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Kinetics of Multidentate Ligand Substitution Reactions. XV. Substitution Reactions of 1,2-Cyclohexanediamine-*N*,*N*,*N*′,*N*′-tetraacetic Acid (CyDTA) with Zinc(II) Iminodiacetate (IDA), *N*-(2-Hydroxyethyl)iminodiacetate (HIDA), and Nitrilotriacetate (NTA) Complexes and Those with Cobalt(II)-IDA, -HIDA, NTA, -*N*-(2-Hydroxyethyl)ethylenediamine (EtEN), and Diethylenetriamine (Dien) Complexes

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The kinetics of the substitution reactions of CyDTA with zinc(II)-IDA, -HIDA, and -NTA complexes and those with cobalt(II)-IDA, -HIDA, -NTA, -EtEN, and Dien complexes were studied by using the polarographic technique. All the substitution reactions studied in this paper were found to have a common reaction mechanism. They were first-order with respect to the CyDTA anion, and they were also first-order with respect to the metal(II) complex with a 1 : 1 composition; their reaction mechanism could be formulated as:

$$MX_2^{(2-2m)+} \rightleftharpoons MX^{(2-m)+} + X^{m-} \qquad \text{in a rapid equilibrium}$$

$$MX^{(2-m)+} + \begin{cases} HY^{3-} \rightleftharpoons MY^{2-} + HX^{(1-m)+} \\ Y^{4-} \rightleftharpoons MY^{2-} + X^{m-} \end{cases} \qquad \text{rate determining steps}$$

From a comparison of the observed rate constants with those estimated on the basis of the proposed reaction intermediate, the detailed reaction mechanism and structures of the reaction intermediates were discussed. The steric effect of the cyclohexane ring on the rate of the substitution reaction was also discussed.

We have studied a series of substitution reactions involving metal(II) aminopolycarboxylate complexes and have determined their detailed reaction mechanism.[2] Usually, the nucleophilic substitution reactions involving zinc(II) complexes proceed so rapidly that one can not determine their reaction rates accurately by employing a conventional technique. However, the substitution reaction of CyDTA with the zinc(II) aminopolycarboxylate complex proceeds at a measurable rate under the usual experimental conditions. In this paper, we will deal with the kinetics of the substitution reactions of CyDTA with zinc(II)-IDA, -HIDA, and -NTA complexes, and will discuss the detailed reaction mechanism and the steric effect of the cyclohexane ring on their reaction rates. To describe more precisely the reaction mechanism and the above steric effect, the substitution reactions of CyDTA with the cobalt(II) complexes of IDA, HIDA, NTA, EtEN, and Dien will also be studied.

Experimental

Reagents. The preparation and the standardization of zinc(II) and cobalt(II) solutions were described previously.[3,2a] Reagent-grade IDA, HIDA, NTA, and CyDTA were recrystallized from their aqueous solutions by adding pure hydrochloric acid and ethanol. The Dien and EtEN used in this study were purified by distilling them under reduced pressure. The other chemicals used were of an analytical reagent grade and were used without further purification.

Apparatus and Experimental Procedures. The apparatus and the experimental procedures were the same as those described previously.[2c] In this study, all the measurements were conducted in solutions of an ionic strength of 0.30 ($NaClO_4$ for the IDA, HIDA, and NTA systems; KNO_3 for the EtEN and Dien systems). No buffer reagent was used in this study, because free IDA, HIDA, NTA, EtEN, and Dien have enough buffer capacity to maintain the pH values of sample solutions constant over the entire pH range covered. The sample solutions used in the kinetic study of the substitution reactions of CyDTA with the cobalt(II)-IDA, -HIDA, and -NTA complexes always contained large excesses of complexed and uncomplexed IDA, HIDA, and NTA over CyDTA, while those in the reactions of CyDTA with zinc(II)-IDA, -HIDA, and -NTA complexes and with the cobalt(II)-EtEN and -Dien complexes contained large excesses of CyDTA and uncomplexed IDA, HIDA, NTA, EtEN, and Dien over the metal(II) complex. Therefore, all the substitution reactions studied in this paper could be treated as pseudo first-order reactions. The rates of the substitution reactions of CyDTA with the zinc(II) complexes and those of the reactions with the cobalt(II)-polyamine complexes were followed by measuring the change in the reduction wave-height of the zinc(II) complex and the oxidation wave-height of the cobalt(II) complex respectively. On the other hand, the rates of the substitution reactions with the cobalt(II)-IDA, -HIDA, and -NTA complexes were followed by determining the change in the dissolution wave-height due to the uncomplexed CyDTA.

Results and Discussion

Although not all the results will be shown here, the following facts were found in preliminary experiments. Provided that the other experimental conditions are kept constant, the forward pseudo first-order rate constant, k^{+}_{ap}, obtained from the slope of the linear relation between $\log(i_0/i_t)$ and t, was (1) inversely proportional to the concentration of the uncomplexed

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[2] a) M. Kodama, This Bulletin, **40**, 2575 (1967). b) M. Kodama, C. Sasaki, and M. Murata, *ibid.*, **41**, 1333 (1968). c) M. Kodama, *ibid.*, **42**, 2532 (1969). d) M. Kodama, *ibid.*, **42**, 3330 (1969). e) M. Kodama and T. Ueda, *ibid.*, **43**, 419 (1970).

[3] M. Kodama and N. Oyama, *ibid.*, **45**, 2169 (1972).

IDA, HIDA, NTA, EtEN, and Dien, $[X]_f$, (2) exactly proportional to the concentration of the metal(II) complex (the cobalt(II)-IDA, -HIDA, and -NTA systems), [Me(II)], or the CyDTA concentration (the cobalt(II)-EtEN and -Dien systems and the zinc(II)-IDA, -HIDA, and -NTA systems), $[Y]_f$, and (3) independent of the initial concentration of CyDTA (the cobalt(II)-IDA, -HIDA, and -NTA systems) or that of the metal(II) complex (the cobalt(II)-EtEN and -Dien systems and the zinc(II)-IDA, -HIDA, and -NTA systems). Furthermore, as is shown by the results obtained in the reactions with zinc(II)-HIDA, cobalt(II)-Dien and cobalt(II)-HIDA complexes (Figs. 1, 2, and 3), the k^+_{ap} multiplied by $K_2 \cdot [X]_f \cdot (\alpha_H)_Y/(\alpha_H)_X[Ex]$ is a linear function of the concentration of the hydrogen ion, $[H^+]$, and is given by:

$$\frac{k^+_{ap}K_2[X]_f \cdot (\alpha_H)_Y}{(\alpha_H)_X[Ex]} = k_\alpha + k_\beta \cdot [H^+] \qquad (1_a)$$

where [Ex] denotes $[Y]_f$ or [Me(II)], and where $(\alpha_H)_Y$ and $(\alpha_H)_X$ are the (α_H) values of CyDTA and IDA, HIDA, NTA, EtEN, or Dien respectively, and where the other symbols used in the equation (1) have their usual meanings.[4,5,6] Considering that, under the present experimental conditions ($8.90<pH<9.80$ in the IDA system, $8.30<pH<9.80$ in the HIDA system, $9.00<pH<9.60$ in the NTA system, $9.70<pH<10.70$ in the EtEN system, and $9.50<pH<11.0$ in the Dien system), all the metal ions are considered to exist in the form of $MX_2^{(2-2m)+}$, the above experimental facts suggest that all the substitution reactions have the following common reaction mechanism:

$$MX_2^{(2-2m)+} \rightleftharpoons MX^{(2-m)+} + X^{m-} \quad \text{in a rapid equilibrium}$$

$$MX^{(2-m)} + \begin{cases} HY^{3-} \overset{k_H}{\rightleftharpoons} MY^{2-} + HX^{(1-m)+} \\ Y^{4-} \overset{k_0}{\rightleftharpoons} MY^{2-} + X^{m-} \end{cases} \quad \text{rds}$$

For the above reaction mechanism, Eq. (1_a) can be rewritten as:

$$\frac{k^+_{ap} \cdot K_2 \cdot [X]_f \cdot (\alpha_H)_Y}{(\alpha_H)_X[Ex]} = k_o + k_H \cdot \frac{[H^+]}{|K_4} \qquad (1_b)$$

where $|K_4$ is the fourth dissociation constant of CyDTA. From the slopes and the intercepts of the linear relations between $k^+_{ap} \cdot K_2 \cdot [X]_f \cdot (\alpha_H)_Y/(\alpha_H)_X \cdot [Ex]$ and $[H^+]$, the k_H and k_0 values were determined; they are listed in Tables 1, 2, and 3. As is clear from the data in Table 1, the rates of the substitution reactions of CyDTA with zinc(II) complexes are much larger than

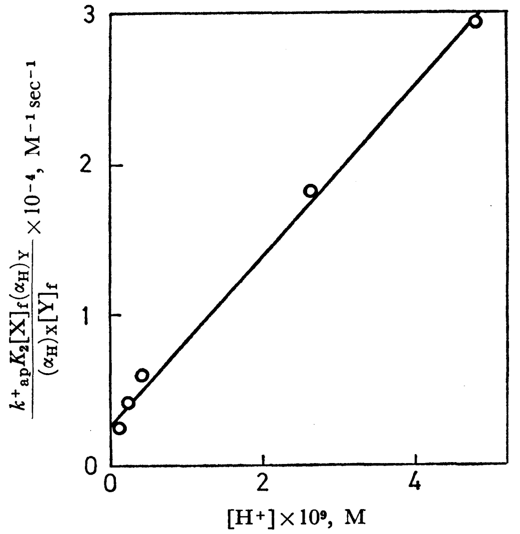

Fig. 1. The plot of $k^+_{ap} \cdot K_2 \cdot [X]_f \cdot (\alpha_H)_Y/(\alpha_H)_X \cdot [Y]_f$ against $[H^+]$ 0 °C, $\mu=0.30$.
The concentration of zinc(II) ion = 1.0 mM
The concentration of CyDTA = 12.5 mM
The concentration of uncomplexed HIDA = 17.8 mM
pH ranged from 8.30 to 9.80

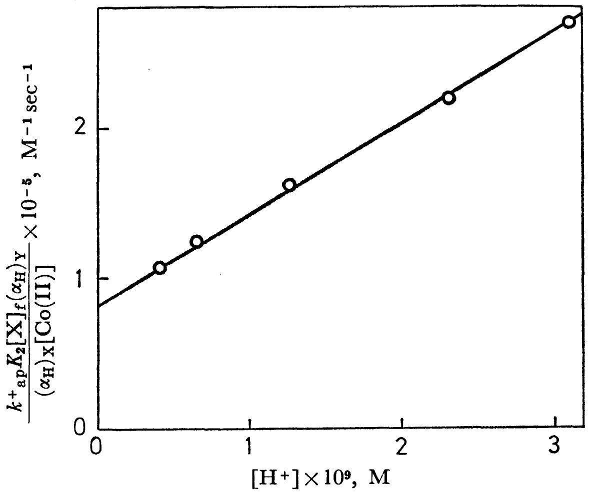

Fig. 2. The plot of $k^+_{ap} \cdot K_2 \cdot [X]_f \cdot (\alpha_H)_Y/(\alpha_H)_X \cdot [Co(II)]$ against $[H^+]$ 25.0 °C, $\mu=0.30$.
The concentration of cobalt(II) ion = 7.27 mM
The concentration of CyDTA = 0.545 mM
The concentration of uncomplexed HIDA = 10.9 mM
pH ranged from 8.50 to 9.50

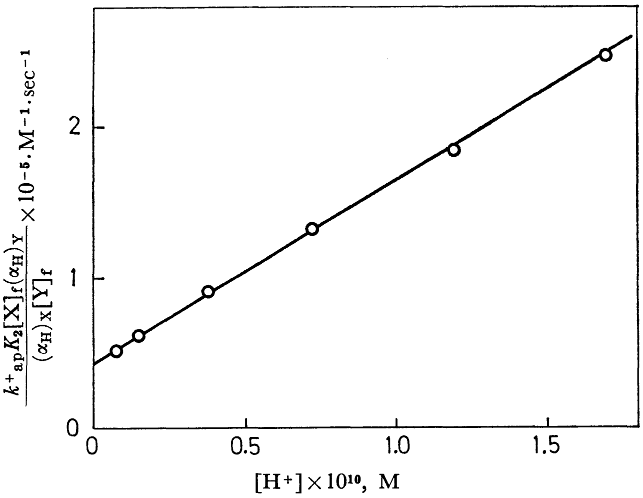

Fig. 3. The plot of $k^+_{ap} \cdot K_2 \cdot [X]_f \cdot (\alpha_H)_Y/(\alpha_H)_X \cdot [Y]_f$ against $[H^+]$ 0 °C, $\mu=0.30$.
The concentration of cobalt(II) ion = 1.16 mM
The concentration of CyDTA = 11.6 mM
The concentration of uncomplexed Dien = 131 mM

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[4] M. Kodama, S. Karasawa, and T. Watanabe, *ibid.*, **44**, 1815 (1971).

[5] M. Kodama, T. Sato, and S. Karasawa, *ibid.*, **45**, 2757 (1972).

[6] M. Kodama and N. Oyama, *ibid.*, **44**, 2849 (1971).

Table 1. Rate constants for the substitution reactions of CyDTA with the zinc(II) complexes
0 °C, $\mu = 0.30$

System		IDA	HIDA	NTA
k_o, $M^{-1} sec^{-1}$		$2.7_7 \times 10^{4}$[a)]	$2.6_5 \times 10^3$	7.5
k_H, $M^{-1} sec^{-1}$		5.90×10^2	2.08×10^1	5.4×10^{-2}
$\log K_{MX}$		6.72	8.02	10.0
$\log K_{st}$		0.30	0.30	0.48
$\log K_{elec}$		−0.50	−0.50	−1.0
$\Delta \log k$	calcd	1.30	0	−2.30
	obsd k_o	1.02[a)]	0	−2.55
	obsd k_H	1.45	0	−2.59

a) Less accurate.

Table 2. Rate constants for the substitution reactions of CyDTA with the cobalt(II) aminopolycarboxylate complexes
25.0 °C, $\mu = 0.30$

System		IDA	HIDA	NTA
k_o, $M^{-1} sec^{-1}$		—	8.2×10^4	8.5×10^1
k_H, $M^{-1} sec^{-1}$		3.17×10^3	$2.3_0 \times 10^2$	0.58
$\log K_{MX}$		6.64	7.66	10.15
$\log K_{st}$		0.30	0.30	0.48
$\log K_{elec}$		−0.50	−0.50	−1.0
$\Delta \log k$	calcd	1.02	0	−2.81
	obsd k_o	—	0	−2.98
	obsd k_H	1.19	0	−2.61

Table 3. Rate constants for the substitution reactions of CyDTA with the cobalt(II)-polyamine complexes
0 °C, $\mu = 0.30$

System		EtEN	Dien
k_o, $M^{-1} sec^{-1}$		8.7×10^5	4.3×10^4
k_H, $M^{-1} sec^{-1}$		4.49×10^4	4.53×10^3
$\log K_{MX}$		6.58	8.00
$\log K_{st}$		0	0.30
$\Delta \log k$	calcd	1.12	0
	obsd k_o	1.30	0
	obsd k_H	1.00	0

their corresponding dissociation rates.[7)] This can be explained in terms of the formation of the mixed-ligand-complex reaction intermediates involving the CyDTA anion. As was attempted in the substitution reaction of EDTA or EDTAOH with the nickel(II) ethylenediaminemonoacetate (EDMA) complex,[8)] we tried to estimate the structure of the reaction intermediate in the substitution reaction by comparing the relative rate constant observed with that calculated on the basis of the proposed reaction intermediate. The substitution reactions of CyDTA with the zinc(II)-HIDA and -NTA complexes proceed at measurable rates, but the corresponding EDTA reactions proceed so rapidly that one can not determine their rates by employing a conventional method. Usually, this can be ascribed to the steric effect of the cyclohexane ring on the substitution reaction. Generally speaking, it is reasonable to believe that the steric hindrance which will be encountered in the substitution reaction of CyDTA with the zinc(II)-HIDA complex is quite similar to that in the reaction with the zinc(II)-NTA complex. If the above assumption is correct, one can determine the structure of the reaction intermediate by comparing the relative rate constants for the zinc(II)-HIDA and -NTA complexes with those estimated on the basis of the proposed reaction intermediates. In the polarographic study of zinc(II)-HIDA and -NTA complexes in an acetate buffer solution, we found that these complexes dissociate through the glycinate reaction intermediate, where the leaving group is bonded to the zinc(II) ion through the glycinate chelate ring.[7)] Therefore, it is natural to consider that the HIDA and NTA anions in the reaction intermediates in the substitution reactions of CyDTA are also bonded to the zinc(II) ion through the glycinate chelate ring. As is shown by the data in Table 1, the relative rate constants calculated with the aid of this well-known relation: $k = k_{rds} \cdot K_L \cdot K_A \cdot K_{st} \cdot K_{elec} / K_{MX}$,[5)] on the basis of reaction intermediates given in Fig. 4 agree well with those observed. The relative rate constants calculated on the basis of the reaction intermediates other than those shown in Fig. 4 showed no satisfactory agreement with the observed ones. Since it is reasonable to consider that the steric effect brought about by the cyclohexane ring in the CyDTA reaction of the zinc(II)-NTA complex is not different from that of the zinc(II)-HIDA complex, the above agreement can be said to be an indication that the CyDTA anion in the reaction intermediate coordinates to the zinc(II) ion through the iminodiacetate group. In the calculation of the relative rate constants, the formation constants determined at 20 °C were used. Previously,[4)] we ascribed the sluggishness of the substitution reaction of CyDTA with the nickel(II)-HIDA complex to the steric interaction of the cyclohexane ring with the hydroxyethyl group of the HIDA anion. However, the Fisher-Hirschfelder-Taylor molecular model shows that the steric interaction of the

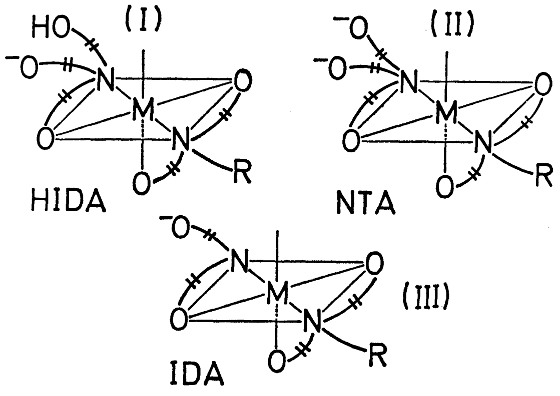

Fig. 4. Reaction intermediates.

[7)] M. Kodama, K. Namekawa, and T. Horiuchi, This Bulletin, to be published.

[8)] M. Kodama, M. Hashimoto, and T. Watanabe, *ibid.*, **45**, 2761 (1972).

cyclohexane ring with the hydroxyethyl group of the HIDA anion in the reaction intermediate is negligibly small. Furthermore, the fact that the rates of the reactions with zinc(II)- and cobalt(II)-IDA complexes can also be understood by assuming the reaction intermediates III (Tables 1 and 2) shows that the sluggishness of the CyDTA reaction with the metal(II)-HIDA complex can not be ascribed solely to the above steric interaction. For the successful formation of I and II in Fig. 4, the approach of the CyDTA anion to the coordination sphere and the formation of the zinc(II)-CyDTA bond should not be hindered by the steric interaction between the glycinate chelate ring, through which the leaving group is bonded to the zinc(II) ion, and the free iminodiacetate group of the CyDTA anion. The above steric requirement will be satisfied completely only when the rotation of the uncoordinated IDA group of CyDTA around the C–N bond is not hindered. However, as is shown by the molecular model, the cyclohexane ring in the CyDTA anion provides a greater barrier to the rotation of its uncoordinated IDA group. Therefore, the I and II structures can be formed, but only with some difficulty. Thus, the slow substitution reaction of CyDTA can be ascribed mainly to the above difficulty encountered in the reaction-intermediate formation. Undoubtedly, if the above steric effect of the cyclohexane ring on the rate of the substitution reaction can be neglected, the rate constant ratio between the dissociation of the zinc(II)-HIDA complex and its substitution reaction with CyDTA should be $10^{7.58}$. The observed ratio was $10^{3.42}$. Although the dissociation and substitution rates were determined at different temperatures (25 and 0 °C respectively), the above discrepancy can be accounted for by the steric effect of the CyDTA anion on the substitution reaction. Previously,⁵⁾ we mentioned in our kinetic study of the substitution reactions of Calmagite with the cobalt(II) and nickel(II) aminopolycarboxylate complexes that the reaction of the cobalt(II) complex proceeds through a reaction intermediate with the same structure as that in the reaction of the nickel(II) complex. Therefore, the finding that the reaction intermediate in the substitution reaction involving the zinc(II) aminopolycarboxylate complex has the same structure as that of the reaction involving thenickel(II) complex⁴⁾ suggests that the substitution reactions of CyDTA with the cobalt(II)-aminopolycarboxylate complexes proceed through the same reaction intermediate as that of the zinc(II) complex. In Table 2, the relative rate constant calculated on the basis of the reaction intermediates in Fig. 4, using the numerical data listed there also are compared with those observed. The calculated values agreed well with the observed ones. As in the case of the substitution reaction of CyDTA with the nickel(II) aminopolycarboxylate complex, the k_H value is much smaller than the k_0 value. Since the protonation of the CyDTA anion bonded to the metal(II) ion will reduce the electrostatic repulsion between the uncoordinated carboxylate groups and will stabilize the reaction intermediate, the fact that the k_H value is smaller than the k_0 value suggests the importance of the deprotonation of the attacking group in the formation of the reaction intermediate. The molecular model also shows that the protonation of the nitrogen atom in the uncoordinated IDA group in the CyDTA anion will provide a greater barrier to the formation of the reaction intermediate. Thus, the small k_H value can be understood in terms of the above barrier to the formation of the reaction intermediate. In this investigation, we also dealt with the substitution reactions of CyDTA with the cobalt(II)-EtEN and -Dien complexes. The rate constants for the two elementary reaction pathways are listed in Table 3. Previously,⁸⁾ we reported that the substitution reaction of EDTA with the nickel(II)-Dien complex proceeds through the outer-sphere complex, where the leaving Dien is bonded to the nickel(II) ion through the ethylenediamine chelate ring. The rates of the substitution reactions of CyDTA with the cobalt(II)-EtEN and -Dien complexes can also be understood by assuming an outer-sphere complex formation between the cobalt(II) complex ion and CyDTA anion. The rate constant ratio between the Dien and EtEN systems, calculated on the basis of the outer-sphere complex in which the leaving group is bonded to the cobalt(II) ion through the ethylenediamine chelate ring, agrees fairly well with the observed one. The k_H values for the cobalt(II)-polyamine systems are about ten times smaller than the k_0 values. This factor is clearly consistent with the relative electrostatic attraction of the ions concerned. Although the substitution reaction involving the cobalt(II)-EtEN complex was studied at 0 °C, the k_0 value is nearly identical to the characteristic rate constant for the water-loss from the cobalt(II) aquo ion at 25 °C. In considering the fact that the rate constant for the water loss at 0 °C must be smaller than that at 25 °C, and the fact that the equilibrium constant for the outer-sphere association between the cobalt(II) complex and the CyDTA anion is larger than unity,⁹⁾ the above agreement can also be taken as evidence for the water-loss mechanism proposed for the reactions of CyDTA with the cobalt(II)-polyamine complexes.

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9) R. M. Fuoss, *J. Amer. Chem. Soc.*, **80**, 5059 (1958).