

KINETICS AND MECHANISM OF THE COMPLEXATION REACTIONS OF Ni(II) AND Co(II) WITH L-4-HYDROXY-2-PYRROLIDINECARBOXYLIC ACID

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(Received 9 December 1992; Revised 16 July 1993;

Accepted 28 October 1993)

Kinetics of the complexation of Ni(II) and Co(II) with L-4-hydroxy-2-pyrrolidincarboxylic acid has been studied as a function of pH and temperature in 0.1 M KNO₃ using stopped-flow spectrophotometer. Specific rate constants corresponding to the different reactive forms of the ligand have been evaluated and the corresponding activation parameters have also been determined. Complexation reaction of cobalt with L-4-hydroxy-2-pyrrolidincarboxylic acid was found to be faster than of nickel. The values of k_{os} (outer sphere complex formation constant) and k_0 (rate constant) for exchange of water molecule have also been determined. A reaction scheme on the basis of complete chelation process, consistent with our kinetic data has been suggested.

Key Words: Kinetics; Complexation; Ni(II) and Co(II); L-4-Hydroxy-2-Pyrrolidincarboxylic Acid

Introduction

L-4-hydroxy-2-pyrrolidincarboxylic acid is an important constituent of Collagen¹ which is a fibrous protein present in skin cartilage, bones and teeth. Presence of calcium salts in bones is due to the complexation of calcium ions with Collagen. Collagen is also known to form complexes with certain heavy metal ions resulting in the marked improvement in mechanical and chemical properties of the fibres.

Excessive excretion of L-4-hydroxy-2-pyrrolidincarboxylic acid causes osteoporosis disease. However, this can be avoided by retaining L-4-hydroxy-2-pyrrolidincarboxylic acid through the formation of metal complexes.

To understand the complex biological processes and steps of metal binding to the ligand, a kinetic study on the interaction of Ni(II) and Co(II) with L-4-hydroxy-2-pyrrolidincarboxylic acid was carried out.

Materials and Methods

L-4-hydroxy-2-pyrrolidincarboxylic acid (SISCO), Ni(NO₃)₂·6H₂O and Co(NO₃)₂·6H₂O (both Merck), 2,6-lutidine (Merck Schuchardt) and bromothymol blue were used.

2,6-Lutidine and HCl were used to adjust the pH of ligand solution and metal ion solution to the same value. However, a slight change in the pH value (~0.5 unit) was observed after mixing of two solutions. Final pH was recorded on a radiometer pH meter (model pH M 26, Copenhagen).

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Table I

Second order rate constants k_{obs} for the complexation of Ni(II) and Co(II) with L-4-hydroxy-2-pyrrolidinedicarboxylic acid at different pH's and temperatures

$$[\text{Ni(II)}] = 4.02 \times 10^{-2} \text{M}, [4\text{-Hydroxy-L-proline}] = 6.2 \times 10^{-3} \text{M}$$

$$[\text{Co(II)}] = 4.95 \times 10^{-2} \text{M}, [4\text{-Hydroxy-L-proline}] = 1.15 \times 10^{-3} \text{M}$$

$$I = 0.1 \text{ M KNO}_3$$

Ni(II)-L-4-Hydroxy-2-pyrrolidinedicarboxylic acid		Co(II)-L-4-Hydroxy-2-pyrrolidinedicarboxylic acid	
pH	$k_{\text{obs}} \times 10^{-1} \text{M}^{-1} \text{S}^{-1}$	pH	$k_{\text{obs}} \times 10^{-2} \text{M}^{-1} \text{S}^{-1}$
Temp. = 25 °C			
6.25	3.33	6.11	6.89
6.45	4.02	6.32	7.46
6.55	4.60	6.48	8.14
6.74	5.91	6.58	8.95
6.95	7.92	6.79	10.70
7.10	10.30	7.00	13.20
7.15	11.20	7.11	16.00
Temp. 30 °C			
6.25	4.06	6.14	8.45
6.45	4.84	6.34	9.45
6.49	5.30	6.54	10.91
6.72	7.21	6.61	11.50
6.95	10.26	6.72	12.70
7.10	13.50	6.95	17.02
7.14	14.61	7.10	21.20
Temp. 35 °C			
6.20	4.52	6.01	9.95
6.40	5.72	6.24	11.19
6.49	6.27	6.45	12.79
6.70	8.62	6.55	14.37
6.93	12.58	6.79	17.91
7.06	16.23	6.92	21.80
7.12	18.33	7.06	27.20
Temp. = 40 °C			
6.19	5.51	6.01	11.62
6.36	6.73	6.25	13.71
6.48	7.66	6.38	14.37
6.70	11.04	6.60	17.91
6.92	16.23	6.79	22.38
7.06	21.21	6.90	26.01
		7.08	34.20

Kinetic measurements were made on Aminco Morrow stopped-flow spectrophotometer under pseudo first order conditions, i.e., $[\text{M(II)}] \gg [4\text{-Hydroxy-L-proline}]$. The temperature of the system was maintained at 25-40 °C (± 0.5 °C) with immersion type thermostat (German model).

The transmittance change of indicator² due to the formation of a complex was monitored at 620 nm. This was desirable as very small changes in transmittance values were observed in the absence of the indicator. The pseudo first order rate constants were evaluated from the $\log \Delta V$ versus time plots, where ΔV 's are directly proportional to the concentration changes.

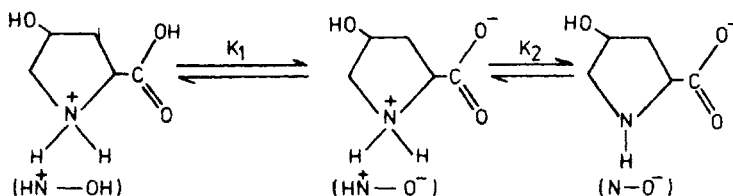
From first order rate constants, second order rate constants (Table I) were computed using the relation

$$k_{\text{obs}} = \frac{k'_{\text{obs}}}{[M(\text{II})]}, \quad k'_{\text{obs}} \text{ is the pseudo first order rate constant.}$$

Results and Discussion

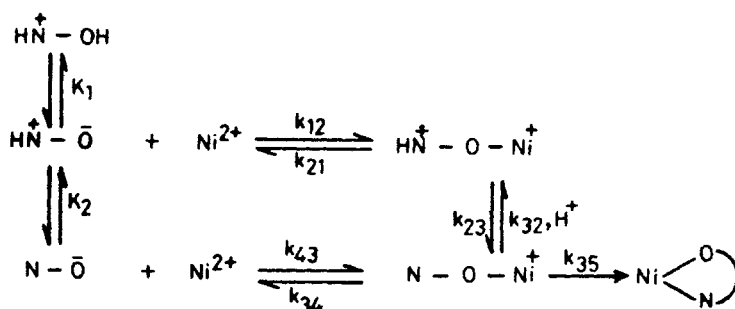
The kinetics of the interaction of Ni(II) and Co(II) with L-4-hydroxy-2-pyrrolidincarboxylic acid has been investigated in the pH range 6.11-7.06 at temperatures 25-40 (± 0.05) °C and at ionic strength 0.1 M KNO_3 .

The zwitterionic form of L-4-hydroxy-2-pyrrolidincarboxylic acid can exist in the following equilibria.



Interaction of Ni(II) with L-4-hydroxy-2-pyrrolidincarboxylic acid

The stepwise interaction of Ni(II) with diprotonated, monoprotonated and deprotonated forms of the ligand can be represented as shown in Scheme 1.



Scheme-1

The overall differential rate equation for the reaction between Ni(II) and 4-hydroxy-2-pyrrolidine carboxylic acid is given as

$$\text{Rate} = -\frac{d}{dt} [\text{Ni}^{\text{II}}] = -\frac{d}{dt} [4\text{-hydroxy-L-proline}] \quad \dots (1)$$

$$= k_{\text{obs}}[\text{Ni}^{\text{II}}][4\text{-hydroxy-L-proline}] \quad \dots (2)$$

$$= k'_{\text{obs}} [4\text{-hydroxy-L-proline}] \quad \dots (3)$$

where

$$k'_{\text{obs}} = k_{\text{obs}} [\text{Ni}^{\text{II}}]. \quad \dots (4)$$

In terms of different forms of the ligand, the rate can be written as

$$\text{Rate} = k'_{\text{obs}} \{[\text{HN}^{\dagger}-\text{OH}] + [\text{HN}^{\dagger}-\bar{\text{O}}] + [\text{N}-\bar{\text{O}}]\} \quad \dots (5)$$

From Scheme 1, since equilibria involving rate constants k_{12} , k_{43} and k_{23} are fast, rate of chelate formation can be written as

$$\text{Rate} = k_{35}[\text{N}-\text{O}-\text{Ni}^{\dagger}] \quad \dots (6)$$

Assuming that both mono protonated and deprotonated forms react with Ni^{2+} ions and using the steady state approximation for the intermediates $\text{HN}^{\dagger}-\text{O}-\text{Ni}^{\dagger}$ and $\text{N}-\text{O}-\text{Ni}^{\dagger}$ and substituting the value of $[\text{HN}^{\dagger}-\text{O}-\text{Ni}^{\dagger}]$ in terms of $[\text{N}-\text{O}-\text{Ni}^{\dagger}]$, we get

$$\text{Rate} = \frac{k_{12} k_{23} k_{35} [\text{HN}^{\dagger}-\bar{\text{O}}] + k_{23} k_{35} k_{43} [\text{N}-\bar{\text{O}}][\text{Ni}(\text{II})]}{k_{21} k_{32} [\text{H}^{\dagger}] + k_{23} (k_{34} + k_{35})} \quad \dots (7)$$

+ From Scheme - 1, $[\text{N}-\bar{\text{O}}]$ and $[\text{HN}-\bar{\text{O}}]$ can be represented in terms of $[\text{HN}-\text{OH}]$. Using these values and after rearrangement we get

$$\text{Rate} = \frac{k_{12} k_{35} k_{23} [\text{H}^{\dagger}] + k_{23} k_{35} k_{43} K_1 K_2}{k_{21} k_{32} [\text{H}^{\dagger}] + k_{23} (k_{34} + k_{35})} \times \frac{[\text{HN}^{\dagger}-\text{OH}][\text{Ni}(\text{II})]}{[\text{H}^{\dagger}]^2} \quad \dots (8)$$

Substituting the values of $[\text{HN}^{\dagger}-\bar{\text{O}}]$ and $[\text{N}-\bar{\text{O}}]$ in terms of $[\text{HN}^{\dagger}-\text{OH}]$ in eq. (5) and after rearrangement we get

$$\text{Rate} = k_{\text{obs}} \{[\text{H}^{\dagger}]^2 + K_1 [\text{H}^{\dagger}] + K_1 K_2\} \frac{[\text{HN}^{\dagger}-\text{OH}][\text{Ni}(\text{II})]}{[\text{H}^{\dagger}]^2} \quad \dots (9)$$

Comparing equations (8) and (9) we get

$$k_{\text{obs}} \{[\text{H}^{\dagger}]^2 + K_1 [\text{H}^{\dagger}] + K_1 K_2\} = \frac{k_{12} k_{35} k_{23} K_1 [\text{H}^{\dagger}] + k_{23} k_{43} k_{35} K_1 K_2}{k_{21} k_{32} [\text{H}^{\dagger}] + k_{23} (k_{34} + k_{35})} \quad \dots (10)$$

At high pH $k_{21} k_{32} [\text{H}^{\dagger}] \ll k_{23} (k_{34} + k_{35})$ and assuming³ $k_{34} < k_{35}$, eqn (10) can be written as

$$k_{\text{obs}} \frac{\{[\text{H}^{\dagger}]^2 + K_1 [\text{H}^{\dagger}] + K_1 K_2\}}{K_1 [\text{H}^{\dagger}]} = k_{12} + \frac{k_{43} K_2}{[\text{H}^{\dagger}]} \quad \dots (11)$$

Specific rate constants k_{12} and k_{43} (Table II) were evaluated from the intercepts and slopes of the plots of

$$k_{\text{obs}} \frac{\{[\text{H}^+]^2 + K_1[\text{H}^+] + K_1 K_2\}}{K_1[\text{H}^+]} \text{ vs } [\text{H}^+]^{-1}$$

Table II

Values of k_{12} , k_{43} and k_0 for the complexation of Ni(II) with L-4-hydroxy-2-pyrrolidinecarboxylic acid

Temp. °C	$k_{12} \times 10^{-1}$ $\text{M}^{-1}\text{S}^{-1}$	$k_{43} \times 10^{-4}$ $\text{M}^{-1}\text{S}^{-1}$	$k_0 \times 10^{-4}$ S^{-1}
25	2.2	1.86	0.94
30	2.4	1.90	0.96
35	2.9	1.96	0.99
40	3.3	2.03	1.02

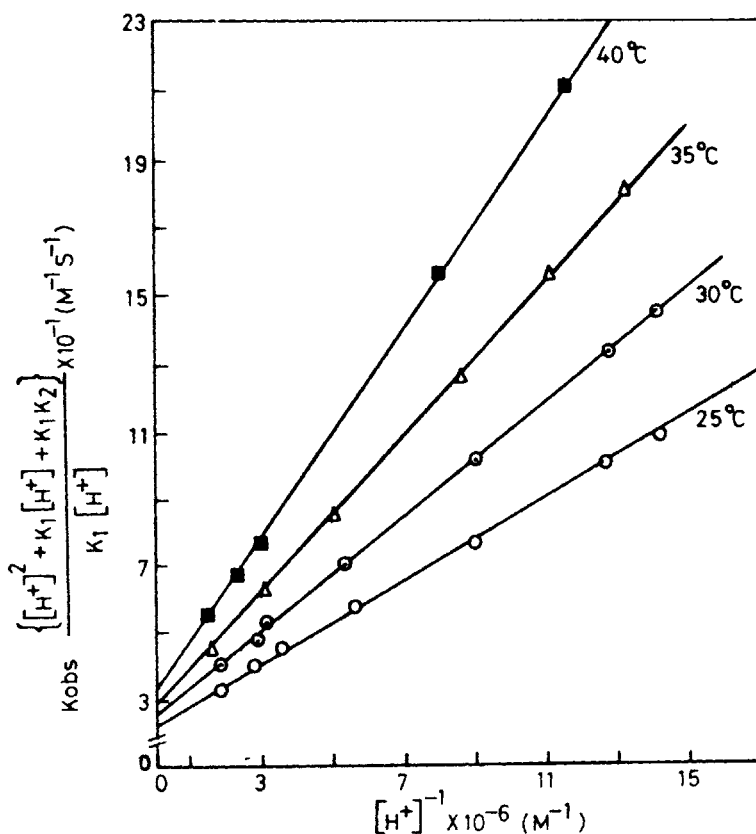


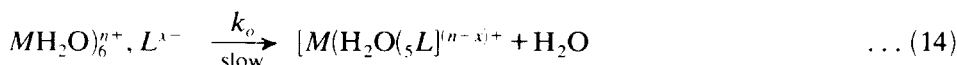
Fig 1 Plots of $k_{\text{obs}}\{[\text{H}^+]^2 + K_1[\text{H}^+] + K_1 K_2\}/K_1[\text{H}^+]$ versus $[\text{H}^+]^{-1}$ for Ni(II)-L-4-hydroxy-2-pyrrolidinecarboxylic acid interaction at different temperatures

at different temperatures as shown in Fig. 1. Literature⁴ values of pK_1 and pK_2 at 25 °C are 1.80 and 9.46. These values were corrected for different temperatures using the relation

$$pK^{T_2} = \frac{\Delta H_a (T_2 - T_1)}{4.576 T_1 T_2} + pK^{25^\circ} \quad \dots (12)$$

where ΔH_a represents heat of reaction for the equilibrium between protonated and deprotonated forms of the ligand. Activation parameters corresponding to the specific rate constants k_{12} and k_{43} were calculated from the plots of $\log(k/T)$ vs $(1/T)$. These values are reported in Table III.

Scheme—1 can be further corroborated by the Eigen mechanism. According to this mechanism, in the complex formation with the six coordinate transition metal ion, the loss of water molecule from the metal ion in the ion pair is thought to be the rate controlling step⁵.



Eq. (14) represents dissociative interchange mechanism. From equations (13) and (14) the rate law in terms of outer sphere complex formation constant (K_{os}) and the rate constant of water exchange (k_o) can be written as

$$\text{Rate} = \frac{d}{dt} [Ni^{II}L] = K_{os} k_o [Ni^{II}][L]. \quad \dots (15)$$

From Scheme—1, k_{35} is the rate constant for chelate formation. Water exchange is taking place only through steps k_{12} and k_{43} . Thus in terms of reactive forms of the ligand, the rate can be written as

$$\text{Rate} = k_{12} [Ni^{2+}][HN^+-\bar{O}] + k_{43} [Ni^{2+}][N-\bar{O}] \quad \dots (16)$$

Table III

Values of activation parameters for the reaction of Ni(II) with L-4-hydroxy-2-pyrrolidinecarboxylic acid

	k_{12}	k_{43}
ΔH^\ddagger (kcal mol ⁻¹)	4.8	0.628
ΔE^\ddagger (kcal mol ⁻¹)	5.3	0.869
ΔS^\ddagger (cal K ⁻¹ mol ⁻¹)	-36.24	-37.15

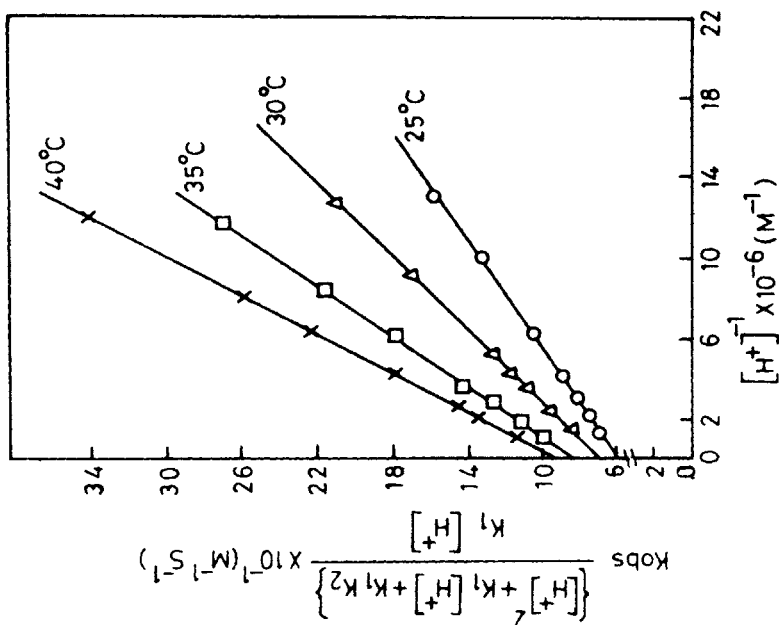


Fig. 3 Plots of $k_{obs}/[H^+]^2 + K_1[H^+] + K_2/K_1/[H^+]$ versus $[H^+]^{-1}$ for Co(II)-L-4-hydroxy-2-pyrrolidinecarboxylic acid interaction at different temperatures

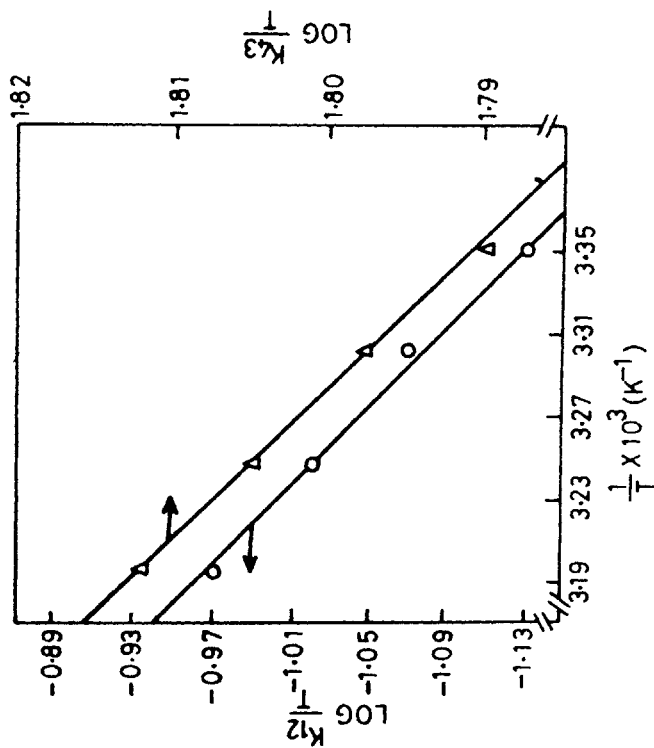


Fig. 2 Variation of $\log k_{12}/T$ and $\log k_{13}/T$ with $1/T$ for Ni(II)-L-4-hydroxy-2-pyrrolidinecarboxylic acid interaction

Since $k_{12} \ll k_{43}$ as reported in Table II, eq. (16) reduces to the form

$$\text{Rate} = k_{43}[\text{Ni}^{2+}][\text{N} - \bar{\text{O}}] \quad \dots (17)$$

Correlation between Scheme—1 and the Eigen mechanism can be made from eq. (15) and (17).

Comparing eq. (15) and (17) we get,

$$k_{43} = K_{os} K_0 \quad \dots (18)$$

The value of k_0 can be calculated by substituting the value of k_{os} which can be determined using Fuoss equation⁶. The value of K_{os} can be approximated to $1.98 M^{-1}$ at all temperatures. Using this, the values of k_0 were calculated (Table II).

The calculated value of k_0 at 25 °C is $0.94 \times 10^4 \text{S}^{-1}$ which is in satisfactory agreement with the value of water exchange reported by Swift and Connick⁷. However, as expected⁸ the value of k_0 for the complexation reaction with 4-hydroxy-L-proline is found to be less as compared to the value for the complexation with L-proline⁹, (k_0 at 25 °C is $2.6 \times 10^4 \text{S}^{-1}$). This is due to hydrogen bonding between the OH group of the ligand and water coordinated to the nickel which makes the orientation of the ligand within the ion-pair relatively unfavourable for the interchange step.

From the values of rate constants given in Table II, it could be said that deprotonated form is more reactive than zwitterionic form. This is further con-

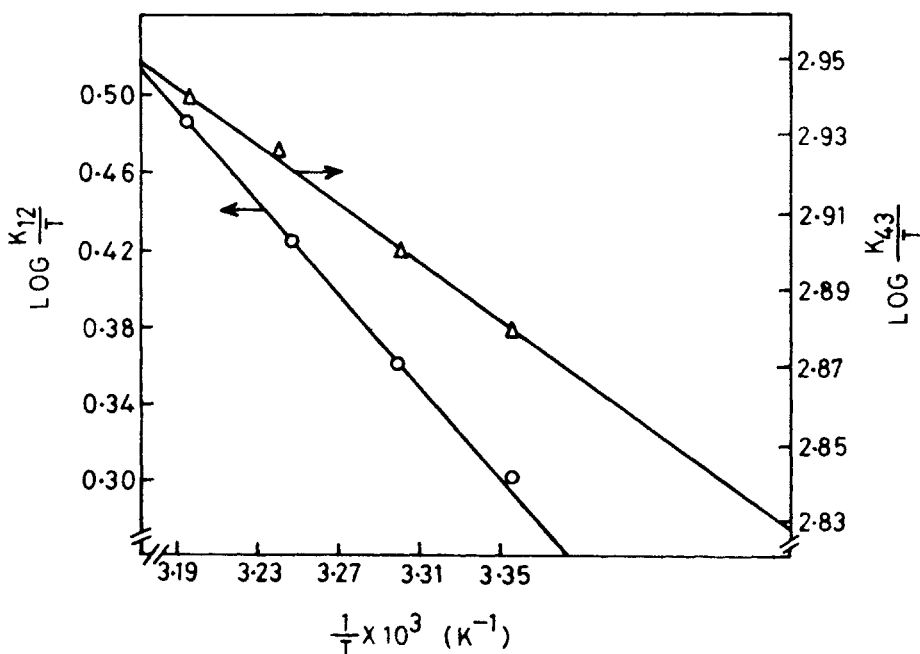


Fig 4 Variation of $\log k_{12}/T$ and $\log k_{43}/T$ with $1/T$ for Co(II)-L-4-hydroxy-2-pyrrolidinecarboxylic acid interaction

Table IV

Values of k_{12} , k_{43} and k_0 for the complexation reaction of Co(II) with L-4-hydroxy-2-pyrrolidine-carboxylic acid

Temp. °C	$k_{12} \times 10^{-1}$ M ⁻¹ S ⁻¹	$k_{43} \times 10^{-5}$ M ⁻¹ S ⁻¹	$k_0 \times 10^{-4}$ S ⁻¹
25	6.00	2.23	1.12
30	7.00	2.40	1.21
35	8.20	2.59	1.31
40	9.60	2.72	1.37

Table V

Values of activation parameters for the interaction of Co(II) with L-4-hydroxy-2-pyrrolidine-carboxylic acid

	k_{12}	k_{43}
ΔH^* (kcal mol ⁻¹)	5.49	1.83
ΔE^* (kcal mol ⁻¹)	5.94	2.50
ΔS^* (cal K ⁻¹ mol ⁻¹)	-27.45	-28.28

firmed by the activation parameters (Table III) which can be calculated from the equation based on the transition state theory. Negative value for the activation entropy for the process suggests an associatively activated mechanism.

Interaction of Co(II) with L-4-hydroxy-2-pyrrolidinecarboxylic Acid

In case of bidentate ligands, only monoprotonated and deprotonated forms are generally considered for the reaction^{2,10}.

$$\text{Linear plots of } k_{\text{obs}} = \frac{\{[\text{H}^+]^2 + K_1[\text{H}^+] + K_1 K_2\}}{K_1[\text{H}^+]} \text{ vs } [\text{H}^+]^{-1}$$

(Fig. 3) suggest that Scheme 1 is also applicable for the interaction of Co²⁺ with L-4-hydroxy-2-pyrrolidinecarboxylic acid. The complexation follows the same mechanism of fast association followed by rate determining dissociative interchange.

Since eq. (11) is also valid in this case, the values of specific rate constants k_{12} and k_{43} have been calculated from the intercepts and slopes respectively of the linear plots, and are reported in Table IV. Activation parameters calculated from the plots of $\log(k/T)$ vs $(1/T)$ are reported in Table V.

The low value of ΔH^\ddagger (Table V) corresponding to k_{43} shows that the deprotonated form is highly reactive. High negative value of entropy of activation in case of k_{43} path suggests a rapid ion-pair formation.

References

- 1 *Metal Ion in Biological Systems* (Ed Helmut Siegel) Vol III
- 2 J C Cassatt and R G Wilkins *J Am chem Soc* **90** (1968) 5045
- 3 H C Malhotra and Gain Chand Sharma *J Indian chem Soc* **66** (1989) 144
- 4 E Martell and R M Smith *Critical Stability Constants Amino Acids* Plenum Press London (1974) Vol I
- 5 Ralph G Pearson and Oren P Anderson *Inorg Chem* **9** (1970) 39
- 6 R M Fuoss *J Am chem Soc* **80** (1968) 5059
- 7 T J Swift and R E Connick *J chem Phys* **37** (1962) 307
- 8 J Burgess *Metal Ions in Solution* Ellis Horwood Limited England (1978)
- 9 H C Malhotra and Yogeshwara Sharma *J Indian chem Soc* (Communicated)
- 10 J C Cassatt, A W Johnson, L M Smith and R G Wilkins *J Am chem Soc* **94** (1972) 8399