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Photoregulated Ion-binding to Azobenzene-linked Ethylenediamines and Iminodiacetic Acids[1)]

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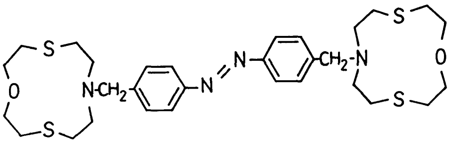
New photoresponsive complexones bearing two iminodiacetic acid units or ethylenediamine units at the two sides of an azobenzene through CH_2 or $(CH_2)_2$ (AzoIDA(n=1,2) and AzoED(n=1,2), respectively) have been synthesized. The CH_2 and $(CH_2)_2$ spacers were selected in order to examine the influence of the spacer length on the intramolecular cooperativity for the two ligands in the cis-isomers to coordinate to one metal ion. The thermal cis-to-trans isomerization of AzoIDA was efficiently suppressed by Zn(II) and Cu(II) while that of AzoED was suppressed only by Cu(II). The rate suppression supports the formation of the intramolecular chelate complexes with the metal ion. The measurements of ESR spectra of the cis-isomer·Cu(II) complexes indicated that the square-planar structure of the complexes is somewhat distorted and probably close to a lozenge. The stability constants (K_s) were determined by a displacement method. The K_s values for the cis-isomers were generally greater than those for the trans-isomers, and the K_s for n=2 series increased more clearly. In particular, the K_s for *cis*-AzoED(n=2)+Cu(II) was improved by 43.8 fold. The photoresponsive change in the stability constants suggests a possible application of the present system as light-driven ion pumps for heavy metal ions.

Azobenzene derivatives which exhibit photoinduced reversible cis-trans isomerism have frequently been employed as a photoantenna to control physical and chemical functions of membranes,[2–5)] microemulsions,[6)] synthetic polymers,[7–9)] polypeptide chains,[10,11)] cyclodextrins,[12,13)] and crown ethers.[14–18)] The ideas are all associated with the photoresponsive, large geometrical change between *trans*- and *cis*-azobenzene. These systems are interesting not only as candidates for the storage of light energy but also as models of natural photoresponsive systems mediating the conversion of light into other forms of energy.

The purpose of our investigation has been to control the functions of a crown ether family by light, which would lead to photoresponsive ion extraction and light-driven ion-transport across membranes.[18)] We and others have synthesized several photoresponsive crown ethers, but the research effort has mainly been devoted toward photoresponsive binding of alkali and alkaline earth metal ions.[14–20)] In contrast, very few precedents exist for photoresponsive binding of heavy metal ions. Irie *et al.*[21)] synthesized a thioindigo derivative with ethylene glycol chains which exhibits photoresponsive affinity with Ag(I), Hg(II), Cu(II), *etc.* We synthesized azobenzene-capped and azopyridine-capped thiacrown ethers which exhibit affinity with Cu(II) and Hg(II).[22)] Blank *et al.*[23)] extended this concept to a complexone, 4,4′-bis[bis(carboxymethyl)-aminomethyl]azobenzene(AzoIDA(n=1)). It is known that the stability constants (K_s) of complexones are efficiently increased through cooperative binding of plural ligand groups.[24–26)] Thus, the *cis*-isomer of AzoIDA(n=1) (*i.e.*, *cis*-AzoIDA(n=1)) which can form an intramolecular complex with a single metal ion gives the K_s greater than the trans-isomer of AzoIDA(n=1) (*i.e.*, *trans*-AzoIDA(n=1)). Blank *et al.*[23)] established on the basis of a polarographic method that *cis*-AzoIDA(n=1) forms a 1:1 metal/AzoIDA complex with Zn(II). On the other hand, we recently studied the photoresponsive behavior of a copper complex of 4,4′-bis(1-oxa-4,10-dithia-7-azacyclododec-7-ylmethyl)azobenzene (**1**).[27)] The most noteworthy result in this paper is that the Cu(I) complex is capable of binding O_2 in a partially reversible manner only when **1** is photoisomerized to the *cis*-form. Therein, we found that both *trans*- and *cis*-**1** bind two copper ions to form the 1:1 copper/crown complex. The finding suggests that the two crown ether rings act quite independently and that most probably, two nitrilo nitrogens of *cis*-AzoIDA(n=1) are too far to bind intramolecularly to one metal ion.



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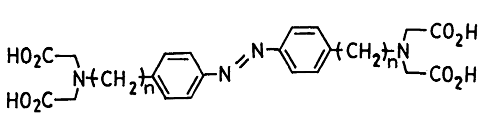
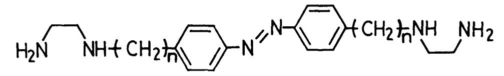


trans-AzoIDA(n=1,2)



trans-AzoED(n=1,2)

It occurred to us that if appropriate spacers are inserted between azobenzene and iminodiacetic acid, two nitrilo nitrogens may be able to coordinate intramolecularly to one metal ion. Examination of Corey-Pauling-Koltun (CPK) molecular models of AzoIDA(n=1,2) suggests that (i) four carboxy groups in *cis*-AzoIDA(n=1) favorably occupy the tetrahedral coordination sites and it is fairly difficult for two nitrilo nitrogens to coordinate to one metal ion and (ii) four carboxy groups in *cis*-AzoIDA(n=2) possibly be placed in either (tetrahedral and planar) coordination structure and two nitrilo nitrogens can interact with one metal ion. We thus synthesized AzoIDA(n=1,2) and AzoED(n=1,2) and examined whether or not metal affinities of these azobenzene-linked ligands change in response to photoinduced trans-cis isomerization. We employed Zn(II) and Cu(II) as metal ions, because Zn(II) is classified as a relatively "hard" metal ion and adopts the tetrahedral coordination, whereas Cu(II) is a "soft" metal ion and favors the square-planar coordination.

Experimental

Materials. *trans*-AzoIDA(n=1) and *trans*-AzoIDA(n=2) were synthesized by the reaction of iminodiacetic acid with 4,4′-bis(chloromethyl)azobenzene and 4,4′-bis(2-chloroethyl)azobenzene, respectively.

trans-*4,4′-Bis[bis(carboxymethyl)aminomethyl]azobenzene-*(trans-*AzoIDA(*n*=1)).* 4,4′-Bis(chloromethyl)azobenzene (0.28 g; 1.0 mmol) in 40 ml of methanol and iminodiacetic acid (0.54 g; 4.1 mmol) in 50 ml of water containing K_2CO_3 (0.80 g; 5.79 mmol) were mixed and refluxed for 21 h. The progress of the reaction was followed by TLC. Methanol was removed from the reaction mixture by evaporation under reduced pressure. The residual solution was turbid (probably owing to monosubstituted compound). It was filtered after treatment with active charcoal, and orange crystals precipitated from the filtrate on the addition of NaCl were recovered by filtration. The crystals were dissolved in water and reprecipitated by adding concd HCl; mp 225.5—226.5 °C (lit,[23] 208—209 °C), yield 38%. Found: C, 55.03; H, 5.06; N, 11.67%. Calcd for $C_{22}H_{24}N_4O_8$: C, 55.93; H, 5.12; N, 11.86%. IR (KBr): ν_{OH} 3000 cm^{-1}, $\nu_{C=O}$ 1725 cm^{-1}, $\nu_{N=N}$ 1635 cm^{-1}. NMR (Me$_2$SO-d_6): NCH$_2$CO, δ=3.50, 8H; ArCH$_2$N, 3.99, 4H; aromatic protons, 7.63 and 7.91, 4H each.

trans-*4,4′-Bis[2-[bis(carboxymethyl)amino]ethyl]azobenzene-*(trans-*AzoIDA(*n*=2)).* First, *trans*-4,4′-bis(2-hydroxyethyl)azobenezene was prepared from 1-(2-hydroxyethyl)-4-nitrobenzene. 1-(2-Hydroxyethyl)-4-nitrobenzene (5.0 g; 29.9 mmol) in 30 ml of ethanol and NaOH (1.3 g; 32.5 mmol) in 6 ml of water were mixed in a 100 ml flask, and zinc powder (16.1 g; 0.246 mol) was added to the stirred solution. The reaction mixture was refluxed for 1 h. The hot solution was filtered and the solid was washed with ethanol. To the combined solution air was introduced for 2 h. After filtration, ethanol in the filtrate was removed under reduced pressure, and the residual solution was diluted with water. The precipitate was recovered by filtration and recrystallized from ethanol; mp 140.5—142.5 °C, yield 75%. Found: C, 70.84; H, 6.80; N, 10.34%. Calcd for $C_{16}H_{18}N_2O_2$: C, 71.09; H, 6.71; N, 10.36%. IR(KBr): ν_{OH} 3240—3340 cm^{-1}, $\nu_{N=N}$ 1580 cm^{-1}. NMR (Me$_2$SO-d_6): Ar-CH$_2$, δ=2.82, 4H; CH$_2$O, 3.68, 4H; OH, 4.69, 2H; aromatic protons, 7.41 and 7.79, 4H each.

trans-4,4′-Bis(2-hydroxyethyl)azobenzene was converted to *trans*-4,4′-bis(2-chloroethyl)azobenzene by treatment with thionyl chloride. *trans*-4,4′-Bis(2-hydroxyethyl)azobenzene (3.0 g; 11.1 mmol) was heated in 30 ml of thionyl chloride for 4 h in the presence of one drop of *N,N*-dimethylformamide. The progress of the reaction was followed by TLC. The hot solution was filtered using a glass filter and evaporated to dryness *in vacuo*. The residual crystals were recrystallized from benzene; mp 120—121 °C, yield 91%. Found: C, 62.22; H, 5.23; N, 9.03%. Calcd for $C_{16}H_{16}N_2Cl_2$: C, 62.55; H, 5.25; N, 9.12%.

trans-AzoIDA(n=2) was synthesized in a manner similar to *trans*-AzoIDA(n=1); mp 215 °C (dec), yield 35%. Found: C, 57.76; H, 5.75; N, 10.98%. Calcd for $C_{24}H_{28}N_4O_8$: C, 57.59; H, 5.64; N, 11.19%. IR(KBr): ν_{OH} 2960—3020 cm^{-1}, $\nu_{C=O}$ 1725 cm^{-1}, $\nu_{N=N}$ 1630 cm^{-1}. NMR(Me$_2$SO-d_6): ArCH$_2$ and NCH$_2$, δ=2.92 and 2.94, 4H each; NCH$_2$CO, 3.55, 8H; aromatic protons, 7.49 and 7.86, 4H each.

trans-*4,4′-Bis[(2-aminoethyl)aminomethyl]azobenzene(*trans-*AzoED(*n*=1)).* 4,4′-Bis(chloromethyl)azobenzene (1.00 g; 3.58 mmol) in 100 ml of acetonitrile was added slowly (for 75 min) into stirred acetonitrile solution (200 ml) of ethylenediamine (4.31 g; 7.17 mmol) containing finely powdered K_2CO_3 (9.90 g; 71.6 mmol). The mixture was refluxed for 2 h and the completion of the reaction was confirmed by TLC. The hot solution was filtered to remove KCl and K_2CO_3, the filtrate being evaporated to dryness. The residue was crystallized by benzene-diisopropyl ether. The crystals were dissolved in hot water, the insoluble material removed by filtration, and the filtrate was acidified by concd HCl. On cooling, *trans*-AzoED(n=1) was recovered as its tetrahydrochloride salt; mp>300 °C, yield 35%. Found: C, 45.21; H, 6.36; N, 17.93%. Calcd for $C_{18}H_{30}N_6Cl_4$: C, 45.78; H, 6.40; N, 17.79%. IR(KBr): ν_{NH} 2890—3030 and 2735—2770 cm^{-1}, $\nu_{N=N}$ 1585 cm^{-1}.

trans-*4,4′-Bis[2-[(2-aminoethyl)amino]ethyl]azobenzene(*trans-*AzoED(*n*=2)).* This compound was synthesized from *trans*-4,4′-bis(2-chloroethyl)azobenzene and ethylenediamine in a manner similar to *trans*-AzoED(n=1) and isolated at its tetrahydrochloride; mp 279—281 °C, yield 63%. Found: C, 46.89; H, 6.88; N, 16.40%. Calcd for $C_{20}H_{34}N_6Cl_4 \cdot 0.66H_2O$: C, 46.89; H, 6.95; N, 16.40%. IR(KBr): ν_{NH} 2735—2770 and 2890—3030 cm^{-1}, $\nu_{N=N}$ 1560 cm^{-1}.

Measurements of ESR Spectra. The ligand (1.00×10^{-3} M†) in the buffer solution (pH 9.02) was irradiated by UV light and then mixed with an equal amount of the buffer solution containing CuSO$_4$(1.00×10^{-3} M). ESR spectra were measured at −50 °C with JEOL-JES-FE-1X and simulated by using a computer program made by Dr. M. Iwamoto. The ligand after photoirradiation was a mixture of trans- and cis-isomer (see Table 1). We first made a simulation of the ESR spectra of trans-isomer·Cu(II) complexes and reduced these spectra from the observed ESR spectra. The remaining spectra thus obtained were regarded to be those of "pure" cis-isomer·Cu(II) complexes and analyzed by computer simulation.

Photoisomerization and Kinetic Measurements. A 100-W high-pressure Hg-lamp with a color glass filter ($330<\lambda<380$ nm) was used for the trans-to-cis photoisomerization. The thermal cis-to-trans isomerization was followed spectrophotometrically at 30 °C by monitoring the appearance of the absorption maximum of trans-isomers. The details of the method have been described.[16,17] The thermal isomerization of *cis*-AzoIDA(n=1) in the presence of metal ions was very slow. At [Zn(II)]/[AzoIDA(n=1)]=1.0, for example, the $(A_\infty - A_0)/(A_\infty - A_t)$ after 48 h was only 1.014. We

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† 1 M = 1 mol dm^{-3}.

thus calculated the first-order rate constant (k) for this system from about 2% change in the optical density. Other systems gave much greater spectral changes, so that the k values could be determined by a usual first-order rate equation.

Estimation of Stability Constants. A displacement method was employed to estimate the stability constants of AzoIDA(n=1,2) and AzoED(n=1,2).[28] Eriochrome Black T (EBT) and 1-(2-pyridylazo)-2-naphthol (PAN) were used as indicators for Zn(II)- and Cu(II)-complexes, respectively: $\log K_{\mathrm{EBT}}=10.4$ for Zn(II) and $\log K_{\mathrm{PAN}}=12.6$ for Cu(II).[29,30] The employed wavelengths were 650 nm for EBT–Zn(II) and 550 nm for PAN–Cu(II). For an equilibrium in Eq. 1, one can derive Eq. 2 where K_e is the displacement equilibrium constant and K_I and K_s are the stability constants of I (indicator) and L (ligand), respectively.[28]

$$\mathrm{I{\cdot}M(II)} + \mathrm{L} \overset{K_e}{\rightleftharpoons} \mathrm{I} + \mathrm{L{\cdot}M(II)} \tag{1}$$

$$K_s = K_e \cdot K_I \tag{2}$$

As the indicators have the stability constants greater than $10^{10}\ \mathrm{M}^{-1}$, one can consider that the indicator and the metal ion (added in a 1:1 mole ratio) totally exist as the complex form. Thus, the degree of the spectral change induced by ligand addition is readily ascribed to the production of the free indicator. From this spectral change one can estimate the K_e for trans-isomers.[28] In the present system, however, one should pay attention to the possibility that AzoIDA and AzoED may form $\mathrm{L{\cdot}M(II)_2}$ in addition to $\mathrm{L{\cdot}M(II)}$. In order to obviate this problem we employed excess L over M(II) (see Tables 4 and 5).

The analysis of the spectral change induced by the addition of the cis/trans mixture is more complex. The magnitude of the spectral change ($\Delta\mathrm{OD_{photo}}$) can be regarded as the sum of $\Delta\mathrm{OD_{trans}}$ and $\Delta\mathrm{OD_{cis}}$. That is,

$$\Delta\mathrm{OD_{photo}} = \frac{\mathrm{trans\%}}{100}\cdot\Delta\mathrm{OD_{trans}} + \frac{\mathrm{cis\%}}{100}\cdot\Delta\mathrm{OD_{cis}} \tag{3}$$

Since trans%, cis%, and $\Delta\mathrm{OD_{trans}}$ are known, one can estimate $\Delta\mathrm{OD_{cis}}$ which corresponds to hypothetical ΔOD induced by the "pure" cis-isomer. By using $\Delta\mathrm{OD_{cis}}$ thus estimated, we calculated K_e and K_s for cis-isomers.

In a separate study, we determined the K_s for iminodiacetic acid and ethylenediamine by a titration method and a displacement method.[28,31] The K_s values determined by two different methods agreed with the satisfactory accuracy (see Tables 4 and 5). The K_s values determined by the displacement method are therefore reliable.

Results and Discussion

Effects of Metal Ions on Photo and Thermal Isomerization. The spectroscopic properties of AzoIDA and AzoED are summarized in Table 1. These compounds gave two absorption bands at around 330 nm and 427 nm, which are attributed to π-π^* and n-π^* transition, respectively. The photoisomerization was carried out using a 100-W high-pressure Hg-lamp equipped with a colored glass filter ($330<\lambda<380$ nm). In aqueous solution buffered to pH 9.02, the isomerization reached a photostationary state after 5 min.

TABLE 1. SPECTROSCOPIC PROPERTIES AND PHOTOISOMERIZATION OF AzoIDA AND AzoED[a)]

Ligand	$\lambda_{\max}$/nm		$\varepsilon_{\max}$ of π-π^* /cm^{-1}M^{-1}	*cis/trans*
	π-π^*	n-π^*		
trans-AzoIDA(n=1)	329	428	25200	61/39
trans-AzoIDA(n=2)	332	426	24000	63/37
trans-AzoED(n=1)	333	427	19400	66/34
trans-AzoED(n=2)	333	426	19300	67/33

a) pH 9.02 with 0.01 M $\mathrm{NH_3}$ buffer, μ=0.10 with KCl.

The cis/trans ratios are collected in Table 1. The cis concentration at the photostationary was not affected in the presence of an equimolar amount of $\mathrm{ZnSO_4}$. In the dark in the absence of metal ions, the cis-isomers isomerized, although very slowly, to the corresponding trans-isomers and the initial spectra of the trans-isomers were regenerated. The appearance of the absorption maximum of the trans-isomers satisfied a first-order rate equation for up to three-half lives. The first-order rate constants (k) were obtained by analyzing the time-dependence.

We previously investigated the metal effect on the photoresponsive behaviors of azobis(benzocrown ether)s.[17,32] It has been found that in the presence of metal ions which can form intramolecular 1:2 metal/crown sandwich-type complexes with cis-isomers, the rate of the thermal cis-to-trans isomerization is suppressed. This novel phenomenon is attributed to the "lock-in" effect of metal ions flanked by two crown rings. That is, an additional free energy of activation is required for the cis-to-trans isomerization process, which reflects the need to disrupt favorable interactions between the metal ion and the crown ethers. In contrast, such an inhibitory effect was not seen for an analogous photoresponsive crown ether in which crown ether groups are linked to the two sides of an azobenzene *via* methylene spacers (*i.e.*, $\mathrm{CrCH_2}$-p-$\mathrm{C_6H_4}$-$\mathrm{N{=}NC_6H_4}$-p-$\mathrm{CH_2Cr}$ where Cr denotes monoaza-15-crown-5).[33] Probably, free-rotating methylene spacers act as an absorber of the geometrical change occurring at the N=N bond. One may conclude, therefore, that the "lock-in" effect is operative only in fairly rigid molecules.

In AzoIDA and AzoED, ligand groups are linked to an azobenzene *via* methylene or ethylene spacers. Nevertheless, we observed that the rates of thermal cis-to-trans isomerization are efficiently inhibited by Zn(II) and Cu(II). The inhibitory effect of Zn(II) is illustrated in Fig. 1. The rates for AzoIDA were strongly inhibited by Zn(II) and the plots provided a minimum at [Zn(II)]/[AzoIDA]=1.0. This may be taken as evidence that both *cis*-AzoIDA(n=1) and *cis*-AzoIDA(n=2) form intramolecular 1:1 metal/ligand complexes: that is, two intramolecular iminodiacetate moieties coordinate to one Zn(II) ion. This finding is in agreement with the conclusion obtained from a polarographic study.[23] The slight rate increase at

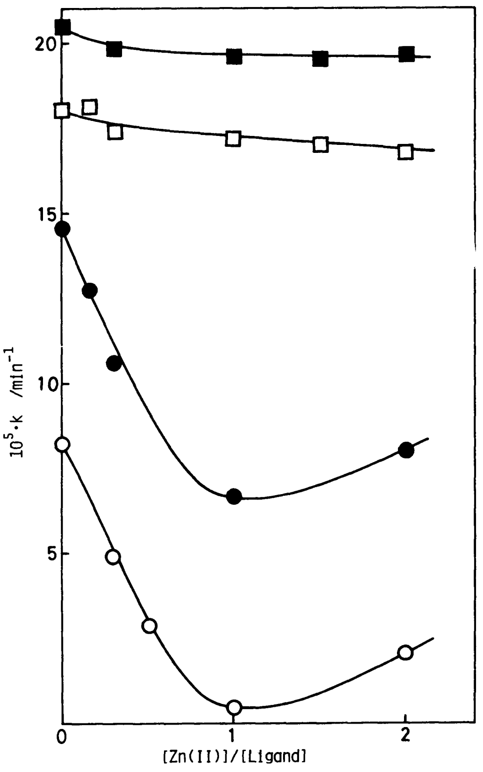

Fig. 1. Influence of added $ZnSO_4$ on the first-order rate constants for the thermal cis-to-trans isomerization. 30 °C, pH 9.02 with 0.01 M NH_3 buffer, μ=0.10 with KCl, [ligand]=1.67×10^{-5} M.
○: AzoIDA(n=1), ●: AzoIDA(n=2), □: AzoED(n=1), ■: AzoED(n=2).

Table 2. Pseudo-first-order rate constants(k) for the thermal cis-to-trans isomerization[a]

Ligand	$10^5\cdot k/\text{min}^{-1}$		
	No metal	Zn(II)[b]	Cu(II)[b]
AzoIDA(n=1)	8.2	0.5	2.2
AzoIDA(n=2)	14.5	6.7	7.9
AzoED(n=1)	18.0	17.2	8.8
AzoED(n=2)	20.5	19.6	10.5

a) 30 °C, pH 9.02 with 0.01 M NH_3 buffer, μ=0.1 with KCl, [ligand]=1.67×10^{-5} M. b) [Zn(II) or Cu(II)]/[ligand]=1.00.

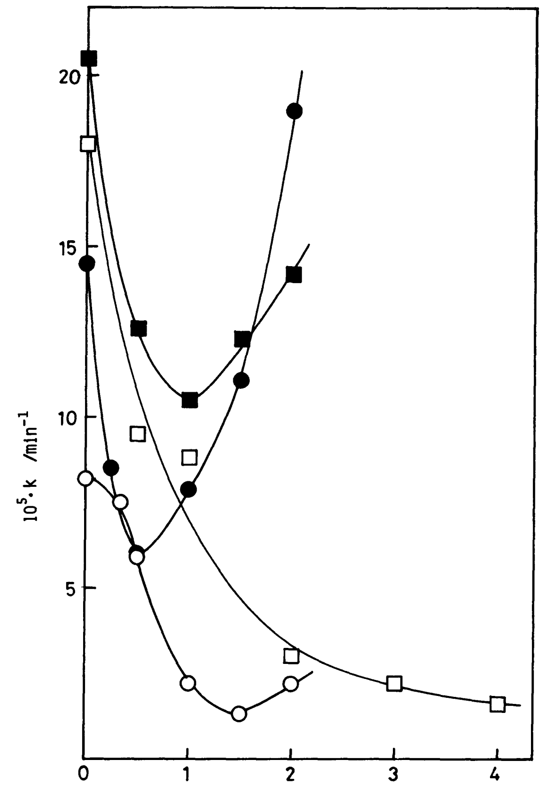

Fig. 2. Influence of added $CuSO_4$ on the first-order rate constants for the thermal cis-to-trans isomerization. The reaction conditions and symbols are identical to those in Fig. 1.

[Zn(II)]/[AzoIDA]>1 may be attributed either to the catalytic effect of Zn(II) on the thermal isomerization through the Zn(II)-azo interaction[27,35] or to the electrostatic repulsion between two Zn(II) ions[32] if *cis*-AzoIDA·$Zn(II)_2$ is formed at [Zn(II)]>[AzoIDA]. In contrast, the rates of AzoED were scarcely affected by Zn(II). The marked difference between AzoIDA and AzoED is probably rationalized in terms of low affinity of "soft" ethylenediamines with "hard" Zn(II) ion. In fact, AzoED gave the K_s much smaller than AzoIDA (*vide post*).

The k values at [Zn(II)]/[ligand]=1.0 are summarized in Table 2. The k observed for *cis*-AzoIDA(n=1)+Zn(II)(5×10^{-6} min^{-1}) is the smallest rate constant we have ever observed: thus, extra free energy of activation ($\Delta\Delta G^{\neq}=\Delta G^{\neq}_{\text{no metal}}-\Delta G^{\neq}_{\text{Zn(II)}}$) required to disrupt the interaction between Zn(II) and the iminodiacetate moieties is roughly estimated to be 7.1 kJ mol^{-1}. This value is comparable with those required to disrupt the interaction between *cis*-azobis(benzocrown ether)s and alkali metal ions (2.5—7.1 kJ mol^{-1}).[17,32] The fact that the thermal isomerization of *cis*-AzoIDA is efficiently inhibited in spite of the presence of the spacers suggests that the Zn(II)iminodiacetate interaction should be stronger than the alkali metal-crown interaction, because the inhibitory effect in the latter system has disappeared in the presence of the spacers.[33]

The effect of Cu(II) on the thermal cis-to-trans isomerization is illustrated in Fig. 2. The most distinct difference from Fig. 1 is that Cu(II) can suppress not only the thermal isomerization of *cis*-AzoIDA but also that of *cis*-AzoED. Conceivably, "soft" Cu(II) can interact with the ethylenediamine moieties more strongly. However, the k values for *cis*-AzoIDA are still smaller than those for *cis*-AzoED. It is interesting to note that the ligand which has the relatively small rate constant gives the large K_s (see Table 5).

Here, one may notice that the plots in Fig. 2 are more complex than those in Fig. 1 and the rate minimum does not always appear at [Cu(II)]/[ligand]=1.0. The complexity is associated with overlapping of two contrasting effects of Cu(II): that is, an inhibitory effect due to intramolecular chelation and an accelerative effect due to interaction between Cu(II) and the azo linkage.[27,34] We have examined the catalytic effect of various metal ions on the thermal cis-to-trans isomerization of *cis*-azobenzene derivatives.[27,35] Among metal ions tested therein, Cu(II) exerted the greatest accelerative effect while Zn(II) acted as very weak catalyst.

The plots of *k vs.* [Cu(II)]/[ligand] for *cis*-AzoIDA-(n=1), *cis*-AzoIDA(n=2), and *cis*-ED(n=2) provided a minimum, whereas the plot for *cis*-AzoED(n=1) decreased monotonously with increasing Cu(II) concentration. It is also seen from Fig. 2 that after experiencing a minimum, the rate constants for n=2 series are enhanced at high Cu(II) concentrations. In contrast, the accelerative effect of Cu(II) ion is scarcely operative on n=1 series. Examination of CPK models suggests that the intramolecular complexes with the n=1 cis-isomers are more rigid than the corresponding complexs with the n=2 cis-isomers. In fact, the complexes of n=2 series showed a considerable flexibility due to ethylene spacers. The absence of the accelerative effect on n=1 series implies, therefore, that in *cis*-azobenzenes rigidified through metal complexation, the thermal isomerization is rather insusceptible to the metal catalysis.

ESR Spectra of cis-Isomer·Cu(II) Complexes. Subsequently, we measured the ESR spectra of *cis*-isomer·Cu(II) complexes in order to obtain a further insight into the coordination structure. Practically, the ESR spectra were measured for the mixture of trans- and cis-isomers. The process we obtained the spectra of "pure" cis-isomer·Cu(II) complexes is following (Fig. 3): first, we measured the ESR spectra of trans-isomer·Cu(II) complexes and then eliminated this spectra from the observed spectra taking trans% at the photostationary state (see Table 1) into account. The remaining spectra which can be regarded as those of "pure" cis-isomer·Cu(II) complexes were analyzed by computer simulation. The results are summarized in Table 3 and Fig. 4.

Examination of Table 3 and Fig. 4 reveals that basically, all Cu(II) complexes adopt square-planar or octahedral coordination, but the *xy* planes are somewhat distorted from a neat square-planar structure because the third g value is required in order to fully simulate the spectra. Probably, the *xy* planes of the cis-isomer·Cu(II) complexes are more or less close to a lozenge.

With respect to g_1 in *cis*-AzoIDA, the g_1 for n=1 is somewhat greater than that for n=2, while the reverse is true in *cis*-AzoED. This difference may be rationalized in connection with the spacer effect. Provided that the nitrilo nitrogens in *cis*-AzoIDA(n=1) cannot coordinate to central Cu(II) because of steric hindrance, it serves as a tetradentate ligand. In this case, the g_1 for *cis*-AzoIDA(n=1) reflects the axial coordination of solvent or buffer base(NH_3). On the other hand, *cis*-AzoIDA(n=2) possibly serves as a hexadentante ligand owing to the flexibility increased by the ethylene spacers, and the g_1 would reflect the axial coordination of intramolecular ligand groups. In fact, *cis*-AzoIDA(n=1) shows an ESR pattern characteristic of square-planar coordination, whereas that of *cis*-AzoIDA(n=2) is rather close to octahedral coordination. It is very likely, therefore, that the distance from central Cu(II) to the intermolecular ligand is longer than that to the intramolecular one. On the other hand, *cis*-AzoED(n=2) has the g_1 greater than *cis*-AzoED(n=1). Since *cis*-AzoED series act as tetradentate ligands, the g_1 values are definitely governed by

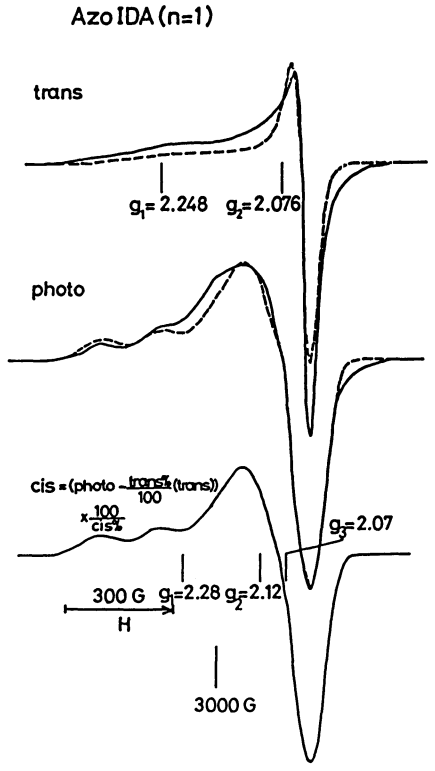

Fig. 3. ESR simulation of the "pure" *cis*-AzoIDA(n=1)·Cu(II) complex. The spectrum of *trans*-AzoIDA(n=1)·Cu(II) could be simulated by using two g values. The spectrum of *cis*-AzoIDA-(n=1)·Cu(II) was obtained by subtracting this spectrum from photo spectrum observed under photoirradiation.

Table 3. ESR parameters for the cis-isomer·Cu(II) complexes[a)]

Ligand	g value		
	g_1	g_2	g_3
cis-AzoIDA(n=1)	2.28	2.12	2.07
cis-AzoIDA(n=2)	2.23	2.15	2.06_5
cis-AzoED(n=1)	2.20	2.10	2.05_5
cis-AzoED(n=2)	2.34	2.10	2.05_2

a) −50 °C, [ligand]=5.00×10^{-4} M, [$CuSO_4$]=5.00×10^{-4}M, pH 9.02 with 0.01 M NH_3 buffer, μ=0.1(KCl).

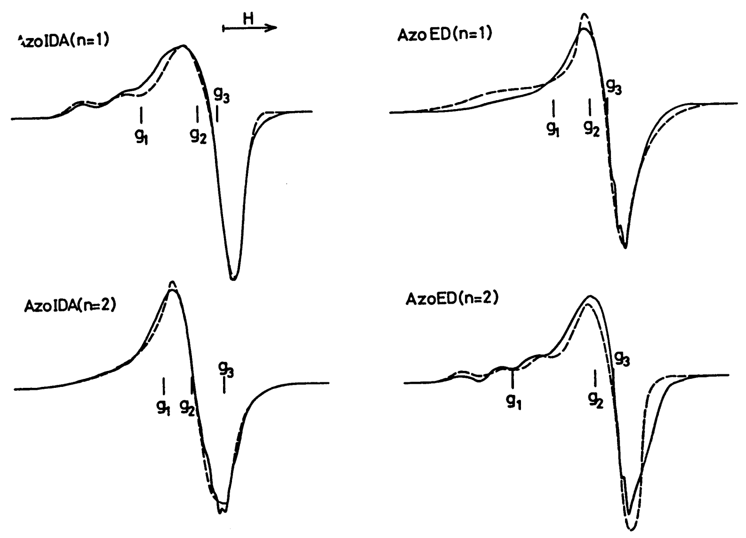

Fig. 4. ESR spectra (solid line) and simulated spectra (dotted line) of the Cu(II) complexes with the photoirradiated ligands. The g values inserted in the figure are those determined for the "pure" cis-isomer·Cu(II) complexes. −50 °C, [ligand]=5.00×10^{-4} M, pH 9.02 with 0.01 M NH_3 buffer, μ=0.1(KCl).

TABLE 4. DISPLACEMENT EQUILIBRIUM CONSTANTS (K_e) AND STABILITY CONSTANTS (K_s) OF AzoIDA AND AzoED FOR Zn(II)[a]

Ligand	K_e		$10^{-8}\cdot K_s/M^{-1}$	
	dark or trans-isomer	cis-isomer	dark or trans-isomer	cis-isomer
$HN(CH_2COOH)_2$	1.71×10^{-3}	—	0.43[b]	—
AzoIDA(n=1)	0.230	0.327	57.8	82.1
AzoIDA(n=2)	1.86	3.30	467	829
$H_2N(CH_2)_2NH_2$	8.36×10^{-5}	—	0.021[c]	—
AzoED(n=1)	1.10×10^{-3}	1.95×10^{-3}	0.28	0.49
AzoED(n=2)	4.00×10^{-3}	0.0188	1.00	4.72

a) pH 9.02 with 0.01 M NH_3 buffer, μ=0.10 with KCl, [EBT]=[$ZnSO_4$]=3.00×10^{-6} M, [ligand]=1.50×10^{-5} M.
b) $K_s=2.75\times10^{7}$ M^{-1} from titration. c) $K_s=1.26\times10^{6}$ M^{-1} from titration.

TABLE 5. DISPLACEMENT EQUILIBRIUM CONSTANTS (K_e) AND STABILITY CONSTANTS (K_s) OF AzoIDA AND AzoED FOR Cu(II)[a]

Ligand	K_e		$10^{-9}\cdot K_s/M^{-1}$	
	dark or trans-isomer	cis-isomer	dark or trans-isomer	cis-isomer
$HN(CH_2COOH)_2$	7.32×10^{-4}	—	2.91[b]	—
AzoIDA(n=1)	0.0163	0.0226	64.9	89.9
AzoIDA(n=2)	0.0180	0.0376	71.7	150
AzoED(n=1)	1.18×10^{-4}	7.70×10^{-4}	0.47	3.06
AzoED(n=2)	3.02×10^{-4}	0.0132	1.20	52.5

a) pH 9.02 with 0.01 M NH_3 buffer, μ=0.10 with KCl, [PAN]=[$CuSO_4$]=3.14×10^{-6} M, [ligand]=3.05×10^{-4} M.
b) $K_s=4.79\times10^{9}$ M^{-1} from titration.

the axial coordination of solvent or buffer base. The g_1(=2.34) for *cis*-AzoED(n=2) much greater than others is characterized by the elongation of the distance from Cu(II) to the axial ligand. This may be induced by the stable coordination of the ethylenediamine moieties in the xy plane which is brought forth by the ethylene spacers. In fact, the K_s for *cis*-AzoED(n=2) was much greater than that for *cis*-AzoED(n=1) (*vide post*). These findings consistently suggest that the structure of the cis-isomer·Cu(II) complexes is significantly affected by the spacer length.

Photoresponsiveness of Stability Constants. The stability constants (K_s) were determined according to a displacement method[28] and are summarized in Tables 4 and 5 together with the displacement equilibrium constants (K_e). Since one of our objects is to specify whether or not the amine nitrogens in AzoIDA can contribute to the complex formation, we evaluated the K_s at pH 9.02 where they are mostly dissociated.31) As reference ligands, we employed Eriochrome Black T (EBT) and 1-(2-pyridylazo)-2-naphthol(PAN) for Zn(II) and Cu(II), respectively. Further details of the experimental methods and measurement conditions are described in Experimental and footnotes to Tables 4 and 5. In order to give full assurance to this method, we determined the K_s for iminodiacetic acid and ethylenediamine by a titration method.28,31) The K_s values determined by two different methods agreed within the allowable error (see Tables 4 and 5). Therefore, the displacement method with EBT and PAN is reliable enough to make discussions on the photoirradiation effect. Here, note that we have defined K_s= [M(II)·AzoIDA(or AzoED)]/[M(II)][AzoIDA(or AzoED)].

Blank *et al.*23) who first synthesized AzoIDA(n=1) reported that (i) *cis*-AzoIDA(n=1) forms an intramolecular 1:1 metal/ligand complex with Zn(II), (ii) the K_s for *cis*-AzoIDA(n=1)+$ZnSO_4$ determined in aqueous solution (no buffer) is $1.1\times10^5\,M^{-1}$, and (iii) *trans*-AzoIDA (n=1) scarcely interacts with Zn(II). The last conclusion sounds a little strange, because it has been established that iminodiacetic acid and its derivatives usually have the K_s of 10^7—$10^9\,M^{-1}$.31) As shown in Table 4, the K_s values for AzoIDA+Zn(II) determined in buffered (pH 9. 02) aqueous solution lie between 8.13×10^9—$1.16\times10^{11}\,M^{-1}$ and those for AzoED+Zn(II) between 3.0×10^7—$4.64\times10^8\,M^{-1}$.36) As for the association with Zn(II), the marked photoresponsive difference reported by Blank *et al.*23) could not be realized under the present conditions. Detailed examination of Table 4 indicates, however, that the K_s values for AzoIDA(n=1), AzoIDA(n=2), and AzoED(n=1) are enhanced by 1.4—1.8 fold by photoirradiation, and that for AzoED(n=2) is further enhanced (4.7 fold). The slight but perceptible improvement in *cis*-AzoED(n=2) may be ascribed to superiority of the ethylene spacer over the methylene spacer to form the intramolecular complexes.

It is known that Zn(II) absolutely favors the tetrahedral coordination. On the other hand, the ESR studies established that all Cu(II) complexes tested herein adopt the planar coordination. Examination of CPK models suggests that one can easily make the molecuar models of either tetrahedral or planar coordination from n=2 series, whereas it is pretty difficult to make the molecular models of planar coordination from n=1 series without any steric distortion. One may expect, therefore, that the effect of the spacer length appears more clearly in the association with Cu(II). As recorded in Table 5, the photoinduced K_s increases are relatively small for AzoIDA(1.4-fold for n=1 and 2.1-fold for n=2). The lack of the spacer effect is probably rationalized as follows: the K_s values for *cis*-AzoIDA are primarily governed by the interaction with four carboxyl groups and the interaction with the amines exerts only the additional stabilization effect. Thus, the K_s values are scarcely changed by the spacer length. In contrast, the distinct spacer effect was observed for AzoED: the photoirradiation increases the K_s values for AzoED(n=1) and AzoED(n=2) by factors of 6.5 and 43.8, respectively, and the K_s for *cis*-AzoED(n=2) is 17 times greater than that for *cis*-AzoED(n=1). The K_s for *cis*-AzoED is crucially governed by whether or not the four nitrogens can coordinate intramolecularly to one Cu(II) ion. In other words, when the coordination of two nitrogens close to the benzene ring accompanies some steric distortion (probably, *cis*-AzoED(n=1) is the case), it directly leads to the lowering of K_s. Consequently, *cis*-AzoED(n=2) having the longer spacer becomes more advantageous in the intramolecular complexation to one Cu(II) ion. These findings suggest that in order to realize the large spacer effect, the heteroatom which has a straightforward influence on the complex formation should be placed next to the spacer moiety.

Conclusion. The present study has demonstrated that the stability constants for typical complexones such as iminodiacetic acid and ethylenediamine can be photocontrolled by means of induced structural changes arising from the photoisomerization of azobenzene. Although several examples for photoresponsive binding of alkali and alkaline earth metal ions have been reported, few examples ever exist for photoresponsive binding of heavy metal ions. This study newly suggests, although the reversibility of the photoinduced isomerization in the presence of metal ions is not fully studied in this paper, possible applications of photoresponsive complexones to ion-extraction, ion transport, light-driven ion pumps, *etc.*

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