Binuclear Copper(II) Chelates of Amide-Based Cyclophanes

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A chelating cyclophane has been synthesized by cyclocondensation of two ethylenediaminetetraacetic (EDTA) units with two *p*-phenylenediamine units: the resulting cyclophane is 2,9,18,25-tetraoxo-4,7,20,23-tetrakis-(carboxymethyl)-1,4,7,10,17,20,23,26-octaaza[10.10]paracyclophane, abbreviated as (bis-edtapdn)H$_4$. Cyclocondensation of two EDTA and two 1,5-diaminonaphthalene units has given the naphthalenophane, 2,9,22,29-tetraoxo-4,7,24,27-tetrakis(carboxymethyl)-1,4,7,10,21,24,27,30-octaaza[10.10](1,5)naphthalenophane, (bis-edtanap)H$_4$. Studies of electronic and EPR spectra have been carried out on the binuclear Cu^{2+} complexes of these new ligands and of related chelating cyclophanes, 2,9,25,32-tetraoxo-4,7,27,30-tetrakis(carboxymethyl)-1,4,7,10,24,-27,30,33-octaaza[10.1.10.1]paracyclophane, abbreviated as (bis-edtabpm)H$_4$, and 2,9,25,32-tetraoxo-4,7,27,30-tetrakis(carboxymethyl)-1,4,7,10,24,27,30,33-octaaza-17,40-dioxa[10.1.10.1]paracyclophane, abbreviated as (bis-edtabpe)H$_4$. Common features of these chelating cyclophanes are as follows: (1) amino, amide, and pendant carboxymethyl donor groups are substituents in the cyclophane ring, and (2) the amide groups are directly bound to the aromatic groups. These ligands formed neutral binuclear Cu^{2+} chelates [Cu$_2$L]^0 that are water-insoluble. In alkaline solutions, these Cu^{2+} complexes were converted to anionic chelates [Cu$_2$(LH$_{-4}$)]$^{4-}$ in which deprotonated amide nitrogens coordinated Cu^{2+} ions. These anionic metal chelates of (bis-edtapdn)H$_4$, (bis-edtabpm)H$_4$, and (bis-edtabpe)H$_4$ exhibited three $\pi-\pi^*$ transition bands in the spectral range 240−340 nm, in contrast to the uncoordinated cyclophanes, which showed a single band in this spectral range. The unusual $\pi-\pi^*$ transition spectra of the [Cu$_2$(LH$_{-4}$)]$^{4-}$ complexes originate from the combined effect of metal−ligand charge transfer and proximity of the π systems. The absorption and emission spectra of (bis-edtanap)H$_4$ were also influenced by coordination with copper. The EPR spectrum of [Cu$_2$(bis-edtanapH$_{-4}$)]$^{4-}$ in a methanol glass matrix showed a hyperfine structure due to the spin exchange between two Cu^{2+} ions. These unusual spectral and magnetic properties arise from the strong coordination between Cu^{2+} ions and deprotonated amide nitrogens that are bound to the π systems.

Introduction

The electronic absorption spectra of [*n.n*]paracyclophanes with $n = 1-3$ show three $\pi-\pi^*$ transition bands in the spectral range 245−320 nm, in contrast to acyclic para-substituted benzene derivatives which show a single electronic band with vibrational structure in this spectral range.[1−3] This abnormality of the spectra arises from the proximity of the two phenyl groups and the distortion of the phenyl rings, and it decreases with increasing length of the bridges between the phenyl groups;[1−4] the spectra of paracyclophanes with $n \geq 4$ are practically identical with those of acyclic *p*-dialkylbenzenes. Systematic studies of various types of macrocycles containing two aromatic groups in the ring systems have shown that the spectral properties are sensitive to the stacking mode of the aromatic systems.[5] Cyclophanes that have donor groups in the ring systems undergo ring contraction upon coordination with metal

ions.[6] When strong donor groups are appropriately arranged in a cyclophane, therefore, its metal chelate may have a $\pi-\pi$ (or transannular) interaction. The $\pi-\pi$ interaction in such a metal chelate will be pronounced when the π systems are coupled with a metal−ligand charge transfer. The coordination of copper is especially expected to be effective, because some Cu^{2+} complexes of tetraazamacrocycles that have an unsaturated ring show a strong metal−ligand charge transfer.[7−9]

We have reported that a condensation reaction between ethylenediaminetetraacetic (EDTA) dianhydride and *p*-xylene-diamine gives an anionic chelating cyclophane **1**, 3,10,21,28-tetraoxo-5,8,23,26-tetrakis(carboxymethyl)-2,5,8,11,20,23,26,29-octaaza[12.12]paracyclophane,[10] abbreviated as (bis-edtaxan)H$_4$, in which two EDTA units and two aromatic diamine units are linked by four amide bonds.[11] One of the features of this

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† Universidad de Sonora.
‡ University of Arizona.
(1) Cram, D. J.; Allinger, N. L.; Steinberg, H. *J. Am. Chem. Soc.* **1954,** *76,* 6132.
(2) Cram, D. J.; Bauer, R. H.; Allinger, N. L.; Reeves, R. A.; Wechter, W. J.; Heilbronner, E. *J. Am. Chem. Soc.* **1959,** *81,* 5977.
(3) Brown, C. J. *J. Chem. Soc.* **1953,** 3265.
(4) Tsuji, T.; Ohkita, M.; Konno, T.; Nishida, S. *J. Am. Chem. Soc.* **1997,** *119,* 8425.
(5) Haenel, M. W.; Schweitzer, D. *Adv. Chem. Ser.* **1988,** *217,* 333.

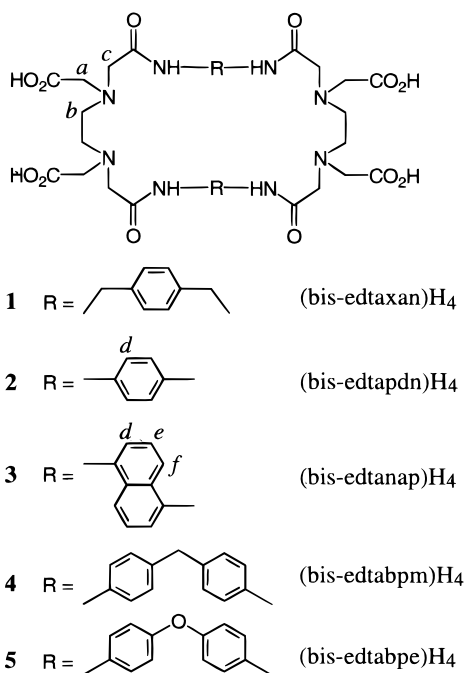(6) Baldes, R.; Schneider, H.-J. *Angew. Chem., Int. Ed. Engl.* **1995,** *34,* 321.
(7) Curtis, N. F. *Coord. Chem. Rev.* **1968,** *3,* 3.
(8) Palmer, J. M.; Papaconstantinou, E.; Endicott, J. F. *Inorg. Chem.* **1969,** *8,* 1516.
(9) Urbach, F. L. In *Coordination Chemistry of Macrocyclic Compounds*; Melson, G. A., Ed.; Plenum Press: New York, 1979; p 345.
(10) The nomenclature of cyclophanes follows Diederich: Diederich, F. *Cyclophanes*; The Royal Society of Chemistry: Cambridge, U.K., 1991.
(11) Inoue, M. B.; Medrano, F.; Inoue, M.; Raitsimring, A.; Fernando, Q. *Inorg. Chem.* **1997,** *36,* 2335.

1 R = ⟨structure⟩   (bis-edtaxan)H_4

2 R = ⟨structure, labeled *d*⟩   (bis-edtapdn)H_4

3 R = ⟨structure, labeled *d*, *e*, *f*⟩   (bis-edtanap)H_4

4 R = ⟨structure⟩   (bis-edtabpm)H_4

5 R = ⟨structure⟩   (bis-edtabpe)H_4

cyclophane is that three types of donor groups, amino, amide, and pendant carboxymethyl groups, are arranged in the ring system. An X-ray study of its Zn^{2+} complex, [Zn_2(bis-edtaxan)]^0, has demonstrated that the two phenyl groups of the chelate molecule are brought closer by the metal coordination.[11] The Cu^{2+} complex, in basic solutions, forms [Cu_2(bis-edtaxanH_{-4})]$^{4-}$, in which the amide nitrogen atoms are deprotonated and the resulting negatively charged nitrogen atoms are coordinated to the central metal ions. The $\pi-\pi*$ transition band (located at 266 nm) of this Cu^{2+} complex is stronger, by a factor of 12, than that of the uncoordinated macrocycle.[11] The effect of metal coordination on the electronic spectra in the UV region is expected to be pronounced in cyclophanes in which amide nitrogens are bound directly to the aromatic systems. In this work, therefore, we have synthesized a chelating cyclophane (**2**) and a naphthalenophane (**3**) and studied the absorption, emission, and electron paramagnetic resonance (EPR) spectra of their Cu^{2+} complexes: cyclophane **2** is 2,9,18,25-tetraoxo-4,7,20,23-tetrakis(carboxymethyl)-1,4,7,10,17,20,23,26-octaaza-[10.10]paracyclophane, abbreviated as (bis-edtapdn)H_4, and naphthalenophane **3** is 2,9,22,29-tetraoxo-4,7,24,27-tetrakis-(carboxymethyl)-1,4,7,10,21,24,27,30-octaaza[10.10](1,5)naphthalenophane, abbreviated as (bis-edtanap)H_4. Spectroscopic studies also have been carried out on the Cu^{2+} chelates of analogous cyclophanes **4** and **5**, which have four phenyl groups in the cyclophane ring system: cyclophane **4** is 2,9,-25,32-tetraoxo-4,7,27,30-tetrakis(carboxymethyl)-1,4,7,10,24,-27,30,33-octaaza[10.1.10.1]paracyclophane, abbreviated as (bis-edtabpm)H_4, and cyclophane **5** is 2,9,25,32-tetraoxo-4,7,27,30-tetrakis(carboxymethyl)-1,4,7,10,24,27,30,33-octaaza-17,40-dioxa[10.1.10.1]paracyclophane, abbreviated as (bis-edtabpe)H_4. These chelating cyclophanes form binuclear Cu^{2+} chelates with strong coordination bonds between deprotonated amide nitrogens and Cu^{2+} ions, and the resulting Cu^{2+} chelates show unusual spectroscopic properties.

Experimental Section

Synthesis of (bis-edtapdn)H_4. A dry dimethylformamide (DMF) solution (70 mL) containing 2.1 g (20 mmol) of *p*-phenylenediamine (Aldrich) was added dropwise, through a dropping funnel, to 5.0 g (20

mmol) of ethylenediaminetetraacetic (EDTA) dianhydride (Aldrich) in 250 mL of DMF with vigorous agitation over a period of 5 h. After the resulting reaction mixture was left to stand overnight, any solid formed was removed by filtration, and the filtrate was concentrated to an oil. A 30% v/v solvent of ethanol−water was added to it to separate a pale brown solid, which was washed by suspension in water. An ammoniacal solution (pH ≈ 7) of the resulting solid was acidified to pH ≈ 4, and a brown solid formed was removed by filtration. Further acidification of the filtrate to pH ≈ 3 gave a colorless solid. The solid was dissolved again in an ammoniacal solution, and the pH was adjusted to approximately 4. A brown solid, if formed, was removed by filtration. Concentration of the filtrate gave the pure product, which was suspended in dilute HCl (pH ≈ 2) so that NH_4^+ ions were completely removed. The product was washed well with water and dried in a vacuum. Yield: 10%. Anal. Calcd for $C_{32}H_{40}N_8O_{12}\cdot H_2O$: C, 51.46; H, 5.67; N, 15.01. Found: C, 51.82; H, 5.55; N, 15.07 (The elemental analyses were performed by Desert Analytics, Tucson, AZ). ^1H NMR (D_2O/Na_2CO_3, pD = 10.0, 250 MHz, referenced to DSS): δ = 2.84 (8H, s, assigned to H*b*), 3.28 (8H, s, H*a*), 3.42 (8H, s, H*c*), 7.12 (8H, s, H*d*); for labeling see formula **2**. ^{13}C NMR ($D_2O/NaOH$, pD = 10.0, 62.9 MHz, DSS): δ = 55.6 (C*b*), 61.4 and 61.8 (C*a*, C*c*), 124.7 (C*d*), 135.9 (phenyl C−N), 175.5 (CONH), 182.1 (CO$_2^-$). MS (electrospray ionization): m/z = 726.8 (14), [M − H$^+$]$^-$; 362.8 (100), [M − 2H$^+$]$^{2-}$; 241.5 (3), [M − 3H$^+$]$^{3-}$. The brown solid separated in the process of purification was characterized as a mixture of linear oligopeptides with different chain lengths; the mass spectrum did not give a definite molecular weight, and the ^1H NMR showed that the oligopeptide chains were terminated by approximately 10 units on the average.

Synthesis of (bis-edtanap)H_4. A DMF solution (70 mL) containing 3.2 g (20 mmol) of 1,5-diaminonaphthalene (Aldrich) was added to 5.0 g (20 mmol) of EDTA dianhydride in 300 mL of DMF. Any solid formed was removed by filtration, and the filtrate was concentrated to a viscous liquid. Addition of ethanol gave a pale pink solid. When the crude product was dissolved in dilute NH_3, followed by adjustment of the pH to 5 with dilute HCl, the naphthalenophane precipitated. A contaminant originating from the starting material, 1,5-diaminonaph-thalene, showed a very strong absorption band at 500 nm. The purification procedure was repeated until this band disappeared. The purified product was suspended in dilute HCl at pH ≈ 2 so that NH_4^+ ions were completely removed. The product was washed well with water and dried in a vacuum. Yield: 7%. Anal. Calcd for $C_{40}H_{44}N_8O_{12}\cdot$ H_2O: C, 56.73; H, 5.47; N, 13.23. Found: C, 56.90; H, 5.36; N, 13.22. ^1H NMR (D_2O/Na_2CO_3, pD = 10.0, 250 MHz, DSS): δ = 3.06 (8H, s, H*b*); 3.42 (8H, s, H*a*); 3.55 (8H, s, H*c*); 7.04 (4H, d × d, *J* = 8 Hz, 7 Hz, H*e*); 7.14 (4H, d, *J* = 7 Hz, H*f*); 7.46 (4H, d, *J* = 8 Hz, H*d*); for labeling see formula **3**. ^{13}C NMR ($D_2O/NaOH$, pD = 10.0, 62.9 MHz, DSS): δ = 55.7 (C*b*), 61.5 and 61.6 (C*a*, C*c*), 123.6, 125.7, and 128.3 (C*d*, C*e*, C*f*), 130.9 and 133.8 (phenyl *tert*-C), 177.1 (CONH), 181.9 (CO$_2^-$). MS (ESI): m/z = 826.9 (11), [M − H$^+$]$^-$; 412.8 (100), [M − 2H$^+$]$^{2-}$; 274.9 (5), [M − 3H$^+$]$^{3-}$.
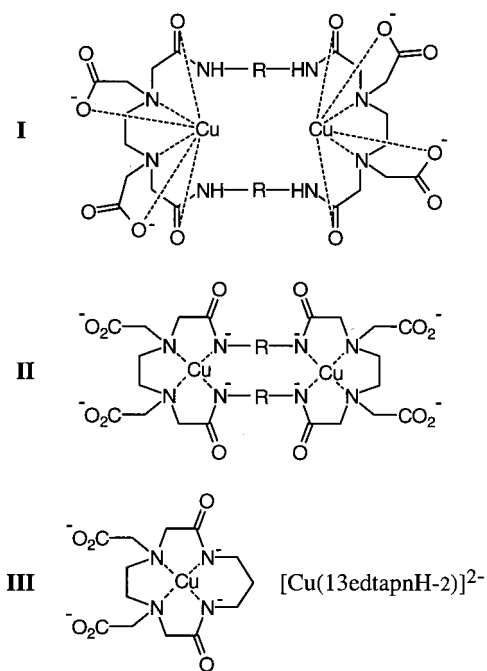
Syntheses of (bis-edtabpm)H_4 and (bis-edtabpe)H_4. These cyclophanes were synthesized by the methods reported previously.[12] The absence of impurities such as oligopeptides was confirmed by ^1H NMR.

Syntheses of Copper Complexes. An appropriate ligand was suspended in water and solubilized by adding a minimum amount of solid Na_2CO_3. When the resulting solution with pH ≤ 7 was added to an aqueous solution containing a slight excess of $CuCl_2\cdot 2H_2O$, the binuclear copper complex precipitated in an almost quantitative yield.

Anal. for [Cu_2(bis-edtapdn)]$^0\cdot 2H_2O$. Calcd for $Cu_2C_{32}H_{40}N_8O_{14}$: C, 43.29; H, 4.54; N, 12.62. Found: C, 43.46; H, 4.43; N, 12.61. MS (ESI): m/z (for $^{63}Cu-^{63}Cu$ pair) = 848.8 (55), [(Cu_2L) − H$^+$]$^-$; 423.9 (100), [(Cu_2L) − 2H$^+$]$^{2-}$.

Anal. for [Cu_2(bis-edtanap)]$^0\cdot 3H_2O$. Calcd for $Cu_2C_{40}H_{46}N_8O_{15}$: C, 47.76; H, 4.61; N, 11.14. Found: C, 47.66; H, 4.52; N, 11.18. MS (ESI): m/z ($^{63}Cu-^{63}Cu$) = 950.0 (17) [(Cu_2L) − H$^+$]$^-$; 474.0 (100), [(Cu_2L) − 2H$^+$]$^{2-}$.

(12) Inoue, M. B.; Velazquez, E. F.; Inoue, M.; Fernando, Q. *J. Chem. Soc., Perkin Trans. 2* **1997**, 2113.

Chart 1

Anal. for $[Cu_2(bis\text{-}edtabpm)]^0 \cdot 6H_2O$. Calcd for $Cu_2C_{46}H_{60}N_8O_{18}$: C, 48.46; H, 5.30; N, 9.83. Found: C, 48.35; H, 5.21; N, 9.84. MS (ESI): m/z ($^{63}Cu-^{63}Cu$) = 1030.3 (26), $[(Cu_2L) - H^+]^-$; 513.9 (100), $[(Cu_2L) - 2H^+]^{2-}$.

Anal. for $[Cu_2(bis\text{-}edtabpe)]^0 \cdot 7H_2O$. Calcd for $Cu_2C_{44}H_{58}N_8O_{21}$: C, 45.47; H, 5.03; N, 9.64. Found: C, 45.41; H, 4.49; N, 9.69. MS (ESI): m/z ($^{63}Cu-^{63}Cu$) = 516.0 (49), $[(Cu_2L) - 2H^+]^{2-}$; 343.7 (100), $[(Cu_2L) - 3H^+]^{3-}$; 257.6 (7) $[(Cu_2L) - 4H^+]^{4-}$.

Spectroscopic Measurements. The solution electronic spectra were obtained by the use of a Perkin-Elmer Lambda 2 UV−vis spectrometer. The emission spectra were recorded on a JASCO 821-FP spectrofluorometer equipped with a microcell. The pH of the sample solutions was adjusted by adding a minium amount of dilute NaOH solution or solid Na_2CO_3. The electrospray ionization (ESI) mass spectra were obtained by the use of a JEOL HX 110A spectrometer for sample solutions of an ammonia−methanol (5:95) mixture. The NMR spectra were obtained on a Bruker AM 250 spectrometer with reference to sodium 2,2-dimethyl-2-silapentane-5-sulfonate, DSS. The EPR spectra of the binuclear Cu^{2+} complex were obtained by means of a Bruker EP-300 spectrometer for 60% aqueous methanol solutions; the sample solutions were prepared by adding appropriate amounts of methanol to basic solutions (pH ≈ 10) of Cu^{2+} complexes, the final concentration of each complex being approximately 2×10^{-3} M.

Results and Discussion

Formation of the two new macrocycles, (bis-edtapdn)H_4 and (bis-edtanap)H_4, has been confirmed by ^1H NMR, ^{13}C NMR, and electrospray ionization mass spectroscopy. Reactions between $CuCl_2 \cdot 2H_2O$ and (bis-edtapdn)H_4, (bis-edtabpm)H_4, (bis-edtanap)H_4, or (bis-edtabpe)H_4 at pH ≤ 7 gave neutral Cu^{2+} complexes, $[Cu_2L]^0$. The resulting metal chelates can be assumed to have a structure of type **I** (Chart 1) in which each Cu atom is coordinated to two carboxylate oxygens, two amine nitrogens, and two amide oxygen atoms, on the basis of the X-ray structure reported for $[Zn(bis\text{-}edtaxan)]^0$ chelate;[11] one of the amide oxygen atoms may be replaced by a water oxygen atom as reported for the metal complexes of analogous dioxotetraazacycloalkanediacetic acids.[13] These Cu^{2+} complexes were practically insoluble in water, but highly soluble in alkaline

solutions. The mass spectra of ammoniacal methanol solutions of the Cu^{2+} complexes showed peaks assignable to $[(Cu_2L) - xH^+]^{x-}$ species, which can be described by $[(Cu_2LH_{-4}) + nH^+]^{n-4}$ because amide nitrogens are the only potential deprotonation sites in $[Cu_2L]^0$. This observation supports the formation of the binuclear Cu^{2+} chelates of the macrocycles. Molecular ion peaks attributable to mononuclear species $[(CuLH_{-2}) + nH^+]^{n-4}$ were not detected for the (bis-edtapdn)-H_4 complex; for the other three complexes, only a $[CuL]^{2-}$ peak was detected with an intensity of 4−9% of that of the main peak $[Cu_2L - 2H^+]^{2-}$. The binuclear chelates are, therefore, hardly dissociated in solutions to the corresponding mononuclear chelates and metal ions. $[Cu_2LH_{-4}]^{4-}$ is supposed to have a type **II** structure in which each Cu atom is bonded to two deprotonated amide nitrogens and two amino nitrogens. The coordination mode of amide groups in a dioxotetraazamacrocycle can be determined by an examination of the properties of the d−d bands: when the two amide nitrogens are deprotonated and coordinated to a Cu^{2+} ion together with the amino nitrogens, an intense d−d band is observed at $\lambda \approx 600$ nm with a molar absorptivity of the order of 200 M^{-1} cm^{-1}; when amide oxygens are coordinated, a d−d band is observed at a longer wavelength with a lower molar absorptivity ($\lambda_{max} \approx 700-800$ nm, $\epsilon_{max} \approx 50$).[11,13] The alkaline solutions of all the binuclear Cu^{2+} complexes exhibited an intense d−d band at about 650 nm with $\epsilon \approx 240-300$ M^{-1} cm^{-1} for each Cu^{2+} (the spectral data are summarized in Table 1). These observations support the formation of $[Cu_2LH_{-4}]^{4-}$ with a type **II** coordination. The d−d bands showed a red-shift accompanied by a decrease in the molar absorptivity, with decreasing pH. At lower pH, therefore, a part of the complexes of type **II** are converted to the corresponding complexes of type **I** with the coordination of amide oxygen. The conversion of amide coordination with pH has been reported for a Cu^{2+} complex **III** with dioxotetraazacyclotridecanediacetate (13edtapn)$^{2-}$ and a number of Cu^{2+} complexes with amide-based ligands.[13−25]

The uncoordinated cyclophanes showed a $\pi-\pi^*$ transition band in the spectral region 248−261 nm (footnote in Table 1), as reported for the usual benzene derivatives. Upon coordination of copper in basic solutions, however, the UV spectra were markedly changed. For example, the 261 nm band of uncoordinated (bis-edtadpn)$^{4-}$ was weakened upon coordination with Cu^{2+} ions, and new bands appeared at 242, 291, 335, and 411 nm (Table 1). Such a large spectral change was not observed in the presence of Ni^{2+} or Zn^{2+} ions; the shift of the 261 nm $\pi-\pi^*$ band was less than 5 nm at pH ≈ 9, and no new band was observed in the UV spectral region, although the molar absorptivity of the 261 nm band was decreased by approximately

(13) Inoue, M. B.; Oram, P.; Andreu-de-Riquer, G.; Inoue, M.; Borbat, P.; Raitsimring, A.; Fernando, Q. *Inorg. Chem.* **1995**, *34*, 3528.

(14) Bell, J. D.; Freeman, H. C.; Wood, A. M.; Driver, R.; Walker, W. R. *J. Chem. Soc., Chem. Commun.* **1969**, 1441.

(15) Kimura, E.; Koike, T.; Shiota, T.; Iitaka, Y. *Inorg. Chem.* **1990**, *29*, 4621.

(16) Kodama, M.; Kimura, E. *J. Chem. Soc., Dalton Trans.* **1979**, 325.

(17) Kodama, M.; Kimura, E. *J. Chem. Soc., Dalton Trans.* **1981**, 694.

(18) Kimura, E. *Tetrahedron* **1992**, *48*, 6175.

(19) Kodama, M.; Yatsunami, T.; Kimura, E. *J. Chem. Soc., Dalton Trans.* **1979**, 1783.

(20) Kimura, E.; Dalimunte, C. A.; Yamashita, A.; Machida, R. *J. Chem. Soc., Chem. Commun.* **1985**, 1041.

(21) Di Casa, M.; Fabbrizzi, L.; Perotti, A.; Poggi, A.; Tundo, P. *Inorg. Chem.* **1985**, *24*, 1610.

(22) Kimura, E. *J. Coord. Chem.* **1986**, *15*, 1.

(23) Toki, T.; Mikuriya, M.; Okawa, H.; Murase, I.; Kida, S. *Bull. Chem. Soc. Jpn.* **1984**, *57*, 2098.

(24) Hiratani, K.; Kasuga, K.; Hirose, T.; Taguchi, K.; Fujiwara, K. *Bull. Chem. Soc. Jpn.* **1992**, *65*, 2381.

(25) Zhu, S.; Kou, F.; Lin, H.; Lin, C.; Lin, M.; Chen, Y. *Inorg. Chem.* **1996**, *35*, 5851.

Table 1. Electronic Absorption ($\pi-\pi^*$ Transition, Charge Transfer, and d$-$d Transition) Bands of [Cu$_2$(LH$_{-4}$)]$^{4-}$ Complexes
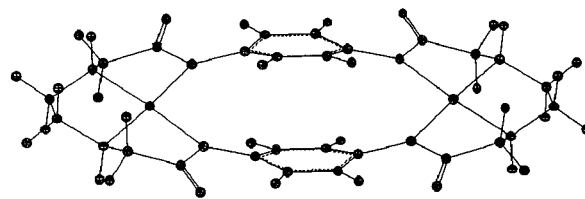
		λ/nm (log ϵ/M^{-1} cm^{-1})^a	
ligand	pH	$\pi-\pi^{*\ b,c}$ and CT bands	d$-$d band
(bis-edtapdn)H$_4$	9.3	242 (4.34), 291 (4.00), 335 (3.79), 411 (3.56)	650 (2.48)
(bis-edtabpm)H$_4$	10.0	238 (4.62), 272 (4.36), 304 (4.11), 374 (3.52)	650 (2.45)
(bis-edtabpe)H$_4$	10.0	240 (4.56), 275 (4.30), 315 (4.00), 380 (3.34)	660 (2.45)
(bis-edtanap)H$_4$	10.0	296 (4.27), 381 (3.63), 470 (3.21), 541 (2.92)	640 (2.38)
(bis-edtaxan)H$_4{}^d$	10.2	266 (3.92)	660 (2.18)
[2.2]paracyclophane^e		249sh (3.5), 284 (2.4), 302 (2.2)	

^{a} The molar absorptivity ϵ per ligand molecule is given for the $\pi-\pi^*$ and CT bands, and the ϵ value per Cu ion is given for the d$-$d band. ^{b} The $\pi-\pi^*$ bands of the uncoordinated ligands in alkaline solutions: (bis-edtapdn)H$_4$, 261 nm (log ϵ = 4.51); (bis-edtabpm)H$_4$, 248 nm (4.78); (bis-edtabpe)H$_4$, 254 nm (4.74); (bis-edtanap)H$_4$, 305 nm (4.20); (bis-edtaxan)H$_4$, 261 nm (2.86). ^{c} The absorption band of the Cu^{2+} complex in the UV spectral region at pH = 3: [Cu$_2$(bis-edtapdn)]^0, 256 nm (log ϵ = 4.84); [Cu$_2$(bis-edtabpm)]^0, 251 nm (4.74); [Cu$_2$(bis-edtabpe)]^0, 259 nm (4.56); [Cu$_2$(bis-edtaxan)]^0, 250 nm (sh, $\approx$ 3.9). The solubility of [Cu$_2$(bis-edtanap)]^0 was too low for spectroscopic measurements, below pH = 5.4; at this pH, 291 nm (4.22), 381 (3.56), 470 (3.02), 541 (2.79), 640 (2.22). ^{d} Reference 11. ^{e} References 1 and 2; an essentially identical spectrum was reported for [3.3]paracyclophane.
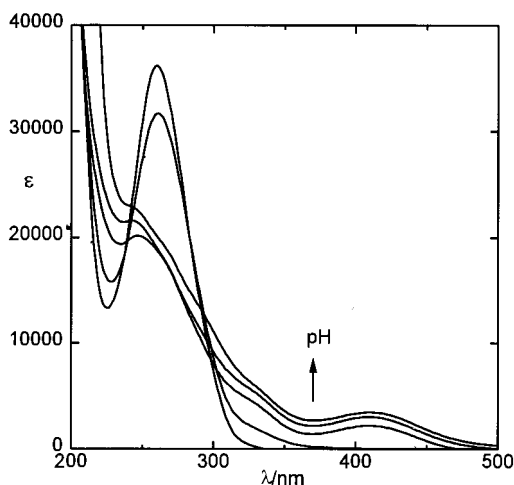
Figure 1. Solution electronic spectra of Cu$_2-$(bis-edtapdn)H$_4$ at different pH values, 4.8, 6.2, 7.5, 9.2, and 12.2.

Figure 2. A possible structure obtained for the ring system of [Cu$_2$-(bis-edtapdnH$_{-4}$)]$^{4-}$ by geometry optimization with SYBYL molecular mechanics in the program SPARTAN 4.0. The carboxymethyl arms were not included in the calculation. The structure was constrained to C_{2h} symmetry. The closest C$-$C distance between two phenyl rings is 2.6 Å, and the Cu$-$Cu distance 8.4 Å.

10% for [Ni]/[L] = 2 and 30% for [Zn]/[L] = 2. The solution spectrum of Cu$_2-$(bis-edtapdn)H$_4$ was strongly pH dependent, as shown in Figure 1. Similar characteristic properties of $\pi-\pi^*$ bands were observed for the alkaline solutions of Cu^{2+} complexes with (bis-edtabpm)H$_4$ and (bis-edtabpe)H$_4$; the spectral data are summarized in Table 1. The unusual $\pi-\pi^*$ transition bands of all the Cu$^{2+}-$cyclophane chelates studied were observed only in the pH range where [Cu$_2$(LH$_{-4}$)]$^{4-}$ species of type **II** were formed with the coordination of deprotonated amide nitrogens to copper, and they were weakened rapidly with decreasing pH at pH values around 7; at pH below 6, the spectrum was practically identical with that of the uncoordinated ligand (Figure 1).

The Cu^{2+} chelate **III** of (13edtapn)H$_2$ exhibited a well-defined absorption band at 256 nm (log ϵ/M^{-1} cm^{-1} = 3.70) at a pH of 10.3 where two amide nitrogens were coordinated to the central metal ion together with two amino nitrogens. This absorption band weakened and showed a blue shift with decreasing pH; at a pH of 4.0, where a neutral chelate, [Cu(13edtapn)]^0, was formed with the coordination of amide oxygen, only an ill-defined shoulder was observed at 240 nm (log ϵ = 3.5$_5$). The 256 nm band observed for [Cu(13edtapnH$_{-2}$)]$^{2-}$ at pH = 10.3 can be explained by a metal$-$ligand charge transfer; a back-donation occurs from a metal d orbital to a π^* orbital of the N$^-$$-C=$O system in which the N$-$C bond has a partial double bond character, and the resulting Cu$-$N$-$C$=$O conjugation gives the 256 nm band, as reported for Cu^{2+} complexes of some unsaturated tetraazamacrocycles.[7-9] The same type of charge transfer is expected to be present in the cyclophane chelates. If

the absorption band that may be caused by the Cu$-$N$-$C$=$O conjugation simply overlaps the $\pi-\pi^*$ transition band of the phenyl groups, the molar absorptivities in the 250 nm region should increase. Contrary to this simple expectation, the molar absorptivities of the cyclophane chelates in this spectral region decreased at high pH values where amide nitrogens coordinated copper. In the Cu^{2+} chelates of the cyclophanes having amide nitrogens directly bound to the phenyl groups, the π orbitals of the aromatic groups interact with the orbitals of the Cu$-$N$-$C$=$O conjugation, leading to the formation of an extended π system. The resulting extended π systems may have mutual orbital interaction when the two phenyl groups are brought closer by metal coordination. In [Cu$_2$(bis-edtapdnH$_{-4}$)]$^{4-}$, for example, two amide nitrogens on either side of an EDTA moiety coordinate a Cu^{2+} ion, and the resulting $-$N$-$Cu$-$N$-$ linkages lead to the proximity of two phenyl groups as tentatively visualized in Figure 2, which suggests a similarity of the transannular contact to that in [3.3]paracyclophane. In [$n.n$]-paracyclophanes with $n = 1-3$, the π orbitals of the two bent phenyl groups are overlapped so as to form new π molecular orbitals with a small HOMO$-$LUMO energy gap; as a result, the paracyclophanes with short bridges exhibit the characteristic absorption spectra that differ from those of acyclic p-dialkyl-benzenes.[4] The $\pi-\pi$ interaction in [Cu$_2$(bis-edtapdnH$_{-4}$)]$^{4-}$ is strong enough to influence the extended π system and result in $\pi-\pi^*$ transition bands similar to those of [3.3]paracyclophane as shown in Table 1. [Cu$_2$(bis-edtaxanH$_{-4}$)]$^{4-}$, in which two phenyl groups are bridged by two $-$CH$_2$$-N-Cu-N-CH_2$$-$ linkages, exhibited a single $\pi-\pi^*$ band at practically the same wavelength as for the uncoordinated cyclophane, although the band of the former is much more intense.[11] The quasi π system formed by the metal and amide groups in [Cu$_2$(bis-edtaxanH$_{-4}$)]$^{4-}$ is isolated from the phenyl groups by CH$_2$ groups, and the transannular interaction caused by the $-$CH$_2$$-N-Cu-N-CH_2$$-$ bridges is as weak as in [5.5]paracyclophane, which

shows a normal $\pi-\pi^*$ transition band.[1] Thus, the metal chelation effect is pronounced in the cyclophanes in which amide nitrogens are bound directly to the aromatic groups.

A freshly prepared alkaline solution of [Cu(bis-edtanap)]^0 was green and showed a number of charge-transfer bands in the 350−580 nm region in addition to the $\pi-\pi^*$ (296 nm) and d−d (640 nm) bands (Table 1). The color of the solution gradually turned to brown in a few days, and the charge-transfer bands were slightly strengthened whereas the molar absorptivities of the $\pi-\pi^*$ and d−d bands were practically unchanged. The observation of an intense d−d band suggests the formation of a [Cu$_2$(LH$_{-4}$)]$^{4-}$ type complex in which deprotonated amide nitrogens coordinate copper ions. This is supported by the observation of [(Cu$_2$L) − xH$^+$]$^{x-}$ species, or [(Cu$_2$LH$_{-4}$) + nH$^+$]$^{n-4}$ species, in the mass spectrum of an ammoniacal solution of the complex. The uncoordinated naphthalenophane showed a $\pi-\pi^*$ transition band at 305 nm at pH = 10. This band showed a blue shift and strengthened upon coordination with Cu^{2+} ions, in contrast to the Cu$_2$−cyclophane systems. The $\pi-\pi^*$ transition bands of [$n.n$]naphthalenophanes with different types of linkages show a variety of spectral patterns depending on the stacking mode of the naphthyl groups.[5] Probably, two naphthyl groups in [Cu$_2$(bis-edtanapH$_{-4}$)]$^{4-}$ are stacked in such a way that the effect of Cu^{2+} coordination does not appear explicitly in the absorption spectrum.

The naphthalenophane showed an emission band at λ_{em} = 415 nm (at the excitation wavelength λ_{ex} = 290 nm), while the emissions of the cyclophanes studied were very weak; the emission intensity (λ_{em} = 293 nm with λ_{ex} = 220 nm) of (bis-edtapdn)H$_4$, for example, was approximately one-thirtieth of that of (bis-edtanap)H$_4$ at the same concentration. In the presence of Cu^{2+} ions with [Cu]/[L] = 2, the intensity of the emission from the naphthalenophane was less than 0.01 of that from the uncoordinated ligand at pH = 10. In contrast, the coordination of Zn^{2+} ions enhanced the emission intensity: F(Zn$_2$L)/F(L) = 6.8 at pH = 8.5. The enhancement of the emission by the coordination of Zn^{2+} is caused by an increase in the rigidity of the ligand molecule upon metal coordination;[26] if the self-absorption effect is predominant, the emission should be weakened because the molar absorptivity at the excitation wavelength of 290 nm is increased by 10% in the presence of Zn^{2+} with [Zn]/[L] = 2. The self-absorption effect in the Cu^{2+} complex reduces the emission intensity, because the molar absorptivity at 290 nm is ≈20% higher than that of the uncoordinated ligand. A more dominant effect that quenches the emission in the Cu^{2+} complex is a Cu^{2+}−fluorophore charge transfer,[27] which overcomes the emission enhancement that may be caused by an increase in the molecular rigidity upon metal coordination.

Figure 3 shows the EPR spectra of [Cu$_2$(bis-edtanapH$_{-4}$)]$^{4-}$ in a basic 60% methanol solution (pH ≈ 10) at different temperatures; EPR studies in the acidic region could not be carried out owing to the low solubility of the complex. At temperatures below 150 K, where the metal chelate ions were frozen in the glass matrix, a well-defined hyperfine structure consisting of seven peaks was observed in the $g_{||}$ region. This spectral pattern was unchanged down to liquid nitrogen temperature, while the signal strengthened obeying the Curie law with decreasing temperature. At higher temperatures where the methanol matrix had melted, the signals broadened and the position of the $g_{||}$ component shifted to higher field, with

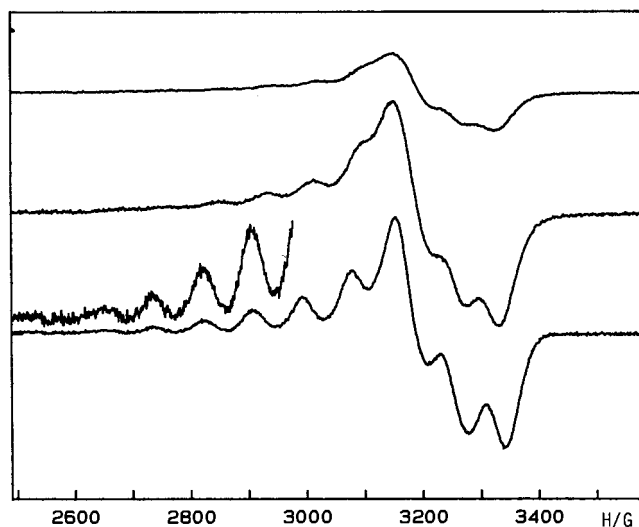**Figure 3.** EPR spectra of [Cu$_2$(bis-edtanapH$_{-4}$)]$^{4-}$ in 60% methanol (pH ≈ 10) at different temperatures: from the bottom to the top, 150, 243, and 253 K (the spectral pattern was unchanged below 150 K). The resonance frequency was 9.34463 GHz. The sample concentration was ≈2 × 10^{-3} M.

increasing temperature (Figure 3). At room temperature, the signal was centered at g = 2.09 and had no structure; the signal shape was slightly asymmetric with a maximum slope width of 140 G. A rapid molecular tumbling in solution collapses the hyperfine structure and averages out the g anisotropy. In the spectrum observed at 150 K and lower temperatures, the hyperfine structure in the $g_{||}$ region consists of seven peaks at regular intervals of 85 G, the set of the seven peaks being centered at $g_{||}$ = 2.30 (Figure 3). This hyperfine structure can be explained by assuming that two unpaired electrons, each located on a Cu^{2+} ion, are exchanged with an energy larger than the hyperfine coupling energy; in such a case each unpaired electron ($S = {}^1/_2$) couples with the two Cu nuclei ($I_{Cu} = {}^3/_2$) in an equivalent manner, and the hyperfine structure consists of seven lines due to the coupling ($A_{||}$/2)$S{\cdot}I$ where I = 3 and $A_{||}$ is the electron spin−nuclear spin coupling constant of a Cu^{2+} ion.[28−30] The coupling constant $A_{||}$ = 2 × 85 G is in the range observed for common Cu^{2+} complexes.[31] The g anisotropy was not averaged out by the spin exchange at the temperatures where the hyperfine structure was clearly observed. The exchange energy is, therefore, between the energy of the $S{\cdot}I$ coupling (170 G, 3 × 10^{-25} J) and that corresponding to the difference between the g components, |$H(g_{||}) − H(g_{\perp})$| ≈ 300 G (5 × 10^{-25} J). The Cu−Cu distance in [Cu$_2$(bis-edtanapH$_{-4}$)]$^{4-}$ is approximated to be 8.9 Å by SYBYL molecular mechanics in the program SPARTAN. This distance yields a dipolar field μ/r^3 of 25 G. This dipolar interaction energy is much smaller than the spin-exchange energy, 170−300 G, predicted from the EPR data. The difference can be attributed to superexchange interaction that is operative between Cu^{2+} ions through the π electron systems of the bridging naphthyl groups, in a mechanism similar to that reported for Cu^{2+} complexes with bridging nitrogen

(26) Krasovitskii, B. M.; Bolotin, B. M. *Organic Luminescent Materials*; Vopian, V. G., Translator; VCH: Weinheim, Germany, 1988; p 13.
(27) Fabbrizzi, L.; Poggi, A. *Chem. Soc. Rev.* **1995**, *24*, 197.

(28) Kokoszka, G. F.; Allen, H. C., Jr.; Gordon, G. *J. Chem. Phys.* **1965**, *42*, 3693.
(29) Bubnov, N. N.; Solodovnikov, S. P. In *Modern Physics in Chemistry*; Fluck, E., Goldanskii, V. I., Eds.; Academic Press: London, 1976; Vol. 1, p 53.
(30) Forrester, A. R.; Hay, J. M.; Thomson, R. H. *Organic Chemistry of Stable Free Radicals*; Academic Press: New York, 1968; p 233.
(31) Goodman, B. A.; Raynor, J. B. In *Advances in Inorganic Chemistry and Radiochemistry*; Eméleus, H. J., Sharpe, A. G., Eds.; Academic Press: New York, 1970; Vol. 12, p 313.

heterocyclic ligands.[32−35] [Cu$_2$(bis-edtabpmH$_{−4}$)]$^{4−}$ and [Cu$_2$-(bis-edtabpeH$_{−4}$)]$^{4−}$ in basic glass matrixes (pH ≈ 10) at liquid nitrogen temperature showed normal EPR spectra with hyperfine structures that could be explained by $A_{||}S\cdot I$ with $I = \frac{3}{2}$; no exchange spin interaction is operative between Cu^{2+} ions in these binuclear chelates. The EPR spectrum of [Cu$_2$(bis-edtapdnH$_{−4}$)]$^{4−}$ in a glass matrix (pH ≈ 10, T ≈ 80 K) showed seven peaks in the $g_{||}$ region (the spectrum has been deposited as Supporting Information). The irregular intervals between the peaks suggest that the spin-exchange interaction energy was comparable to the energy of the hyperfine coupling constant.[29,30] The spin interaction is weaker than that in [Cu$_2$(bis-edtanapH$_{−4}$)]$^{4−}$, although the Cu−Cu distance is shorter than

that in the latter complex; the molecular mechanics calculations gave a Cu−Cu distance of 8.4 Å ($\mu/r^3 = 30$ G). Superexchange interaction through a bridging naphthyl group is expected to be stronger than that through a phenyl group owing to the higher π conjugation in the former.

In conclusion, the new series of chelating cyclophanes form binuclear Cu^{2+} complexes that show the spectral properties due to the conjugation of the metal−amide bonds with aromatic groups. This coordination effect is related to (1) the formation of strong coordination bonds between the negatively charged amide nitrogens and Cu^{2+} ions and (2) the amide groups that are bound directly to the aromatic systems of the ligands.

(32) Hatfield, W. E. In *Theory and Applications of Molecular Paramagnetism*; Boudreaux, E. A., Mulay, L. N., Eds.; John Wiley: New York, 1976; p 349.
(33) Losee, D. B.; Richardson, H. W.; Hatfield, W. E. *J. Chem. Phys.* **1973**, *59*, 3600.
(34) Inoue, M.; Kubo, M. *Coord. Chem. Rev.* **1976**, *21*, 1.
(35) Inoue, M. *J. Magn. Reson.* **1977**, *27*, 159.