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Preparations of Low-Spin Tetra Cyano Iron Complexes of *N*-Benzyl-1,2-ethanediamine and Its Oxidative Dehydrogenation: Isolation of the Intermediate with Monoimine Ligand

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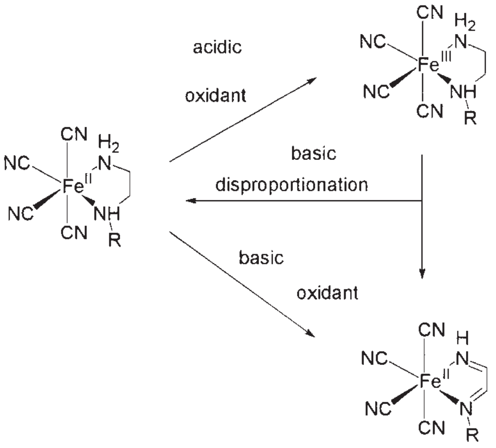
The oxidation of tetracyano(*N*-benzyl-1,2-ethanediamine) with one equivalent oxidant, hydrogen peroxide or peroxodisulfate, under neutral or basic conditions yielded tetracyano(2-benzylimino-ethylamine)ferrate(II), owing to an acceleration of disproportionation by the presence of *N*-benzyl substituents. Further oxidation yielded the corresponding conjugated 1,2-diimineferrate(II) complex.

The metal-assisted oxidation of peptides is one of the causes of damage to proteins, and is pointed out as being a plausible cause of aging.[1] The participation of iron and the lysine side chain and proline was suggested.[1] The metal-assisted oxidative dehydrogenation of amines has been extensively studied using group-18 triad, Fe,[2–7] Ru,[8–13] and Os.[14,15] The general mechanism involves the oxidation of metal ions to the high-valent state and the base-promoted disproportionation of the latter, shown in Scheme 1.[4,10,16] The amines so far employed encompass from simple amine to diamines and macrocyclic tetraamines. The secondary amine site is more susceptible to disproportionation than primary amine sites by 3000 times.[2]

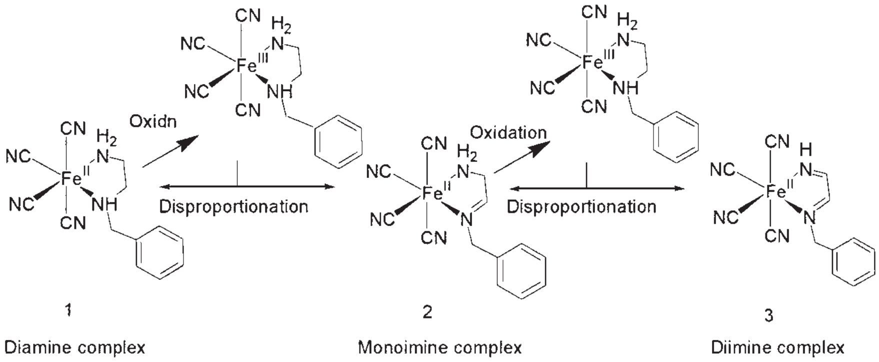
For iron complexes, there is a strong tendency to form a conjugated 1,2-diimine complex by the dehydrogenation of 1,2-diamine because of a high reactivity in the disproportionation of the presumed intermediate monoimine complex. We have reported that *N*,*N*′-dimethyl-1,2-ethanediamine, when coordinated to the tetracyanoferrate moiety, is subject about 3000 times to dehydrogenation,[4] but we could not detect or isolate the corresponding monoimine complex. In this study, *N*-benzyl-1,2-ethanediamine was employed as a ligand and in the preparation of the iron complex, **1**. Its oxidation to yield a dehydrogenated ligand including a monoimine stage, **2**, and a diimine stage, **3**, shown in Scheme 2, is described, including their isolation.

Experimental

Materials. Ferrous perchlorate hexahydrate (Alfa) was used without further purification. Diethylenetriamine (dien) and *N*-benzyl-1,2-ethanediamine (Been) was obtained from Wako. All other materials were commercially purchased and used without further purification.



Scheme 1.



Scheme 2.

$Na_2[Fe(CN)_4(Been)]$ (1). To a vigorously stirred solution of $Fe(ClO_4)_2 \cdot 6H_2O$ (14.5 g, 40 mmol) in 80 mL of anhydrous methanol, a methanol solution of Been (18.1 g, 120 mmol in 20 mL) was added, followed by an aqueous solution of NaCN (7.8 g, 160 mmol, 12 mL) at room temperature under argon. Yellow crystals were separated upon the addition of ethanol (80 mL). The mixture was kept at 0 °C for 1 h, and yellow crystals were collected by filteration and washed with acetone (30 mL) and ether (20 mL) successively. A crude product (4.0 g) was recrystallized by dissolving it in 85 mL of a mixture of water–methanol (2:8 v/v) at 50 °C, followed by filtration and the addition of 180 mL of acetonitrile. Yellow crystals. Yield, 1.74 g (37.6%). ^{1}H NMR (D_2O) δ 2.00 (m, 1H, CH_2CH_2), 2.34 (m, 2H, CH_2CH_2), 2.73 (m, 1H, CH_2CH_2), 3.70 (d, 1H, CHH), 4.30 (d, 1H, CHH), 7.30–7.40 (5H, Ph). ^{13}C NMR (D_2O, int. ref. dioxane = 67.4 ppm) δ 45.0 (C(1)), 52.0 (C(2)), 60.5 (C(3)), 130.6, 131.6, 132.1, 141.5. Anal. Calcd for $Na_2[Fe(CN)_4(Been)]$: C, 43.85; H, 3.96; N, 23.60%. Found: C, 43.08; H, 3.81; N, 23.25%.

$Na_2[Fe(CN)_4$(2-benzylimino-ethylamine = Been-2H)]$\cdot$1.5H_2O (2). **1** (557 mg, 1.6 mmol) was suspended in a mixture of water–methanol (5 mL, 2:8 in volume) and 0.78 mL of 2 M aqueous hydrogen peroxide (1.6 mmol) was added at 50 °C, resulting in a yellow solution. Yellow crystals were separated upon the addition of 15 mL of acetone and chilling in an ice bath. The yellow crystals were collected on a filter. The crude product was recrystallized by dissolving in water (1 mL) and adding acetone. Yield, 40 mg (6.6%). ^{1}H NMR (D_2O) δ 3.62 (s, methylene), 4.94 (s, benzyl), 7.18 (s, azomethine), 7.37–7.42 (Ph). ^{13}C NMR (D_2O, int. ref. dioxane = 67.4 ppm) δ 52.5 (C(1)), 67.1 (C(3)), 130.7, 131.5, 132.8, 139.6 (Ph), 171.8 (C(2)). Anal. Calcd for $Na_2[Fe(CN)_4(Been\text{-}2H)] \cdot 1.5H_2O$: C, 40.97; H, 3.97; N, 22.05%. Found: C, 40.17; H, 3.86; N, 22.07%.

$Na_2[Fe(CN)_4(Been\text{-}4H)] \cdot H_2O$ (3). To a mixture of water–methanol (6 mL, 2:8 in volume) of $Na_2[Fe(CN)_4(Been)]$ (535 mg, 1.5 mmol), 0.75 mL of an aqueous 4 M hydrogen peroxide was added at 50 °C. The resultant deep-red solution was stirred for 5 min and concentrated under reduced pressure. A red residue was dissolved in 1 mL of water and applied to the top of a Sephadex G-15 column (2.6 cm ϕ × 80 cm) and eluted with water. The fractions that showed absorption maxima at 530 nm were combined and concentrated under reduced pressure, yielding red crystals. These crystals were stored in vacuo. Yield, 167 mg (30.1%). ^{1}H NMR (D_2O) δ 5.38 (s, benzyl), 7.43 (Ph), 8.09 (s, azomethine H(2)), 8.43 (s, azomethine H(3)). ^{13}C NMR (D_2O, int. ref. dioxane = 67.4 ppm) δ 68.4 (C(3)), 130.8, 131.6, 132.6, 139.8 (Ph), 164.4 (C(1)), 168.6 (C(2)). Anal. Calcd for $Na_2[Fe(CN)_4(Been\text{-}4H)] \cdot H_2O$: C, 42.19; H, 3.27; N, 22.70%. Found: C, 42.08; H, 3.26; N, 22.34%.

Physical Measurements. Electronic spectra of the aqueous solutions of the Fe(II) complexes were recorded on a Shimadzu UV-2200 spectrophotometer. Infrared spectra were recorded on a JEOL JIR-6500 FT-IR spectrophotometer using KBr disks. The ^{1}H and ^{13}C NMR spectra of the Fe(II) complexes were measured by dissolving a weighed sample (15–20 mg) into D_2O (0.35 mL) containing sodium 3-(trimethylsilyl)propionate-*2,2,3,3-d*$_4$ as an internal standard (−0.02 ppm for ^{1}H NMR and −1.91 ppm for ^{13}C NMR) degassed by several freeze–pump–thaw cycles, followed by sealing a tube of 5 mm-diameter. The ^{1}H and ^{13}C NMR spectra were recorded on a JEOL JNM-GX-400 and a JEOL JNM-EX270 spectrometer.

Kinetic Measurements. An aqueous solution of **1** in a buffered solution (50 mM phosphate buffer, pH 5.0, 5.5, 6.0) was placed in an optical cell in a spectrophotometer kept at constant temperature (25 °C) by circulating thermostated water. A buffered aqueous solution of potassium hexacyanoferrate(III) was added to the Fe(II) solution and the change in absorbance at 525 nm was recorded. The initial velocity was obtained by $v_0 = (1/\mathcal{E}_{525}) \cdot (\Delta \mathrm{Abs}/\Delta t)_{t=0}$, where $\mathcal{E}_{525}$ is the molar absorption coefficient of **3**.

Electrochemical Measurements. Cyclic voltammetry measurements were made with a BAS Model CV-27 voltammograph and a Riken Denshi F-3EH XY recorder using a saturated Ag–AgCl electrode as a reference electrode and a glassy carbon and platinum-wire as the working and auxiliary electrodes. Measurements were made on a solution containing 10^{-3} M iron complex, using 0.1 M NaCl as a supporting electrolyte; argon was passed for 10 min prior to the measurements.

Results

Preparation of Iron(II) and Iron(III) Complexes. Complex (**1**) was prepared under argon by the successive addition of 2 equivalents of Been to form a bis(Been) complex and 4 equivalents of sodium cyanide. The dehydrogenated products of a monoimine complex (**2**) and a diimine complex (**3**) were obtained by oxidation with 1 equivalent and 2 equivalent amounts of hydrogen peroxide, respectively.

Spectroscopic Property of Iron(II) and Iron(III) Complexes. Visible spectra of **1**, **2**, and **3** in 1 mM hydrochloric acid (Fig. 1) showed weak absorptions due to d–d transitions at 395 nm and 320 nm for **1**, but intensive absorption at 354 nm with $\mathcal{E}$ of 1620 for **2**. A low-spin Fe(II) complex having monoimine bonds in a macrocyclic ligand, bis(acetonitrile)-(5,7,7,12,14,14-hexamethyl-1,4,8,11-tetraazacyclotetradeca-4,11-diene)iron(II), has been reported to have a metal → π^* transition of C=N–Fe at 361 nm with $\mathcal{E} = 2440$.[17] The characteristic Fe(II) to 1,2-diimine charge-transfer band was observed for **3** at 525 nm with $\mathcal{E}$ of 4800 as well as a band at 370 nm.

The ^{1}H NMR spectra of **1**, **2**, and **3** showed characteristic signals: for **1**, all C–H protons of the 1,2-ethanediamine moiety appeared as separated signals and benzyl protons appeared as an AB quartet at 3.70 and 4.30 ppm: for **2**, both $NH_2\text{–}C\underline{H_2}\text{–}$ and benzyl $C\underline{H_2}$ appeared as singlets at 3.62 and 4.94 ppm, and a new azomethine signal appeared at 7.18 ppm; for **3**, a benzyl proton appeared at 5.38 ppm and two azomethine pro-

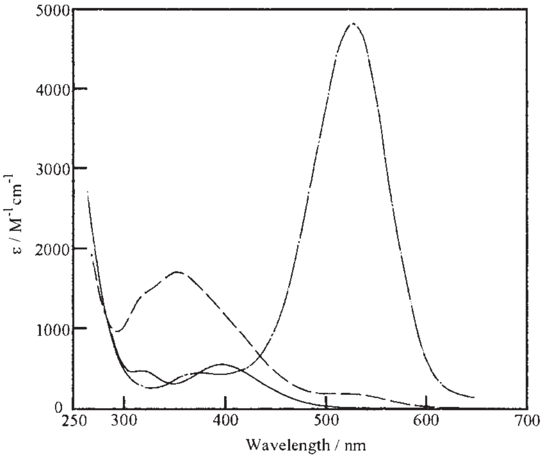


Fig. 1. Visible spectra of (**1**) (——), (**2**) (- - - -), and (**3**) (-•-•-).

tons appeared at 8.09 and 8.43 ppm. The ^{13}C NMR spectra of **1**, **2**, and **3** also showed the characteristic signals for **1**; three signals appeared at methylene carbon region, but the number decreased by 1 and 2 for **2** and **3** and one and two azomethine carbon(s) appeared in the region between 160 and 172 ppm for **2** and **3**. The ^{1}H NMR spectrum of $[Co(CN)_4(Been)]^-$, which is isoelectronic to **1**, has been reported.[18] Each signal of **1** was found to appearance upper field than that of the corresponding Co(III) complex. Based on the NMR data, we identified **2** as being an isolated product among the possible three compounds for the monoimine stage shown in Chart 1. The azomethine signal of **2** appeared at 7.18 ppm and shifted upfield compared to those of $[Fe(CN)_4(CH_3{-}N{=}CH{-}CH{=}NH)]^{2-}$ (7.53, 7.66 ppm). This upfield shift reflects that this proton locates above the intramolecular phenyl ring.

Electrochemical Property. Cyclic voltammograms of **1**, **2**, and **3** in 1 mM hydrochloric acid (I = 0.1 M NaCl) and **1** and **2** in pH 8 (borate buffer) are shown in Fig. 2. One $Fe^{2+/3+}$ quasi-reversible wave was found for each **1** through **3** under acidic conditions with increasing the $Fe^{II/III}$ redox potential in the order of **1** (0.13 V vs Ag/AgCl), **2** (0.19 V), and **3** (0.41 V), while two-step processes were found for **1** and **2** under basic conditions, and their redox potentials were 0.19 and 0.41 V, which is in agreement with the redox potentials of **2** and **3** under acidic conditions. This shows that the Fe(III) complex for **1** generated by one-electron oxidation converts rapidly to **2** and **3** under the conditions of pH 8. As expected from the kinetic measurement described below, the Fe^{III} form of **1** is not stable under basic conditions.

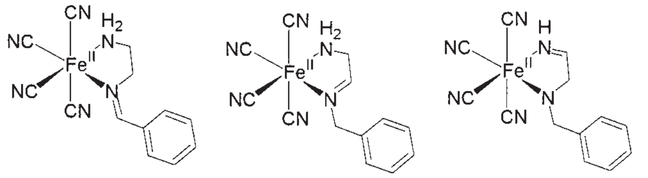


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Chart 1.

Dehydrogenation of Been Coordinated to Tetracyanoferrate(II) and (III). The oxidative dehydrogenation of diamines of tetracyano(diamine)ferrate(II) is dependent on the pH of the medium as well as the concentration and nature of the oxidant. In this study, we used N-benzyl-1,2-ethanediamine, which is a 1,2-ethanediamine substituted at one end of amines. The visible absorption spectral change of **1** upon oxidation with ammonium peroxodisulfate at pH 10.66 borate buffer (12.5 mM, I = 0.3 M (NaCl)) is shown in Fig. 3. When the concentration of ammonium peroxodisulfate was two-times that of **1**, an intermediate having an absorption maximum at 354 nm and a shoulder at 320 nm appeared, and the absorbance of this species reached a maximum at 15 min. The absorbance at 525 nm was rapidly increased along with a decrease in the absorbance at 354 nm (Fig. 3A). When one equivalent amount of ammonium peroxodisulfate was added, the increase in the absorbance at 525 nm was suppressed, and the absorbance at 354 nm increased, and no decrease was observed (Fig. 3B). These observations show that one equivalent oxidant was consumed in the dehydrogenation of **1** to yield **2**, according to

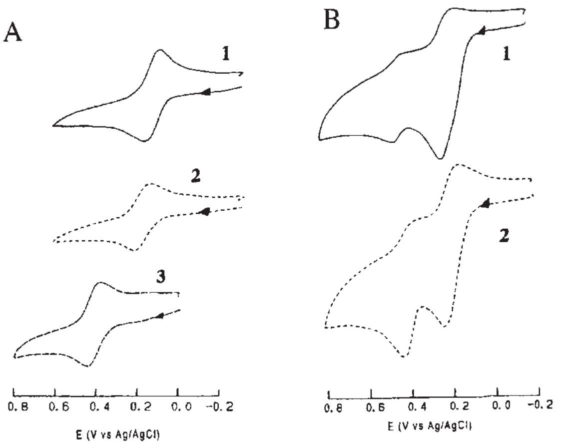

Fig. 2. Cyclic voltammograms of **1**, **2**, and **3** under acidic conditions (1 mM HCl) (A) and **1** and **2** at pH 8 (B).

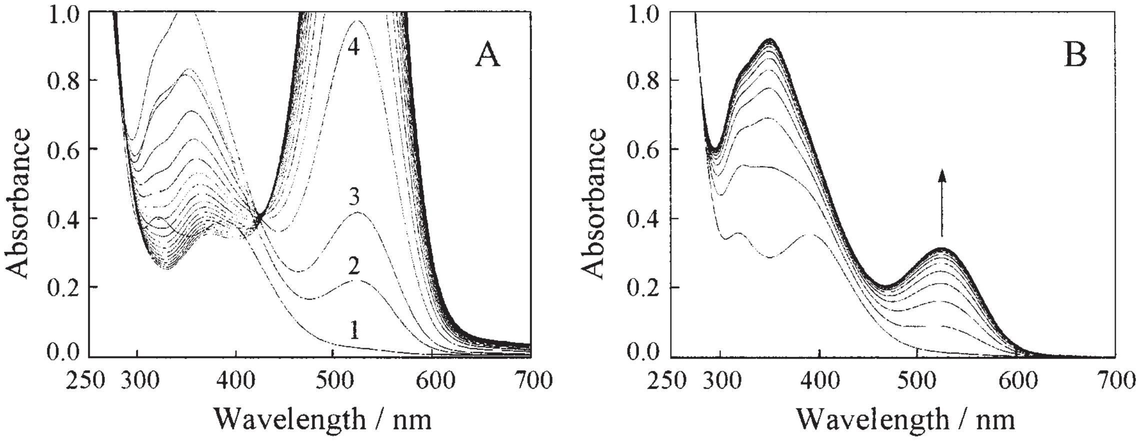

Fig. 3. (A) Spectral change for the reaction of (**1**) (0.6 mM) with $(NH_4)_2(S_2O_8)$ (1.2 mM) at pH 10.66 borate buffer, repetition period, 5 min; (B) Spectral change for the reaction of (**1**) (0.6 mM) with $(NH_4)_2(S_2O_8)$ (0.6 mM) at pH 10.66 borate buffer, repetition period, 5 min.

Table 1. Results of Kinetics of Dehydrogenation of Tetracyano(*N*-benzyl-1,2-ethanediamine)ferrate(II) **1**

pH	$\mathbf{1}/10^{-4}$ M	$[Fe(CN)_6{}^{3-}]/10^{-3}$ M	$\Delta Abs/\Delta t$ (s^{-1})	$v_0/10^{-9}$ M s^{-1}	$k_{obs}/10^3$ M^{-1} s^{-1}	$k/10^6$ M^{-2} s^{-1}
5.02	2.33	5.0	8.52	1.84	1.58	1.58
5.02	2.34	10.0	17.0	3.67	1.58	1.58
4.98	2.33	20.0	22.7	4.90	1.05	1.05
5.55	2.33	5.03	22.7	4.90	4.20	1.40
5.52	2.34	9.98	37.6	8.13	3.49	1.16
5.52	2.33	20.0	83.8	18.1	3.89	1.16
5.98	2.33	4.99	54.2	11.7	10.0	1.00
5.99	2.33	9.96	123	26.6	11.4	1.14
5.98	2.33	20.0	297	64.1	13.8	1.38

$$[Fe(CN)_4(Been)]^{2-}(1) + S_2O_8{}^{2-} \rightarrow [Fe(CN)_4(Been\text{-}2H)]^{2-}(2) + 2H^+ + 2SO_4{}^{2-}. \quad (1)$$

If the oxidant is present in two equivalents, a further oxidation of **2** to **3** proceeds smoothly under basic conditions,

$$[Fe(CN)_4(Been\text{-}2H)]^{2-}(2) + S_2O_8{}^{2-} \rightarrow [Fe(CN)_4(Been\text{-}4H)]^{2-}(3) + 2H^+ + 2SO_4{}^{2-}. \quad (2)$$

When the oxidation was carried out at pH 3.71 acetate buffer (0.2 M, $I = 0.3$ M (NaCl)), no formation of **2** and **3** was observed, and the corresponding ferrate(III) complex of **1**, which has an absorption maximum at 375 nm and a shoulder at 305 nm, were formed (data not shown).

The dehydrogenation of **2** with ammonium peroxodisulfate occurred rapidly at pH 8 borate buffer with an isosbestic point. However, under acidic conditions (1 mM hydrochloric acid), only a small amount of **3** was formed, but new species, presumably $[Fe^{III}(CN)_4(Been\text{-}2H)]^-$, which had absorptions at 405, 375, and 315 nm, were formed.

The kinetics of the formation of **3** from **1** was evaluated in the presence of excess potassium hexacyanoferrate(III) as an oxidant at pH 5.0, 5.5, and 6.0. The initial increase in the absorption at 525 nm was converted to the rate. The data of the kinetics are tabulated in Table 1. Since the initial rate is proportional to the concentration of the oxidant, the second-order rate constant (k_{obs}) was obtained using $v_0 = k_{obs}[\mathbf{1}][Fe(CN)_6{}^{3-}]_0$. Further, the pH profile of k_{obs} showed a straight line having a slope of 0.95. Therefore, the total rate equation is expressed as

$$v_0 = k[\mathbf{1}][Fe(CN)_6{}^{3-}]_0[OH^-], \quad (3)$$

and the third-order rate constant is determined to be $k = 1.3 \times 10^6$ M^{-2} s^{-1}.

Discussion

The expected intermediate of tetracyano(monoimine)-ferrate(II) has not been isolated so far using 1,2-diamines by oxidation. This is ascribed to the high susceptibility to disproportionation of the monoimine complex compared to the diamine complex. In this study, based on the fact that the methylation of aminonitrogens of 1,2-diamine caused an increase in the disproportionation by about 3000 times, benzyl substituent was chosen as the most efficient enhancer for disproportionation.

The redox potentials of **1** and **3** have similar values with typical tetracyano(diamine)ferrate(II) and tetracyano(diimine)-ferrate(II).[4] The value of the redox potential of **2** was nearer to **1** than **3**. This shows that the conjugated 1,2-diimine greatly stabilized Fe(II) state, but the stabilization by monoimine group is not large.

When **1** was oxidized with 1 equivalent of oxidant, new species were detected in the visible spectra, and this was determined to be **2**. The effect of benzyl group seems to be its strong electron-withdrawing effect. Thus, deprotonation from the CH_2-group next to the *N*-benzyl group was sufficiently enhanced to overcome an acceleration effect of the monoimine group to dehydrogenate, yielding the diimine complex. Thus, the isolation of **2** was attained by kinetic control of the reaction.

The rate of dehydrogenation of **1** to **3** was proportional to the concentration of the oxidant, and when the logarithm of the observed rate constant was plotted against pH, a straight line with a slope of about 1 was obtained. The third-order rate constant (k) was 1.3×10^6 M^{-2} s^{-1}. At a pH lower than 5.0, the spectral change showed that both **1** and **2** were oxidized at the iron center, but were not dehydrogenated. From this, the rate of oxidation of the central atom was not dependent on the pH, and base-assisted disproportionation occurred at pH values higher than 5.

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