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Oxidation of amino acid by hexacyanoferrate(III) using chloro complex of ruthenium(III) as homogeneous catalyst

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ABSTRACT

The kinetics of ruthenium(III) catalysed oxidation of L-lysine by hexacyanoferrate(III) in aqueous alkaline medium was studied spectrophotometrically at constant ionic strength of the medium. The reaction shows first order dependence on oxidant, substrate and the catalyst. Initial addition of reaction products did not affect the rate significantly. The active species of catalyst and oxidant have been identified. The oxidation reaction in alkaline medium has been shown to proceed via a Ru(III) – L-lysine complex, which further reacts with one molecule of hexacyanoferrate(III) in a rate determining step followed by other fast steps to give the products. The main products were identified. The activation parameters with respect to the slow step of the mechanism are computed and discussed and thermodynamic quantities are also determined. A mechanism involving the formation of a complex between active species of catalyst and lysine has been proposed.

Key words: Oxidation, kinetics, amino acid, ruthenium(III), hexacyanoferrate(III).

INTRODUCTION

Biologically significant amino acids are the building blocks in protein synthesis and its oxidation makes a significant contribution to the generation of metabolic energy. L-lysine is one of the essential amino acid and is important to life, especially in cold sores, herpes treatment and finds its applications in pharmaceuticals.

Transition metals are involved to catalyse many redox reaction as they show multiple oxidation states. A considerable number of publication is known to devote to osmium (VIII)[1] as an oxidant [2,3] and a catalyst[4] in the oxidation of organic compounds. The injurious nature of osmium as the formation of toxic 'osmates' in acidic medium[5] restricted its use in alkaline medium. Ruthenium (III)[6,7] and iridium(III)[8,9] have been used as homogeneous catalyst in acidic as well as in alkaline medium. Osmium and ruthenium both belong to the same group but their compounds are stable in their different oxidation states. The redox potentials of Ru(IV)/Ru(III) is +1.3 V and that of Os(VIII)/ Os(VI) is +0.85 V, which is very low as compared to Ru(IV)/Ru(III). This shows that ruthenium is an efficient catalyst[10,11] in +3 state. Ruthenium(III) acts as an efficient catalyst[12] in many redox reactions involving several complexes and different oxidation states of ruthenium.

Several transition metal ions in their complex form act as good oxidants in neutral, acidic or basic medium depending upon their redox potential. It is reported that the redox potential of $[Fe(CN)_6]^{3-}/[Fe(CN)_6]^{4-}$ in alkaline medium is +0.40V and in acidic medium is +0.36 V indicating that hexacyanoferrate (III) is a good oxidizing agent in alkaline medium[13]. It is a single equivalent and stable oxidant. Hence to explore the reaction path of lysine, a single equivalent oxidant, hexacyanoferrate(III) is used as an oxidant and Ru(III) chloride as a catalyst.

EXPERIMENTAL SECTION

All chemicals used were of AR grade. Double distilled water was used to prepare all the solutions for kinetic experiments. A solution of lysine was prepared by dissolving an appropriate amount of recrystallised sample in double distilled water. A stock solution of ruthenium trichloride was prepared by dissolving $RuCl_3$ (Johnson-Matthay Chemical Ltd.) in minimum amount of hydrochloric acid. The concentration was determined by EDTA titration [14]. Mercury was added to ruthenium(III) solution to reduce any ruthenium (IV) formed during the preparation of ruthenium (III). This stock solution was kept overnight. The solutions of sodium hydroxide and potassium chloride, of AR (BDH) grade were used to maintain the alkalinity and ionic strength of the reaction solution respectively. Aqueous solution of $AgNO_3$ was used to study the product effect, Ag(I). The pH of the medium in the solution was measured using pH meter. The dissolved oxygen in distilled water was removed by passing purified nitrogen gas to check the effect of dissolved oxygen on the rate of reaction. It was observed that there is no significant difference between the result obtained under nitrogen atmosphere and in the presence of air.

KINETIC STUDIES

The kinetic measurements were performed on a systronics 2203 double beam UV-Vis spectrophotometer. The kinetics was followed under pseudo first order conditions where the concentration of substrate was kept higher than the concentration of the oxidant. The reaction was initiated by mixing substrate solution maintained at a constant temperature to solution of potassium ferricyanide which also contained required amount of ruthenium (III) chloride, NaOH and KCl. The temperature of the reaction mixture was kept constant at $35 \pm 1\ ^0$ c with an electrically operated thermostat. The progress of the reaction was followed spectrophotometrically at 420 nm to hexacyanoferrate (III). It was clear that there is negligible interference from other species present in the reaction mixture at this wavelength. The –dc/dt values were determined from the absorbance versus time plots. The orders for various reactants were determined from the slopes of plots of –dc/dt versus respective concentration of that reactant except oxidant.

RESULTS AND DISCUSSION

Different sets of reaction mixtures containing an excess of hexacyanoferrate(III) over lysine and constant concentrations of Ru(III), NaOH and ionic strength of the medium was allowed to react for four hours in an inert atmosphere at $35 \pm 0.1\ ^0$C. After completion of the reaction, the remaining concentration of ferricynide was estimated spectrophotometrically at 420nm. The results indicated that two moles of hexacyanoferrate(III) reacted with one mole of L-lysine. The stoichiometry is [L-lysine] : [HCF] = 1 : 2 as given by equation(1),

$$RCHNH_2COO^- + 2Fe(CN)_6^{3-} + OH^- \xrightleftharpoons{Ru(III)} RCHO + 2Fe(CN)_6^{4-} + NH_3 + CO_2 \quad ....(1)$$

R= $-CH_2CH_2CH_2CH_2NH_2$

After completion of the reaction, the reaction mixture was basified, concentrated and extracted with ether. The oxidation products were isolated using TLC separation techniques and characterized by physicochemical spectral studies. The reaction products were identified as hexacyanoferrate(II), 5-aminopental and ammonia. The reaction orders were determined for the oxidation of lysine by hexacyanoferrate(III) catalysed by ruthenium (III) chloride in alkaline medium. Hexacyanoferrate(III) concentration was varied for its manifold variation at constant concentration of lysine, NaOH, Ru(III) chloride and ionic strength of the medium. The rate of the reaction values (-dc/dt) were calculated from the initial slopes of individual graphs between absorbance versus time. The rate constant values obtained by the variation of hexacyanoferrate (III), which did not result any change in pseudo first order rate constant and the linearity of plot of –dc/dt versus time indicate a reaction order of unity (Table 1).The linear behaviour of plot of log –dc/dt versus log[HCF] indicated a reaction order of unity. (r= 1.15)

The lysine concentration was varied keeping the other reactant concentrations and condition constants. The –dc/dt values increased with the increase in concentration of lysine indicating first order kinetics with respect to lysine. (Table1). The effect of alkali on the reaction rate has been studied for the manifold variation of alkali at constant concentration of lysine, hexacyanoferrate (III), catalyst and a constant ionic strength of the medium. The –dc/dt values obtained were found to increase with increase in [OH-] (Table 1). Further, the plots of $1 / k^{\prime}$ versus 1 / [OH-] were shown straight lines with positive intercepts on Y-axis (Fig. 1). It was observed that the alkali shows positive effect on the rate of reaction. The ruthenium(III) chloride concentrations was varied at constant concentration of other reactants. Increase in –dc/dt values with increasing concentrations of the catalyst and fair constancy in the rate values obtained for molar concentration of the catalyst indicate that the reaction follows first order kinetics with respect to ruthenium(III) chloride for its manifold variation in concentration. Initially added products, hexacyanoferrate(II) and 5- aminopentanal did not affect the reaction rate. It was also found that dielectric constant of the medium had no significant effect on the rate of reaction.

In order to test for the intervention of free radicals, the reaction mixture was mixed with acrylonitrile monomer and kept for 24 hours in an inert atmosphere. On dilution with methanol, no precipitate was formed indicating no intervention of free radicals.

The rate of the reaction was measured at four different temperatures i.e. 30^0C, 35^0C, 40^0C, 45^0C keeping other conditions constant. The rate was found to increase with increase in temperature. The energy of activation corresponding to these constants were evaluated from the Arrhenius plot of log k versus 1/T. [15,16]. The value of energy of activation has been calculated from the slope of the Arrhenius plot i.e. Ea= 11.440 Kcal/ mol. The values of entropy of activation and free energy of activation has also been calculated with respect to slow step. The entropy of activation, $\Delta S^{\#}$ = -54.1331 Kcal/ mol and free energy of activation, ΔF = 16.68 Kcal/ mol were obtained by Eyring equation [15, 16].

$$K = \frac{k_B.T}{h} e^{-(\Delta G^{\#}/RT)} = \frac{k_B.T}{h} e^{-(\Delta H^{\#} + T\Delta S^{\#})/RT}$$

k_B is the Boltzmann's constant, R is the gas constant, T is the absolute temperature and $\Delta G\neq$ is the free energy of activation.

It is known that lysine exists in the form of zwitter ion [17] in aqueous medium. In acidic medium, it exists in the protonated form, whereas in basic medium, it is in the deprotonated form according to the following equilibria.

$$RCH_2(NH_2)CH_2COOH \xrightleftharpoons{\text{aqueous}} RCH_2(^+NH_3)CH_2COO^-$$
$$RCH_2(NH_2)CH_2COOH + H^+ \rightleftharpoons RCH_2(^+NH_3)CH_2COOH$$
$$RCH_2(NH_2)CH_2COOH + OH^- \rightleftharpoons RCH_2(NH_2)CH_2COO^- + H_2O$$

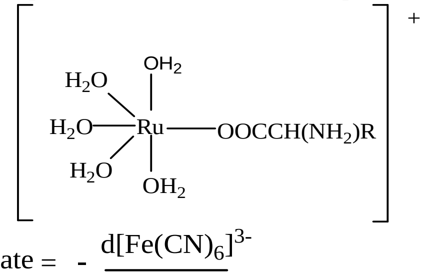
where R= C_6H_{10}

Electronic spectral studies [18,19] have confirmed that ruthenium(III) chloride exist in the hydrated form as $[Ru(H_2O)_6]^{3+}$. In the present study it is quite probable that the species $[Ru(H_2O)_5OH]^{2+}$ might assume the general form $[Ru^{III}(OH)_X]^{3-X}$. The value of x would always be less than six because there are no definite reports of any hexahydroxy ruthenium species. The remainder of the coordination sphere will be filled by water molecules. Hence under the experimental conditions $[OH^-] >> [Ru(III)]$, ruthenium (III) is mostly present [20,21] as the hydrated species, $[Ru(H_2O)_5OH]^{2+}$. The mechanism involves the formation of the active species, $[Ru(H_2O)_5OH]^{2+}$, in a equilibrium step, which reacts with a zwitter ionic form of lysine to give a complex. The complex then reacts with hexacyanoferrate(III) in a slow ste000p to form the product, hexacyanoferrate(II) and the catalyst is regenerated.

$$[Ru(H_2O)_6]^{3+} + OH^- \xrightleftharpoons{K_1} [Ru(H_2O)_5OH]^{2+} + H_2O \text{ --------------(I)}$$
$$RCH(NH_2)COO^- + [Ru(H_2O)_5OH]^{2+} \xrightleftharpoons{K_2} \text{Complex -----------(II)}$$
$$C + Fe(CN)_6^{3-} \xrightarrow[\text{slow}]{k} RCHO + Fe(CN)_6^{4-} + [Ru(H_2O)_5OH]^{2+} + NH_3 + CO_2 \text{ --(III)}$$

where R= $-CH_2CH_2CH_2CH_2NH_2$

The probable structure of the complex is



$$\text{Rate} = -\frac{d[Fe(CN)_6]^{3-}}{dt}$$

$$= \frac{kK_1K_2[S]\,[Fe(CN)_6]^{3-}\,[Ru(III)]\,[OH^-]}{(1+K_1[OH^-])\,(1+K_2[S])\,(1 + K_1[Fe(CN)_6]^{3-})\,(1+K_2[Ru(III)]} \qquad \text{———}(2)$$

At low concentrations of oxidant, substrate and catalyst, the term (1+ $K_1[Fe(CN)_6]^{3-}$), (1+ $K_2[Ru(III)]$) and (1+$K_2[S]$) in the denominator of eq. (2) are approximately equal to unity. Thus eq. (2) becomes,

$$\text{Rate} = -\frac{d[Fe(CN)_6]^{3-}}{dt} = \frac{kK_1K_2[S][Fe(CN)_6]^{3-}\,[Ru(III)]\,[OH^-]}{(1 + K_1[OH^-])}$$

$$k_{obs} = \frac{kK_1K_2[S][OH^-][Ru(III)]}{(1 + K_1[OH^-])}$$

Table 1. Effect of variation of [lysine], [HCF(III)] [Ru(III)], [OH$^-$] on the reaction rate at 35^{0}C. ([HCF(III)]= 1.66 X 10^{-3} M; [Lysine]= 1.25 x 10^{-2} M; [OH$^-$]= 1.66 x 10^{-2} M; [RuCl$_3$]=9.52 x 10^{-6} M; μ= 0.5)

[lysine]x 10^5 (mol dm^{-3})	$K_3[Fe(CN)_6]$ x 10^3 M	[OH$^-$] x 10^5 (mol dm^{-3})	[Ru(III)] x 10^6 (mol dm^{-3})	μ M	-dc/dt x10^5 M. min^{-1}
1.0	1.66	1.66	9.52	0.5	5.00
1.2	1.66	1.66	9.52	0.5	7.10
1.25	1.66	1.66	9.52	0.5	7.20
1.6	1.66	1.66	9.52	0.5	10.0
2.0	1.66	1.66	9.52	0.5	14.0
3.3	1.66	1.66	9.52	0.5	20.0
1.25	2.20	1.66	9.52	0.5	4.10
1.25	5.00	1.66	9.52	0.5	5.50
1.25	7.00	1.66	9.52	0.5	9.00
1.25	10.0	1.66	9.52	0.5	26.0
1.25	15.0	1.66	9.52	0.5	42.0
1.25	20.0	1.66	9.52	0.5	38.4
1.25	1.66	1.00	9.52	0.5	3.50
1.25	1.66	1.66	9.52	0.5	4.20
1.25	1.66	1.50	9.52	0.5	3.80
1.25	1.66	2.00	9.52	0.5	4.50
1.25	1.66	3.30	9.52	0.5	5.00
1.25	1.66	4.00	9.52	0.5	5.50
1.25	1.66	1.66	9.52	0.5	4.00
1.25	1.66	1.66	15.23	0.5	7.20
1.25	1.66	1.66	19.04	0.5	8.40
1.25	1.66	1.66	22.80	0.5	8.00
1.25	1.66	1.66	24.70	0.5	10.0
1.25	1.66	1.66	9.52	0.3	16.6
1.25	1.66	1.66	9.52	0.4	12.0
1.25	1.66	1.66	9.52	0.6	12.0
1.25	1.66	1.66	9.52	0.8	8.50
1.25	1.66	1.66	9.52	0.9	6.00

Table 2. Effect of variation of [HCF(II)] on the reaction rate at 35^{0}C. [HCF(III)]= 1.66 X $^{-3}$ M; [Lysine]= 1.25 x 10^{-2} M; [OH$^-$]= 1.66 x 10^{-2} M; [RuCl$_3$]= 9.52 x 10^{-6} M; μ= 0.5M

$[K_4Fe(CN)_6]$ x 10^3 M	-dc/dt x 10^6 M. min^{-1}
0.83	6.1
1.0	7.4
1.25	7.2
5.0	7.1
7.0	6.6

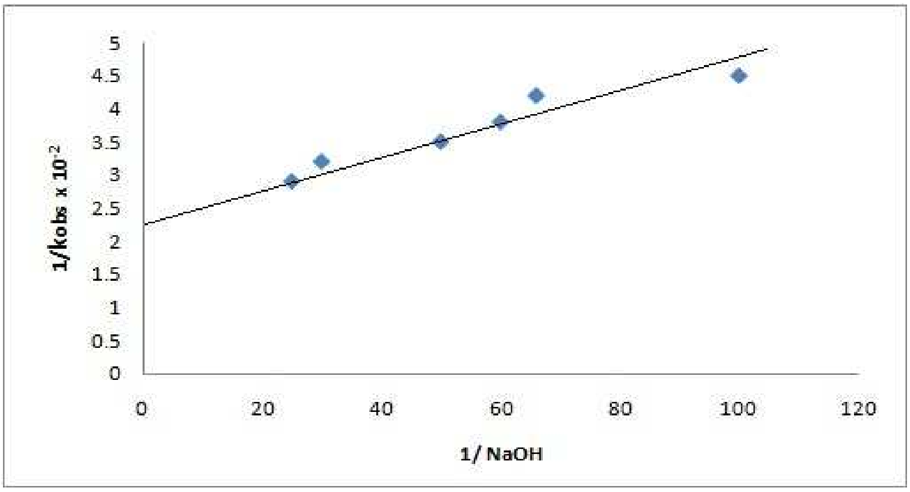


Fig: 1: Plot of 1/ kobs vs 1/NaOH ([HCF(III)]= 1.66 X 10^{-3} M; [Lysine]= 1.25 x 10^{-2} M; [OH^-]= 1.66 x 10^{-2} M; [$RuCl_3$]= 9.52 x 10^{-6} M; μ= 0.5)

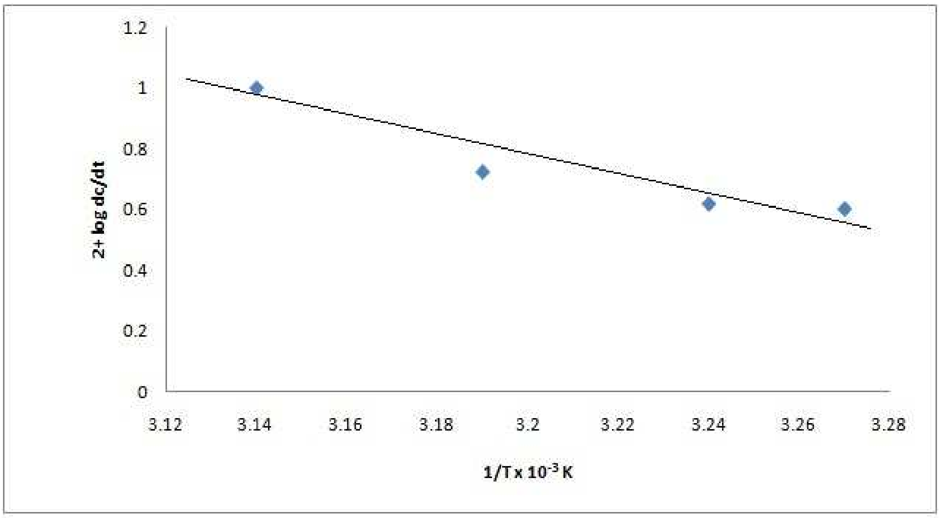


Fig: 2: Effect of temperature on the reaction rate ([HCF(III)]= 1.66 X 10^{-3} M; [Lysine]= 1.25 x 10^{-2} M; [OH]= 1.66 x 10^{-2} M; [$RuCl_3$]= 9.52 x 10^{-6} M; μ= 0.5)

CONCLUSION

The reaction between hexacyanoferrate(III) and lysine catalysed by ruthenium (III) chloride occurs with measurable rate in alkaline media. Ruthenium (III) is known to be an efficient catalyst in alkaline medium which catalyses the reaction at a concentration of 10^{-6} mol dm^{-3}. Among various species of ruthenium(III) in alkaline medium, $[Ru(H_2O)_5OH]^{2+}$ is considered as active species for the reaction. Rate with respect to slow step involved in the mechanism is derived. The mechanism is consistent with all the experimental evidences.

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