reduction of the macrocycle begins in acetonitrile, THF, and 2-methyltetrahydrofuran (2-MeTHF). In tetrahydropyran (THP), the rates of the two reduction steps are sufficiently similar that quantitative reduction to Ni(I) cannot be achieved. Because the maximum conversion to Ni(I) achieved prior to formation of the macrocycle reduced complex was less than 90%, reported product yields in THP are artificially low. The reduction of the macrocycle was faster than the initial reduction to Ni(I) in NMF, 2,5-dimethyltetrahydrofuran (2,5-Me_2THF), and TMEDA. The macrocycle reduced complex was formed directly without buildup of a significant concentration of Ni(I). No reduction occurred in propylene carbonate. The last four solvents listed were not used in the reactivity studies that follow.

In general, the rate of reduction and the stability of $Ni^I(OEiBC)^-$ increase as the polarity of the solvent increases. A glaring exception to this is NMF, which is the most polar solvent by far ($\epsilon = 182$ vs 36.7 for DMF). Unlike DMF, NMF has an amide proton, which can be removed by a base of moderate strength. This suggests that $Ni^I(OEiBC)^-$ could be involved in proton abstraction reactions.

The reduction in HMPA requires further comment. Pretreatment of the solvent with sodium amalgam resulted in a yellow discoloration. When solid Ni(OEiBC) was added, dissolution of the solid and reduction occurred simultaneously in a matter of seconds. Reduction of Ni(OEiBC) in untreated HMPA took a few minutes. Alkali metals dissolve in HMPA to give solutions of the solvated electron.[17] Addition of alkyl halides to these HMPA solutions affords Wurtz coupling products. Our observations suggest that sodium amalgam can give a small concentration of solvated electron in HMPA, too. Thus, amalgam-driven catalytic reactions were not studied in HMPA.

Reaction of $Ni^I(OEiBC)^-$ with Hydrogen Donors. We reacted $Ni^I(OEiBC)^-$ with compounds that are either good donors of protons or of hydrogen atoms. The former category included water, methanol, 1-nitropropane, ammonium salts, and thiophenol. The later category included triphenylmethane and thiophenol. Reactions were examined in several solvents. In all cases, addition of the donor compound resulted in rapid, quantitative reoxidation of Ni(I) to Ni(II).[18]

We analyzed the head-space gases of several reactions for H_2, Table I. The yield of H_2 is essentially quantitative for the most acidic donor compounds and decrease as the pK_A of the donor increases. Little or no hydrogen was observed in the reaction with triphenylmethane. Thus, Ni(I) can act as a base, albeit a weak base, and abstract H^+ from acidic compounds. Nickel hydride complexes may be accessible and play a significant role in the reactions of Ni(OEiBC).

---

[15] (a) Cowper, C. J.; DeRose, A. J. *The Analysis of Gases by Chromatography*; Pergamon Press: Oxford, England, 1983. (b) Thompson, B. *Fundamentals of Gas Analysis by Gas Chromatography*; Varian Associates: Palo Alto, CA, 1977. (c) McNair, H. M.; Bonelli, E. J. *Basic Gas Chromatography*; Varian Associates: Palo Alto, CA, 1968.

[16] Lahiri, G. K.; Stolzenberg, A. M. Manuscript in preparation.

[17] Fraenkel, G.; Ellis, S. H.; Dix, D. T. *J. Am. Chem. Soc.* **1965**, *87*, 1406.

[18] One exception was the reaction with thiophenol in DMF. A small absorption band at 660 nm was observed after the reaction. This band cannot be reproduced by addition of thiol, thiolate, or disulfide to solutions of $Ni^{II}(OEiBC)$.

Table I. H_2 Production from $Ni^I(OEiBC)^- + HA^a$

	THF		DMF	
HA	mol of H_2/mol of Ni(I)	% yield^b	mol of H_2/mol of Ni(I)	% yield^b
C_6H_5SH	0.48	96	0.34	67
H_2O	0.27	54	0.45	90
CH_3OH	0.23	47	0.070	14
$HN(C_4H_9)_3ClO_4$			0.087	17
$(C_6H_5)_3CH$	0.019	4	0	0

^{a} Typical conditions were 2 mM Ni(I). Liquid HA reagents were added neat, 600–3000 molar excess. Solid HA reagents were added as a solution in pretreated solvent, 50–70 molar excess. ^{b} Assumes stoichiometry of 2 mol of Ni(I) consumed/mol of H_2 produced.

Table II. Products of the Reactions of $Ni^I(OEiBC)^-$ with CH_3X, X = I or $OTs^{a,b}$

	mol of product/mol of Ni(I)				
solvent	CH_4	C_2H_6	$H_2{}^c$	% yield^d	C_2:C_1 ratio
		X = I^e			
HMPA	0.10	0.12		44	1.2
NMP^f	0.11	0.077		37	0.70
CH_3CN	0.098	0.055		31	0.56
DMF	0.074	0.033	0.022	21	0.45
THP	0.052	0.0087		12	0.17
2-MeTHF^g	0.22	0.011		46	0.050
DME	0.12	0.020		28	0.17
THF	0.42	0.0037	0.0044	85	0.0088
		X = OTs^h			
HMPA^i	0.22	0.082		60	0.37
THF	0.23	0.00070		47	0.0030

^{a} Typical conditions were 2 mM Ni(I). ^{b} OTs = *p*-toluenesulfonate. ^{c} H_2 was not determined for solvents that have no listing. ^{d} Yield of CH_4 + C_2H_6, assumes a stoichiometry of 2 mol of Ni(I)/mol of alkane. ^{e} 800 mol of CH_3I added/mol of Ni(I). ^{f} 1.0×10^{-3} mol of C_2H_4 also detected. ^{g} 4.9×10^{-4} mol of C_2H_4 also detected. ^{h} 4 mol of CH_3OTs added/mol of Ni(I). ^{i} 7.1×10^{-4} mol of C_2H_4 also detected.

Reaction of $Ni^I(OEiBC)^-$ with CH_3X, X = I or OTs. $Ni^I(OEiBC)^-$ is oxidized to $Ni^{II}(OEiBC)$ upon mixing with CH_3I or CH_3OTs. Although the relative rate for reaction with CH_3OTs is smaller,[2] both reactions have kinetics that are much too fast to be studied by conventional techniques. For both substrates, the principal products are methane and ethane. Lesser amounts of hydrogen are observed. Trace quantities of ethylene (roughly 5×10^{-4} to 1×10^{-3} mol per mole of Ni(I)) are observed in some solvents.

(i) Effect of the $[CH_3X]/[Ni(I)]$ Ratio. The effect on product yields of the $[CH_3X]/[Ni(I)]$ ratio at fixed [Ni(I)] (2 mM) was examined in THF and HMPA. Relatively minor changes occurred. For CH_3I in THF, an increase in the reactant ratio from 4 to 950 resulted in a 30% increase in yield of methane, a 3-fold increase in yield of ethane, and no change in the yield of ethylene. In this solvent, an increase in the reactant ratio favors the coupling reaction. No significant changes in product yields were observed in HMPA when the $[CH_3I]/[Ni(I)]$ ratio was varied over the same range. For CH_3OTs in both solvents, the yield of all products fell by roughly 40% when the ratio was varied from 3 to 650. If solid CH_3OTs contains some water, the drop in yield could reflect an increase in the level of water that was introduced into the reaction as a result of increasing the amount of CH_3OTs added. On the basis of these results, we decided to analyze products yields in reactions with large excesses of CH_3I but small excesses of CH_3OTs.

(ii) Solvent Effects on Product Distributions. Product distributions from the reactions of $Ni^I(OEiBC)^-$ with CH_3I and CH_3OTs in a range of solvents are presented in Table II. Because percentage yields of products depend on the assumed reaction mechanism, we also report the number of moles of product produced per mole of Ni(I).

The mass balance of the reaction is essentially complete for CH_3I in THF. Given the potential for partial reoxidation of Ni(I) and loss of product gases through the once-punctured septum, an 85% combined yield of methane plus ethane (assuming 2:1 stoichiometry for both products) should be considered close to quantitative. Yields are lower in other solvents. The analysis of H_2 produced during the reaction in DMF establishes that the mass balance is not completed by production of large quantities of H_2. We did not detect any other volatile product in the lower yield reactions. The missing products could be solvent derived species that do not distribute into the head-space gases. Alternatively, partial reoxidation of Ni(I) by adventitious oxidants could account for the lowered yields.

The ratio of ethane to methane produced reflects the relative rates of coupling reactions and reduction reactions. The ratio shows a large solvent dependence, changing by a factor of 136 between the solvents HMPA and THF. The relative importance of coupling reactions appears to correlate directly with the polarity of the solvent.

Previously, we reported that the yield of methane was smaller with CH_3OTs than with CH_3I.[2] This observation is true in THF but is not general in all solvents. The reaction of $Ni^I(OEiBC)^-$ with CH_3OTs is somewhat slower than the reaction with CH_3I, and the mass balance is less complete. The ratio of ethane to methane formed from CH_3OTs is roughly 0.25 that observed for CH_3I. Thus, the identity of the X group of the electrophile affects the distribution of products.

(iii) Low-Temperature Reaction of $Ni^I(OEiBC)^-$ with CH_3I. Previous attempts to detect the proposed alkyl–nickel intermediate $CH_3Ni(OEiBC)$ at room temperature were unsuccessful. We examined the reaction at a lower temperature to see if the intermediate could be stabilized. Solutions of $Ni^I(OEiBC)^-$ in either THF or DMF were transferred to a quartz optical dewar. The solutions were cooled to –41 °C by filling the dewar with an acetonitrile/liquid-N_2 slush. The UV–vis spectra of $Ni^I(OEiBC)^-$ did not change upon cooling. Addition of cold CH_3I resulted in immediate, quantitative reoxidation to $Ni^{II}(OEiBC)$ as judged by the UV–vis spectrum. In separate experiments, analysis of the head-space gas over reactions conducted at –41 °C established that there was no detectable delay between CH_3I addition and methane formation.

(iv) Isotopic Labeling Experiments. We examined the reactions of $Ni^I(OEiBC)^-$ with deuterium and ^{13}C-labeled CH_3I in normal and deuteriated solvents. The distribution of isotopes in the products was determined by use of an HP 5990A GC/MS. Background levels of O_2, N_2, and H_2O were relatively high in the instrument available to us. Masses 32, 28, and 18 were totally obscured. The fragmentation patterns and ionization cross section of individual deuteriated methanes and ethanes varies with the compound and with the conditions in the ion source of the mass spectrometer.[19] Thus, we did not attempt to deconvolute the observed mass spectra into quantitative distributions of individual deuteriated compounds. Nonetheless, our qualitative estimates are sufficiently good to draw several important conclusions.

Reaction of $Ni^I(OEiBC)^-$ with CD_3I in THF afforded methane that had a mass spectrum dominated by a peak at mass 19, which corresponds to CD_3H. This suggests that excess CD_3I is not the source of the fourth hydrogen atom in methane. The distribution of masses for ethane were reasonable for the expected fragmentation of C_2D_6.[19,20] Thus, ethane is a product of methyl iodide and does not result from cleavage of an ethyl substituent from the isobacteriochlorin. Ethylene was not detected above the instrument background.

---

(19) (a) Miller, T. M.; McCarthy, T. J.; Whitesides, G. M. *J. Am. Chem. Soc.* **1988**, *110*, 3156. (b) Miller, T. M.; Whitesides, G. M. *J. Am. Chem. Soc.* **1988**, *110*, 3164. (c) Lee, T. R.; Whitesides, G. M. *J. Am. Chem. Soc.* **1991**, *113*, 2568.

(20) Amenomiya, Y.; Pottie, R. F. *Can. J. Chem.* **1968**, *46*, 1735.

An experiment with CD_3I was conducted in THF-d_8 that had been pretreated with sodium amalgam. The mass spectrum of methane had comparable abundances of masses 19 and 20. The product contained both CD_3H and CD_4. Similarly, reaction of $Ni^I(OEiBC)^-$ with CH_3I in pretreated THF-d_8 afforded comparable quantities of CH_4 and CH_3D. Both experiments were repeated using glassware that had been washed with D_2O and then thoroughly dried. The results were essentially unchanged. Thus, one source of the fourth hydrogen in methane is the solvent, but a pool of protons remains available even in deuteriated solvent. Two candidates for the pool of protons are residual water and possibly the isobacteriochlorin ligand, although the latter seems unlikely given the apparent quantitative recovery of Ni(OEiBC).

An experiment conducted with $^{13}CH_3I$ in THF gave a peak at mass 17 for methane and a large mass 31 peak for ethane (mass 32 was obscured by background O_2). Ni(OEiBC) was recovered from the reaction by stripping off all volatiles. The resulting solid was dissolved in $CDCl_3$ and examined by ^{13}C NMR. No new or enhanced ^{13}C peaks were observed. The spectrum was identical to that for natural-abundance Ni(OEiBC). Thus, a methyl iodide derived carbon is not incorporated in any modified OEiBC compound.

(v) Catalytic Reactions. Solutions of $Ni^{II}(OEiBC)$ in pretreated CH_3CN or THF were reacted with approximately 100–200 equiv of sodium amalgam (i.e. mol Na/mol Ni) and excess methyl iodide. The color of the solution remained that of $Ni^{II}(OEiBC)$ throughout the reaction, which suggests that reduction to Ni(I) is the slow step in the catalytic cycle. Head-space gases were sampled periodically to follow the progress of the reaction. The mole ratios of products gases appeared to stay roughly constant during the reaction while the total number of moles of each product increased with time. The amount of methane produced in experiments conducted in CH_3CN suggests that the reducing equivalents in the amalgam are converted to products with relatively little loss to other processes. The conversion efficiency in THF is substantially less or else the reduction stops prematurely.

Product ratios in catalytic and batch reactions are not identical. The ethane to methane ratio drops from 0.56 in batch reactions to 0.030 in catalytic reactions in CH_3CN. In contrast, the ratio increases from 0.0088 in batch to 0.54 in catalytic reactions in THF. The amount of ethylene produced in catalytic reactions is small. The ratio of ethylene to methane is about 2×10^{-3} in THF but only about 7×10^{-6} in CH_3CN. These observations imply that either the course of the catalytic and batch reactions are different or that changes in relative concentrations of the reactive species changes the partitioning between competing reactions.

Reaction of $Ni^I(OEiBC)^-$ with C_2H_5X, X = I or OTs. Product distributions from the reactions of $Ni^I(OEiBC)^-$ with C_2H_5I and C_2H_5OTs in several solvents are reported in Table III. The principal products are ethane, ethylene, and butane. Small amounts of butenes are formed in some solvents. The table lists moles of product produced per mole of Ni(I) and the ratios of ethylene to ethane and of ethylene to butene. Butane was not determined in the experiments in CH_3CN and in 2-MeTHF because its peak was obscured by the solvent peak.

Overall, product yields are significantly lower for C_2H_5I than for CH_3I. One exception to the low yields occurs in HMPA. The total yield of products in this solvent is greater than expected. In particular, much more ethylene is formed in HMPA than in other solvents. The high polarity of the HMPA could promote a solvent-assisted, non-Ni(I)-dependent dehydrohalogenation pathway.

The product ratios exhibit significant solvent dependence. The ethylene to ethane ratio in DMF is approximately 1.0, the value expected for self-reaction of ethyl radicals. However, in other solvents the ratio ranges from 0.025 to 3.6. The ratio of ethylene to butane is generally greater than 1.0 and in some solvents is very large. In general, both product ratios are largest in polar solvents. Dehydrohalogenation and β-hydride elimination[21] involve polar transition states and are favored by an increase in the polarity of the solvent.

Table III. Products of the Reactions of $Ni^I(OEiBC)^-$ with C_2H_5X, X = I or OTs[a,b]

solvent	mol of product/mol of Ni(I) C_2H_6	C_2H_4	C_4H_{10}	C_2H_4:C_2H_6 ratio	C_2H_4:C_4H_{10} ratio
			X = I[c]		
HMPA	0.15	0.53	0.010	3.6	52
NMP	0.059	0.074	0.0027	1.3	27
CH_3CN	0.028	0.036	*d*	1.3	*e*
DMF[f]	0.046	0.047	0.0068	1.0	6.9
THP	0.027	0.0024	0	0.089	large
2-MeTHF	0.11	0.0027	*d*	0.025	*e*
DME[g]	0.039	0.034	0.0025	0.86	14
THF[h,i]	0.070	0.013	0.0038	0.19	3.5
			X = OTs		
DMF[j–l]	0.015	0.00062	0.0015	0.042	0.42
THF[m]	0.027	0.00067	0.00062	0.025	1.0

[a] Typical conditions were 2 mM Ni(I). [b] OTs = *p*-toluenesulfonate. [c] 800 mol of C_2H_5I added/mol of Ni(I). [d] Obscured by solvent peaks. [e] Could not be determined. [f] 0.072 mol of H_2 observed. [g] 1.4×10^{-3} mol of C_4H_8 observed. [h] 5.5×10^{-5} mol of C_4H_8 observed. [i] Checked for H_2; none observed. [j] 180 mol of EtOTs added/mol of Ni(I). [k] 2.4×10^{-3} mol of C_4H_8 observed. [l] 0.033 mol of H_2 observed. [m] 68 mol of EtOTs added/mol of Ni(I).

Reactions of $Ni^I(OEiBC)^-$ with C_2H_5OTs give significantly less ethylene than reaction with C_2H_5I. Coupling to form butane is reduced slightly, too. Again, the identity of the X group of the electrophile affects the distribution of products.

Reactions of $Ni^I(OEiBC)^-$ with Hydrogen Donors and CH_3I. The deuterium labeling experiments described above establish that a pool of hydrogen distinct from that in the solvent takes part in the reaction. The most probable candidate for the pool is the residual water in the "dry" solvent. The concentration of residual water could affect the course of the reaction and the distribution of products. Normally, to address this issue, one would add a known concentration of water or hydrogen donor and determine how it affected the distribution of products. Such experiments are not straightforward here. Addition of a hydrogen donor prior to the reduction of Ni(OEiBC) either prevents the reduction, leads to consumption of the donor, or results in formation of the macrocycle-reduced complex. On the other hand, addition of hydrogen donors to $Ni^I(OEiBC)^-$ results in reoxidation to $Ni^{II}(OEiBC)$ and formation of H_2. One possible way to perform the experiment is to simultaneously add CH_3I and the hydrogen donor in the hope that reduction of the alkyl halide and formation of H_2 occur in competition.

Equimolar mixtures of CH_3I and a proton donor were added in a 300:1 molar excess (per reactant) to $Ni^I(OEiBC)^-$ in THF or DMF. (CH_3I and H_2O were added as a two-phase mixture.) The product distributions are reported in Table IV. The two reactions compete with each other. Comparisons of Table IV with Tables I and II show that the yields of both reactions are significantly lower when run simultaneously than when run independently of each other. Addition of a proton donor decreases the yield of methane in THF by a factor of 4 or more. The presence of CH_3I reduces the yield of H_2 by only about one-third for C_6H_5SH but by more than a factor of 9 for CH_3OH and H_2O. A far more significant change is that the added proton donors completely suppress the coupling reaction that affords ethane from CH_3I. Proton donors do not have that large an effect on the actual yield of methane in DMF. "Dry" DMF is typically 1–2 mM in water.[22] The amount of proton donor that we added

---

(21) (a) Doherty, N. M.; Bercaw, J. E. *J. Am. Chem. Soc.* **1985**, *107*, 2670. (b) Burger, B. J.; Thompson, M. E.; Cotter, W. D.; Bercaw, J. E. *J. Am. Chem. Soc.* **1990**, *112*, 1566.

(22) La Perriere, D. M.; Carroll, W. F., Jr.; Willett, B. C.; Torp, E. C.; Peters, D. G. *J. Am. Chem. Soc.* **1979**, *101*, 7561.

Table IV. Effect of HA on the Products of Reactions of $Ni^I(OEiBC)^-$ with CH_3I[a,b]

HA	mol of product/mol of Ni(I)			% yield[c]	C_2:C_1 ratio
	CH_4	C_2H_6	H_2		
			THF		
C_6H_5SH	0.10	0	0.31	20	0.0
H_2O	0.10	0	0	20	0.0
CH_3OH	0.071	0	0.017	14	0.0
			DMF		
C_6H_5SH	0.096	0.025	0.052	24	0.26
H_2O	0.065	0.026	0.26	18	0.42
CH_3OH	0.054	0.018	0.012	14	0.33

[a] Typical conditions were 2 mM Ni(I). [b] 300 mol each of CH_3I and HA added/mol of Ni(I). [c] Yield of $CH_4 + C_2H_6$, assuming a stoichiometry of 2 mol Ni(I)/mol of alkane.

Table V. Products of the Reactions of $Ni^I(OEiBC)^-$ with 1-Bromo-5-hexene[a]

solvent	HA[b]	relative yields	
		1-hexene	methylcyclopentane
CH_3CN[c]		60	40
DMF		74	26
THP		81	19
DME		90	10
2-MeTHF		92	8
DMF	C_6H_5SH	74	26
DMF	CH_3OH	82	18
DMF	D_2O[d]	81	19
DMF	H_2O[d]	93	7

[a] Typical conditions were 2 mM Ni(I) plus 200 molar excess of 1-bromo-5-hexene. [b] 220 molar excess of HA added simultaneously with bromohexene. [c] Reference 2. [d] Total yield decreases by about 45% relative to yield in DMF without addition of HA.

may not change the concentration of available proton sufficiently to cause a significant decrease in the methane yield. The ratio of ethane to methane is decreased though, especially by C_6H_5SH and CH_3OH. By way of contrast, CH_3I causes a significant reduction in the yield of H_2 from the proton donors in DMF.

Reactions of $Ni^I(OEiBC)^-$ with 1-Bromo-5-hexene. We reported in our initial study that the reaction of $Ni^I(OEiBC)^-$ with excess 1-bromo-5-hexene in CH_3CN afforded a 60:40 mixture of 1-hexene and methylcyclopentane.[2] In light of the sensitivity of product distributions to the identity of the solvent and the presence of hydrogen donors, we decided to reexamine the reaction.

The relative yields of 1-hexene and methylcyclopentane in several dry solvents are reported in Table V. The table also includes data for experiments in which hydrogen donors and 1-bromo-5-hexene were added simultaneously to $Ni^I(OEiBC)^-$ in DMF. 1-Hexene was the major product in all solvents examined. The solvents that afford greater amounts of methylcyclopentane are those that afford more ethane from CH_3I. The product distribution of the reaction in DMF is unaffected by the presence of C_6H_5SH. In contrast, the presence of CH_3OH and H_2O affect the product distribution. The relative yield of 1-hexene climbs from 74% to 93% when H_2O is added. Interestingly, D_2O causes a much smaller increase in the amount of 1-hexene, which may reflect a kinetic isotope effect. The total integrated peak area of products decreases when water is added.

Reactions of $Ni^I(OEiBC)^-$ with Methyl CoM. The natural substrate of methyl coenzyme-M reductase is the 2-(methylthio)ethanesulfonate anion, methyl CoM. The anion is usually isolated as the ammonium salt, which has limited solubility in nonaqueous solvents. Reaction of ammonium methyl CoM with $Ni^I(OEiBC)^-$ in DMF resulted in the immediate oxidation of Ni(I) to Ni(II), but only small quantities of methane (10^{-3} mol/mole Ni) were produced.

We prepared the tetraphenylphosphonium salt of methyl CoM by metathesis in order to prevent oxidation of Ni(I) by the acidic ammonium cation. Reaction of tetraphenylphosphonium methyl CoM with $Ni^I(OEiBC)^-$ in DMF resulted in immediate oxidation of Ni(II). No methane was detected. The catalytic reduction of tetraphenylphosphonium methyl CoM was also attempted. Any impurity in the methyl CoM salt that oxidizes Ni(I) more rapidly than Ni(I) can react with methyl CoM should eventually be consumed in the catalytic reduction. The reaction of Ni(I) with methyl CoM would then be observable. The reduction of Ni(OEiBC) in the presence of excess tetraphenylphosphonium methyl CoM proceeded eventually to Ni(I). No methane was detected during or after the reduction. Reaction of a mixture of tetraphenylphosphonium methyl CoM and C_6H_5SH with $Ni^I(OEiBC)^-$ in DMF led to reoxidation to Ni(II) and production of H_2, but no methane was formed.

Discussion

A satisfactory mechanism for the reactions of $Ni^I(OEiBC)^-$ with electrophilic reagents must account for the following observations: (1) Reactions with alkyl halides and tosylates follow a mixed second-order rate law. (2) The stoichiometry of the reaction with CH_3I is 2:1 Ni(I):CH_3I. (3) The reactivity order follows the trends RI > RBr > ROTs > RCl and $CH_3Br \gg n\text{-}C_4H_9Br > s\text{-}C_4H_9Br > t\text{-}C_4H_9Br$. (4) Ni(OEiBC) mediates electrocatalytic reduction of alkyl halides and tosylates at the potential of the Ni(II)/Ni(I) couple. (5) $Ni^I(OEiBC)^-$ reacts with proton (H^+) donors to afford H_2 with an apparent stoichiometry of 2:1 Ni(I):H_2. (6) Alkyl halides and tosylates afford both reduction ($RX \rightarrow RH$) and coupling ($RX \rightarrow R\text{–}R$) products. (7) Alkyl halides and tosylates that have β-hydrogens also undergo elimination to afford alkenes ($RX \rightarrow R_{-H}$). (8) The relative yields of products shows a strong solvent and leaving group dependence. Polar solvents favor both coupling and alkene formation. (9) The fourth hydrogen atom in methane is derived from the solvent and from an unidentified proton pool (presumed to be residual water) in the solvent. (10) The recovery of $Ni^{II}(OEiBC)$ is quantitative within the limits of detection, even after multiple turnovers. (11) Simultaneous addition of alkyl halide and proton donor increases the yield of reduction products relative to coupling products. In the case of 1-bromo-5-hexene, simultaneous addition of proton donor increases the yield of the reduction product 1-hexene relative to the rearrangment product methylcyclopentane. (12) Trace levels of ethylene and butene are produced from CH_3X and C_2H_5X, respectively.

The mechanism outlined in eqs 2–14 accommodates all of the observations listed above, with the exception of the last one. We will defer a discussion of this observation until later in this paper. The symbol e^- designates a reducing agent, which can be either an electrode poised at a potential ≤ -1.5 V vs SCE or a chemical reducing agent such as sodium amalgam.[2,8] In batch reactions, eqs 4 and 12 do not occur and eq 2 is temporally and spatially separated from eqs 3, 5–11, 13, and 14. In catalytic reactions, eq 2 occurs simultaneously to and in the same vessel as eqs 3–14. The oxidation states indicated for nickel are the formal oxidation states that result if one follows the convention of counting an alkyl or H group as a closed-shell anionic ligand.[24] OEiBC is a dianionic ligand.

Studies of electrocatalytic reduction of alkyl halides by Ni(OEiBC) establish that eq 3 is second order and rate limiting.[2] Given the above observations, a 17-e^- paramagnetic alkylnickel complex $R\text{–}Ni^{III}(OEiBC)$ is the most reasonable product of eq 3. An intermediate of this or of some other type must exist to

---

[23] (a) Ellermann, J.; Kobelt, A.; Pfaltz, A.; Thauer, R. K. *FEBS Lett.* **1987**, *220*, 358. (b) Bobik, T. A.; Olson, K. D.; Noll, K. M.; Wolfe, R. S. *Biochem. Biophys. Res. Commun.* **1987**, *149*, 455.

[24] Collman, J. P.; Hegedus, L. S.; Norton, J. R.; Finke, R. G. *Principles and Applications of Organotransition Metal Chemistry*; University Science: Mill Valley, CA, 1987.

$$\mathrm{Ni^{II}(OEiBC) + e^- \rightarrow Ni^{I}(OEiBC)^-} \qquad (2)$$

$$\mathrm{Ni^{I}(OEiBC)^- + R{-}X \rightarrow R{-}Ni^{III}(OEiBC) + X^-} \qquad (3)$$

$$\mathrm{R{-}Ni^{III}(OEiBC) + e^- \rightarrow R{-}Ni^{II}(OEiBC)^-} \qquad (4)$$

$$\mathrm{R{-}Ni^{III}(OEiBC) + Ni^{I}(OEiBC)^- \rightarrow R{-}Ni^{II}(OEiBC)^- + Ni^{II}(OEiBC)} \qquad (5)$$

$$\mathrm{R{-}Ni^{II}(OEiBC)^- + HA \rightarrow R{-}H + Ni^{II}(OEiBC) + A^-} \qquad (6)$$

$$\mathrm{R{-}Ni^{II}(OEiBC)^- + R{-}X \rightarrow R{-}R + Ni^{II}(OEiBC) + X^-} \qquad (7)$$

$$\mathrm{R{-}Ni^{II}(OEiBC)^- \rightarrow H{-}Ni^{II}(OEiBC)^- + R_{-H}} \qquad (8)$$

$$\mathrm{R{-}Ni^{III}(OEiBC) \rightarrow H{-}Ni^{III}(OEiBC) + R_{-H}} \qquad (9)$$

$$\mathrm{Ni^{I}(OEiBC)^- + R{-}X \rightarrow H{-}Ni^{III}(OEiBC) + R_{-H} + X^-} \qquad (10)$$

$$\mathrm{Ni^{I}(OEiBC)^- + HA \rightleftharpoons H{-}Ni^{III}(OEiBC) + A^-} \qquad (11)$$

$$\mathrm{H{-}Ni^{III}(OEiBC) + e^- \rightarrow H{-}Ni^{II}(OEiBC)^-} \qquad (12)$$

$$\mathrm{H{-}Ni^{III}(OEiBC) + Ni^{I}(OEiBC)^- \rightarrow H{-}Ni^{II}(OEiBC)^- + Ni^{II}(OEiBC)} \qquad (13)$$

$$\mathrm{H{-}Ni^{II}(OEiBC)^- + HA \rightarrow H_2 + Ni^{II}(OEiBC) + A^-} \qquad (14)$$

explain the 2:1 stoichiometry of the overall reaction. Our inability to find direct spectroscopic evidence for R–Ni^{III}(OEiBC) at temperatures as low as –41 °C does not rule out the complex as the intermediate. UV–vis spectroscopy may not be sensitive to the formation of a C–Ni bond. Furthermore, the intermediate(s) must be very reactive because the reaction is essentially complete upon mixing at –41 °C. Stable alkylnickel tetrapyrrole complexes are not known. However, for other metals, reaction of a low-valent metallotetrapyrrole complex with an alkyl halide affords stable alkyl–metallotetrapyrrole complexes.[25] Of greater relevance are two reports of alkylnickel complexes of ligands with an N$_4$ donor set. [CH$_3$Ni^{II}(tmc)][CF$_3$SO$_3$] is sufficiently stable that it can be isolated.[26] A paramagnetic methylnickel(II) F430M complex was prepared at –78 °C and characterized by NMR.[27] The complex decomposes slowly at –20 °C.

R–Ni(OEiBC) can be consumed in several reactions. If R has a β-hydrogen, it could undergo β-hydride elimination, eq 9. R–Ni^{III}(OEiBC) can also be reduced, eq 4 or 5. The standard reduction potentials of alkylnickel complexes are not known. However, the observation that electrocatalysis occurs at the potential of the Ni^{II}(OEiBC)/Ni^{I}(OEiBC)$^-$ couple requires that the standard potential of the R–Ni^{III}(OEiBC)/R–Ni^{II}(OEiBC)$^-$ couple be similar to or positive of the potential of the former couple. If not, a separate reduction wave would be observed for the alkylnickel couple at a more negative potential and the onset of catalytic reduction in the presence of excess alkyl halide would occur near the potential of this second wave.[28] The ordering of potentials is also reasonable because the 17-e$^-$ alkylnickel complex has a hole available in a low-lying orbital.

We intentionally omit protonolysis of R–Ni^{III}(OEiBC), eq 15, from the mechanism. Oxidation of Ni(OEiBC) results in preferential loss of an electron from the OEiBC π-system rather than from Ni(II).[29] Ni^{III}(OEiBC)$^+$, the product of eq 15, is an excited state of the Ni(OEiBC$^\bullet$)$^+$ cation radical. If formed, it should relax to the cation radical, which is unstable in DMF and quickly disproportionates, eq 16.[29] It is difficult to assert that both eqs 17 and 18 are sufficiently rapid in all circumstances to the prevent formation of any Ni(OEC) in DMF solution. The observed quantitative recovery of Ni(OEiBC) requires this to be true if eq 15 plays a significant role in the mechanism.

$$\mathrm{R{-}Ni^{III}(OEiBC) + HA \rightarrow R{-}H + Ni^{III}(OEiBC)^+ + A^-} \qquad (15)$$

$$\mathrm{2Ni(OEiBC^{\bullet})^+ \rightarrow Ni(OEC) + Ni(OEiBC) + 2H^+} \qquad (16)$$

$$\mathrm{Ni(OEiBC^{\bullet})^+ + Ni^{I}(OEiBC)^- \rightarrow 2Ni(OEiBC)} \qquad (17)$$

$$\mathrm{Ni(OEiBC^{\bullet})^+ + e^- \rightarrow Ni(OEiBC)} \qquad (18)$$

Homolysis of R–Ni(OEiBC), eq 19, cannot be ruled out. However, several observations are inconsistent with a major role in the mechanism for homolysis followed by free-radical reactions of the resulting alkyl radicals, eq 20. A mechanism consisting of eqs 2, 3, 19, and 20 has a stoichiometry of 1:1 Ni(I):CH$_3$I rather than the observed 2:1 stoichiometry. If the products of the reactions of Ni^{I}(OEiBC)$^-$ with alkyl halides are formed solely (or predominantly) via free radicals, the product distributions in these reactions must be identical (or similar) to those determined for free radicals generated by independent means. The ratio of the rate constants for disproportionation and comproportionation reactions of ethyl radicals, eqs 21 and 22, respectively, has been reported for ethyl radicals prepared by several independent methods in different solvents.[30] The ratio, which equals the ratio of ethylene to butane even if other pathways that produce ethane exist, is not strongly affected by the reaction medium. It varies from 0.13 in vacuum to 0.35 in water. This is inconsistent with our results for the reduction of ethyl iodide. Our observed ratios of ethylene to butane are significantly larger and show a strong solvent dependence. It is hard to rationalize how the addition of proton (H$^+$) donors would increase the yield of methane but decrease the yield of ethane from methyl free radicals. Finally, the predominance of nonrearranged products in the reductions of 1-bromo-5-hexene requires that any free radicals formed be rapidly captured, as in eq 23. Radical capture reactions of this type were proposed in the reactions of Ni^{I}(tmc)$^+$ with alkyl halides and were estimated to have rate constants approaching 10^8 M^{-1}

$$\mathrm{R{-}Ni^{III}(OEiBC) \rightarrow Ni^{II}(OEiBC) + R^{\bullet}} \qquad (19)$$

$$\mathrm{R^{\bullet} \rightarrow (R{-}H + R{-}R + R_{-H})} \qquad (20)$$

$$\mathrm{2C_2H_5^{\bullet} \rightarrow C_2H_6 + C_2H_4} \qquad (21)$$

$$\mathrm{2C_2H_5^{\bullet} \rightarrow C_4H_{10}} \qquad (22)$$

$$\mathrm{R^{\bullet} + Ni^{I}(OEiBC)^- \rightarrow R{-}Ni^{II}(OEiBC)^-} \qquad (23)$$

---

(25) (a) Brothers, P. J.; Collman, J. P. *Acc. Chem. Res.* **1986**, *19*, 209. (b) Guilard, R.; Lecomte, C.; Kadish, K. M. *Struct. Bonding* **1987**, *64*, 205. (c) Guilard, R.; Kadish, K. M. *Chem. Rev.* **1988**, *88*, 1121.

(26) D'Aniello, M. J., Jr.; Barefield, E. K. *J. Am. Chem. Soc.* **1976**, *98*, 1610.

(27) Lin, S.-K.; Jaun, B. *Helv. Chim. Acta* **1991**, *74*, 1725.

(28) Lexa, D.; Savéant, J.-M.; Wang, D. L. *Organometallics* **1986**, *5*, 1428.

(29) Stolzenberg, A. M.; Stershic, M. T. *Inorg. Chem.* **1988**, *27*, 1614.

(30) (a) Sheldon, R. A.; Kochi, J. K. *J. Am. Chem. Soc.* **1970**, *92*, 4395. (b) Gibian, M. J.; Corley, R. C. *Chem. Rev.* **1973**, *73*, 441. (c) Bakac, A.; Espenson, J. H. *J. Phys. Chem.* **1986**, *90*, 325.

s^{-1}.[12a] Note that the sum of eqs 19 and 23 represents the same net change as eq 5.

The proposed product-forming reactions include eq 6, which affords the reduction product, eq 7, which affords the coupling product, and for R groups that have a β-hydrogen, eq 8, which affords the HX elimination product. These are respectively protonation, alkylation, and internal proton-transfer reactions of $R–Ni^{II}(OEiBC)^-$. The product distribution reflects the relative rates at which the three reactions consume this common intermediate. Because eqs 6 and 7 follow mixed second-order kinetics and eq 8 follows first-order kinetics, the product distribution should be sensitive to the identities and concentrations of RX and HA and to the identity of the solvent. This is consistent with our observations. The rate of eq 7 and the relative amount of coupled product should increase with the reactivity of the electrophile RX. As expected, the relative yield of ethane is higher for the more reactive CH_3I than for CH_3OTs. Similarly, the relative yield of butane is greater for C_2H_5I than for C_2H_5OTs. For reactions in "dry" solvents, the concentration of HA is set by the level of residual water and the availability of protons from the solvent. Intentional addition of an acidic compound will increase this concentration and should favor the rate of eq 6 over that of eq 7. Simultaneous addition of CH_3I and acidic compounds does increase the yield of methane (reduction) relative to ethane (coupling), Table IV.

$R–Ni^{II}(OEiBC)^-$ functions as a base and as a nucleophile, respectively, in eqs 6 and 7. The complex is expected to be both a strong base and nucleophile. $R–Ni^{II}(OEiBC)^-$ is isoelectronic with $CH_3–Ni^{II}(F430M)$ and $CH_3–Ni^{II}(tmc)^+$. The three complexes differ in overall charge because of the charges of their macrocyclic ligands are dianionic, monoanionic, and neutral ligands, respectively. The difference in charge has a substantial affect on the reactivity of the tmc and F430M complexes. $CH_3–Ni^{II}(tmc)^+$ hydrolyzes in alkaline aqueous solution ($9 < pH < 13$) on a time scale of 1–15 min at 25 °C.[12a,31] $CH_3–Ni^{II}(F430M)$ decays slowly at −20 °C in nonaqueous solution, presumably by irreversible formation of methane after proton transfer from an amide or lactam group of F430M.[27] Addition of acid results in immediate hydrolysis of $CH_3–Ni^{II}(F430M)$ and $CH_3–Ni^{II}(tmc)^+$. Given its negative charge, $R–Ni^{II}(OEiBC)^-$ should be even more reactive.

To this point in the discussion, the reactions that produce alkenes, eqs 8 and 9, involve intermediates that are common to reactions that afford other products. Alkene formation is also possible by an independent mechanism. $Ni^{I}(OEiBC)^-$ could function as a base in an E_2 elimination of HX from RX, eq 10.

Reduction of protons to H_2 by Ni(I) tetraazamacrocyclic complexes has been observed.[32] The mechanism is thought to involve protonation of the Ni(I) complex to afford a hydrido–Ni(III) complex.[32,33] We invoke an analogous step, eq 11, in the mechanism of H_2 production by $Ni^{I}(OEiBC)^-$. Reduction of the resulting $H–Ni^{III}(OEiBC)$, eq 12 or 13, followed by a second protonation, eq 14, affords H_2. The thermodynamic feasibility of eqs 12 and 13 can be supported by arguments similar to those used in the case of eqs 4 and 5.

The equilibrium in eq 11 appears to favor $Ni^{I}(OEiBC)^-$ unless HA is a strong acid or present in large excess. Consequently, $H–Ni^{III}(OEiBC)^-$ that is produced in eqs 8–10 can dissociated and regenerate $Ni^{I}(OEiBC)^-$. In general, Ni(I) complexes do not appear to be particularly strong bases toward protons. $Ni^{I}(tmc)^+$ is stable for hours in alkaline (pH = 11) aqueous solution.[12] Electrocatalytic reduction of CO_2 competes effectively with H_2 production when nickel tetraazamacrocyclic complexes are reduced under a CO_2 atmosphere in weakly acidic (pH = 4) aqueous solution.[32] This discrimination toward substrates is remarkable given the weak coordinating ability of CO_2, the large concentration of proton in solution, and more favorable thermodynamics for H_2 production over CO_2 reduction.

Relationship of Reaction Mechanism and the Structural Preferences of Ni(I). The discussion above does not address the detailed mechanisms of eq 6, 7, or 14. Mechanisms that require initial cleavage of the C–Ni bond can be neglected. Arguments presented against product formation via eqs 19 and 20 apply equally well to homolysis to $R–Ni^{II}(OEiBC)^-$. Heterolysis to yield Ni(OEiBC) and R^- is unreasonable because R^- has much too high a free energy to be formed as an intermediate in solution.[31]

Two potential types of mechanisms for eqs 6 and 7 differ with respect to the polarization of the C–Ni bond. The α-carbon of the alkyl group has significant carbanionic character in mechanisms of the first type. Equation 6 proceeds by formation of a C–H bond between the α-carbon and the proton and simultaneous cleavage of the C–Ni bond. Similarly, eq 7 involves a nucleophilic attack by the α-carbon on R–X and proceeds with compensating bond making (C–C) and bond breaking (C–Ni and C–X) processes. In mechanisms of the second type, the nickel atom is the nucleophilic site. Equation 6 involves protonation of the nickel atom of $R–Ni^{II}(OEiBC)^-$, eq 24, followed by reductive elimination, eq 25. Equation 7 also proceeds in two steps: alkylation of $R–Ni^{II}(OEiBC)^-$ to afford a dialkylnickel complex, eq 26, followed by reductive elimination to yield the coupled alkane product, eq 27.

$$R–Ni^{II}(OEiBC)^- + HA \rightarrow (R)(H)Ni^{IV}(OEiBC) + A^- \quad (24)$$

$$(R)(H)Ni^{IV}(OEiBC) \rightarrow R–H + Ni^{II}(OEiBC) \quad (25)$$

$$R–Ni^{II}(OEiBC)^- + R'–X \rightarrow (R)(R')Ni^{IV}(OEiBC) + X^- \quad (26)$$

$$(R)(R')Ni^{IV}(OEiBC) \rightarrow R–R' + Ni^{II}(OEiBC) \quad (27)$$

Precedents exist for organonickel complexes reacting by both types of mechanisms. The key intermediates in the nickel-catalyzed coupling of aryl halides and cross coupling of alkyl and aryl halides are diarylnickel(III) and arylalkylnickel(II) complexes, respectively.[34] On the other hand, hydrolysis of $R–Ni(tmc)^+$ complexes was suggested to occur by direct reaction of the α-carbon with the proton donor.[31] Organonickel complexes $NC(CH_2)_3CH_2Ni(tmc)^+$ and $CH_2{=}CH(CH_2)_3CH_2Ni(tmc)^+$ undergo cyclization of the alkyl group in concert with hydrolysis to afford cyclopentanone and methylcyclopentane, respectively.[12a,35] The cyclization is presumed to involve a nickel-bound carbanion, in analogy to the cyclization of hexenyl alkali metal compounds.[36]

Two mechanisms can be proposed for the reaction of $H–Ni^{II}(OEiBC)^-$ in eq 14 that are analogous to the possibilities discussed above for $R–Ni^{II}(OEiBC)^-$. They differ with respect to the polarization of the Ni–H bond. Protonation on nickel, eq 28, affords a classical dihydride complex, which then undergoes reductive elimination to afford H_2, eq 29. Alternatively, pro-

---

[31] Ram, M. S.; Espenson, J. H.; Bakac, A. *Inorg. Chem.* **1986**, *25*, 4115.

[32] (a) Fisher, B.; Eisenberg, R. *J. Am. Chem. Soc.* **1980**, *102*, 7361. (b) Beley, M.; Collin, J.-P.; Ruppert, R.; Sauvage, J.-P. *J. Am. Chem. Soc.* **1986**, *108*, 7461.

[33] Tait, A. M.; Hoffman, M. Z.; Hayon, E. *Inorg. Chem.* **1976**, *15*, 934.

[34] (a) Morrell, D. G.; Kochi, J. K. *J. Am. Chem. Soc.* **1975**, *97*, 7262. (b) Tsou, T. T.; Kochi, J. K. *J. Am. Chem. Soc.* **1979**, *101*, 7548. (c) Yamamoto, T.; Kohara, T.; Osakada, K.; Yamamoto, A. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 2147. (d) Amatore, C.; Jutand, A. *Organometallics* **1988**, *7*, 2203.

[35] Bakac, A.; Espenson, J. H. *J. Am. Chem. Soc.* **1986**, *108*, 5353.

[36] (a) Garst, J. F.; Hines, J. B., Jr. *J. Am. Chem. Soc.* **1984**, *106*, 6443. (b) Bailey, W. F.; Patricia, J. J.; DelGobbo, V. C.; Jarret, R. M.; Okarma, P. J. *J. Org. Chem.* **1985**, *50*, 1999.

$$\text{H-Ni}^{\text{II}}(\text{OEiBC})^- + \text{HA} \rightarrow (\text{H})_2\text{Ni}^{\text{IV}}(\text{OEiBC}) + \text{A}^- \quad (28)$$

$$(\text{H})_2\text{Ni}^{\text{IV}}(\text{OEiBC}) \rightarrow \text{Ni}^{\text{II}}(\text{OEiBC}) + \text{H}_2 \quad (29)$$

$$\text{H-Ni}^{\text{II}}(\text{OEiBC})^- + \text{HA} \rightarrow (\eta^2\text{-H}_2)\text{Ni}^{\text{II}}(\text{OEiBC}) + \text{A}^- \quad (30)$$

$$(\eta^2\text{-H}_2)\text{Ni}^{\text{II}}(\text{OEiBC}) \rightarrow \text{Ni}^{\text{II}}(\text{OEiBC}) + \text{H}_2 \quad (31)$$

tonation on the hydride, eq 30, affords an η^2-H_2 complex, which then dissociates H_2, eq 31. Dihydrogen complexes of metalloporphyrins are known.[37] The isotopic exchange of H/D between D_2 and EtOH that is catalyzed by a Ni–salicylaldehyde thiosemicarbanzone cation was proposed to involve a nickel dihydrogen intermediate.[38]

An objection might be raised to the reactions proposed in eqs 25, 27, and 29 and for that matter in eqs 8 and 9. Reductive elimination, β-hydride elimination, and migratory insertion reactions require cis coordination sites.[24] Porphyrins and tetraazamacrocycle generally are effective at blocking all available coordination sites cis to an axial ligand.[25a] Thus, the apparent CO insertion into the Fe–C bond of alkyliron(III) porphyrins to afford an acyliron(III) porphyrin[39] or into the Rh–H bond of hydridorhodium porphyrins to afford a formylrhodium porphyrin[40] follows radical mechanisms rather than the conventional organometallic mechanisms. Similarly, β-hydride elimination in the macrocyclic complex R–Co(dmg-BF_2)$_2$py$^-$ proceeds by transfer of a β-hydrogen of the alkyl group (formally as a hydride) to a macrocycle nitrogen atom.[41] The structural characteristics of Ni(I) and the flexibility of isobacteriochlorins might obviate the objection.

Ni(I) complexes of tetraazamacrocycles,[42] F430M,[43] and isobacteriochlorins[9] have been characterized by EXAFS spectroscopy and, in the case of one of the tetraazamacrocyclic complexes, by X-ray crystallography. In all cases, reduction of Ni(II) to Ni(I) results not only in an expansion of the macrocycle core but also in a significant distortion in the Ni–N bond lengths within the complex. For the tetrapyrrole complexes, the change is from four equivalent Ni–N distances of roughly 1.90–1.93 Å in the low-spin Ni(II) forms of the complexes to two Ni–N distances of 1.85–1.88 Å and two Ni–N distances of 2.00–2.03 Å in the Ni(I) forms of the complexes. Preliminary XAFS data for $\text{Ni}^{\text{I}}(\text{OEiBC})^-$ are consistent with these observations.[44]

The distortion of the Ni(I) coordination sphere is unexpected and unexplained. Although Ni(I) is d^9 and subject to Jahn–Teller distortions, the tetragonal ligand field associated with absent or weakly coordinating axial ligands would give the required nondegenerate ground state. EXAFS data for the isoelectronic d^9 Cu(OEiBC) are consistent with four equivalent Cu–N distances of 2.00 Å.[44] One possibility is that the macrocycle begins to distort toward a trigonal bipyramidal environment around Ni(I). The Ni–N distances will split into two distinct sets if two nitrogens each occupy "axial" and "equatorial" sites. On the basis of molecular mechanics calculations, Zimmer and Crabtree suggested that F430 can bend to accommodate a trigonal bipyramidal "tacolike" conformation of this type.[45] At present, the available evidence suggests that Ni(I) complexes are four-coordinate.[9,42–44] The nascent fifth site (an equatorial site) could be occupied by a lone pair in an orbital derived from the original d_{z^2} or by a loosely coordinated counterion. Some reduced Ni tetraazamacrocycle complexes coordinate CO to afford true 5-coordinate Ni(I) complexes.[42] EXAFS data for these complexes suggest that the Ni–C distance is short and that Ni(I) moves out of the plane of the four nitrogens. These observations are consistent with a trigonal bipyramidal (or square pyramidal) structure. The structures of the R–Ni(OEiBC) complexes should be similar to a first approximation. A sixth, cis coordination site should be relatively easy to open, given that the Ni is already out of plane and the macrocycle is already bent. This would permit the reactions in eqs 8, 9, 25, 27, and 29 to proceed via normal organometallic mechanisms.

Implications of Trace Products. Trace quantities of ethylene and butene (10^{-4} to 10^{-3} mol/mol of Ni(I)) are produced during the respective reductions of CH_3X and C_2H_5X, where X = I and OTs. Control experiments show that formation of these products depends on the presence of $\text{Ni}^{\text{I}}(\text{OEiBC})^-$ and is not artifactual. Any mechanism proposed for the reactions of $\text{Ni}^{\text{I}}(\text{OEiBC})^-$ must explain how these products form. It is difficult to envision reactions in which methyl radicals afford ethylene or ethyl radicals afford butene. However, extensions of the nickel-based reactions proposed above can provide reasonable explanations.

Ethylene appears to result from the reaction of $\text{Ni}^{\text{I}}(\text{OEiBC})^-$ with CH_2I_2, which GC analyses show is present as a roughly 0.1% impurity in some samples of CH_3I. Reaction of $\text{Ni}^{\text{I}}(\text{OEiBC})^-$ with pure CH_2I_2 affords significant quantities of ethylene and lesser amounts of methane. When mixed, CH_2I_2 competes successfully with CH_3I for $\text{Ni}^{\text{I}}(\text{OEiBC})^-$. A close precedent is found in the reaction of K_2[Ru(TPP)] with CH_2X_2 (X = Cl, I) in THF to afford a mixture of Ru(TPP)($CH_2{=}CH_2$) and Ru(TPP)(THF)$_2$.[46] Direct evidence for a Ru=CH_2 carbene intermediate was not found. However, bimolecular coupling of M=CH_2 complexes to afford mixtures of M($CH_2{=}CH_2$) and M(solvent) complexes is known.[47] Loss of ethylene from ($CH_2{=}CH_2$)Ni(OEiBC) should be facile. Obviously, a CH_2I_2 impurity cannot account for ethylene formed in reactions of $\text{Ni}^{\text{I}}(\text{OEiBC})^-$ with CH_3OTs. The ethylidene complex Ru(OEP)($CHCH_3$) results from Ru(OEP)(CH_2CH_3)$_2$ when homolysis of the latter affords an ethyl radical which then abstracts an α-hydrogen from a second molecule of the starting complex.[48] Production of "Ni(OEiBC)(CH_2)" by an analogous mechanism must occur at trace levels if, as argued above, the contribution of free radical chemistry to the overall mechanism is relatively unimportant.

The formation of butene from C_2H_5X can be explained by a simple reaction sequence. Significant amounts of ethylene are produced from C_2H_5X. Therefore, some ethylene will be present in solution *during* the reaction. Insertion of ethylene into an ethyl–nickel bond affords butylnickel complexes, eq 32. Butene results from β-hydride elimination, eq 33. An insertion step analogous to eq 32 is proposed in the coupling of alkyl bromides and acrylonitrile that is mediated by the Ni(I) complex Ni(teta)$^+$.[11b]

Biological Significance. Ni(OEiBC) and F430 differ in some important respects. The hydrocorphinoid macrocycle of F430

---

(37) Collman, J. P.; Wagenknecht, P. S.; Hembre, R. T.; Lewis, N. S. *J. Am. Chem. Soc.* **1990**, *112*, 1294.

(38) Zimmer, M.; Schulte, G.; Luo, X.-L.; Crabtree, R. H. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 193.

(39) (a) Arafa, I. M.; Shin, K.; Goff, H. M. *J. Am. Chem. Soc.* **1988**, *110*, 5228. (b) Gueutin, C.; Lexa, D.; Momenteau, M.; Saveant, J.-M. *J. Am. Chem. Soc.* **1990**, *112*, 1874.

(40) (a) Wayland, B. B.; Woods, B. A. *J. Chem. Soc., Chem. Commun.* **1981**, 700. (b) Paoness, R. S.; Thomas, N. C.; Halpern, J. *J. Am. Chem. Soc.* **1985**, *107*, 4333.

(41) Shi, S.; Bakac, A.; Espenson, J. H. *Inorg. Chem.* **1991**, *30*, 3410.

(42) Furenlid, L. R.; Renner, M. W.; Szalda, D. J.; Fujita, E. *J. Am. Chem. Soc.* **1991**, *113*, 883.

(43) Furenlid, L. R.; Renner, M. W.; Fajer, J. *J. Am. Chem. Soc.* **1990**, *112*, 8987.

(44) Fajer, J.; Furenlid, L. R.; Lahiri, G. K.; Renner, M. W.; Stolzenberg, A. M. To be published.

(45) Zimmer, M.; Crabtree, R. H. *J. Am. Chem. Soc.* **1990**, *112*, 1062.

(46) Collman, J. P.; Brothers, P. J.; McElwee-White, L.; Rose, E. *J. Am. Chem. Soc.* **1985**, *107*, 6110.

(47) (a) Schrock, R. R. *J. Am. Chem. Soc.* **1975**, *97*, 6577. (b) Merrifield, J. H.; Lin, G.-Y.; Kiel, W. A.; Gladysz, J. A. *J. Am. Chem. Soc.* **1983**, *105*, 5811.

(48) Collman, J. P.; McElwee-White, L.; Brothers, P. J.; Rose, E. *J. Am. Chem. Soc.* **1986**, *108*, 1332.

$$CH_2{=}CH_2 + CH_3CH_2Ni(OEiBC)^{n-} \rightarrow CH_3CH_2CH_2CH_2Ni(OEiBC)^{n-} \quad (n = 0, 1) \quad (32)$$

$$CH_3CH_2CH_2CH_2Ni(OEiBC)^{n-} \rightarrow C_4H_8 + HNi(OEiBC)^{n-} \quad (n = 0, 1) \quad (33)$$

coordinates as a monoanionic ligand. In contrast, OEiBC is a dianion. Thus, the Ni(II) form of F430M is a monocationic complex whereas Ni(OEiBC) is a neutral complex. Reactions with organometallic reagents like $(CH_3)_2Mg$ that are facile with cationic F430M fail to occur for neutral Ni(OEiBC), because the absence of an anionic counterion eliminates the large favorable contribution to ΔH that is associated with the formation of MgX_2. Furthermore, the positive charge contributes to the roughly 600-mV anodic shift of the reduction potential of the Ni(II)/Ni(I) couple of F430 M relative to Ni(OEiBC).[2,7,8,9a,10,43] The presence of the cyclohexanone ring in F430 is also thought to contribute to the anodic shift.[9a] The shift in reduction potentials appears to make $Ni^{I}(OEiBC)^-$ considerably more reactive than Ni^{I}F430M.

Despite these differences, the reactivities of $Ni^{I}(OEiBC)^-$ and of Ni^{I}F430M share many common features. Both react rapidly with CH_3I and more slowly with CH_3OTs to afford CH_4 and the Ni(II) complex. The fact that Ni^{I}F430M reacts with CH_3OTs suggests strongly that Ni^{I}F430M, like $Ni^{I}(OEiBC)^-$, reacts by a two-electron mechanism rather than by a single-electron transfer mechanism. Labeling studies show that the fourth hydrogen in methane is transferred in a protonation step, presumably of an alkylnickel intermediate, and appears to be derived from residual water in the solvent. Compelling evidence exists for the methylnickel F430 intermediate. Addition of CH_3I to Ni^{I}F430M at −60 °C causes an immediate color change, but CH_4 evolution only occurs slowly on warming to room temperature or immediately upon addition of 0.1 M aqueous HCl.[10] ^2H NMR spectroscopy provides direct evidence for the existence of CD_3–nickel F430M, prepared by reaction of F430M and $(CD_3)_2Mg$ at −78 °C.[27] Evidence for the intermediacy of R–Ni(OEiBC) complexes is circumstantial, because the complexes appear to be much more reactive. There is no perceptible lag between oxidation and CH_4 evolution upon low-temperature addition of CH_3I to $Ni^{I}(OEiBC)^-$.

The coupling product ethane is not mentioned as a product of the reaction of Ni^{I}F430M with CH_3I in DMF.[10] However, ethane is a product of the F430-mediated reduction of polychlorinated methanes by titanium(III) citrate in aqueous solution.[4] In addition to methane and ethane, the second reaction also produces significant quantities of nonvolatile, yet unidentified, products. Thus, the yield of volatile hydrocarbon products is less than quantitative, just as we observe for $Ni^{I}(OEiBC)^-$ in some solvents.

The most curious similarity in the reactivities of $Ni^{I}(OEiBC)^-$ and of the Ni(I) form of F430 is that neither appears to react with thioethers. This includes methyl coenzyme M, $CH_3SCH_2CH_2SO_3^-$, the natural substrate of F430 containing methyl coenzyme M reductase. Does this imply that the reactivity of $Ni^{I}(OEiBC)^-$ and of Ni^{I}F430 is irrelevant to the chemistry carried out by the enzyme?

It is premature to draw such a conclusion. The reactivity of the Ni(I) complexes is almost certainly of direct relevance to the extent that the enzyme is involved in the reductive dehalogenation of chlorinated hydrocarbons by methanogenic bacteria. The situation is less certain as regards enzymatic catalysis of eq 1. Several possibilities remain open. First, the enzymatic mechanism could involve chemistry based on Ni(III) species rather than on Ni(I) species. Second, the failure of Ni(I) complexes to react directly with methyl coenzyme M might be apparent rather than real. Other more rapid reactions could consume Ni(I) before it had time to react with a thioether. Reactions of Ni^{I}F430M with proton donors have not been investigated. Methyl coenzyme M was almost certainly added as the ammonium salt. Did the ammonium ion rapidly oxidize Ni^{I}F430M and form hydrogen as in the case of $Ni^{I}(OEiBC)^-$? Third, methyl coenzyme M could require activation prior to reaction with Ni^{I}F430.[10] One proposal is that the thiyl radical of cofactor HTP, which is postulated to result from one-electron reduction of F430 by HTP–S^-, couples with methyl coenzyme M to afford the sulfuranyl radical, HTP–S–$S^{\bullet}(CH_3)$(CoM).[49,50] The sulfuranyl radical should be a better alkylating agent than a thioether. Finally, Ni^{I}F430 could require activation by conversion to a form other than present in Ni^{I}F430M. Some possibilities include coordination of a protein side chain, coordination of the thio cofactor HTP–S–H, or protonation by HTP–S–H. The latter would imply that a nickel hydride is the reactive intermediate rather than a Ni(I) complex. In essence, the enzyme would function as a biological equivalent of Raney nickel. Formation of a small amount of methane in the reaction of $Ni^{I}(OEiBC)^-$ with the ammonium salt of methyl CoM is interesting in this light. It must be stressed that the failure to observe methane when tetraphenylphosphonium methyl CoM and thiophenol were simultaneously added to $Ni^{I}(OEiBC)^-$ does not eliminate the hydride intermediate from consideration. The rate of oxidation of $Ni^{I}(OEiBC)^-$ by the acidic thiophenol may be too rapid to permit any nickel hydride to react with methyl CoM.

A significant conclusion can be drawn from our results if Ni^{I}F430 is involved in the chemistry of methyl coenzyme M reductase. The protein environment of the enzyme is extremely important in imposing one reaction pathway on a very reactive reduced nickel species.

Acknowledgment. This work was supported by the National Institutes of Health (Grant GM 33882).

Supplementary Material Available: Text containing discussions of construction and operation of the gas sample valve system, calibration of GC detectors, independent confirmation of analytical methods, and control experiments and a figure showing a line drawing of the gas sample valve system (9 pages). Ordering information is given on any current masthead page.

---

(49) Jaun, B. *Helv. Chim. Acta* **1990**, *73*, 2209.
(50) Berkessel, A. *Bioorg. Chem.* **1991**, *19*, 101.