Kinetics and Mechanisms of Ligand Substitution and Metal Exchange Reactions of Macromolecule-Metal Complexes

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Metal Exchange Reaction between Cu(II)-Poly(vinyl Alcohol) Complex and Zn(II)-Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution

CHAPTER 1

General Introduction

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General Introduction

No system designed by scientists has the complexity or functionality present in the natural system such as visible light energy conversion (photosynthesis)[1], catalysis (metallo-enzymes)[2], selective gas transport (hemoglobin)[2] and others. Nature has developed a superbness to organize macromolecule-metal complexes for solving these subjects. Approaches to the establishment of similar functionality in artificial systems are the aim of much active research[3] today. Because macromolecule complexes are a combination of various molecules on a molecular level, there are unlimited possibilities for providing a wide variety of previously unknown functions. Therefore, activities for these system have increased in recent years.

In macromolecule-metal complexes various dynamic interactions (weak coordinations, allosteric phenomena), soft interactions (molecular recognitions, separation, transport) and multiple interactions (electronic interactions, photon interactions, electron transfer) exist which provide several different functions to be considered[4]. Properties and applications of macromolecule-metal complexes presently under investigations are summarized exemplarily in the following table[5]:

Properties	**Applications**
electron, photoelectron conduction	molecular devices photoconductors lasergraphy
ionic conduction	ECD devices super conductors polymer battery
mixed valence systems	multi-electron transfer catalysis artificial photosynthesis electrochemistry
nonlinear optical effect	modulator integrated optics high power laser
preceramics	thermally stable compounds quantum devices
selectivity	gas transport separation sensor
solid-state photon interactions	photovoltaic cell photoelectrochemistry

On the other hand, many works on the reaction mechanisms of inorganic compounds and coordination compounds having low molecular weight ligands have been done, a lot of information[6,7] has been stocked. The ligand substitution reactions of metal complexes with multidentate ligands have been extensively studied by many authors[8-10]. Some of these studies have shown that ligands coordinated to a central metal ion affect the rate of substitution. These knowledge are important to understand many behaviors and functions of macromolecule-metal complexes.

Reaction kinetics and mechanisms of macromolecule-metal complexes have been investigated in a few works[11-13]. It is possible to consider, viewed from another angle, almost of all reactions concerning with metal complexes are ligand substitution or metal exchange reaction. One of the main objects of this work was to make the reaction mechanisms and kinetics of macromolecule-metal complexes clear, and accumulate the basics of these reactions.

This study is focused on the kinetics and mechanisms of ligand substitution and metal exchange reaction between Cu(II)-poly(vinyl alcohol) complex and other ligands or complexes in aqueous solution. The structure, thermodynamical properties and functionality of Cu(II)-poly(vinyl alcohol) complex in aqueous solution have already reported in detail by Dr. Hirofusa Shirai and Dr. Nobumasa Hojo[14].

This thesis is composed of following 5 chapters.

Chapter 2: Kinetics and mechanism of ligand substitution reaction between Cu(II)-ammine complex and poly(viny alcohol) in aqueous solution.

Chapter 3: Kinetics and mechanism of ligand substitution reaction between Cu(II)-poly(viny alcohol) complex and ethylenediamine-N,N,N',N'-tetraacetic acid in aqueous solution.

Chapter 4: Kinetics and mechanism of metal exchange reaction between Cu(II)-poly(viny alcohol) complex and Ca(II)-ethylenediamine-N,N,N',N'-tetraacetic acid in aqueous solution.

Chapter 5: Kinetics and mechanism of metal exchange reaction between Cu(II)-poly(viny alcohol) complex and Zn(II)-ethylenediamine-N,N,N',N'-tetraacetic acid in aqueous solution.

Chapter 6: Kinetics and mechanism of ligand substitution reaction between Cu(II)-Silk fibroin complex and ethylenediamine-N,N,N',N'-tetraacetic acid in aqueous solution.

References

1 T. Matsuo, 'Kagaku Sosetsu', **20**, 232 (1978).

2 N. Hojo, H. Shirai, and M. Kaneko, 'Seitai to Kinzoku Ion', Gakkai Shuppan Center, Tokyo, 1991.

3 H. Hirai, and N. Toshima, 'Kobunshi Sakutai Syokubai', Gakkai Shuppan Center, Tokyo, 1982.

4 E. Tsuchida, 'Kobunshi Sakutai - Douteki Sogo Sayo to Denshi Katei', Gakkai Shuppan Center, Tokyo, 1991.

5 D. Wöhle, 2nd Circular of MMC-V, Bremen 1993.

6 F. Basolo, and R. G. Pearson, 'Mechanisms of Inorganic Reactions', Wiley & Sons, New York, 1967.

7 J. O. Edwards, 'Inorganic Reaction Mechanisms', W. A. Benjamin Inc., New York, 1964.

8 D. B. Rorabacher, and D. W. Margerum, *Inorg. Chem.*, **3**, 382 (1964).

9 W. H. Baddley, and F. Bassolo, *J. Amer. Chem. Soc.*, **88**, 2944 (1966).

10 S. Funahashi, and M. Tanaka, *Inorg. Chem.*, **9**, 2092 (1970).

11 J. C. Cassatt, *J. Biolo, Chem.*, **248**, 6129 (1973).

12 A. Udom and F. O. Brady, *Biochem. J.*, **187**, 329 (1980).

13 J. S. Valentine, N. W. Pantoliano, P. J. McDonnell, A. R. Burger, and S. J. Lippard, *Proc. Natl. Acad. Sci. USA*, **76**, 4245 (1979).

14 N. Hojo, H. Shirai, K. Sakata, and M. Fukuda, *Kogyo Kagaku Zasshi*, **73**, 1862 (1970).

H. Shirai, and N. Hojo, *Nippon Kagaku Zasshi*, **1972**, 1954 (1972).

H. Shirai, and N. Hojo, *Seisan to Gijyutsu*, **25**, (9)90 (1973).

CHAPTER 2

Ligand Substitution Reaction between Cu(II)-ammine Complex and Poly(vinyl Alcohol) in Aqueous Solution

CHAPTER
2

Ligand Substitution Reaction between Cu(II)-ammine Complex and Poly(viny Alcohol) in Aqueous Solution

SUMMARY: The kinetics of the ligand substitution reaction of the Cu(II)-ammine complex and poly(vinyl alcohol) (PVA) has been studied by a stopped-flow method at pH 9-10, at $\mu = 0.1$ (NH_4Cl) and at 25℃. The reaction is initiated by the formation of unstable $[Cu(NH_3)_3]^{2+}$ by the attack of H^+ on Cu(II)-ammine complex, and proceeds through the mixed complex $\{[Cu(NH_3)_3(O\text{-}PVA)]^{2+}\}$. This step may be rate-determining, followed by a rapid reaction. Finally, the Cu(II) ion is taken up by PVA. The rate is given by $d[Cu(II)PVA]/dt = k[H+]\{[Cu(NH_3)_4]^{2+}\}[PVA]/[NH_4Cl]$, where $k = k_1 + k_2[H^+]$, $k_1 = 4.25 \times 10\ s^{-1}$ and $k_2' = 5.20 \times 10^{11}\ l\ mol^{-1}\ s^{-1}$.

2-1 Introduction

In a previous series of papers, H. Shirai *et al.* have studied the complex formation of several transition metal ions with polymeric ligands such as poly(vinyl alcohol)[1,2], the coordination structure[3], the conformation changes of the polymeric chain by the coordination of metal ions to the polymeric ligands[2] and the chemical functions of the macromolecule-metal complexes obtained[4,5]. They have also reported on complex formation of Cu(II) with PVA, discussed thermodynamically, and showed a 'polymeric effect' in the formation of macromolecule-metal complex[6,7]. Many works have been devoted to the thermodynamic consideration of complex formation between polymeric ligands and metal ions[8]. However, there are few kinetic data available on the formation of macromolecule-metal complexes.

The kinetics and mechanisms for the substitution reactions of low molecular weight metal complexes with polymeric ligands seem of interest in view of the model reactions for metal transport *in vivo* [9].

As a first study, the ligand substitution reaction of Cu(II)-ammine complex with PVA was carried out in aqueous solution under various conditions including variation of the pH in the reaction media and variation of the concentration of the reaction species. The mechanism in the ligand substitution reaction was discussed from the results obtained.

2-2 Experimental

2-2-1 *Materials*

PVA (NM-14), a product of Nippon Synthetic Chemical Industry Co. Ltd., was used. The PVA was separated into several fractions of different average molecular weight according to the method given by Matsumoto[10], and each fraction was completely hydrolyzed by alkali in methanol[11].

The concentration of the stock solution of PVA was 0.16 mol/l. Cu(II)-ammine complex solutions[11] were prepared as follows: a solution of 0.25 mol/l of NH_4OH aqueous solution was added dropwise with stirring to an aqueous solution containing 4×10^{-4} mol/l $CuCl_2$ and the pH of the mixed solution was adjusted to the desired pH value with NH_4OH.

The ionic strength of the solution was maintained at 0.1 mol/l with NH_4Cl. A violet-blue aqueous solution of the Cu(II)-ammine complex $\{[Cu(NH_3)_4]Cl_2\}$ was obtained.

The complex solutions thus obtained were kept at 25℃ for 24 h before each experiment. The other reagents used here were of analytical grade from commercial origin and were used without further purification.

2-2-2 *Kinetic Measurements*

The reactions were carried out in a Union Giken RA-401 stopped-flow apparatus or in a Shimazu UV-200 spectrophotometer. pH measurements were carried out with a Hitachi-Horiba F7-SS pH meter.

Kinetic measurements were generally made as follows. One solution containing 8 × 10^{-3} mol/l PVA was brought to the starting pH with an NH_4OH-NH_4Cl buffer solution. A second solution containing 4 × 10^{-4} mol/l Cu(II)-ammine complex and NH_4Cl was brought to the same pH. The ionic strengths of these solutions were maintained at 0.1 mol/l with NH_4Cl.

These solutions were mixed in the ratio 1:1 (v/v) in a 1 cm cell of the stopped-flow spectrophotometer. The 0 to 0.1 optical density range at 400 nm was used in the spectrophotometer. A National VP-526A storage oscilloscope equipped with a Polaroid camera was used to record the data. All rates were measured at 25 ± 0.1℃.

2-3 Results and Discussion

2-3-1 Spectral Results

When the solution containing Cu(II)-ammine complex is added to a solution containing PVA at pH 9.5 and at 25℃, the color changes from violet-blue to green. The changes in electronic spectra observed before and after the reaction are shown in ***Figure 1*** as an example.

The formation of a complex of PVA with Cu(II) ion was confirmed by the appearance of peaks at 640 as well as at 260 nm, and an absorption shoulder at about 360 nm[2]. As shown in this figure, the formation of Cu(II)-PVA complex can be detected by the appearance of an absorption shoulder at ~360 nm and a peak at 640 nm after the reaction. This suggests that ligand substitution between Cu(II)-ammine complex and PVA is occurring by mixing the solutions. We can observe the time course of the substitution reaction by detecting the remarkable absorption increase at 400 nm.

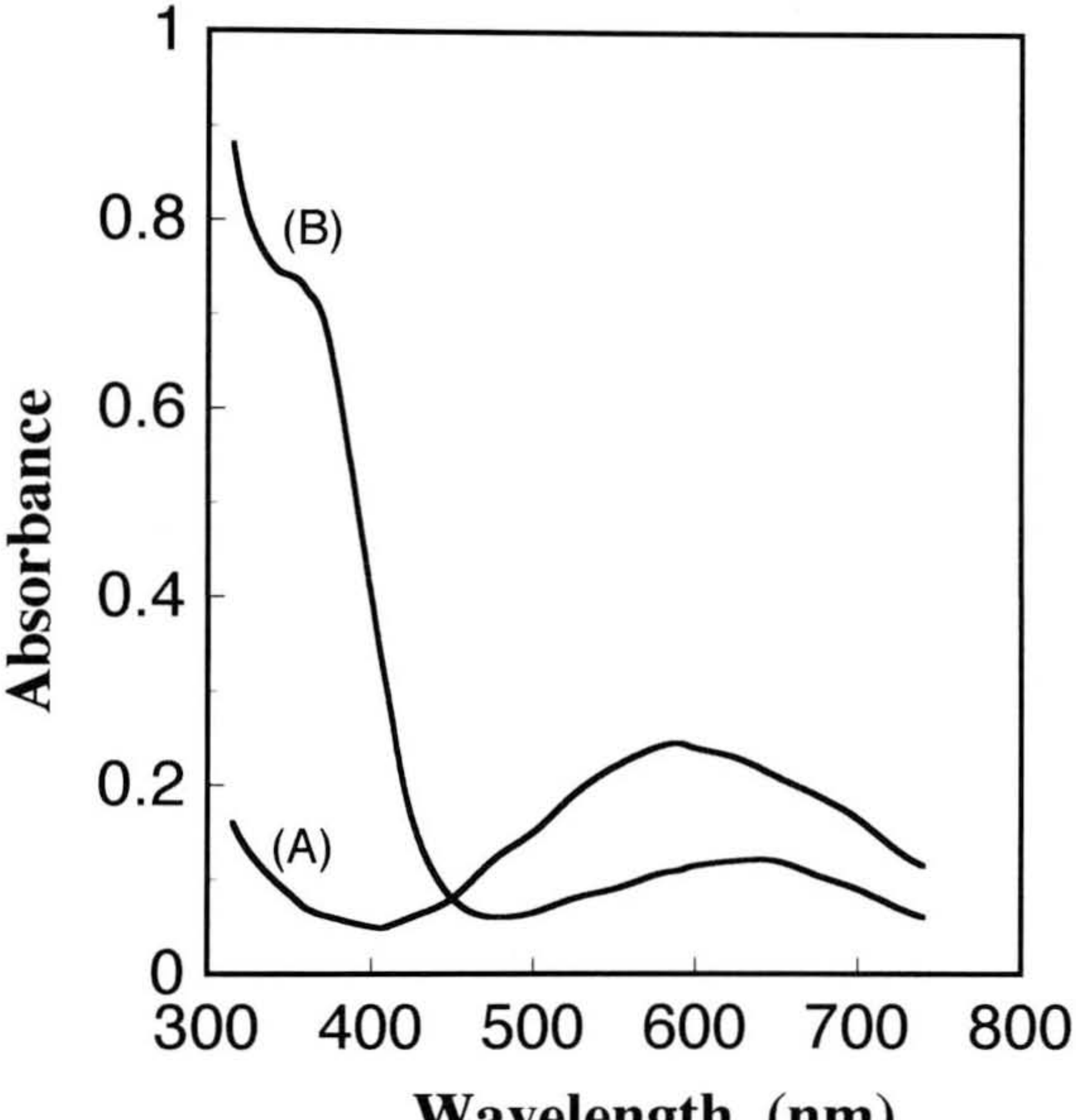


Figure 1 Cange in electronic spectra observed **(A)** before and **(B)** after the reaction between $[Cu(NH_3)_4]^{2+}$ ion and PVA: $[Cu(NH_3)_4]^{2+} = 4 \times 10^{-4}$ mol l^{-1}; [PVA] = 8×10^{-3} mol l^{-1}; pH 10.5; $\mu = 0.1(NH_4cl)$; 25℃.

2-3-2 Kinetic Results

The rates of reactions produced by mixing Cu(II)-ammine complexes with a large excess of PVA were followed by monitoring the appearance of the absorption at 400 nm. The stopped-flow oscilloscope traces displayed in ***Figure 2*** show the decrease of transmitted light intensity as the reaction proceeds. A plot of $\log(A_\infty - A_t)$ as a function of time was obtained using an approximate value for A_∞. A typical run is shown in ***Figure 3*** and appropriate plots in ***Figure 4***.

In general, straight lines were obtained for the reactions. All plots obtained in these experiments showed, as expected, that the reactions in the presence of an excess of PVA and buffered conditions were pseudo-first order. From these findings, the reaction of Cu(II)-ammine complex with excess PVA followed the rate expression:

$$\frac{d[\mathrm{Cu(II)\text{-}PVA}]}{dt} = k_{\mathrm{obs}}\{[\mathrm{Cu(NH_3)_4}]^{2+}\} \qquad (1)$$

where, k_{obs} is the observed rate constant of this ligand substitution reaction.

The ligand substitution reactions were carried out at 25℃ and $\mu = 0.1$ (NH_4Cl), varying the pH in the range pH 9.0-10.0 and keeping the concentrations of Cu(II)-ammine complex and PVA constant. ***Figure 5*** shows k_{obs} plotted against the initial concentration of hydrogen ion. From the figure it was found that k_{obs} is proportional to $[H^+]^{1.0}$. Thus the reactions exhibit specific acid catalysis.

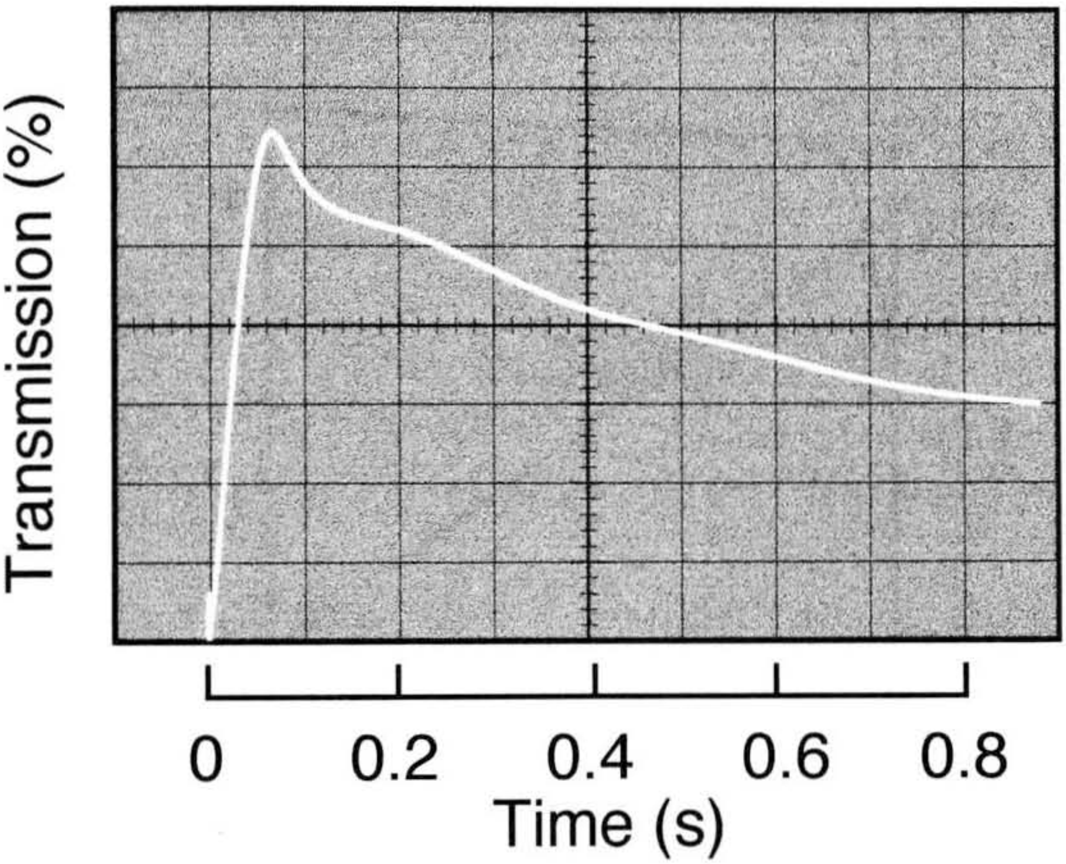


Figure 2 Change in D_{400} for the reaction of $[Cu(NH_3)_4]^{2+}$ with PVA at pH 9.40: $[Cu(NH_3)_4]^{2+} = 4 \times 10^{-4}$ mol l^{-1}; [PVA] = 8×10^{-3} mol l^{-1}; $\mu = 0.1(NH_4cl)$; 25℃.

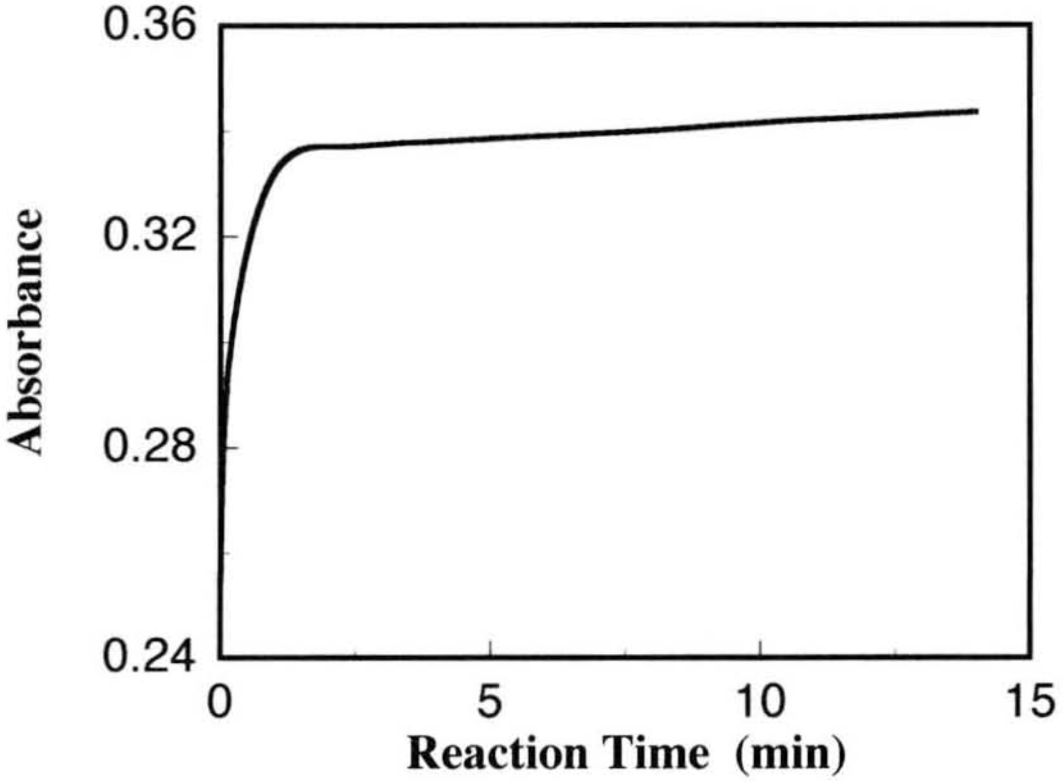


Figure 3 Change in D_{400} for the typical ligand exchange reaction between $[Cu(NH_3)_4]^{2+}$ ion and PVA: $[Cu(NH_3)_4]^{2+} = 4 \times 10^{-4}$ mol/l; [PVA] = 8×10^{-3} mol/l; pH 9.50; $\mu = 0.1(NH_4cl)$; 25℃.

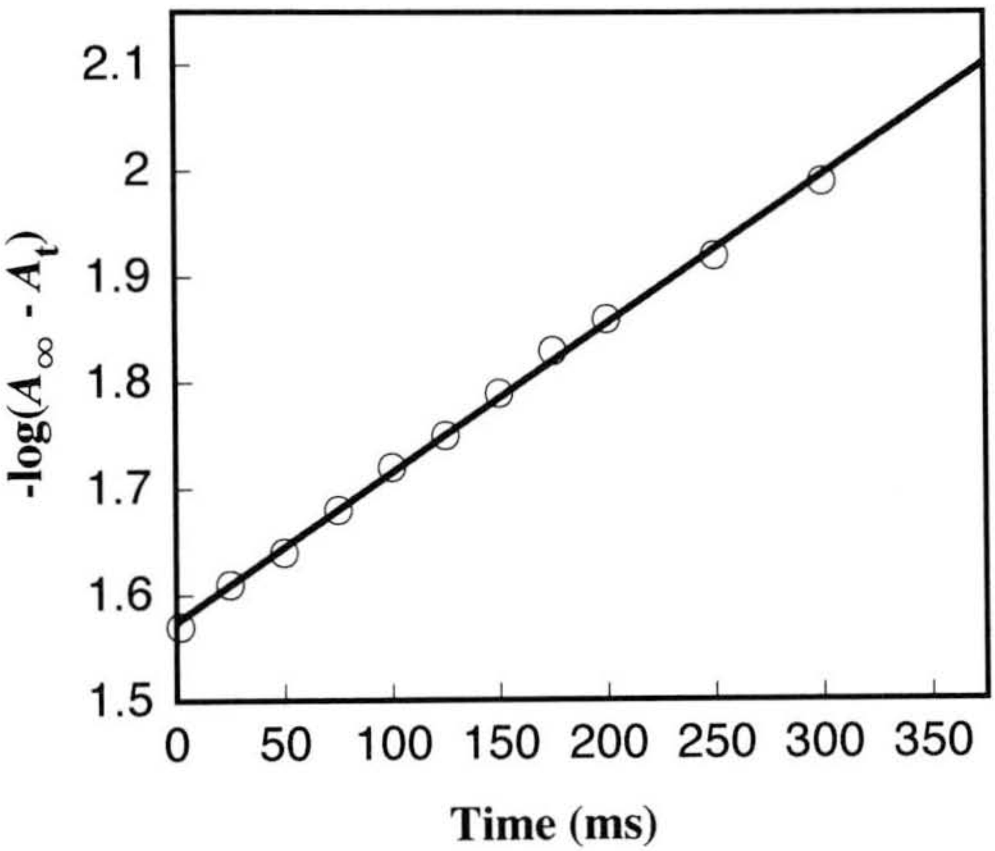


Figure 4 Semilog plots of $(A_{\infty} - A_t)$ as a function of time for the initial part of the reaction shown in Fig. 3.

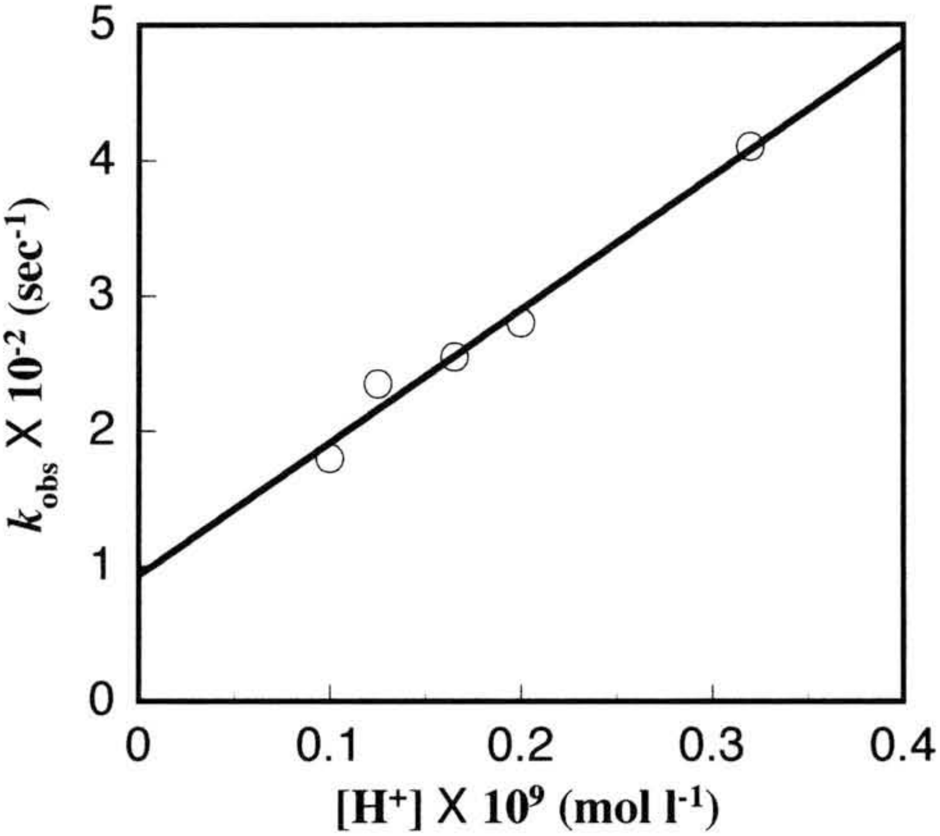


Figure 5 k_{obs} as a function of hydrogen ion concentration: $[Cu(NH_3)_4]^{2+}$ = 4 x 10^{-4} mol l^{-1}; [PVA] = 8 x 10^{-3} mol l^{-1}; μ = 0.1(NH_4cl); 25℃.

In another series of runs, the dependence of k_{obs} on the initial concentration of PVA was studied at constant concentration of Cu(II)-ammine complex, at pH 9.5, at $\mu = 0.1$ (NH_4Cl) and at 25℃ (***Figure 6***).

From *Figure 6* it was found that the rate of the substitution reaction was proportional to the PVA concentration under the condition that the value was below 1.5×10^{-4} mol/l; on the other hand, above this the rate was not proportional to the PVA concentration and was approximately constant.

Finally, the ligand substitution reactions were carried out at 25℃ and pH 9.5, varying the concentration of NH_4Cl, and keeping the concentrations of Cu(II)-ammine complex as well as PVA constant. The dependence of k_{obs} on the initial concentration of NH_4Cl is shown in ***Figure 7***. From the results in *Figure 7* it was found that k_{obs} is inversely proportional to $[NH_4Cl]^{1.0}$.

From these findings, the rate of the substitution reaction is proportional to $\{[Cu(NH_3)_4]^{2+}\}$, as well as [PVA], and varies inversely with respect to $[NH_4Cl]$.

Therefore, the rate is given by

$$\frac{d[\text{Cu(II)-PVA}]}{dt} = k\,\frac{[H^+]\,\{[Cu(NH_3)_4]^{2+}\}[\text{PVA}]}{[NH_4Cl]} \tag{2}$$

$$= k_{0(\text{H})}\,\frac{\{[Cu(NH_3)_4]^{2+}\}[\text{PVA}]}{[NH_4Cl]} \tag{3}$$

$$= k_1\,\frac{\{[Cu(NH_3)_4]^{2+}\}[\text{PVA}]}{[NH_4Cl]} + k_2\,\frac{\{[Cu(NH_3)_3\text{---}(NH_3\cdots H^+)]^{3+}\}[\text{PVA}]}{[NH_4Cl]} \tag{4}$$

$$= k_1\,\frac{\{[Cu(NH_3)_4]^{2+}\}[\text{PVA}]}{[NH_4Cl]} + k'_2\,\frac{[H^+]\,\{[Cu(NH_3)_4]^{2+}\}[\text{PVA}]}{[NH_4Cl]} \tag{5}$$

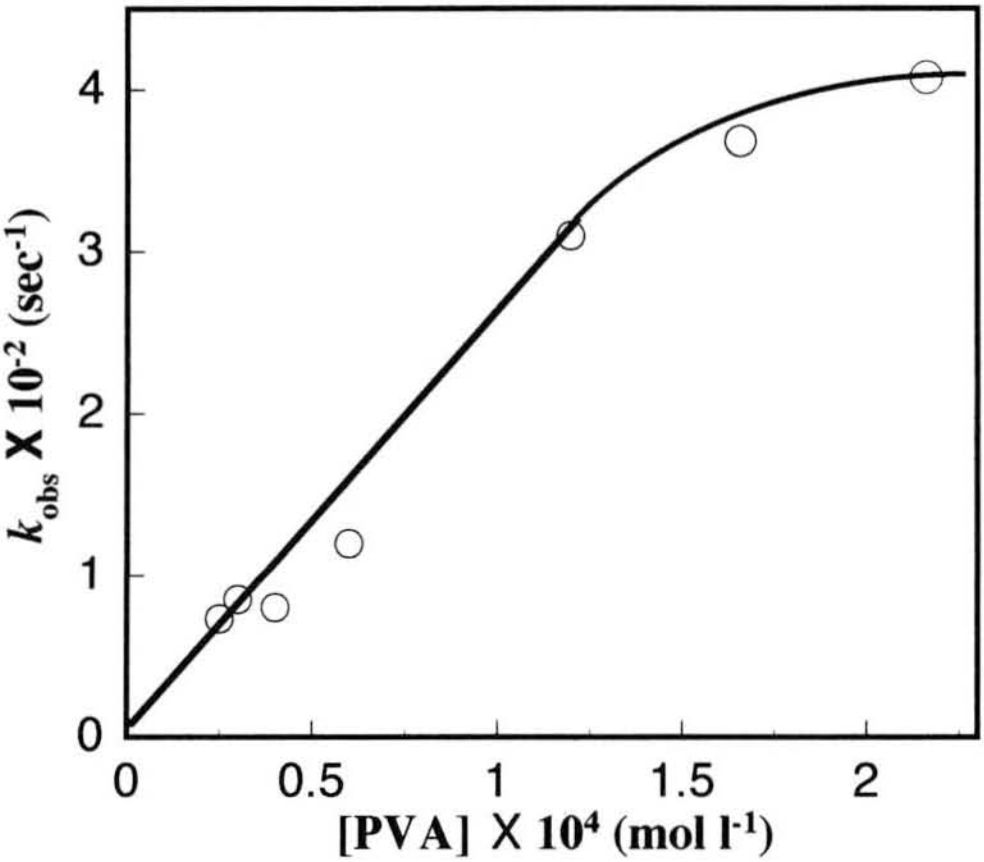


Figure 6 Effect of PVA concentration on the reaction of $[Cu(NH_3)_4]^{2+}$ with PVA: $[Cu(NH_3)_4]^{2+} = 4 \times 10^{-4}$ mol l^{-1}; pH 10.5; $\mu = 0.1(NH_4cl)$; 25℃.

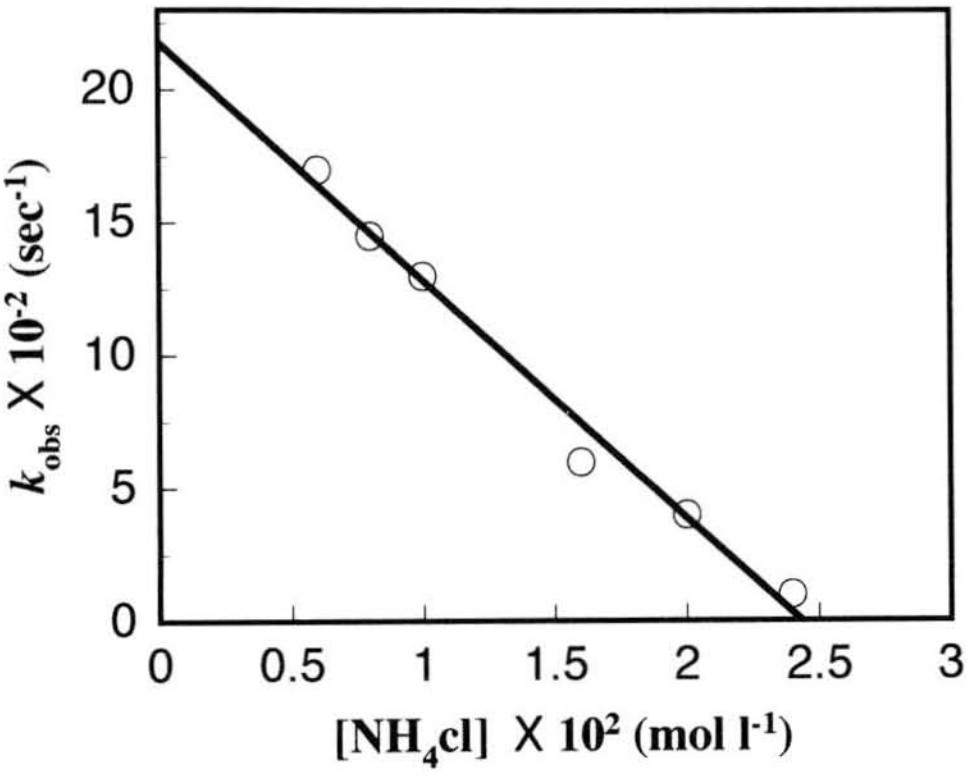


Figure 7 Effect of NH_4cl concentration on the reaction of $[Cu(NH_3)_4]^{2+}$ with PVA: $[Cu(NH_3)_4]^{2+} = 4 \times 10^{-4}$ mol l^{-1}; [PVA] = 8×10^{-3} mol l^{-1}; pH 10.5; 25℃.

$$= (k_1 + k'_2[\mathrm{H}^+]) \frac{\{[\mathrm{Cu(NH_3)_4}]^{2+}\}[\mathrm{PVA}]}{[\mathrm{NH_4Cl}]} \tag{6}$$

where

$$k_{0(\mathrm{H})} = k_1 + k'_2[\mathrm{H}^+] = k_{\mathrm{obs}} \frac{[\mathrm{NH_4Cl}]}{[\mathrm{PVA}]} \tag{7}$$

In ***Figure 8***, the values of $k_{0(\mathrm{H})}$ determined at various pHs and concentrations of $[\mathrm{Cu(NH_3)_4}]^{2+}$ complex and of PVA are plotted against the hydrogen ion concentration. It is evident from the figure that $k_{0(\mathrm{H})}$ is linearly related to hydrogen ion concentration.

From the slope of the graph in *Figure 8*, $k'_2 = 5.20 \times 10^{11}$ l mol^{-1} s^{-1} for the dissociation of the Cu(II)-ammine complexes at pH 9.0-10.0 and 25℃. The plots give zero intercept. The presence of a small positive intercept may reflect an $[\mathrm{H}^+]$ term.

From this intercept, $k_1 = 4.25 \times 10$ s^{-1}, and combining and rearranging equations (4) and (5), we obtain

$$\frac{k'_2}{k_2} = \frac{\{[\mathrm{Cu(NH_3)_3{-}{-}{-}(NH_4^+)}]^{3+}\}}{[\mathrm{H}^+]\,\{[\mathrm{Cu(NH_3)_4}]^{2+}\}} = \boldsymbol{K}^{\mathrm{H}^+}_{\mathrm{Cu(NH3)4}} \tag{8}$$

$$k_2 = \frac{k'_2}{\boldsymbol{K}^{\mathrm{H}^+}_{\mathrm{Cu(NH3)4}}} \tag{9}$$

where $\boldsymbol{K}^{\mathrm{H}^+}_{\mathrm{Cu(NH3)4}}$ is the successive acid hydrolysis constant[12]. Therefore, $k_2 = 5.20 \times 10^5$ l mol^{-1} s^{-1}.

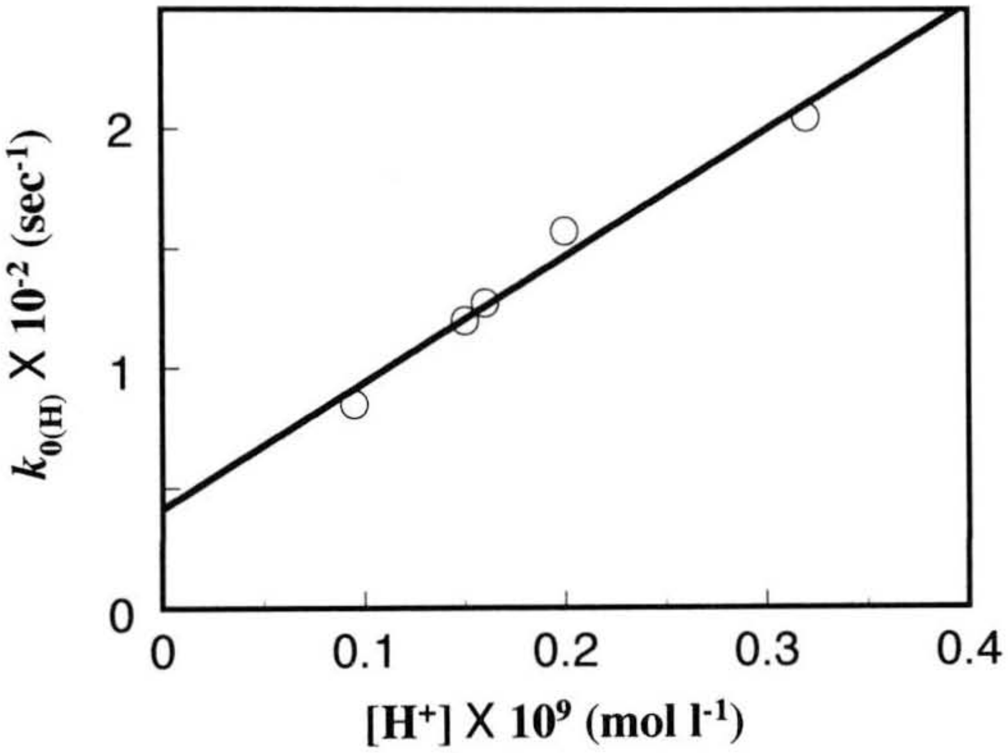


Figure 8 $k_{0(H)}$ as a function of hydrogen ion concentration: $[Cu(NH_3)_4]^{2+}$ = 4 x 10^{-4} mol l^{-1}; [PVA] = 8 x 10^{-3} mol l^{-1}; μ = 0.1(NH_4cl); 25℃

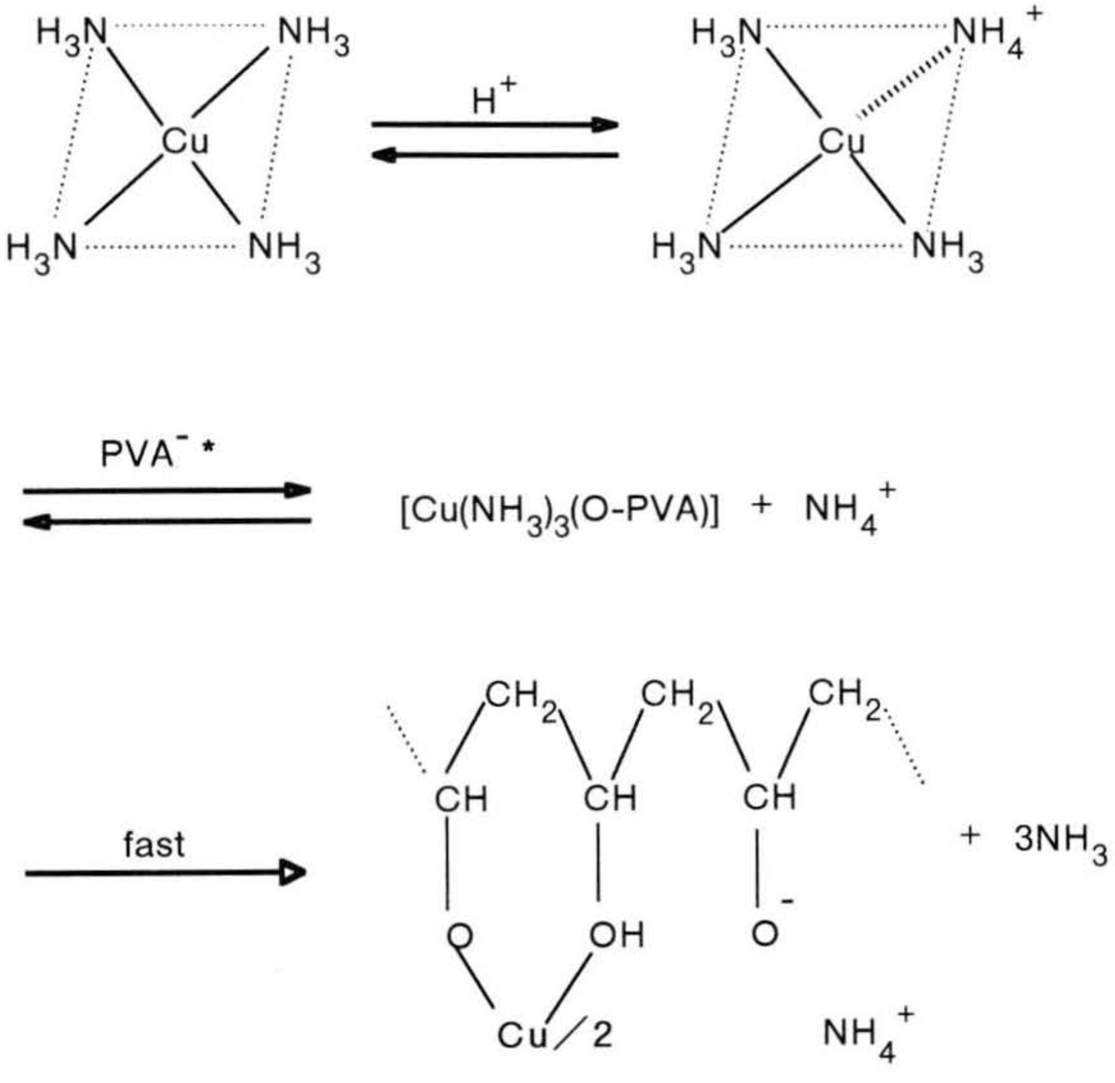
2-3-3 Mechanism of the Ligand substitution Reaction

In the substitution of Cu(II)-ammine complex with PVA, a proton first attacks the $[Cu(NH_3)_4]^{2+}$ complex and the resulting NH_4^+ is released from $[Cu(NH_3)_4]^{2+}$. Once the NH_4^+ is released, the Cu(II)-ammine complex becomes unstable, and the $[Cu(NH_3)_3]^{2+}$ is attacked by PVA. A mixed complex $[Cu(NH_3)_3(O\text{-}PVA)]^+$ may be formed. This step may be rate-determining, followed by a rapid reaction, and Cu(II) ion is taken up by PVA.

OH groups in PVA dissociate into O^- ions in more alkaline solution[2]: pK_a = 10.67, μ = 0.1 (KNO_3), 25℃. Therefore, NH_4^+ released from $[Cu(NH_3)_4]^{2+}$ may be trapped by partially dissociated PVA anions. These steps can be described as in ***Figure 9***.

After this ligand substitution reaction, NH_4^+, Cl^- and free NH_3 were removed by dialysis from the reaction mixture. From the solutions thus obtained, Cu(II)-PVA film was prepared by casting on polyethylene film in dust-free air at 30℃. The film was dried under vacuum for several days. Elemental analysis of the film was carried out. From the result, the N content of Cu(II)-PVA film is found to be zero.

The infra-red and electronic spectra of the film were identical with those of Cu(II)-PVA complexes in a previous series of papers[11,13]. Therefore, it was found that the coordination of NH_3 to Cu(II) atom in Cu(II)-PVA may not occur.



* p*Ka* of poly(vinyl alcohol) is 10.65 at 25℃ and $\mu = 0.1$(Kcl)[6]

Figure 9 Schematic representation of the reaction of $[Cu(NH_3)_4]^{2+}$ complex with poly(vinyl alcohol) in aqueous solution.

References

1 N. Hojo, and H. Shirai, *Kagaku Sosetsu* **17**, 183 (1976).

2 N. Hojo, S. Hayashi, and H. Shirai, *J. Polym. Sci., Polym. Symp. Edn.*, **47**, 229 (1974).

3 H. Shirai, *Nippon Kagaku Kaishi*, **1973**, 384 (1973).

4 N. Hojo, Y. Chujo, S. Hayashi, and H. Shirai, *J. Polym. Sci., Polym. Chem. Edn.*, **16**, 447 (1978).

5 H. Shirai, Y. Nio, A. Kurose, S. Hayashi, and N. Hojo, *Nippon Kagaku Kaishi*, **1978**, 117 (1978).

6 N. Hojo, and H. Shirai, *Nippon Kagaku Kaishi*, **1972**, 1316 (1972).

7 H. Shirai, and N. Hojo, *Nippon Kagaku Kaishi*, **1972**, 1954 (1972).

8 N. Hojo, and H. Shirai, 'Chelate Resin and Ion Exchange Resin', (Ed. N. Hojo), Kodan-sha, Tokyo, 1976, pp. 1-126.

9 T. Suzuki, H. Shirai, F. Shimizu, and N. Hojo, *Polym. J.*, **15**, 409 (1983).

10 M. Matsumoto, *Kobunshi Kagaku*, **18**, 169 (1961).

11 H. Shirai, *Nippon Kagaku Kaishi*, **1973**, 390 (1973).

12 J, Bjerrum, 'Metal-Ammine Formation in Aqueous Solution', Hasse and Son, Copenhagen, 1957.

13 H. Shirai, and N. Hojo, *Nippon Kagaku Kaishi*, **1972**, 2223 (1972).

14 N. Hojo, H. Shirai, K. Nakajima, and S. Hayashi, *Kobunshi Ronbunshu*, **37**, 665 (1980).

CHAPTER 3

Ligand substitution Reaction between Cu(II)-Poly(vinyl Alcohol) Complex and Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution

CHAPTER
3

Ligand substitution Reaction between Cu(II)-Poly(vinyl Alcohol) Complex and Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution

SUMMARY: The kinetics of the ligand substitution reaction of the Cu(II)-poly(vinyl alcohol) (PVA) complex with ethylenediamine-N,N,N',N'-tetraacetic acid ($edtaH_4$) was studied by a stopped-flow method at pH 9.34 -11.05, at μ = 0.1 (KNO_3) and at 25.0℃. The substitution reaction proceeds simultaneously through two different reaction paths. In one path, the reaction is initiated by the attack of H^+ on the bond between Cu(II) ion and dissociated $-O^-$ of PVA to form unstable Cu(II)-H-PVA. In the other path, solvolysis by water as a nucleophilic reagent proceeds. The rate law is written as

$-d[\mathrm{Cu(II)\text{-}PVA}]/dt = k\,[\mathrm{Cu(II)\text{-}PVA}]/[\mathrm{PVA}]$, where $k = k_1 + k_2'[H^+]$,

$k_1 = 3.62 \times 10^{-3}$ M s^{-1} and $k_2' = 2.83 \times 10^{7}$ s^{-1} respectively. The rates were found to be independent of the edta anion concentration. A possible mechanism for the substitution reaction is discussed.

3-1 Introduction

In a previous series of papers[1-5], the complex formation of several metal ions with polymeric ligands such as poly(vinyl alcohol) have been studied in the viewpoints of the coordination structure, conformation change of polymeric chain and the chemical functions of the macromolecule-metal complexes.

Much research has been carried out on the kinetics and mechanisms of the ligand substitutions of metal complexes between other low molecular weight ligands[6-8]. However, there are little similar kinetic data available on macromolecule-metal complexes[9]. The kinetics and mechanisms of the ligand substitution reactions of macromolecule-metal complexes with other monomeric or polymeric ligands seem of interest in view of the model reactions for the metal transport *in vivo* and the basis of mechanochemical reactions by ligand substitution reactions as well as the incorporation of metal ions into chelate resins[10,11].

In chapter 2, the ligand substitution reaction between the Cu(II)-ammine complex and poly(vinyl alcohol) has been studied by a stopped-flow method and the kinetics and mechanism of the substitution reaction were discussed. The present chapter concerns the kinetics and mechanism of the ligand substitution reaction between Cu(II)-poly(vinyl alcohol) (PVA) complexes and ethylenediamine-N,N,N',N'-tetraacetic acid (edta-H_4) in aqueous solution.

3-2 Experimental

3-2-1 Materials

PVA(NM-14), a product of Nippon Synthetic Chemical Industry Co., Ltd., was used. The PVA was separated into several fractions of different average molecular weights according to the fractional precipitation given by Matsumoto[12]; each fraction was completely hydrolyzed by alkali in methanol[4]. The concentration of PVA (Pn=1400) used in these experiments was 0. 16 mol/l.

Reagent grade Na_2edtaH_2 was obtained from Wako Pure Chemical Ind. and purified by recrystallization four times from methanol-water. Na_2edtaH_2 dried in air at 80℃ was dissolved in 0.2 mol/l KNO_3 aqueous solution. The concentration of a stock solution of Na_2edtaH_2 was 2×10^{-2} mol/l. Cu(II) ion solutions were prepared from a stock solution of $Cu(NO_3)_2 \cdot 3H_2O$ standardized by an atomic absorption spectrophotometer (Hitachi 207 type).

Cu(II)-PVA complex solutions were prepared as follows. An aqueous solution of Cu(II) ion was added to the PVA solution, and the pH of the mixed solution was adjusted to the desired pH value with KOH. The ionic strengths of the Cu(II)-PVA complex solutions were maintained at 0. 1 mol/l with KNO_3. The complex solutions thus obtained were kept at 25℃ for 24hs before each experiment. The other reagents used here were of analytical grade obtained from commercial sources and used without further purification.

3-2-2 Kinetic Measurements

Electronic spectra were measured on a Shimadzu UV-200 spectrophotometer. The reactions were carried out in a stopped-flow apparatus of Union Giken RA-401 (dead time=1ms) or a Shimadzu UV-200 spectrophotometer. The pH measurements were carried out with a Hitachi-Horiba F7-SS pH meter.

In most cases, the kinetic measurements were made as follows. One solution containing ~1.6×10^{-1} mol/l PVA and 8×10^{-6} mol/l Cu^{2+} ion was brought to the starting pH. Ionic strength was maintained at 0.10 mol/l with KNO_3. A second solution of Na_2edtaH_2 and KNO_3 (concentration necessary to bring the ionic strength 8×10^{-3} to 0.1 mol/l) was brought to the same pH.

These solutions were mixed in the ratio of 1 : 1 in a 1 cm cell inserted into a stopped-flow spectrophotometer. The optical density range of 0 to 0.35 at 360 nm was used for the absorption measurements. A National VP-526A storage oscilloscope equipped with a Polaroid camera was used to record the data. All rates were measured at 25 ± 0.1℃ and were the average from at least five runs.

3-3 Results and Discussion

3-3-1 Spectral results

Cu(II)-poly(vinyl alcohol) (PVA) complex imparts a green color to aqueous solution above pH 7.3. The 640 nm, 260 nm peaks and an absorption shoulder at about 360 nm in the electronic spectra of the solution correspond to the formation of complexes of PVA with Cu(II) ion[4].

When a solution containing edta anions is added to a solution of the Cu(II)-PVA complex, the color of solution changes from green to light blue. This suggest that the ligand substitution reaction between the Cu(II)-PVA complex and edta anion occurs under the experimental condition and is much favored to the right so that the reaction goes to completion; the reverse reaction can be neglected in the kinetic study. The overall ligand substitution may be described as

$$\text{Cu(II)-PVA} + \text{edta} \rightarrow \text{Cu(II)-edta} + \text{PVA} \qquad (1)$$

where edta refers to ethylenediamine-N,N,N'.N'-tetraacetic acid anion species. The decomposition of the Cu(II)-PVA complex by edta anion can be detected by the disappearance of the absorption shoulder at about 360 nm. The reaction rates produced by mixing Cu(II)-PVA complexes with a large excess of edta anions were followed by monitoring the disappearance of absorption at 400 nm. Too fast to be measured by conventional means, the rates of this reaction were measured by stopped-flow techniques.

3-3-2 Kinetic results

Plots of log $(A_t - A_\infty)$ as a function of time were obtained using an approximate value (infinite value for the reaction) for $A_t - A_\infty$; t is the time after the beginning of the reaction; $A_t - A_\infty$ and A_∞ are the absorbances of the reaction system at $t = t$, and ∞, respectively.

A typical run is shown in ***Figure 1***. In general, straight lines were obtained for the reaction. All plots obtained in these experiments showed, as expected, that the reactions in the presence of a large excess of edta anions and under buffered conditions (0.1 mol/l KNO_3) were of the pseudo-first order.

Thus, the reaction of Cu(II)-PVA complex with a large excess of edta anion is expressed as:

$$-\frac{d[\text{Cu(II)-PVA}]}{dt} = k_{\text{obs}}[\text{Cu(II)-PVA}] \qquad (2)$$

where k_{obs} is the conditional rate constant.

The dependence of k_{obs} on the initial concentration of edta anions was studied at a constant concentration of Cu(II)-PVA and at pH 10.5. The value of k_{obs} was plotted against the initial concentration of edta anions in ***Figure 2***. The reaction order with respect to the initial concentration of edta anions was found to be zero.

Next, the ligand substitution reaction between Cu(II)-PVA complex and edta anion was carried out at pH 10.5 and at 25℃. In these experiments, the Cu(II)-PVA complexes were prepared keeping the concentration of Cu(II) ions constant and varying the ratio of the total concentration of Cu(II) ions to the concentration of ligand ($T_{Cu^{2+}}/T_{HL}$). The results are shown in ***Figure 3***. The figure shows k_{obs} to be inversely proportional to the concentration of PVA.

From these findings, the rate of the ligand substitution reaction between Cu(II)-PVA complex and edta anion is expressed as:

$$-\frac{d[\mathrm{Cu(II)\text{-}PVA}]}{dt} = k_{0(H)}\frac{[\mathrm{Cu(II)\text{-}PVA}]}{[\mathrm{PVA}]} \qquad (3)$$

where $k_{0(H)}$ refers to the conditional rate constant involving the concentration term of hydrogen ions.

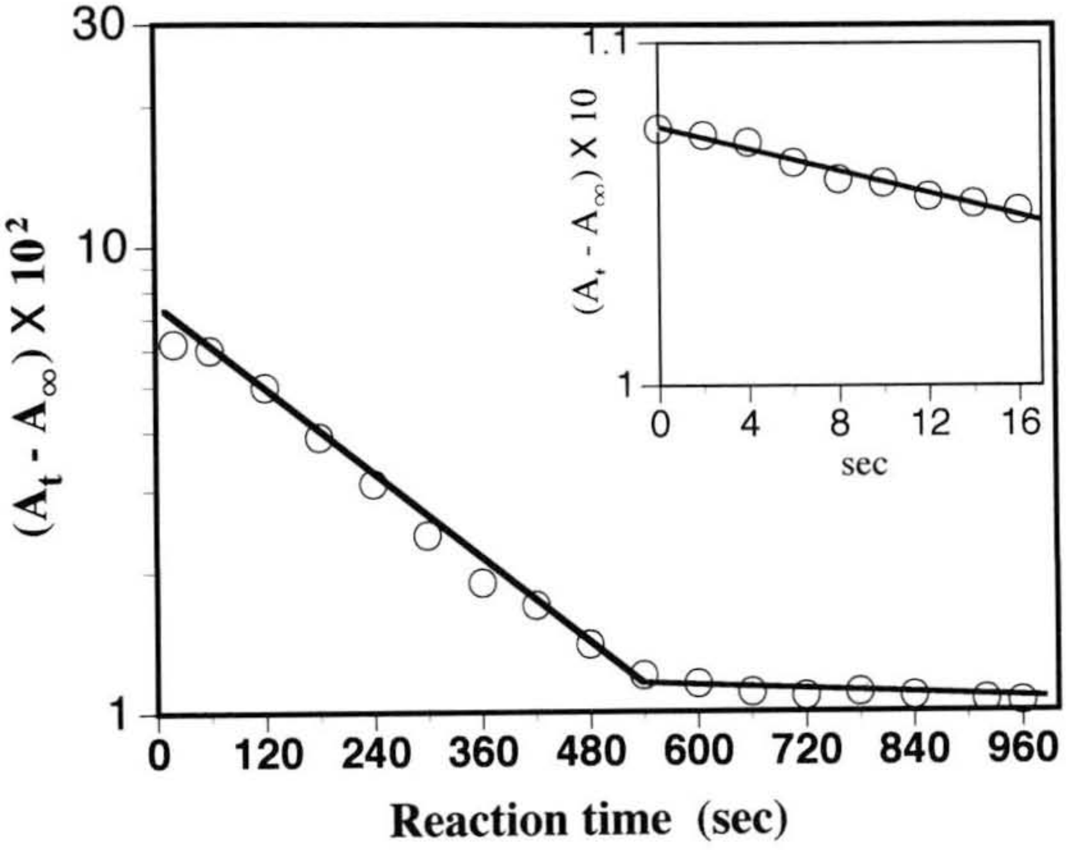


Figure 1 Semilog plots of (A_t - A_∞) as a function of time for the reaction of Cu(II)-PVA complex with edta anion in aqueous solution at pH 10.5, μ = 0.1(KNO_3) and at 25℃: [Cu(II)-PVA] = 4×10^{-4} mol l^{-1}; [EDTA] = 4×10^{-3} mol l^{-1}; $T_{Cu^{2+}}/T_{HL}$ = 0.05.

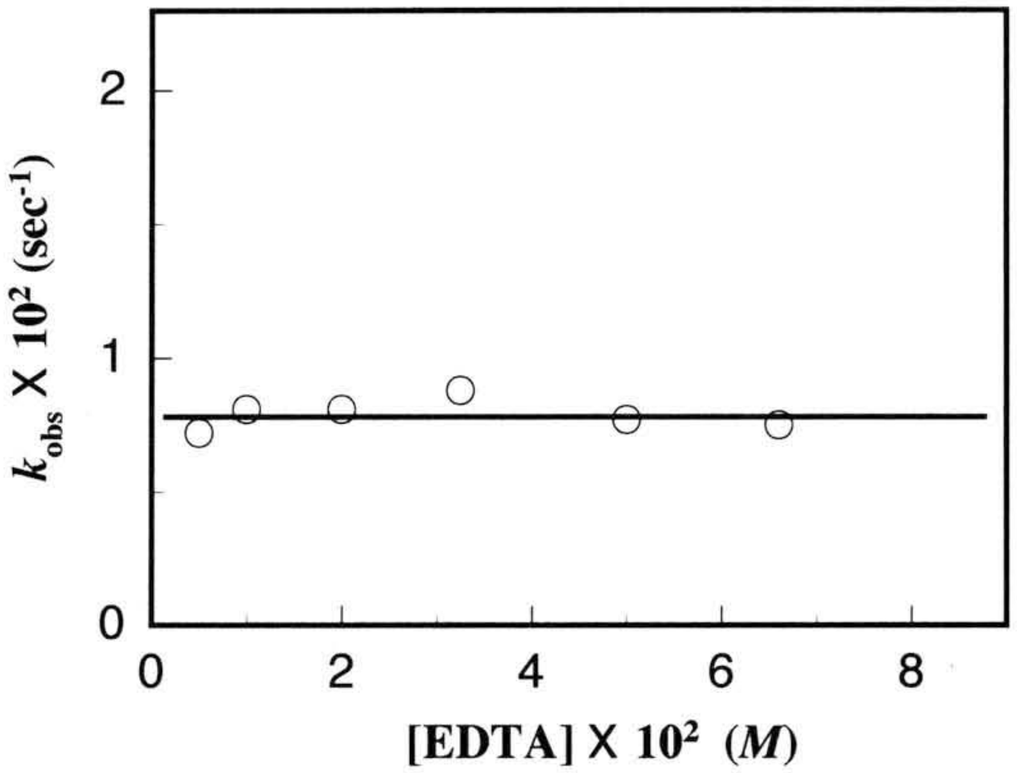


Figure 2 k_{obs} as a function of edta anion concentration: [Cu(II)-PVA]= 4 x 10^{-4} mol l^{-1}; [PVA] = 3.2 x 10^{-2} mol l^{-1}; pH 10.5; $T_{Cu^{2+}}/T_{HL}$ = 0.05; μ = 0.1(KNO_3); 25℃.

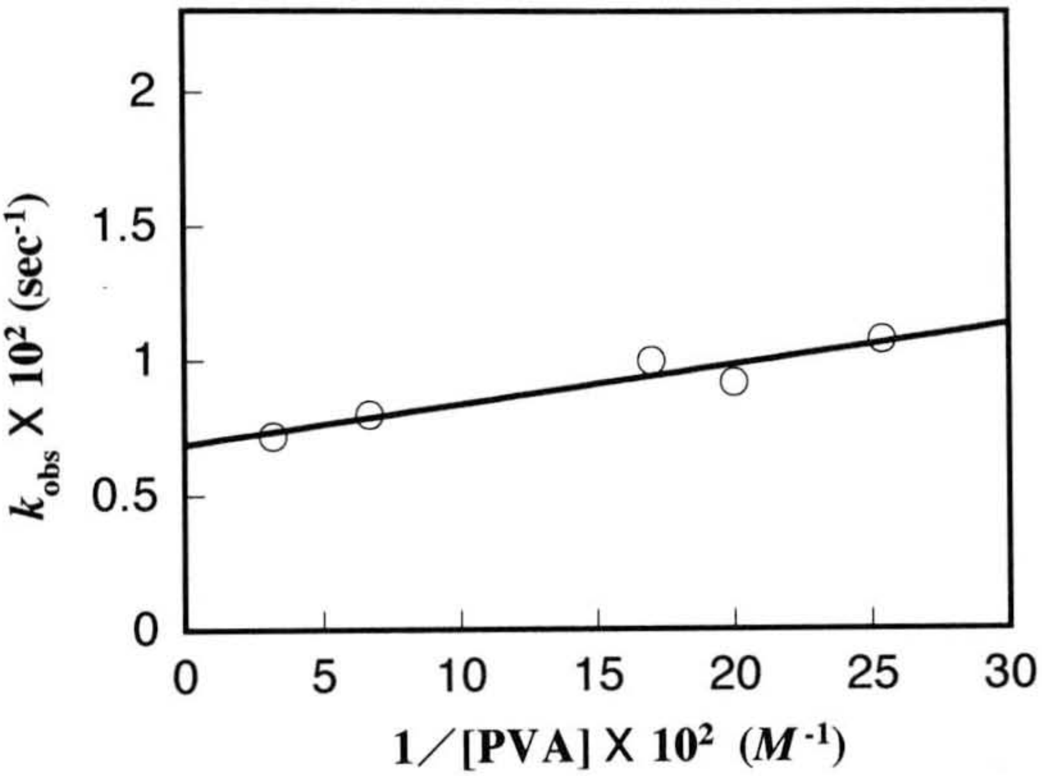


Figure 3 k_{obs} as a function of PVA concentration for the ligand exchange reaction: [Cu(II)]= 4 x 10^{-4} mol l^{-1}; [EDTA] = 4 x 10^{-3} mol l^{-1}; pH 10.5; $T_{Cu^{2+}}/T_{HL}$ = 0.05; μ = 0.1(KNO_3); 25℃.

Finally, the ligand substitution reaction was carried out at 25℃, varying the pH in the range 9.34 - 11.05, and keeping Cu(II)-PVA and edta anion concentrations constant. ***Figure 4*** shows $k_{0(H)}$ plotted against the initial hydrogen ion concentration. It is evident from Figure 4 that $k_{0(H)}$ is linearly related to the hydrogen ion concentration.
Thus, we obtain the following rate expression[13,14]:

$$-\frac{d\,[\mathrm{Cu(II)\text{-}PVA}]}{dt} = k_1\frac{[\mathrm{Cu(II)\text{-}PVA}]}{[\mathrm{PVA}]} + k_2'\frac{[\mathrm{H^+}][\mathrm{Cu(II)\text{-}PVA}]}{[\mathrm{PVA}]} \tag{4}$$

From the intercept and slope in Figure 4, k_1 and k_2' may be obtained: $k_1 = 3.62 \times 10^{-3}\ M\,\mathrm{s}^{-1}$ and $k_2' = 2.38 \times 10^{7}\ \mathrm{s}^{-1}$.

3-3-3 Mechanism of the Ligand substitution Reaction

The complex formation of PVA with Cu(II) ion is expressed by the following two successive steps[3]:

$$\mathrm{Cu^{2+} + HL \underset{K^{-H}_{Cu(II)\text{-}L}}{\rightleftarrows} Cu(II)\text{-}L + H^+} \tag{5}$$

$$\mathrm{Cu(II)\text{-}L + HL \underset{K^{-H}_{Cu(II)\text{-}L_2}}{\rightleftarrows} Cu(II)\text{-}L_2 + H^+} \tag{6}$$

where HL refers to two monomeric units of PVA. The rate law of the ligand substitution reaction between Cu(II)-PVA complex and edta anion as in eq (4) is consistent with the following mechanism.

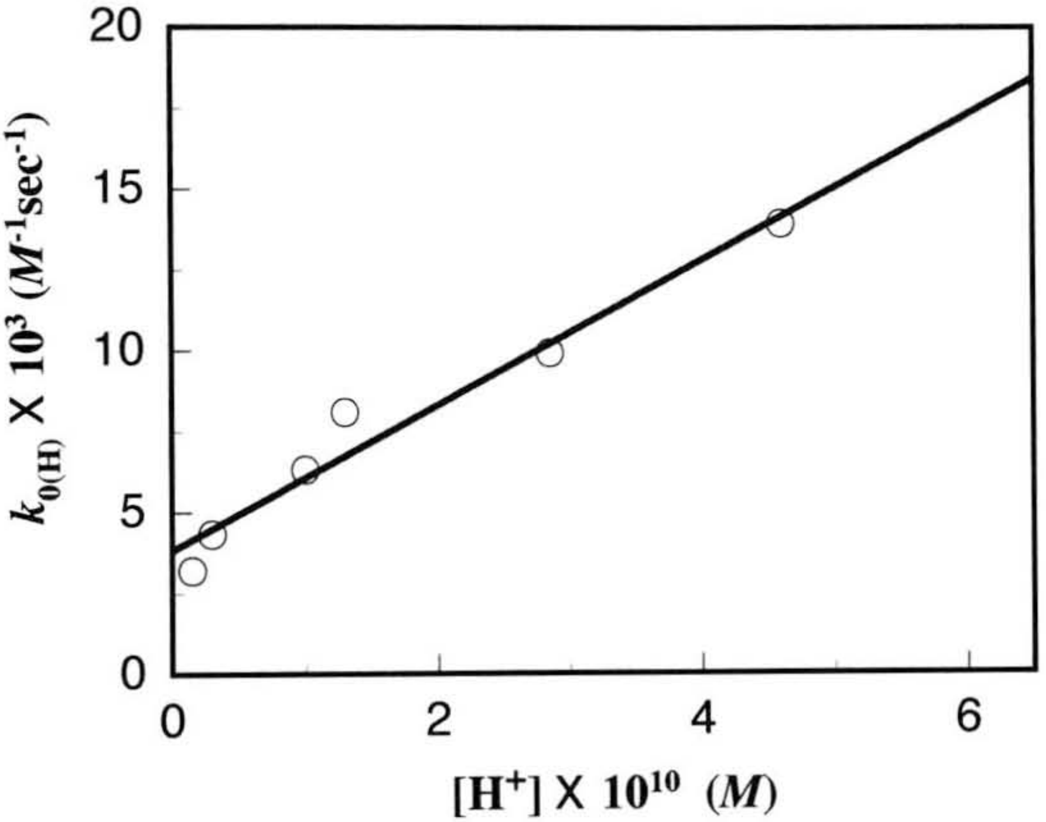
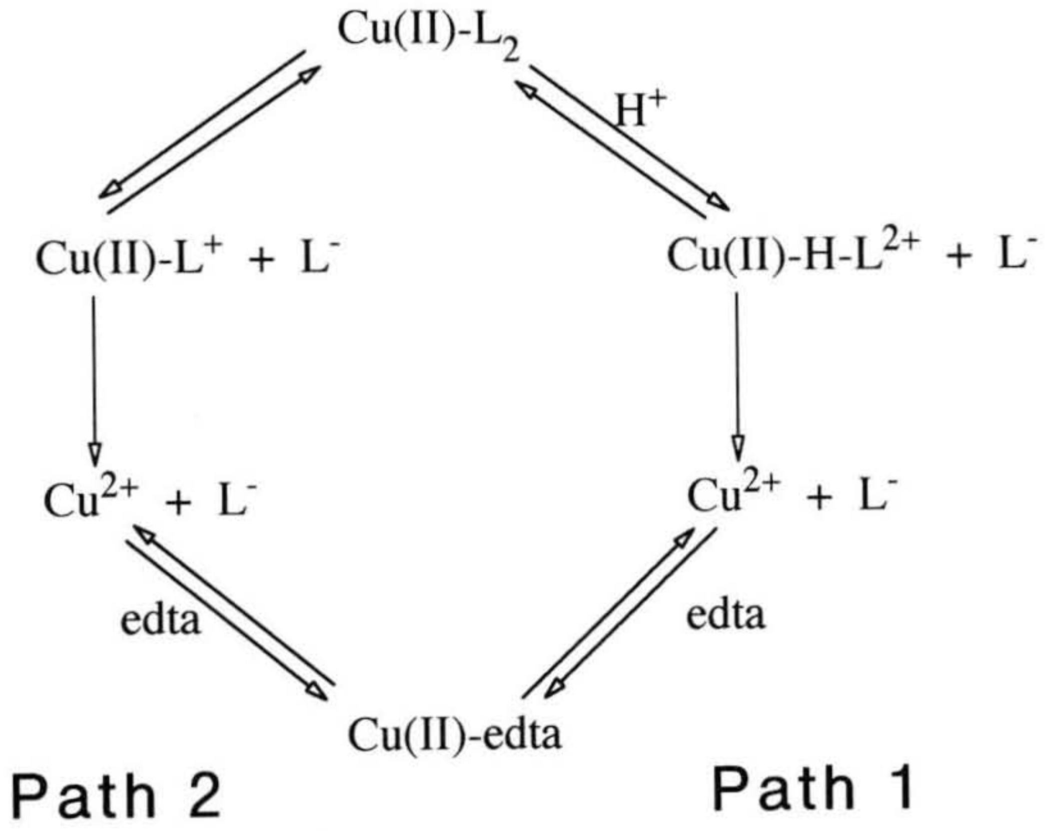


Figure 4 $k_{0(H)}$ as a function of hydrogen ion concentration for the ligand exchange reaction: [Cu(II)-PVA] = 4 x 10^{-4} mol l^{-1}; [EDTA] = 4 x 10^{-3} mol l^{-1}; $T_{Cu^{2+}}/T_{HL}$ = 0.05; μ = 0.1(KNO_3); 25℃.

Under the experimental conditions, ethylenediamine-N,N,N',N'-tetraacetic acid is given in the form of edtaH^{3-} (37%) and edta^{4-} (63%) (pK_{a4} = 10.26)[15]. In **Path 1** of the mechanism, a proton from edtaH^{3-} first attacks the bond between the Cu(II) ion and dissociated $-O^-$ of PVA to form unstable Cu(II)-H-PVA. Once protonated, the Cu(II)-PVA complex becomes unstable and PVA is partially dissociated from the complex. It hardly seems possible that edta^{4-} attacks the free site of partially dissociated Cu(II)-H-PVA to form a ternary complex edta-Cu(II)-H-PVA. The dissociation of PVA from the Cu(II)-H-PVA complex should be the rate-determining step, and then free Cu(II) ions are taken up by edta^{4-}. This dissociative process is supported by the experimental evidence that the rate of the reaction is independent of the concentration term of edta anions. The mechanism of this reaction belongs to the D-mechanism proposed by Langford[16]. The fact that the rate of the ligand substitution reaction is dependent on the concentration of $[PVA]^{-1.0}$ indicates the participation of PVA in the step prior to the rate-determining step.

On the other hand, **Path 2** of the mechanism is solvolysis by water as a nucleophilic reagent. But it seems reasonable to consider that the contribution of this path to the reaction rate is smaller than the proton-assisted path because of the stability of the Cu(II)-L_2 complex under the experimental conditions.


$Cu(II)-L_2$
H^+
$Cu(II)-L^+ + L^-$
$Cu(II)-H-L^{2+} + L^-$
$Cu^{2+} + L^-$
$Cu^{2+} + L^-$
edta
edta
Cu(II)-edta
Path 2
Path 1

Scheme 1

The second term of eq (4) shows the participation of the protonated complex Cu(II)-H-PVA. Thus, substituting the successive stability constant of Cu(II)-PVA complex shown in eq (6), we have

$$-\frac{d[\mathrm{Cu(II)\text{-}PVA}]}{dt} = k_1\frac{[\mathrm{Cu(II)\text{-}PVA}]}{[\mathrm{PVA}]} + k_2' K^{-\mathrm{H}}_{\mathrm{Cu(II)\text{-}PVA}}\frac{[\mathrm{Cu(II)\text{-}PVA}]}{[\mathrm{PVA}]} \tag{7}$$

$$= k_1\frac{[\mathrm{Cu(II)\text{-}PVA}]}{[\mathrm{PVA}]} + k_2\frac{[\mathrm{Cu(II)\text{-}H\text{-}PVA}]}{[\mathrm{PVA}]} \tag{8}$$

Therefore, $k_2 = k_2' K^{-\mathrm{H}}_{\mathrm{Cu(II)\text{-}PVA}} = 3.68 \times 10^4\ \mathrm{M\ s^{-1}}$.

The ligand substitution reactions between Cu(II)-PVA and edta anion varying the concentration of neutral salt were carried out at pH 10.5 and at 25℃. ***Figure 5*** shows k_{obs} plotted against the ionic strength, μ. The value increased with increasing concentration of KNO_3 in the reaction media. This fact was attributed to an electrostatic repulsion between the partly negative charged PVA chain (pK_a of PVA = 10.64)[2] bonded to Cu(II) ion and also negative charged edta^{4-} ion. Namely, owing to addition of neutral salt the attack of edta^{4-} to Cu(II) ion is facilitated more by the relaxation of the electrostatic repulsion. At higher concentrations of potassium nitrate, the ligand substitution path may approach the associative path as was proposed for the ligand substitution reaction between the low molecular weight ligand complex with polyamine.[17]

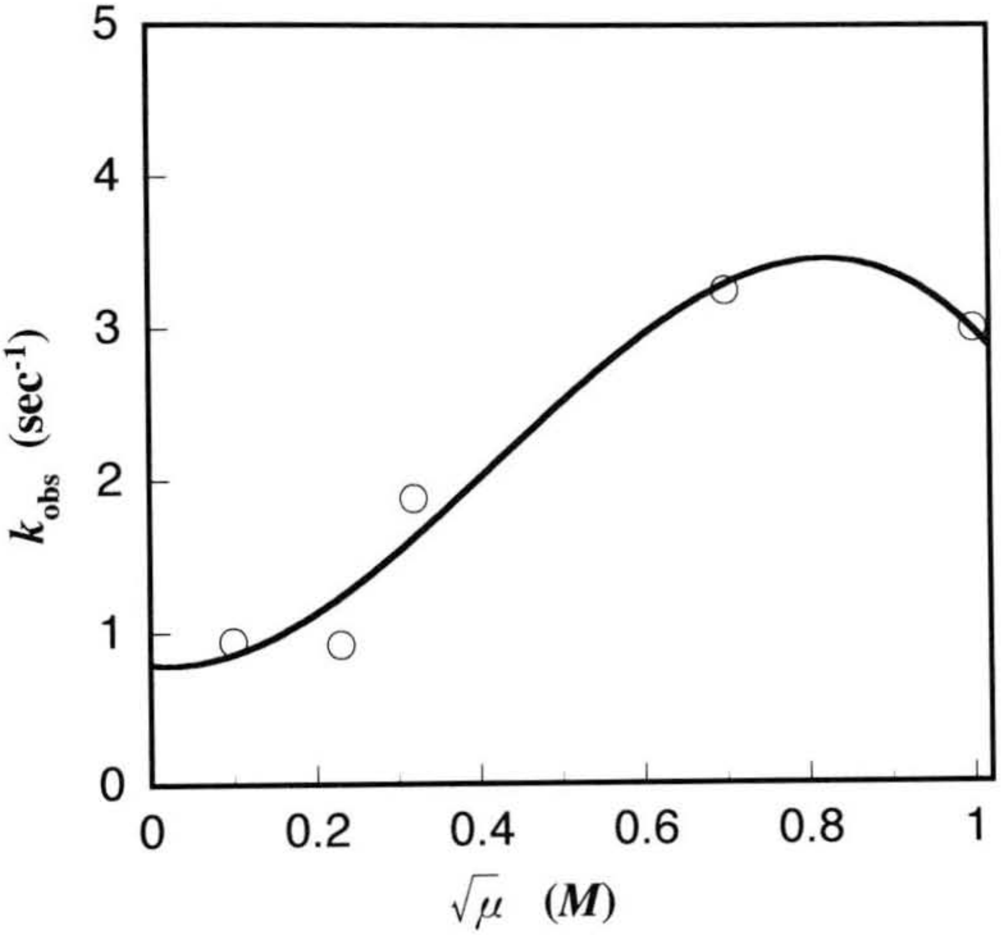


Figure 5 Effect of ionic strength on the rate constants for the ligand exchange reaction: [Cu(II)-PVA] = 4 x 10^{-4} mol l^{-1}; [EDTA] = 4 x 10^{-3} mol l^{-1}; pH 10.5; $T_{Cu^{2+}}/T_{HL}$ = 0.05; 25℃.

References

1 N. Hojo, H. Shirai, K. Sakata, and M. Fukuda, *Kogyo Kagaku Zasshi*, **73**, 1862 (1970).

2 N. Hojo, and H. Shirai, *Nippon Kagaku Zasshi*, 1972, 1316 (1972).

3 H. Shirai, and N. Hojo, *Nippon Kagaku Zasshi*, 1972, 1954 (1972).

4 N. Hojo, H. Shirai, and S. Hayashi, *J. Polym. Sci., Polym. Symp.*, **47**, 229 (1974).

5 N. Hojo, H. Shirai, Y. Chujo, and S. Hayashi, *J. Polym. Sci.. Polym. Chem. Ed.*, **16**, 447 (1978).

6 B. Bosnic, F. P. Dwyer, and A. M. Sargeson, *Nature*, **186**, 966 (1962).

7 R. A. Libby and D. W. Margerum, *Biochemistry*, **4**, 916 (1965).

8 M. Tanaka, S. Funabashi, and K. Shirai, *Inorg. Chem.*, **7**, 573 (1968).

9 S. Lau and B. Sarkar, *Can. J. Chem.*, **53**, 710 (1975).

10 N. Hojo, H. Shirai, and Y. Kameyama, *Kogyo Kagaku Zasshi*, **74**, 269 (1968).

11 N. Hojo and H. Shirai, "Chelate Resin and Ion Exchange Resin", ed. by N. Hojo, Kodan-sha, Tokyo, 1976, pp 1−126.

12 M. Matsumoto, *Kobunshi Kagaku*, **18**, 169 (1961).

13 G. K. Pagenkopf and D. W. Margerum, *J. Am. Chem. Soc.*, **90**, 6963 (1968).

14 S. Funabashi, S. Yamada, and M. Tanaka, *Bull. Chem. Soc. Jpn.*, **43**, 769 (1970).

15 K. Ueno, "Chemistry of EDTA Complexan", Nanko-do, Tokyo, 1977, pp 105 − 110.

16 C. H. Langford and H. B. Gray, "Ligand Substitution Processes", Benjamin, New York, 1966.

17 D. W. Margerum and H. M. Rosen, *Inorg. Chem.*, **7**, 299 (1968).

CHAPTER 4

Metal Exchange Reaction between Cu(II)-Poly(vinyl Alcohol) Complex and Ca(II)-ethylenediamine-N,N,N',N' tetraacetic Acid in Aqueous Solution

CHAPTER

4

Metal Exchange Reaction between Cu(II)-Poly(vinyl Alcohol) Complex and Ca(II)-Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution

SUMMARY: The kinetics of the metal exchange reaction between the Cu(II)-poly(vinyl alcohol) complex (Cu(II)-PVA) and Ca(II)-ethylenediamine-N,N,N',N'-tetraacetic acid (Ca(II)-EDTA) were studied by mixing both solutions in a spectrophotometer at pH 9.7-11.0, at μ = 0.10(KNO_3) and at 25 ℃. The reaction is initiated by the formation of unstable Cu(II)-H-PVA by the attack of H^+ to Cu(II)-PVA, and while both ligand exchange and metal exchange steps occur, the latter may be rate-determining. The kinetic expression of this reaction was determined as $-d[\mathrm{Cu(II)\text{-}PVA}]/dt = k[\mathrm{Cu(II)\text{-}PVA}][H^+][\mathrm{PVA}]/[\mathrm{Ca(II)\text{-}EDTA}]$, where $k = k_1 + k_2'[H^+]$,

$k_1 = 3.85 \times 10^{-2}\ \mathrm{sec}^{-1}$, $k_2 = k_2' \cdot K^{-H}_{\mathrm{Cu(II)\text{-}H\text{-}PVA}} = 9.59 \times 10^{5}\ \mathrm{l\ mol^{-1}\ sec^{-1}}$.

4-1 Introduction

The mechanisms of metal exchange reaction of macromolecule-metal complexes are of interest in view of the model reaction for metal transport *in vivo*. In a previous chapters, the kinetics of the ligand exchange reactions of the Cu(II)-poly(vinyl alcohol) complex and the ethylenediamine-N,N,N',N'-tetraacetic acid, and between the Cu(II)-ammine complex and poly(vinyl alcohol) and in aqueous solution[1,2] were discussed. These ligand exchange reactions were classified as SN2 type substitution according to those kinetic data.

D. C. Olson and D. W. Margerum have presented a chain reaction mechanism for the metal exchange reaction between Ni(II)-triethylenetetramine and Cu(II)-EDTA[3], but there are few reports about the substitution reaction of macromolecule-metal complexes[4]. This chapter concerned with the kinetics and mechanism of the metal exchange reaction between Cu(II)-PVA and Ca(II)-ethylenediamine-N,N,N',N'-tetraacetic acid.

4-2 Experimental

4-2-1 *Materials*

PVA(NM-14) a product of Nippon Synthetic Chemical Industry Co, Ltd. was used. The PVA was separated into several fractions of different average molecular weight according to the method given by Matsumoto[5], and each fraction was completely hydrolyzed by alkali in methanol[6]. The concentration of

PVA used in these experiments was 0.08 mol/l.

Ca(II)-EDTA4Na obtained from Wako Pure Chemical Industry was purified by recrystallization three times from methanol-water and dried in air at 80℃. The concentration of a stock solution of Ca(II)-edta anion (0.16 mol/l) was standardized by a Hitachi 207 atomic absorption spectrophotometer.

An aqueous solution of Cu(II) ions was added into the PVA solution, and the pH of the mixed solution was adjusted to desired pH value with KOH. The ionic strengths of Cu(II) solutions and Ca(II)-EDTA solutions were maintained at 0.1 mol/l with KNO_3. Cu(II)-PVA complex solutions were kept at 25℃ for 24 hours before each experiment. Other reagents used here were of analytical grade of commercial origin, and were used without further purification.

4-2-2 Kinetic Measurements

Electronic spectra of Cu(II)-PVA and Ca(II)-EDTA solutions were measured on a Shimazu UV-200 spectrophotometer. The exchange reactions were carried in a UV spectrophotometer, and pH measurements were carried out with a Hitachi-Horiba F7-SS pH meter. Kinetic measurements were generally made as follows:

One solution containing ~4×10^{-4} mol/l of Cu(II)-PVA (the ratio of Cu(II) ion to OH groups in PVA, $T_{Cu^{2+}}/T_{HL} = 0.05$) was brought to the starting pH with 0.1*N* KOH. These solutions were mixed in the ratio of 1:1(V/V) in a 1cm cell spectrophotometer. An optical density range 0 to 0.1 to 0.1 were used. All rate were measured at 25 ± 0.1℃.

4-3 Results and Discussion

4-3-1 Spectral results

When a Cu(II)-PVA solution is added to a solution containing the Ca(II)-edta anion complex, the color of the solution gradually changes from green to blue. The change in electronic spectra observed before and after the reaction is shown by ***Figure 1***. The complex formation of PVA with Cu(II) ion is confirmed by the appearance of peaks at 640 nm as well as 260 nm[6] and an absorption shoulder at about 360 nm. The remarkable absorption of Cu(II)-PVA complex decays at 360 nm. This suggests that a metal exchange reaction between Cu(II)-PVA and Ca(II)-edta anion is occurring on the mixing of both solutions. We can observe the progress of the metal exchange reaction by detecting the remarkable decrease in absorbance at 400 nm.

4-3-2 Kinetic results

The rates of reactions produced by mixing Cu(II)-PVA solution with Ca(II)-edta anion solution were followed by monitoring the disappearance of the absorption at 400 nm. ***Figure 2*** shows the decrease of transmitted light intensity as the reaction proceeds. Plots of $\log(A_t - A_\infty)$ as a function of time were obtained using an approximate value for A_∞. A plot obtained from a typical run is shown in ***Figure 3***. In general, straight lines were obtained for the reaction. All plots obtained in these experiments showed, as expected, that the reactions in the presence of an excess of Ca(II)-edta anions and under buffered

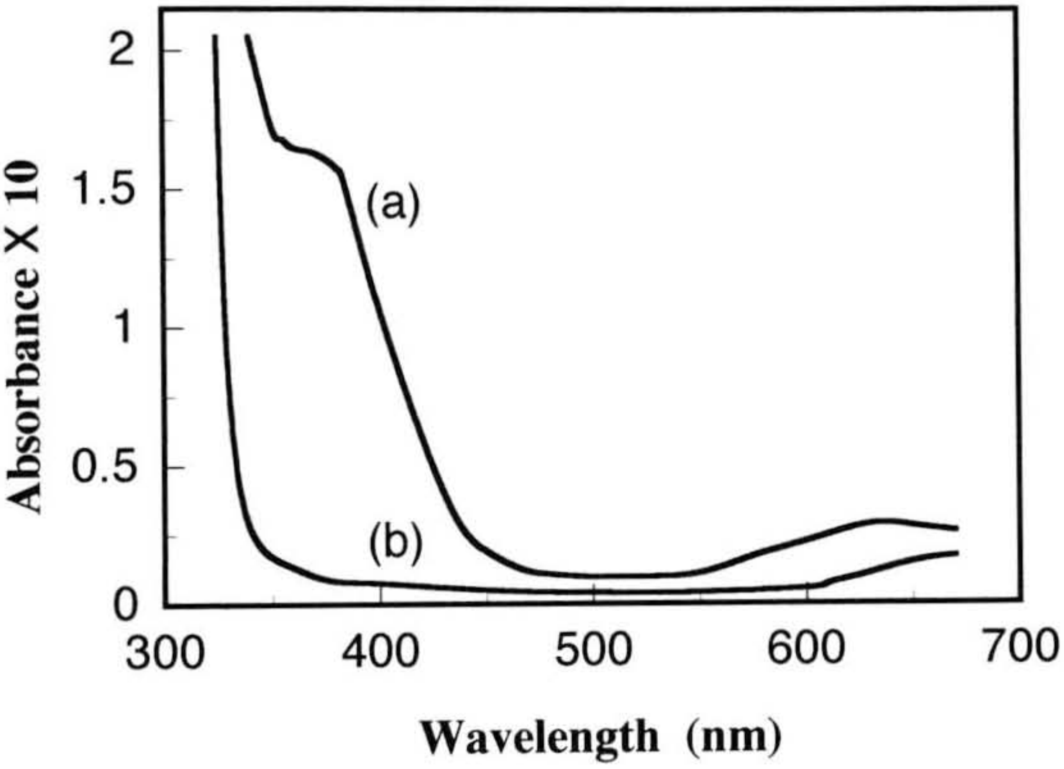


Figure 1 Electronic spectra for the reaction of Cu(II)-PVA complex with Ca(II)-edta anion (a) before and (b) after the reaction in aqueous solution: [Cu(II)-PVA] = 4×10^{-4} mol l^{-1}; [Ca(II)-EDTA] = 2×10^{-2} mol l^{-1}; pH 10.5, $\mu = 0.1(KNO_3)$; $T_{Cu^{2+}}/T_{HL} = 0.05$; 25℃.

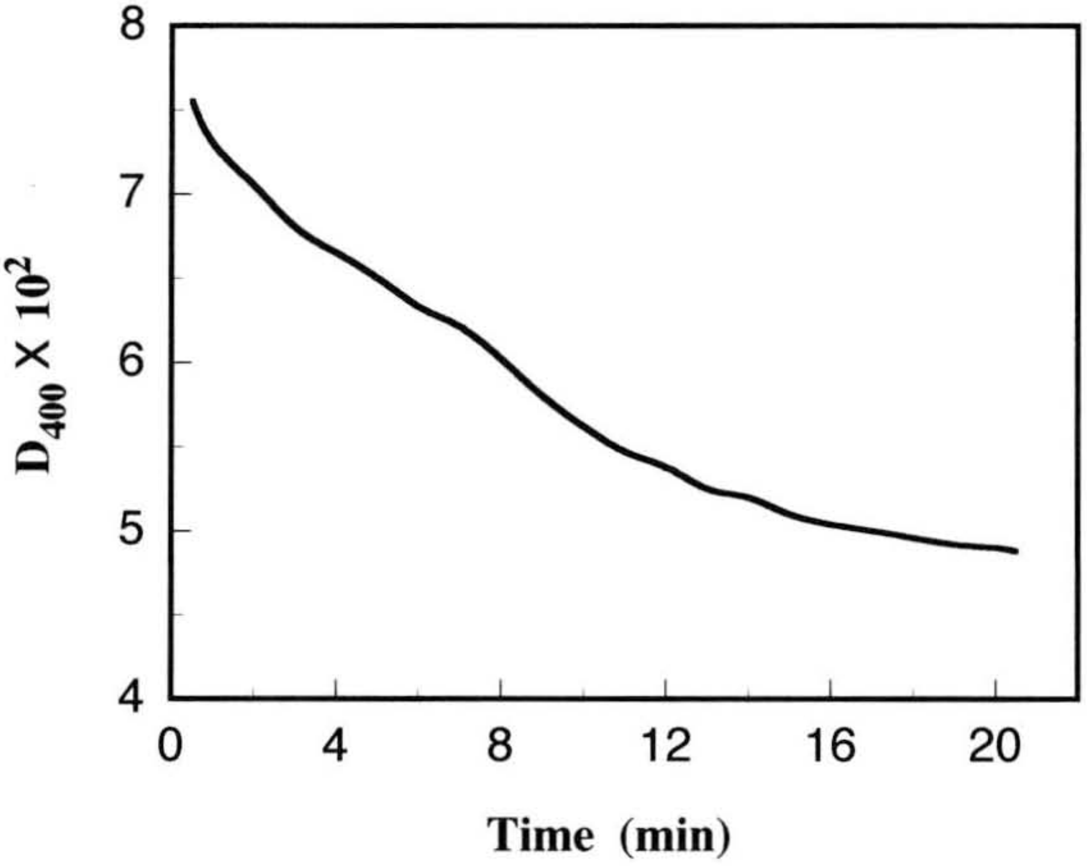


Figure 2 Change in D_{400} for the reaction of Cu(II)-PVA complex with Ca(II)-edta anion in aqueous solution: [Cu(II)-PVA] = 4 x 10^{-4} mol l^{-1}; [Ca(II)-EDTA] = 2 x 10^{-2} mol l^{-1}; pH 10.5, μ = 0.1(KNO_3); $T_{Cu^{2+}}/T_{HL}$ = 0.05; 25℃.

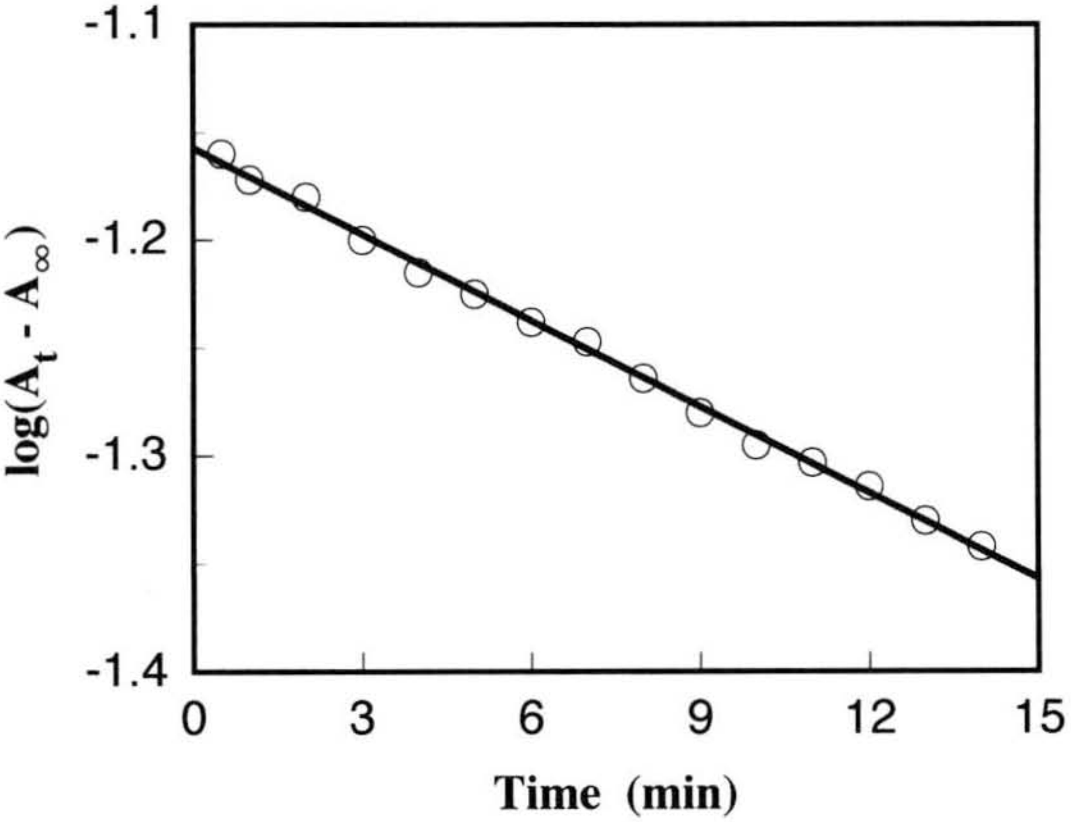


Figure 3 Relationship between (A_t - A_∞) and reaction time obtained from Fig. 2.

conditions were pseudo-first order. From these findings, the reaction of the Cu(II)-PVA complex with excess Ca(II)-edta anion followed the rate expression;

$$-\frac{d[\mathrm{Cu(II)\text{-}PVA}]}{dt} = k_{\mathrm{obs}}[\mathrm{Cu(II)\text{-}PVA}] \qquad (1)$$

where k_{obs} is the observed rate constant.

The metal exchange reactions were carried out at 25℃ and at μ =0.1(KNO_3) varying the pH 9.7-11.0 and keeping the concentrations of Cu(II)-PVA and Ca(II)-edta anions constant. ***Figure 4*** shows the k_{obs} plotted against the initial concentration of hydrogen ions. From this figure it was found that k_{obs} was proportional to $[H^+]^{1.0}$. Thus the reaction exhibits specific acid catalysis. In another series of runs, the dependence of k_{obs} on the initial concentrations of PVA was studied at constant concentration of Ca(II)-edta anions and Cu(II) ions at pH = 10.5, μ =0.1(KNO_3) and 25℃ (***Figure 5***). From Figure 5 it was found that the rate of the exchange reaction was also proportional to $[\mathrm{PVA}]^{1.0}$.

Finally, the metal exchange reactions were carried out at 25℃, pH 10.5 and μ = 0.1(KNO_3) varying the concentration of Ca(II)-edta anions, and keeping the concentration of Cu(II)-PVA constant as shown in ***Figure 6***. This figure shows that k_{obs} is inversely proportional to the concentration of Ca(II)-edta anions. Because the exchange reaction can not occur without Ca(II)-edta anion, the formation of $Ca(OH)_2$ at higher pH seems to have any influence of the exchange reaction;

$$\mathrm{Ca(II)\text{-}EDTA^{2-}} \rightleftarrows \mathrm{Ca^{2+}} + \mathrm{EDTA^{4-}} \qquad (2)$$

$$\mathrm{Ca^{2+}} + 2\mathrm{OH^-} \rightleftarrows \mathrm{Ca(OH)_2}. \qquad (3)$$

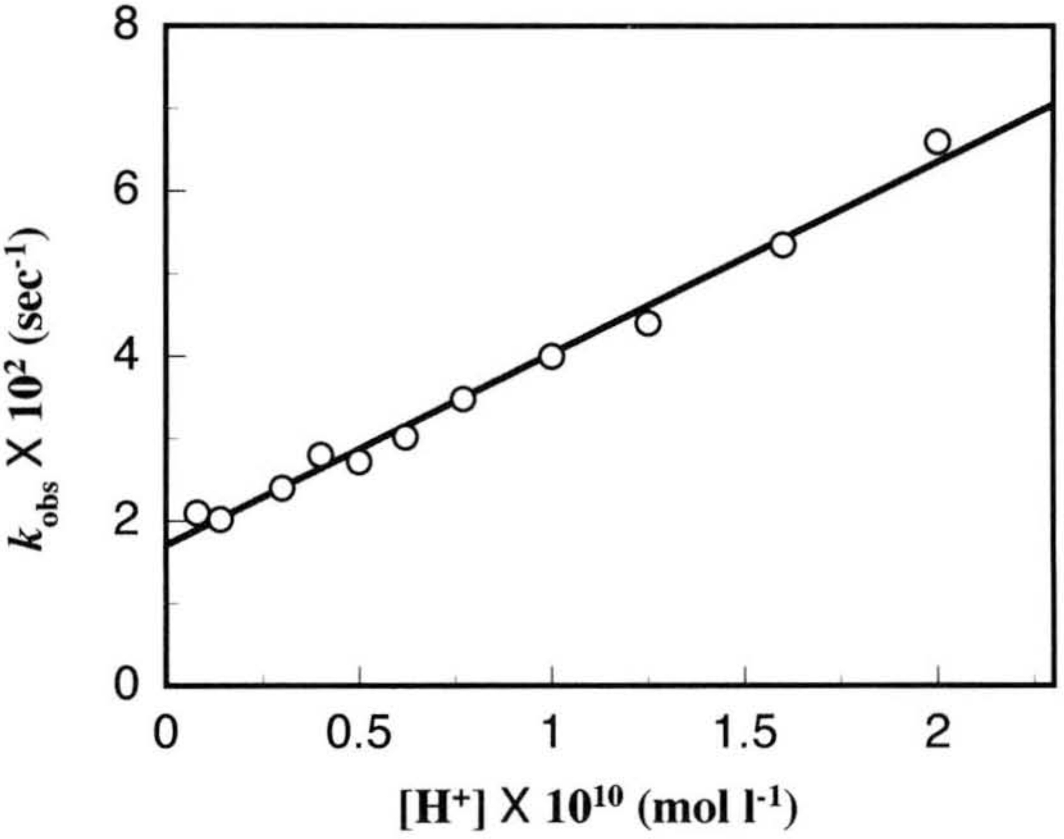


Figure 4 k_{obs} as a function of hydrogen ion concentration: [Cu(II)-PVA] = 4×10^{-4} mol l^{-1}; [Ca(II)-EDTA] = 2×10^{-2} mol l^{-1}; $T_{Cu^{2+}}/T_{HL} = 0.05$; $\mu = 0.1(KNO_3)$; 25℃

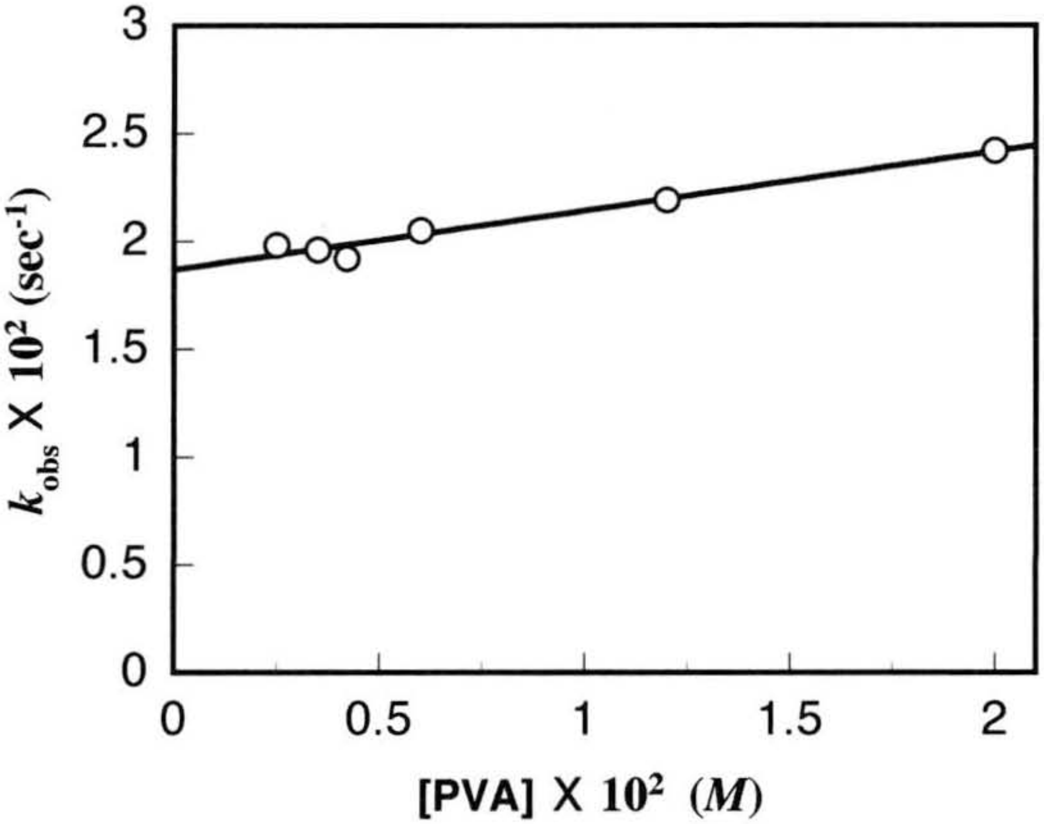


Figure 5 k_{obs} as a function of PVA concentration for the metal exchange reaction: [Cu^{2+}]= 4 x 10^{-4} mol l^{-1}; [Ca(II)-EDTA] = 2 x 10^{-2} mol l^{-1}; $T_{Cu^{2+}}$／T_{HL} = 0.05: pH 10.5; μ = 0.1(KNO_3); 25℃

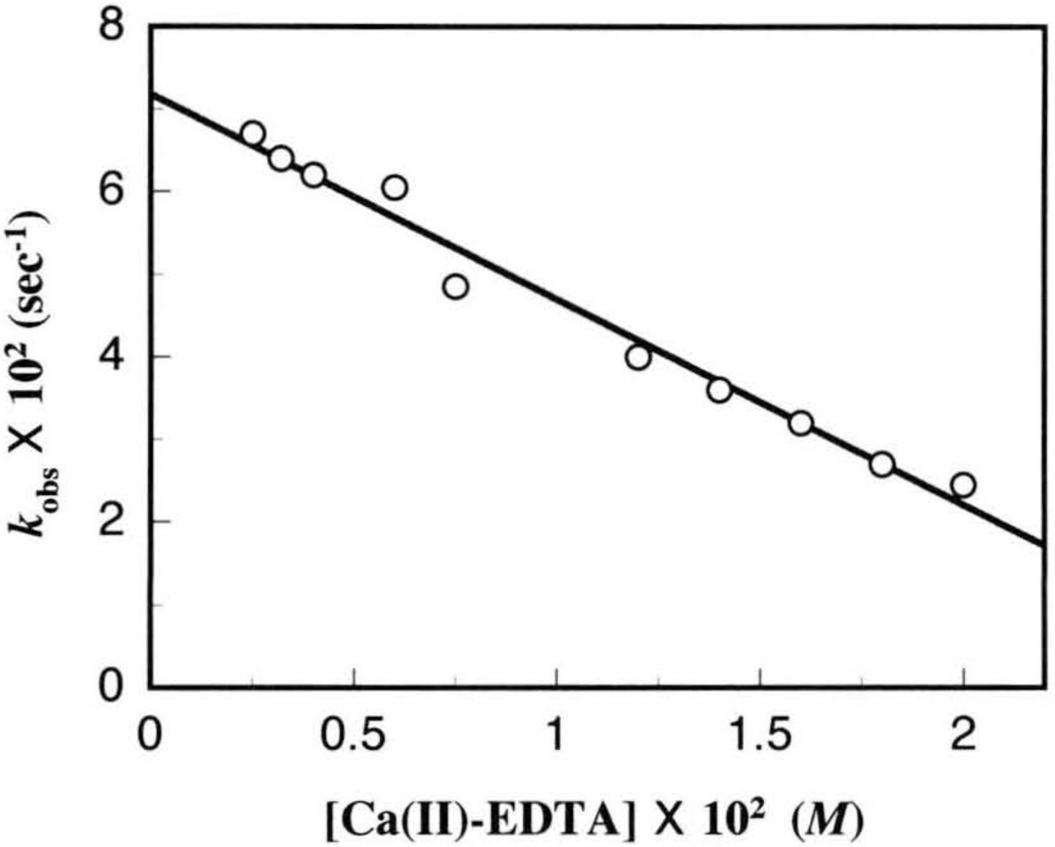


Figure 6 k_{obs} as a function of Ca(II)-EDTA concentration for the metal exchange reaction: [Cu(II)-PVA]= 4 x 10^{-4} mol l^{-1}; pH 10.5; $T_{Cu^{2+}}/T_{HL} = 0.05$; $\mu = 0.1(KNO_3)$; 25℃.

Figure 7 shows the dependence of k_{obs} on the concentration of added $Ca(OH)_2$ at pH 10.5, μ=0.1(KNO_3) and 25℃. As expected the rate of the exchange reaction is proportional to $[Ca(OH)_2]^{-1}$.

On the other hand, the rate of the exchange reaction was accelerated by the addition of free edta anions. This fact suggests the ligand exchange reaction by edta anions formed in EQ.(2) is occurring.

As mentioned above, the rate law of this reaction is given by

$$-\frac{d[\mathrm{Cu(II)\text{-}PVA}]}{dt} = k\frac{[\mathrm{Cu(II)\text{-}PVA}][\mathrm{H^+}][\mathrm{PVA}]}{[\mathrm{Ca(II)\text{-}EDTA}]} \tag{4}$$

$$= k_{0(\mathrm{H})}\frac{[\mathrm{Cu(II)\text{-}PVA}][\mathrm{PVA}]}{[\mathrm{Ca(II)\text{-}EDTA}]} \tag{5}$$

$$= k_1\frac{[\mathrm{Cu(II)\text{-}PVA}][\mathrm{PVA}]}{[\mathrm{Ca(II)\text{-}EDTA}]} + k_2\frac{[\mathrm{Cu(II)\text{-}H\text{-}PVA}][\mathrm{PVA}]}{[\mathrm{Ca(II)\text{-}EDTA}]} \tag{6}$$

$$= k_1\frac{[\mathrm{Cu(II)\text{-}PVA}][\mathrm{PVA}]}{[\mathrm{Ca(II)\text{-}EDTA}]} + k_2'\frac{[\mathrm{Cu(II)\text{-}PVA}][\mathrm{PVA}][\mathrm{H^+}]}{[\mathrm{Ca(II)\text{-}EDTA}]} \tag{7}$$

$$= (k_1 + k_2'[\mathrm{H^+}])\frac{[\mathrm{Cu(II)\text{-}PVA}][\mathrm{PVA}]}{[\mathrm{Ca(II)\text{-}EDTA}]} \tag{8}$$

where, $k_{0(\mathrm{H})} = k_1 + k_2'[\mathrm{H^+}]$ (9)

$$= k_{obs}\frac{[\mathrm{Ca(II)\text{-}EDTA}]}{[\mathrm{PVA}]} \tag{10}$$

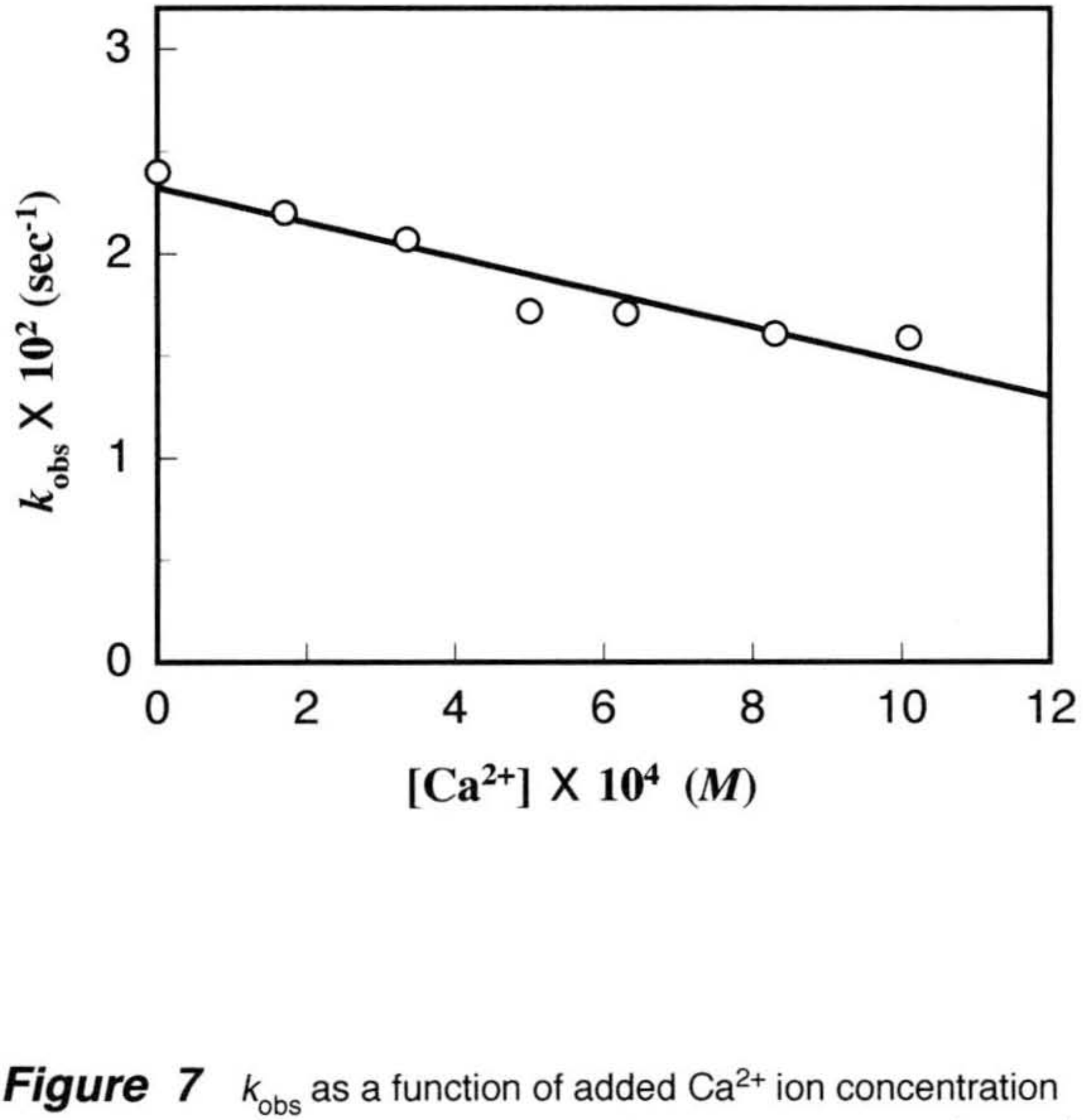


Figure 7 k_{obs} as a function of added Ca^{2+} ion concentration for the metal exchange reaction: [Cu(II)-PVA]= 4 x 10^{-4} mol l^{-1}; [Ca(II)-EDTA] = 2 x 10^{-2} mol l^{-1}; pH 10.5; $T_{Cu^{2+}}/T_{HL}$ = 0.05; pH 10.5; μ = 0.1(KNO_3); 25℃.

In ***Figure 8***, the value of $k_{0(H)}$ determined at various pHs are plotted against the $[H^+]$. It is evident that $k_{0(H)}$ is linearly related to $[H^+]$. From the slope of this line in Fig. 8, $k_2' = 6.23 \times 10^8$ l mol^{-1} sec^{-1}, and from the y intercept, $k_1 = 3.85 \times 10^{-2}$ sec^{-1} at $\mu = 0.1(KNO_3)$ and 25℃.

From EQ.(6) and (7), we obtain

$$k_2[\text{Cu(II)-H-PVA}] = k_2'[\text{Cu(II)-PVA}][H^+] \tag{11}$$

$$\frac{k_2}{k_2'} = \frac{[\text{Cu(II)-PVA}][H^+]}{[\text{Cu(II)-H-PVA}]} \tag{12}$$

$$= K^{-H}_{\text{Cu(II)-H-PVA}} = 10^{-2.81} \text{ (Ref. 3)} \tag{13}$$

therefore,

$$k_2 = k_2' \cdot K^{-H}_{\text{Cu(II)-H-PVA}} = 9.59 \times 10^5 \text{ l mol}^{-1} \text{ sec}^{-1}. \tag{14}$$

4-3-3 Mechanism of the Metal Exchange Reaction

In the metal exchange reaction of the Cu(II)-PVA complex with Ca(II)-EDTA, firstly, a proton attacks Cu(II)-PVA to form the intermediate complex Cu(II)-H-PVA, and the reaction then initiates. Once protonated, the Cu(II)-PVA complex becomes unstable, and is attacked by free edta anions formed in EQ.(2). This step is the ligand exchange reaction.

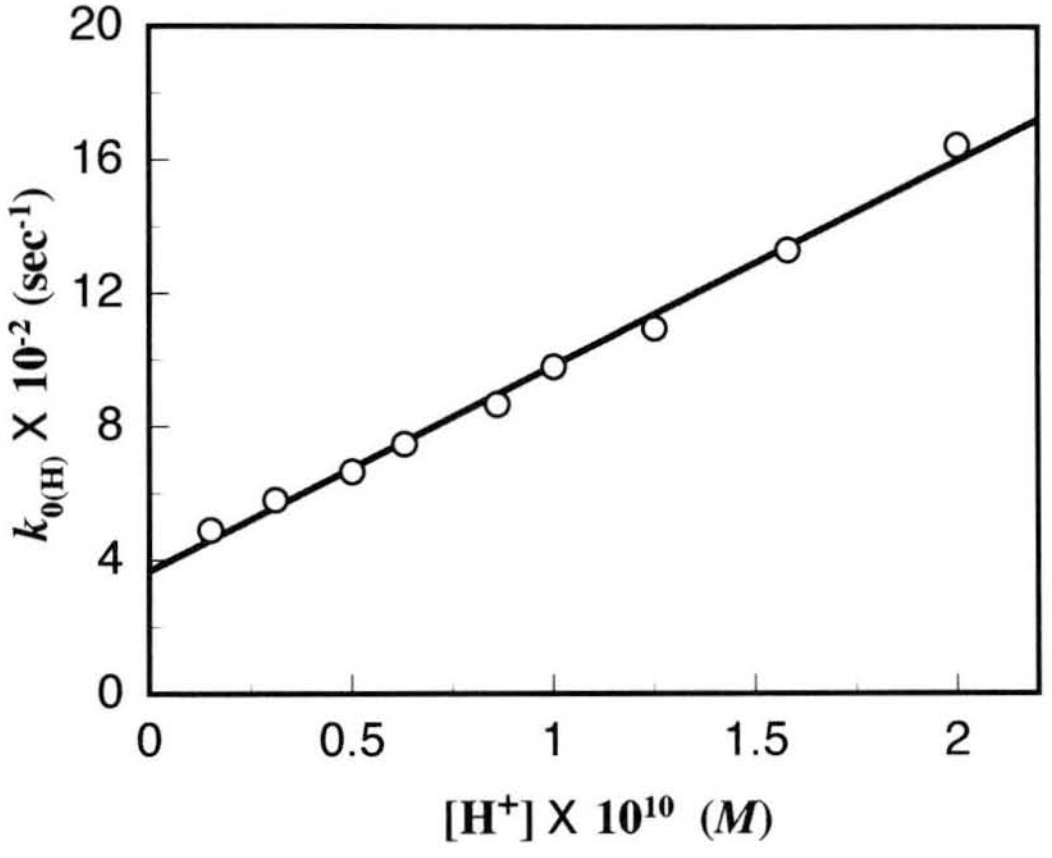


Figure 8 $k_{0(H)}$ as a function of hydrogen ion concentration for the metal exchange reaction: [Cu(II)-PVA] = 4 x 10^{-4} mol l^{-1}; [Ca(II)-EDTA] = 2 x 10^{-2} mol l^{-1}; $T_{Cu^{2+}}/T_{HL}$ = 0.05; μ = 0.1(KNO_3); 25℃.

The proton attacks the unstable site of the complex and prevents the recombination of the multidentate ligand, as well as promoting the dissociation of the ligand electrostatically.

$$\mathbf{Cu(II)\text{-}PVA + H^+ \rightleftarrows Cu(II)\text{-}H\text{-}PVA} \tag{15}$$

$$\mathbf{2Ca(II)\text{-}EDTA \rightleftarrows 2Ca^{2+} + 2EDTA^{4-}} \tag{16}$$

$$\mathbf{Cu(II)\text{-}H\text{-}PVA + EDTA^{4-} \rightleftarrows Cu(II)\text{-}EDTA + H\text{-}PVA} \tag{17}$$

$$\mathbf{Cu(II)\text{-}PVA + Ca^{2+} \rightleftarrows Cu(II)\text{-}PVA\text{-}Ca^{2+}} \tag{18}$$

$$\mathbf{Cu(II)\text{-}PVA\text{-}Ca^{2+} \rightleftarrows Ca(II)\text{-}PVA + Cu^{2+}} \tag{19}$$

$$\mathbf{Cu^{2+} + EDTA^{4-} \rightleftarrows Cu(II)\text{-}EDTA} \tag{20}$$

$$\mathbf{Ca^{2+} + 2OH^- \rightleftarrows Ca(OH)_2} \tag{21}$$

On the other hand, free Ca^{2+} ions attack the Cu(II)-PVA complex to form the binuclear intermediate Cu(II)-PVA-Ca^{2+}, and a Cu^{2+} ion is subsequently released from this intermediate. This step is the metal exchange reaction. In metal exchange reactions of low molecular weight ligand complexes, such as reaction between Ni(II)-EDTA and Zn^{2+} [7-9], the step eliminating a metal ion from the binuclear intermediate is the rate-determining step. Eliminated Cu^{2+} ion is caught by free edta anion.

The protonation of the Cu(II)-PVA complex is very rapid, but the binuclear intermediate is not protonated, so the addition of free Ca^{2+} to Cu(II)-PVA solution before mixing, serves to slow down the rate of the exchange reaction. This Cu^{2+} elimination from the intermediate is rate-determining, and the metal exchange step determines the exchange rate.

References

1 T. Suzuki, H. Shirai, S. Tokutake, and N. Hojo, *Polymer,* **24**, 335 (1983).

2 T. Suzuki, H. Shirai, F. Shimizu, and N. Hojo, *Polymer Journal,* **15**, 409 (1983).

3 D. C. Olson, D. W. Margerum, *J. Amer. Chem. Soc.,* **85**, 297 (1963).

4 D. W. Margerum, D. L. Janes, and H. M. Rosen, *J. Amer. Chem. Soc.,* **87**, 4463 (1965).

5 M. Matsumoto, *Kobunshi Kagaku,* **18**, 169 (1961).

6 N. Hojo, H. Shirai, K. Sakata, and M. Fukuda, *Kogyo Kagaku Zasshi,* **73**, 1862 (1970).

7 D. W. Margerum, and T. J. Bydalek, *Inorg. Chem.,* **2**, 683 (1963).

8 N. Tanaka, and K. Kato, *Bull. Chem. Soc. Japan,* **32**, 1376 (1959).

9 D. W. Margerum, and T. J. Bydalek, *Inorg. Chem.,* **1**, 852 (1962).

CHAPTER 5

Metal Exchange Reaction between Cu(II)-Poly(vinyl Alcohol) Complex and Zn(II)-Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution

CHAPTER
5

Metal Exchange Reaction between Cu(II)-Poly(vinyl Alcohol) Complex and Zn(II)-Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution

SUMMARY: The kinetics of the metal exchange reaction between Cu(II)-poly(vinyl alcohol) [Cu(II)-PVA] and Zn(II)-ethylenediamine-N,N,N',N'-tetraacetic acid [Zn(II)-EDTA] has been studied by mixing both solutions in a spectrophotometer at pH 9.76 to 11.57, ionic strength $\mu = 0.10(KNO_3)$, and at 15 to 35 ℃. The reaction initiates by the formation of unstable Cu(II)-H-PVA through attack of H^+ ion on Cu(II)-PVA complex, and both reactions, ligand exchange and metal exchange, proceed simultaneously. The metal exchange step may be rate-determining. The rate equation and rate constants of this reaction were determined as follows:

$-d[\mathrm{Cu(II)\text{-}PVA}]\ /\ dt\ =\ k_{0(\mathrm{H})}\ [\mathrm{PVA}^-]\ [\mathrm{Cu(II)\text{-}PVA}]\ [\mathrm{Zn(II)\text{-}EDTA}]$, where $k_{0(\mathrm{H})}\ =\ k_1\ +\ (k_2'+k_3')\ [\mathrm{H}^+]$, $k_1\ =\ 5.98\ \pm\ 1.64\ M^{-1}\,\mathrm{s}^{-1}$ and $k_2\ +\ k_3\ =\ k_2'\ K^{-\mathrm{H}}_{\mathrm{Cu(II)\text{-}H\text{-}PVA}}\ +\ k_3'\ K^{\mathrm{H}}_{\mathrm{Zn(II)\text{-}EDTA}}\ =\ (5.91\ \pm\ 1.64)\times 10^7\ M^{-2}\,\mathrm{s}^{-1}$.

5-1 Introduction

Macromolecule-metal complexes which are composed of polymeric ligands and metal ions differ from the corresponding monomeric complexes by their specific properties and chemical properties. To obtain detailed information about the reactivities, catalytic action, and polymeric effects of the macromolecule-metal complexes, their structure and kinetics must be elucidated. The kinetics and mechanisms of exchange reactions of macromolecule-metal complexes are of interest in model reactions for metal transport *in vivo*.

The exchange reactions of macromolecule-metal complexes are classified into five types: (a) ligand substitution reactions M-L + PL $\leftrightarrows$ M-PL + L (type 1), M-PL + L $\leftrightarrows$ M-L + PL (type 2), M-PL + PL' $\leftrightarrows$ M-PL' + PL (type 3), (b) metal exchange reactions M-PL + M'-L $\leftrightarrows$ M'-PL + M-L (type 4) and M-PL + M'-PL' $\leftrightarrows$ M'-PL + M-PL' (type 5), where L and L' are low molecular weight ligands, M-L, M-L' and M'-L are low molecular weight metal complexes, PL and PL' are polymeric ligands, and M-PL, M'-PL, M-PL' and M'- PL' are macromolecule-metal complexes.

In previous chapters the kinetics of the ligand substitution reaction between Cu(II)-ammine complex and poly(vinyl alcohol) (PVA) (type 1)[1], ligand substitution reaction between Cu(II)-PVA and EDTA (type 2)[2], and metal exchange reaction between Cu(II)-PVA complex and Ca(II)-EDTA complex (type 4)[3] have been discussed. The present chapter is concerned with the metal exchange reaction between Cu(II)-PVA complex and Zn(II)-EDTA complex (type 4) in aqueous solution.

5-2 Experimental

5-2-1 Materials

PVA (degree of polymerization, 1400), a product of Nippon Synthetic Chemical Industry Co. Ltd., was used. The PVA was separated into several fractions of different average molecular weights by the method of Matsumoto[4], and each fraction was completely hydrolyzed by alkali in methanol, as reported previously[5]. The concentration of PVA used in these experiments was 0.16 mol/l.

Zn(II)-EDTA, obtained from Wako Pure Chemical Co. Ind., was purified by recrystallization three times from methanol-water. Zn(II)-EDTA was dried in air at 80 ℃ and dissolved in a 0.2 mol/l KNO_3 aqueous solution. The concentration of a stock solution of Zn(II)-EDTA was standardized by atomic absorption spectrophotometry (Hitachi A-1800). Cu(II)-PVA complex solutions were prepared by the method reported previously[1]. The ionic strength of Cu(II)-PVA complex solutions was maintained at 0.1 mol/l with KNO_3. The complex solutions were kept at 25℃ for 24 hours before each experiment.

The other reagents used here were of analytical grade and were used without further purification.

5-2-2 Kinetic Measurements

Electronic spectra were measured with a UV-vis spectrophotometer (Hitachi 228A). The exchange reactions between Cu(II)-PVA solutions and Zn(II)-EDTA solutions were also carried out in the UV-vis spectrophotometer. pH measurements were carried out with a Hitachi-Horiba F7-ss pH-meter.

Kinetic measurements were generally made as follows: One solution containing 4×10^{-4} mol/l Cu(II)-PVA [ratio of Cu(II) ion to OH groups in PVA, $T_{Cu^{2+}} / T_{HL} = 0.05$] was brought to the starting pH with a 0.1*N* KOH solution. A second solution containing 7.58×10^{-3} mol/l Zn(II)-EDTA was brought to the same pH. The ionic strengths of these solutions were maintained at 0.1 mol/l with KNO_3. These solutions were mixed at the ratio 1:1 (v : v) in a 1-cm cell of a UV-vis spectrophotometer. The optical density range 0 to 0.1 at 400 nm was used. The fast reactions in the initial step were carried out in a 1-cm cell of a stopped-flow spectrophotometer (Hitachi RA-401, dead time, 1 ms). All rates were measured at 15 to 35 ± 0.1℃.

5-3 Results and Discussion

5-3-1 Spectral Results

When a Cu(II)-PVA solution is added to a solution containing Zn(II)-EDTA, the color changes from green to light blue. Electronic spectra observed before and after the reactions are shown in ***Figure 1***. Remarkable absorptions based on the Cu(II)-PVA complex[5] at about 360 and 640 nm decreased after the exchange reaction. A new absorption peak, based on the formation of the Cu(II)-EDTA, appears at 745 nm.

The stability constants (log *K*) of reactants and products that are formed after the exchange reaction are $\log K_{Cu(II)\text{-}PVA} = 16.50$[6], $\log K_{Zn(II)\text{-}EDTA} = 16.69$[7], $\log K_{Cu(II)\text{-}EDTA} = 18.89$[8] and $\log K_{Zn(II)\text{-}PVA} = 14.09$[6], respectively.

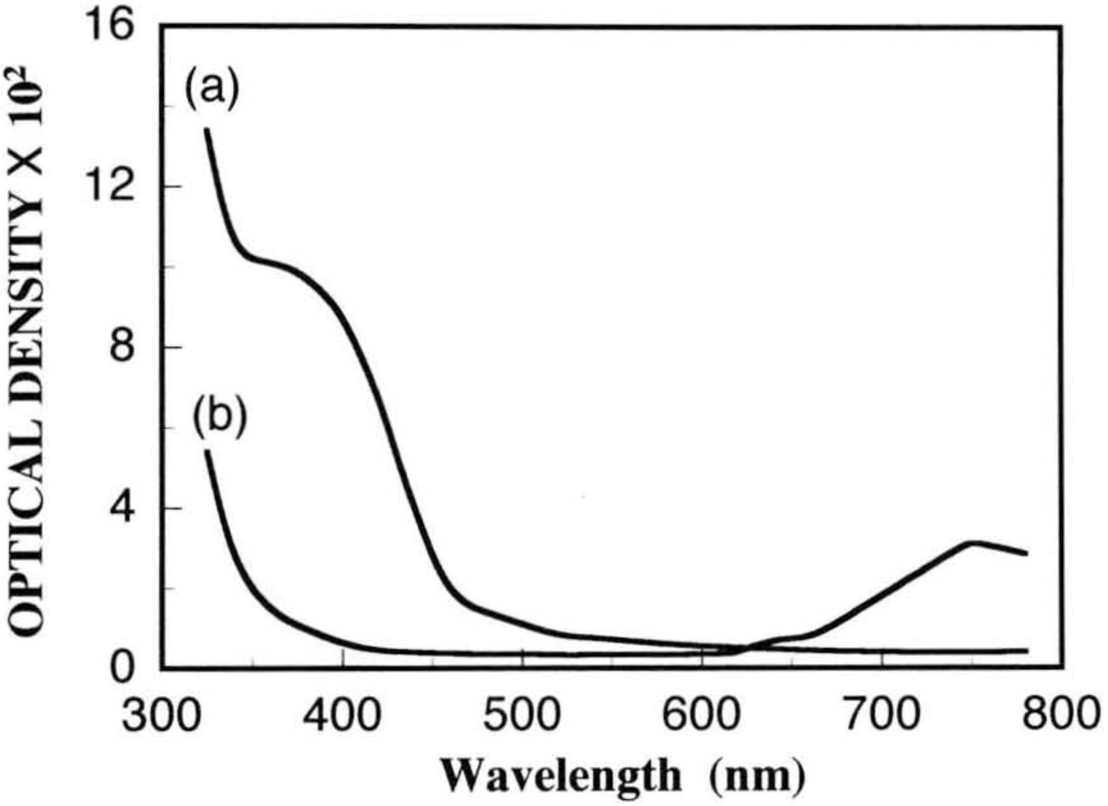


Figure 1 Electronic spectra for the reaction of Cu(II)-PVA complex with Zn(II)-EDTA (a) before and (b) after the reaction in aqueous solution: [Cu(II)-PVA] = 4×10^{-4} mol l^{-1}; [Zn(II)-EDTA] = 1.52×10^{-2} mol l^{-1}; pH 10.5, $\mu = 0.1(KNO_3)$; $T_{Cu^{2+}}/T_{HL} = 0.05$; 25℃.

The data suggest that the metal exchange reaction between the Cu(II)-PVA complex and Zn(II)-EDTA occurs when both solutions are mixed. The time course of the metal exchange reaction is observed by detecting the absorption decrease at 400 nm (***Figure 2***). The overall change of this reaction is observed with the UV spectrophotometer and stopped-flow spectrophotometer.

5-3-2 Kinetic Results

Plots of $\log(A_t - A_\infty)$ as a function of time were obtained using an approximate value for A_∞ (A, absorbance). A plot from a typical run (Fig. 2) is shown in ***Figure 3***. In general, straight lines were obtained for the reactions. All plots from these experiments in the presence of an excess buffered Zn(II)-EDTA were pseudo-first order in Cu(II)-PVA concentration. Thus, the reaction of Cu(II)-PVA complex with excess Zn(II)-EDTA complex followed the rate expression:

$$-\frac{d\,[\mathrm{Cu(II)\text{-}PVA}]}{dt} = k_{\mathrm{obs}}\,[\mathrm{Cu(II)\text{-}PVA}] \qquad (1)$$

where k_{obs} is the observed rate constant under the conditions of these experiments.

The metal exchange reactions were carried out at 25 ℃ and at $\mu = 0.1$ (KNO_3), with the pH varying from 9.76 to 11.57. The concentration of Cu(II)-PVA and Zn(II)-EDTA was kept constant. ***Figure 4*** shows the values of k_{obs} plotted against the initial concentrations of hydrogen ion. It is found that k_{obs} is proportional to $[H^+]^{1.0}$. Thus the reactions exhibit specific acid catalysis[1-3].

In another series of experiments, the dependence of k_{obs} on the initial concentration of free PVA was studied at constant concentration of Zn(II)-EDTA and Cu(II) at pH = 10.5, $\mu = 0.1$ (KNO_3), and 25℃ (***Figure 5***).

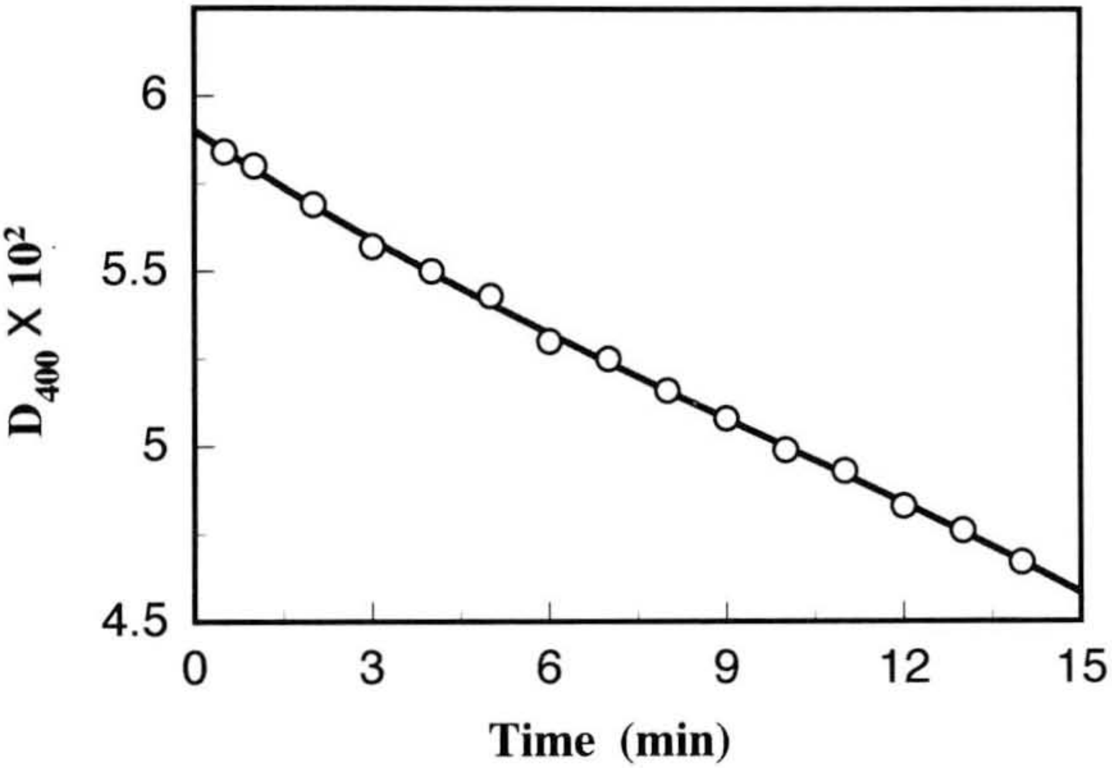


Figure 2 Change in D_{400} for the reaction of Cu(II)-PVA complex with Zn(II)-EDTA in aqueous solution: [Cu(II)-PVA] = 4 x 10^{-4} mol l^{-1}; [Zn(II)-EDTA] =1.52 x 10^{-2} mol l^{-1}; pH 10.5, μ = 0.1(KNO_3); $T_{Cu^{2+}}/T_{HL}$ = 0.05; 25℃.

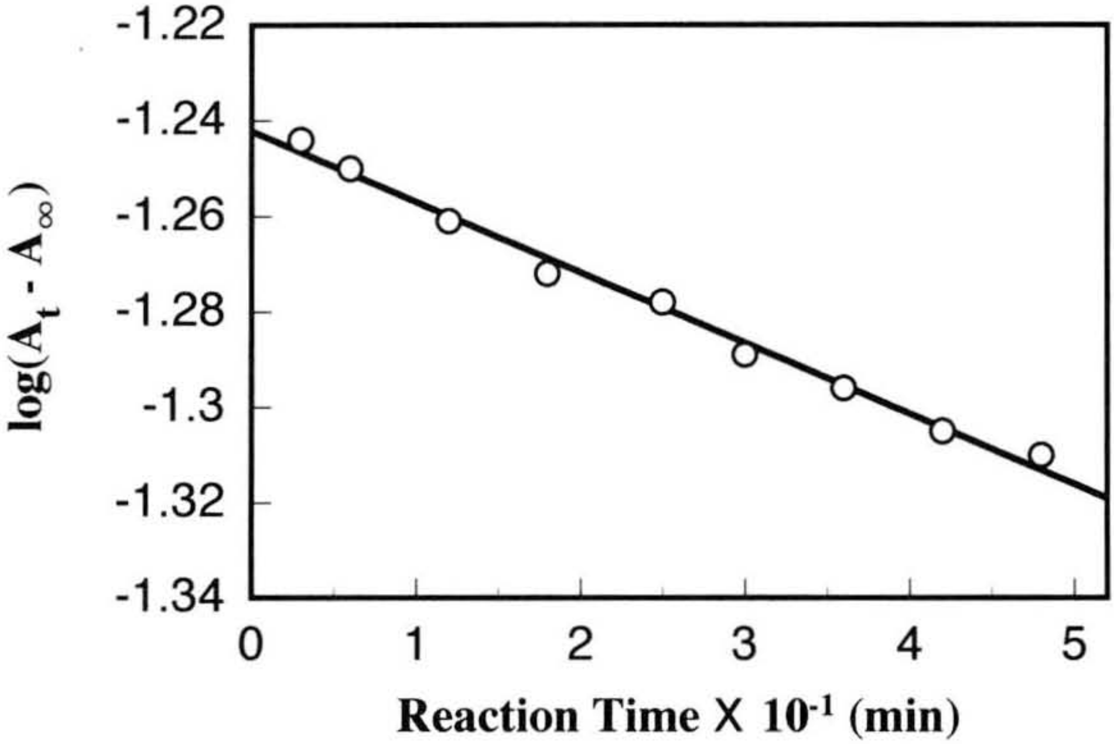


Figure 3 Relationship between (A_t - A_∞) and reaction time for the reaction between Cu(II)-PVA complex and Zn(II)-EDTA in aqueous solution: [Cu(II)-PVA] = 4×10^{-4} mol l^{-1}; [Zn(II)-EDTA] =1.52×10^{-2} mol l^{-1}; pH 10.5, μ = 0.1(KNO_3); $T_{Cu^{2+}}/T_{HL}$ = 0.05; 25℃.

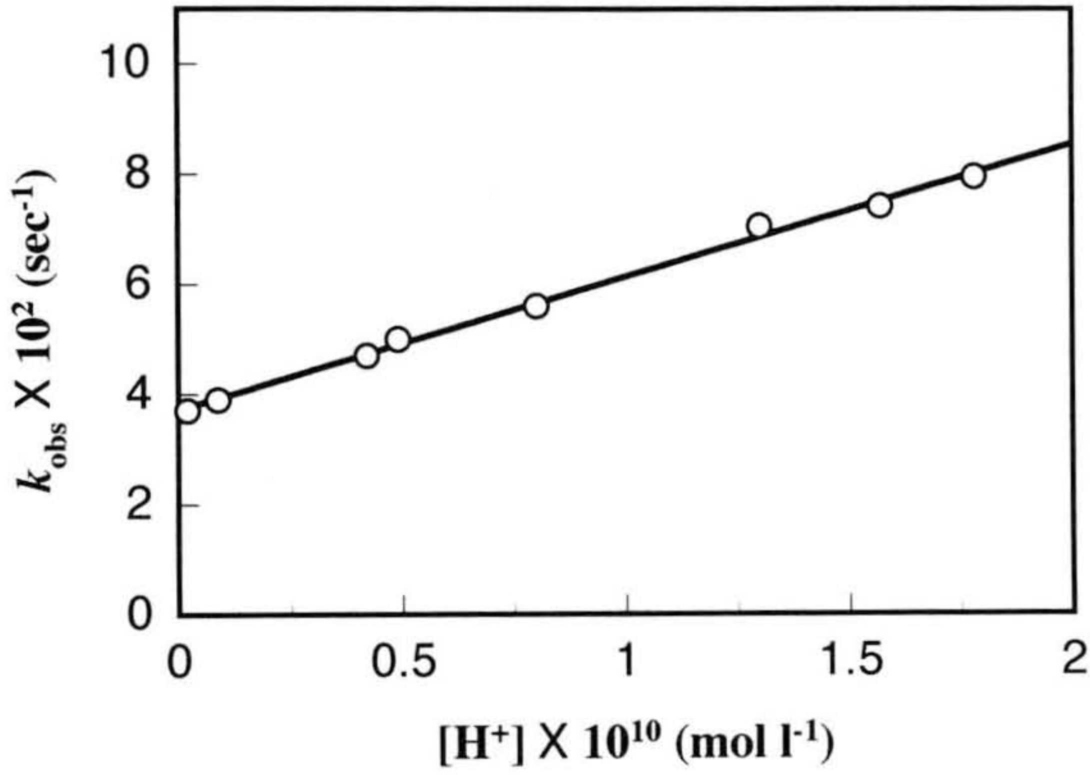


Figure 4 k_{obs} as a function of hydrogen ion concentration: [Cu(II)-PVA] = 4×10^{-4} mol l^{-1}; [Zn(II)-EDTA] = 7.58×10^{-2} mol l^{-1}; $T_{Cu^{2+}}/T_{HL} = 0.05$; $\mu = 0.1(KNO_3)$; 25℃.

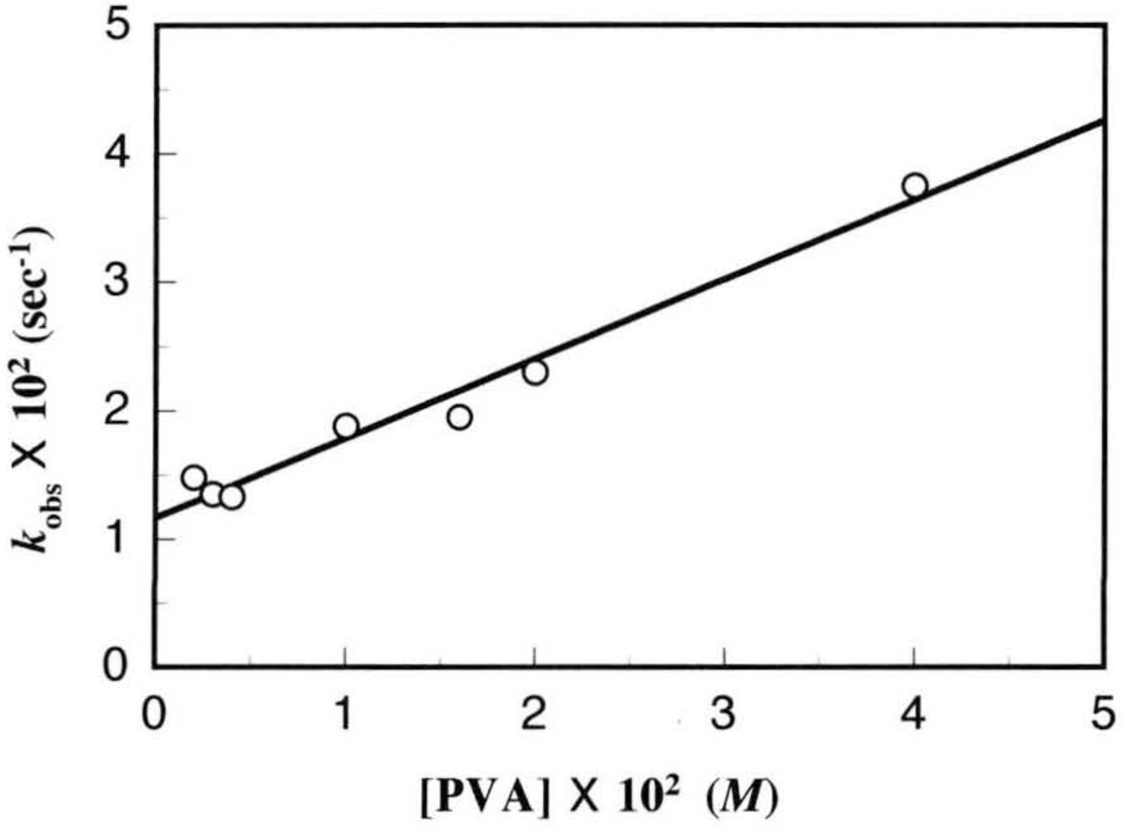


Figure 5 k_{obs} as a function of PVA concentration for the metal exchange reaction: [Cu^{2+}]= 4 x 10^{-4} mol l^{-1}; [Zn(II)-EDTA] = 1.52 x 10^{-2} mol l^{-1}; $T_{Cu^{2+}}/T_{HL}$ = 0.05; pH 10.5; μ = 0.1(KNO_3); 25℃.

The rate of the exchange reaction is also proportional to $[PVA^{-1}]^{1.0}$. PVA^{-1} shows partially dissociated PVA anion ($pK_a = 10.65^5$).

Finally, the metal exchange reactions were carried out at 25℃, pH = 10.5, $\mu = 0.1$ (KNO_3), and varying concentrations of Zn(II)-EDTA. The concentration of Cu(II)-PVA was kept constant. The dependence of k_{obs} on the initial concentration of Zn(II)-EDTA is shown in ***Figure 6***. The k_{obs} values are also first order with respect to [Zn(II)-EDTA]. Therefore, the rate law of this reaction is given by

$$-\frac{d\,[\text{Cu(II)-PVA}]}{d\text{t}} = k\,[H^+][PVA^{-1}][\text{Cu(II)-PVA}][\text{Zn(II)-EDTA}] \quad (2)$$

$$= k_{0(H)}[PVA^{-1}][\text{Cu(II)-PVA}][\text{Zn(II)-EDTA}] \quad (3)$$

$$= k_1[PVA^{-1}][\text{Cu(II)-PVA}][\text{Zn(II)-EDTA}]$$

$$+ k_2[PVA^{-1}][\text{Cu(II)-H}^+\text{-PVA}][\text{Zn(II)-EDTA}]$$

$$+ k_3[PVA^{-1}][\text{Cu(II)-PVA}][\text{Zn(II)-H}^+\text{-EDTA}] \quad (4)$$

$$= k_1[PVA^{-1}][\text{Cu(II)-PVA}][\text{Zn(II)-EDTA}]$$

$$+ k_2'[H^+][PVA^{-1}][\text{Cu(II)-PVA}][\text{Zn(II)-EDTA}]$$

$$+ k_3'[H^+][PVA^{-1}][\text{Cu(II)-PVA}][\text{Zn(II)-EDTA}] \quad (5)$$

$$= \{k_1 + (k_2' + k_3')[H^+]\}[PVA^{-1}][\text{Cu(II)-PVA}][\text{Zn(II)-EDTA}] \quad (6)$$

where

$$k_{0(H)} = k_1 + (k_2' + k_3')[H^+] \quad (7)$$

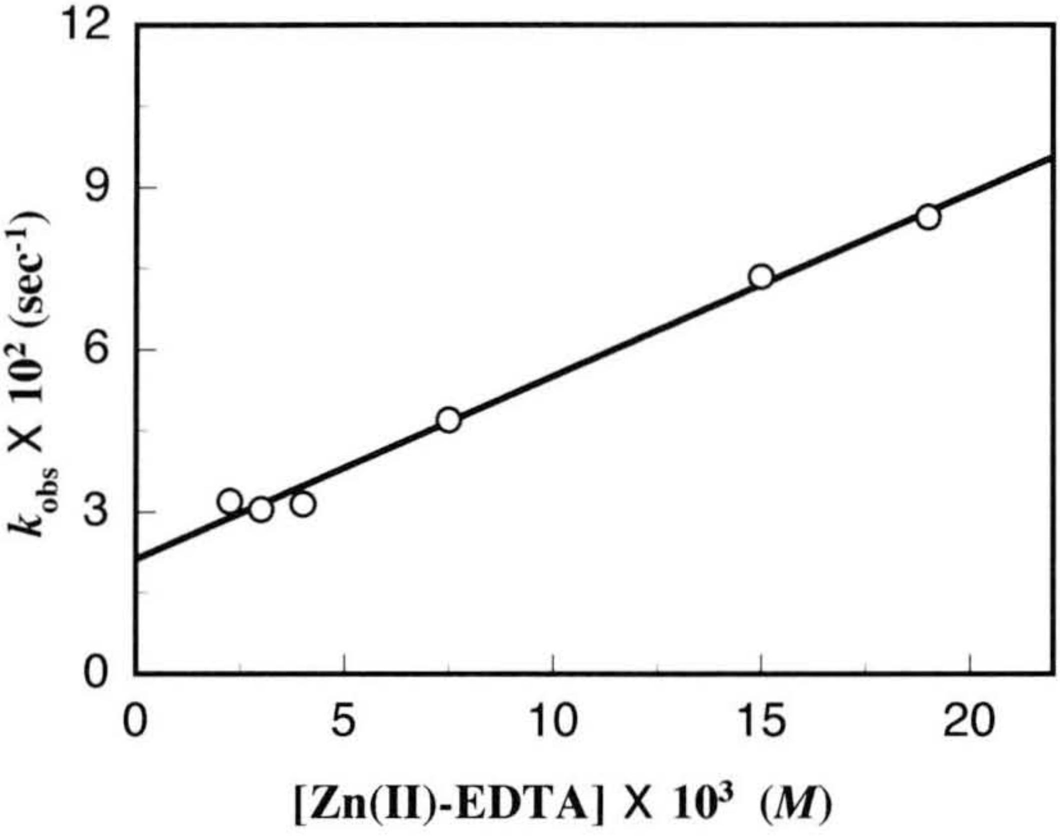


Figure 6 k_{obs} as a function of Zn(II)-EDTA concentration for the metal exchange reaction: [Cu(II)-PVA]= 4 x 10^{-4} mol l^{-1}; pH 10.5; $T_{Cu^{2+}}/T_{HL} = 0.05$; $\mu = 0.1(KNO_3)$; 25℃.

From Eqs. (1), (6) and (7),

$$k_{0(\mathrm{H})} = \frac{k_{\mathrm{obs}}}{[\mathrm{PVA}^{-1}][\mathrm{Zn(II)\text{-}EDTA}]} \tag{8}$$

The values of $k_{0(\mathrm{H})}$, determined at various pH levels, are plotted against hydrogen ion concentration in ***Figure 7***. The $k_{0(\mathrm{H})}$ values are a linear function of the hydrogen ion concentrations in the range of pH 9.76-11.57. From the intercept, $k_1 = 5.98 \pm 1.64\,M^{-1}\,\mathrm{s}^{-1}$; and from the slope, $k_2' + k_3' = (4.18 \pm 0.72)\,10^{10}\,M^{-2}\,\mathrm{s}^{-1}$ at $\mu = 0.1(\mathrm{KNO_3})$ and 25 ℃.

Equations (11) and (12) are obtained from Eqs. (4) and (5).

$$\begin{aligned} &k_2[\mathrm{PVA}^{-1}][\mathrm{Cu(II)\text{-}H^+\text{-}PVA}][\mathrm{Zn(II)\text{-}EDTA}] \\ &\qquad = k_2'[\mathrm{H^+}][\mathrm{PVA}^{-1}][\mathrm{Cu(II)\text{-}PVA}][\mathrm{Zn(II)\text{-}EDTA}] \end{aligned} \tag{9}$$

$$\begin{aligned} &k_3[\mathrm{PVA}^{-1}][\mathrm{Cu(II)\text{-}PVA}][\mathrm{Zn(II)\text{-}H^+\text{-}EDTA}] \\ &\qquad = k_3'[\mathrm{H^+}][\mathrm{PVA}^{-1}][\mathrm{Cu(II)\text{-}PVA}][\mathrm{Zn(II)\text{-}EDTA}] \end{aligned} \tag{10}$$

$$\frac{k_2}{k_2'} = \frac{[\mathrm{H^+}][\mathrm{Cu(II)\text{-}PVA}]}{[\mathrm{Cu(II)\text{-}H^+\text{-}PVA}]} = K^{-\mathrm{H}}_{\mathrm{Cu(II)\text{-}PVA}} = 10^{-2.81} \text{ Ref. 5} \tag{11}$$

$$\frac{k_3'}{k_3} = \frac{[\mathrm{Zn(II)\text{-}H^+\text{-}EDTA}]}{[\mathrm{H^+}][\mathrm{Zn(II)\text{-}EDTA}]} = K^{\mathrm{H}}_{\mathrm{Zn(II)\text{-}EDTA}} = 10^{2.9} \text{ Ref. 8} \tag{12}$$

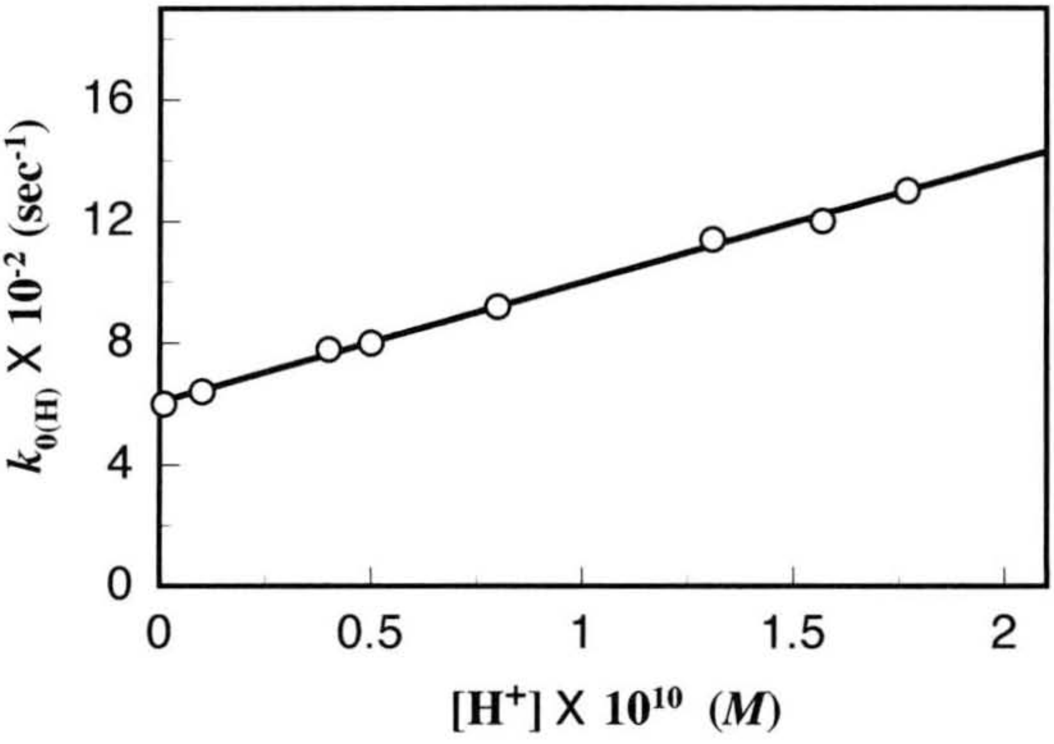


Figure 7 $k_{0(H)}$ as a function of hydrogen ion concentration for the metal exchange reaction: [Cu(II)-PVA] = 4 x 10^{-4} mol l^{-1}; [Zn(II)-EDTA] = 1.52 x 10^{-2} mol l^{-1}; $TC_{u^{2+}}/T_{HL}$ = 0.05; μ = 0.1(KNO_3); 25℃.

Therefore,

$$k_2 + k_3 = k_2^{'} \cdot K_{\mathrm{Cu(II)\text{-}H\text{-}PVA}}^{\mathrm{-H}} + k_3^{'} / K_{\mathrm{Zn(II)\text{-}EDTA}}^{\mathrm{H}} \tag{13}$$

$$= (5.91 \pm 0.89) \times 10^{7}\ M^{-2}\,\mathrm{s}^{-1}.$$

5-3-3 Mechanism of the Metal Exchange Reaction

Upon substitution of Cu(II)-PVA complex for Zn(II)-EDTA complex, first, reaction is initiated by protonation of Cu(II)-PVA to form Cu(II)-H^+-PVA, followed by dissociation to Cu^{2+} and H-PVA^-. Once protonated, the Cu(II)-PVA complex becomes unstable and is attacked by a dissociated $EDTA^{4-}$ anion [Eq. (16) and (17)]. This step is the ligand substitution reaction discussed in chapter 3[2]. It was found in the study that ligand substitution has two reaction paths, with $k_1 = (3.62 \pm 1.05) \times 10^{-3}\ M\,\mathrm{s}^{-1}$ and $k_2 = (3.68 \pm 0.48) \times 10^{4}\ M\,\mathrm{s}^{-1}$. The rate-determining step of ligand substitution reaction is the path that includes the formation of a ternary complex {PVA-H^+-Cu(II)-EDTA}. This step is followed by the rapid reaction to form Cu(II)-EDTA and H^+-PVA.

On the other hand, Cu^{2+} formed in Eq. (15) attacks Zn(II)-$EDTA^{2-}$ to form the stable Cu(II)-$EDTA^{2-}$ via the intermediate {Cu(II)-EDTA-Zn(II)}. This step is the metal exchange reaction that has been investigated by K. Kato[9], and a value of $k_1 = 1.5 \times 10^{11}\ \mathrm{L \cdot mol^{-1} \cdot s^{-1}}$ was reported.

This reaction sequence can be described as follows:

$$\mathrm{Cu^{2+}\text{-}PVA + H^{+} \rightleftharpoons Cu^{2+}\text{-}H^{+}\text{-}PVA} \tag{14}$$

$$\mathrm{2Cu^{2+}\text{-}PVA + 2H^{+} \rightleftharpoons 2Cu^{2+} + 2(H^{+}\text{-}PVA)} \tag{15}$$

$$\mathrm{2Zn^{2+}\text{-}EDTA^{4-} + 2H^{+} \rightleftharpoons 2Zn^{2+} + 2(H\text{-}EDTA^{3-})} \tag{16}$$

$$\mathrm{Cu^{2+}\text{-}H\text{-}PVA + H\text{-}EDTA^{3-} \rightleftharpoons Cu^{2+}\text{-}EDTA^{4-} + H^{+}\text{-}PVA + H^{+}} \tag{17}$$

$$\begin{aligned}\mathrm{Cu^{2+} + Zn^{2+}\text{-}EDTA^{4-}} &\rightleftharpoons \mathrm{Cu^{2+}\text{-}EDTA^{4-}\text{-}Zn^{2+}} \\ &\rightarrow \mathrm{Cu^{2+}\text{-}EDTA^{4-} + Zn^{2+}}\end{aligned} \tag{18}$$

$$\mathrm{Cu^{2+} + H\text{-}EDTA^{3-} \rightleftharpoons Cu^{2+}\text{-}EDTA^{4-} + H^{+}} \tag{19}$$

$$\begin{aligned}\mathrm{3Zn^{2+} + 3(H^{+}\text{-}PVA)} &\rightleftharpoons \mathrm{3Zn^{2+}\text{-}H^{+}\text{-}PVA} \\ &\rightleftharpoons \mathrm{3Zn^{2+}\text{-}PVA + 3H^{+}}\end{aligned} \tag{20}$$

The step in Eq. (19) is a rapid reaction. Dissociated Zn^{2+} ions in Eq. (16) and (18) are caught by free PVA and form a Zn(II)-PVA complex[6] [Eq. (20)]. From a comparison of rate constants, ligand substitution [Eq. (17)] is slower than metal exchange [Eq. (18)]. Therefore, the ligand substitution process of the macromolecule-metal complex, Cu(II)-PVA [Eq. (17)], should be the rate-determining step.

The metal exchange reactions were also carried out at pH 10.5 and μ = 0.1(KNO_3), in the presence of different amounts of free EDTA anion. The concentration of Cu(II)-PVA and Zn(II)- EDTA in aqueous solution at 25℃ was also constant. ***Figure 8*** shows the plot of k_{obs} versus the concentration of added free EDTA anion. The k_{obs} increased markedly in the presence of either small amounts or a saturated solution of free EDTA anion. This fact suggests that the augmentation of free EDTA anion concentration accelerates the ligand substitution step [Eq. (17)], and the mechanism of this metal exchange reaction is a chain reaction.

Other experiments were carried out in aqueous solution from 15 to 35℃. The overall activation energy culculated from Arrhenius plots was 10.5 ± 1.7 kcal／mol.

To summarize, the reaction of Cu(II)-PVA with Zn(II)-EDTA is initiated by the formation of unstable Cu(II)-H^+-PVA by the attack of H^+ on Cu(II)-PVA. Both the ligand exchange and the metal exchange reactions take place successively, and the ligand exchange step of the macromolecule-metal complex may be rate-determining.

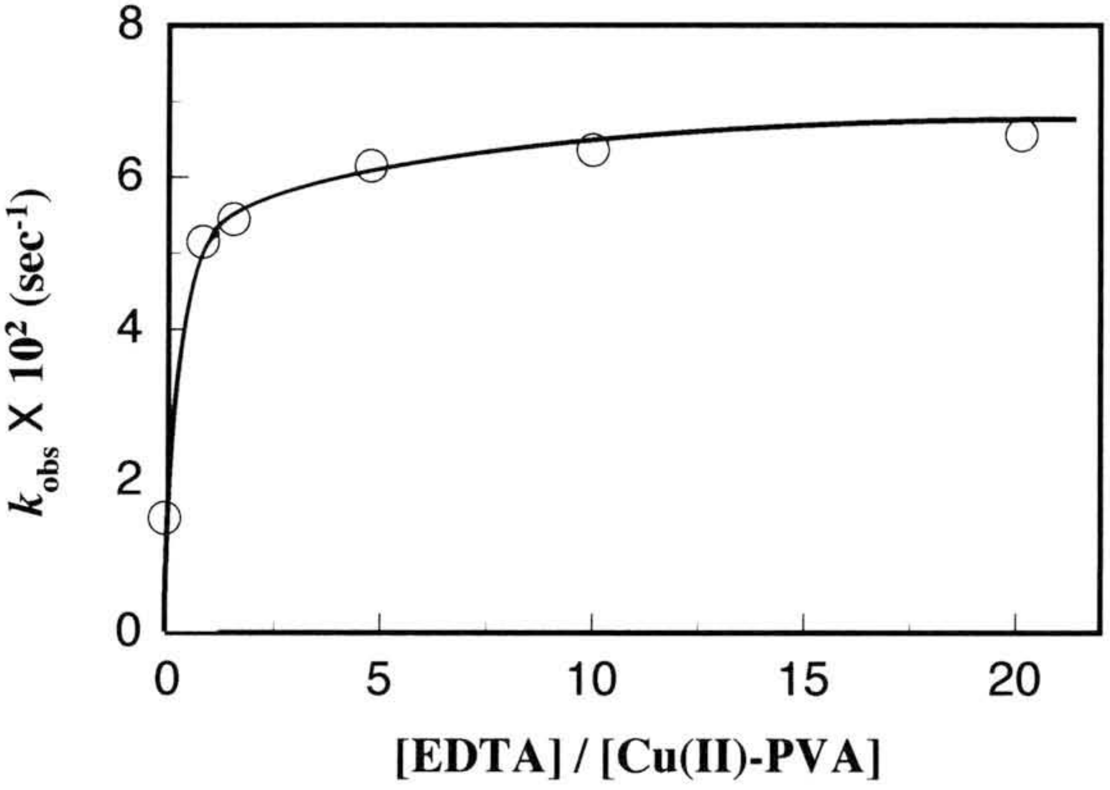


Figure 8 Effect of free EDTA addition on the rate of the metal exchange reaction between Cu(II)-PVA and Zn(II)-EDTA: [Cu(II)-PVA] = 4 x 10^{-4} mol l^{-1}; [Zn(II)-EDTA] = 1.52 x 10^{-2} mol l^{-1}; pH 10.5; $T_{Cu^{2+}} / T_{HL}$ = 0.05; μ = 0.1(KNO_3); 25℃.

References

1 T. Suzuki, H. Shirai, S. Tokutake, and N. Hojo, *Polymer*, **24**, 335 (1983).

2 T. Suzuki, H. Shirai, F. Shimizu, and N. Hojo, *Polym. J.*, **15**, 409 (1983).

3 T. Suzuki, H. Shirai, and N. Hojo, *Makromol. Chem. Macromol. Symp.*, **59**, 247 (1992).

4 M. Matsumoto, *Kobunshi Kagaku*, **18**, 169 (1961).

5 N. Hojo, H. Shirai, K. Sakata, and M. Fukuda, *Kogyo Kagaku Zasshi*, **73**, 1862 (1970).

6 N. Hojo and H. Shirai, *J. Polym. Sci. (Polym. Symp. Ed.)*, **47**, 229 (1974); N. Hojo and H. Shirai, *Kogyo Kagaku Zasshi*, **1972**, 1316 (1972).

7 G. Schwarzenbach and G. Anderegg, *Helv. Chim. Acta*, **40**, 1773 (1957).

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

9 K. Kato, *Bull. Chem. Soc. Jap*, **33**, 600 (1960).

CHAPTER 6

Ligand Substitution Reaction between Cu(II)-Silk fibroin Complex and Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution

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SUMMARY: The kinetics of the ligand substitution reaction between Cu(II)-Silk fibroin (*bombyx mori*) complex (Cu(II)-SF) and ethylenediamine-N,N,N',N'-tetraacetic acid disodium salt (EDTA) has been studied by mixing both solutions in a stopped-flow spectrophotometer at pH 9.48 to 11.50, ionic strength μ = 0.10(KNO_3), and at 15 to 30℃. The reaction is initiated by the formation of unstable Cu(II)-SF-H^+ through attack of H^+ ion on the Cu(II)-SF complex. EDTA segment attacks the unstable site of Cu(II)-SF-H^+, and the ternary complex EDTA-Cu(II)-SF-H^+ is formed. Silk fibroin segment is thrown from the ternary complex because of the high stability of Cu(II)-EDTA complex.

This step may be rate-determining. The rate equation and rate constants of this reaction were determined as follows:

$-d[\mathrm{Cu(II)\text{-}SF}] / dt = k_1 [\mathrm{Cu(II)\text{-}SF}] / [\mathrm{SF}^-] + k_2'[\mathrm{H}^+] [\mathrm{Cu(II)\text{-}SF}] / [\mathrm{SF}^-]$,

$k_1 = (1.84 \pm 0.38) \times 10^{-3}\ M^{-1}\ \mathrm{s}^{-1}$ and $k_2' = k_2 / K^{-\mathrm{H}^+}_{\mathrm{Cu(II)\text{-}SF\text{-}H}^+} = (2.58 \pm 0.25) \times 10^{9}\ \mathrm{s}^{-1}$.

6-1 Introduction

The treatments using metal compounds on fiber materials are done with the purpose of giving deorderizing activity, antibacterial activity, flame-resistance, heat-resistance, color fastness for lightning, mothproofing, improvement of strength, anti-staticity to fiber in the field of fiber finishing[1,2]. The salts of heavy metals such as Cr, Fe, Cu, Sn, Al, Co, Ni, Mn and Zn are also well used in the dyeing process of fiber manufactures[2]. Metal complex dyes have been consuming on a large scale in dyeing works for their high color fastness. From the view point of complex chemistry, these processes can be regarded as the ligand substitution reaction between metal complexes and fiber or other anions.

It is very important to elucidate the behavior of metal ions and metal complexes in these processes standing with the bases of metal complex chemistry. It has been pointed out[3], for example, that there are some cases to reveal the reverse effect by the ratio of metal ion to ligand and the species of complex in case of improving heat-resistance of fiber. In recent years, basic studies have been accumulated not only low molecular weight metal complexes but also polymer-metal complexes[4]. But, there are few studies about the ligand or metal exchange reaction of macromolecule-metal complexes[5-7].

Ligand substitution reaction and metal exchange reaction are also very important in enzyme reaction, metal transportation *in vivo*, molecular design of functional polymer and microanalysis[8]. In chapter 2-5[9-12] the exchange reactions of macromolecule-metal complexes are discussed from the view points of biochemistry and its functional applications. The functional fiber processing that metal complex participates in can be regarded as a substitution reaction between polymer and metal complex, and a good model of metallo-enzyme.

In this chapter the kinetics and mechanism of the ligand substitution reaction between Cu(II)-silk fibroin (*bombyx mori*) complex (Cu(II)-SF) and ethylenediamine-N,N,N',N'-tetraacetic acid disodium salt (EDTA) were considered by using stopped-flow method.

6-2 Experimental

6-2-1 Materials

The *bombyx mori* silk cocoons were refined by treating them; first, with 50 times of 40℃ water (v/w) for 30 minutes, and with 50 times of 90℃ water containing 20% o.w.f. Marseilles soap for 1 hour. After the same treatment with a soap solution of same density one more time, the silk was washed tree times with warm water containing 3, 2, 1% sodium carbonate respectively[13]. The sample was washed several times with warm distilled water to obtain refined fibroin. The refined fibroin was extracted with ether for 48 hours. The fibroin was dissolved in 9.3 mol/l lithium bromide aqueous solution. The regenerated fibroin solution was obtained by dialyzing the solution against distilled water for 3 days using cellulose tube and by filtering off the impurities. After having decided the protein concentration of the dialyzed solution, the concentration of the solution was adjusted to 0.02 mol/l (0.25% protein concentration) assuming 1 molar of silk fibroin as $(\text{-Gly-Ala-})_n$ [14].

The Cu(II)-SF complex solutions were prepared as follows: 0.02 mol/l solution of copper nitrate was added dropwise to the silk fibroin solution at the molar ratio of 1 : 10 with stirring, pH of the mixed solution was adjusted to the desired value by 0.05*N* KOH. The ionic strength of the solution was maintained at 0.1 mol/l with KNO_3. The complex solutions thus obtained were kept at 25℃ before each experiment for 24 hours. EDTA was recrystallized from methanol-water twice, and dissolved into distilled water at 0.02 mol/l, and the ionic strength of the solution was maintained at 0.1 mol/l with KNO_3. The other reagents used here were of analytical grade and were used without further purification.

6-2-2 Kinetic Measurements

The reaction was carried out in a Hitachi RA-401 stopped-flow spectrophotometer (dead time, 1 ms) or a Hitachi 228A spectrophotometer. pH measurement was carried out with a Hitachi Horiba F7-SS pH meter. The kinetic measurements were generally made as follows: A complex solution containing 8×10^{-3} mol/l Cu(II)-SF and EDTA solution of 1.6×10^{-2} mol/l were mixed in the ratio 1 : 1 (v/v) in a 1 cm cell of stopped-flow spectrophotometer. 0 - 0.1 optical density range at 535 nm was used in a spectrophotometer. Microcomputers and National VP-526A oscilloscope connected to the stopped-flow apparatus were used to record the data. Rates were usually measured at 25 ± 0.1℃.

6-3 Results and Discussion

6-3-1 Spectral Results

It has been already reported[14] that the Cu(II)-silk fibroin complex shows a strong absorption at 535 nm based on the $[Cu(N_4)]^{2-}$ structure above pH 8.5. When a EDTA solution is added to a solution containing Cu(II)-SF, the color changes from violet to colorless at this concentration. Electronic spectra observed before and after the reaction are shown in ***Figure 1***. Remarkable absorptions based on the Cu(II)-SF complex at about 535 nm disappeared after the substitution reaction. The time course of the ligand substitution reaction is observed by detecting the absorption decrease at 535 nm.

The overall change of this reaction is observed with a UV spectrophotometer, and the rapid reaction in the initial part of this reaction can be followed by a stopped-flow spectrophotometer. ***Figure 2*** shows the oscilloscope screen showing the stopped-flow spectrum of a typical run, and ***Figure 3*** is the change of optical density at 535 nm obtained from Figure 2.

6-3-2 Kinetic Results

Plots of $\log(A_t - A_\infty)$ as a function of time were obtained using an approximate value for A_∞ (A, absorbance). A plot from a typical run (Fig. 2) is shown in ***Figure 4***. In general, straight lines were obtained for the reactions.

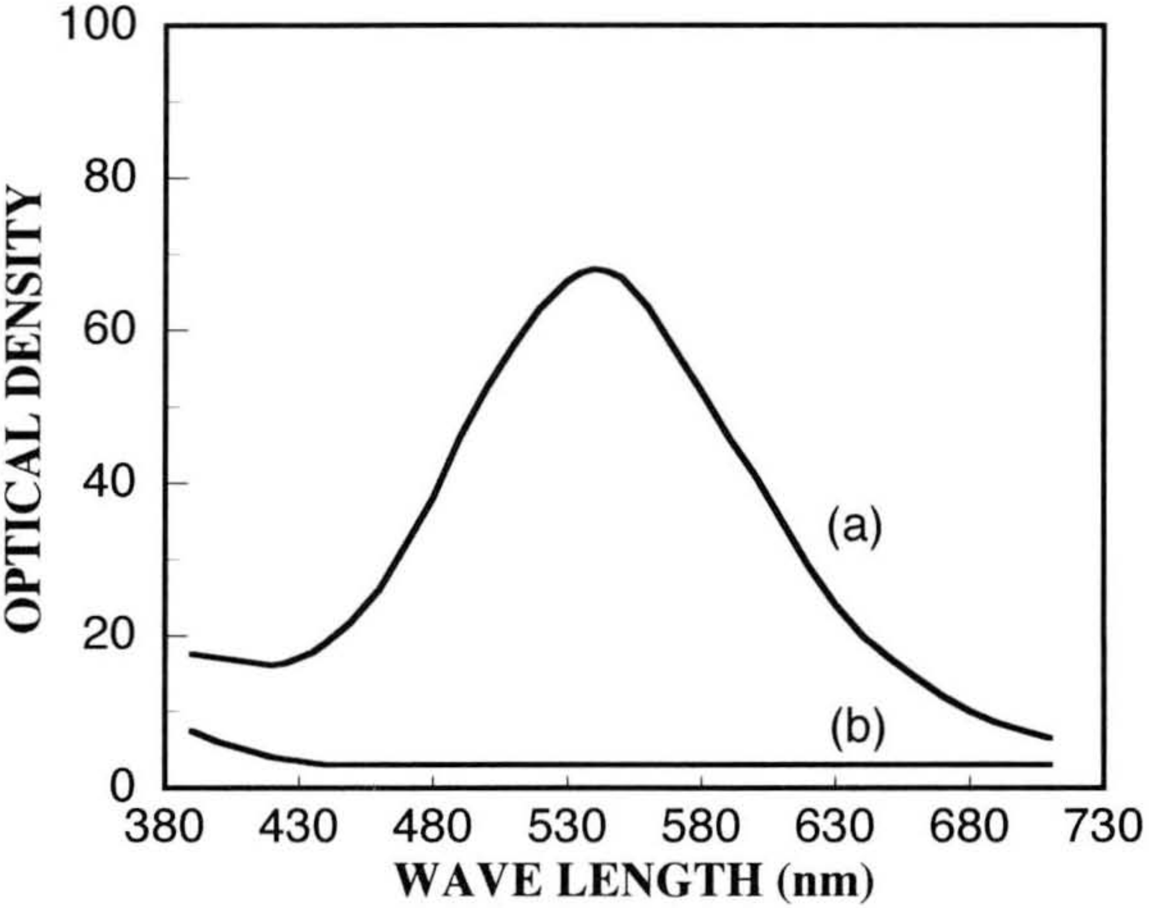

Figure 1 Electronic spectra of Cu(II)-SF complex and Cu(II)-SF + EDTA system:

(a): 8×10^{-4} mol/l Cu(II)-SF complex, pH = 10.5 $T_{Cu^{2+}}/T_{HL} = 0.1$,

(b): (a) + 1.6×10^{-2} mol/l EDTA, pH = 10.5, $\mu = 0.1(KNO_3)$, pass length 5.0cm, 25℃.

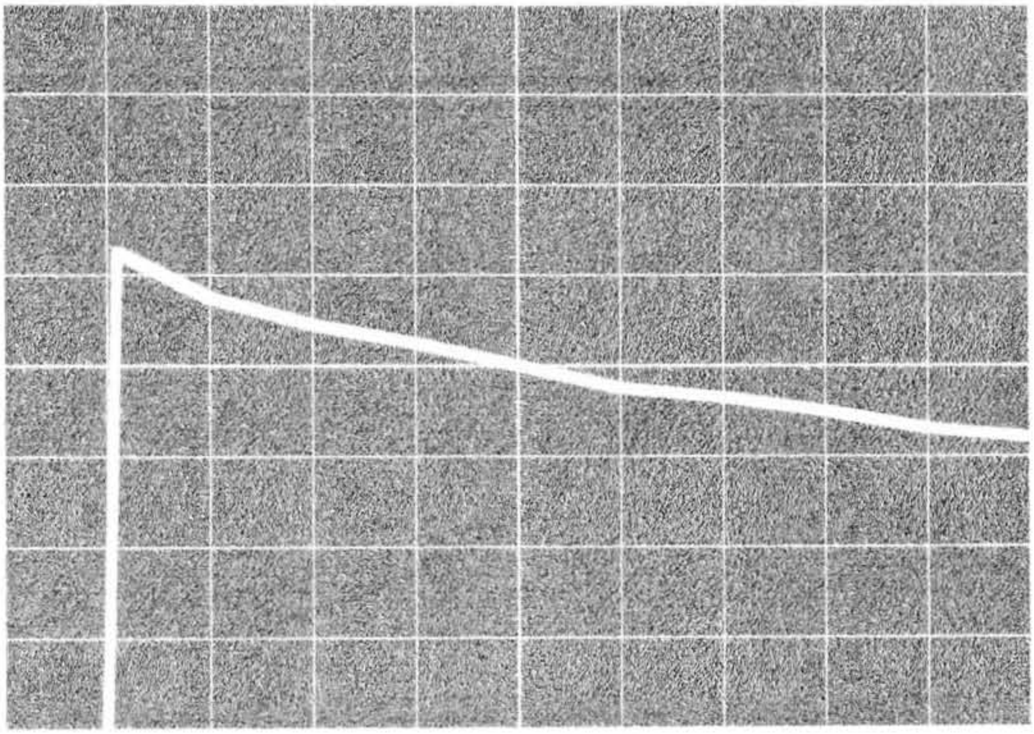

Figure 2 Oscilloscope screen showing stopped-flow spectrum obtained for the reaction between Cu(II)-SF and EDTA: [Cu(II)-SF]= 8 x 10^{-4} mol/l; [EDTA] = 1.6 x 10^{-2} mol/l; $T_{Cu^{2+}}/T_{HL}$ = 0.1; pH 10.5; μ = 0.1(KNO_3); 25℃.

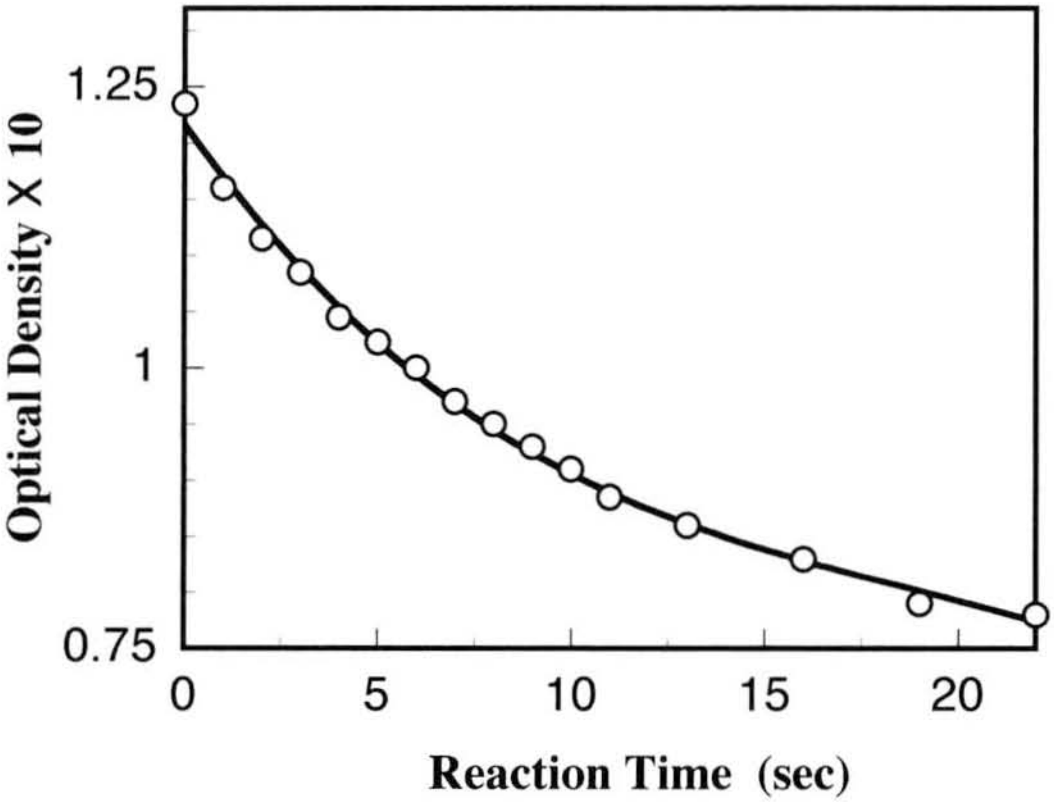

Figure 3 Change in D_{535} for the reaction of Cu(II)-SF complex with EDTA in aqueous solution: [Cu(II)-SF] = 8×10^{-4} mol l^{-1}; [EDTA] = 1.6×10^{-2} mol l^{-1}; pH 10.5, $\mu = 0.1(KNO_3)$; $T_{Cu^{2+}}/T_{HL}$ = 0.1; 25℃.

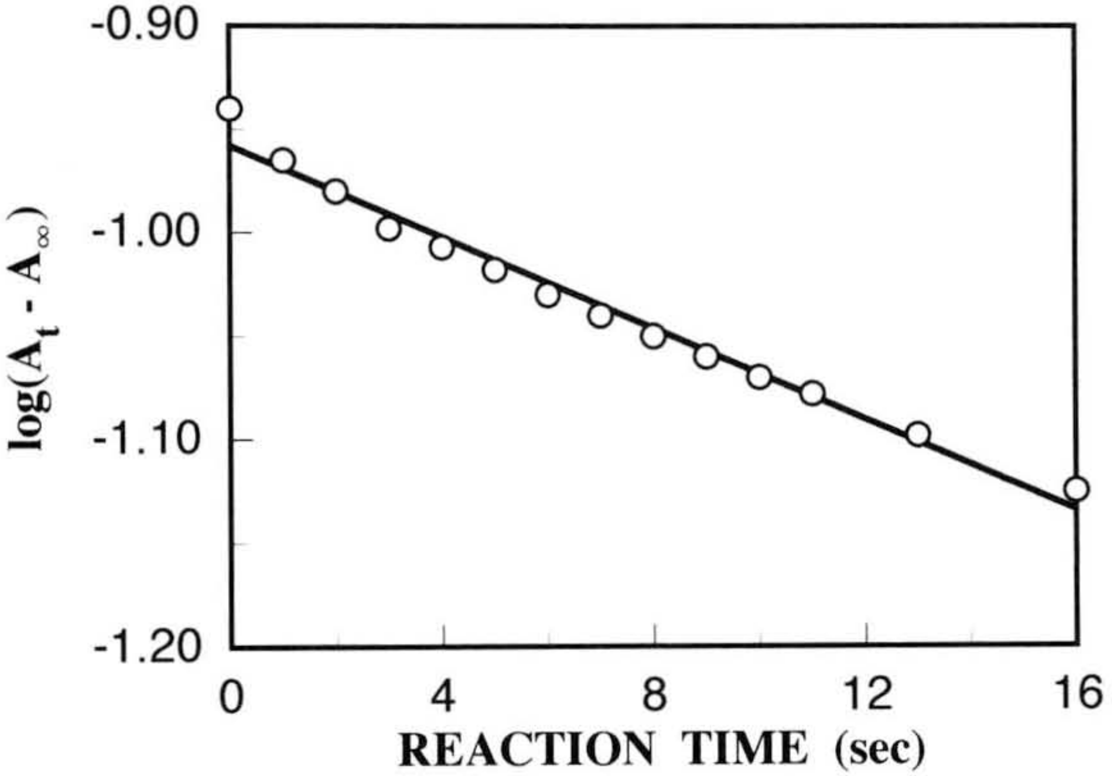

Figure 4 $\log(A_t - A_\infty)$ for the reaction of Cu(II)-SF complex with EDTA in aqueous solution: [Cu(II)-SF] = 8×10^{-4} mol/l; [EDTA] = 1.6×10^{-2} mol/l; pH 10.5, μ = 0.1(KNO_3); $T_{Cu^{2+}}/T_{HL}$ = 0.1; 25℃.

These plots showed, as expected, that the reactions in the presence of an excess of EDTA and under buffered conditions were pseudo-first order. Thus, the reaction of Cu(II)-SF complex with excess EDTA followed the rate expression

$$-\frac{d\,[\mathrm{Cu(II)\text{-}SF}]}{d\,\mathrm{t}} = k_{\mathrm{obs}}\,[\mathrm{Cu(II)\text{-}SF}] \tag{1}$$

where, k_{obs} is the observed rate constant under the experimental conditions.

The ligand substitution reactions were carried out at 25℃ and at $\mu = 0.1$ (KNO_3), with the pH varying from 9.48 to 11.50. The concentration of Cu(II)-SF and EDTA was kept constant. ***Figure 5*** shows the values of k_{obs} plotted against the initial concentrations of hydrogen ion. The reaction order with respect to the initial concentration of hydrogen ion was found to be 1.0.

In another series of experiments, the dependence of k_{obs} on the initial concentration of EDTA was studied at constant concentration of Cu(II)-SF at pH = 10.5, $\mu = 0.1$ (KNO_3), and 25℃ (***Figure 6***). The rate of the substitution reaction is constant on [$EDTA^{4-}$]. EDTA exists as $EDTA^{4-}$ at this pH (pK_{a4} = 10.23[15]).

Finally, the metal exchange reactions were carried out at 25℃, pH = 10.5, $\mu = 0.1$ (KNO_3), and varying the concentrations of Cu(II)-SF. The concentration of EDTA and Cu^{2+} were kept constant. The dependence of k_{obs} on the concentration of silk fibroin is shown in ***Figure 7***. The k_{obs} values are inversely proportional to [SF^-]. SF^- shows partially dissociated SF anion.

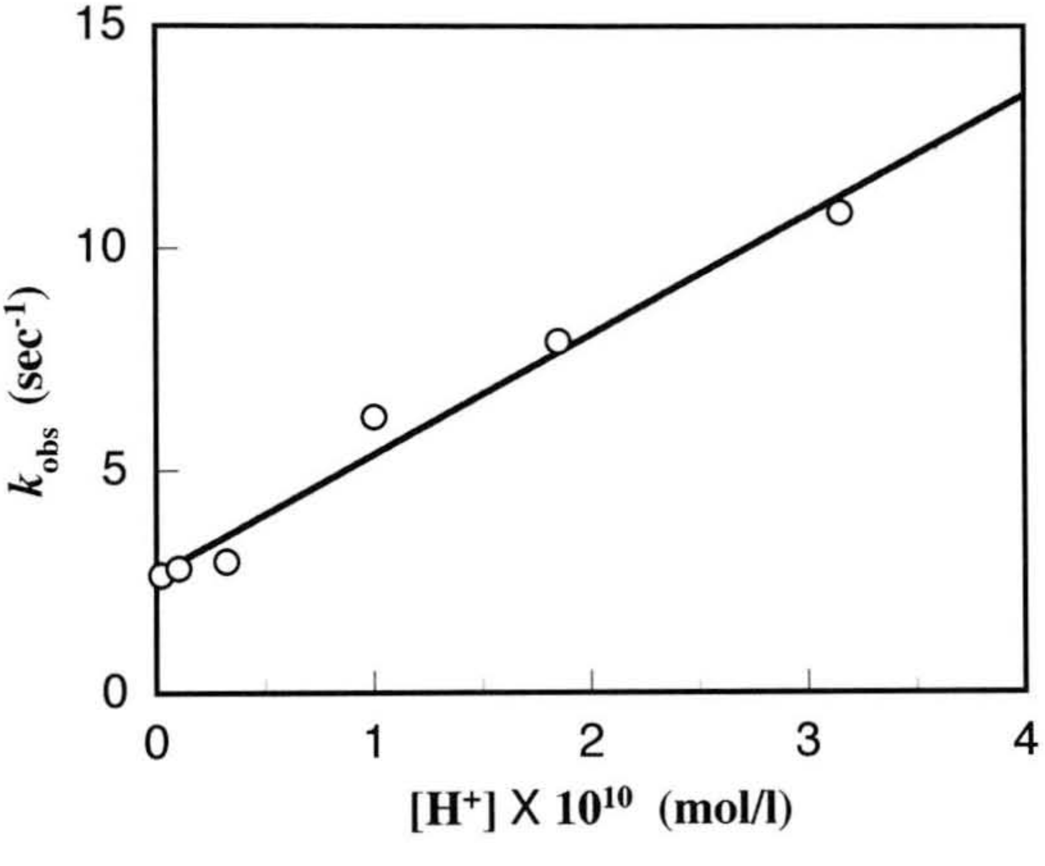

Figure 5 k_{obs} as a function of hydrogen ion concentration: [Cu(II)-SF] = 8×10^{-4} mol/l; [EDTA] = 1.6×10^{-2} mol/l; $T_{Cu^{2+}}/T_{HL} = 0.10$; $\mu = 0.1(KNO_3)$; 25℃

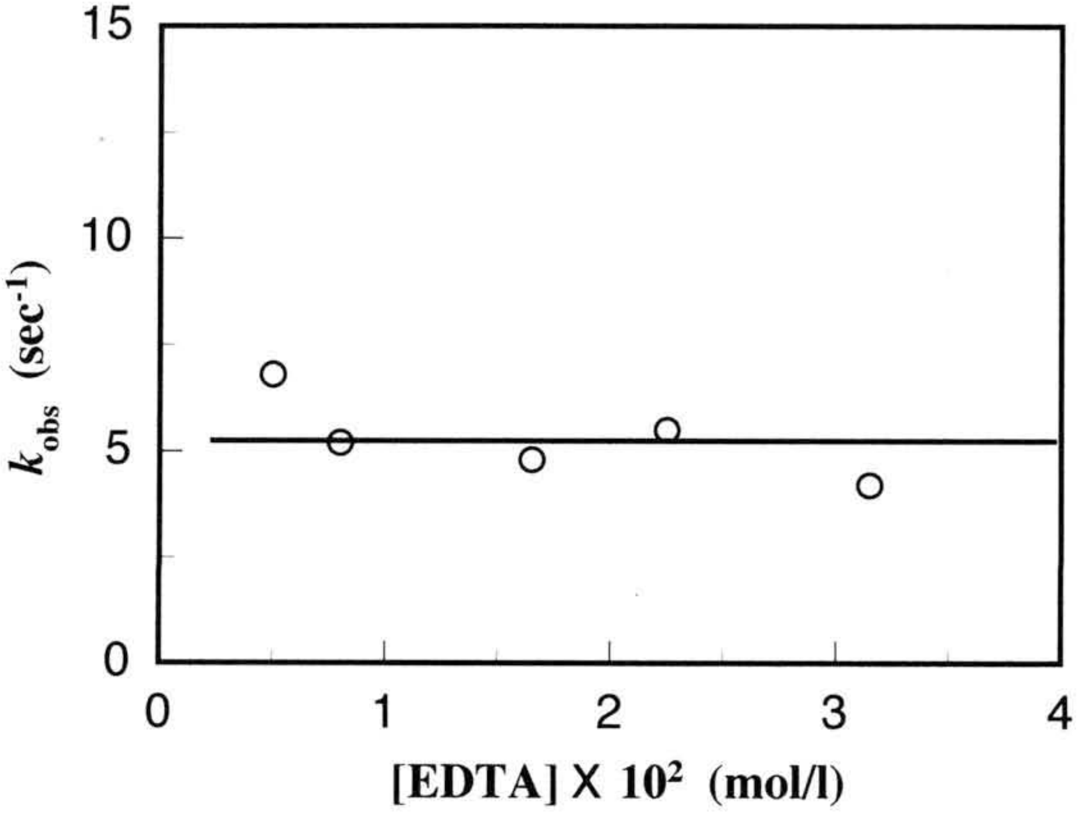

Figure 6 Relationship between k_{obs} and EDTA concentration: [Cu(II)-SF]= 8×10^{-4} mol/l; $T_{Cu^{2+}}/T_{HL} = 0.1$; pH 10.5; $\mu = 0.1(KNO_3)$; 25℃.

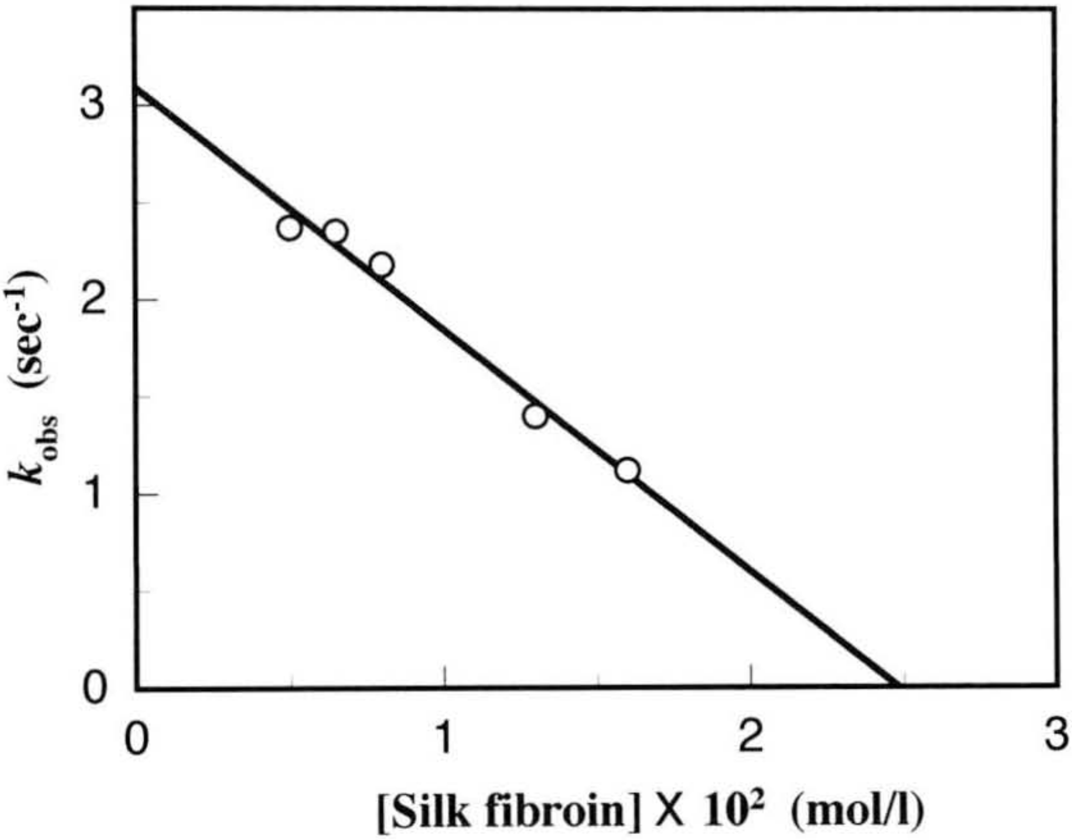

Figure 7 Relationship between k_{obs} and silk fibroin concentration: $[Cu^{2+}] = 8 \times 10^{-4}$ mol/l; [EDTA] = 1.6×10^{-2} mol/l; $T_{Cu^{2+}}/T_{HL} = 0.1$; pH 10.5; $\mu = 0.1(KNO_3)$; 25℃.

Therefore, the rate law of this substitution reaction is given by

$$-\frac{d\,[\mathrm{Cu(II)\text{-}SF}]}{dt} = k\,\frac{[\mathrm{H^+}][\mathrm{Cu(II)\text{-}SF}]}{[\mathrm{SF^-}]} \tag{2}$$

$$= k_{0(\mathrm{H})}\frac{[\mathrm{Cu(II)\text{-}SF}]}{[\mathrm{SF^-}]} \tag{3}$$

$$= k_1\frac{[\mathrm{Cu(II)\text{-}SF}]}{[\mathrm{SF^-}]} + k_2\frac{[\mathrm{Cu(II)\text{-}SF\text{-}H^+}]}{[\mathrm{SF^-}]} \tag{4}$$

$$= k_1\frac{[\mathrm{Cu(II)\text{-}SF}]}{[\mathrm{SF^-}]} + k_2'\frac{[\mathrm{H^+}][\mathrm{Cu(II)\text{-}SF}]}{[\mathrm{SF^-}]} \tag{5}$$

$$= (k_1 + k_2'[\mathrm{H^+}])\frac{[\mathrm{Cu(II)\text{-}SF}]}{[\mathrm{SF^-}]} \tag{6}$$

From Eqs. (1), (3) and (6),

$$k_{0(\mathrm{H})} = k_1 + k_2'[\mathrm{H^+}] = k_{\mathrm{obs}} \times [\mathrm{SF^-}] \tag{7}$$

The values of $k_{0(\mathrm{H})}$, determined at various pH levels, are plotted against hydrogen ion concentration in ***Figure 8***. The $k_{0(\mathrm{H})}$ values are a linear function of the hydrogen ion concentrations in the range of pH 9.48 - 11.50. From the intercept of this figure, $k_1 = (1.84 \pm 0.38) \times 10^{-3}\ M^{-1}\ \mathrm{s}^{-1}$, and from the slope, $k_2' = (2.58 \pm 0.25) \times 10^{9}\ \mathrm{s}^{-1}$ at $\mu = 0.1(\mathrm{KNO_3})$ and 25℃.

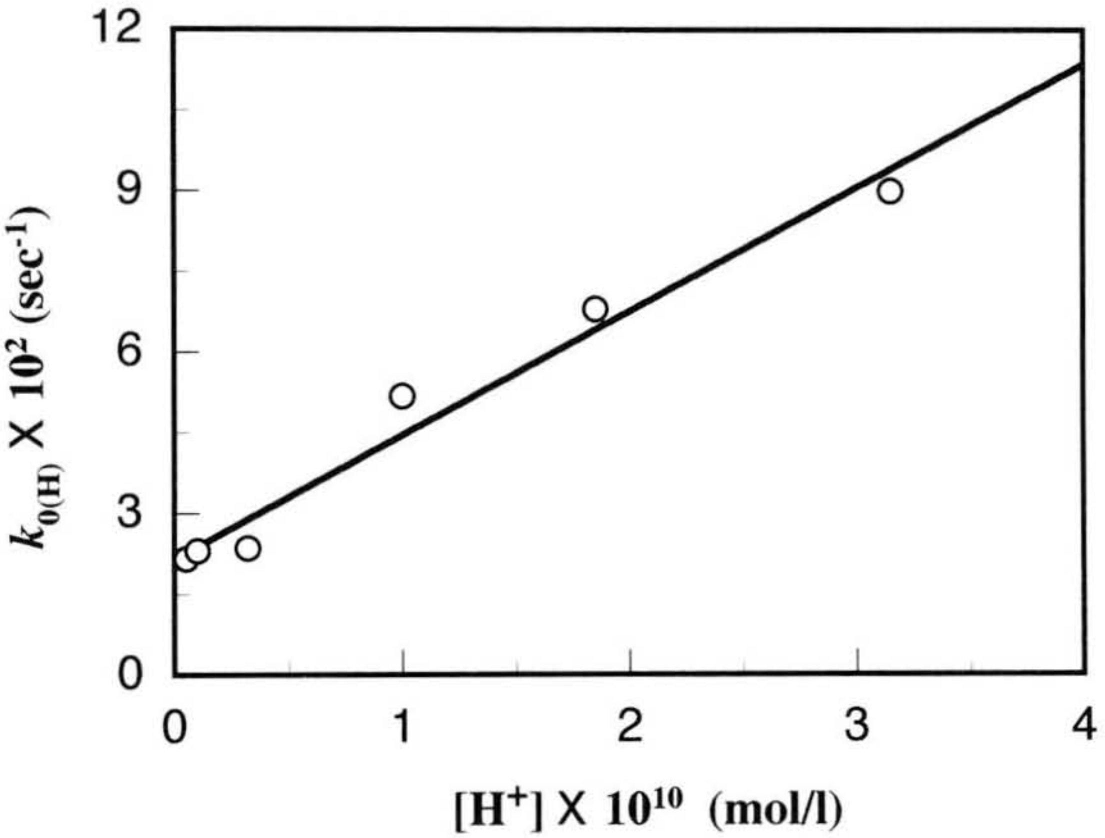

Figure 8 $k_{0(H)}$ as a function of hydrogen ion concentration for the ligand exchange reaction between Cu(II)-SF complex and EDTA: [Cu(II)-SF] = 8×10^{-4} mol/l; [EDTA] = 1.6×10^{-2} mol l^{-1}; $T_{Cu^{2+}}/T_{HL} = 0.1$; $\mu = 0.1(KNO_3)$; 25℃.

Equation (8) is obtained from Eqs. (4) and (5).

$$k_2 \frac{[\mathrm{Cu(II)\text{-}SF\text{-}H^+}]}{[\mathrm{SF^-}]} = k_2' \frac{[\mathrm{H^+}][\mathrm{Cu(II)\text{-}SF}]}{[\mathrm{SF^-}]} \tag{8}$$

$$\frac{k_2}{k_2'} = \frac{[\mathrm{H^+}][\mathrm{Cu(II)\text{-}SF}]}{[\mathrm{Cu(II)\text{-}SF\text{-}H^+}]} = K^{\mathrm{-H^+}}_{\mathrm{Cu(II)\text{-}SF\text{-}H^+}} \tag{9}$$

Therefore,

$$k_2 = k_2' \cdot K^{\mathrm{-H^+}}_{\mathrm{Cu(II)\text{-}SF\text{-}H^+}} \tag{10}$$

6-3-3 Mechanism of the Ligand Substitution Reaction

The reaction sequence that is consistent with the data and rate equation obtained above is shown by Eqs. (11) - (14). Upon this substitution of Cu(II)-Silk fibroin complex for EDTA anion, first, the reaction is initiated by protonation of Cu(II)-SF to form Cu(II)-SF-H^+. Once protonated, the Cu(II)-SF complex becomes unstable and is attacked by a dissociated $EDTA^{4-}$ anion, and the ternary complex EDTA-Cu(II)-SF-H^+ is formed. The rate-determining step is the dissociation of silk fibroin from the ternary complex, and this is substantiated by the experimental fact that the rates were independent of the EDTA concentration. This step is followed by the rapid reaction to form Cu(II)-EDTA and SF-H^+. The reaction sequence can be described as follows:

$$\mathbf{Cu(II)\text{-}SF + H^+ \leftrightarrows Cu(II)\text{-}SF\text{-}H^+} \qquad (11)$$

$$\mathbf{Cu(II)\text{-}SF\text{-}H^+ \overset{EDTA}{\leftrightarrows} EDTA\text{-}Cu(II)\text{-}SF\text{-}H^+} \qquad (12)$$

$$\mathbf{EDTA\text{-}Cu(II)\text{-}SF\text{-}H^+ \rightarrow Cu(II)\text{-}EDTA + SF\text{-}H^+} \qquad (13)$$

$$\mathbf{SF\text{-}H^+ \leftrightarrows SF + H^+} \qquad (14)$$

6-3-4 Effects of Ionic Strength, Temperature and other Chelating Agents on the Rates

The ligand substitution reactions were also carried out at pH 10.5 varying the ionic strength, μ , by 0.1*N* KNO_3. The concentrations of Cu(II)-SF and EDTA were kept constant. ***Figure 9*** shows the plot of k_{obs} versus the ionic strength of the solution. The k_{obs} increased with the increasing concentration of KNO_3 in the reaction media. This fact was attributed to an electrostatic repulsion between the partly negative charged silk fibroin chain bounded to Cu(II) ion and negative charged attacking $EDTA^{4-}$. By the addition of neutral salt the attack of $EDTA^{4-}$ to Cu(II) ion is facilitated more by the relaxation of the electrostatic repulsion between ligands. In our previous study about the kinetics of the ligand substitution reaction between Cu(II)-PVA and EDTA, similar increase of k_{obs} with μ was observed[8]. At higher concentration of neutral salt, the ligand substitution reaction path of this macromolecule-metal complex may approach to the associative mechanism that was proposed for the ligand substitution reaction between low molecular weight ligand Cu(II) complex and EDTA[16,17].

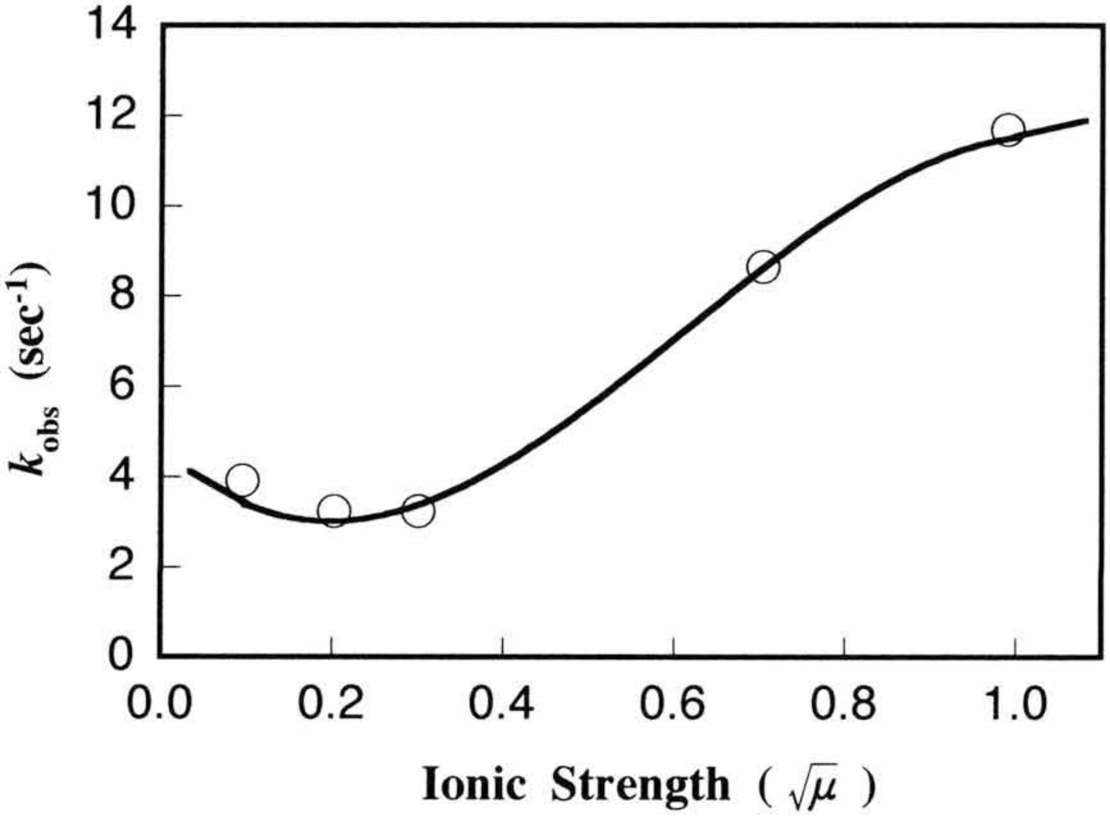

Figure 9 Effect of ionic strength(KNO_3) on the ligand exchange reaction between Cu(II)-SF and EDTA: [Cu(II)-SF]= 8×10^{-4} mol/l; [EDTA]= 1.6×10^{-2} mol/l; $T_{Cu^{2+}}/T_{HL} = 0.1$; pH 10.5; $\mu = 0.1(KNO_3)$; 25℃.

Other experiments were carried out in aqueous solution varying the temperature from 15 to 35℃. The relationship between observed rate constants and reaction temperature is shown in ***Figure 10***. The overall activation energy from Arrhenius plots was 10.5 ± 1.7 kcal/mol. In case of Cu(II)-PVA complex PVA chain becomes flexible with temperature at 15 - 35℃, and the intramolecular complex is stabilized more, while on this complex the random structure of silk fibroin is turned to the β-structure gradually at this temperature region, especially above 30℃[13]. So the stability of the Cu(II)-SF complex become lower with temperature, and the ligand substitution is facilitated to occur.

Observed rate constants of the ligand substitution reaction between Cu(II)-SF complex and other polyaminopolycarboxylic acids were measured at the same experimental condition. Attacking ligands were CyDTA(trans-1,2-Cyclohexanediamine-N,N,N',N'-tetraacetic acid), DTPA(Diethylenetriamine-N,N,N',N",N"-pentaacetic acid), EDDHA(Ethylenediamine-di(o-hydroxyphenylacetic acid), IDA(Iminodiacetic acid) and NTA(Nitrilotriacetic acid). The order of their k_{obs} was as follows:

EDDHA > IDA > **EDTA** > NTA > DTPA > CyDTA.

The fact that k_{obs} were different among these attacking ligands substantiates the structure of ternary complex formed in the reaction mechanism described above.

To summarize, the ligand substitution reaction of Cu(II)-SF with EDTA is initiated by the formation of unstable Cu(II)-SF-H^+ by the attack of H^+ on Cu(II)-SF. EDTA segment attack the partially dissociated site of this protonated complex, and the ternary complex EDTA-Cu(II)-SF-H^+ is formed. And finally silk fibroin chain is dissociated from the intermediate. The dissociation step of silk fibroin from the ternary intermediate may be rate-determining.

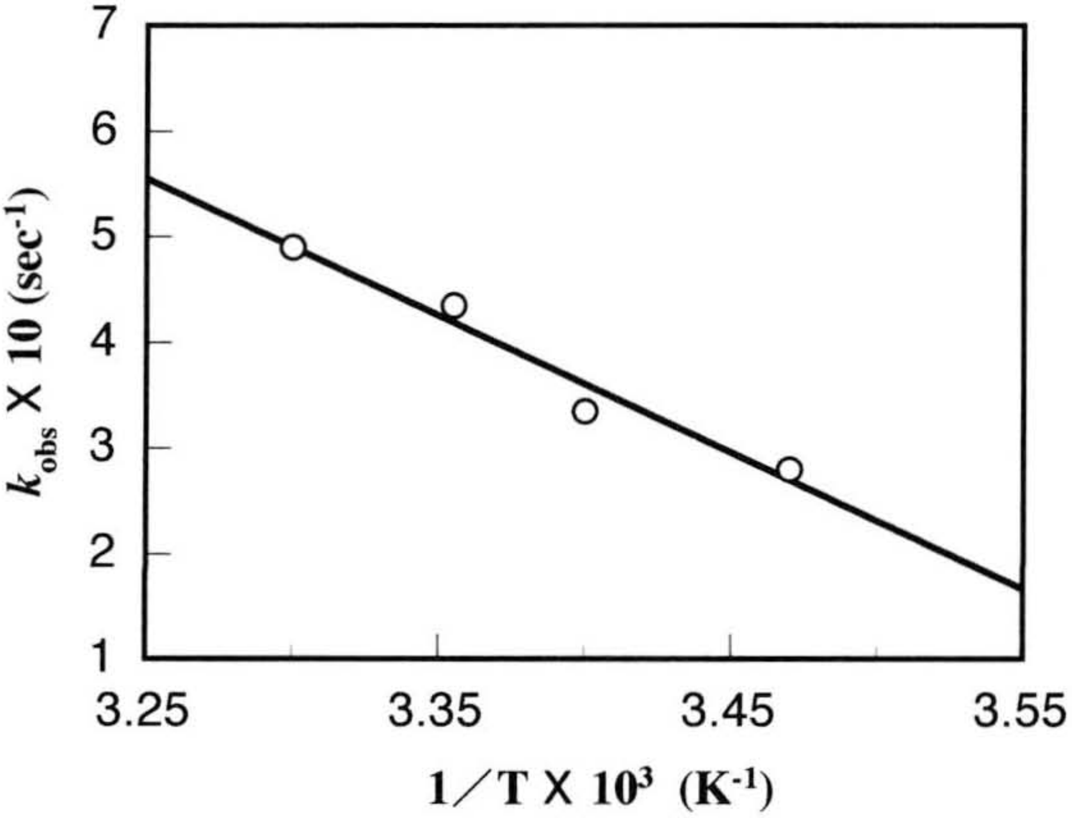

Figure 10 Arrhenius plots for the ligand exchange reaction between Cu(II)-SF complex with EDTA: [Cu(II)-SF] = 8 x 10^{-4} mol l^{-1}; [EDTA] = 1.6 x 10^{-2} mol l^{-1}; pH 10.5; $T_{Cu^{2+}}/T_{HL}$ = 0.1; μ = 0.1(KNO_3); 25℃.

References

1 H. Shirai, *Sen'i To Kogyo*, **50**, 388 (1994).

2 F. Shimizu, *'Seitai to Kinzoku Ion'*, (N. Hojo, H. Shirai, and M.Kaneko, Ed.), Gakkai Shuppan Center, Tokyo, 1991, pp 281-296.

3 A. Kurose, H. Shirai, F. Shimizu, and N. Hojo, *Text. Res. J.*, **55**, 258 (1985).

4 Y. Kurimura and E. Tsuchida, *'Kobunshi Sakutai no Kiso'*, Gakkai Shuppan Center, Tokyo, 1989.

5 J. C. Cassatt, *J. Biolo, Chem.*, **248**, 6129 (1973).

6 A. Udom and F. O. Brady, *Biochem. J.*, **187**, 329 (1980).

7 J. S. Valentine, N. W. Pantoliano, P. J. McDonnell, A. R. Burger, and S. J. Lippard, *Proc. Natl. Acad. Sci. USA*, **76**, 4245 (1979).

8 N. Hojo, *'Seitai to Kinzoku Ion'*, (N. Hojo, H. Shirai, and M. Kaneko, Ed.), Gakkai Shuppan Center, Tokyo, 1991, pp 1-9.

9 T. Suzuki, H. Shirai, F. Shimizu, and N. Hojo, *Polym. J.*, **15**, 409 (1983).

10 T. Suzuki, H. Shirai, S. Tokutake, and N. Hojo, *Polymer*, **24**, 335 (1983).

11 T. Suzuki, H. Shirai, and N. Hojo, *Makromol. Chem. Macromol. Symp.*, **59**, 247 (1992).

12 T. Suzuki, H. Shirai, and N. Hojo, *Journal of Inorganic and Organometallic Polymers*, **4**, 251 (1994).

13 M. Minagawa, *'Kinu no Kagaku'*, Kansai Iseikatsu Kenkyukai, Kyoto, 1983, pp 65.

14 N. Hojo, H. Shirai, and K. Owa, *Sen'i Gakkaishi*, **73**, 1862 (1970).

15 K. Ueno, *'EDTA -Chemistry of Complexan-'*, Nanko-do, Tokyo, 1977, pp 12.

16 S. Funahashi, S. Yamada, and M. Tanaka, *Bull. Chem. Soc. Japan*, **43**, 769 (1970).

17 M. Tanaka, S. Funahashi, and K. Shirai, *Inorg. Chem.*, **7**, 573 (1968).

Conclusion

This thesis describes a study on the kinetics and mechanisms of ligand substitution and metal exchange reactions of macromolecule-metal complexes. Ligand substitution and metal exchange reactions of macromolecule-metal complexes are very important to understand the mechanisms of biochemical reactions and to develop the applications of biosystem into artificial materials.

One of the main objectives was to make the kinetics and mechanisms of ligand substitution and metal exchange reactions of macromolecule-metal complexes clear. Cu(II)-poly(vinyl alcohol) complex was chosen as a macromolecule-metal complex because the coordinate structure and the thermodynamic constants have been defined in previous studies. As a ligand ethylenediamine-N,N,N',N'-tetraacetic acid was used because its properties are also well investigated.

In chapter 2, the kinetics and mechanism of ligand substitution reaction between Cu(II)-ammine complex and poly(viny alcohol) in aqueous solution was decided by using the stopped-flow method.

$$[\mathrm{Cu(NH_3)_4}]^{2+} + \mathrm{PVA} \leftrightarrows \mathrm{Cu(II)\text{-}PVA} + 4\mathrm{NH_3}$$

The rate law and constants of this ligand substitution reaction were

$$d[\mathrm{Cu(II)PVA}]/dt = k[\mathrm{H+}]\ \{[\mathrm{Cu(NH_3)_4}]^{2+}\}\ [\mathrm{PVA}] / [\mathrm{NH_4Cl}]$$

where $k = k_1 + k_2[\mathrm{H^+}]$, $k_1 = 4.25 \times 10\ \mathrm{s^{-1}}$ and $k_2{}' = 5.20 \times 10^{11}\ \mathrm{l\ mol^{-1}\ s^{-1}}$.

The reaction mechanism that is consistent with the rate law was offered. First a proton attacks a Cu(II)-ammine complex, and a minus charged PVA approaches to this unstable site. Once the coordination between $\mathrm{Cu^{2+}}$ and $-\mathrm{O^-}$ of PVA is formed, $-\mathrm{O^-}$s in the same PVA chain coordinate as a chain reaction, and the ligand substitution was finished. The step which the coordination bond is formed between Cu(II) and PVA is the rate-determining.

In chapter 3, the kinetics and mechanism of ligand substitution reaction between Cu(II)-poly(viny alcohol) complex and ethylenediamine-N,N,N',N'-tetraacetic acid in aqueous solution was studied by means of the same stopped-flow method used in chapter 2.

$$\text{Cu(II)-PVA} + \text{EDTA} \leftrightarrows \text{Cu(II)-EDTA} + \text{PVA}$$

The rate law and constants of this ligand substitution reaction were

$$-d[\text{Cu(II)-PVA}]/dt = k\,[\text{Cu(II)-PVA}]/[\text{PVA}]$$

where $k = k_1 + k_2'[\mathrm{H^+}]$, $k_1 = 3.62 \times 10^{-3}$ mol $\mathrm{l^{-1}}$ $\mathrm{s^{-1}}$, $k_2' = 2.83 \times 10^{7}$ $\mathrm{s^{-1}}$.

In chapter 4, the kinetics and mechanism of metal exchange reaction between Cu(II)-poly(viny alcohol) complex and Ca(II)-ethylenediamine-N,N,N',N'-tetraacetic acid in aqueous solution was studied by means of the same method using UV spectrophotometer.

$$\text{Cu(II)-PVA} + \text{Ca(II)-EDTA} \leftrightarrows \text{Cu(II)-EDTA} + \text{Ca(II)-PVA}$$

The rate law and constants of this metal exchange reaction were

$$-d[\text{Cu(II)-PVA}]/dt = k[\text{Cu(II)-PVA}][\mathrm{H^+}][\text{PVA}]/[\text{Ca(II)-EDTA}]$$

where $k = k_1 + k_2'[\mathrm{H^+}]$, $k_1 = 3.85 \times 10^{-2}$ $\mathrm{sec^{-1}}$, $k_2 = k_2' \cdot K^{-H}_{\text{Cu(II)-H-PVA}} = 9.59 \times 10^{5}$ l $\mathrm{mol^{-1}}$ $\mathrm{sec^{-1}}$.

In chapter 5, the kinetics and mechanism of metal exchange reaction between Cu(II)-poly(viny alcohol) complex and Zn(II)-ethylenediamine-N,N,N',N'-tetraacetic acid in aqueous solution was studied by means of the same method using UV spectrophotometer.

$$\text{Cu(II)-PVA} + \text{Zn(II)-EDTA} \leftrightarrows \text{Cu(II)-EDTA} + \text{Zn(II)-PVA}$$

The rate law and constants of this metal exchange reaction were

$$-d[\text{Cu(II)-PVA}]/dt = k_{0(\mathrm{H})}\,[\mathrm{PVA^-}][\text{Cu(II)-PVA}][\text{Zn(II)-EDTA}]$$

where $k_{0(\mathrm{H})} = k_1 + (k_2' + k_3')\,[\mathrm{H}^+]$, $k_1 = 5.98 \pm 1.64\ M^{-1}\,\mathrm{s}^{-1}$, $k_2 + k_3 = (5.91 \pm 1.64) \times 10^7\ M^{-2}\,\mathrm{s}^{-1}$.

In chapter 6, the kinetics and mechanism of ligand substitution reaction between Cu(II)-Silk fibroin complex and ethylenediamine-N,N,N',N'-tetraacetic acid in aqueous solution was studied by means of the same stopped-flow method used in chapter 2.

$$\text{Cu(II)-Silk fibroin + EDTA} \leftrightarrows \text{Cu(II)-EDTA + Silk fibroin}$$

The rate law and constants of this ligand substitution reaction were

$$-d[\mathrm{Cu(II)\text{-}SF}]/dt = k_1\,[\mathrm{Cu(II)\text{-}SF}]\,/\,[\mathrm{SF}^-] + k_2'[\mathrm{H}^+][\mathrm{Cu(II)\text{-}SF}]\,/\,[\mathrm{SF}^-]$$

$k_1 = (1.84 \pm 0.38) \times 10^{-3}\ M^{-1}\,\mathrm{s}^{-1}$, $k_2' = k_2 / K^{-\mathrm{H}^+}_{\mathrm{Cu(II)\text{-}SF\text{-}H}^+} = (2.58 \pm 0.25) \times 10^9\ \mathrm{s}^{-1}$.

Publishments

Papers

1. Tuneo Suzuki, Hirofusa Shirai, Sonoko Tokutake, and Nobumasa Hojo, Kinetics of ligand exchange reaction of Cu(II)-ammine complex with poly(vinyl alcohol) in aqueous solution, *Polymer*, **24**, 335 (1983).

2. Tuneo Suzuki, Hirofusa Shirai, Fukashi Shimizu, and Nobumasa Hojo, Kinetics of Ligand Exchange Reaction of Cu(II)-Poly(vinyl alcohol) Complex with Ethylenediamine-N,N,N',N'-tetraacetic Acid, *Polym. J.*, **15**, 409 (1983).

3. Tuneo Suzuki, Hirofusa Shirai, and Nobumasa Hojo, KINETICS OF METAL EXCHANGE REACTION OF Cu(II)-POLY(VINYL ALCOHOL) COMPLEX WITH Ca(II)-ETHYLENEDIAMINE-N,N,N',N'-TETRAACETIC ACID IN AQUEOUS SOLUTION, *Makromol. Chem. Macromol. Symp.*, **59**, 247 (1992).

4. Tuneo Suzuki, Hirofusa Shirai, and Nobumasa Hojo, Kinetics of the Metal Exchange Reaction of a Cu(II)-Poly(vinyl Alcohol) Complex with Zn(II)-Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution, *Journal of Inorganic and Organometallic Polymers.*, **4**, 251 (1994).

Proceedings of International Symposium

1. T. Suzuki, H. Shirai, and N. Hojo, Kinetics of Metal Exchange Reaction of Cu(II)-Poly(vinyl Alcohol) Complex with Ca(II)-Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution in the Fourth International Symposium on Macromolecule-Metal Complexes (MMC-IV), Siena (Italy), Oct 1991, pp. 183.

2. Tuneo Suzuki, Hirofusa Shirai, and Nobumasa Hojo, Kinetics of Metal Exchange Reaction of a Cu(II)-Poly(vinyl Alcohol) Complex with Zn(II)-Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution in the Fifth International Symposium on Macromolecule-Metal Complexes (MMC-V), Bremen (FRG), Oct 1993, pp. 222.

3. Tuneo Suzuki, Hirofusa Shirai, and Nobumasa Hojo, Ligand Exchange Reaction between Silkfibroin-Cu(II) complex with Ethylenediamine-N,N,N',N'-tetraacetic Acid in Aqueous Solution in The International Symposium on Fiber Science and Technology (ISF '94), Yokohama, Oct 1994, pp. 48.

4. Tuneo Suzuki, Hirofusa Shirai, Kenji Hanabusa, Toshiki Koyama, Masaki Gotou, and Nobumasa Hojo, Antibacterial Activities of Amorphous Rayon-Cu(II) Fiber in the Sixth International Symposium on Macromolecule-Metal Complexes (MMC-VI), Guangzhou (China), Nov 1995, pp. 205.

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