Monatshefte für Chemie 131, 857–866 (2000)

Monatshefte für Chemie
Chemical Monthly

Kinetic Studies on the Complexation of Chromium(III) with some Amino Acids in Aqueous Acidic Medium

Nabila M. Guindy*, **Zeinab M. Abou-Gamra,** and **Michel F. Abdel-Messih**

Department of Chemistry, Faculty of Science, Ain-Shams University, Abbassia, Cairo, Egypt

Summary. The kinetics of the formation of the 1:3 complex of chromium(III) with *L*-glutamic acid and *DL*-lysine were studied spectrophotometrically at $\lambda_{max} = 550$ and 550 nm. The reaction was found to be first order in both reactants. Increasing the hydrogen ion concentration from 3.2×10^{-5} to 1.0×10^{-3} mol · dm^{-3} retarded the reaction rate which is of the form $k_{obs} = a + b[H^+]^{-1}$. Values of 28.8 and 63.6 kJ · mol^{-1} were obtained for the energy of activation and -184 and -116 J · K^{-1} · mol^{-1} for the entropy of activation for *L*-glutamic acid and *DL*-lysine. The logarithms of the formation constants of the two complexes were found to be 5.9 and 5.1.

Keywords. Kinetics; Complexation; Cr(III); Amino acids.

Introduction

Complexation of Cr(III) with amimo acids is of biological importance. Cr(III) complexes occuring in brewer's yeast and other food called glucose tolerance factor are of outstanding biological activity. Efforts to purify this factor have led to the detection of Cr(III) complexes of nicotinic acid, glycine, glutamic acid, and cysteine. Synthetic Cr(III) complexes with these ligands have similar biological activity to those of the purified yeast fraction [1].

The kinetics of the reaction between chromium(III) and glycine, *L*-phenylalanine, serine, valine, α-alanine, aspartic acid, and *DL*-tryptophan has been the subject of previous studies [2–11]. The present investigation is concerned with the kinetics of the complexation of Cr(III) with glutamic acid and lysine since these amino acids are ubiquitous in nature. Moreover, lysine is an essential amino acid to man [12, 13]. The study involves factors affecting the rate of the reaction as well as the measurement of the formation constant of the complexes.

Results and Discussion

The composition and formation constants of the complexes between chromium(III) and the amino acids under investigation were determined using *Hill*'s equation [14]

* Corresponding author

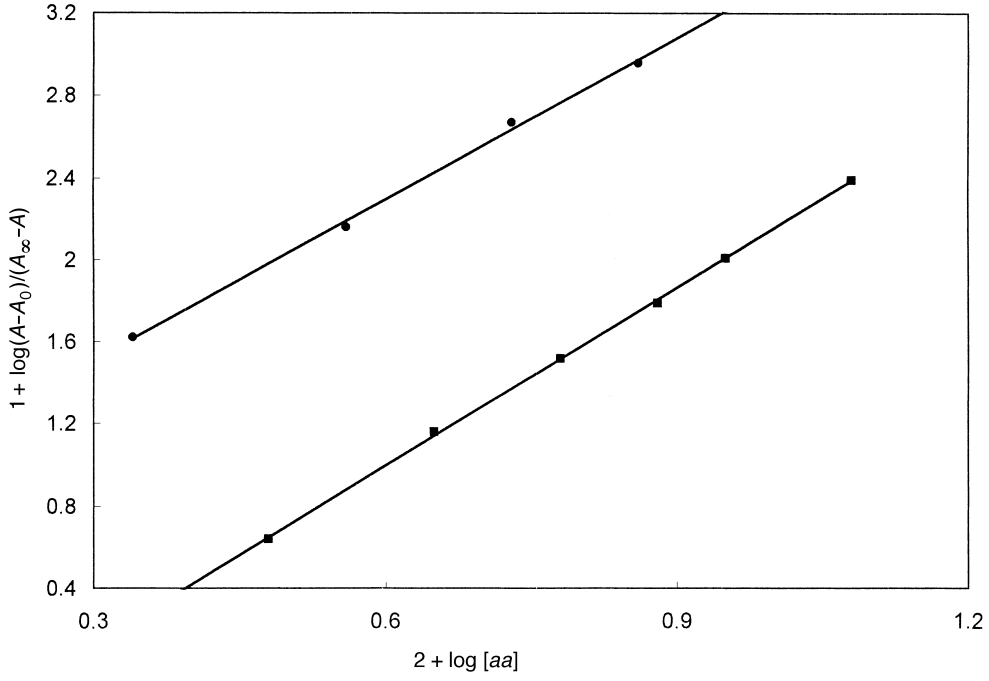

Fig. 1. Plot of $\log(A-A_o)/(A_\infty-A)$ *vs.* $\log[aa]$; $t=30°C$, $[H^+]=7.9\times10^{-5}\,mol\cdot dm^{-3}$ $I=0.2\,mol\cdot dm^{-3}$, $[Cr(III)]=6\times10^{-3}\,mol\cdot dm^{-3}$; ●: *L*-glutamic acid, ■: *DL*-lysine

(Eq. 1) where A is the absorbance reached at the end of the reaction, A_o is the absorbance at zero amino acid concentration, and A_∞ is the equilibrium absorbance for the highest concentration of amino acid used. Plots of $\log(A-A_o)/(A_\infty-A)$ *vs.* $\log[aa]_t$, where $[aa]_t$ is the total amino acid concentration, yield straight lines of slope = 3 (number of amino acid molecules attached to one chromium(III) atom) and an intercept of $\log K = 5.9$ and 5.1 for the complexes with *L*-glutamic acid and *DL*-lysine, respectively (Fig. 1). The kinetic study showed that the reaction is of first order in chromium(III); the observed first-order rate constant, k_{obs}, did not vary appreciably with chromium(III) concentration (Tables 1 and 2).

$$\log(A - A_o)/(A_\infty - A) = \log K + n\log[aa]_t \qquad (1)$$

The effect of variation of the amino acid concentration on the reaction rate is also given in Tables 1 and 2. A plot of $\log k_{obs}$ *vs.* $\log[aa]$ (Fig. 2) is linear with a slope of unity, indicating that the reaction is also of first order in amino acid.

Variation of the ionic strength of the reaction medium in the range from 0.2 to $0.4\,mol\cdot dm^{-3}$ (adjusted by potassium chloride) had an insignificant effect on the reaction rate (Tables 1 and 2). KCl was used since the chloride ion is already present (see experimental part) and, according to the spectrochemical series, water replaces chloride ions.

The effect of proton concentration on the rate of the reaction was studied in the range from 3.2×10^{-5} to $1.0\times10^{-3}\,mol\cdot dm^{-3}$ for both *L*-glutamic acid and *DL*-lysine at various temperatures (Table 3). The results obtained show that the

Table 1. Observed first order rate constant for the reaction of Cr(III) and *L*-glutamic acid at 42°C

$[Cr(III)] \times 10^3$ / mol · dm^{-3}	$[Glu] \times 10^2$ / mol · dm^{-3}	$[H^+] \times 10^5$ / mol · dm^{-3}	I / mol · dm^{-3}	$k_{obs} \times 10^4$ / s^{-1}
4.5	9.6	3.16	0.2	6.033
6.0				6.167
8.0				6.283
10.0				6.667
6.0	6.0	7.94	0.2	4.417
	7.2			5.667
	8.4			6.500
	9.6			7.730
6.0	6.0	3.16	0.2	5.900
	7.2			6.933
	8.4			8.150
	9.6			9.367
6.0	9.6	3.16	0.25	9.167
			0.30	9.000
			0.35	9.183
			0.40	9.267

Table 2. Observed first order rate constant for the reaction of (CrIII) and *DL*-lysine at 42°C

$[Cr(III)] \times 10^3$ / mol · dm^{-3}	$[Lys] \times 10^2$ / mol · dm^{-3}	$[H^+] \times 10^5$ / mol · dm^{-3}	I / mol · dm^{-3}	$k_{obs} \times 10^5$ / s^{-1}
6.0	15.00	7.90	0.2	24.80
9.0				24.00
6.0	7.50	7.90	0.2	8.77
	11.25			15.80
	22.25			27.00
	30.00			37.30
6.0	7.50	12.58	0.2	5.55
	11.25			9.99
	22.25			17.10
	30.00			23.60
6.0	15.00	7.90	0.20	25.00
			0.25	26.00
			0.30	26.80
			0.35	27.50

reaction is accelerated by lowering the proton concentration, and a plot of the observed first order rate constant *vs*. the inverse of the proton concentration yielded a straight line (Fig. 3) obeying Eq. (2) where a and b are the acid-independent and acid-dependent rate constants. The increase of the reaction rate by decreasing the proton concentration can be explained by assuming that hexaaquo and

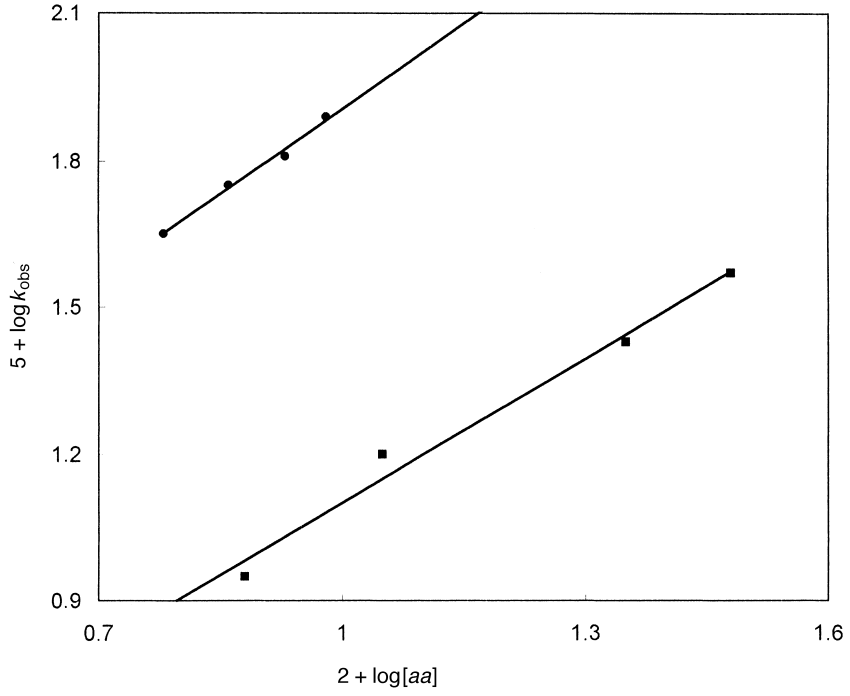

Fig. 2. Variation of $\log k_{obs}$ with $\log[aa]$ at $t = 42°C$; $[Cr(III)] = 6 \times 10^{-3}\,mol \cdot dm^{-3}$ $[H^+] = 7.9 \times 10^{-5}$ $I = 0.2\,mol \cdot dm^{-3}$; ●: *L*-glutamic acid, ■: *DL*-lysine

pentaaquohydroxo chromium(III) species are involved in the reaction mechanism according to Eq. (3).

$$k_{obs} = a + b/[H^+] \tag{2}$$

$$[Cr(H_2O)_6]^{3+} \overset{K_h}{\rightleftharpoons} [Cr(H_2O)_5OH]^{2+} + H^+ \tag{3}$$

The latter species is more reactive than the former due to the presence of OH^- which causes an increase of water labilities due to its π-bonding ability [2, 7–9, 14–23]. The mechanism suggested also involves the interaction of these two species and the predominant form of the amino acid, H*A* (zwitter ion present by 87–99.5% in the range of *pH* studied since $pK_a \cong 2.1$) according to the *Eigen-Tamm* process [24].

$$[Cr(H_2O)_6]^{3+} + HA \overset{K_1}{\rightleftharpoons} IP1 \tag{4}$$

$$[Cr(H_2O)_5](OH)]^{2+} + HA \overset{K_2}{\rightleftharpoons} IP2 \tag{5}$$

$$IP1 \xrightarrow{k_1} [Cr(H_2O)_5(HA)]^{3+} + H_2O \tag{6}$$

$$IP2 \xrightarrow{k_2} [Cr(H_2O)_4(OH)(HA)]^{2+} + H_2O \tag{7}$$

$$[Cr(H_2O)_5(HA)]^{3+} + HA \xrightarrow{fast} product + nH_2O \tag{8}$$

$$[Cr(H_2O)_4(OH)(HA)]^{2+} + HA \xrightarrow{fast} product + nH_2O \tag{9}$$

Table 3. Kinetic data for the interaction of Cr(III) with *L*-glutamic acid and *DL*-lysine at various temperatures and proton concentrations; $[Cr(III)] = 6 \times 10^{-3}\,mol \cdot dm^{-3}$ $I = 0.2\,mol \cdot dm^{-3}$, $[Glu] = 9.6 \times 10^{-2}\,mol \cdot dm^{-3}$, $[Lys] = 15 \times 10^{-2}\,mol \cdot dm^{-3}$

$\frac{t}{^\circ C}$	$\frac{[H^+] \times 10^5}{mol \cdot dm^{-3}}$	$\frac{k_{obs}(Glu) \times 10^4}{s^{-1}}$	$\frac{k_{obs}(Lys) \times 10^5}{s^{-1}}$
30	100.00	0.38	
	31.60	1.08	
	12.59	2.92	
	7.94	4.52	
	5.01	7.68	
	3.16	11.28	
35	100.00	–	0.86
	31.60	–	2.45
	12.59	4.08	5.17
	7.94	6.07	8.17
	5.01	9.65	12.83
	3.16	14.62	15.10
40	12.59	4.42	8.83
	7.94	7.18	13.67
	5.01	10.70	21.50
	3.16	16.82	–
42	12.59		9.83
	7.94		15.51
	5.01		26.28
45	12.59	5.83	12.37
	7.94	8.60	19.83
	5.01	14.07	30.33
	3.16	22.48	–

IP1 and IP2 are the hexaaquo and pentaaquohydroxo ion-pair complexes of Cr(III) and the amino acids. The rate of exchange of the first water molecule in the inner coordination sphere of the metal center is slow and therefore the rate determining step (Eqs. (6) and (7), [2, 6–8, 11, 15–20]). As soon as one molecule of the amino acid enters into the inner coordination sphere and $[Cr(H_2O)_5HA]^{+3}$ and $[Cr(H_2O)_4(OH)(HA)]^{+2}$ are formed (Eqs. (6) and (7)), the electron density on Cr(III) is increased owing to the inductive effect. As a result, the remaining water ligands are labilized very easily.

From the suggested mechanism k_{obs} was found to be

$$k_{obs} = \frac{(k_1 \cdot K_1 + k_2 \cdot K_2 \cdot K_h \cdot [H^+]^{-1}) \cdot [HA]}{(1 + K_h \cdot [H^+]^{-1}) + (K_1 + K_2 \cdot K_h \cdot [H^+]^{-1}) \cdot [HA]} \tag{10}$$

The inverse of Eq. (10) gives Eq. (11).

$$\frac{1}{k_{obs}} = \frac{K_1 + K_2 \cdot K_h \cdot [H^+]^{-1}}{k_1 \cdot K_1 + k_2 \cdot K_2 \cdot K_h [H^+]^{-1}} + \frac{(1 + K_h \cdot [H^+]^{-1})[HA]^{-1}}{k_1 \cdot K_1 + k_2 \cdot K_2 \cdot K_h \cdot [H^+]^{-1}} \tag{11}$$

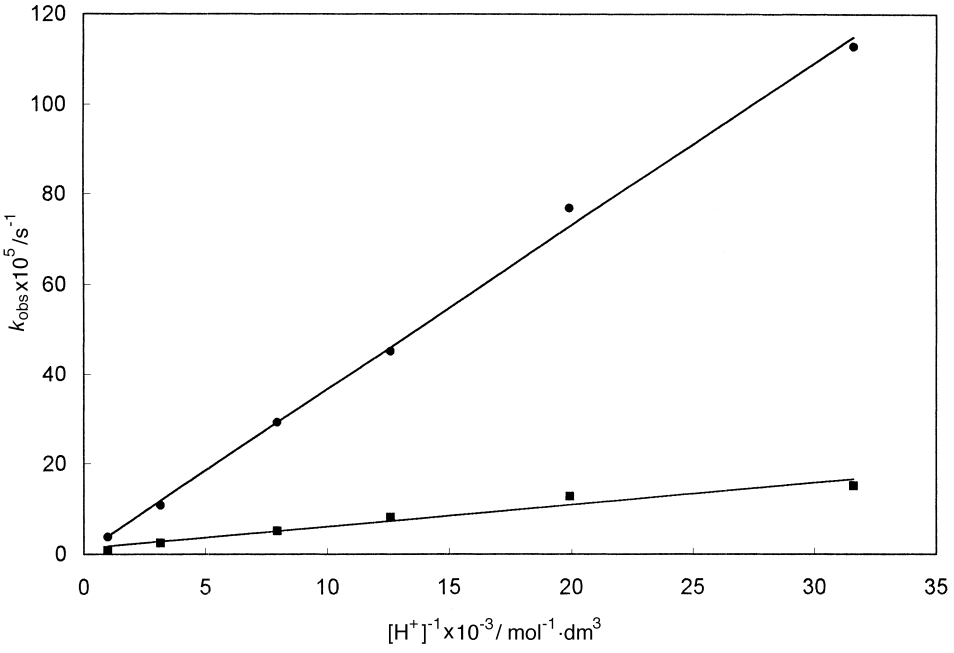

Fig. 3. Variation of k_{obs} with $1/[H^+]$ at $[Cr(III)] = 6 \times 10^{-3}\,mol \cdot dm^{-3}$ and $I = 0.2\,mol \cdot dm^{-3}$; ●: *L*-glutamic acid, $t = 30°C$, $[Glu] = 9.6 \times 10^{-2}\,mol \cdot dm^{-3}$; ■: *DL*-lysine, $t = 35°C$, $[Lys] = 15 \times 10^{-2}\,mol \cdot dm^{-3}$

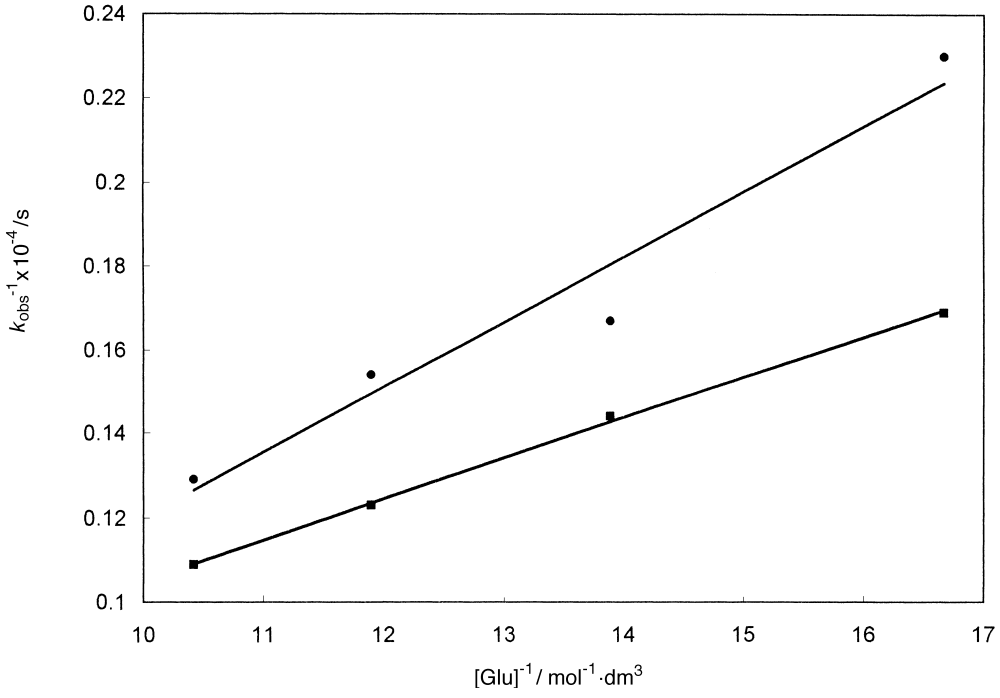

Fig. 4. Variation of $1/k_{obs}$ with 1/[Glu] at different proton concentrations; $t = 42°C$, $[Cr(III)] = 6 \times 10^{-3}\,mol \cdot dm^{-3}$, $I = 0.2\,mol \cdot dm^{-3}$ ●: $[H^+] = 7.9 \times 10^{-5}\,mol \cdot dm^{-3}$, ■ $[H^+] = 3.16 \times 10^{-5}\,mol \cdot dm^{-3}$

By plotting $1/k_{obs}$ *vs.* $1/[aa]$, straight lines were obtained for different proton concentrations; slope, intercept, and intercept-to-slope ratio are given below (Eqs. (12)–(14), Fig. 4).

$$\frac{1 + K_h \cdot [H^+]^{-1}}{k_1 \cdot K_1 + k_2 \cdot K_2 \cdot K_h[H^+]^{-1}} \tag{12}$$

$$\frac{K_1 + K_2 \cdot K_h[H^+]^{-1}}{k_1 \cdot K_1 + k_2 \cdot K_2 \cdot K_h[H^+]^{-1}} \tag{13}$$

$$\frac{K_1 + K_2 \cdot K_h \cdot [H^+]^{-1}}{1 + K_h \cdot [H^+]^{-1}} \tag{14}$$

Applying Eq. (14) at two different proton concentrations and using $K_h = 7.94 \times 10^{-5}$ [25], values of 0.59 and $0.37\,mol^{-1} \cdot dm^3$ were obtained for K_1 for *L*-glutamic acid and *DL*-lysine, respectively, and 1.21 and $1.41\,mol^{-1} \cdot dm^3$ for K_2.

Using values of 7.94×10^{-5} and $7.9 \times 10^{-5}\,mol \cdot dm^{-3}$ for K_h and $[H^+]$, Eq. (10) reduces to Eq. (15).

$$k_{obs} = (k_1 \cdot K_1 + k_2 \cdot K_2 \cdot K_h[H^+]^{-1}) \cdot [HA]/2 \tag{15}$$

Comparing Eq. (2) with Eq. (15) we get

$$a = k_1 \cdot K_1 \cdot [HA]/2, \quad b = k_2 \cdot K_2 \cdot K_h[HA]/2 \tag{16}$$

From Eq. (16), values of k_1 and k_2 were calculated and found to be 1.3×10^{-3} and $8.6 \times 10^{-3}\,s^{-1}$ for *L*-glutamic acid and 4.6×10^{-3} and $7.8 \times 10^{-3}\,s^{-1}$ for *DL*-lysine.

The effect of the dielectric constant on the rate of reaction was studied at different concentrations of ethanol-water mixtures. An increase in k_{obs} was obtained with decreasing dielectric constant of the reaction medium; similar results were obtained for 1,4-dioxane-water mixtures. Applying *Bjerrum*'s equation [26], a plot of $\log k_{obs}$ *vs.* $1/\varepsilon$ turned out to be linear with a positive slope, indicating that the reaction is of an ion-pair type [11] (Fig. 5). The effect of temperature on the rate of reaction was studied at 30, 35, 40, and 45°C at different proton concentrations (Table 3). The activation parameters were calculated using *Arrhenius* plots and the *Eyring* equation and were found to be 28.8 and $63.6\,kJ \cdot mol^{-1}$ for the energy of activation of *L*-glutamic acid and *DL*-lysine, respectively, whereas values of -184 and $-116\,J \cdot K^{-1} \cdot mol^{-1}$ were obtained for the entropy of activation.

It is well known that the substitution reactions of hexaaquachromium(III) with a variety of ligands (organic and inorganic) proceed by associative [2–11, 27–30] and dissociative [31–33] mechanisms. *Swaddle* [34] and *Lincoln* [35] have reviewed the activation parameters and mechanism of octahedral substitution and have concluded that an associative mechanism is operative for octahedral cationic complexes of all trivalent metal ions except for Co(III) with ionic radii greater than 60 pm. The field-free ionic radius of Cr(III) is 68–69 pm [36], which demands an associative character for the substitution reaction of $Cr(H_2O)^{+3}$.

The values of the unimolecular rate constants for the reaction of hexaaquachromium(III) amino acids are given in Table 4 together with those of some analogous systems. The results show a significant dependence of the rate constants on the nature of the incoming ligand which also supports an associative mechanism [10].

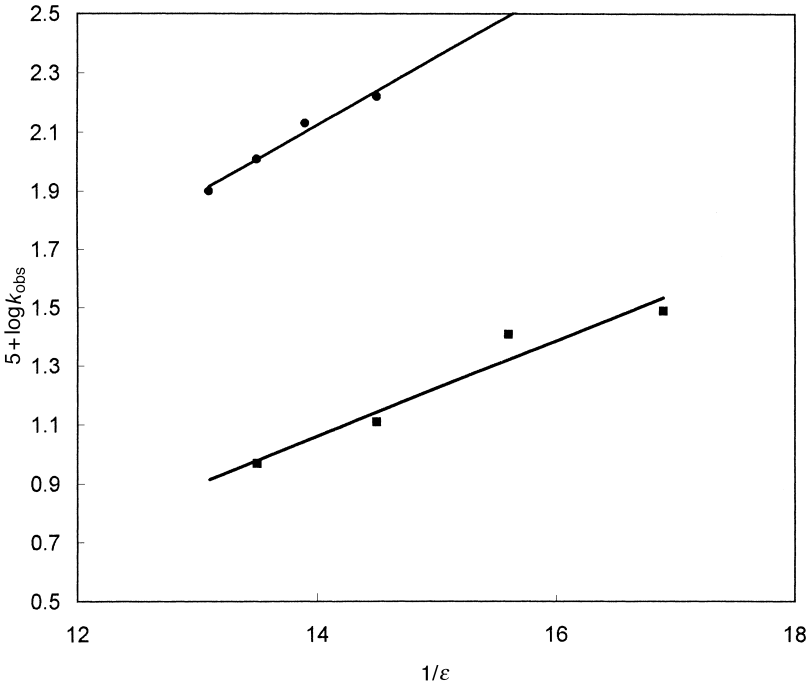

Fig. 5. Variation of $\log k_{obs}$ with $1/\varepsilon$ in an ethanol-water mixture at $t = 30°C$ and $I = 0.2\,mol \cdot dm^{-3}$; $[Cr(III)] = 6 \times 10^{-3}\,mol \cdot dm^{-3}$, $[H^+] = 7.9 \times 10^{-5}\,mol \cdot dm^{-3}$ ●: *L*-glutamic acid, $[Glu] = 9.6 \times 10^{-2}\,mol \cdot dm^{-3}$; ■: *DL*-lysine, $[Lys] = 12 \times 10^{-2}\,mol \cdot dm^{-3}$

Table 4. Comparison of rate contant and activation parameters of analogous systems

System	k / s^{-1} (35°C)	$\Delta H^{\#}$ / $kJ \cdot mol^{-1}$	$\Delta S^{\#}$ / $J \cdot K^{-1} \cdot mol^{-1}$	Ref.
$[Cr(H_2O)_6]^{+3}$-$^{18}OH_2$	4.17×10^{-6}	109.6	+12.0	[37]
$[Cr(H_2O)_6]^{+3}$-glycine	3.34×10^{-4}	58.0	−129.2	[2]
$[Cr(H_2O)_6]^{+3}$-serine	0.62×10^{-4}	78.0	−72.5	[6]
$[Cr(H_2O)_6]^{+3}$-valine	2.35×10^{-4}	90.4	−21.0	[7]
$[Cr(H_2O)_6]^{+3}$-alanine	0.58×10^{-4}	64.9	−113.6	[8]
$[Cr(H_2O)_6]^{+3}$-anthranilic acid	4.66×10^{-4}	86.4	−36.6	[38]
$[Cr(H_2O)_6]^{+3}$-salicylic acid	17.82×10^{-4}	74.5	−60.5	[39]
$[Cr(H_2O)_6]^{+3}$-tryptophan	1.17×10^{-4}	65.6	−112.4	[11]
$[Cr(H_2O)_6]^{+3}$-leucine	4.80×10^{-4}	38.0	−159.0	[40]
$[Cr(H_2O)_6]^{+3}$-*L*-glutamic acid	14.62×10^{-4}	28.8	−184.0	this work
$[Cr(H_2O)_6]^{+3}$-*DL*-lysine	1.51×10^{-4}	63.6	−116.0	this work

The associative mechanism is further supported by (*i*) the lowering of enthalpy and the large negative entropy of activation for substitution of water by amino acids compared to water exchange (Table 4) and (*ii*) the same isokinetic temperature as obtained from the isokinetic plot for the hexaaquachromium(III) ion with various ligands (Fig. 6).

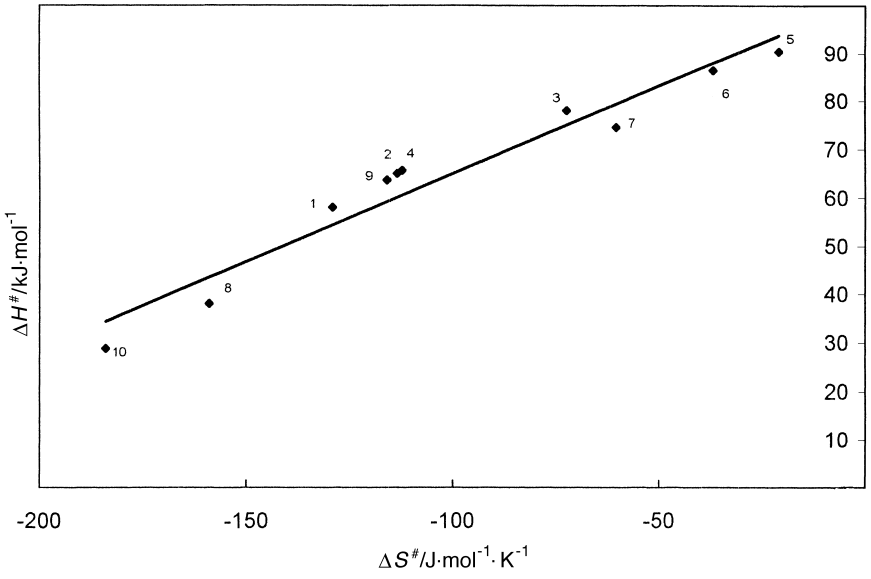

Fig. 6. Isokinetic plot for the substitution of water in $[Cr(H_2O)_6]^{+3}$ by glycine (1), alanine (2), serine (3), tryptophan (4), valine (5), anthranilic acid (6), salicy acid (7), leucine (8), *DL*-lysine (9), and *L*-glutamic acid (10)

Experimental

All chemicals were of pure grade and were used without further purification. All solutions were prepared using bidistilled water. The absorbance measurements were performed using a thermostatted 292 Cecil spectrophotometer, *pH* measurements were conducted with a Griffin *pH* meter fitted with a glass-calomel electrode standardized by potassium hydrogen phthalate.

Kinetic experiments were conducted by mixing thermostatted solutions of *L*-glutamic acid and *DL*-lysine with aquachromium(III) and adjusting $[H^+]$ to the required value with KOH. Aquachromium(III) was obtained by dissolving $CrCl_3$ in H_2O and leaving the solution for 24 h at 40°C, whereupon the green colour of $CrCl_3$ changed to the blue colour of aqua-Cr(III) [25]. The solution was then introduced into the reaction vessel, which was previously thermostatted at the desired temperature. The progress of the reaction was monitered at 550 and 560 nm for *L*-glutamic acid and *DL*-lysine. *Pseudo*-first-order conditions were always maintained using at least a ten fold excess of the ligand to (Cr(III). Values of the observed rate constants were obtained from the slope of the first-order plots of $\log(A_\infty - A_t)$ *vs.* time, where A denotes the measured absorbance and subscripts refer to the time of the reaction. A_∞ was obtained directly after ensuring completion of the reaction. First-order plots were linear for more than three half lives.

The composition of the complexes formed in solution during the course of the reaction was studied by mixing different concentration ratios of Cr(III) and the amino acid in the range from 1:4 to 1:12 and from 1:5 to 1:20 for *L*-glutamic acid and *DL*-lysine, respectively, at 30°C ($[H^+] = 7.9 \times 10^{-5}$ mol · dm^{-3}, $[Cr(III)] = 6 \times 10^{-3}$ mol · dm^{-3})

References

[1] Toefler EW, Mertz W, Polansky MM, Wolf WR (1977) J Agric Food Chem **25**: 162
[2] Khan IA, Kabir-ud-Din (1981) J Inorg Nucl Chem **43**: 1082
[3] Ramasami T, Taylor RS, Sykes AG (1976) Inorg Chem **15**: 1318

[4] Banergjea D, Duttachaudhuri S (1968) J Inorg Nucl Chem **30**: 871
[5] Niogy BK, De GS (1984) J Indian Chem Soc **61**: 389
[6] Khan IA, Shahid M, Kabir-ud-Din (1983) Indian J Chem **22A**: 382
[7] Khan IA, Kabir-ud-Din (1984) Indian J Chem **23A**: 98
[8] Khan IA, Kabir-ud-Din (1985) Int J Kin **17**: 1263
[9] Niogy BK, De GS (1983) Proc Indian Acad Sci Chem Sci **92A**: 153
[10] Khan IA, Kabir-ud-Din (1986) Transition Met Chem **11**: 391
[11] Shahid M, Khan IA, Kabir-ud-Din (1990) J Chem Soc Dalton Trans 3007
[12] Fox SW, Foster JF (1957) Introduction to Protein Chemistry, chap 2. Wiley, New York
[13] Finar IL (1982) Organic Chemistry, vol 2, chap 13. Toppan, Longman, UK
[14] Abdulah MA, Barrett J, Obrien P (1984) J Chem Soc Dalton Trans 1647
[15] Secco F, Venturini M (1975) Inorg Chem **14**: 1978
[16] Perlmutter-Hayman B, Secco F, Tapuhi E, Venturini M (1980) J Chem Soc Dalton Trans 1124
[17] Campisi A, Tregloan PA (1985) Inorg Chim Acta **100**: 251
[18] Pelizzett E, Mentasti E, Giraudi G (1975) Inorg Chim Acta **15**: L1
[19] Mentasti E, Secco F, Venturini M (1982) Inorg Chem **21**: 602
[20] Funahashi S, Ishihara K, Tanaka M (1983) Inorg Chem **22**: 2072
[21] Kimura M, Shirai J (1978) J Inorg Nucl Chem **40**: 1085
[22] Krishnamoorthy CR, Harris GM (1980) J Coord Chem **10**: 55
[23] Kabir-ud-Din, Shahid M, Khan IA (1990) Z Phys Chem (4.c. Leipzig) **271**: 101
[24] Eigen M, Tamm K (1962) Z Electochem **66**: 93
[25] Emorson K Graven WM (1959) J Inorg Nucl Chem **11**: 309
[26] Basolo F, Pearson RG (1958) Mechanism of Inorganic Reaction, 2nd edn. Wiley, New York, chap 6
[27] Hamm RE, Davis RE (1953) J Am Chem Soc **75**: 3085
[28] Hamm RE, Perkins RH (1955) J Am Chem Soc **77**: 2083
[29] Hamm RE, Johnson RL, Perkins RH, Davis RE (1958) J Am Chem Soc **80**: 4469
[30] Banerjea D, Dutta Chaudhuri S (1970) J Inorg Nucl Chem **32**: 1617
[31] Espenson JH (1969) Inorg Chem **8**: 1554
[32] Thusius D (1971) Inorg Chem **10**: 1106
[33] Tyagi SC, Khan AA (1978) J Inorg Nucl Chem **40**: 1899
[34] Swaddle TW (1974) Coord Chem Rev **14**: 217; Swaddle TW, Xu FC, Krouse HR (1985) Inorg Chem **24**: 267
[35] Lincoln SF, Merbach AE (1995) Adv Inorg Chem **42**: 1
[36] Shannon RE, Prewit CR (1969) Acta Crystallogr Sec B: 1925
[37] Plane RA, Taube H (1952) J Phys Chem **56**: 33
[38] Tyagi SC, Khan AA (1978) Indian J Chem **19A**: 657
[39] Tyagi SC, Khan AA (1978) J Inorg Nucl Chem **40**: 1899
[40] Guindy NM, Abou-Gamra ZM, Abdel Messih MF (1999) J Chim Phys **96**: 851

Received January 7, 2000. Accepted (revised) March 8, 2000