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Multidentate Ligand Kinetics. XI. Polyamine Reactions with Copper Complexes of Ethylenediaminetetraacetate and Cyclohexylenediaminetetraacetate Ions

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Received August 4, 1966

The rates of the ligand-exchange reactions of penten, tetren, trien, dien, and en with copper–EDTA and copper–CyDTA are measured. The reaction of dien is faster than the series trien $\gtrsim$ tetren $\gtrsim$ penten $>>$ en. Two molecules of en are necessary for displacement. In the proposed mechanism, three polyamine nitrogens are bonded to copper before the rate-determining step. Polyamines with more than three nitrogens are thermodynamically more favored in the exchange reaction, but are kinetically less favored. The rate constants decrease as the pH decreases and the assignment of rate constants to each of the protonated polyamine species is consistent with the proposed mechanism. The cyclohexane ring in CyDTA does not change the general reaction mechanism, but it affects the exchange rate and reactions with copper–CyDTA are 50,000 times slower than those with copper–EDTA. The rates of reaction of polyamines with copper–EDTA are about 2,000,000 times faster than the analogous reaction with nickel–EDTA. Nevertheless, the reaction mechanisms with copper and nickel appear to be very similar.

Introduction

Certain multidentate ligands can rapidly replace other multidentate ligands from their metal complexes.[2–5] On the other hand, solvent (or its conjugate acid or base) often is extremely slow to displace a multidentate ligand.[6,7] The phenomenon of *coordination chain reactions*[2,8,9] is one consequence. These catalytic exchange reactions of two complexes occur when the ratio of the ligand–ligand-replacement rate to the solvent–ligand-replacement rate is large for both complexes. The chain reactions are useful for ultratrace analysis.[10]

The present work examines the effect which the number of coordinating groups and the structure of multidentate ligands have on the rate of some ligand–ligand-replacement reactions of copper(II). In one set of reactions, polyamines (penten, tetren, trien[11]) displace EDTA from its copper complex. The rates of the reactions are very fast and require stopped-flow techniques to study.

Another set of reactions uses CyDTA in place of EDTA and the polyamines are tetren, trien, dien, and en. The reactions with dien and en give the bis complexes of copper. The general effect of the cyclohexane ring is to slow the reactions by a factor of about 50,000. Nevertheless, direct ligand reaction with copper–CyDTA is observed whereas direct metal ion reaction with metal–CyDTA complexes is not observed.[12] In several ways CyDTA represents an extreme in steric hindrance for aminocarboxylate derivatives of EDTA. The cyclohexane ring makes it impossible to unwrap the ligand from copper. It also makes rotation difficult and crowds the coordination sites in the twisted configurations of CyDTA proposed for reaction intermediates.

The importance of mixed-ligand complexes as intermediates in these reactions is illustrated by the formation of stable complexes with smaller polyamines. There is a good correlation between the rate-determining step proposed for this work and that postulated for previous studies with nickel polyamines and EDTA.

Experimental Section

EDTA and CyDTA were purified by recrystallization as the free acid. Trien and tetren were recrystallized as their sulfate salts. Penten was prepared and purified by gas liquid partition chromatography. Diethylenetriamine (Aldrich Chemical Co.) and ethylenediamine (Fisher Certified) were shown by gas chromatography to contain no other amines and were used without further purification. The gas chromatographic conditions used were described previously[9] and gave excellent resolution of polyamines.

Standard solutions of copper–EDTA and copper–CyDTA were prepared by adding 5% excess of copper nitrate solution to a standard ligand solution and removing the excess metal by hydroxide precipitation at pH 10.

Recrystallized $NaClO_4$ was used to control the ionic strength for the trien and tetren reactions with copper–CyDTA. In other reactions KCl was used.

Sodium borate-boric acid and 2,6-dimethylpiperidine and its acid salt were used as buffer systems. The pH was measured with a Beckman Model G pH meter.

The reactions of penten, tetren, and trien with copper–EDTA and those of dien and en with copper–CyDTA were studied by a stopped-flow technique (2-mm cell path) as described previously.[8] The en reactions also were studied with a syringe-mixing device to fill 5-cm cells in less than 10 sec. The reactions of tetren and trien with copper–CyDTA were followed by conventional spectrophotometry with a Beckman DU. A Cary 14 spectrophotometer was used for spectral scans. All equipment had circulating water baths to maintain constant temperature to ±0.1°.

Some of the reactions were significantly reversible and rate

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[11] Abbreviations used are: penten, N,N,N,'N'-tetrakis(2-aminoethyl)-ethylenediamine; tetren, tetraethylenepentamine; trien, triethylenetetramine; dien, diethylenetriamine; en, ethylenediamine; $EDTA^{4-}$, ethylenediaminetetraacetate ion; $CyDTA^{4-}$, *trans*-1,2-diaminocyclohexane-N,N,-N,'N'-tetraacetate ion.

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constants for reversible second-order dependence with equal concentration of reactants were routinely calculated using a computer program. In some cases a large excess of polyamine was present and the reactions were pseudo-first order in the forward direction and second order in the reverse direction.[13] When necessary, the trien and tetren reactions with copper–CyDTA were treated by the initial slopes method (for the first 40% and the first 70% of reaction, respectively) to eliminate the effect of reversibility. The stability constants of the copper complexes are: $\log K_1 = 18.8$ (EDTA), 22.0 (CyDTA), 22.4 (penten), 22.9 (tetren), and 20.4 (trien); $\log \beta_2 = 21.3$ (dien) and 20.7 (en).[14] Equilibrium absorbance values were determined for all reaction mixtures.

Repetitive spectral scans (300–700 mμ) of a mixture of excess en with copper–CyDTA (curves 2–6, Figure 1) show an isosbestic point at 616 mμ. A spectrum of $Cu(en)_2^{2+}$ (curve 7) also passes through this point; however, the copper–CyDTA spectrum does not. This indicates a very rapid (too fast for stopped flow) addition of en to copper–CyDTA to form a mixed-ligand species. The species is believed to be $Cu(en)CyDTA^{2-}$ which reacts with a second molecule of en to displace CyDTA and form $Cu(en)_2^{2+}$.

The stability constant for the mixed hydroxide complex, $Cu(OH)CyDTA^{3-}$, was measured spectrophotometrically at 700 mμ. A total concentration of copper–CyDTA of 6.78×10^{-3} M showed a decrease in absorbance from 0.705 to 0.500 in a 1.0-cm cell when the pH was raised from 10.1 to 13.2. Results were consistent with a monohydroxide complex. This hydroxide

$$K_{\mathrm{Cu(OH)CyDTA}} = \frac{[\mathrm{Cu(OH)CyDTA^{3-}}]}{[\mathrm{CuCyDTA^{2-}}][\mathrm{OH^-}]} = 3.1 \qquad (1)$$

complex is much weaker than the corresponding complex with copper–EDTA. Values for the latter are reported[15,16] to be 100 and 120.

Protonation dissociation constants[14] were used for the graphical and computer resolutions of the pH data to give individual rate constants. The stepwise pK values for H_nL are: EDTA: 1.99, 2.67, 6.16, 10.26; CyDTA: 2.43, 3.52, 6.12, 12.35; penten: 1.4, 8.56, 9.14, 9.70, 10.20; tetren: 3.15, 4.83, 8.14, 9.39, 9.78; trien: 3.25, 6.55, 9.08; dien: 4.34, 9.13, 9.94; en: 7.47, 10.18.

Results

penten, tetren, and trien.—All reactions were run with several different reactant concentrations to determine the order of each reactant (Table I). The reactions of trien, tetren, and penten with both copper–EDTA and copper–CyDTA were shown to be first order in polyamine and first order in the copper complex. The general rate expression is given in eq 2 in terms of the total concentration of uncomplexed polyamine. An analogous expression holds for copper–CyDTA.

$$\text{rate} = k_{\text{obsd}}[\text{polyamine}]_{\text{total}}[\mathrm{CuEDTA^{2-}}] \qquad (2)$$

Figure 2 shows that the second-order rate constants for the penten, tetren, and trien reactions with copper–EDTA increase many times with increase in pH and level off at high pH. A similar behavior is seen in Figure 3 for the trien and in Figure 4 for the tetren reactions with copper–CyDTA but the rate constants do not undergo as big a change.

The pH profile in Figure 2 of the rate constant for trien and copper–EDTA includes four points obtained from temperature-jump methods (pH 8.5–10.4) and four points from chain reaction studies[2] (pH 6.2–6.7).

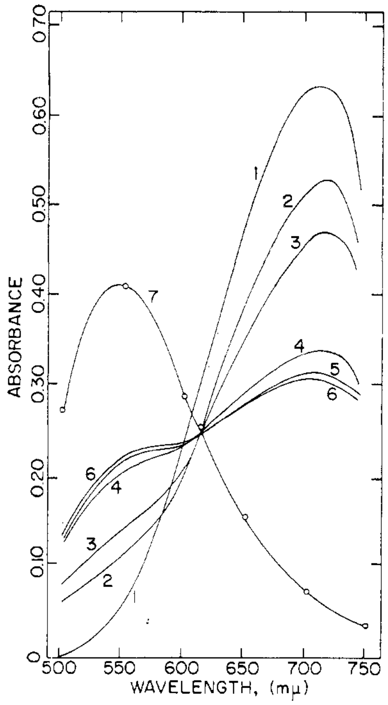

Figure 1.—Repetitive spectral scans of the reaction between copper–CyDTA and en. Curve 1 is $CuCyDTA^{2-}$ (6.16×10^{-3} M) and curves 2–6 are 10–360 sec after mixing in 1.0 M en. Curve 7 is $Cu(en)_2^{2+}$ (6.16×10^{-3} M). The isosbestic point for curves 2–7 is attributed to the slow conversion of $Cu(CyDTA)en^{2-}$ to $Cu(en)_2^{2+}$ which follows the rapid addition of en to $CuCyDTA^{2-}$. Conditions are 25°, $\mu = 0.10$, and a 1-cm cell.

Table I

Reaction Conditions Used for the Rate Studies of Polyamines with Copper–EDTA and Copper–CyDTA at 25.0° and $\mu = 0.1$ M

	$[\text{Polyamine}]_i$, M	$[\text{Cu complex}]_i$, M	pH range
	Polyamine + Copper–EDTA		
penten	1.22×10^{-3}	1.22×10^{-3}	7.4–9.0
	1.22×10^{-3}	9.85×10^{-5}	8.2–11.4
tetren	2.97×10^{-3}	2.97×10^{-3}	6.1–10.3
	9.90×10^{-5}	9.90×10^{-5}	6.6–8.6
	9.75×10^{-2}	2.96×10^{-3}	5.8–6.7
	2.96×10^{-3}	9.85×10^{-5}	6.3
trien	4.58×10^{-3}	9.85×10^{-5}	8.0–8.1
	5.50×10^{-4}	9.85×10^{-5}	8.5–9.6
	9.85×10^{-5}	9.85×10^{-5}	8.8–11.2
	Polyamine + Copper–CyDTA		
tetren	0.501×10^{-3}	1.06×10^{-3}	8.9–10.5
	1.67×10^{-3}	1.06×10^{-3}	8.8–8.9
	0.501×10^{-3}	0.530×10^{-3}	8.8–11.4
	0.501×10^{-3}	1.59×10^{-3}	8.8–9.0
trien	0.848×10^{-3}	1.06×10^{-3}	6.7–9.1
	1.67×10^{-3}	0.530×10^{-3}	6.7
	0.424×10^{-3}	0.530×10^{-3}	9.9–11.4
dien	2.97×10^{-2}	6.75×10^{-5}	8.5–10.7
	2.97×10^{-3}	6.75×10^{-5}	9.6–11.4
	1.67×10^{-2}	6.75×10^{-5}	8.8–12.2
	1.67×10^{-3}	6.75×10^{-5}	10.3–11.7
	5.00×10^{-2}	3.39×10^{-3}	10.2–12.3
	5.00×10^{-2} [a]	9.05×10^{-5}	10.2–10.9

[a] Run in the presence of 9.05×10^{-3} M CyDTA.

All other points are from stopped-flow data. This pH profile agrees with the one reported previously[10] at

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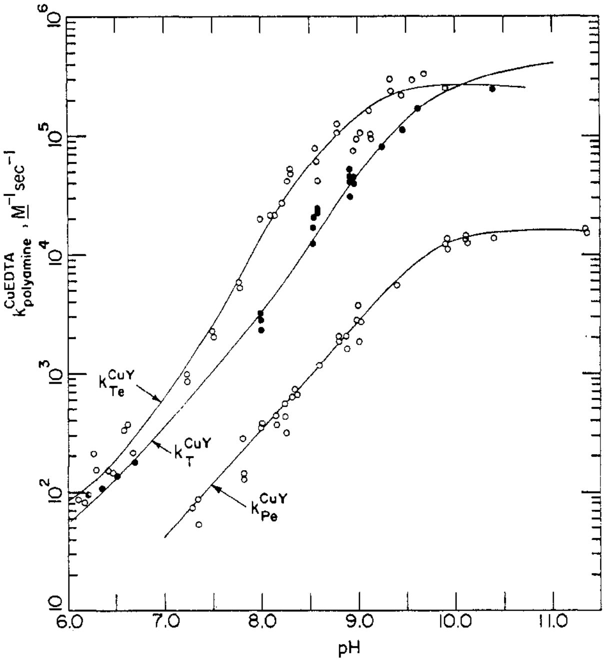

Figure 2.—Rate constant–pH profile for the reaction of polyamines with copper–EDTA at 25.0° and μ = 0.10. Curves are calculated from the resolved rate constants in Table III.

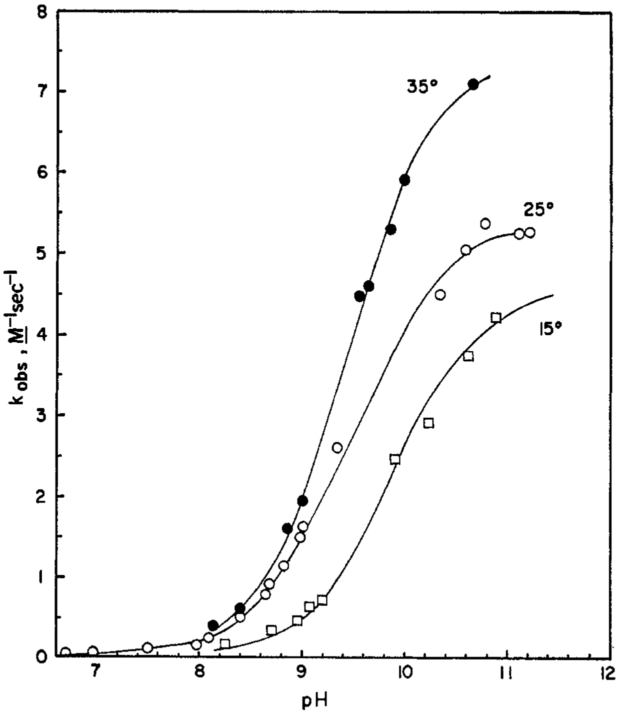

Figure 3.—Rate constant–pH profile for the reaction of trien with copper–CyDTA at 15, 25, and 35°. Curves are calculated from the resolved rate constants using pK_a values for Htrien$^+$, H_2trien^{2+}, and H_3trien^{3+} equal to 9.56, 8.85, and 6.32 at 35°; 9.80, 9.08, and 6.55 at 25°; 10.05, 9.32, and 6.79 at 15° and μ = 0.10.

high and at low pH but gives larger (and more accurate) rate constants in the intermediate pH range.

dien, en, and NH_3 Reactions with Copper–EDTA.—The reaction of dien with copper–EDTA was too fast to be measured on the stopped-flow apparatus. dien can add to copper without displacing the EDTA.

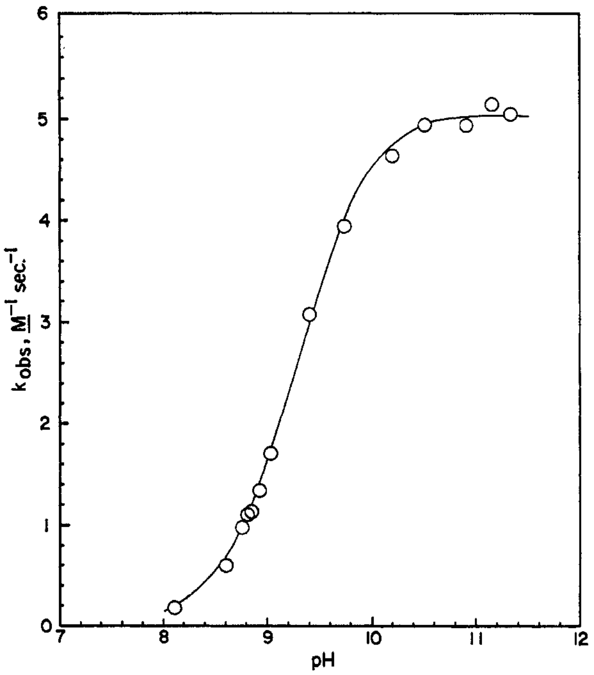

Figure 4.—Rate constant–pH profile for the reaction of tetren with copper–CyDTA at 25° and μ = 0.10. The curve is calculated from the resolved rate constants in Table III.

Similarly, the reaction of Cu(dien)$^{2+}$ and EDTA (both 1.5 × 10^{-3} M) was too rapid for the stopped-flow technique in the pH range 7–11. A stable mixed complex of Cu(dien)EDTA^{2-} has been found[17] and the stability constant relative to CuEDTA^{2-} and dien is 2 × 10^3.

Stable mixed complexes of ammonia and of en with copper–EDTA were observed in this work and have been reported previously.[15,18,19]

dien Reaction with Copper–CyDTA.—The reaction of dien with copper–CyDTA gives Cu(dien)$_2$$^{2+}$ and a small amount of mixed complex believed to be Cu(CyDTA)dien^{2-}. The reaction is first order in dien concentration over a 17-fold range (Table I), where the concentration of CuCy(dien)$^{2-}$ is negligible and the observed rate constant results from eq 3. The rate of the exchange reaction was measured using stopped-flow techniques and results are given in Figure 5. The

$$\text{CuCyDTA}^{2-} + \text{dien} \underset{k_{-3}}{\overset{k_3}{\rightleftharpoons}} \text{Cu(dien)}^{2+} + \text{CyDTA}^{4-} \quad (3)$$

$$\text{Cu(dien)}^{2+} + \text{dien} \xrightarrow{\text{fast}} \text{Cu(dien)}_2^{2+} \quad (4)$$

series of reactions run in the presence of excess uncomplexed CyDTA confirmed the exchange nature of the reaction being measured. The excess CyDTA and excess dien caused the reaction to be pseudo-first order in each direction. Consequently, the slope of a plot of $-\ln (A - A_\infty)$ equals k_3[dien] + k_{-3}[CyDTA]. The observed constants in this situation are greater than those run in the absence of excess CyDTA, indicating that the forward reaction involves the release of CyDTA from the copper complex.

The solid curve in Figure 5 is based on resolved rate

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(18) B. Kirson and I. Citron, *Bull. Soc. Chim. France*, 365 (1959).

(19) C. K. Jørgensen, *Acta Chem. Scand.*, 365 (1959).

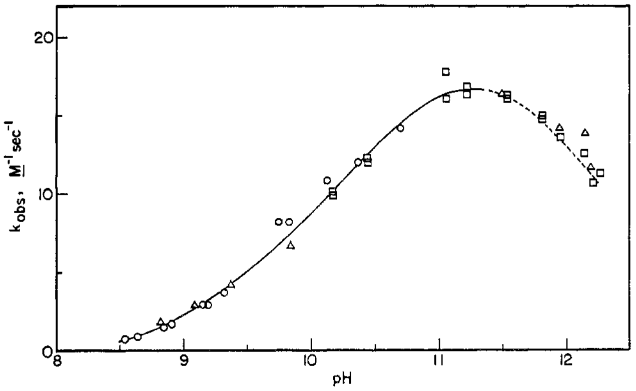


Figure 5.—Rate constant–pH profile for the reaction of dien with copper–CyDTA at 25.0° and $\mu = 0.10$: □, △, and ○ are for 0.050, 0.0167, and 0.0297 M dien, respectively. The solid line is calculated from the resolved rate constants which are valid below pH 11.

constants for dien and Hdien$^+$ and is valid only below pH 11. Above pH 11.2 the second-order rate constant decreases with increasing pH but the low value of $K_{\mathrm{Cu(OH)CyDTA}}$ makes it impossible to ascribe this decrease in rate constant to interference from the hydroxide complex. The reason for the decrease in rate constant which is inversely proportional to the hydrogen ion concentration from pH 11.2 to 12.3 is not clear. A change must occur in the rate-determining step when the pH is too high for the leaving CyDTA readily to add a proton ($\log K_1 = 12.35$).

en and NH$_3$ Reactions with Copper–CyDTA.—The observed rate constants and conditions for the reaction of en with copper–CyDTA are shown in Table II. The reaction was first order in each reactant, but one reactant was Cu(CyDTA)en^{2-}. Ethylenediamine was present in large excess (to force the reaction to completion) and formation of the mixed complex was rapid (Figure 1). The reaction sequence is

$$\mathrm{CuCyDTA^{2-} + en \xrightarrow{fast} Cu(CyDTA)en^{2-}} \qquad (5)$$

$$\mathrm{Cu(CyDTA)en^{2-} + en \longrightarrow Cu(en)_2^{2+} + CyDTA^{4-}} \qquad (6)$$

Spectral evidence indicates that ammonia forms a mixed complex with copper–CyDTA. The reaction of tetren with copper–CyDTA was carried out in the presence of 0.10 M NH$_3$ at pH 10.2. The second-order rate constant was 2.55 instead of 4.59 M^{-1} sec^{-1} measured in the absence of ammonia, so ammonia blocks the reaction of tetren rather than assisting it.

Resolution of Rate Constants.—The pH dependence of the rate constants can be expressed in terms of the protonated and free polyamine species present in solution, *e.g.*, with trien

$$k_{\mathrm{obsd}}[\mathrm{trien}]_{\mathrm{total}} = k_{\mathrm{trien}}{}^{\mathrm{CuL}}[\mathrm{trien}] + k_{\mathrm{Htrien}}{}^{\mathrm{CuL}}[\mathrm{Htrien^+}] + k_{\mathrm{H_2trien}}{}^{\mathrm{CuL}}[\mathrm{H_2trien^{2+}}] \qquad (7)$$

The individual values of the rate constants were resolved graphically where possible. For cases in which the closeness of the ligand protonation constants or the similarity of the individual rate constants or the experimental scatter complicated this graphical approach, the observed rate constants were resolved by use of a linear regression analysis which fit the entire pH profile to eq 7 or its equivalent (see Table III). This was accomplished by means of a weighted regression analysis program carried out on an IBM 7094 computer.[8] The graphical resolution of tetren with copper–CyDTA was checked by the computer method and gave good agreement.

Table II

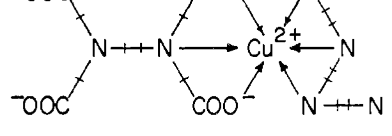
Second-Order Rate Constants for Reaction of Ethylenediamine with Copper–CyDTA–en at $\mu = 0.10$ and 25.0°

pH	10^4[CuCy]$_i$, M	[en]$_i$, M	k_{obsd}/[en]$_i$, M^{-1} sec^{-1}
10.60	5.00	0.100	0.12
10.60	5.00	0.200	0.13
10.39	61.6	0.0988	0.16

Discussion

Need for Three Nitrogen Donors.—Ammonia and en form stable mixed complexes with copper–EDTA and copper–CyDTA and are very poor displacing ligands. On the other hand dien and other polyamines with three or more nitrogen donor atoms do displace CyDTA and EDTA. Even though a mixed complex of copper–EDTA–dien forms, it loses the EDTA portion rapidly. The ring in CyDTA blocks the formation of a stable mixed complex so that dien forces CyDTA off the copper ion. The reaction of dien is faster than trien > tetren > penten. In general three nitrogen donor atoms in a polyamine are sufficient for the displacement of EDTA or CyDTA, and, although additional nitrogen donors may make the reaction more favorable thermodynamically, they make it less favorable kinetically.

If three nitrogen atoms from the polyamine bond to copper before the rate-determining step, then at least half of the EDTA ion must be unwrapped[3] as shown in structure I for the reaction with trien. (*In this and in subsequent structures copper–carboxylate bonds are included to give a maximum coordination number of six.*



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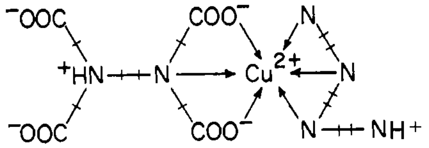
However, two of the six coordinate bonds would be expected to be weak and it is not essential to the argument that the carboxylate groups be coordinated.) The effect of acidity on the reactions and the significance of the resolved rate constants in Table III can be understood in terms of such a reaction intermediate. In the pH range studied the number of sites available for protonation equals $N - 2$, where N is the number of polyamine nitrogen atoms. The proton sites are $N - 3$ from the coordinated polyamine and +1 is from the EDTA as shown in structure II. Comparison of the resolved rate constants in Table III shows that when the number of protons, x, initially associated with the



II

Table III

Resolved Second-Order Rate Constants for Polyamine Reactions with Copper–EDTA and Copper–CyDTA at 25.0° and $\mu = 0.1$

Polyamine	$k_{\text{polyamine}}{}^{\text{CuEDTA}}$, M^{-1} sec^{-1}	$k_{\text{polyamine}}{}^{\text{CuCyDTA}}$, M^{-1} sec^{-1}
penten	$(1.7 \pm 0.3) \times 10^{4\,b}$	
Hpenten$^+$	$(1.6 \pm 0.3) \times 10^{4\,b}$	
H_2penten^{2+}	3.0×10^3	
H_3penten^{3+}	1.5×10^3	
tetren	$(2.2 \pm 1.1) \times 10^{5\,b}$	5.0
Htetren$^+$	$(3.7 \pm 0.3) \times 10^{5\,b}$	4.7
H_2tetren^{2+}	$(6.7 \pm 1.6) \times 10^{3\,b}$	0.2
H_3tetren^{3+}	$(3.4 \pm 2.5) \times 10^{1\,b}$	0.007 (estd)
trien	$(4.3 \pm 0.5) \times 10^{5\,b}$	5.4
Htrien$^+$	$(3.5 \pm 0.5) \times 10^{4\,b}$	2.5
H_2trien^{2+}	$(2.1 \pm 0.4) \times 10^{2\,b}$	0.04
dien		15
Hdien$^+$		3.4
en		0.12^a

[a] This is the rate constant for the en reaction with Cu(en)-CyDTA^{2-} at pH 10.6. [b] Computer resolved.

polyamine is greater than $N - 2$ there is no reaction. If $x = N - 2$, a reaction is possible but at a greatly diminished rate compared to $x = 0$. If $x < N - 2$, there is relatively little difference in the rate constants. Hence the listing of rate constants for Hdien$^+$, H_2trien^{2+}, and H_3tetren^{3+} is only for convenience in resolution of the pH profiles. Proton transfer to the leaving EDTA ion permits three nitrogen donor groups from the polyamine to bond to copper in each case.

Comparison to Nickel–EDTA Reactions.—Table IV shows a nearly constant ratio of 2×10^6 for the reaction rate constants of polyamine species with copper–EDTA compared to nickel–EDTA. This constant ratio indicates a close parallel in the two reaction mechanisms. In the nickel reactions the rate-determining step proposed was the rupture of the second EDTA–nitrogen bond after three polyamine–nitrogen bonds had formed. The same mechanism fits for copper and an important part of the 2,000,000-fold increase in rate can be accounted for in the greater stability of copper–nitrogen bonds. The estimated ratio in eq 8 predicts an even larger effect than that observed experimentally. However, there are several reasons why the estimate is too large. First, the Jahn–Teller effect with copper may give a lower stability for the copper–dien segment because of the difficulty of achieving a planar configuration in the stepwise replacement of EDTA. Second, the water or ligand replacement rates from highly chelated metals differ from the aquo ions and nickel–dien has been observed to be particularly labile in ammonia–water replacement reactions.[20]

$$\frac{k_{\text{polyamine}}{}^{\text{CuEDTA}}}{k_{\text{polyamine}}{}^{\text{NiEDTA}}} = \frac{K_{\text{Cu(dien)}}K_{\text{NiEDTA}}}{K_{\text{Ni(dien)}}K_{\text{CuEDTA}}}\frac{k_{-\text{H}_2\text{O}}{}^{\text{Cu}}}{k_{-\text{H}_2\text{O}}{}^{\text{Ni}}} = 2 \times 10^9 \text{ (estimated)} \tag{8}$$

Table IV

Comparison of Rate Constants of tetren, trien, and Their Protonated Ions with Copper–EDTA, Copper–CyDTA, and Nickel–EDTA[a] at 25.0° and 0.10 μ

Polyamine	$k_{\text{polyamine}}{}^{\text{NiEDTA}}$, M^{-1} sec^{-1}	$k_{\text{polyamine}}{}^{\text{CuEDTA}}/k_{\text{polyamine}}{}^{\text{CuCyDTA}}$	$k_{\text{polyamine}}{}^{\text{CuEDTA}}/k_{\text{polyamine}}{}^{\text{NiEDTA}}$
tetren	1.0×10^{-1}	4.4×10^4	2.2×10^6
Htetren$^+$	2.5×10^{-1}	7.9×10^4	1.5×10^6
H_2tetren^{2+}	4.7×10^{-3}	3.4×10^4	1.4×10^6
H_3tetren^{3+}	9.5×10^{-6}	4.8×10^2	3.6×10^6
trien	1.0×10^{-1}	8.0×10^4	4.3×10^6
Htrien$^+$	2.3×10^{-2}	1.4×10^4	1.5×10^6
H_2trien^{2+}	3.0×10^{-4}	5.3×10^3	0.67×10^6

[a] The rate constants for nickel–EDTA are calculated from the reverse rate constants[3] and appropriate stability constants.

Comparison of EDTA and CyDTA.—The reactions of most polyamine species (Table IV) are about 5×10^4 faster with copper–EDTA than with copper–CyDTA. The close parallel of these rate constants, the reactivity of dien, and the need for two en molecules to react with copper–CyDTA indicate a mechanism similar to that for EDTA despite the much greater steric hindrance of CyDTA. An earlier paper[12] discussed the inability of metal ions to react with metal–CyDTA complexes owing to steric factors. Structures such as I and II in which half of an EDTA segment is unwrapped and completely rotated away from the copper are not possible with CyDTA. Nevertheless, a configuration in which one iminodiacetate group of CyDTA is twisted away from the other appears to be the explanation for the proton-dissociation reaction[12] and fits the present case. Hence, three polyamine nitrogens can coordinate and the reaction path parallels that of EDTA but there is diminished reactivity because of steric hindrance.

The stability constant of copper–CyDTA is $10^{21.95}$ compared to $10^{18.80}$ for copper–EDTA. The more basic nitrogen atoms and cagelike structure of CyDTA account for its stronger complexes. In the proposed reaction path both factors contribute to a smaller rate constant because both stabilize the reactant but not the transition state.

The activation energy measured for the reaction of unprotonated trien with copper–CyDTA is 4.5 kcal/mole and $\log A = 4.0$. The frequency factor is very low and suggests steric blocking and a highly ordered reaction pathway.

Comparison of the Resolved Rate Constants for Protonated Polyamines.—Electrostatically the more protonated polyamines would have greater attraction for the negative copper–EDTA and –CyDTA complexes, but the reaction rate decreases with increased polyamine protonation owing to the need for nitrogen donors. Only with tetren and penten does the addition of one proton give the same or a larger rate constant (Table III). Otherwise one or more protons on the polyamine diminish the rate constant.

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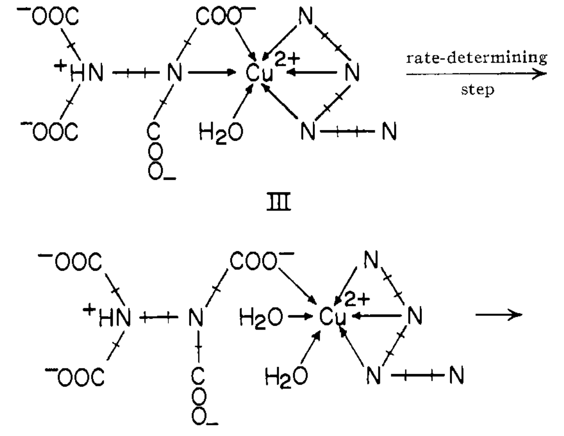
(20) D. W. Margerum and H. M. Rosen, *J. Am. Chem. Soc.*, **89**, 1088 (1967).

Protons can assist the removal of EDTA as well as prevent the coordination of all of the polyamine and there is sufficient time for proton transfer to occur during the reaction. Hence, to understand the acid dependence, consideration must be given to what are the most basic sites before the rate-determining step. The reaction intermediate shown in structure II is applicable for the reaction of H_2trien^{2+} and $CuEDTA^{2-}$ and represents a much more favorable reaction path than would be the case if both protons stayed on the trien. Even when $Htrien^{+}$ is the reactant, the proton should transfer to the EDTA segment before the rate-determining step[21] as shown in eq 9. The proton is expected to transfer to the EDTA nitrogen in structure III because this site is more basic and the electrostatic repulsion from Cu^{2+} will be better shielded. Furthermore, the proton in this position will assist the bond rupture of the second EDTA nitrogen. Nevertheless $Htrien^{+}$ is only $^1/_{12}$ as effective as trien in displacing EDTA because in free $Htrien^{+}$ the proton stability constant is $10^{9.8}$ and this is greatly reduced when the proton is on an EDTA nitrogen only three atoms removed from a 2+ metal ion. With H_2trien^{2+} the rate constant drops by another factor of 170 because of the difference in $K_2 = 10^{9.1}$ and the stability of the proton on a polyamine nitrogen adjacent to the copper (structure II).

$Htrien^{+} + CuEDTA^{2-} \longrightarrow$

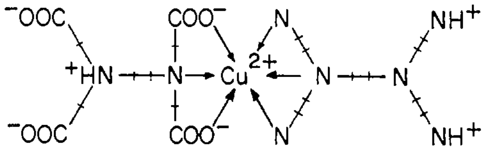


III

IV

$$HEDTA^{3-} + Cu(trien)^{2+} \qquad (9)$$

The magnitude of each of the rate constants in Table III can be understood by assigning protons to the more basic sites and a consistent pattern is found in agreement with the proposed mechanism. For example, protonation of penten causes only a small change in rate constant, three protons lowering the value by only a factor of 10, because the protons can be dispersed as seen in structure V.



V

Rate Constant–pH Profiles.—In the general case, where one multidentate ligand replaces another, the pH dependence will be determined by the number and basicity of the donor groups in each ligand and by the bonding in the transition state. In the present case the transition state resembles the polyamine complexes more than the EDTA complex but the number of coordination sites and steric factors limit the polyamines to three coordinate bonds before the rate-determining step. The rate constants decrease with decreasing pH because the proton competition hinders polyamine formation more than it helps EDTA dissociation—a direct result of the number of strong donor groups in each ligand. In the reaction of EDTA with zinc–penten[9] the leaving group has the greater number of strongly basic sites and the rate constant decreases with increasing pH. Reactions in which similar ligands replace one another will have intermediate behavior, thus with $CdEDTA^{2-}$ the kinetic reactivity[5] is $EDTA^{4-} > HEDTA^{3-} \sim H_2EDTA^{2-}$.

Acknowledgments.—This work was supported in part by National Science Foundation Grant G 22566, by a David Ross Grant from the Purdue Research Foundation (R. A. L.), and by a Minnesota Mining and Manufacturing Co. fellowship (J. D. C.).

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(21) The value for $k^{\text{CuEDTA}}_{\text{Htrien}}$ is $3.5 \times 10^{-4}\ M\ \text{sec}^{-1}$, while the rate constant for Cu–NH_3 dissociation should be $\sim 10^{4}\ \text{sec}^{-1}$. Rupture of the Cu–N bond in glycine should give an even smaller first-order rate constant. This is not inconsistent because the stability constant of III should be >1. The reactant concentrations are too small to give measurable concentrations of III.