Kinetics of Multidentate Ligand-substitution Reactions. XVIII.* Substitution Reactions of Triethylenetetraaminehexaacetate (TTHA) with Nickel(II)–Dien, –EDMA, and –NTA Complexes

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The kinetics of the substitution reactions of TTHA with nickel(II) complexes of diethylenetriamine (Dien), ethylenediaminemonoacetate (EDMA), and nitrilotriacetate (NTA) were studied systematically by employing the polarographic technique. All the substitution reactions were found to have a common reaction mechanism. They were first-order with respect to TTHA and also first-order with respect to a 1 : 1-ratio nickel(II) complex of Dien, EDMA, or NTA. In all the substitution reactions, the rate constants for the reactions involving a completely-deprotonated TTHA anion were nearly identical to those for the corresponding DTPA (diethylenetriaminepentaacetate) reactions, suggesting that the TTHA reaction has the same reaction mechanism as the DTPA reaction. In the Dien system, the rate constant for the reaction of the quadrivalent TTHA anion is nearly identical to that of the quinquivalent TTHA anion, whereas, in the reactions of NTA and EDMA complexes, the reaction of the quadrivalent TTHA anion is drastically slower than that of the quinquivalent TTHA anion. These facts suggest that the proton transfer from the entering group to the leaving group plays an important role in determining the rate of the multidentate ligand-substitution reaction.

The present author has previously studied a series of substitution reactions involving metal(II)–aminopolycarboxylate complexes and has discussed their detailed reaction mechanism.[1–6] In this paper, he will also deal with the kinetics of the substitution reactions of TTHA with nickel(II) complexes of NTA, EDMA, and Dien as an extension of earlier investigations involving metal(II)–aminopolycarboxylate complexes, and will discuss the effect of the basicity of the ligand on the reaction rate. The substitution reactions of DTPA in acid and neutral media will also be studied, and their rates will be compared with those of the TTHA reaction.

Experimental

Reagents. The preparation and standardization of the nickel(II) nitrate solution were described in a previous paper.[1] Reagent-grade NTA and DTPA were recrystallized as their acid forms from their aqueous solutions. The way of purification of Dien used in this study was described in a previous paper.[2] The preparation and recrystallization of the acid forms of TTHA and EDMA were also given previously.[7,8] All the other chemicals used were of an analytical reagent grade and were used without further purification.

Apparatus and Experimental Procedures. The apparatus and experimental procedures employed were the same as those given previously.[9,10] In the EDMA system, no buffer reagent was used, because all the sample solutions always contained a large excess of uncomplexed EDMA and had a big enough buffer capacity over the entire pH range covered ($9.20<\mathrm{pH}<10.50$, and $6.30<\mathrm{pH}<7.65$). Phosphate ($6.00<\mathrm{pH}<8.00$) and acetate ($4.60<\mathrm{pH}<5.80$) buffers were used in the Dien and NTA systems respectively.

All the kinetic measurements were conducted under experimental conditions in which all the reactions could be treated as pseudo first-order reactions. The rate of the substitution reaction was determined by measuring the change in the dissolution wave-height due to the uncomplexed TTHA or DTPA. The ionic strength of the sample solution was adjusted to 0.30 by adding an appropriate amount of potassium nitrate. The pseudo first-order rate constant, $\boldsymbol{k}_{\mathrm{ap}}$, was determined from the slope of the linear relation between log (i_0/i_t) and time, t.[1]

Results and Discussion

In this study, all the kinetic measurements were conducted under experimental conditions in which the 2 : 1 ratio nickel(II)–TTHA complex was not involved in the mixture of the reaction products. All reactions were run with several different reactant concentrations in order to determine the reaction order with respect to each reactant. Although the results will not be shown here, the rates for all the reactions studied were 1) exactly proportional to the total concentration of the nickel(II) ion, $[\mathrm{Ni(II)}]_t$, 2) inversely proportional to $(1+K_2[\mathrm{X}]_f/(\alpha_{\mathrm{H}})_{\mathrm{X}})$, and 3) proportional to the initial concentration of TTHA, $[\mathrm{TTHA}]_i$, when the other experimental conditions are kept constant. These findings suggest that all the reactions studied in this paper are first-order with respect to the 1 : 1 ratio nickel(II) complex of Dien, EDMA, or NTA, and also first-order with respect to TTHA, corresponding to the following rate expression:

$$\mathrm{Rate}=\boldsymbol{k}_{\mathrm{ap}}\cdot[\mathrm{TTHA}]_{\mathrm{i}}=k_{\gamma}\cdot\frac{[\mathrm{Ni(II)}]_{\mathrm{t}}}{1+\dfrac{K_2}{(\alpha_{\mathrm{H}})_{\mathrm{X}}}\cdot[\mathrm{X}]_{\mathrm{f}}}\cdot[\mathrm{TTHA}]_{\mathrm{i}} \tag{1}$$

Here, $[\mathrm{X}]_f$ means the concentration of uncomplexed Dien, EDMA, or NTA; K_2, the second successive formation constant of the nickel(II)–Dien, EDMA, or NTA complex, and $(\alpha_{\mathrm{H}})_{\mathrm{X}}$, the (α_{H}) value of Dien, EDMA, or NTA, defined as $1+[\mathrm{H}^+]/K_n+[\mathrm{H}^+]^2/K_n\cdot K_{n-1}+\cdots+[\mathrm{H}^+]^n/K_n\cdots K_1$, where K_i stands for the i-th deprotonation constant of $\mathrm{H}_n\mathrm{X}^{n-m}$. $k\gamma$ in Eq. (1) is a function of the hydrogen-ion concentration.

Dien System. In the pH range from 8.80 to 10.00, the plot of $\boldsymbol{k}_{\mathrm{ap}}\cdot(\alpha_{\mathrm{H}})_{\mathrm{Z}}\cdot(1+K_2[\mathrm{X}]_{\mathrm{f}}/(\alpha_{\mathrm{H}})_{\mathrm{X}})$ against

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* Part XVII: M. Kodama, This Bulletin, **47**, 2200 (1974).

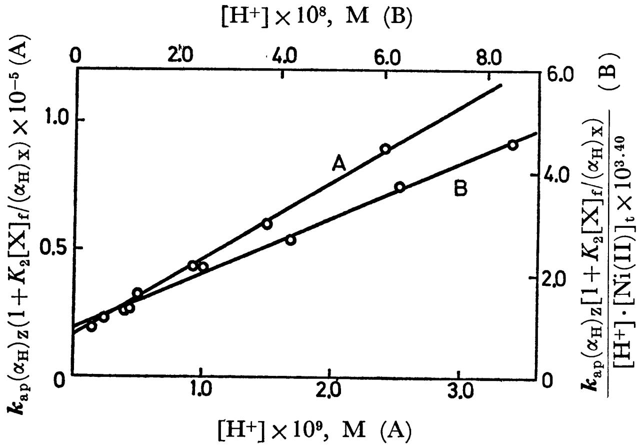

Fig. 1. The relation between $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2[X]_f/(\alpha_H)_X)$ and the hydrogen-ion concentration, $[\mathrm{H^+}]$, (A), and that between $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2[X]_f/(\alpha_H)_X)/[\mathrm{H^+}]$ and $[\mathrm{H^+}]$ (B).
$\mu=0.30$, $[\mathrm{Ni(II)}]_t=10.0$ mM
$[\mathrm{TTHA}]_i=1.0$ mM
(A) Solution pH ranged from 8.80 to 10.00 25 °C, $[\mathrm{Dien}]_f=100$ mM
(B) Solution pH ranged from 6.35 to 7.65 1.0 °C, $[\mathrm{Dien}]_f=80$ mM

the hydrogen-ion concentration, $[\mathrm{H^+}]$, invariably gave a straight line with an intercept of a finite value (25 °C). This indicates that the reaction proceeds through two simultaneous reaction pathways involving completely deprotonated and quinquivalent TTHA anions, $\mathrm{Z^{6-}}$ and $\mathrm{HZ^{5-}}$. Here, $(\alpha_H)_Z$ is defined as $1+[\mathrm{H^+}]/K_6+\cdots+[\mathrm{H^+}]^6/K_6\cdot K_5\cdots K_1$, where K_i stands for the i-th dissociation constant of $\mathrm{H_6Z}$. On the other hand, in the pH range from 6.35 to 7.65, the plot of $k_{ap}\cdot(\alpha_H)_Z\times(1+K_2[X]_f/(\alpha_H)_X)/[\mathrm{H^+}]$ against $[\mathrm{H^+}]$ gave a linear relation with an intercept of a finite value (1.0 °C) (Fig. 1). This fact suggests that the reaction in this pH range proceeds through two reaction pathways involving $\mathrm{HZ^{5-}}$ and $\mathrm{H_2Z}.^{4-}$ Furthermore, thermodynamic calculations using the reported equilibrium constants for the nickel(II)–TTHA and –Dien complexations reveal that the reaction product for the substitution reaction contains an appreciable amount of the protonated nickel(II)–TTHA complex, $\mathrm{NiHZ}.^{3-}$ Accordingly, the above findings lead to the conclusion that the reaction proceeds through two simultaneous reaction pathways, (3) and (4), in the pH range from 8.80 to 10.00 and in the pH range from 6.35 to 7.65 through (4) and (5), both reactions being preceded by the rapid dissociation of $\mathrm{NiX_2}^{2-2m}$ (2).

$$\mathrm{NiX_2}^{2-2m} \rightleftharpoons \mathrm{NiX}^{2-m} + \mathrm{X}^{m-} \qquad \text{rapid} \tag{2}$$

$$\mathrm{NiX}^{2-m} + \left\{\begin{array}{lr} \mathrm{Z^{6-}} \xrightleftharpoons{k_0} \mathrm{NiZ^{4-}} + \mathrm{X}^{m-} & (3) \\ \mathrm{HZ^{5-}} \xrightleftharpoons{k_H} \mathrm{NiHZ^{3-}} + \mathrm{X}^{m-} & (4) \\ \mathrm{H_2Z^{4-}} \xrightleftharpoons{k_{2H}} \mathrm{NiHZ^{3-}} + \mathrm{HX}^{1-m} & (5) \end{array}\right\} \text{slow}$$

As in the case of the reaction of the nickel(II)–NTA complex with DTPA,⁹⁾ the rate constants, k_0, k_H, and k_{2H}, for the reaction of TTHA with the nickel(II)–Dien complex were determined from the intercepts and slopes of the linear relations in Fig. 1; they are listed in Table 1.

Table 1. Rate constants ($\mathrm{M^{-1}\,s^{-1}}$, $\mu=0.30$)

System		k_0	k_H	k_{2H}	Temp. °C
DTPA	NTA⁹⁾	9.1×10^2	3.06×10^2	1.78	25
	EDMA¹²⁾	1.4×10^3	2.58×10^2	—	25
		—	8.32×10^1	5.90×10^1	1.0
	Dieen¹²⁾	7.2×10^5	9.80×10^4	—	25
		—	3.0×10^4	2.0×10^4	1.0
TTHA	NTA	2.8×10^3	9.65×10^2	1.06	25
	EDMA	4.3×10^3	2.86×10^3	4.36	25
	Dien	1.5×10^6	5.46×10^5	—	25
		—	2.7×10^4	3.0×10^3	1.0

EDMA System. In the EDMA system, all the kinetic measurements were conducted at 25 °C. in the pH range from 8.40 to 10.30, a straight line with an intercept of a finite value could be obtained by plotting $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2[X]_f/(\alpha_H)_X\cdot)$ against $[\mathrm{H^+}]$, whereas, in the pH range from 7.00 to 8.14, it could be obtained by plotting the $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2[X]_f/(\alpha_H)_X)/[\mathrm{H^+}]$ value against $[\mathrm{H^+}]$. Therefore, the reaction of the EDMA complex can be concluded to proceed through (3) and (4) in the former pH range and through (4) and (5) in the latter pH range. From the intercept and slope of the linear relation between $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2[X]_f/(\alpha_H)_X)$ and $[\mathrm{H^+}]$, the k_0 and k_H values were determined. The k_{2H} value was determined from the slope of the linear relation between $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2[X]_f/(\alpha_H)_X)/[\mathrm{H^+}]$ and $[\mathrm{H^+}]$ obtained in the pH range from 7.00 to 8.14. They are also listed in Table 1. The k_H value estimated from the intercept of the linear relation at pH's lower than 8.14 agreed well with that estimated from the slope of the linear relation at pH's higher than 8.40. The influence of the phosphate buffer on the reaction rate was also investigated. No effect on the rate constant was observed that can be attributed to the buffer reagent.

NTA System. As in the case of the EDMA system, the reaction rates were determined at 25 °C. In the pH range from 8.46 to 9.50, the $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2[X]_f/(\alpha_H)_X$ value gave a straight line with an intercept of a finite value when it was plotted against $[\mathrm{H^+}]$, whereas, in the pH range from 4.50 to 5.70, the $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2[X]_f/(\alpha_H)_X)/[\mathrm{H^+}]^2$ gave a linear relation when it was plotted against $[\mathrm{H^+}]$. These facts indicate that the reaction proceeds through (3) and (4) in the range from 8.40 to 9.50, and through (5) and (6) in the pH range from 4.50 to 5.70.

$$\mathrm{NiX_2}^{2-m} \rightleftharpoons \mathrm{NiX}^{2-m} + \mathrm{X}^{m-} \qquad \text{rapid} \tag{2}$$

$$\mathrm{NiX}^{2-m} + \mathrm{H_3Z^{3-}} \xrightleftharpoons[\text{slow}]{k_{3H}} \mathrm{NiH_2Z^{2-}} + \mathrm{HX}^{1-m} \tag{6}$$

The rate constants, k_0 and k_H, were determined from the intercept and slope of the linear relation between the $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2\cdot[X]_f/(\alpha_H)_X)$ value and $[\mathrm{H^+}]$, and the k_{2H} value from the intercept of the linear relation between $k_{ap}\cdot(\alpha_H)_Z\cdot(1+K_2\cdot[X]_f/(\alpha_H)_X)/[\mathrm{H^+}]^2$ and $[\mathrm{H^+}]$. The calculation using the rate constant for the proton-assisted dissociation of the 1 : 1 ratio nickel(II)–NTA complex determined by Kimura[11] reveals that, under the present experimental conditions, the contribution of the dissociation of the nickel(II)–NTA complex to the overall reaction rate is negligibly small. The k_H and k_{2H} values for the DTPA reactions with the nickel(II)–EDMA and –Dien complexes (1.0 °C) and with the nickel(II)–NTA complex (25 °C) were also determined by examining the effect of the solution's pH on the reaction rate. The rate constants for the DTPA reactions obtained are also listed in Table 1.

Previously, the present author determined the detailed reaction mechanism of DTPA reactions with the nickel(II)–NTA,[6] –EDMA,[3,12] and –Dien[3,12] complexes from a comparison of the observed rate constants. The substitution reaction of DTPA with the NTA complex was found to proceed through a glycinate reaction intermediate, where the leaving NTA anion and the entering DTPA anion are bonded to the nickel(II) ion through the glycinate and iminodiacetate chelate rings (glycinate reaction mechanism) respectively, while those with the nickel(II)–EDMA and –Dien complexes proceeded through an ethylenediamine reaction intermediate, in which the leaving EDMA or Dien anion and the entering DTPA anion are bonded to the nickel(II) ion through ethylenediamine (En) and glycinate (Gly) chelate rings respectively (ethylenediamine reaction mechanism). As is shown in Table 1, the k_0 values of the TTHA reactions are nearly identical to those of the corresponding DTPA reactions. This fact evidently suggests that the rates of the TTHA reaction with the NTA complex can be understood by assuming the glycinate reaction mechanism, and those with the EDMA and Dien complexes, by assuming the ethylenediamine reaction mechanism. Furthermore, the above fact indicates that, despite its large molecular size, the entering TTHA anion exerts practically no steric effect on the reaction rate. This can be cheifly ascribable to the free-bond rotation of the TTHA anion and the leaving ligand involved.

In the EDMA and NTA systems, the addition of the first proton to the TTHA anion, Z^{6-}, exerts little effect on the reaction rate, whereas the addition of the second proton to the TTHA anion remarkably diminishes the rate constant. In the Dien system, however, the second proton addition of the entering ligand causes only a small change in the reaction rate. Bohigian and Martell[13] have reported that the second protonation constant of the TTHA anion is nearly identical to its first protonation constant. This suggests that, in the quadrivalent TTHA anion, H_2Z^{4-}, two terminal nitrogen atoms are protonated. The present author has mentioned in his polarographic study of the zinc(II)–GEDTA (2,2′-ethylenedioxydi(ethylamine)-*N,N,N′N′*-tetraacetate) complex that the deprotonation of one of two terminal nitrogen atoms of the divalent GEDTA anion is required in its complexation reaction with the zinc(II) ion.[14] Similarly, in the reaction of the quadrivalent TTHA anion with the metal(II) complex ion, the deprotonation of one of the two terminal nitrogen atoms is also required. In the formation of the reaction intermediate of the multidentate ligand-substitution reaction, the protons of the entering ligand will be redistributed between it and the leaving ligand, depending on the relative basicity of their coordination sites. In the light of the structures of the reaction intermediates proposed, the free basic site of the leaving ligand, which can act as a proton acceptor in the NTA and EDMA systems, is the weakly basic carboxylate group, whereas that in the Dien system is the amino group. Therefore, in the latter system, the leaving group can accept the proton from the quadrivalent TTHA anion easily, and the ethylenediamine reaction intermediate is formed between the 1 : 1 ratio nickel(II)–Dien complex and H_2Z^{4-} without any difficulty. Thus, the second proton addition of the entering ligand, the TTHA anion, causes only a small change in the reaction rate. On the other hand, in the former systems, because of the weak basicity of the carboxylate group, the second protonation of the terminal nitrogen atom of the TTHA anion hinders the formation of the reaction intermediate and diminishes the rate constant remarkably. The rate constants obtained for the DTPA reactions listed in Table 1 also support the above explanation of the effect of the protonation of the entering ligand on the reaction rate.

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