1814 Bull. Chem. Soc. Jpn., 78, 1814–1820 (2005)

μ-Hydroxo-μ-phenolato Dinuclear Nickel(II) Complexes in a Mixed-Spin State and Their Urea Adduct as Relevance to the Urease Active Site

Rie Amase, Hitomi Shiraishi, Yuji Miyasato, Masaaki Ohba,† and Hisashi Ōkawa*

Department of Chemistry, Faculty of Science, Kyushu University, Hakozaki 6-10-1, Higashi-ku, Fukuoka 812-8581

Received March 28, 2005; E-mail: okawascc@mbox.nc.kyushu-u.ac.jp

Dinucleating compartmental ligands (2,6-bis{*N*-[(2-dimethylamino)ethyl]iminomethyl}-4-methylphenol (HL^1) and 2-{*N*-[(2-dimethylamino)ethyl]iminomethyl}-6-{*N*-methyl-*N*-[2-(dimethylamino)ethyl]aminomethyl}-4-methylphenol (HL^2)) have afforded the following dinuclear nickel(II) complexes: $[Ni_2(L^1)(OH)(py)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1**), $[Ni_2(L^2)(OH)(MeOH)(H_2O)](ClO_4)_2 \cdot CH_3CN$ (**2**), and $[Ni_2(L^2)(OH)(dmf)_2](ClO_4)_2$ (**3**). X-ray crystallographic studies for **1** and **3** have clarified a μ-hydroxo-μ-phenolato dinuclear structure in a mixed-spin state with one pseudo octahedral Ni(II) ($S = 1$) and one planar Ni(II) ($S = 0$). The urea adducts, $[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1′**) and $[Ni_2(L^2)(OH)(urea)(H_2O)](ClO_4)_2$ (**2′**), were prepared by the reaction of **1** and **2** with urea, respectively, and were structurally characterized to be in the mixed-spin state. The relevance of **1′** and **2′** to urease is discussed.

Urease is a nickel-dependent enzyme that catalyzes the hydrolysis of urea to ammonium carbamate.[1] An X-ray crystallographic study on urease from *Klebsiella aerogenes* has clarified a dinuclear nickel structure bridged by a carbamoylated lysine residue in a Ni···Ni separation of 3.5 Å.[2] One nickel Ni(1) has a pseudo tetrahedral geometry with two hystidine groups, an oxygen atom of the bridging carbamate group and a water molecule; the fourth position is only partially occupied by the water molecule and is considered to be the site for accommodating urea in biological catalysis. The geometry about the other nickel Ni(2) is trigonal-bipyramidal with two hystidine groups, a water molecule, an oxygen atom of asparagine residue, and an oxygen atom of the bridging carbamate group. It must be noted that the water molecule attached to Ni(2) is situated close to Ni(1), suggesting that a μ-aqua or a μ-hydroxo dinuclear nickel(II) species is formed under physiological conditions. The generally accepted mechanism for urea hydrolysis proposed by Zerner et al.[3] involves the nucleophilic attack of hydroxide ion provided on one Ni center to the carbonyl carbon of urea accommodated on the other Ni center. Some model studies of urease have been made using dinuclear nickel(II) complexes, and urea adducts have been obtained for inspecting the urease–urea interaction.[4–12] Yamaguchi et al.[7] reported on the ethanolysis of urea by a dinuclear nickel(II) complex, but, to the best of our knowledge, the hydrolysis of urea was not effected by synthetic dinuclear nickel(II) complexes.

In the context mentioned above, μ-aqua and μ-hydroxo dinuclear nickel(II) complexes are of particular interest for modeling the active site of urease, but such complexes are still limited.[7,10,12–14] Phenol-based compartmental ligands of "end-off" type, such as 2,6-bis{*N*-[(2-dimethylamino)ethyl]iminomethyl}-4-methylphenol (HL^1) and 2-{*N*-[(2-dimethylamino)ethyl]iminomethyl}-6-{*N*-methyl-*N*-[2-(dimethylamino)ethyl]aminomethyl}-4-methylphenol (HL^2) (Fig. 1), have often been used for producing μ-X-μ-phenolato dinuclear complexes together with an endogenous bridging group, X^-. In this work, HL^1 and HL^2 were used to prepare the following dinuclear nickel(II) complexes: $[Ni_2(L^1)(OH)(py)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1**), $[Ni_2(L^2)(OH)(MeOH)(H_2O)](ClO_4)_2 \cdot CH_3CN$ (**2**), and $[Ni_2(L^2)(OH)(dmf)_2](ClO_4)_2$ (**3**). X-ray crystallographic studies for **1** and **3** have clarified a μ-hydroxo-μ-phenolato dinuclear structure in a mixed-spin state with a pseudo octahedral Ni(II) and a planar Ni(II). The reaction of **1** and **2** with urea afforded $[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1′**) and $[Ni_2(L^2)(OH)(urea)(H_2O)](ClO_4)_2$ (**2′**), respectively, both of which proved to be mixed-spin complexes with a pseudo octahedral Ni(II) and a planar Ni(II). The relevance of **1′** and **2′** to urease is discussed.

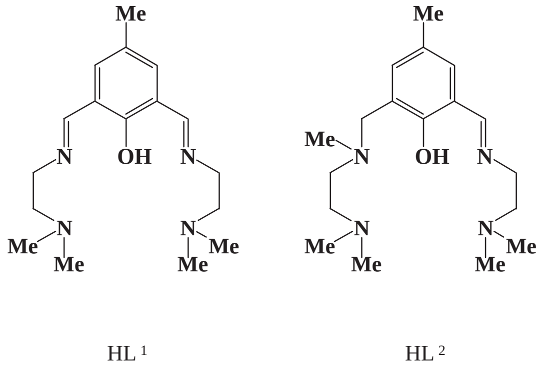


Fig. 1. Chemical structures of HL^1 and HL^2.

Experimental

Measurements. Elemental analyses of carbon, hydrogen, and nitrogen were obtained at the Service Center of Elemental Analy-

---

[†] Present address: Graduate School of Engineering, Department of Synthetic Chemistry and Biological Chemistry, Kyoto University, Katsura, Nishikyo-ku, Kyoto 615-8510

Published on the web October 4, 2005; DOI 10.1246/bcsj.78.1814

sis of Kyushu University. Analyses of Ni were performed on a Shimadzu AA-680 Atomic Absorption/Flame Emission Spectrophotometer. Infrared spectra were measured using KBr disk on a Perkin Elmer Spectrum BX FT-IR system. Electronic absorption spectra in ethanol were recorded on a Shimadzu UV-3100PC spectrophotometer. Magnetic susceptibilities on powdered sample were measured on a Quantum Design MPMS XL SQUID susceptometer.

Synthesis. 2,6-Diformyl-4-methylphenol[15] and 3-{*N*-methyl-*N*-(2-dimethylamino)ethyl}aminomethyl-5-methylsalicylaldehyde[16] were prepared by literature methods. Other chemicals were purchased from commercial sources and used without further purification.

$[Ni_2(L^1)(OH)(py)(H_2O)](ClO_4)_2 \cdot H_2O$ (1): A solution of 2,6-diformyl-4-methylphenol (164 mg, 1.0 mmol) and *N*,*N*-dimethylethylenediamine (196 mg, 2.2 mmol) in pyridine (15 cm^3) was heated at the reflux temperature for 10 min. To the resulting yellow solution were added $Ni(ClO_4)_2 \cdot 6H_2O$ (737 mg, 2.0 mmol) and triethylamine (100 mg), and the mixture was refluxed for 30 min. The reaction mixture was cooled to room temperature and diffused with 2-propanol to give green crystals. The crystals were dissolved in ethanol and the solution was slowly evaporated to afford reddish crystals. The yield was 630 mg (84.5%). Anal. Found: C, 35.58; H, 4.87; N, 9.23; Ni, 15.72%. Calcd for $C_{22}Cl_2H_{37}N_5Ni_2O_{12}$: C, 35.14; H, 4.96; N, 9.31; Ni, 15.62%. Selected IR data [ν/cm^{-1}] using KBr: 3569, 1645, 1630, 1557, 1459, 1338, 1090, 626. μ_{eff} per molecule: 2.90 μ_B at 298 K. UV–vis [λ/nm (ε/M^{-1} cm^{-1}) in ethanol: 322 (4200), 403 (6200), 480 (320).

$[Ni_2(L^2)(OH)(MeOH)(H_2O)](ClO_4)_2 \cdot CH_3CN$ (2): A solution of 3-{*N*-methyl-*N*-(2-dimethylamino)ethyl}aminomethyl-5-methylsalicylaldehyde (261 mg, 1.0 mmol) and *N*,*N*-dimethylethylenediamine (84 mg, 1.0 mmol) in acetonitrile (15 cm^3) was heated at the reflux temperature for 10 min. To this solution were added $Ni(ClO_4)_2 \cdot 6H_2O$ (737 mg, 2.0 mmol) and triethylamine (100 mg), and the mixture was refluxed for 30 min. The reaction solution was cooled to room temperature and diffused with 2-propanol to obtain orange microcrystals. The yield was 520 mg (72%). Anal. Found: C, 34.23; H, 5.85; N, 9.67; Ni, 15.71%. Calcd for $C_{21}Cl_2H_{41}N_5Ni_2O_{12}$: C, 33.91; H, 5.56; N, 9.41; Ni, 15.78%. Selected IR data [ν/cm^{-1}] using KBr: 3580, 1635, 1567, 1466, 1315, 1088, 626. μ_{eff} per molecule: 2.93 μ_B at 298 K. UV–vis [λ/nm (ε/M^{-1} cm^{-1}) in ethanol: 342 (3800), 395 (3300), 475 (230).

$[Ni_2(L^2)(OH)(dmf)_2](ClO_4)_2$ (3): This was obtained as red crystals by the recrystallization of **2** from DMF. The yield was 72%. Anal. Found: C, 36.11; H, 5.74; N, 10.57; Ni, 14.69%. Calcd for $C_{24}Cl_2H_{46}N_6Ni_2O_{12}$: C, 36.08; H, 5.80; N, 10.52; Ni, 14.92%. Selected IR data [ν/cm^{-1}] using KBr: 3559, 1655, 1635, 1566, 1467, 1316, 1087, 626. μ_{eff} per molecule: 2.91 μ_B at 298 K. UV–vis [λ/nm (ε/M^{-1} cm^{-1}) in ethanol: 337 (3900), 392 (3400), 475 (260).

$[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2 \cdot H_2O$ (1′): A solution of **1** (189 mg, 0.3 mmol) and urea (90 mg, 1.5 mmol) in ethanol (20 cm^3) was stirred at the reflux temperature for 12 h. The resulting orange solution was filtered and evaporated in open air to obtain orange crystals of **1′**. The yield was 31 mg (14%). It effloresced in open air and the analytical data were obtained for the effloresced sample. Anal. Found: C, 30.37; H, 4.85; N, 11.83; Ni, 16.60%. Calcd for $[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2$ ($=C_{18}Cl_2H_{36}N_6Ni_2O_{13}$): C, 30.33; H, 4.81; N, 11.79; Ni, 16.47%. Selected IR data [ν/cm^{-1}] using KBr: 3574, 1667, 1645, 1627, 1557, 1462, 1338, 1084, 625. μ_{eff} per molecule: 2.93 μ_B at 298 K. UV–vis [λ/nm (ε/M^{-1} cm^{-1}) in ethanol: 327 (4000), 409 (6300), 480 (290).

$[Ni_2(L^2)(OH)(urea)(H_2O)](ClO_4)_2$ (2′): This was obtained as orange crystals by the reaction of **2** with urea in ethanol. The yield was 12%. Anal. Found: C, 31.46; H, 5.25; N, 11.85; Ni, 15.73%. Calcd for $C_{19}Cl_2H_{38}N_6Ni_2O_{12}$: C, 31.22; H, 5.24; N, 11.50; Ni, 16.07%. Selected IR data [ν/cm^{-1}] using KBr: 3598, 1660, 1640, 1466, 1315, 1101, 625. μ_{eff} per molecule: 2.95 μ_B at 298 K. UV–vis [λ/nm (ε/M^{-1} cm^{-1}) in ethanol: 341 (4200), 394 (3200), 473 (270).

X-ray Crystallographic Studies. The crystal structures of $[Ni_2(L^1)(OH)(py)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1**), $[Ni_2(L^2)(OH)(dmf)_2](ClO_4)_2$ (**3**), $[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1′**), and $[Ni_2(L^2)(OH)(urea)(H_2O)](ClO_4)_2$ (**2′**) were determined by single crystal X-ray method. Measurements were made on a Rigaku MSC Mercury CCD diffractometer using graphite monochromated Mo Kα radiation ($\lambda = 0.7107$ Å) at -90 °C for **1** and **1′** and at -95 °C for **3** and **2′**. A symmetry-related absorption correction using the program ABSCOR and an empirical absorption correction based on azimuthal scans of several reflections were applied.

The structures were solved by a direct method and expanded using the Fourier technique. The non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included in the structure analysis, but not refined. All calculations were performed using the teXsan crystallographic software package of molecular Structure Corporation.[17] Pertinent crystallographic parameters are given in Table 1.

Crystallographic data have been deposited at the Cambridge Crystallographic Data Center as supplementary publication Nos. CCDC 264719–264722. Copies of the data can be obtained free of charge via http://www.ccdc.cam.ac.uk/conts/retrieving.html (or from the Cambridge Crystallographic Data Center, 12, Union Road, Cambridge, CB2 1EZ, UK; Fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk).

Results and Discussion

Synthesis and General Properties. The green crystalline product obtained by the reaction of HL^1 with $Ni(ClO_4)_2 \cdot 6H_2O$ in pyridine was shown to be $[Ni_2(L^1)(OH)(py)_2](ClO_4)_2$ with a μ-hydroxo-μ-phenolato dinuclear core in our previous study.[18] In this work, $[Ni_2(L^1)(OH)(py)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1**) was produced as red crystals when $[Ni_2(L^1)(OH)(py)_2](ClO_4)_2$ was crystallized from dichloromethane. $[Ni_2(L^2)(OH)(MeOH)(H_2O)](ClO_4)_2 \cdot CH_3CN$ (**2**) was obtained as red crystals by the reaction of HL^2 with $Ni(ClO_4)_2 \cdot 6H_2O$ in acetonitrile in the presence of triethylamine, followed by crystallization of the crude product from methanol. $[Ni_2(L^2)(OH)(dmf)_2](ClO_4)_2$ (**3**) was obtained as red crystals upon the recrystallization of **2** from DMF.

The IR spectra of **1–3** each have a sharp band at 3560–3580 cm^{-1}, characteristic of the ν(O–H) mode of bridging hydroxo group.[19,20] The two bands at 1645 and 1630 cm^{-1} of **1** may be associated with the ν(C=N) vibration of the azomethine linkage of L^1. The observation of two ν(C=N) modes suggests that the two azomethine linkages in the molecule are not equivalent. Complexes **2** and **3** display one broad ν(C=N) mode at ~1635 cm^{-1}. The IR band at 1655 cm^{-1} of **3** may be ascribed to the ν(C=O) vibration of coordinated DMF molecule. The perchlorate ion in each complex is free from co-

Table 1. Crystallographic Parameters for $[Ni_2(L^1)(OH)(py)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1**), $[Ni_2(L^2)(OH)(dmf)_2](ClO_4)_2$ (**3**), $[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1′**), and $[Ni_2(L^2)(OH)(urea)(H_2O)](ClO_4)_2$ (**2′**)

	1	**3**	**1′**	**2′**
Formula	$C_{22}H_{37}N_5Cl_2Ni_2O_{12}$	$C_{24}H_{46}N_6Cl_2Ni_2O_{12}$	$C_{18}H_{36}N_6Cl_2Ni_2O_{13}$	$C_{19}H_{38}N_6Cl_2Ni_2O_{12}$
Formula weight	751.87	798.97	732.82	730.85
Crystal system	monoclinic	triclinic	triclinic	monoclinic
Space group	$P2_1/c$ (No. 14)	$P\bar{1}$ (No. 2)	$P\bar{1}$ (No. 2)	$P2_1/c$ (No. 14)
a/Å	15.577(4)	8.442(3)	9.699(4)	12.112(1)
b/Å	10.877(3)	10.421(3)	10.319(4)	18.941(1)
c/Å	18.978(5)	20.632(6)	15.029(6)	13.014(1)
α/°		93.610(4)	87.25(1)	
β/°	108.64(1)	91.626(3)	72.71(1)	105.017(3)
γ/°		103.940(5)	77.21(1)	
V/Å^3	3049.6(1)	1756.4(1)	1400.2(1)	2883.5(1)
Z value	4	2	2	4
$D_{\rm calc}$/g cm^{-3}	1.637	1.511	1.738	1.683
μ(Mo Kα)/cm^{-1}	14.77	12.88	16.09	15.60
No. observations	6906	7711	6220	6467
R (all data)	0.071	0.082	0.076	0.052
$R1$ ($>2.0\sigma(I)$)	0.051	0.054	0.055	0.036
Rw	0.135	0.174	0.139	0.098

ordination, as judged from the ν_3 and ν_4 vibrations at ~1090 and ~625 cm^{-1}, respectively.

Complexes **1**–**3** have a magnetic moment of 2.90–2.93 $\mu_{\rm B}$ per molecule at room temperature, and the moments are practically independent of temperature. This fact means the complexes to be in the mixed-spin state with one paramagnetic Ni(II) ($S = 1$) and one diamagnetic Ni(II) ($S = 0$). Electronic absorption spectra of **1**–**3** in ethanol resemble each other and show three absorption bands at 322–337, 395–403, and 475–480 nm. The visible absorption at 475–480 nm with a moderate intensity (ε: 230–320 M^{-1} cm^{-1}) is a d–d band typical of planar diamagnetic Ni(II):[21] d–d bands due to paramagnetic Ni(II) are concealed by this band and are not resolved. An intense band at 395–403 nm is associated with the π–π^* transition of the azomethine linkage.[22,23] The intensity of this band for **1** is about two-times that for **2** and **3**, in accord with the number of azomethine groups within L^1 and L^2. The involvement of a planar Ni(II) in **1** and **3** has been demonstrated by X-ray crystallographic studies, as discussed later.

The urea adducts, $[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1′**) and $[Ni_2(L^2)(OH)(urea)(H_2O)](ClO_4)_2$ (**2′**), were obtained as orange crystals by the reaction of **1** and **2** with urea in ethanol, respectively. The involvement of urea in these complexes is inferred from an IR band at 1665–1660 cm^{-1}. The absorption spectra of **1′** and **2′** in ethanol resemble the spectra of **1** and **2**, respectively, suggesting that **1′** and **2′** are also mixed-spin complexes. In fact, **1′** and **2′** have a magnetic moment corresponding to two unpaired electrons per molecule (2.93 and 2.95 $\mu_{\rm B}$, respectively), and the moments are practically independent of temperature.

Crystal Structures. **$[Ni_2(L^1)(OH)(py)(H_2O)](ClO_4)_2 \cdot H_2O$ (1):** An ORTEP[24] view of **1** is given in Fig. 2 together with the atom numbering scheme. Selected bond distances and angles are summarized in Table 2.

Two Ni ions of **1** are bridged by the phenolic oxygen atoms of L^1 and a hydroxide oxygen atom, affording a μ-hydroxo-μ-phenolato dinuclear nickel(II) structure with a Ni···Ni interatomic separation of 2.967(1) Å. The dinuclear $\{Ni_2(L^1)(OH)\}$ core is nearly coplanar and one Ni (Ni(1)) has a six-coordinate environment together with a pyridine nitrogen atom N(5) and an aqua oxygen atom O(3) at the axial positions. The axial Ni(1)–N(5) and Ni(1)–O(3) bond distances are 2.112(3) and 2.152(2) Å, respectively, and the mean of the Ni(1)-to-donor bond distances is 2.076 Å. The other Ni (Ni(2)) has a planar geometry with short Ni(2)-to-donor distances (average: 1.879 Å). The Ni(1)–O(1)–Ni(2) and Ni(1)–O(2)–Ni(2) angles are 99.2(1)° and 98.4(1)°, respectively.

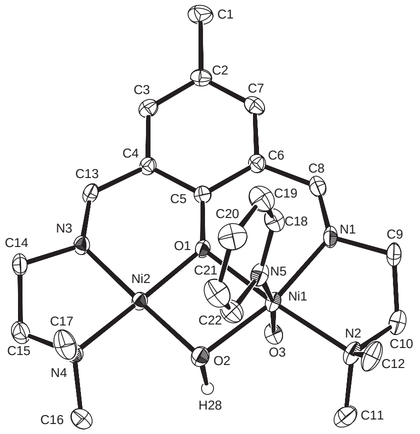


Fig. 2. An ORTEP view of $[Ni_2(L^1)(OH)(py)(H_2O)]$-$(ClO_4)_2 \cdot H_2O$ (**1**) with the atom numbering scheme.

$[Ni_2(L^2)(OH)(dmf)_2](ClO_4)_2$ (3): An ORTEP view of **3** is given in Fig. 3 together with the atom numbering scheme. Selected bond distances and angles are summarized in Table 3.

The complex cation has a μ-hydroxo-μ-phenolato dinuclear structure, similar to that of **1**, except that the ligand L^2 assumes a non-planar arrangement with out-of-plane coordination of the terminal nitrogen of the *N*-methyl-*N*-[2-(dimethylamino)ethyl]aminomethyl arm. The Ni(1) bound to this arm has a six-coordinate geometry together with two dmf mole-

Table 2. Selected Bond Distances and Angles of $[Ni_2(L^1)(OH)(py)(H_2O)](ClO_4)_2 \cdot H_2O$ (**1**)

Bond distances/Å			
Ni(1)–O(1)	2.033(2)	Ni(1)–O(2)	2.039(2)
Ni(1)–O(3)	2.152(2)	Ni(1)–N(1)	1.996(3)
Ni(1)–N(2)	2.124(3)	Ni(1)–N(5)	2.112(3)
Ni(2)–O(1)	1.860(2)	Ni(2)–O(2)	1.877(2)
Ni(2)–N(3)	1.848(3)	Ni(2)–N(4)	1.932(3)
Ni(1)···Ni(2)	2.967(1)		
Bond angles/degree			
O(1)–Ni(1)–O(2)	76.90(9)	O(1)–Ni(1)–O(3)	86.76(9)
O(1)–Ni(1)–N(1)	89.9(1)	O(1)–Ni(1)–N(2)	172.6(1)
O(1)–Ni(1)–N(5)	88.7(1)	O(2)–Ni(1)–O(3)	86.51(9)
O(2)–Ni(1)–N(1)	166.4(1)	O(2)–Ni(1)–N(2)	108.5(1)
O(2)–Ni(1)–N(5)	85.9(1)	O(3)–Ni(1)–N(1)	89.4(1)
O(3)–Ni(1)–N(2)	88.4(1)	O(3)–Ni(1)–N(5)	171.9(1)
N(1)–Ni(1)–N(2)	84.4(1)	N(1)–Ni(1)–N(5)	97.3(1)
N(2)–Ni(1)–N(5)	96.7(1)		
O(1)–Ni(2)–O(2)	85.3(1)	O(1)–Ni(2)–N(3)	93.0(1)
O(1)–Ni(2)–N(4)	175.7(1)	O(2)–Ni(2)–N(3)	178.3(1)
O(2)–Ni(2)–N(4)	94.8(1)	N(3)–Ni(2)–N(4)	86.9(1)
Ni(1)–O(1)–Ni(2)	99.2(1)	Ni(1)–O(2)–Ni(2)	98.4(1)

Table 3. Selected Bond Distances and Angles of $[Ni_2(L^2)(OH)(dmf)_2](ClO_4)_2$ (**3**)

Bond distances/Å			
Ni(1)–O(1)	2.083(2)	Ni(1)–O(2)	2.010(2)
Ni(1)–O(3)	2.080(2)	Ni(1)–O(4)	2.082(2)
Ni(1)–N(1)	2.101(2)	Ni(1)–N(2)	2.143(2)
Ni(2)–O(1)	1.865(2)	Ni(2)–O(2)	1.863(2)
Ni(2)–N(3)	1.850(2)	Ni(2)–N(4)	1.938(2)
Ni(1)···Ni(2)	2.992(1)		
Bond angles/degree			
O(1)–Ni(1)–O(2)	74.89(8)	O(1)–Ni(1)–O(3)	91.93(8)
O(1)–Ni(1)–O(4)	172.35(8)	O(1)–Ni(1)–N(1)	90.96(8)
O(1)–Ni(1)–N(2)	98.12(8)	O(2)–Ni(1)–O(3)	96.38(9)
O(2)–Ni(1)–O(4)	99.57(8)	O(2)–Ni(1)–N(1)	164.48(9)
O(2)–Ni(1)–N(2)	91.67(8)	O(3)–Ni(1)–O(4)	83.36(9)
O(3)–Ni(1)–N(1)	90.36(9)	O(3)–Ni(1)–N(2)	168.49(9)
O(4)–Ni(1)–N(1)	95.08(9)	O(4)–Ni(1)–N(2)	87.21(9)
N(1)–Ni(1)–N(2)	83.90(9)		
O(1)–Ni(2)–O(2)	83.79(8)	O(1)–Ni(2)–N(3)	94.6(1)
O(1)–Ni(2)–N(4)	177.37(9)	O(2)–Ni(2)–N(3)	176.02(9)
O(2)–Ni(2)–N(4)	94.73(9)	N(3)–Ni(2)–N(4)	86.7(1)
Ni(1)–O(1)–Ni(2)	98.37(8)	Ni(1)–O(2)–Ni(2)	101.10(9)

cules. The average of the Ni(1)-to-donor bond distances is 2.083 Å. The Ni(2) bound to the *N*-[(2-dimethylamino)ethyl]-iminomethyl arm has a planar geometry in short Ni-to-donor bond distances (average: 1.879 Å). The Ni(1)···Ni(2) interatomic separation is 2.992(1) Å and the Ni(1)–O(1)–Ni(2) and Ni(1)–O(2)–Ni(2) angles are 98.4(1)° and 101.1(1)°, respectively.

$[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2 \cdot H_2O$ (1′): An ORTEP drawing of **1′** is shown in Fig. 4 together with the atom numbering scheme. Selected bond distances and angles are summarized in Table 4.

The structure of **1′** is compared to that of **1**. The Ni(1) has a six-coordinate environment together with an aqua oxygen atom O(3) and a urea oxygen atom O(4) at the axial positions. The average Ni(1)-to-donor bond distance is 2.077 Å. The urea is bonded through its oxygen atom, O(4), in a Ni(1)–O(4) distance of 2.156(2) Å; this is common for the Ni–O (urea) bond.[6–9,11] The Ni(2) has a planar geometry with an average Ni-to-donor distance of 1.888 Å. The Ni(1)···Ni(2) interatomic separation is 2.977(1) Å and the Ni(1)–O(1)–Ni(2) and Ni(1)–O(2)–Ni(2) angles are 99.7(1)° and 99.4(1)°, respectively.

The urea is bonded to Ni(1) with a Ni(1)–O(4)–C(18) angle of 129.3(2)°. The O(4)–C(18) distance of the bound urea is 1.264(4) Å and the N(5)–C(18) and N(6)–C(18) distances are 1.328(4) and 1.355(4) Å, respectively.

$[Ni_2(L^2)(OH)(urea)(H_2O)](ClO_4)_2$ (2′): An ORTEP

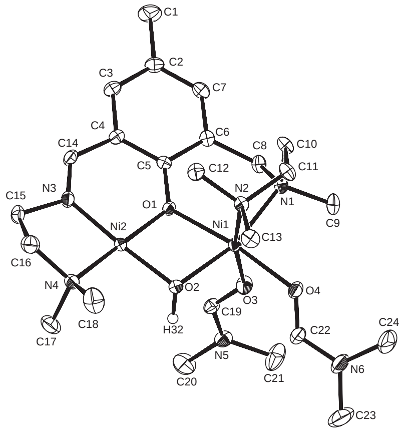


Fig. 3. An ORTEP view of $[Ni_2(L^2)(OH)(dmf)_2](ClO_4)_2$ (**3**) with the atom numbering scheme.

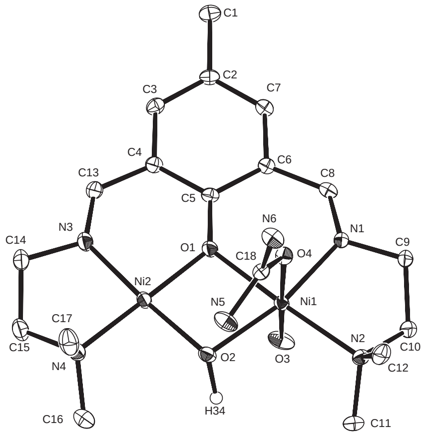


Fig. 4. An ORTEP view of $[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2\cdot H_2O$ (**1′**) with the atom numbering scheme.

Table 4. Selected Bond Distances and Angles of $[Ni_2(L^1)(OH)(urea)(H_2O)](ClO_4)_2\cdot H_2O$ (**1′**)

Bond distances/Å			
Ni(1)–O(1)	2.083(2)	Ni(1)–O(2)	2.010(2)
Ni(1)–O(1)	2.026(2)	Ni(1)–O(2)	2.013(2)
Ni(1)–O(3)	2.156(3)	Ni(1)–O(4)	2.156(2)
Ni(1)–N(1)	1.993(3)	Ni(1)–N(2)	2.116(3)
Ni(2)–O(1)	1.867(2)	Ni(2)–O(2)	1.888(2)
Ni(2)–N(3)	1.857(3)	Ni(2)–N(4)	1.937(3)
Ni(1)···Ni(2)	2.977(1)	C(18)–O(4)	1.264(4)
C(18)–N(5)	1.328(4)	C(18)–N(6)	1.355(4)
Bond angles/degree			
O(1)–Ni(1)–O(2)	74.9(1)	O(1)–Ni(1)–O(3)	91.9(1)
O(1)–Ni(1)–O(2)	76.3(1)	O(1)–Ni(1)–O(3)	87.6(1)
O(1)–Ni(1)–O(4)	89.3(1)	O(1)–Ni(1)–N(1)	90.5(1)
O(1)–Ni(1)–N(2)	174.2(1)	O(2)–Ni(1)–O(3)	90.5(1)
O(2)–Ni(1)–O(4)	94.4(1)	O(2)–Ni(1)–N(1)	167.3(1)
O(2)–Ni(1)–N(2)	107.3(1)	O(3)–Ni(1)–O(4)	173.5(1)
O(3)–Ni(1)–N(1)	87.3(1)	O(3)–Ni(1)–N(2)	88.4(1)
O(4)–Ni(1)–N(1)	87.0(1)	O(4)–Ni(1)–N(2)	94.3(1)
N(1)–Ni(1)–N(2)	85.2(1)	O(1)–Ni(2)–O(2)	84.0(1)
O(1)–Ni(2)–N(3)	93.2(1)	O(1)–Ni(2)–N(4)	176.8(1)
O(2)–Ni(2)–N(3)	175.5(1)	O(2)–Ni(2)–N(4)	95.4(1)
N(3)–Ni(2)–N(4)	87.2(1)	Ni(1)–O(1)–Ni(2)	99.7(1)
Ni(1)–O(2)–Ni(2)	99.4(1)	Ni(1)–O(4)–C(18)	129.3(2)
N(5)–C(18)–O(4)	122.1(3)	N(6)–C(18)–O(4)	120.2(3)
N(5)–C(18)–N(6)	117.7(3)		

drawing of **2′** is shown in Fig. 5 together with the atom numbering scheme. Selected bond distances and angles are summarized in Table 5.

The urea adduct, **2′**, has a μ-hydroxo-μ-phenolato dinuclear structure similar to that of **3**. The ligand L^2 assumes a non-planar arrangement with out-of-plane coordination of the terminal nitrogen of the *N*-methyl-*N*-[2-(dimethylamino)ethyl]aminomethyl arm. The Ni(1) bound to this arm has a six-coordinate geometry together with a water molecule and a urea molecule. The average of the Ni(1)-to-donor distances is 2.086 Å. The urea is bonded through its oxygen atom O(3) in the Ni(1)–O(3) distance of 2.074(2) Å. The Ni(2) bound to the *N*-[(2-dimethylamino)ethyl]iminomethyl arm has a planar geometry in short Ni(2)-to-donor distances (average: 1.878 Å). The Ni(1)···Ni(2) interatomic separation is 2.992(1) Å and the Ni(1)–O(1)–Ni(2) and Ni(1)–O(2)–Ni(2) angles are 98.9(1)° and 100.9(1)°, respectively.

The urea is bonded to Ni(1) with a Ni(1)–O(3)–C(19) angle of 131.1(1)°. The O(3)–C(19) distance of the bound urea is 1.253(3) Å and the N(5)–C(19) and N(6)–C(19) distances are 1.328(4) and 1.355(4) Å, respectively.

Relevance to Urease. The magnetic property of jack bean urease was initially interpreted in terms of an antiferromagnetic interaction between two paramagnetic Ni centers,[25] but subsequent studies have clarified a mixed-spin state with a low-spin Ni(II) and a high-spin Ni(II) without invoking a magnetically interacting dinuclear core.[26] Therefore, the urea adducts, **1′** and **2′**, are regarded as models of the native urease. Howev-

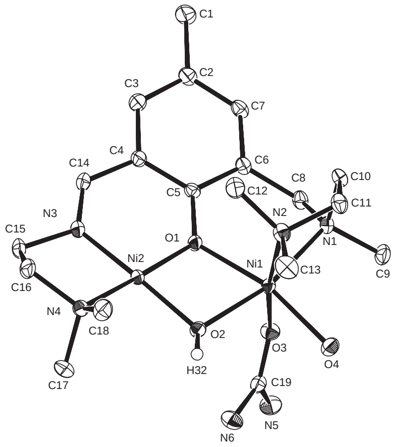


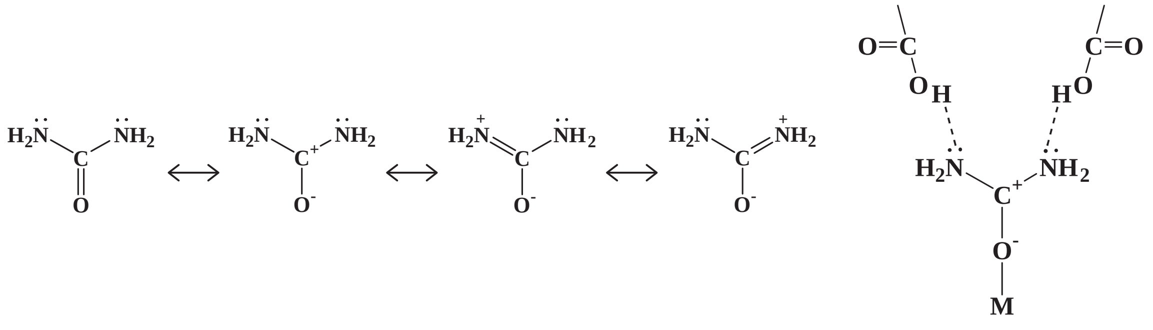
Fig. 5. An ORTEP view of $[Ni_2(L^2)(OH)(urea)(H_2O)](ClO_4)_2$ (**2′**) with the atom numbering scheme.

er, it is shown that the bound urea of **1′** and **2′** is not hydrolyzed. The inertness of urea toward hydrolysis is explained by its electronic structure in a conjunction with the lone pair of the NH_2 groups (Fig. 6a). That is, the C–O distance (1.24 Å) of free urea is elongated relative to C=O double bond (1.20 Å) whereas the C–N distance (1.35 Å) is significantly shortened relative to C–N single bond (1.47 Å). In the present urea adducts **1′** and **2′**, the C–O bond of the urea is further elongated (1.264(4) and 1.253(3) Å, respectively), whereas the C–N bond is further shortened (average distance: 1.342 and 1.340 Å, respectively), indicating a considerable double-bond character of the C–N bond.

From the results of biochemical studies, the presence of carboxyl group at the active site of jack bean urease was proposed,[3] and the crystal structural results of the urease from *Klebsiella aerogenes* demonstrates the presence of carboxyl residues (Glu^{220} and Asp^{221}) in the vicinity of Ni(2).[2] These acidic carboxyl residues from peptide can be involved in bind-

Table 5. Selected Bond Distances and Angles of $[Ni_2(L^2)(OH)(urea)(H_2O)](ClO_4)_2$ (**2′**)

Bond distances/Å			
Ni(1)–O(1)	2.067(1)	Ni(1)–O(2)	2.021(2)
Ni(1)–O(3)	2.074(2)	Ni(1)–O(4)	2.089(2)
Ni(1)–N(1)	2.106(2)	Ni(1)–N(2)	2.156(2)
Ni(2)–O(1)	1.866(1)	Ni(2)–O(2)	1.856(2)
Ni(2)–N(3)	1.843(2)	Ni(2)–N(4)	1.943(2)
Ni(1)···Ni(2)	2.992(1)	C(19)–O(3)	1.253(3)
C(19)–N(5)	1.328(4)	C(19)–N(6)	1.355(4)
Bond angles/degree			
O(1)–Ni(1)–O(2)	74.3(1)	O(1)–Ni(1)–O(3)	86.4(1)
O(1)–Ni(1)–O(4)	166.7(1)	O(1)–Ni(1)–N(1)	92.7(1)
O(1)–Ni(1)–N(2)	98.3(1)	O(2)–Ni(1)–O(3)	95.8(1)
O(2)–Ni(1)–O(4)	94.4(1)	O(2)–Ni(1)–N(1)	166.4(1)
O(2)–Ni(1)–N(2)	94.3(1)	O(3)–Ni(1)–O(4)	87.9(1)
O(3)–Ni(1)–N(1)	87.1(1)	O(3)–Ni(1)–N(2)	169.6(1)
O(4)–Ni(1)–N(1)	99.0(1)	O(4)–Ni(1)–N(2)	89.4(1)
N(1)–Ni(1)–N(2)	83.5(1)	O(1)–Ni(2)–O(2)	83.1(1)
O(1)–Ni(2)–N(3)	94.1(1)	O(1)–Ni(2)–N(4)	174.4(1)
O(2)–Ni(2)–N(3)	172.9(1)	O(2)–Ni(2)–N(4)	96.3(1)
N(3)–Ni(2)–N(4)	87.1(1)	Ni(1)–O(1)–Ni(2)	98.9(1)
Ni(1)–O(2)–Ni(2)	100.9(1)	Ni(1)–O(3)–C(19)	131.1(1)
N(5)–C(19)–O(3)	119.7(2)	N(6)–C(19)–O(3)	122.0(2)
N(5)–C(19)–N(6)	118.3(2)		



(a) (b)

Fig. 6. (a) Resonance of urea and (b) interaction of urea with carboxyl residues supposed for native urease.

ing NH_2 groups of urea (Fig. 6b), reducing the double-bond character of the C–N bond, and thence facilitating the nucleophilic attack of hydroxide ion to the carbonyl carbon of the bound urea. Such an interaction between the urea amino groups and acidic residues must be taken into consideration for modeling urease.

Previously, we[10] and Meyer et al.[12] reported on the conversion of urea into cyanate (NCO^-) on a dinuclear nickel(II) core. Apart from the hydrolysis of urea by urease, the chemical conversion of urea into NCO^- is of our particular interest in view of bimetallic catalysis. It is supposed, based on studies using *N*-substituted urea derivatives, that the bridge of ureate (H_2N–CO–NH^-) through the carbonyl oxygen and the amido nitrogen is involved in the conversion of urea into NCO^-. Such *N*,*O*-bridge of ureate has been confirmed for dinuclear nickel(II) and iron(III) complexes.[12,27] In the urea adducts **1′** and **2′**, the bound urea is not converted into NCO^-, since the planar nickel(II) hardly accepts the donation of ureate nitrogen at the axial site.

This work was supported by a Grant-in-Aid for Scientific Research (No. 07454178) from the Ministry of Education, Culture, Sports, Science and Technology.

References

1 R. P. Hausinger, "Biochemistry of Nickel," Plenum Press, New York (1993).

2 E. Jarbi, M. B. Carr, R. P. Hausinger, and P. A. Karplus, *Science*, **268**, 998 (1995).

3 N. E. Dixon, P. W. Riddles, C. Gazzola, R. L. Blakeley, and B. Zerner, *Can. J. Biochem.*, **58**, 1335 (1980).

4 a) D. Volkmer, B. Hommerich, K. Griesar, W. Haase, and B. Krebs, *Inorg. Chem.*, **35**, 3792 (1996). b) D. Volkmer, A. Hörstmann, K. Griesar, W. Haase, and B. Krebs, *Inorg. Chem.*, **35**, 1132 (1996).

5 R. M. Buchanan, M. S. Mashuta, K. J. Oberhausen, and J. F. Richardson, *J. Am. Chem. Soc.*, **111**, 4497 (1989).

6 H. E. Wages, K. L. Taft, and S. J. Lippard, *Inorg. Chem.*, **32**, 4985 (1993).

7 K. Yamaguchi, S. Koshino, F. Akagi, M. Suzuki, A. Uehara, and S. Suzuki, *J. Am. Chem. Soc.*, **119**, 5752 (1997).

8 M. Arnold, D. A. Brown, O. Deeg, W. Errington, W. Haase, K. Herlihy, T. J. Kemp, N. Nimir, and R. Werner, *Inorg. Chem.*, **37**, 2920 (1998).

9 T. Koga, H. Furutachi, H. Nakamura, N. Fukita, M. Ohba, K. Takahashi, and H. Ōkawa, *Inorg. Chem.*, **37**, 989 (1998).

10 S. Uozumi, H. Furutachi, M. Ohba, H. Ōkawa, D. E. Fenton, K. Shindo, S. Murata, and D. J. Kitko, *Inorg. Chem.*, **37**, 6281 (1998).

11 a) H. Carlsson, M. Haukke, and E. Nordlander, *Inorg. Chem.*, **41**, 4981 (2002). b) H. Carlsson, M. Haukke, A. Bousseksou, J.-M. Latour, and E. Nordlander, *Inorg. Chem.*, **43**, 8252 (2004).

12 a) F. Meyer and H. Pritzkow, *J. Chem. Soc., Chem. Commun.*, **1998**, 1555. b) F. Meyer, M. Konrad, and E. Kaifer, *Eur. J. Inorg. Chem.*, **1999**, 1851. c) S. Buchler, F. Meyer, E. Kaifer, and H. Pritzkow, *Inorg. Chim. Acta*, **337**, 371 (2002). d) S. V. Kryatow, E. V. Rybak-Akimova, F. Meyer, and H. Pritzkow, *Eur. J. Inorg. Chem.*, **2003**, 1581, and references therin.

13 P. Chaudhuri, H.-J. Kuppers, K. Wieghardt, S. Gehring, W. Haase, B. Nuber, and J. Weiss, *J. Chem. Soc., Dalton Trans.*, **1988**, 1367.

14 a) M. Ahlgrén, U. Turpeinen, and R. Hämäläinen, *Acta Chem. Scand., Ser. A*, **32**, 189 (1978). b) M. Ahlgrén and U. Turpeinen, *Acta Crystallogr., Sect. B*, **38**, 1580 (1982). c) U. Turpeinen, R. Hämäläinen, and J. Reedijk, *Polyhedron*, **6**, 1603 (1987).

15 D. A. Denton and H. Suchitzky, *J. Chem. Soc.*, **1963**, 4741.

16 J. D. Crane, D. E. Fenton, J.-M. Latour, and A. J. Smith, *J. Chem. Soc., Dalton Trans.*, **1991**, 2979.

17 "TeXsan Crystal Structure Analysis Package," Molecular Structure Corporation, Houston, TX (1985 and 1999).

18 K. Matsufuji, H. Shiraishi, Y. Miyasato, T. Shiga, M. Ohba, T. Yokoyama, and H. Ōkawa, *Bull. Chem. Soc. Jpn.*, **78**, 851 (2005).

19 K. Motoda, H. Sakiyama, N. Matsumoto, H. Ōkawa, and D. E. Fenton, *J. Chem. Soc., Dalton Trans.*, **1995**, 3419.

20 L. Borer, L. Thalken, C. Cecarelli, M. Glick, J. H. Zhang, and W. M. Reiff, *Inorg. Chem.*, **22**, 1719 (1983).

21 S. Yamada, *Coord. Chem. Rev.*, **1**, 415 (1966).

22 B. Bosnich, *J. Am. Chem. Soc.*, **90**, 627 (1968).

23 R. S. Downing and F. L. Urbach, *J. Am. Chem. Soc.*, **91**, 5977 (1969).

24 C. K. Johnson, "Report 3794, Oak Ridge National Laboratory," Oak Ridge, TN (1965).

25 P. A. Clark and D. E. Wilcox, *Inorg. Chem.*, **28**, 1326 (1989).

26 a) E. P. Day, J. Peterson, M. J. Todd, and R. P. Hausinger, *J. Inorg. Biochem.*, **36**, 305 (1989). b) E. P. Day, J. Peterson, M. S. Sendava, M. J. Todd, and R. P. Hausinger, *Inorg. Chem.*, **32**, 634 (1993).

27 a) S. V. Kryatov, A. Y. Nazarenko, P. D. Robinson, and E. V. Rybak-Akimova, *J. Chem. Soc., Chem. Commun.*, **2000**, 921. b) S. Taktak, S. V. Kryatov, and E. V. Rybak-Akimova, *Inorg. Chem.*, **42**, 7196 (2004).