the reaction involves a metal rather than hydrogen, the more stable chelate will further weaken the C–H (or C–D) bond of the α carbon of the amino acid by electron withdrawal and increase the rate of reaction, the effect being greater for the C–H than the C–D bond. This would qualitatively account for the greater ratio of k_H/k_D when a metal ion is present but the ratio could also be increased by an increase in concentration of the Schiff base.

Experimental

Isolation and Purification of L-Deuterio-alanine.—The isolation of L-deuterio-alanine from the algae *Scenedesmus obliquus* has been described elsewhere.[6] A modification for desalting the amino acid was carried out: The amino acid was dissolved in a small volume of one molar hydrochloric acid and passed through a 10-cm. column (0.9 cm. in diameter) of Dowex 50-X8 resin. The column was washed with water until the eluate was pH 7.0 and was chloride free. The column then was eluted with 15% aqueous ammonia and after the first drop of eluate was pH 8.0 a volume of 100 ml. was collected. The ammonium hydroxide removed the amino acid from the column without removing the sodium ions. The eluate was evaporated to dryness on a steam bath, the residue was decolorized with charcoal and recrystallized from ethanol. The identity of the deuterated amino acid was again established by chromatogramming 5 λ of a 1% solution, 5 λ of a 1% solution of ordinary amino acid, and a 5 λ aliquot of a mixed solution of both known and unknown compounds. Elemental analysis and optical rotation measurements indicated pure L-deuterio-alanine

$$CD_3-\overset{\overset{\textstyle D}{|}}{\underset{\underset{\textstyle NH_2}{|}}{C}}-COOH$$
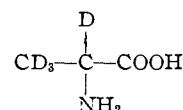
Data obtained from a Spinco amino acid analysis indicated a purity better than 99%.

L-Alanine.—L-Alanine was obtained from the Nutritional Biochemical Corporation and the purity was checked by chromatographic analysis.

Pyridoxal.—Pyridoxal was obtained as the hydrochloride from the same source and its purity checked by analysis.[8]

Water.—Water was triply distilled and deionized.

D₂O.—D₂O of 99.6% concentration was distilled from a Barnstead conductivity still after digestion with hot alkaline permanganate. Other chemicals were analytical reagent grade. All chemicals were checked for metal content by spectrographic analysis.

Measurements of pH were made with a Beckman Model 76 expanded scale pH meter.

Kinetic Measurements.—Stock solutions were prepared for each run from weighed quantities of alanine and pyridoxal hydrochloride. This solution, with buffer added where required, was transferred to 5-ml. ampoules, sealed and placed in a boiling water bath at 100° at time zero. At suitable intervals ampoules were removed, plunged into ice water and the contents analyzed for pyridoxal at room temperature using a Coleman Junior spectrophotometer.[8] The stability of the pyridoxal at 100° was tested and found to be stable for periods of five hours over the pH range 3 to 9 in the presence and absence of added buffer.

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, PURDUE UNIVERSITY, LAFAYETTE, IND.]

Coördination Chain Reactions. Exchange between Ethylenediaminetetraacetatocuprate(II) and Triethylenetetraminenickel(II)

BY D. C. OLSON AND D. W. MARGERUM[1]

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A chain reaction mechanism is proposed for the exchange of triethylenetetramine and ethylenediaminetetraacetate between their nickel(II) and copper(II) complexes. This exchange proceeds at a much faster rate than the aqueous dissociation rate of these complexes. The chain reaction is initiated by a trace of either of these multidentate ligands. In the chain-propagation steps one multidentate ligand displaces another from its metal complex and *vice versa*. Very sensitive control of the reaction rate is possible because the chain propagators are stable ligands whose concentration can be adjusted. Metal ions terminate the chain and the reaction can be used for trace metal determination.

Introduction

The kinetics of ligand (or metal) exchange between two multidentate ligand complexes is shown to proceed by a chain reaction mechanism. The exchange occurs between the complex ions triethylenetetraminenickel-(II) and ethylenediaminetetraacetatocuprate(II), abbreviated NiT^{+2} and CuY^{-2}, respectively.

$$NiT^{+2} + CuY^{-2} \longrightarrow CuT^{+2} + NiY^{-2} \qquad (1)$$
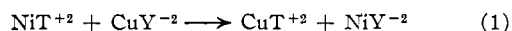
Triethylenetetramine (trien) occupies four sites in the metal coördination sphere[2,3] and its complexes with nickel(II) and copper(II) have stability constants with log K_1 values of 14.0 and 20.4, respectively.[4] Ethylenediaminetetraacetic acid (EDTA) occupies five coördination sites in the case of nickel[5] and its complexes with nickel(II) and copper(II) have stability constants with log K_1 values of 18.56 and 18.79, respectively.[6] These constants indicate that reaction

1 goes essentially to completion so that the reverse reaction can be neglected in the kinetic study.

The rate of dissociation of NiT^{+2} and its pH dependence has been studied by Clarke[7a] and Latterell.[7b] The rate of dissociation of CuY^{-2} can be calculated from its stability constant and its rate of formation.[8] The rate of reaction 1 is much faster than the rate of dissociation of either NiT^{+2} or CuY^{-2}, indicating that the exchange is not controlled by their dissociation rates.

The rate of attack of Ni^{+2} on CuY^{-2} and of Cu^{+2} on NiT^{+2} have been recently measured[7b,9] and are both too slow to contribute significantly to the reaction rate because of the low concentrations of the aquo metal ions in the reaction system. On the other hand, the rate of attack of EDTA on NiT^{+2} is known to be extremely rapid even at very low ligand concentration,[7a] and recent work in this Laboratory[10] has shown that in a similar manner the rate of trien attack on 1,2-diaminocyclohexanetetraacetocuprate-(II) is much greater than the rate of dissociation of

(1) Correspondence to be addressed to this author.

(2) H. B. Jonassen and B. E. Douglas, *J. Am. Chem. Soc.*, **71**, 4094 (1949).

(3) H. B. Jonassen and A. W. Meibohm, *J. Phys. Colloid Chem.*, **55**, 726 (1951).

(4) G. Schwarzenbach, *Helv. Chim. Acta*, **33**, 974 (1950).

(5) G. S. Smith and J. L. Hoard, *J. Am. Chem. Soc.*, **81**, 556 (1959).

(6) G. Schwarzenbach, R. Gut and Z. Anderegg, *Helv. Chim. Acta*, **37**, 937 (1954).

(7) (a) J. F. G. Clarke, Ph.D. Thesis, Purdue University, 1960; (b) J. J. Latterell, M.S. Thesis, Purdue University, 1962.

(8) H. Ackermann and G. Schwarzenbach, *Helv. Chim. Acta*, **35**, 485 (1952).

(9) T. J. Bydalek and D. W. Margerum, *J. Am. Chem. Soc.*, **83**, 4326 (1961).

(10) D. W. Margerum and R. A. Libby, to be published.

this complex. Therefore, the reactions

$$Y_T + NiT^{+2} \longrightarrow NiY^{-2} + T_T$$

$$T_T + CuY^{-2} \longrightarrow CuT^{+2} + Y_T$$
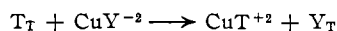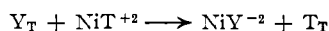
where Y_T and T_T represent the sum of the uncomplexed species of EDTA and trien, respectively, are proposed as chain-propagating steps which permit the relatively rapid exchange of ligands to occur in reaction 1. This occurs even at very low free ligand concentrations. This mechanism is supported by the catalytic effect of a very low concentration of multidentate ligand on the rate and by the inhibition of the rate by low concentrations of metal ion. It is further supported by the reaction orders determined under a variety of concentration and pH conditions.

The chain reaction process proposed for reaction 1 is believed to be the first example of a chain reaction for coördination substitution reactions where no oxidation or reduction occurs. However, it should not be a unique path but a likely path for many metal complex–metal complex exchange reactions and should be particularly important for multidentate ligand complexes.

The application of coördination chain reactions to the determination of trace metals or ligands appears very promising.

Experimental

Precautions were taken to ensure that there was no excess ligand or metal ion in either reactant and that there was minimal interference from trace impurities of metal ions. A mixed-bed ion exchange column was used to reduce metal ion contamination in the water and the glassware used for rate solutions was rinsed consecutively with 0.5 M HCl, 0.01 M alkaline EDTA and deionized water.

Solutions of NiT^{+2}, CuY^{-2}, NiY^{-2} and CuT^{+2} were prepared by the addition of a slight excess of the metal perchlorate to a known quantity of ligand followed by precipitation of the excess as the metal hydroxide at about pH 10.5. The solutions were adjusted to about pH 7 for storage.

The metal perchlorates were prepared from the corresponding carbonates and perchloric acid. The perchlorates were recrystallized before use. Their solutions were standardized by EDTA titration.[11]

The EDTA and 1,2-diaminocyclohexanetetraacetic acid (CyDTA) were recrystallized several times from water and dissolved in two equivalents of sodium hydroxide. Their solutions were standardized by titration[11] with a standard copper(II) solution prepared from pure copper wire. The trien disulfate (J. T. Baker Chemical Co.) was recrystallized[12] and was standardized by a spectrophotometric titration utilizing the CuT^{+2} absorbance.

A 0.005 to 0.01 M sodium borate–boric acid and mannitol buffer system was used to control the pH. The kinetics of the reaction were pH sensitive but were independent of the concentration of this buffer and gave the same results with a recommended non-coördinating buffer,[13] 2,6-lutidine and its perchlorate salt. The sodium borate and boric acid were added to the NiT^{+2} solution and the mannitol was added to the CuY^{-2} solution, so that the pH of the rate solution was established upon mixing the reactants.

A Beckman DU spectrophotometer with a thermostated cell compartment ($\pm 0.1°$) was used for the rate data. Reaction 1 was followed at 550 and 590 mμ. The molar absorptivities (ϵ) of the species are given in Table I. When a large excess of NiT^{+2} is present in a reaction, the (CuY^{-2}) is equal to ($A_\infty - A$)/$b\Delta\epsilon$, where A_∞ is the absorbance of the reaction at completion, A is the absorbance at any time, $\Delta\epsilon$ is the difference in ϵ between products and reactants and b is the cell length. When an excess of CuY^{-2} is present, this expression is equal to the concentration of NiT^{+2}.

Sodium perchlorate was used to maintain the ionic strength of the reactions below pH 7.9. Potassium chloride was used for higher pH runs because it had less metallic interference. To avoid interference from potassium perchlorate in the pH measurements, sodium chloride was substituted for potassium chloride in the calomel electrode.

(11) F. J. Welcher, "The Analytical Uses of Ethylenediaminetetraacetic Acid," D. Van Nostrand Co., Inc., New York, N. Y., 1958, p. 241.

(12) C. N. Reilley and M. V. Sheldon, *Talanta*, **1**, 127 (1958).

(13) J. G. Pritchard and R. A. Long, *J. Am. Chem. Soc.*, **79**, 2365 (1957).

TABLE I

MOLAR ABSORPTIVITIES

Species	ϵ, 550 mμ	ϵ, 590 mμ
Ni^{+2}	6.33	5.69
CuY^{-2}	6.02	20.0
NiY^{-2}	5.65	8.39
CuT^{+2}	142	148

Results

Rate of Dissociation of the Reactants.—The dissociation of NiT^{+2} into Ni^{+2} and T_T is greatly accelerated by acid. This reaction rate has been measured[7a,b] at 25.0° and is equal to $(55[H^+][NiT^{+2}] + 7 \times 10^8[H^+]^2[NiT^{+2}])$ M min.$^{-1}$.

The formation rate constant for the Cu^{+2} reaction with EDTA is known[8] at 0° and also has been measured in this Laboratory at 25.0° and 0.1 μ giving $k_{Cu}^{HY} = 7.5 \times 10^{10}$ M^{-1} min.$^{-1}$. The acid dissociation rate of CuY^{-2} at 25° can be calculated from the appropriate equilibrium constants and equals 2.2 $\times$ 10^2 $[H^+][CuY^{-2}]$ M min.$^{-1}$ (the term corresponding to $[H^+]^2[CuY^{-2}]$ is negligible above pH 5). Dissociation rate constants for NiT^{+2} and CuY^{-2} which do not involve H^+ terms are so small that they have not been detected up to pH 7.5.

The above expressions permit the dissociation rate of the reactants to be compared with the experimentally observed exchange rate. In Table II, runs 3 and 4 are at the lowest pH and for these runs with excess $[NiT^{+2}]$ the dissociation reactions are as rapid or more rapid than the observed exchange reaction. A pre-equilibrium of NiT^{+2} and T_T is a possibility for reactions at this pH with step B rate determining in the mechanism discussed later. This would give the ABD path and the pre-equilibrium would give a reaction order with $[NiT^{+2}]^{1/2}$ as observed.

However, at higher pH and in particular for all other runs in Table II the exchange reaction is more rapid than the dissociation rate of either reactant. For example, in run 1 at pH 6 the exchange is 50% complete in less than 13 minutes. This is five times faster than the dissociation of the corresponding small fraction of NiT^{+2} and is two hundred times faster than the dissociation of 50% of CuY^{-2}. For run 7 at the same pH with the concentration conditions for the reactants reversed the exchange is now 240 times faster than 50% NiT^{+2} dissociation and about five times faster than the necessary small fraction of CuY^{-2} dissociation. At pH 6.5 (run 6) the discrepancy between the exchange rate and the dissociation rate is even greater. The observed time for 10% exchange is about 30 minutes while both dissociation reactions would require about 1200 minutes.

Thus, an important restriction on any general reaction mechanism is that it be possible for the exchange rate to exceed the dissociation rate of the reactants. This is consistent with the chain mechanism proposed.

Experimental Reaction Orders.—Two variations of the differential method[14] were used in the determination of the reaction order with respect to $[CuY^{-2}]$ and $[NiT^{+2}]$. In the first method the system was swamped with one species and the reaction order was obtained for the other species from the slope of a plot of $-\log$

(14) K. J. Laidler, "Chemical Kinetics," McGraw-Hill Book Co., Inc., New York, N. Y., 1950, p. 14.

$[-d(A_\infty - A)/dt]$ against $-\log(A_\infty - A)$. The $-d(A_\infty - A)/dt$ term was obtained from tangents to the curve of $(A_\infty - A)$ against time. In the second differential method two or more reactions were run keeping the concentration of one species constant and varying the other. The order with respect to the concentration, C, of the species varied was obtained by plotting $-\log[-d(A_\infty - A)/dt]$ against $-\log C$. The reaction orders with respect to $[NiT^{+2}]$ in the presence of a small excess of $[CuY^{-2}]$ at pH values of 6.28 and 6.50 and with respect to $[CuY^{-2}]$ in the presence of a small excess of $[NiT^{+2}]$ at pH 6.20, were determined in this manner. The CuY^{-2} and NiT^{+2} solutions were both brought to equilibrium at the pH of the run before mixing to avoid reaction induction periods.

Table II shows that the reaction orders are complex and vary with the ratio of concentration of reactants and

TABLE II

Summary of Reaction Orders Determined by Differential Methods 25.0°, 0.10 and 0.20 μ (NaClO₄)

Run	Initial concentrations [NiT^{+2}]	[CuY^{-2}]	pH	Reaction order with respect to [NiT^{+2}]	[CuY^{-2}]
1	2.50×10^{-3}	2.00×10^{-4}	6.01	..	0.91
2	2.50×10^{-3}	5.00×10^{-4}	6.08	..	0.93
3	1.50×10^{-3}	1.00×10^{-4}	5.41 ⎱	0.46	..
4	1.00×10^{-3}	1.00×10^{-4}	5.41 ⎰		
5	1.50×10^{-3}	1.00×10^{-4}	5.99 ⎱	0.44	..
6	3.50×10^{-4}	1.00×10^{-4}	5.99 ⎰		
7	2.00×10^{-4}	2.50×10^{-3}	6.01	2.0	..
8	5.00×10^{-4}	2.50×10^{-3}	6.00	1.7	..
9	2.00×10^{-4}	2.50×10^{-3}	6.01 ⎱	..	0.92
10	2.00×10^{-4}	4.50×10^{-3}	6.00 ⎰		
11	1.03×10^{-2}	1.42×10^{-2}	6.23 ⎤ [a]		
12	1.03×10^{-2}	1.05×10^{-2}	6.21 ⎬	..	0.7
13	1.03×10^{-2}	7.02×10^{-3}	6.20 ⎦		
14	1.25×10^{-4}	2.66×10^{-3}	7.35 ⎱	..	-0.09
15	1.25×10^{-4}	1.33×10^{-3}	7.35 ⎰		
16	1.47×10^{-2}	1.67×10^{-2}	6.51 ⎤ [a]		
17	9.76×10^{-3}	1.67×10^{-2}	6.50 ⎬	1.5	..
18	4.88×10^{-3}	1.67×10^{-2}	6.51 ⎦		
19	1.45×10^{-2}	1.65×10^{-2}	6.29 ⎤ [a]		
20	1.45×10^{-2}	1.65×10^{-2}	6.30 ⎬	1.5	..
21	9.64×10^{-3}	1.65×10^{-2}	6.28 ⎪		
22	4.84×10^{-3}	1.65×10^{-2}	6.27 ⎦		

[a] Ionic strength is 0.20. Runs 1, 2, 7 and 8 used the first differential method and all other runs used the second differential method.

with pH. If the results are rounded to the nearest half-power, the rate law with an excess of NiT^{+2} present is

$$-d[CuY^{-2}]/dt = d[CuT^{+2}]/dt = k_{X,NiT}[CuY^{-2}][NiT^{+2}]^{1/2}$$
(2)

When $[CuY^{-2}]$ is in excess the order with respect to $[NiT^{+2}]$ appeared to vary from 1.5 to 2.0 and the order with respect to $[CuY^{-2}]$ appeared to vary from zero to one, according to the pH. At the higher pH values the rate law with excess CuY^{-2} would be

$$d[CuT^{+2}]/dt = k_{X,CuY}[NiT^{+2}]^{1/2}$$
(3)

Induction Period.—When NiT^{+2} is in excess and a reaction is run at a pH lower than the pH of the NiT^{+2} solution before mixing, an induction period is observed. Figure 1 shows such a reaction where the NiT^{+2} solution was initially above pH 8 and the reaction was run at pH 6 without pre-equilibration. The equilibrium concentration of trien is on the order of 10^{-5} M at the lower pH compared to 10^{-7} M at the higher pH. The reaction gives a first-order slope only after an induction period corresponding to the time necessary for the trien concentration to grow to the higher level.[15] The dissociation rate of NiT^{+2} is still
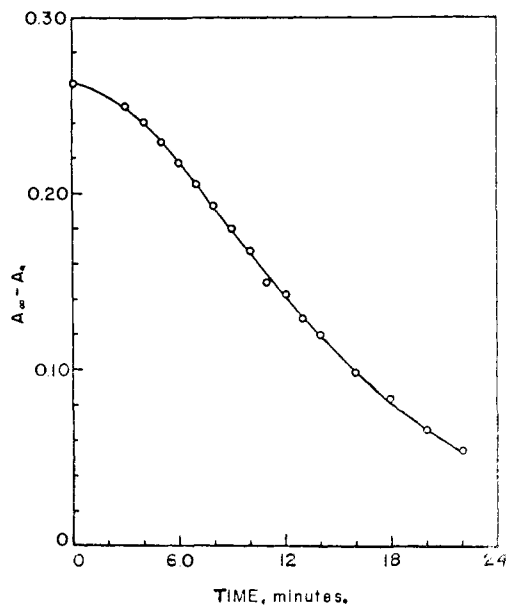

Fig. 1.—A zero-order plot of the exchange of NiT^{+2} (initially 2.50×10^{-3} M at pH >8) and CuY^{-2} (initially 2.00×10^{-4} M at pH 10) run at pH 6, 25.0°, 0.10 μ. The induction period is attributed to the growth of the concentration of free trien from less than 10^{-7} M to about 10^{-5} M at the pH of the reaction.
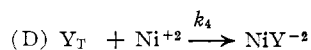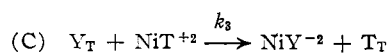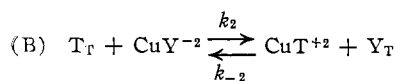
slower than the observed exchange reaction, but less than 1% of the NiT^{+2} needs to dissociate to bring the trien to its new equilibrium level. The free trien concentration plays a large part in the rate of the reaction and its growth is responsible for the induction period. By contrast, when an excess of CuY^{-2} was present, no induction periods were observed. The reason for this behavior is discussed after a consideration of the proposed mechanism. The induction periods with NiT^{+2} in excess disappeared with prior equilibration of the NiT^{+2} solution at the pH of the exchange reactions. Thus, the induction period is not a characteristic of all runs but is indicative of the type of reaction system.

Effect of Trace Quantities of Additional Trien, EDTA and Metal Ions.—As shown later in the determination of individual rate constants and in the analytical application, the presence of 10^{-6} M added ligand at higher pH values greatly accelerates the rate of reaction 1. Conversely, similar concentrations of complexing metal ions greatly inhibit the reaction rate.

Proposed Chain Reaction Mechanism.—A chain reaction consistent with the observed kinetics is proposed for the exchange reaction.
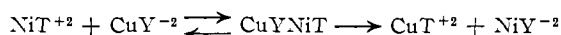
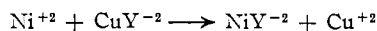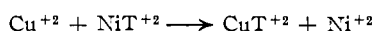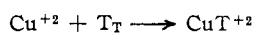$$(A) \quad NiT^{+2} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} Ni^{+2} + T_T$$
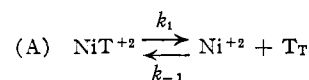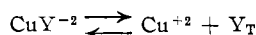
(15) S. W. Benson, "The Foundations of Chemical Kinetics," McGraw-Hill Book Co., Inc., New York, N. Y., 1960, pp. 52, 334.

$$\text{(B)} \quad T_T + CuY^{-2} \underset{k_{-2}}{\overset{k_2}{\rightleftarrows}} CuT^{+2} + Y_T$$

$$\text{(C)} \quad Y_T + NiT^{+2} \xrightarrow{k_3} NiY^{-2} + T_T$$

$$\text{(D)} \quad Y_T + Ni^{+2} \xrightarrow{k_4} NiY^{-2}$$

Step A is the chain-initiating step which provides small concentrations of T_T to the system. Steps B and C are chain-propagating steps which maintain the free ligand concentration. Step D is chain-terminating in that it removes Y_T from the reaction and slows the exchange but it does give the reaction product and can be important under certain conditions. The reverse step in A is also chain terminating and it inhibits the reaction. No reverse reaction for C is written as the stability constants of NiT^{+2} and NiY^{-2} show that the ratio, k_3/k_{-3}, where k_{-3} is the rate constant for the reverse reaction, varies from $10^{7.6}$ at pH 6 to $10^{4.5}$ at pH 9. Under the most adverse conditions used in this work (pH 9, $[T_T]/[Y_T] = 10^{-3}$), the forward rate in step C is about thirty times the reverse rate.

Several possible reactions omitted from the mechanism are

$$CuY^{-2} \rightleftarrows Cu^{+2} + Y_T$$

$$Cu^{+2} + T_T \longrightarrow CuT^{+2}$$

$$Cu^{+2} + NiT^{+2} \longrightarrow CuT^{+2} + Ni^{+2}$$

$$Ni^{+2} + CuY^{-2} \longrightarrow NiY^{-2} + Cu^{+2}$$

$$NiT^{+2} + CuY^{-2} \rightleftarrows CuYNiT \longrightarrow CuT^{+2} + NiY^{-2}$$

The slow rate of dissociation of CuY^{-2} and the low level of concentrations of Cu^{+2} and Y_T prevent the first three of these steps from contributing to the mechanism. The rate of the fourth step is known[9] to be too slow to be of importance. No evidence could be found for the last reaction, which is the direct exchange of ligands.

General Kinetic Expression.—In the ABCD mechanism the rate of exchange depends upon the rate of the chain-propagating step B (or step C)

$$d[CuT^{+2}]/dt = k_2[T_T][CuY^{-2}] - k_{-2}[Y_T][CuT^{+2}] \quad (4)$$

The concentrations of T_T and Y_T may be obtained by application of the steady-state approximation to both species and substituted into equation 4 to give the general rate expression

$$\frac{d[CuT^{+2}]}{dt} = \frac{k_1k_2[CuY^{-2}][NiT^{+2}](k_3[NiT^{+2}] + k_4[Ni^{+2}])}{k_2k_4[Ni^{-2}][CuY^{-2}] + k_{-1}[Ni^{+2}](k_3[NiT^{+2}] + k_4[Ni^{+2}] + k_{-2}[CuT^{+2}])} \quad (5)$$

Excess NiT^{+2}.—When $[NiT^{+2}]$ is in excess its terms in both the numerator and denominator of eq. 5 become predominant and the other terms may be neglected. Equation 5 then becomes

$$\frac{d[CuT^{+2}]}{dt} = \frac{k_1k_2[CuY^{-2}][NiT^{+2}]}{k_{-1}[Ni^{+2}]} \quad (6)$$

The ratio k_1/k_{-1} is the apparent (or effective) instability constant of NiT^{+2}. Since step C rapidly regenerates T_T due to the excess NiT^{+2}, the equilibrium concentration of T_T is maintained and the term $[NiT^{+2}]/[Ni^{+2}]$ in eq. 6 may be replaced by $[NiT^{+2}]^{1/2}$. The rate expression is then

$$d[CuT^{+2}]/dt = k_2(k_1/k_{-1})^{-1/2}[CuY^{-2}][NiT^{+2}]^{1/2} \quad (7)$$

which agrees with the experimental rate law in eq. 2 where $k_{x,NiT}$ is $k_2(k_1/k_{-1})^{-1/2}$. The experimental rate expression could be obtained by a mechanism involving steps A, B and C as above, or by a mechanism involving steps A, B and D. In order to maintain an equilibrium concentration of T_T by the ABD path, the rate of dissociation of NiT^{+2} would have to be greater than the observed rate of exchange. Since this is not the case except at low pH, the ABC path must predominate giving eq. 7.

The induction period already described occurs with excess NiT^{+2} and a shift to lower pH because of the time required for step A to adjust to an equilibrium concentration of T_T.

Excess CuY^{-2}.—Equation 5 may be simplified by again assuming that $k_3[NiT^{+2}]$ is much greater than $k_4[Ni^{+2}]$, which can be justified by the extremely low $[Ni^{+2}]$ at the pH of the NiT^{+2} solution before mixing and the slowness of NiT^{+2} dissociation compared to the exchange reaction. A second assumption which can be made for solutions at higher pH is that the $[CuY^{-2}]$ term predominates in the denominator when it is in excess. This reduces eq. 5 to

$$d[CuT^{+2}]/dt = k_1k_3[NiT^{+2}]^2/k_4[Ni^{+2}] \quad (8)$$

The $[Ni^{+2}]$ and the sum of $[T_T]$ and $[Y_T]$ are equal from consideration of the ABCD mechanism and eq. 8 can be solved using the sum of the steady-state solutions for these terms to give

$$\frac{d[CuT^{+2}]}{dt} =$$
$$\left(\frac{k_1k_2}{k_4}\right)^{1/2} \frac{k_3[NiT^{+2}]^{3/2}[CuY^{-2}]^{1/2}}{(k_3[NiT^{+2}] + k_{-2}[CuT^{+2}] + k_2[CuY^{-2}])^{1/2}} \quad (9)$$

Again assuming that the $[CuY^{-2}]$ term predominates in the denominator gives

$$d[CuT^{+2}]/dt = (k_1/k_4)^{1/2} k_3[NiT^{+2}]^{3/2} \quad (10)$$

which agrees with the experimental rate law given in eq. 3. The zero order dependence in $[CuY^{-2}]$ is particularly significant since this fits runs 14 and 15 where these approximations are best. The $[CuY^{-2}]$ is in 10- to 20-fold excess and although k_3 is greater than k_2 at higher pH, its value decreases more rapidly with decreased pH, so the approximation is valid. The agreement with $[NiT^{+2}]^{3/2}$ for runs 16–22 may be fortuitous because the $[CuY^{-2}]$ excess is not so great and we do not know the ratio of k_2 to k_3 at these lower pH values. In addition, as the pH is lowered from 7 to 6 this rate expression will not hold because the ratio k_{-2}/k_2 increases with decreasing pH so that the k_{-2}-$[CuT^{+2}]$ term becomes important. This gives the rate a dependence on CuY^{-2} as found, but the product inhibition probably causes the variable orders found.

No induction period occurs with excess CuY^{-2} because the rate does not depend on the equilibrium concentration of T_T. The concentration of T_T is always extremely small because the excess CuY^{-2} in step B rapidly converts it to Y_T and step D prevents Y_T from increasing.

In summary, it is possible to obtain a reasonable fit of the variable reaction orders using the proposed mechanism and the general kinetic expression. However, as the next section shows, the complications and approximations may all be eliminated simply by the addition of excess ligand which provides the best evidence for the chain reaction. The preceding results are still of importance, however, because they give some

estimate of the initiation and termination steps. The individual rate constants obtained in the next section are consistent with those estimated from the preceding work, but are more accurate because impurity corrections have been made.
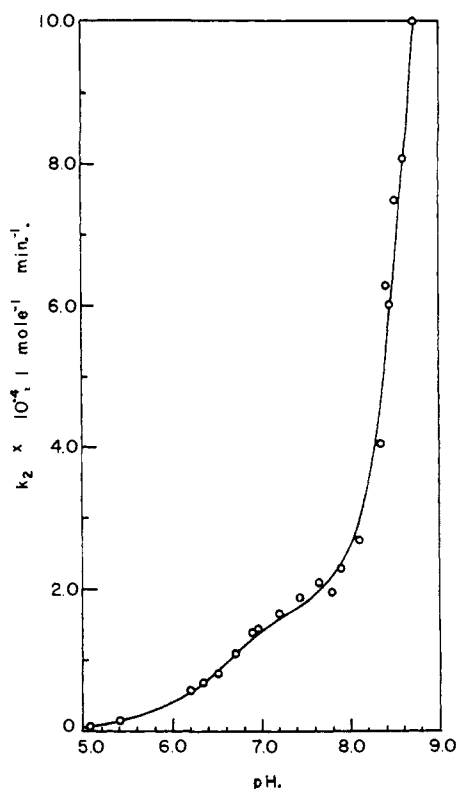

Fig. 2.—Effect of pH on the second-order rate constant for the trien attack of CuY^{-2}; 25.0°, 0.1 μ, 1.00 × 10^{-4} M $[CuY^{-2}]_0$ and a 12- to 25-fold excess $[NiT^{+2}]_0$ with 10^{-6} to 10^{-5} M extra trien added. Points are rate constants from individual runs using eq. 12 or from groups of runs to check impurity levels such as in Fig. 3. The curve represents the fit of these data to the constants assigned in Table IV.

Study of the Chain Propagation Rate Constants.—
The chain-initiating step A and chain-terminating step D may be eliminated from the exchange reaction by the addition of an excess of either trien or EDTA to the reaction. If the pH of the NiT^{+2} and CuY^{-2} solutions are high before mixing, the equilibrium concentrations of free metal ion and ligand are very low compared to the added ligand concentration. The amount added should be sufficient to cause the exchange to proceed much faster than the rate of dissociation of NiT^{+2}. Under these conditions only the chain-propagating steps B and C contribute to the rate.

Determination of k_2.—If NiT^{+2} is present in large excess the added free ligand will be predominantly present as T_T because of step C. Since $[Y_T]$ will be very low, the reverse reaction of step B can be neglected and eq. 4 becomes

$$d[CuT^{+2}]/dt = -d[CuY^{-2}]/dt = k_2[T_T]_0[CuY^{-2}] \quad (11)$$

where $[T_T]_0$ is the concentration of T_T added to the reaction. No product inhibition was found in agreement with eq. 11. Equation 11 indicates a reaction first-order in CuY^{-2} and independent of the extent of excess NiT^{+2}. This was confirmed experimentally. Values of k_2 determined over a wide pH range shown in Fig. 2 were obtained from plotting eq. 12. The condi-

tions were 10^{-4} M CuY^{-2}, a 12-fold or greater excess of NiT^{+2} and 10^{-6} to 10^{-5} M extra trien.

$$\log [CuY^{-2}] = \frac{-k_2[T_T]_0 t}{2.303} + \log [CuY^{-2}]_0 \quad (12)$$

The values of k_2 at pH 5.06 and 5.41 were determined under different conditions because step A becomes more rapid at low pH. A large excess of NiT^{+2} and Ni^{+2} was added without excess trien. Under these conditions the value of k_2 was determined from the slope of a first-order plot of the integrated form of eq. 6.
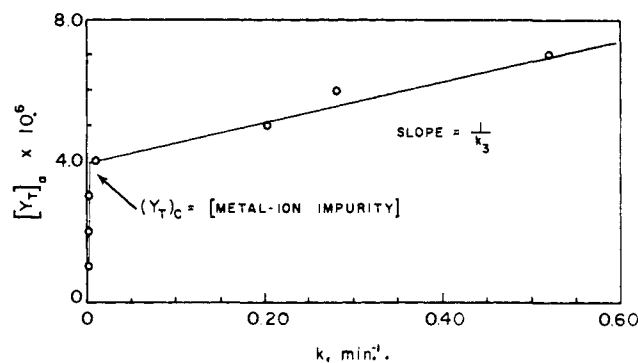

Fig. 3.—The effect of trace concentrations of the chain propagator (EDTA) on the exchange rate constant. A complexing impurity removes the initial traces of EDTA and the exchange rate is virtually constant until uncomplexed EDTA is available. The conditions are those required for eq. 13 and 14: 9.65 × 10^{-5} $[NiT^{+2}]_0$, 1.76 × 10^{-3} $[CuY^{-2}]_0$, borate buffer pH 8.90, 25.0°, 0.10 μ.

Determination of k_3.—A large excess of CuY^{-2} keeps the added free ligand present predominantly as Y_T because of step B. The rate of the reverse step in B was kept negligible by using a high pH where the ratio of k_2/k_{-2} is large. Thus, at the lowest pH used, 8.70, it can be shown from the stability constants of CuT^{+2} and CuY^{-2} that the forward rate constant in B is 30 times the reverse rate constant. No product inhibition was observed. The rate of the exchange reaction equals $k_3[Y_T]_0[NiT^{+2}]$ which can be integrated to give

$$\log [NiT^{+2}] = -(k_3[Y_T]_0 t/2.303) + \log [NiT^{+2}]_0 \quad (13)$$

The values of k_2 in Table III were determined from plots of eq. 13 and of eq. 14 as described below. The conditions were 10^{-4} M NiT^{+2} with a 15-fold excess of

TABLE III

Effect of pH on the Second-order Rate Constant for the EDTA Attack on NiT^{+2}

25.0°, 0.10 μ 10^{-4} M $[NiT^{+2}]_0$ with a 15-fold excess $[CuY^{-2}]_0$, extra EDTA added from 10^{-6} to 10^{-5} M

pH	k_3, l. mole^{-1} min.$^{-1}$ × 10^{-5}	pH	k_3, l. mole^{-1} min.$^{-1}$ × 10^{-5}
8.80	1.6	9.21	3.2
8.90	1.7	9.84	3.7
8.91	2.4	10.34	4.0
9.02	3.5		

CuY^{-2} and with 10^{-6} to 10^{-5} M extra EDTA added. A slope was determined for each pH in the same manner as in Fig. 3 to give k_3. This rate constant increases very rapidly with pH and the Y^{-4} ion appears to be the

most reactive attacking species. The scatter in the data is due to the great sensitivity of this system to traces of EDTA-complexing impurities and the k_3 term was not resolved further.

Correction for Metal Ion Impurities.—Sodium perchlorate was first used to control the ionic strength in the determination k_3, but the results were erroneous due to an impurity present which complexed part of the EDTA. The EDTA concentration in these runs was $1.0 \times 10^{-5}\ M$. When potassium chloride was used to control the ionic strength the rate increased by a factor of about one hundred. A metal ion impurity was still present in these runs, but at a much lower concentration level. The chain reaction was used to analyze for this impurity and the value of k_3 was obtained by correcting for the amount of added ligand complexed. Under conditions where eq. 13 was used it can be shown that

$$[Y_T]_a = (k/k_3) + [Y_T]_c \qquad (14)$$

where $[Y_T]_a$ is the amount of EDTA added, k is the observed first-order rate constant obtained from a plot of eq. 13 and $[Y_T]_c$ is the amount of EDTA complexed by the metal ion impurity. Figure 3 shows such an analysis at pH 8.9 where a $4 \times 10^{-6}\ M$ EDTA complexing impurity was present. The added EDTA does not accelerate the rate of exchange until all the impurity has been exhausted and then the abrupt change in rate is found.

In a similar manner eq. 12 may be used to give

$$[T_T]_a = (k'/k_2) + [T_T]_c \qquad (15)$$

where k' is the observed rate constant from a plot of eq. 12 and $[T_T]_c$ is the concentration of a trien complexing impurity. The values of k_2 were obtained by correcting for the impurity found from eq. 15. In this case the concentration of impurity found in the potassium chloride was approximately the same as that found with added EDTA. On the other hand, the sodium perchlorate gave negligible interference with added trien as opposed to strong interference in the case of added EDTA. This illustrates possible selectivity in this type of analysis.

Resolution of k_2 into Terms for H_2T^{+2}, HT^+ and T.—The increase in k_2 with increased pH may be accounted for in terms of the various trien species present. In the range pH 5.0 to 7.0 the predominant forms of trien are H_3T^{+3} and H_2T^{+2}. Assuming these ions attack CuY^{-2} with rate constants k_{H_3T} and k_{H_2T}, eq. 16 can be derived

$$k_2\left(1 + \frac{K_{H_3T}}{[H^+]}\right) = \frac{k_{H_3T}K_{H_3T}}{[H^+]} + k_{H_2T} \qquad (16)$$

where K_{H_3T} is the ionization constant of H_3T^{+3} at $25.0°$, $\mu = 0.1$. The pK_{H_3T} was estimated to be 6.55 from literature[16] values at $20.0°$, $\mu = 0.1$, and the heat of ionization from $30°$ to $40°$ at $\mu = 1.0$. A plot of the lefthand side of eq. 16 against $1/[H^+]$ gives a straight line passing through the intercept for six points up to $1/[H^+] = 5 \times 10^{-6}$. This indicates a negligible value for k_{H_3T} compared to k_{H_2T} and the slope is used to find k_{H_3T}. A slight deviation of the linear relationship occurs at higher pH where very small amounts of HT^+ begin to contribute to the reaction.

Above pH 8 the rate may be written in terms of the rate constants k_{H_2T}, k_{HT} and K_T giving

$$k_2\left(1 + \frac{K_{HT}}{[H^+]} + \frac{[H^+]}{K_{H_2T}}\right) - \frac{k_{H_2T}}{K_{H_2T}} = \frac{k_TK_{HT}}{[H^+]} + k_{HT} \qquad (17)$$

where K_{H_2T} and K_{HT} are the ionization constants which were estimated in the same manner as H_3T^{+3}; $pK_{H_2T} = 9.08$, $pK_{HT} = 9.74$. Using the value of k_{H_2T} from above, eq. 17 was solved for k_{HT} and k_T. The best fit of values are given in Table IV.

TABLE IV

RATE CONSTANTS FOR TRIEN ATTACK ON CuY^{-2}, $25.0°$, $\mu = 0.10$

Trien	Rate constant, 1. mole^{-1} min.$^{-1}$
H_3T^{+3}	$k_{H_3T} < 10^2$
H_2T^{+2}	$k_{H_2T} = 1.81 \times 10^4$
HT^+	$k_{HT} = 8.0 \times 10^4$
T	$k_T = 2.7 \times 10^6$

Temperature Dependence of k_2 and k_{H_2T}.—Table V gives the temperature effect for the individual rate constant k_{H_2T} and for k_3 at pH 8.8, when the latter has not been resolved into the pH dependent terms. The Arrhenius and transition state parameters are also given.

TABLE V

TEMPERATURE DEPENDENCE OF k_3 (pH 8.8) AND k_{H_2T}

T, °C.	k_{H_2T}, 1. mole^{-1} min.$^{-1}$ $\times 10^{-4}$	k_3, 1. mole^{-1} min.$^{-1}$ $\times 10^{-5}$	——Kinetic parameters——		
				k_{H_2T}	k_3
15.0	1.11	1.65	E_a kcal.	11.7	9
25.0	1.81	2.00	pZ, cm.$^{-1}$	1.1×10^{11}	1×10^{10}
35.0	4.28	5.10	$\Delta H^{\ddagger}$, kcal.	11.1	8
			$\Delta S^{\ddagger}$, e.u.	-7.9	-12

Analytical Application of the Chain Reaction.—As shown in the correction for metal ion impurities, eq. 14 and 15 can be used to determine trace quantities of metal ions if they complex trien or EDTA. Similarly, trace quantities of ligands can be determined if they displace trien or EDTA from their complexes. The results of some determinations are given in Table VI where the conditions used were those suitable for

TABLE VI

TRACE ANALYSIS BY COÖRDINATION CHAIN REACTION RATES[a]

Metal ion or ligand	Added moles/l. $\times 10^6$	Found moles/l. $\times 10^6$	Deviation, %
Ni^{+2}	3.23	3.05	$- 6$
Cu^{+2}	4.27	4.58	$+ 7$
$Cu^{+2} + Ni^{+2}$	3.01	3.23	$+ 7$
CyDTA	2.62	2.33	-13
CN^-	6.5	7.9	$+22$

[a] CyDTA is 1,2-diaminocyclohexanetetraacetic acid. The cyanide analysis is based on $Ni(CN)_4^{-2}$ formation. The percentage deviation is high because of errors in correcting for background impurities.

eq. 15. With the calibration curve established the time required for a determination was about 15 minutes.

Discussion

The data presented give very strong support to the proposed coördination chain reaction. There can be little doubt that the ligands rapidly displace one another from their complexes compared to the displacement by water and that this leads to the proposed chain propagation steps. For instance at pH 8.8 the half-life

(16) J. Bjerrum, G. Schwarzenbach and L. G. Sillén, "Stability Constants Part I, Organic Ligands." The Chemical Society, London, 1957.

for the dissociation of NiT^{+2} (assuming no hydroxide attack) is about 10^6 minutes while the value of k_3 gives a half-life of a few seconds if EDTA and NiT^{+2} are present at $10^{-3}\,M$. The process involved in the formation of NiY^{-2} helps to discharge the trien from the nickel. An initial intermediate can be postulated in which both complexes are bound to nickel, $NiTH_xY^{-2+x}$, which can form by an EDTA chelate substituting for two water molecules bound to the nickel. A sequence of reactions then occurs in which trien dentates are released by nickel and substituted by EDTA dentates.

The fact that $\Delta S^{\ddagger}$ for k_2 is -12 e.u. despite the charge reduction in bringing the species together and the probable release of coördinated water from the NiT^{+2} indicates a highly orientated transition state. A stepwise equilibrium of decreasing trien dentate number with the breaking of the last chelate as a rate-determining step has been proposed for its dissociation from nickel.[7a] This is in agreement with the polyamine dissociation data of Ahmed and Wilkins.[17] The role of EDTA in this reaction is to increase the concentration of a partially unwrapped trien intermediate by blocking the coördination position left by breaking a nickel–nitrogen (trien) bond. This increase in concentration of partially coördinated trien is magnified relative to the water displacement because the process can repeat itself by further reducing the extent of trien coördination leaving only a single chelate. In effect, EDTA crowds trien off the nickel ion.
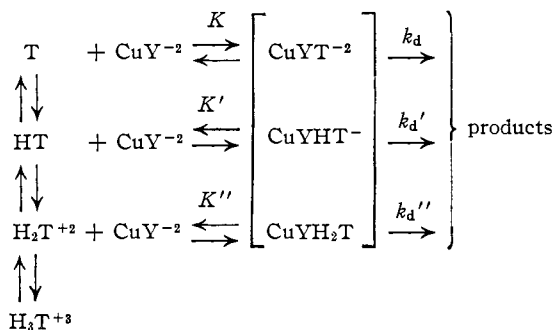
A similar effect is seen in step B with trien attack of CuY^{-2}. Since it was possible to resolve k_3 into terms for H_2T^{+2}, HT^+ and T, it is worthwhile to consider possible mechanisms in greater detail. The very large ratio of k_{H_3T}/k_{H_4T} suggests that the first intermediate must involve at least two copper–trien bonds as
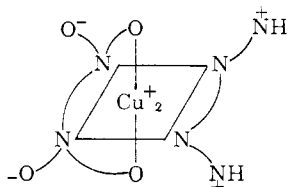
The complex $CuYen^{-2}$ has been reported[18] and is more stable than either CuY^{-2} or $Cu(en)_2^{+2}$ in the pH range 7.5 to 10. Therefore, the mixed $CuYH_2T$ complex is very probable. The increase in rate constants in going from H_2T^{+2} to HT^+ to T can be correlated with greater trien coördination and lower EDTA coördination to copper.

The resolution of the trien rate constants into the individual constants for H_2T^{+2}, HT^+ and T attack of CuY^{-2} fits the complicated pH dependence in Fig. 2 very well as shown by the calculated curve. However, if intermediates consisting of trien, copper and EDTA precede the rate-determining step, then proton equilibration of the intermediates would be expected as

long as the proton transfers do not involve additional formation or cleavage of coördinate bonds. The rate constants for the neutralization of ammonium groups by hydroxide ion[19] indicate that the protons on trien in an intermediate could equilibrate more rapidly than the rate of the ligand exchange reaction. Thus suggests the following mechanism where the intermediates shown all have the same bonding to copper and are all in equilibrium with the reactants. The additional intermediates with different bonding to copper are encompassed in the k_d, $k_d{}'$ and $k_d{}''$ rate constants.

$$
\begin{array}{c}
T + CuY^{-2} \overset{K}{\underset{}{\rightleftharpoons}} \left[CuYT^{-2} \right] \overset{k_d}{\longrightarrow} \\
\updownarrow \\
HT + CuY^{-2} \overset{K'}{\longleftarrow} \left[CuYHT^- \right] \overset{k_d{'}}{\longrightarrow} \\
\updownarrow \\
H_2T^{+2} + CuY^{-2} \overset{K''}{\longleftarrow} \left[CuYH_2T \right] \overset{k_d{''}}{\longrightarrow} \\
\updownarrow \\
H_3T^{+3}
\end{array}
\quad\Big\} \text{ products}
$$

The rate of product formation is

rate $= k_d[CuYT^{-2}] + k_d{}'[CuYHT^-] + k_d{}''[CuYH_2T]$, or

rate $= (k_d K[T] + k_d{}'K'[HT^+] + k_d{}''K''[H_2T^{+2}])[CuY^{-2}]$

which gives the same resolution of rate constants as before ($k_d K = k_T$ etc.). The assumption is that these intermediates form and dissociate rapidly compared to the subsequent steps in the exchange of the ligands.

Chain mechanisms for metal complex–metal complex exchange reactions could be written for many other systems and should be expected when sufficient free ligand is available to increase the dissociation rate of the complexes. Multidentate complexes should be particularly susceptible to this type of reaction because their dissociation rates are slower and lower concentrations of these ligands are needed to accelerate their displacement than in the case of mono- or bidentate ligands. Chain mechanisms can be expected with excess metal ion as well as with excess ligand. The steric effects in the displacement of multidentate ligands are extremely important and should permit selectivity in this type of reaction.

The analytical application of a coördination chain reaction system to trace analysis could be extended to a p.p.b. range if all impurities could be removed from the present system. If NiT^{+2} were replaced by the corresponding tetraethylenepentamine complex a lower range of trace analysis would be possible. It should also be possible to gain selectivity by pH control and by masking with ligands not capable of entering the chain reaction.

(17) A. K. S. Ahmed and R. G. Wilkins, J. Chem. Soc., 3700 (1959).
(18) B. Kinson, Bull. soc. chim. France, 1897 (1960).
(19) M. T. Emerson, E. Grunwald and R. A. Kromhout, J. Chem. Phys., 33, 547 (1960).