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Electron Transfer. 129. Copper Catalysis in the Thiol Reduction of Oxime-Bound Nickel(IV)[1]

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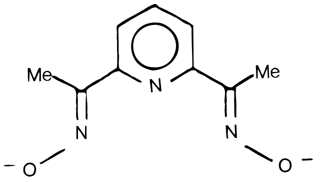
Solutions of the Ni(IV) complex of the dianion of 2,6-diacetylpyridine dioxime (chelate **II** in text) are reduced very slowly by 2-aminoethanethiol at pH 2.3−3.0, but this reaction is catalyzed dramatically and specifically by dissolved copper, with Cu(I) the active reductant. When the [thiol]/[Ni^{IV}] ratio exceeds 1.6, each Ni(IV) oxidizes two molecules of thiol, forming Ni(II) and R_2S_2. At low concentrations of catalyst and reductant, reaction profiles are almost exponential, but at higher concentrations of either, curves become progressively more nearly linear. Reactions are sharply retarded by increases in acidity. Profiles for 14 runs, carried out with $[H^+] = 0.001-0.0040$ M, $[Ni^{IV}] = (0.94-1.2) \times 10^{-5}$ M, $[\text{thiol}] = (2.0-32) \times 10^{-4}$ M, and $[Cu^{2+}] = (2.5-80) \times 10^{-6}$M, are consistent with a reaction sequence (eqs 2−10 in text) in which Cu(I) is generated in competing homolyses of the complexes $Cu^{II}(SRH)$ and $Cu^{II}(SRH)_2$. Reduction of Ni(IV) appears then to proceed through a $Ni^{IV}Cu^{I}$ adduct, which can undergo electron transfer (yielding Ni^{III} and Cu^{II}), either in a unimolecular fashion or, alternatively, as a result of attack by a second Cu(I) species. The $Ni^{IV}Cu^{I} + Cu^{I}$ process is reflected in approach to second-order dependences on [Cu^{II}] and [thiol] (which generate Cu^{I}) at high concentrations of these reagents. Reductions of the Ni(III) intermediate are taken to be much more rapid than those of Ni(IV). Kinetic trends in the present system stand in contrast to the more familiar catalytic patterns such as those seen when the same combination of thiol and catalyst is used to reduce superoxo complexes of cobalt(III). With the latter reactions, decay profiles for the oxidant tend to be exponential at high reagent concentrations but approach linearity at low.

Since 1970 the array of known coordination compounds of hypervalent nickel has been augmented impressively. Over 300 complexes of Ni(III) have been characterized, and there is now on hand a smaller, but growing, family of Ni(IV) species.[2] Quickening of interest in these states reflects, in part, expanding evidence that the modes of action of several enzymes such as CO dehydrogenases and (NiFe)-hydrogenases entail Ni(III) centers.[3]

In line with the increased availability of such complexes, there has been a marked outbreak of mechanistic studies dealing with their reductions to the dominant dipositive state.[4] In the case of Ni(IV), as with other reagents undergoing net two-unit redox changes,[5] concern persists as to whether conversion to Ni(II) invariably requires passage through a Ni(III) intermediate or whether a direct 2e transaction may occur under favorable conditions.

In our initial contribution to this area,[6] we examined the reactions of the bischelated Ni(IV) complex of the dianion (**I**) of 2,6-diacetylpyridine dioxime, a $Ni^{IV}N_6$ species (**II**)[7] which is significantly more stable in media of low pH than are other derivatives of this type. Chelate **II** is readily reduced by the 1e reagents Fe^{2+}(aq) and I^- but is quite inert to the 2e reductants H_3PO_2 and H_3AsO_3. Reaction with U(IV) appears to proceed through the odd-electron state U(V), whereas the path for the slow reduction by Sn^{II}(aq) remains undetermined.



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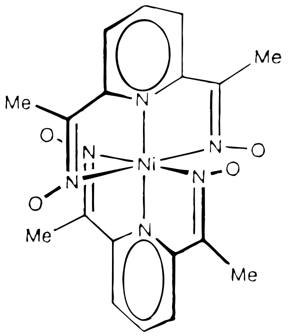

II

The present report describes the reaction of this Ni(IV) chelate with 2-aminoethanethiol ($HSCH_2CH_2NH_3^+$, abbreviated RSH_2^+), a remarkably slow reduction which is, however, catalyzed dramatically and specifically by dissolved copper, leading to a kinetic picture featuring unexpected facets.

Experimental Section

Materials. Glycine and 2-aminoethanethiol hydrochloride (Aldrich Chemicals), copper sulfate hexahydrate and perchloric acid (Fisher), and iron(III) perchlorate (Alfa) were used as received. Solutions for kinetic runs were made from Millipore water which was treated with

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(1) Sponsorship of this work by the National Science Foundation (Grant 9314113) is gratefully acknowledged.

(2) Reviews: (a) Sacconi, I.; Mani, F.; Bencini, A. In *Comprehensive Coordination Chemistry*; Wilkinson, G., Ed.; Pergamon: Oxford, U.K., 1987; Vol. 5, pp 287−300. (b) Haines, R. J.; McAuley, A. *Coord. Chem. Rev.* **1981**, *39*, 77. (c) Nag, K.; Chakravorty, A. *Coord. Chem. Rev.* **1980**, *33*, 87.

(3) See, for example: (a) Lancaster, J. R., Jr. *Science* **1982**, *216*, 1324. (b) *The Bioinorganic Chemistry of Nickel*; Lancaster, J. R., Jr., Ed.; VCH Publishers: New York, 1988; Chapters 2−4. (c) Kruger, H.-J.; Holm, R. H. *J. Am. Chem. Soc.* **1990**, *112*, 2955.

(4) See, for example: (a) Macartney, D. H.; McAuley, A.; Olubyide, O. *Inorg. Chem.* **1985**, *24*, 307. (b) Lappin, A. G.; Martone, D. P.; Osvath, P.; Marusak, R. A. *Inorg. Chem.* **1988**, *27*, 1863. (c) Bhattacharya, S.; Ali, M.; Gangopadhyay, S.; Banerjee, P. *J. Chem. Soc., Dalton Trans.* **1994**, 3733.

(5) See, for example: Ghosh, M. C.; Gelerinter, E.; Gould, E. S. *Inorg. Chem.* **1991**, *30*, 1039.

(6) Mandal, S.; Gould, E. S. *Inorg. Chem.* **1995**, *34*, 3993.

(7) (a) Baucom, E. I.; Drago, R. S. *J. Am. Chem. Soc.* **1971**, *93*, 6469. (b) Sproul, G.; Stucky, G. D. *Inorg. Chem.* **1973**, *12*, 2898.

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Table 1. Stoichiometry of the Reduction of Oxime-Bound Nickel(IV) with 2-Aminoethanethiol (Red) As Catalyzed by Copper(II)[a]

$[Ni^{IV}]$, M × 10^5	[Red], M × 10^5	$\Delta[Ni^{IV}]$, M × 10^5	$\Delta[Red]/\Delta[Ni^{IV}]$
11.2	10.0	5.5	1.79
11.3	15.0	8.1	1.85
11.2	18.0	9.1	1.98
7.7	8.0	4.3	1.86
5.9	8.0	4.4	1.82
5.0	8.0	4.2	1.91

[a] Reductions of the bischelated nickel(IV) complex (**II**) of 2,6−diacetylpyridine dioximate were carried out under N_2 at 25 °C in 14:86 methanol/water; $\lambda = 572$ nm. $[Cu(II)] = 5.0 \times 10^{-6}$ M. Solutions were not buffered. Waiting period was 30 s in each case.

zinc amalgam as described,[8] filtered, boiled for 2 h, and then sparged with N_2 for 2 h more to remove dissolved O_2. Bis(2,6-diacetylpyridine dioximato)nickel(IV) (complex **II**) was prepared as described[6] by a modification of the method of Baucom and Drago.[7a] Although this complex is very nearly insoluble in water, very dilute (supersaturated) solutions for redox experiments could be prepared by dissolving the powdered crystalline product in 1:1 water/methanol under reflux for 2 h with stirring, cooling, and then diluting with distilled water. Solutions used in kinetic studies contained 2−4% CH_3OH, but measured kinetic profiles were found to be independent of the methanol content within this range. Such solutions, which deteriorated slowly on standing, were prepared fresh for each set of runs. The low-energy maximum at 615 nm in DMF[3c] is shifted [7a] to 572 nm ($\epsilon = 1.28 \times 10^4$ M^{-1} cm^{-1}) in 98:2 H_2O/CH_3OH.

Stoichiometric Experiments. For stoichiometric determinations, which were carried out under N_2, measured deficient quantities of the thiol (as its hydrochloride) were added to a known excess of the Ni(IV) complex. To ensure complete reaction within a convenient time interval, reactions were carried out at pH 6.8, rather than at the higher acidities (near pH 2.7) used in the kinetic runs. After reaction had ceased (24 s), decreases in absorbance at 572 nm were compared with those resulting from addition of an excess of the reductant. Results are summarized in Table 1.

Kinetic Studies. Reactions were run under N_2 and were monitored at 572 nm using either a Beckman Model 5260 or a Cary 14 recording spectrophotometer. Ionic strength was maintained at 0.018 M while $[H^+]$ was varied between 1.1×10^{-3} and 4.0×10^{-3} M by addition of known quantities of glycine to 0.018 M $HClO_4$ (thus yielding a series of Gly/$GlyH^+$ buffers). Excess reductant was used in all kinetic runs. Reactions at pH values near 2.7 in the absence of added transition metal ions were so slow that rate measurements were seriously complicated by the decomposition of the Ni(IV) complex in this medium.[6] Redox reactions were, however, strikingly catalyzed by Cu^{II} (but not by Fe^{III} or Ni^{II}) and were sharply retarded by increases in acidity, with this inhibition more marked than that corresponding to a $[H^+]^{-1}$-dependence. Reaction profiles were almost exponential at [thiol] ≤ 4×10^{-4} M and $[Cu^{II}] \leq 5 \times 10^{-6}$ M; within this range, pseudo-first-order rate constants were very nearly proportional both to $[Cu^{II}]$ and to [thiol]. At higher concentrations of reductant and/or catalyst, initial portions of the decay curves became more nearly linear, with zero-order character growing progressively more prominent as concentrations of these reagents were further increased (see Figure 1). The profile at [thiol] = 8×10^{-4} M and $[Cu^{II}] = 8 \times 10^{-5}$ M (the most rapid reaction examined) corresponded closely to linearity. Comparisons of initial rates throughout the series of runs yielded no evidence for kinetic saturation with respect either to [thiol] or to $[Cu^{II}]$; moreover, dependency on [thiol] was somewhat more pronounced at higher concentrations of reductant than at lower. Temperatures were kept at 25.0 ± 0.2 °C during all rate measurements.[9]

Results and Discussion

The stoichiometry of the Ni(IV)−thiol reaction is seen (Table 1) to approach 2:1 when the oxidant is held in slight excess but falls below this figure when the ratio [Ni(IV)]/[Red] taken is increased. The principal reaction may then be represented as eq 1. Perceptible departures from the indicated ratio at greater $[Ni^{IV}]$ may reflect further oxidation of the disulfide to a derivative of electropositive sulfur. This complication may be taken to be negligible in the kinetic experiments, which feature the reductant in large excess.

$$Ni^{IV}(Lig^{2-})_2 + 2RSH_2^+ \rightarrow Ni^{II} + R_2S_2 + 2LigH_2 \quad (1)$$

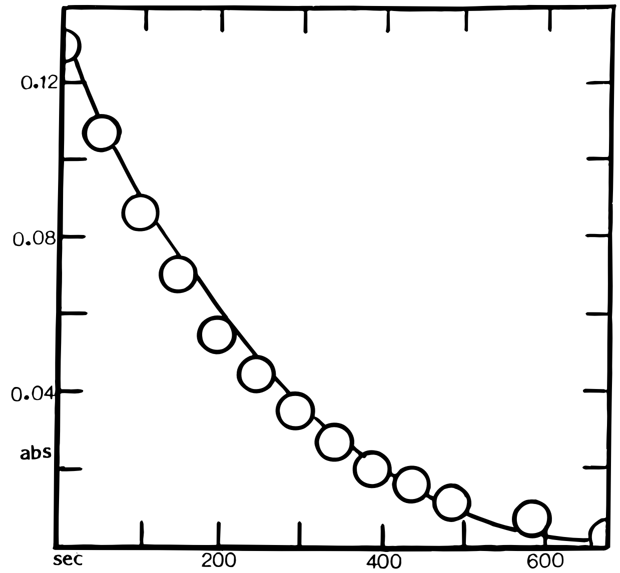

Figure 1. Kinetic profile at 572 nm for reduction of the Ni(IV) chelate of 2,6-diacetylpyridine dioximate (**II**) (1.02×10^{-5} M) with 2-aminoethanethiol (8×10^{-4} M) as catalyzed by Cu(II) (1.00×10^{-5} M) in 98:2 water/methanol at 25 °C, $[H^+] = 0.0024$ M, and $\mu = 0.018$ M (ClO_4^-). The solid line is the experimental curve whereas the circles are absorbances calculated from numerical integration of differential equations based on the sequence (2)−(10), taking parameters from Table 2. The extinction coefficient used for the Ni(IV) complex was 1.28×10^4 M^{-1} cm^{-1}, and the other species were considered to be negligibly absorbant. Optical path length = 1.00 cm.

The reported[6] ease with which metal-center 1e reductants reduce Ni(IV) indicates that the active reductant is a Cu(I) species, for this state is known to be formed readily from the reaction of Cu(II) with a variety of thiols.[10] The severity of inhibition with increasing acidity allows us to assume the operation of at least two preequilibria involving release of H^+.

The observed alteration in the nature of the decay profiles as [thiol] and $[Cu^{II}]$ are increased points to a gradual change in the rate-limiting process in the reaction sequence. At low concentrations of reductant and catalyst, rates are determined mainly by the electron transfer from Cu(I) to Ni(IV), with the reaction of thiol with Cu(II) simply controlling the steady state concentration of Cu(I). At higher values of [thiol] and [catalyst], rates become less dependent on $[Ni^{IV}]$, and the most rapid reaction in this series is seen to be zero order in this oxidant, implying that the consumption of Ni(IV) has become too rapid to be rate-determining. This relatively unusual shift in pattern

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(8) Saha, S. K.; Ghosh, M. C.; Gould, E. S. *Inorg. Chem.* **1992**, *31*, 5439.

(9) Reductions of the same Ni(IV) complex with other thiols yielded less satisfactory kinetic pictures. Reductions with cysteine were catalyzed by both Cu(II) and Fe(III), but replicate runs were not reproducible. Reductions with mercaptoacetic acid, as catalyzed by Cu(II), were rapid and exhibited nearly exponential profiles near pH 4.5, but the resulting data at various reagent concentrations did not establish a meaningful rate law.

(10) See, for example: (a) Lappin, A. G.; McAuley, A. *J. Chem. Soc., Dalton Trans.* **1978**, 1606. (b) Davis, F. J.; Gilbert, B. C.; Norman, R. O. C.; Symons, M. C. R. *J. Chem. Soc., Perkin Trans. 2* **1983**, 1763.

can occur only if the loss of Ni(IV) is more sensitive to [thiol] and [Cu^{II}] than is the generation of Cu(I). Since the latter process is subject to no kinetic saturation within the ranges examined, the implication here is that the Ni(IV)−Cu(I) reaction proceeds, at least in part, by a path leading to a second (or higher) order dependence on dissolved copper.

Data for all runs appear to be consistent with the sequence (2)−(10), in which the Cu(II)−thiol intermediates, $Cu^{II}(SRH)$ and $Cu^{II}(SRH)_2$, are presumed to feature Cu−S linkages, with

$$Cu^{II} + RSH_2^+ \overset{K_2}{\rightleftharpoons} Cu^{II}(SRH) + H^+ \qquad (2)$$

$$Cu^{II}(SRH) + RSH_2^+ \overset{K_3}{\rightleftharpoons} Cu^{II}(SRH)_2 + H^+ \qquad (3)$$

$$Cu^{II}(SRH) \overset{K_4}{\rightleftharpoons} Cu^{I} + RSH^{\bullet +} \qquad (4)$$

$$Cu^{II}(SRH)_2 \xrightarrow{k_5} Cu^{I} + RSH^{\bullet +} + RSH \qquad (5)$$

$$Cu^{I} + Ni^{IV} \overset{K_6}{\rightleftharpoons} Cu^{I}Ni^{IV} \qquad (6)$$

$$Cu^{I}Ni^{IV} \xrightarrow{k_7} Cu^{II} + Ni^{III} \qquad (7)$$

$$Cu^{I}Ni^{IV} + Cu^{I} \xrightarrow{k_8} Ni^{III} + Cu^{II} + Cu^{I} \qquad (8)$$

$$Ni^{III} + Cu^{I} \xrightarrow{k_9} Ni^{II} + Cu^{II} \qquad (9)$$

$$2RSH^{\bullet +} \xrightarrow{k_{10}} R_2S_2 + 2H^+ \qquad (10)$$

the neighboring amino group remaining protonated. The initial two ligation steps, (2) and (3), each generating H^+, are in accord with the strong inhibition, by acid, of the overall reaction and also with the increased kinetic dependence on [thiol] at greater concentrations of the latter. Of the two proposed steps, (4) and (5), which produce Cu(I), the $Cu^{II}(SRH)_2$ route competes more effectively as [thiol] is raised. Two parallel paths, (7) and (8), for reduction of Ni(IV) by Cu(I) are suggested, the second of these accounting for the higher order dependence on [catalyst].

Expression of this sequence as a series of differential equations and numerical integration using an adaptation of the program KINSIM[11] yielded the concentrations of participating species at appropriate time intervals during the course of each reaction, and incorporation of the extinction coefficient of the Ni(IV) oxidant (the only species absorbing appreciably at the wavelength chosen) yielded calculated values for the absorbance of the reaction mixture at each point.

Values of rate constants and equilibrium quotients giving optimal agreement between calculated and observed absorbances for all curves are listed in Table 2.[12] Note that the parameters describing the proposed sequence are not wholly independent. Our experiments allow us to estimate values of the products K_2K_3, K_2K_4, and K_6k_8, but not the individual parameters. The reduction, with Cu(I), of the proposed Ni(III) intermediate, (9), is assumed to be much more rapid than that of the Ni(IV) oxidant (and therefore kinetically silent) in accord with previous comparisons of the reactions of these two hypervalent states with 1e metal-center reductants.[6] The rate constant for recombination of two $RSH^{\bullet +}$ fragments, k_{10}, is taken to be slightly less than that for two $CH_3S^{\bullet}$ radicals (3×10^{10} M^{-1} s^{-1})[13] since (10) involves the interaction of two unipositive species ($^+H_3NCH_2CH_2S^{\bullet}$).[14,15] Absorbances calculated from the parameters in Table 2 are compared to a representative experimental curve in Figure 1.

Table 2. Rate Constants and Equilibrium Quotients Contributing to the Reaction of Bis(2,6-diacetylpyridine dioximato)nickel(IV) (Chelate **II**) with 2-Aminoethanethiol As Catalyzed by Cu(II)[a]

K_2K_3	6.7×10^{-7}	k_7	1×10^{-4} s^{-1}
K_2K_4	1.1×10^{-8}M	k_9	1×10^{8} M^{-1} s^{-1}
k_5	1×10^{8} s^{-1}	k_{10}	1×10^{9} M^{-1} s^{-1}
K_6k_8	3.6×10^{8} M^{-2} s^{-1}		

[a] Parameters pertain to the sequence (2)−(10) in text. Reactions were run in 98:2 water/methanol at 25 °C, $\mu = 0.018$ M ($C10_4^-$), [H^+] = 0.0010−0.0040 M, $\lambda = 572$ nm, [Ni^{IV}] = (0.94−1.17) × 10^{-5} M, [Red] = (2.0−32) × 10^{-4} M, and [Cu^{2+}] = (2.5−80) × 10^{-6} M. Values listed are those giving optimum agreement between calculated and observed absorbances for 14 runs in which concentrations of reagents and catalyst and acidity were systematically varied.

Although K_2, pertaining to the formation of $Cu^{II}(SRH)$, cannot be directly evaluated from our data, it must be small enough to allow the ratio [$Cu^{II}(SRH)$]/[Cu^{II}] to be very nearly proportional to [thiol] and inversely proportional to [H^+] within the ranges examined; i.e., there should be no approach to kinetic saturation. The largest K_2 value consistent with this constraint is about 3×10^{-2}, from which K_3 may be taken to be near 2×10^{-5}. The indicated ratio, $K_3/K_2 = 10^{-3}$, is not an unreasonable measure of the relative ease of attaching a second thiol ligand to a Cu(II) center which is already monoligated. Extension of this reasoning leads to a lower limit of 4×10^{-7} M for K_4.

The present kinetic picture is quite different from those encountered when the same combination of thiol and catalyst is used to reduce the μ-superoxo complexes of $(Co^{III})_2$, $[Co_2(O_2)(CN)_{10}]^{5-}$, and $[Co_2(O_2)(NH_3)_{10}]^{5+}$.[16,17] Because both of these binuclear species are less reactive than Ni(IV) chelate **II**, reductions of the superoxo derivatives were carried out at greater pH values (mainly in the range 4−7) where the concentrations of the deprotonated forms of the reductant, RSH and RS^-, are 10−10^4 times as great. Hence, kinetic saturation effects with respect to [reductant] and [H^+], attributable to very nearly complete ligation of Cu(II) to a Cu(II)−thiol precursor complex, do not appear in the Ni(IV) system, and dramatic inhibition of the reaction at high [thiol],[16] almost certainly stemming from partial conversion of Cu(I) to a much less reactive Cu(I)−thiol species, is likewise not observed.

The catalyzed reductions of the superoxo−$(Co^{III})_2$ complexes, like that of Ni(IV), feature progressive changes in kinetic patterns as exponential curves give way to profiles exhibiting marked linear character. With the superoxocobalt reductions, exponential decays of the oxidant are seen at relatively high concentrations of thiol and Cu(II) with linearity becoming more

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[11] Barshop, B. A.; Wrenn, R. F.; Frieden, C. *Anal. Biochem.* **1983**, *130*, 134. The original KINSIM program, for which we thank Dr. Carl Frieden, was developed for use on a VAX computer system. This was modified, using FORTRAN-77, to a "fixed-length" format and executed on an IBM 308ID system.

[12] Since the KINSIM procedure does not employ equilibrium quotients as such, these were expressed as ratios of rate constants for forward and back reactions. Typically, for K_6 (=2.9×10^3), we included k_6 as 10^9 M^{-1} s^{-1} and k_{-6} as 3.4×10^5 M^{-1} s^{-1}.

[13] (a) Graham, D. M.; Mieville, R. L.; Pallen, R. H.; Sivertz, C. *Can. J. Chem.* **1964**, *42*, 2250. (b) Burshtein, A. I.; Khudyakov, I. V.; Yakobsen, B. I. *Prog. React. Kinet.* **1984**, *13*, 221.

[14] See, for example, Espenson, J. H. *Chemical Kinetics and Reaction Mechanisms*; McGraw-Hill: New York, 1981; p 169.

[15] For evidence that a second route may be available for the destruction of the radical $RSH^{\bullet +}$, see, for example: Asmus, K.-D. *Methods Enzymol.* **1990**, *186*, 168. Such an alternate path would come into play after the rate-determining steps in the suggested sequence and should not affect the net kinetic pattern.

[16] Ghosh, S. K.; Saha, S. K.; Ghosh, M. C.; Bose, R. N.; Reed, J. W.; Gould, E. S. *Inorg. Chem.* **1992**, *31*, 3358.

[17] Ghosh, S. P.; Saha, S. K.; Bose, R. N.; Reed, J. W.; Ghosh, M. C.; Gould, E. S. *Inorg. Chem.* **1993**, *32*, 2261.

pronounced at lower, a region where rates are determined mainly by the generation of Cu(I). This type of trend, which is not unexpected for catalytic systems, is however reversed for the Ni(IV) reduction at hand, which yields linear profiles at higher [thiol] and [Cu^{II}] but exponential at low. The key to this unusual turnaround is the competition between reactions 7 and 8, which is reflected in a shift in the rate-determining step and an approach to a second-order dependence on Cu(I) as the concentration of the latter rises.

If the proposed sequence, or one closely related to it, be correct, our observations may be taken to imply the intervention of a Ni(IV)−Cu(I) species, (with Cu^+ probably bound to an oximate oxygen), which suffers partition between a unimolecular (k_7) and a bimolecular (k_8) transformation. Profiles for the present system are also consistent with a sequence in which (8) is replaced by (8′), a direct conversion of Ni(IV) to Ni(II)

$$Cu^{I}Ni^{IV} + Cu^{I} \rightarrow Ni^{II} + 2Cu^{II} \qquad (8')$$

by cooperative action of two units of Cu^I, one bound and the other external. However, in view of the marked reluctance of Ni(IV) to undergo reduction by bona fide 2e reductants,[6] we favor a path in which all redox steps are clearly 1e transactions. Nevertheless, the precise manner by which precoordination by the first Cu^I facilitates reduction by a second remains a puzzling point.

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