

Reduction of *N*-Cyanomethyl Groups on a Macrocyclic Nickel(II) Complex Using Sodium Borohydride: Synthesis of a Complex Bearing Two *N*-(2-Aminoethyl) Pendant Arms

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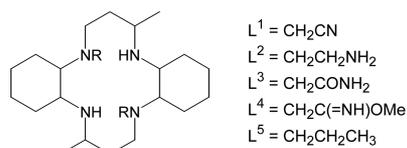
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There has been a considerable interest in the preparation of various types of aliphatic and aromatic amines, since such compounds can be important chemicals in a variety of industries.¹⁻³ Among the methods available for the synthesis of primary amines, reduction of nitriles has been utilized as a fundamental process. In general, however, this method requires relatively strong reducing agents, such as LiAlH₄ and Raney nickel, or catalytic hydrogenation and often suffers from a number of drawbacks, such as high temperature or high pressure.¹⁻³

Sodium borohydride (NaBH₄), a relatively mild reducing agent, is known to be insufficient for the reduction of nitriles to amines, unless a strong Lewis acid or a catalyst is also used.⁴ However, some works show that nitriles can be reduced by NaBH₄ when they are coordinated to a transition metal ion.^{5,6} For example, [Ru(MeCN)₃(triaris)]²⁺ (triaris = MeC(CH₂AsPh₂)₃) reacts with NaBH₄ in methanol to yield [RuH(MeCH₂NH₂)₂(triaris)]⁺.⁵ Until now, examples of borohydride reduction of nitriles to amines are limited in number, and the roles of solvents and metal ion on the reaction have remained largely unexplored.



Several groups have reported the metal-promoted reactions of *N*-(CH₂)_nCN (n = 1 or 2) pendant arms attached to polyaza macrocyclic complexes.⁷⁻¹⁴ For instance, the *N*-CH₂CN groups of [NiL¹]²⁺ react with water or methanol under mild conditions to yield [NiL³]²⁺ or [NiL⁴]²⁺ bearing two *N*-CH₂CONH₂ or *N*-CH₂C(=NH)OCH₃ pendant arms.⁷ In this work, we attempted the reduction of the *N*-CH₂CN groups on [NiL¹]²⁺ under various experimental conditions. Interestingly, [NiL¹]²⁺ reacts with NaBH₄ in the presence of methanol to form [NiL²]²⁺ bearing two *N*-CH₂CH₂NH₂ pendant arms, even though the *N*-CH₂CN groups are not involved in coordination. To the best of our knowledge, reports on the reduction of *N*-(CH₂)_nCN pendant arms attached to polyaza macrocycles using sodium borohydride are unprecedented.

Experimental

Measurements. Elemental analyses were performed at the Research Center for Instrumental Analysis, Daegu University, Gyeongsan, Korea. FAB MS spectra were performed at the Korea Basic Science Institute, Daegu, Korea. Infrared spectra were recorded with a Genesis II FT IR spectrometer, electronic absorption spectra with an Analytik Jena Specord 200 UV/Vis spectrophotometer, and NMR spectra with a Bruker WP 300 FT NMR spectrometer. Conductance measurements were performed with a Z18 Oyster Conductivity/Temperature meter. Magnetic moments were calculated from magnetic susceptibility data obtained at 293 K using a Johnson Matthey MK-1 magnetic susceptibility balance.

Caution! Perchlorate salts of metal complexes with organic ligands are often explosive and should be handled with great caution.

Preparation of [NiL²](ClO₄)₂ (L² = 2,13-bis(2-aminoethyl)-5,16-dimethyl-2,6,13,17-tetraazatricyclo-[16.4.0.0^{7,12}]-docosane). To a warm (50-60 °C) methanol-DMSO (1:3) solution (ca. 15 mL) of [NiL¹](ClO₄)₂ [Ref. 7] (1.0 g, 1.5 mmol) was added NaBH₄ (0.3 g, 8.0 mmol) in alternate small portions over 30 min with stirring. The mixture was stirred for ca. 2 h at 50-60 °C and then for ca. 12 h at room temperature. The addition of NaClO₄ (2.0 g) and water (30 mL) to the solution precipitates a purple solid. The solid collected by filtration was dissolved in minimum volume of 0.1 M HClO₄ acetonitrile-water (2:1). The resulting orange solution was filtered to remove any solid. The pH of the filtrate was adjusted to ca. 12 through the addition of 2.0 M NaOH aqueous solution. The resulting purple solution was evaporated to precipitate a purple solid. The product was collected by filtration, washed with methanol, and dried in air. Yield: ~70%. Anal. Found: C, 42.80; H, 7.71; N, 12.60. Calc. for C₂₄H₅₀N₆Cl₂NiO₈: C, 42.37; H, 7.41; N, 12.35%. FAB MS (*m/z*): 579.5 {[CuL² + ClO₄]⁺} and 479.5 {[CuL² - H]⁺}. IR (cm⁻¹): 3357 (ν_{N-H}), 3296 (ν_{N-H}), 3273 (ν_{N-H}), 3184 (ν_{N-H}), 1602 δ(NH₂), and 1100 (ν_{Cl-O}, ClO₄⁻). μ_{eff} = 2.81 μ_B at room temperature.

Preparation of [Ni(H₂L²)](ClO₄)₄. To an acetonitrile-water (2:1) suspension (20 mL) of [NiL²](ClO₄)₂ (1.0 g) was added concentrated HClO₄ (ca. 2.0 mL). The resulting orange-

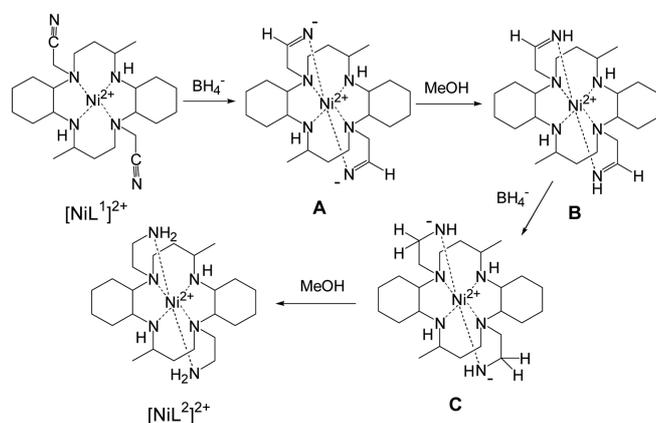
red solution was evaporated in an open beaker to precipitate an orange solid. The product was collected by filtration, washed with ethanol, and dried in air. Yield: ~80%. *Anal.* Found: C, 31.69; H, 6.01; N, 9.08. Calc. for $C_{24}H_{56}N_6Cl_4NiO_{18}$: C, 31.43; H, 6.15; N, 9.16%. IR (cm^{-1}): 3100-3350 (ν_{N-H} , *br*), 1605 ($\delta(NH_2)$), 1100 (ν_{Cl-O} , ClO_4^-). ^{13}C NMR (CD_3NO_2) δ 17.0, 25.8, 26.3, 28.7, 30.8, 31.6, 37.0, 46.6, 48.1(*d*), 59.4, 76.9 ppm.

Crystal Structure Determination. Single crystals of $[Ni(H_2L^2)](ClO_4)_4 \cdot 2H_2O \cdot 4DMSO$ suitable for X-ray study were grown from water-DMSO solution. Intensity data were collected on a Rigaku R-Axis RAPID II-S diffractometer. A total of 240 oscillation images were collected at 100 k using widths of 3° in. The raw data were processed to give structure factors using the RAPID AUTO program. The structure was solved by direct method and refined by full matrix least squares against F^2 for all data using SHELXL-97.¹⁵

Crystal and Refinement Data: $C_{32}H_{80}Cl_4N_6NiO_{22}S_4$, $M = 1229.77$, $P21/c$, $a = 12.919(3)$, $b = 15.348(2)$, $c = 13.804(2)$ Å, $\beta = 101.15(2)^\circ$, $V = 2685.4(5)$ Å³, $Z = 2$, $D_{calc} = 1.521$ g cm^{-3} , $m = 7.13$ cm^{-1} , Goodness-of-fit on $F^2 = 1.041$, Final $R_1 = 0.0743$, $wR_2 = 0.2089$ ($I > 2\sigma(I)$), $R_1 = 0.0829$, $wR_2 = 0.2175$ (all data).

Results and Discussion

Synthesis. Our initial attempts to prepare $[NiL^2]^{2+}$ bearing two $N-CH_2CH_2NH_2$ pendant arms from the reaction of $NaBH_4$ with $[NiL^1]^{2+}$ in DMSO were unsuccessful; the major product prepared in wet DMSO was found to be $[NiL^3]^{2+}$. As described in the Experimental Section, however, $[NiL^2]^{2+}$ can be prepared in high yield (~70%) by the reaction in methanol-DMSO solution. It has been suggested that methanol serves as the source of H^+ ion.⁵ Reaction of L^1 with $NaBH_4$ was also attempted under similar experimental conditions, but failed. This strongly indicates that the reduction of $[NiL^1]^{2+}$ is promoted by the central metal; the formation of coordination bonds between the functional pendant arms and the central metal in the product and/or the



Scheme 1. Reaction of $[NiL^1]^{2+}$ with $NaBH_4$ in the presence of methanol.

Table 1. Electronic absorption spectral data of the Nickel(II) complexes^a

Complex	λ_{max} , nm (ϵ , $M^{-1}cm^{-1}$)		
$[NiL^1](ClO_4)_2$ ^b	492(77)		
$[NiL^2](ClO_4)_2$	337(4.1)	517(5.0)	807(3.5)
	520(5.3) ^c	810(3.6) ^c	
	334(5.1) ^d	518(4.2) ^d	790(2.9) ^d
	330 ^e	515 ^e	770 ^e
	491(81) ^f		
$[Ni(H_2L^2)](ClO_4)_4$	365(75)	558(22)	795(3.8)
	363(48) ^c	555(21) ^c	810(4.0) ^c
	490 ^e	492(78) ^g	
	365(6.1) ^h	493(76) ^h	390 ^h
	364(48) ⁱ	552(22) ⁱ	810(3.4) ⁱ
	492(82) ^j		
$[NiL^3](ClO_4)_2$ ^k	525(6.9) ^l		
$[NiL^4](ClO_4)_2$ ^k	513(12) ^l		
$[NiL^5](PF_6)_2$ ^m	484(109) ^g	486(103) ^h	

^aIn DMSO solution at 20 °C unless otherwise specified. ^bRef. 7. ^cIn DMF. ^dIn water-DMSO (1:1). ^eIn Nujol mull. ^fIn 1.0 M $HClO_4$ water-DMSO (1:1). ^gIn nitromethane. ^hIn acetonitrile. ⁱIn water-acetonitrile (1:1). ^jIn 1.0 M $HClO_4$ water-acetonitrile (1:1). ^kRef. 7. ^lIn water. ^mRef. 16.

intermediate(s) plays an important role in the reaction. The proposed route to give $[NiL^2]^{2+}$ is shown in Scheme 1. The reaction may begin with the attack of H^- (BH_4^-) ion to the carbon atom of the nitrile group.⁵ The resultant intermediate A reacts with methanol to yield the imine complex (B). The attack of H^- to B forms C that reacts with methanol to yield $[NiL^2]^{2+}$.

The complex $[Ni(H_2L^2)](ClO_4)_4$ was prepared by the addition of excess $HClO_4$ to a solution of $[NiL^2](ClO_4)_2$.

FAB mass, infrared, and ^{13}C NMR spectra of $[NiL^2](ClO_4)_2$ and/or $[Ni(H_2L^2)](ClO_4)_4$ as well as elemental analyses are listed in the Experimental section. The magnetic moment (2.81 μ_B) of $[NiL^2](ClO_4)_2$ corresponds to a d^8 electronic configuration in high-spin octahedral coordination geometry. On the other hand, $[Ni(H_2L^2)](ClO_4)_4$ was found to be a diamagnetic substance. The electronic absorption spectra (Table 1) of $[NiL^2](ClO_4)_2$ measured in Nujol mull and various solvents show three bands at *ca.* 335, 520, and 800 nm, indicating that the pendant $N-CH_2CH_2NH_2$ groups are coordinated to the metal ion.^{7,14} The spectra of $[Ni(H_2L^2)](ClO_4)_4$ measured in nitromethane, acetonitrile, and Nujol mull show a d-d transition band at *ca.* 492 nm and are similar to those of various square-planar nickel(II) complexes such as $[NiL^1](ClO_4)_2$.⁷ However, the spectra of $[Ni(H_2L^2)](ClO_4)_4$ measured in water, DMF, and DMSO show three bands at *ca.* 364 ($\epsilon = 48-75$ $M^{-1}cm^{-1}$), 552 ($\epsilon = 21-22$ $M^{-1}cm^{-1}$), and 800 nm ($\epsilon = 3.4-3.8$ $M^{-1}cm^{-1}$); although the wavelengths and molar absorption coefficients for $[Ni(H_2L^2)](ClO_4)_4$ are different from those of $[NiL^2](ClO_4)_2$, they are comparable with those of various other octahedral nickel(II) complexes.^{7,11,14} The pH of 2.0×10^{-3} M $[Ni(H_2L^2)](ClO_4)_4$ aqueous solution was found to be *ca.* 2.8, indicating deprotonation of the pendant $N-CH_2CH_2NH_3^+$ groups. Furthermore,

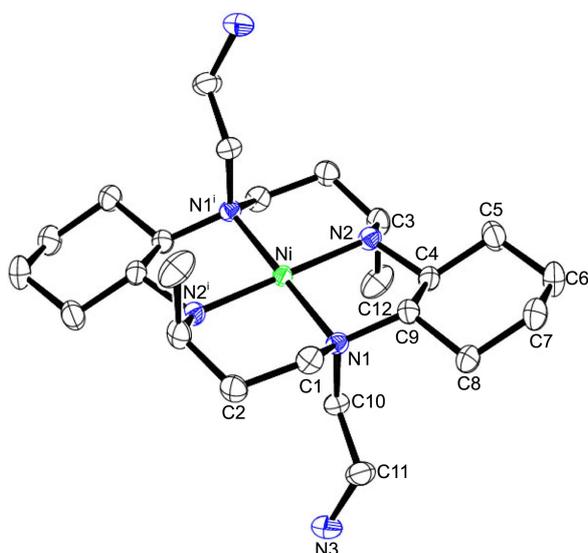


Figure 1. An ORTEP drawing of $[\text{Ni}(\text{H}_2\text{L}^2)](\text{ClO}_4)_4 \cdot 2\text{H}_2\text{O} \cdot 4\text{DMSO}$ with the atomic leveling scheme of non-hydrogen atoms with 50% probability thermal ellipsoids. Perchlorates, lattice waters and DMSO are omitted for the clarity. Symmetry transformation used to generate equivalent atoms: $i = 2-x, -y, 1-z$.

the spectrum of $[\text{Ni}(\text{H}_2\text{L}^2)](\text{ClO}_4)_4$ measured in 1.0 M HClO_4 water, DMF, or DMSO solution is quite similar to that in nitromethane or Nujol mull. Therefore, it can be suggested that $[\text{Ni}(\text{H}_2\text{L}^2)](\text{ClO}_4)_4$ dissolves in water, DMF, or DMSO to give an equilibrium mixture of the square-planar $[\text{Ni}(\text{H}_2\text{L}^2)]^{4+}$ and various types of octahedral species, such as $[\text{NiL}^2]^{2+}$, $[\text{Ni}(\text{HL}^2)\text{S}]^{3+}$ ($\text{S} = \text{water, DMSO, or DMF}$), and/or $[\text{Ni}(\text{H}_2\text{L}^2)(\text{S})_2]^{4+}$.

Crystal Structure of $[\text{Ni}(\text{H}_2\text{L}^2)](\text{ClO}_4)_4 \cdot 2\text{H}_2\text{O} \cdot 4\text{DMSO}$. An ORTEP drawing for the complex cation of $[\text{Ni}(\text{H}_2\text{L}^2)](\text{ClO}_4)_4 \cdot 2\text{H}_2\text{O} \cdot 4\text{DMSO}$ is shown in Figure 1. It shows that the complex has square-planar coordination geometry. The macrocyclic ligand adopts the *trans*-III stereochemistry. The cyclohexane rings and six-membered chelate rings have chair conformation. The *C*-methyl and *N*- $\text{CH}_2\text{CH}_2\text{NH}_3^+$ groups in a six-membered chelate ring are *anti* with respect to the plane. Selected bond distances and angles of the complex are listed in Table 2. The Ni-N(1) and Ni-N(2) distances are 1.987(3) and 1.965(3) Å, respectively. The N(1)-Ni-N(2) angle ($86.6(1)^\circ$) involved in the five-membered chelate ring is smaller than the N(1)-Ni-N(2)ⁱ angle ($93.4(1)^\circ$) involved in the six-membered chelate ring. The Ni-N di-

Table 2. Selected bond distances (Å) and angles ($^\circ$) of $[\text{Ni}(\text{H}_2\text{L}^2)](\text{ClO}_4)_4 \cdot 2\text{H}_2\text{O} \cdot 4\text{DMSO}$

Ni-N(1)	1.987(3)	Ni-N(2)	1.965(3)
C(1)-N(1)	1.504(4)	C(11)-N(3)	1.494(5)
N(1)-Ni-N(1)	180.0(1)	N(2)-Ni-N(2) ⁱ	180.0(1)
N(1)-Ni-N(2)	86.6(1)	N(1)-Ni-N(2) ⁱ	93.4(1)
Ni-N(1)-C(1)	114.3(2)	C(10)-C(11)-N(3)	108.9(3)

Symmetry code: $i = 2-x, -y, 1-z$

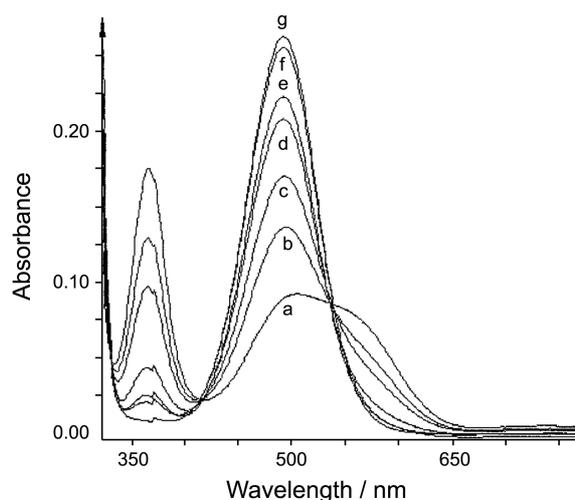


Figure 2. Electronic absorption spectra of $[\text{NiL}^2](\text{ClO}_4)_2$ (3.0×10^{-3} M) in HClO_4 water-DMSO (1:1) solutions at 25°C ; pH 7.5 (a), 4.0 (b), 3.7 (c), 3.5 (d), 3.2 (e), 3.0 (f), and 2.8 (g).

stances and N-Ni-N angles of the complex are comparable with those of various other related square-planar nickel(II) complexes, such as $[\text{NiL}^5](\text{ClO}_4)_2$.¹⁶ The C(11)-N(3) distance (1.494(5) Å) is similar to other C-N single bond distances, such as the C(1)-N(1) distance (1.504(4) Å), but is distinctly shorter than the CN distance of a *N*- CH_2CN group (*ca.* 1.27 Å) on a macrocyclic complex.⁸ The C(10)-C(11)-N(3) angle ($108.9(3)^\circ$) also shows sp^3 hybridization of the C(11) atom.

Solution Behaviors. The protonation behavior of $[\text{NiL}^2]^{2+}$ was monitored by the pH-dependant electronic absorption spectra of the complex. The addition of HClO_4 to an aqueous solution of $[\text{NiL}^2]^{2+}$ causes a two-step spectral change (Figures 2 and 3). At $\text{pH} \geq 2.8$, the decrease in pH increases the absorptions at *ca.* 365 and 560 nm (Figure 2). The absorption at 365 nm reaches maximum at $\text{pH} \sim 2.8$. At $\text{pH} \leq$

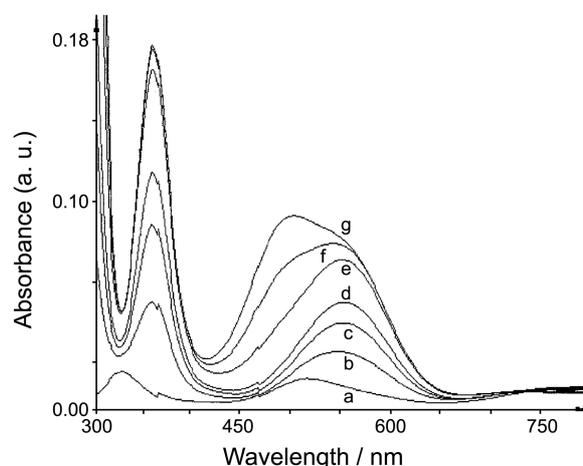
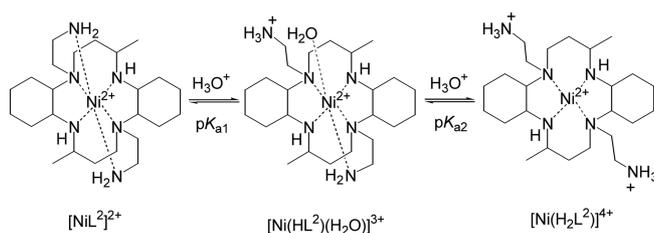


Figure 3. Electronic absorption spectra of $[\text{NiL}^2](\text{ClO}_4)_2$ (3.0×10^{-3} M) in HClO_4 water-DMSO (1:1) solutions at 25°C ; pH 2.8 (a), 2.5 (b), 2.3 (c), 2.0 (d), 1.8 (e), 1.6 (f), and $[\text{HClO}_4] = 1.0$ M (g). The spectrum measured in 2.0 M HClO_4 solution was found to be quite similar to curve g. Curve a is the same spectrum of curve g in Figure 2.



Scheme 2. Reversible two-step protonation of $[\text{NiL}^2]^{2+}$

2.8, another reversible process is observed (Figure 3); the decrease in pH decreases and increases the absorptions at *ca.* 365 and 480 nm, respectively. The spectra measured in $1.0 \geq \text{M HClO}_4$ aqueous solutions are nearly the same as those of $[\text{Ni}(\text{H}_2\text{L}^2)](\text{ClO}_4)_4$ measured in nitromethane and are not influenced significantly by the concentration of the acid. This indicates that two *N*- $\text{CH}_2\text{CH}_2\text{NH}_2$ pendant arms of the complex are completely protonated in 1.0 M HClO_4 aqueous solution. The two-step spectral change is consistent with the equilibrium (Scheme 2) involving the mono- and di-protonated species.

The stepwise protonation constants for $[\text{NiL}^2]^{2+}$ were determined by a spectrophotometric titration.¹⁷ The approximate pK_{a1} value (*ca.* 3.6) was found to be somewhat larger than the pK_{a2} value (*ca.* 2.4), as usual. The low pK_{a1} and pK_{a2} values may be result from the relatively strong interactions between the functional groups and the central metal of the complex.

In summary, NaBH_4 is an efficient reagent for the reduction of $[\text{NiL}^1]^{2+}$ in the presence of methanol, even though the *N*- CH_2CN groups are not involved in coordination. The stepwise protonation constants for $[\text{NiL}^2]^{2+}$ indicate that the pendant amino groups-central metal interactions are relatively strong.

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Supporting Information. CCDC 954016 contains the

supplementary crystallographic data for $[\text{Ni}(\text{H}_2\text{L}^2)](\text{ClO}_4)_4 \cdot 2\text{H}_2\text{O} \cdot 4\text{DMSO}$. These data can be obtained free of charge from The Cambridge Structural Data Centre *via* www.ccdc.cam.ac.uk/data_request/cif.

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