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Kinetics of Multidentate Ligand Substitution Reactions. IV. Substitution Reactions of BT with Cobalt(II) and Nickel(II) Chelates of 1,2-Diaminocyclohexanetetraacetic Acid and Diethylenetriaminepentaacetic Acid

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The substitution reactions of Eriochrom Black T (BT) with cobalt(II) and nickel(II) chelates of 1,2-diaminocyclohexanetetraacetic acid (CyDTA) and of diethylenetriaminepentaacetic acid (DTPA) were studied spectrophotometrically. The reactions of BT with CyDTA and DTPA chelates of these metal(II) ions were found to have the same reaction mechanism as the reactions with EDTA chelates did, but to be considerably slower than the latter reactions. On the basis of a comparison of the observed rate constants with those calculated on the basis of the proposed reaction mechanism (glycinate intermediate), the steric effect due to the cyclohexane ring in the CyDTA or $-CH_2-CH_2-N(CH_2-COO^-)-CH_2-CH_2-N(CH_2-COO^-)_2$ group in DTPA on the reaction rate was discussed in a quantitative manner. The effect due to the former group was estimated to be smaller than that due to the latter group.

We have studied a series of substitution reactions of Eriochrom Black T (BT) with cobalt(II)- and nickel(II)-polyaminocarboxylate chelates.[1-3] The reactions were invariably first-order in BT and first-order in the metal(II)-polyaminocarboxylate chelate.

In the present paper, the kinetics of the substitution reactions of BT with cobalt(II) and nickel(II) chelates of 1,2-diaminocyclohexanetetraacetic acid (CyDTA) and of diethylenetriaminepentaacetic acid (DTPA) are dealt with spectrophotometrically. On the basis of a comparison of the rate constants of the substitution reactions of CyDTA and DTPA chelates with those of EDTA chelates, the steric effect of the cyclohexane ring in the CyDTA or $-CH_2-CH_2-N(CH_2-COO^-)-CH_2-CH_2-N(CH_2-COO^-)_2$ group in DTPA on the rate of the substitution reaction is discussed.

Experimental

Reagents. The preparation and the standardization of solutions of cobalt(II) and nickel(II) perchlorates have been described in previous papers.[1,2] Reagent-grade CyDTA and DTPA recrystallized from water were used. The concentration of the CyDTA solution was standardized against the standard lead(II) solution by a volumetric titration, using BT as an indicator.[4] The concentration of DTPA was determined by the same procedure as has been proposed for the EDTA titration of copper(II).[5] The other reagents were of a guaranteed reagent grade and were used without further purification.

Apparatus and Procedure. The apparatus and the experimental procedure were the same as have been described in a previous paper.[1] In this study, all the measurements were conducted on solutions with an ionic strength of 0.30 ($NaClO_4$), and no buffer reagent was used, because free CyDTA and DTPA have enough buffer capacity to maintain the pH values of solutions constant in the pH range from 9.50 to 10.50 in which the present study was conducted.

Results and Discussion

All the exchange reactions were studied in solutions with pH values from 9.50 to 10.50 containing large excesses of complexed and uncomplexed CyDTA or DTPA. Therefore, the exchange reactions can be treated as pseudo first-odrer reactions. In the cases of the reactions of BT with cobalt(II) and nickel(II) chelates of EDTA,[1,2] EDTA-OH[3] and GEDTA,[3] the apparent rate constants of the pseudo first-order reactions could be determined from the slope of the linear relation

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[1] M. Kodama, This Bulletin, **40**, 2575 (1967).

[2] M. Kodama, C. Sasaki and M. Murata, *ibid.*, **41**, 1333 (1968).

[3] M. Kodama, C. Sasaki and T. Noda, *ibid.*, **41**, 2033 (1968).

[4] C. A. Goetz and F. J. Debbrecht, *Anal. Chem.*, **27**, 1972 (1955).

[5] H. Flaschka, *Microchemie ver. Microchim. Acta*, **39**, 38 (1952).

between $\log(A_D/(A-A_{MD}))$ and time, t. Here, A_D, A, and A_{MD} have the same meanings as were used previously.[2,3] However, in the reactions of BT with CyDTA and DTPA chelates of these metal(II) ions, the concentration of uncomplexed BT at equilibrium, $[BT]_e$, can not be neglected as compared with that at t, $[BT]_f$, and the initial concentration of BT, $[BT]_0$, because the stability constants of cobalt(II) and nickel(II) chelates of CyDTA and DTPA are comparable to those of corresponding BT chelates. Therefore, in the present substitution reactions, the apparent rate constants should be estimated from the slope of the linear relation between $\log([A_D-A_e]/[A-A_e])$ and t. Here A_e denotes the absorbance at equilibrium and $[A_D-A_e]/[A-A_e]$ can be equated with $([BT]_0-[BT]_e)/([BT]_f-[BT]_e)$ in the Eq. (7) in Ref. (1). Hence, the slope of the linear relation of $\log([A_D-A_e]/[A-A_e])$ and t can be exactly expressed as:

$$\text{slope} = k^+\left(1+\frac{[MZ^{2-m}]}{K_h[Z]_f}\right)\cdot\frac{1}{2.303} \qquad (1)$$

where k^+ corresponds to the apparent rate constant of the pseudo first-order reaction (2),[1-3] where $[MZ^{2-m}]$ and $[Z]_f$ are the concentrations of complexed and uncomplexed CyDTA or DTPA, and where $K_h=K_{MD}\cdot(\alpha_H)_z/K_{MZ}\cdot(\alpha_H)_{BT}=k^+\cdot(Z)_f/k^-\cdot[MZ^{2-m}]$.

$$\left\{\begin{array}{l} HD^{2-} \\ \upharpoonleft\downharpoonright \\ D^{3-} \end{array}\right. \underset{k^-}{\overset{k^+}{\rightleftarrows}} \quad MD^- \qquad (2)$$

The other notation definitions used here are as follows. HD^{2-} and D^{3-} mean doubly- and completely-deprotonated BT anions respectively, and MD^-, the metal(II)-BT chelate. K_{MD} and K_{MZ} are stability constants of the metal(II)-BT chelate and the -CyDTA or -DTPA chelate respectively. $(\alpha_H)_Z$ and $(\alpha_H)_{BT}$ have the same meanings as previously.[3]

k^+ in Eq. (1) can also be determined from the apparent initial rate of the reaction, $(-\Delta[BT]/\Delta t)_0$, with the aid of Eq. (3):

$$\left(-\frac{\Delta[BT]}{\Delta t}\right)_0 = k^+\left(1+\frac{[MZ^{2-m}]}{K_h[Z]_f}\right)[BT]_0 \qquad (3)$$

where $(-\Delta[BT]/\Delta t)_0$ and $[BT]_0$ can be equated with $(-\Delta A/\Delta t\cdot\varepsilon_{BT})_0$ and A_D/ε_{BT},[2] respectively.

In the case of the reactions of BT with nickel(II) chelates of CyDTA and DTPA, the absorbance decreases almost linearly with the time. Therefore, the apparent rate constant was determined from the initial slope of the absorbance *versus* time curve. On the other hand, in the case of the reactions of BT with cobalt(II) chelates, the apparent rate constant, k^+, was calculated from the slope of the linear relation between $\log[(A_D-A_e)/(A-A_e)]$ and t. The A_e*1 value used in the log-

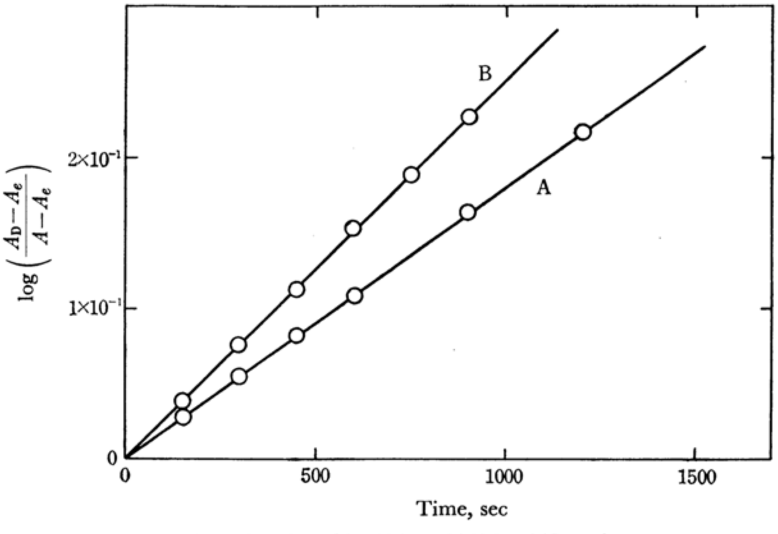

Fig. 1. The plot of $\log[(A_D-A_e)/(A-A_e)]$ against t.
$\mu = 0.30$, $\lambda = 630$ mμ
Initial concentration of BT = 2.5×10^{-5} M
A: Concentration of cobalt(II)-CyDTA chelate = 10.0 mM
Concentration of uncomplexes CyDTA = 10.0 mM
pH = 9.95
B: Concentration of cobalt(II)-DTPA chelate = 7.13 mM
Concetration of uncomplexed DTPA = 10.0 mM
pH = 10.40

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*1 The calculated A_e value agreed well with the observed value.

plot examination was calculated by using K_{MD} and K_{MZ} values. Typical linear relations between $\log[(A_{\mathrm{D}}-A_e)/(A-A_e)]$ and t are shown in Fig. 1.

In all the substitution reactions of BT studied in this paper, we found the following experimental facts with regard to the apparent rate constant, k^+:

i) In solutions of a given pH, a given concentration of the metal(II) chelate of CyDTA or DTPA, and a given initial concentration of BT, k^+ is independent of the concentration of the uncomplexed chelating agent (CyDTA or DTPA) (Table 1).

TABLE 1. DEPENDENCE OF k^+ ON THE CONCENTRATION OF UNCOMPLEXED CHELATING AGENT

$\mu = 0.30$, $\lambda = 630$ mμ

i) Cobalt(II)-CyDTA system

Concentration of CyDTA, mM	k^+ M^{-1} sec^{-1}	
5.0	1.79×10^{-4}	pH = 9.95
10.0	1.78×10^{-4}	$[\mathrm{BT}]_0 = 2.5\times10^{-5}$ M
15.0	1.78×10^{-4}	$[\mathrm{CoZ}^{2-}] = 10.0$ mM

ii) Nickel(II)-CyDTA system

Concentration of CyDTA, mM	k^+ M^{-1} sec^{-1}	
5.0	7.12×10^{-5}	pH = 10.00
10.0	7.13×10^{-5}	$[\mathrm{BT}]_0 = 2.5\times10^{-5}$ M
30.0	7.14×10^{-5}	$[\mathrm{NiZ}^{2-}] = 8.25_5$ mM

iii) Cobalt(II)-DTPA system

Concentration of DTPA, mM	k^+ M^{-1} sec^{-1}	
5.0	2.00×10^{-4}	pH = 10.30
10.0	2.00×10^{-4}	$[\mathrm{BT}]_0 = 2.5\times10^{-5}$ M
20.0	2.02×10^{-4}	$[\mathrm{CoZ}^{3-}] = 7.13$ mM

iv) Nickel(II)-DTPA system

Concentration of DTPA, mM	k^+ M^{-1} sec^{-1}	
5.0	1.27×10^{-5}	pH = 10.12
10.0	1.30×10^{-5}	$[\mathrm{BT}]_0 = 2.0\times10^{-5}$ M
20.0	1.29×10^{-5}	$[\mathrm{NiZ}^{3-}] = 10.45$ mM

TABLE 2. DEPENDENCE OF k^+ ON THE INITIAL CONCENTRATION OF BT

$\mu = 0.30$, $\lambda = 630$ mμ

i) Cobalt(II)-CyDTA system

Concentration of BT, M	k^+ M^{-1} sec^{-1}	
1.0×10^{-5}	1.76×10^{-4}	pH = 9.95
2.5×10^{-5}	1.78×10^{-4}	$[\mathrm{CoZ}^{2-}] = 10.0$ mM
3.5×10^{-5}	1.77×10^{-4}	$[\mathrm{Z}]_f = 10.0$ mM

ii) Nickel(II)-CyDTA system

Concentration of BT, M	k^+ M^{-1} sec^{-1}	
1.25×10^{-5}	7.14×10^{-5}	pH = 10.00
2.50×10^{-5}	7.13×10^{-5}	$[\mathrm{NiZ}^{2-}] = 8.25_5$ mM
3.75×10^{-5}	7.15×10^{-5}	$[\mathrm{Z}]_f = 10.0$ mM

iii) Cobalt(II)-DTPA system

Concentration of BT, M	k^+ M^{-1} sec^{-1}	
2.5×10^{-5}	2.36×10^{-4}	pH = 10.39
3.5×10^{-5}	2.32×10^{-4}	$[\mathrm{CoZ}^{3-}] = 7.13$ mM
5.0×10^{-5}	2.40×10^{-4}	$[\mathrm{Z}]_f = 10.0$ mM

iv) Nickel(II)-DTPA system

Concentration of BT, M	k^+ M^{-1} sec^{-1}	
2.0×10^{-5}	1.32×10^{-5}	pH = 10.12
4.0×10^{-5}	1.30×10^{-5}	$[\mathrm{NiZ}^{3-}] = 10.45$ mM
6.0×10^{-5}	1.33×10^{-5}	$[\mathrm{Z}]_f = 10.0$ mM

ii) In solutions of a given pH and given concentrations of uncomplexed and complexed chelating agents CyDTA or DTPA, k^+ is independent of the initial concentration of BT, $[\mathrm{BT}]_0$ (Table 2).

iii) In solutions of a given pH, a given concentration of a chelating agent (CyDTA or DTPA), and a given initial concentration of BT, k^+ is exactly proportional to the concentration of the metal(II) chelate of CyDTA or DTPA (Table 3).

iv) As is shown by the curves in Fig. 2, in solutions of a given initial concentration of BT and given concentrations of a free chelating agent (CyDTA or DTPA) and its metal(II) chelate, k^+ is a linear function of the reciprocal of the concentration of hydrogen ions and is given by:

$$k^+ = k_\alpha + k_\beta/[\mathrm{H}^+] \qquad (4)$$

As in the case of the exchange reactions of BT with cobalt(II) and nickel(II) chelates of EDTA,[1,2] these facts clearly indicate that the present reactions also proceed through the following two simultaneous reaction paths:

$$\text{i)}\quad \mathrm{HD}^{2-} + \mathrm{MZ}^{2-m} \underset{k_1^-}{\overset{k_1^+}{\rightleftarrows}} \mathrm{MD}^- + \mathrm{HZ}^{1-m}$$

$$\text{ii)}\quad \mathrm{HD}^{2-} \overset{\text{rapid}}{\rightleftarrows} \mathrm{H}^+ + \mathrm{D}^{3-}$$

$$\mathrm{D}^{3-} + \mathrm{MZ}^{2-m} \underset{k_2^-}{\overset{k_2^+}{\rightleftarrows}} \mathrm{MD}^- + \mathrm{Z}^{m-}$$

rate-determining step

where HZ^{1-m} and Z^{m-} mean incompletely- and completely-deprotonated CyDTA or DTPA anions, and MZ^{2-m} the metal(II) chelate of CyDTA or DTPA.

Consequently, k^+ should be given by:

$$k^+ = (k_1^+ + k_2^+\cdot k_2/[\mathrm{H}^+])[\mathrm{MZ}^{2-m}] \qquad (5)$$

where k_2 refers to the dissociation constant of the second phenolic group of BT.[6]

From the slopes of the linear relation between $k^+/[\mathrm{MZ}^{2-m}]$ and $1/[\mathrm{H}^+]$ and the intercepts, the k_1^+ and k_2^+ values were estimated. These values

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[6] G. Schwarzenbach and W. Biedermann, *Helv. Chim. Acta*, **31**, 678 (1948).

TABLE 3. DEPENDENCE OF k^+ ON THE CONCENTRATION OF METAL(II) CHELATE
$\mu = 0.30$, $\lambda = 630$ mμ

i) Cobalt(II)-CyDTA system

Concentration of Co(II)-CyDTA mM	k^+ M^{-1} sec^{-1}	Ratio Calcd	Ratio Obsd	
5.0	8.82×10^{-5}	1.00	1.00	pH = 9.95
10.0	1.78×10^{-4}	2.00	2.02	$[BT]_0 = 2.5\times10^{-5}$ M
15.0	2.73×10^{-4}	3.00	3.10	$[Z]_f = 10.0$ mM

ii) Nickel(II)-CyDTA system

Concentration of Ni(II)-CyDTA mM	k^+ M^{-1} sec^{-1}	Ratio Calcd	Ratio Obsd	
4.13	3.56×10^{-5}	1.00	1.00	pH = 10.00
8.25_5	7.13×10^{-5}	2.00	2.01	$[BT]_0 = 2.5\times10^{-5}$ M
16.51	1.42×10^{-4}	4.00	3.99	$[Z]_f = 10.0$ mM

iii) Cobalt(II)-DTPA system

Concentration of Co(II)-DTPA mM	k^+ M^{-1} sec^{-1}	Ratio Calcd	Ratio Obsd	
5.10	8.14×10^{-5}	1.00	1.00	pH = 10.00
7.13	1.18×10^{-4}	1.40	1.45	$[BT]_0 = 2.5\times10^{-5}$ M
10.20	1.70×10^{-4}	2.00	2.09	$[Z]_f = 10.0$ mM

iv) Nickel(II)-DTPA system

Concentration of Ni(II)-DTPA, mM	k^+ M^{-1} sec^{-1}	Ratio Calcd	Ratio Obsd	
5.0	8.70×10^{-6}	1.00	1.00	pH = 10.12
10.0	1.69×10^{-5}	2.00	1.94	$[BT]_0 = 4\times10^{-5}$ M
15.0	2.55×10^{-5}	3.00	2.93	$[Z]_f = 10.0$ mM

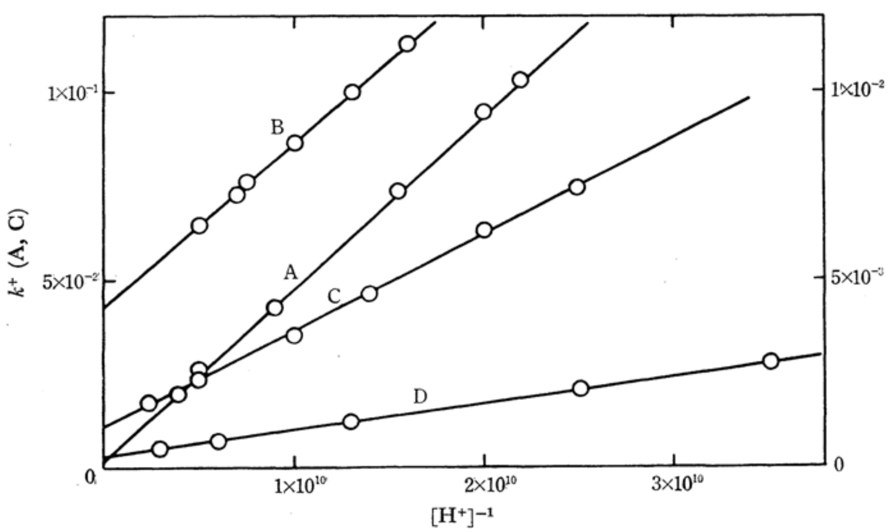

Fig. 2. The relation between $k^+/[MZ^{2-m}]$ and the concentration of hydrogen ion.
$\mu = 0.30$, $\lambda = 630$ mμ
Initial concentration of BT = 2.5×10^{-5} M
A : Co(II)-CyDTA system C : Co(II)-DTPA system
B : Ni(II)-CyDTA system D : Ni(II)-DTPA system

are given in Table 4, together with those for the reactions of EDTA chelates reported previously.[1,2]

Margerum *et al.* have mentioned in their report[7] that, in the substitution reactions of polyamines

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[7] J. D. Carr, R. A. Libby and D. W. Margerum, *Inorg. Chem.*, **6**, 1083 (1967).

TABLE 4. k^+ VALUES

i) Cobalt(II) system (20°C)

System	k_1^{+}* $\mathrm{M^{-1}\,sec^{-1}}$	k_2^{+} $\mathrm{M^{-1}\,sec^{-1}}$
EDTA[1]	—	6.76×10^{2}
CyDTA	1.7×10^{-3}	9.26×10^{-1}
DTPA	1.1×10^{-2}	5.25×10^{-1}

ii) Nickel(II) system (15°C)

System	k_1^{+}* $\mathrm{M^{-1}\,sec^{-1}}$	k_2^{+} $\mathrm{M^{-1}\,sec^{-1}}$
EDTA[2]	—	1.24
CyDTA	4.25×10^{-3}	8.90×10^{-2}
DTPA	2.9×10^{-4}	1.48×10^{-2}

* These values are less accurate.

with a copper(II)-CyDTA chelate, the cyclohexane ring in CyDTA does not change the general reaction mechanism (glycinate intermediate mechanism), but does affect the exchange rate considerably. Generally, if two exchange reactions involving metal chelate have the same reaction mechanism, the reaction with the stable chelate will be slower than that with a less stable chelate, because the stable reactant, as compared with the less stable one, often corresponds to the less stable transition state, and hence, to the diminished reactivity.

TABLE 5. STABILITY CONSTANTS*

1) EDTA chelates
$K_{\mathrm{CoY}} = 10^{15.71}$[10], $K_{\mathrm{NiY}} = 10^{18.02}$[10]
$K_{\mathrm{CuY}} = 10^{18.70}$[15]**
2) CyDTA chelates
$K_{\mathrm{CoZ}} = 10^{18.32}$[10], $K_{\mathrm{NiZ}} = 10^{18.80}$[11]
$K_{\mathrm{CuZ}} = 10^{21.96}$[16]**
3) DTPA chelates[12]
$K_{\mathrm{CoZ}} = 10^{18.17}$, $K_{\mathrm{NiZ}} = 10^{19.38}$
4) *α*-Amino-*α*-methylpropionate[13]
$K_{\mathrm{CoX}} = 10^{3.51}$, $K_{\mathrm{NiX}} = 10^{4.56}$
$K_{\mathrm{CuX}} = 10^{8.26}$**
5) 1-Aminocyclohexanecarboxylate[14]
$K_{\mathrm{CoX}} = 10^{3.87}$, $K_{\mathrm{NiX}} = 10^{4.90}$
$K_{\mathrm{CuX}} = 10^{8.59}$**

* These values are calculated from the relevant stability constants in solutions of ionic strength 0.10 and the activity constants of the ions calculated by means of Davies equation.[17]

** Values at $\mu = 0.10$.

In the exchange reactions of BT with cobalt(II) and nickel(II) chelates of CyDTA have the same reaction mechanism as those with EDTA chelates (glycinate mechanism), we can estimate the relative rate constants as was done previously.[3] Hence, from a comparison of the observed rate constant with the theoretically-calculated one, we can probably estimate the steric effect of the cyclohexane ring on the exchange reaction of BT in a quantitative manner. Relative rate constants calculated with the aid of Eq. (5) of Ref. 3 by using the numerical values listed in Table 5 are given in Table 6, together with the observed values.*2 Here, the calculation was carried out by choosing both *α*-amino-*α*-methylpropionate and 1-aminocyclohexanecarboxylate as models; the statistical factor and the stabilization due to the electrostatic attraction[8] were also taken into consideration. The results clearly show that in the reactions of BT with both cobalt(II) and nickel(II) chelates of CyDTA, the steric effect due to the cyclohexane ring is surprisingly small. A small steric effect of the cyclohexane ring on the oxidation reaction of the iron(II)-CyDTA chelate by dissolved oxygen was also mentioned by Kurimura *et al.*[9] The

TABLE 6. k^+ RATIO

	EDTA		R*	CyDTA			R_1*	R_2*	DTPA		R*
	Calcd	Obsd		Calcd$_1$**	Calcd$_2$***	Obsd			Calcd	Obsd	
Co(II)	1.00	1.00	1.00	5.61×10^{-3}	2.45×10^{-3}	1.37×10^{-3}	4.1	1.8	4.35×10^{-3}	7.76×10^{-4}	5.6
Ni(II)	1.00	1.00	1.00	3.62×10^{-1}	1.66×10^{-1}	8.90×10^{-2}	4.1	1.9	7.90×10^{-2}	1.19×10^{-2}	6.6

* Ratio between k^+ calculated and that observed.

** 1-Aminocyclohexanecarboxylate was chosen as a model.

*** *α*-Amino-*α*-methylpropionate was chosen as a model.

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8) T. J. Bydalek and D. W. Margerum, *Inorg. Chem.*, **2**, 678 (1963).

9) Y. Kurimura, R. Ochiai and N. Matsuura, This Bulletin, **41**, 2234 (1968).

*2 Here, the k_2^{+} values were compared with the calculated ones, because the k_1^{+} values are less accurate.

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

11) J. H. Holloway and C. N. Reilley, *Anal. Chem.*, **32**, 249 (1960).

12) E. J. Durham and D. P. Ryskiewick, *J. Am. Chem. Soc.*, **80**, 4813 (1958).

13) H. Irving and L. D. Pittit, *J. Chem. Soc.*, **1963**, 1946.

14) H. Irving and L. D. Pittit, *ibid.*, **1963**, 1546.

15) B. D. Sarma and P. Ray, *J. Indian Chem. Soc.*, **33**, 841 (1956).

16) G. Anderegg, *Helv. Chim. Acta*, **46**, 1833 (1963).

17) J. N. Butler, "Ionic Equilibrium," Addison-Wesley Publishing Co., Reading, Massachusetts (1964), p. 437.

above explanation, that the diminished activity of CyDTA chelates observed can be ascribed to the steric hindrance due to the cyclohexane ring, is also supported by the fact that ratio between the k^+ ratio calculated and that observed, R, was almost constant, irrespective of the metal(II) ion (Table 6).

In the case of the reaction of copper(II) chelates with polyamine, the ratio between the observed rate constant and the one theoretically predicted on the basis of the glycinate intermediate was calculated to be about 1 : 50. The smaller steric effect of the cyclohexane ring on the reaction of BT can probably ascribed to the planar configuration of the BT anion in the mixed ligand intermediate.

In a similar way, by using the numerical values in Table 5, the relative rate constants for the reactions of BT with DTPA chelates were calculated on the basis of the glycinate mechanism; they are compared with the observed values in Table 6. The results may indicate that the $-CH_2-CH_2-N(CH_2-COO^-)-CH_2-CH_2-N(CH_2-COO^-)_2$ group of DTPA has a larger steric effect on the exchange reactions of BT than does the cyclohexane ring in CyDTA.