Ruthenium (III)-catalyzed oxidative cleavage of thiamine hydrochloride with N-bromosuccinimide in presence of hydrochloric acid medium: A kinetic and mechanistic approach

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ARTICLE INFO

ABSTRACT

The kinetics of ruthenium (III)-catalyzed oxidative cleavage of thiamine hydrochloride (THM, Vitamin B_1) with N-bromosuccinimide (NBS) in HCl medium has been investigated at 308 K. The oxidation reaction follows the rate law, $-d[NBS]/dt = k[NBS][Ru(III)]^a[THM]^b[H^+]^{-c}[Cl^-]^{-d}$, where a, b, c and d are less than unity. The stiochiometry of the reaction was found to be 1:1, and 2-(4-methyl thiazol-5-yl) ethanol and 4-amino-2-methylpyrimidine-5-carbaldehyde were identified as the oxidation products of THM. The reaction was examined with reference to variation of ionic strength of the medium and addition of the deduction product NBS, succinamide (RNH). The change in relative permittivity of the medium affected by changing the solvent composition with acetonitrile has been studied. The reaction constants involved in the mechanism were computed. The overall activation parameters have been evaluated from the Arrhenius plot. HOBr has been postulated as the reactive oxidizing species. The observed results have been explained by plausible mechanisms and the relative rate laws have been deduced.

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1. Introduction

Thiamine (THM) is the first member of vitamin B complex to be isolated and identified as vitamin. THM is fundamentally associated with carbohydrate metabolism. It is phosphorylated in the body to the active coenzyme, thiamine pyrophosphate that functions as co-carboxylase for various reactions in carbohydrate metabolism including the transketolase reaction in the direct oxidative pathway of glucose metabolism [1]. Thiamine might also serve as a modulator of neuromuscular transmission. It binds to isolated nicotinic cholinergic receptors, and neurotransmission is impaired by pyrithiamine, a thiamine antimetabolite [2]. In thiamine deficiency, the oxidation of α-keto acid is impaired, resulting in an increase in the concentration of pyruvate in blood. The requirement of thiamine is related to metabolic rate and is greatest when carbohydrate is a source of energy [3]. The oxidation kinetics and mechanism of thiamine hydrochloride are thus important to the process in vitro.

N-Bromosuccinimide (NBS) is a source of positive halogen, and this reagent has been exploited as an oxidant for a variety of substrates [4–8] in both acidic and alkaline solutions. The use of NBS as an oxidant is extensive in the determination of number of phar-

maceutical compounds [9–12]. Halvatzis and Timotheou-Potamia reported the kinetic-potentiometric method of determination of THM with NBS. The rate of production of bromide was monitored with a bromide-selective electrode [13]. However, a little information exists in the literature on NBS reactions, particularly with respect to the oxidation kinetics of bio-active compounds [14,15]. In view of these facts, it was felt important and interesting to investigate the oxidative behavior of NBS towards THM. The reaction of THM with NBS in presence of HCl solution without a catalyst was found to be sluggish, but the reaction was facile in the presence of micro-quantities of ruthenium (III) catalyst. Therefore the present paper reports for the first time on the detailed kinetics of Ru(III)-catalyzed oxidative cleavage of THM with NBS in HCl medium at 308 K. The work was carried out with a view to elucidate the mechanism of the reaction, put forward appropriate rate law and identify the reactive species of oxidant.

2. Experimental

2.1. Materials

An aqueous solution of NBS (Merck) was prepared afresh each day and its strength was checked by the iodometric method and preserved in brown bottles to prevent its photochemical deterioration. THM (Himedia) was used as received. A solution of $RuCl_3$ was prepared in 0.5 mol dm^{-3} HCl and was used as a catalyst in acid

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medium. Allowances were made for the amount of HCl present in the catalyst solution while preparing solutions for kinetic runs. All other reagents used were of accepted grades of purity. Ionic strength of the reaction mixture was kept constant with a concentrated solution of $NaClO_4$ (Merck). Doubly distilled water was used throughout the investigations.

2.2. Kinetic measurements

All kinetic measurements were performed in glass stoppered Pyrex boiling tubes coated black to eliminate photochemical effects. The reactions were carried out under pseudo-first-order conditions by taking a known excess of THM over $[NBS]_0$ at 308 K. Appropriate amounts of THM, $RuCl_3$, HCl solutions, mercuric acetate, sodium perchlorate and water to keep the total volume constant were equilibrated at constant temperature ($\pm 0.1\,°C$). A measured amount of NBS solution also pre-equilibrated at the same temperature was rapidly added to the mixture. The progress of the reaction was monitored by estimating the amount of unconsumed NBS at regular time intervals iodometrically. The course of reaction was studied for at least two half-lives. The pseudo-first-order rate constants (k'), calculated from the linear plots of log [NBS] versus time were reproducible within $\pm 4\%$. Regression analysis of the experimental data to obtain the regression co-efficient, r was performed using MS-Excel.

2.3. Stoichiometry and product analysis

Reaction mixtures containing various ratios of THM and NBS were equilibrated in the presence of $0.015\,mol\,dm^{-3}$ HCl and $1 \times 10^{-5}\,mol\,dm^{-3}$ $RuCl_3$ catalysts at 308 K for 48 h. Iodometric estimation of unconsumed NBS in the reaction mixture revealed that one mole of NBS was consumed per mole of THM. Accordingly, the following stoichiometric equation can be formulated:

$$C_{12}H_{17}N_4ClOS + RNBr + H_2O$$
$$\rightarrow C_6H_9NSO + C_6H_7N_3O + RNH + HCl + HBr \quad (1)$$
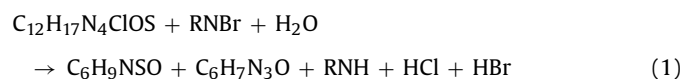
where $R = (CH_2CO)_2$.

The products in the reaction mixture were extracted several times with diethyl ether. The combined ether extract was evaporated and subjected to the column chromatography on silica gel (60–200 mesh) using gradient elusions (chloroform). After initial separation, the products were further purified by recrystallization. The oxidation products of THM were detected by conventional spot tests [16] and identified as 2-(4-methyl thiazol-5-yl) ethanol (Y), 4-amino-2-methyl pyrimidine-5-carbaldehyde (X'') and succinimide (RNH). Further the presence of RNH was confirmed by IR absorption bands. A broad band at ~3450 cm^{-1} for NH stretching mode and a sharp band at 1698 cm^{-1} for C=O stretching mode. Formation of X'' and Y are confirmed by its ^{1}H NMR spectral studies. X'' (CDCl$_3$): δ 2.35 (m, 3H, CH$_3$), 8.34 (s, H, Ar-H), 4.0 (s, 2H, NH$_2$), 9.6 (s, H, CH). Y (CDCl$_3$): δ 2.5 (s, 3H, CH$_3$), 3.8 (t, 2H, CH$_2$), 2.8 (t, 2H, CH$_2$), 8.5 (s, H, Ar-H). ^{1}H NMR spectra were recorded on BRUKER 400 MHz spectrometer using D$_2$O/CDCl$_3$ as solvent and TMS as internal reference.

3. Results

3.1. Effect of varying reactant concentrations on the rate

The reaction was performed in the presence of $RuCl_3$ catalyst and HCl under pseudo-first-order condition ($[THM]_0 \gg [NBS]_0$). Plots of log [NBS] versus time were linear (Fig. 1; $r = 0.997$). The linearity of these plots, together with the constancy of slope for various $[NBS]_0$, indicates a first-order dependence of the reaction rate on
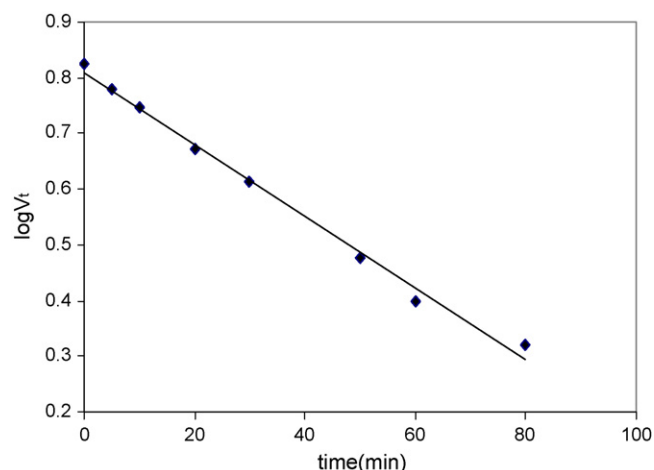

Fig. 1. Plot of log V_t versus time (min) for $0.0005\,mol\,dm^{-3}$ NBS.

Table 1
Effect of varying concentrations of reactants and acid on the reaction rate at 308 K.

10^4 [NBS] (mol dm^{-3})	10^3 [THM] (mol dm^{-3})	10^2 [HCl] (mol dm^{-3})	$10^4 k'$ (s^{-1})
3.0	8.0	1.5	2.56
5.0	8.0	1.5	2.61
7.0	8.0	1.5	2.64
9.0	8.0	1.5	2.59
11.0	8.0	1.5	2.63
5.0	7.0	1.5	2.51
5.0	8.0	1.5	2.61
5.0	10.0	1.5	2.88
5.0	12.0	1.5	3.09
5.0	14.0	1.5	3.31
5.0	8.0	1.0	4.47
5.0	8.0	1.5	2.61
5.0	8.0	2.0	1.75
5.0	8.0	2.5	1.37
5.0	8.0	3.0	0.95
5.0[a]	8.0	1.5	2.58
5.0[b]	8.0	1.5	2.64

$[RuCl_3] = 1 \times 10^{-5}\,mol\,dm^{-3}$; $\mu = 0.1\,mol\,dm^{-3}$; $[Hg(OAc)_2] = 1 \times 10^{-3}\,mol\,dm^{-3}$.
[a] At ionic strength $\mu = 0.2\,mol\,dm^{-3}$.
[b] $\mu = 0.3\,mol\,dm^{-3}$.

[NBS]. The pseudo-first-order rate constants, k' obtained at 308 K are listed in Table 1. Under the similar experimental conditions, an increase in $[THM]_0$ increased the rate (Table 1). Plot of log k' versus log [THM] was linear (Fig. 2; $r = 0.998$) with a slope of 0.43 indicating a fractional-order dependence on $[THM]_0$.
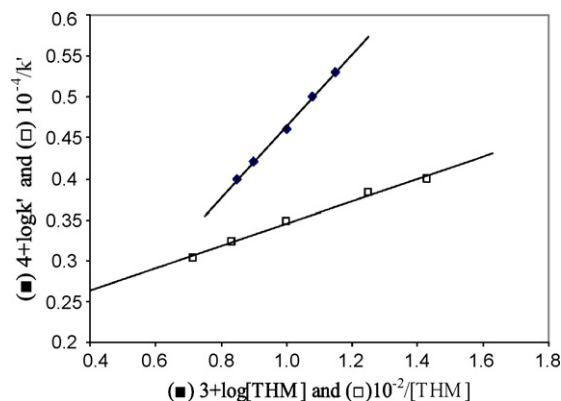

Fig. 2. Plot of (■) 4 + log k' and (□) $10^{-4}/k'$ versus (■) 3 + log [THM] and (□) 10^{-2}/[THM].

Table 2
Effect of varying H^+, Cl^- and $RuCl_3$ concentrations on the reaction rate at 308 K.

10^2 [H^+] (mol dm^{-3})	10^2 [Cl^-] (mol dm^{-3})	10^5 [$RuCl_3$] (mol dm^{-3})	$10^4 k'$ (s^{-1})
1.0	10.0	1.0	3.72
1.5	10.0	1.0	2.64
2.0	10.0	1.0	2.04
2.5	10.0	1.0	1.66
3.0	10.0	1.0	1.45
1.5	2.5	1.0	1.78
1.5	3.0	1.0	1.54
1.5	3.5	1.0	1.39
1.5	4.0	1.0	1.25
1.5	4.5	1.0	1.11
1.5	10.0	0.4	1.48
1.5	10.0	0.6	1.92
1.5	10.0	0.8	2.26
1.5	10.0	1.0	2.61
1.5	10.0	1.2	2.92

[NBS]$_0$ = 5 × 10^{-4} mol dm^{-3}; [THM] = 8 × 10^{-3} mol dm^{-3}; [Hg(OAc)$_2$] = 1 × 10^{-3} mol dm^{-3}; μ = 0.1 mol dm^{-3}.

3.2. Effect of varying [HCl] and [Ru(III)] on the rate

At constant [NBS]$_0$, [THM]$_0$, [RuCl$_3$] and temperature, the reaction rate decreased with increasing [HCl] (Table 1). A plot of $\log k'$ versus $\log$ [HCl] was linear (r = 0.997) with a slope of −1.57. The rate increased with increasing [RuCl$_3$] (Table 2). Plot of $\log k'$ versus $\log$ [RuCl$_3$] (Fig. 3; r = 0.999) was linear with a slope equal to 0.59, confirming a fractional-order dependence on [RuCl$_3$].

3.3. Effect of varying [H^+] and [Cl^-] on the rate

At constant [Cl^-] = 0.10 mol dm^{-3} maintained with NaCl, increase in the concentration of [H^+] using HCl decreased the rate (Table 2). A plot of $\log k'$ versus $\log$ [H^+] was linear (Fig. 4; r = 0.999) with a slope of −0.83 indicating inverse-first-order dependence on [H^+]. Addition of Cl^- in the form of NaCl keeping [H^+] constant (0.015 mol dm^{-3}) decreased the reaction rate (Table 2). From a plot of $\log k'$ versus $\log$ [Cl^-] (Fig. 4; 0.998), the order with respect to [Cl^-] is found to be −0.76.

3.4. Effect of varying [Hg(OAc)$_2$] on the rate

The effect of concentration of mercury (II) acetate in the range 1–4 × 10^{-3} mol dm^{-3} was found to be negligible on the rate of reaction. The function of added mercuric acetate is therefore to fix up Br$^-$ formed in the course of reaction.
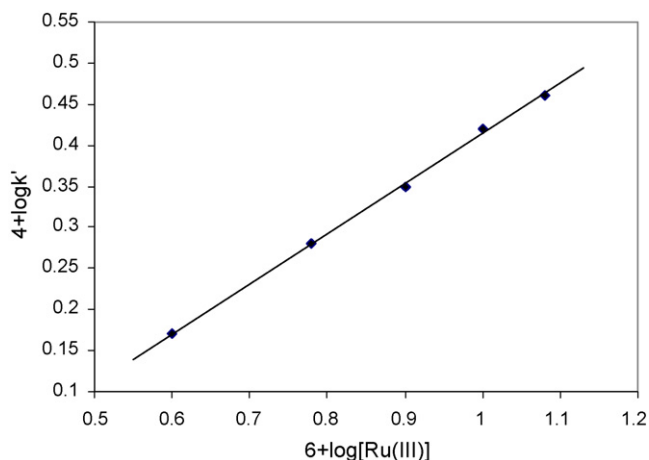
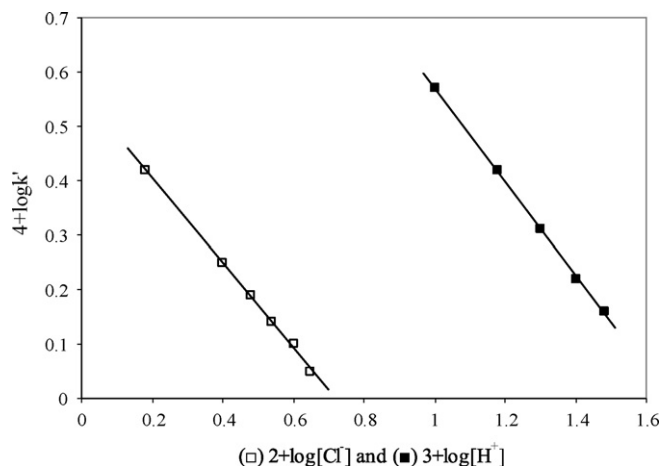**Fig. 3.** Plot of $4 + \log k'$ versus $6 + \log$ [Ru(III)].

Fig. 4. Plot of $4 + \log k'$ versus (□) $2 + \log$ [Cl^-] and (■) $3 + \log$ [H^+].

Table 3
Effect of varying concentration of succinimide (RNH) on the reaction rate at 308 K.

10^4 [RNH] (mol dm^{-3})	$k' \times 10^4$ (s^{-1})
3.0	1.66
5.0	1.39
7.0	1.23
9.0	1.07
12.0	

[NBS] = 5 × 10^{-4} mol dm^{-3}; [THM] = 8 × 10^{-3} mol dm^{-3}; [HCl] = 1.5 × 10^{-2} mol dm^{-3}; [Hg(OAc)$_2$] = 1 × 10^{-3} mol dm^{-3}; μ = 0.1 mol dm^{-3}.

3.5. Effect of succinimide on the rate

Addition of succinimide (RNH), the reduction product of the oxidant retards the reaction rate (Table 3). A plot of $\log k'$ versus $\log$ [RNH] was linear with a slope −0.39, indicating an inverse-fractional-order dependence of the rate on [RNH].

3.6. Effect of varying ionic strength and relative permittivity of the medium

Variation of ionic strength of the medium through addition of NaClO$_4$ (0.1–0.4 mol dm^{-3}) had no significant effect on the rate. The effect of dielectric permittivity (D) of the medium on the reaction rate was studied by adding various proportions of CH$_3$CN (0–20%, v/v) to the reacting system. It was observed that an increase in CH$_3$CN composition decreased the rate and a plot of $\log k'$ versus $1/D$ gave a straight line (r = 0.977) with a negative slope. The values are reported in Table 4. The values of permittivity (D) for CH$_3$CN–H$_2$O mixtures are calculated from the equation, $D = D_W V_W + D_A V_A$, where D_W and D_A are the dielectric permittivities of pure water and acetonitrile and V_W and V_A are the volume fractions of components, water and acetonitrile in the total mixture. Blank experiments per-

Table 4
Effect of temperature and solvent composition on the reaction rate.

Temperature (K)	CH$_3$CN (%, v/v)	$10^4 k'$ (s^{-1})
303	–	1.26
308	–	2.61
313	–	5.22
318	–	8.56
308	5	2.51
308	10	2.40
308	15	2.32
308	20	2.02

[NBS] = 5 × 10^{-4} mol dm^{-3}; [THM] = 8 × 10^{-3} mol dm^{-3}; [HCl] = 1.5 × 10^{-2} mol dm^{-3}; [Hg(OAc)$_2$] = 1 × 10^{-3} mol dm^{-3}; μ = 0.1 mol dm^{-3}.
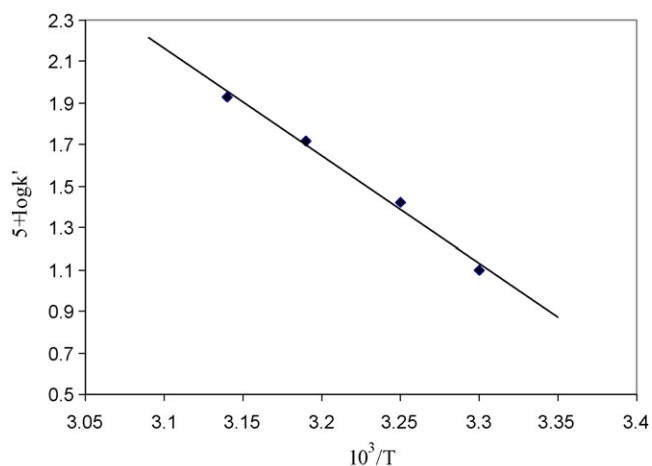
Fig. 5. Plot of $4 + \log k'$ versus $10^3/T$.

formed showed that CH_3CN was not oxidized with NBS under the experimental conditions employed.
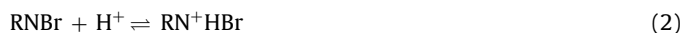
3.7. Effect of temperature on the rate

The reaction was studied at different temperatures (303–318 K), keeping other experimental conditions constant (Table 4). From the Arrhenius plot of $\log k'$ versus $1/T$ (Fig. 5; $r = 0.996$), activation energy and other thermodynamic parameters were found to be $E_a = 114.9\,kJ\,mol^{-1}$, $\Delta H^{\#} = 112.3\,kJ\,mol^{-1}$ $\Delta S^{\#} = 50.3\,JK^{-1}$ $\Delta G^{\#} = 96.7\,kJ\,mol^{-1}$.

3.8. Test for free radicals

The addition of the reaction mixture to aqueous acrylamide monomer solution did not initiate polymerization indicating the absence of in situ formation of free radical species in the reaction sequence.

4. Discussion and mechanism

NBS is a two equivalent oxidant which oxidizes many substrates through NBS itself or Br^+ or N^+HBr, or hypobromite anion. The reactive species responsible for the oxidizing character may depend on the pH of the medium [6]. Depending on the pH of the medium, NBS furnishes different types of reactive species in solutions [17–19] as shown in reactions (2)–(7):

$$RNBr + H^+ \rightleftharpoons RN^+HBr \qquad (2)$$

$$RNBr + H_2O \rightleftharpoons RNH + HOBr \qquad (3)$$

$$HOBr + OH^- \rightleftharpoons OBr^- + H_2O \qquad (4)$$

$$RNBr + H^+ \rightleftharpoons RNH + Br^+ \qquad (5)$$

$$Br^+ + H_2O \rightleftharpoons (H_2OBr)^+ \qquad (6)$$

$$RNBr + OH^- \rightleftharpoons RNH + OBr^- \qquad (7)$$

where R is $(CH_2CO)_2$.

In acidic solutions, the probable reactive species of NBS are NBS itself or Br^+ or protonated NBS viz., RN^+HBr, and the reactive species in alkaline solutions are NBS, HOBr or OBr^-. Most investigations on NBS oxidations of organic substrates have assumed that, the molecular NBS acts only through its positive polar end [20,21]. In the present study, negative effect of [H+] on the reaction rate observed allows us to assume either NBS itself or HOBr as active oxidizing
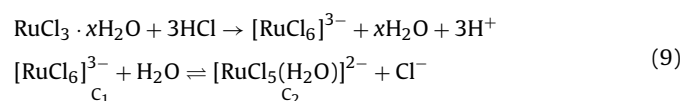
species. Further, retardation of the rate by initial added succinimide (RNH) restricts us to take HOBr as the active oxidizing species.

It may be pointed out that all kinetic studies have been made in presence of mercuric (II) acetate in order to avoid any possible bromine oxidation which may be produced as follows:

$$(8)$$
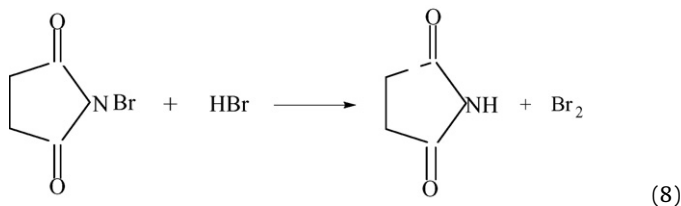
Mercuric (II) acetate acts as a capture agent for any Br^- formed in the reaction and exists as $HgBr_4^{2-}$ or unionized $HgBr_2$ and ensures that oxidation takes place purely through NBS [22,23].

Ruthenium (III) chloride is known to exist in solution in various aquaform. Electronic spectral studies and ion-exchange properties in aqueous media have shown that [24–26], it exists in the hydrated form as $[Ru(H_2O)_6]^{3+}$. However other studies [27–29] have shown that, in acid solutions the following equilibria exist for Ru(III):

$$RuCl_3 \cdot xH_2O + 3HCl \rightarrow [RuCl_6]^{3-} + xH_2O + 3H^+$$

$$\underset{C_1}{[RuCl_6]^{3-}} + H_2O \rightleftharpoons \underset{C_2}{[RuCl_5(H_2O)]^{2-}} + Cl^- \qquad (9)$$

Singh et al. [30,31] used the above equilibrium for Ru(III)-catalyzed oxidation of primary alcohols by chloramine-T and of glycols by N-bromoacetamide in acid medium. In the present studies, however the retarding effect of added Cl^- on the rate favors the equilibrium (9) to the right and hence $[RuCl_5(H_2O)]^{2-}$ has been assumed to be the reactive catalyzing species.

Further, ultraviolet-spectral measurements showed that a sharp absorption band was noticed at 214 nm for $RuCl_3$, 236 nm for NBS and around 216 nm for THM in presence of 0.015 mol dm^{-3} HCl. A mixture of NBS and $RuCl_3$ solutions in the presence of HCl showed an absorption band at 268 nm, while for a mixture of THM and Ru(III) solutions an absorption band was noticed at 215 nm. The spectral evidence showed that, complex formation takes place only between Ru(III) and NBS. Based on the preceding discussions and observed kinetic data, a probable mechanism (Scheme 1) is proposed for the Ru(III)-catalyzed NBS-THM reaction in acid medium.

From slow step of Scheme 1:

$$\text{rate} = -\frac{d[RNBr]}{dt} = k_5[X'] \qquad (10)$$

If $[NBS]_t$ represents total [NBS] in solution, then

$$[NBS]_t = [RNH^+Br] + [RNBr] + [HOBr] + [X] + [X'] \qquad (11)$$
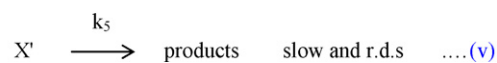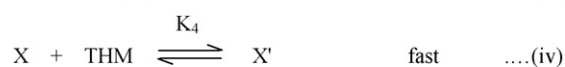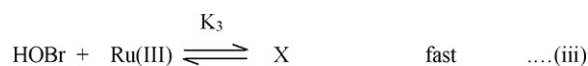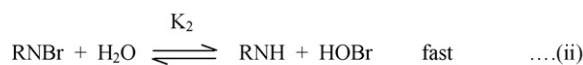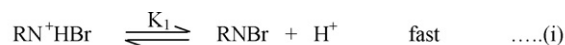
Scheme 1. Kinetic mechanism for the ruthenium (III)-catalyzed oxidation of THM with NBS in acid medium.

$$[\text{RuCl}_6]^{3-} + \text{H}_2\text{O} \underset{K_6}{\overset{}{\rightleftharpoons}} [\text{RuCl}_5(\text{H}_2\text{O})]^{2-} + \text{Cl}^- \quad \text{fast} \quad \ldots\text{(i)}$$
$$\quad\quad C_1 \quad\quad\quad\quad\quad\quad\quad C_2$$

$$\text{RNHBr} \underset{K_1}{\overset{}{\rightleftharpoons}} \text{RNBr} + \text{H}^+ \quad\quad\quad \text{fast} \quad \ldots\text{(ii)}$$

$$\text{RNBr} + \text{H}_2\text{O} \underset{K_2}{\overset{}{\rightleftharpoons}} \text{RNH} + \text{HOBr} \quad\quad \text{fast} \quad \ldots\text{(iii)}$$

$$\text{HOBr} + C_1 \underset{K_3}{\overset{}{\rightleftharpoons}} X + \text{Cl}^- \quad\quad\quad \text{fast} \quad \ldots\text{(iv)}$$

$$X + \text{THM} \underset{K_4}{\overset{}{\rightleftharpoons}} X' \quad\quad\quad\quad\quad \text{fast} \quad \ldots\text{(v)}$$

$$X' \overset{k_5}{\longrightarrow} \text{products} \quad\quad \text{slow and r.d.s} \quad \ldots\text{(vi)}$$

Scheme 2. Kinetic mechanism for the ruthenium (III)-catalyzed oxidation of THM with NBS in presence of chloride ion.

From steps (i), (ii), (iii) and (iv) of Scheme 1,

$$[\text{RNH}^+\text{Br}] = \frac{[\text{RNBr}][\text{H}^+]}{K_1}$$

$$[\text{RNBr}] = \frac{[\text{RNH}][\text{HOBr}]}{K_2[\text{H}_2\text{O}]}$$

$$[\text{HOBr}] = \frac{[X]}{K_3[C_2]}$$

and $[X] = \dfrac{[X']}{K_4[\text{THM}]}$

Substituting these in Eq. (11) and solving for $[X']$ we get,

$$[X'] = \frac{K_1K_2K_3K_4[\text{NBS}]_t[\text{THM}][\text{Ru(III)}][\text{H}_2\text{O}]}{[\text{RNH}]\{[\text{H}^+]+K_1\}+K_1K_2[\text{H}_2\text{O}]\{1+K_3[\text{Ru(III)}]}\,+K_3K_4[\text{Ru(III)}][\text{THM}]\}} \quad (12)$$

By substituting for $[X']$ from Eq. (12) in Eq. (10), the following rate law (13) is obtained:

$$\text{rate} = \frac{K_1K_2K_3K_4k_5[\text{NBS}]_t[\text{THM}][\text{Ru(III)}][\text{H}_2\text{O}]}{[\text{RNH}]\{[\text{H}^+]+K_1\}+K_1K_2[\text{H}_2\text{O}]\{1+K_3[\text{Ru(III)}]}\,+K_3K_4[\text{Ru(III)}][\text{THM}]\}} \quad (13)$$

The rate law (13) is in good agreement with all experimental results. Since rate $= k'[\text{NBS}]_t$, rate law (13) can be transformed into Eqs. (14)–(16):

$$k' = \frac{K_1K_2K_3K_4k_5[\text{THM}][\text{Ru(III)}][\text{H}_2\text{O}]}{[\text{RNH}]\{[\text{H}^+]+K_1\}+K_1K_2[\text{H}_2\text{O}]\{1+K_3[\text{Ru(III)}]}\,+K_3K_4[\text{Ru(III)}][\text{THM}]\}} \quad (14)$$

$$\frac{1}{k'} = \frac{[\text{RNH}][\text{H}^+]}{K_1K_2K_3K_4k_5[\text{THM}][\text{Ru(III)}][\text{H}_2\text{O}]}$$
$$+ \frac{[\text{RNH}]}{K_2K_3K_4k_5[\text{THM}][\text{Ru(III)}][\text{H}_2\text{O}]}$$
$$+ \frac{1}{K_3K_4k_5[\text{THM}][\text{Ru(III)}]} + \frac{1}{K_4k_5[\text{THM}]} + \frac{1}{k_5} \quad (15)$$

Scheme 3. A detailed mechanistic interpretation of ruthenium (III)-catalyzed oxidation of THM by NBS in acid medium.

$$\frac{1}{k'} = \frac{1}{K_4 k_5 [\text{THM}]}$$

$$\times \left\{ \frac{[\text{RNH}][\text{H}^+]}{K_1 K_2 K_3 [\text{Ru(III)}][\text{H}_2\text{O}]} + \frac{[\text{RNH}]}{K_2 K_3 [\text{Ru(III)}][\text{H}_2\text{O}]} + \frac{1}{K_3 [\text{Ru(III)}]} + 1 \right\}$$

$$+ \frac{1}{k_5} \tag{16}$$

Based on Eq. (16), plot of $1/k'$ versus $1/[\text{THM}]$ at constant [Ru(III)] and [H$^+$] and temperature has been found to be linear ($r = 0.995$; Fig. 2). The value of k_5 was calculated from the intercept of the plot ($k_5 = 3.59 \times 10^{-4}\,\text{s}^{-1}$).

In the presence of chloride ion at constant [H$^+$], Scheme 2 is proposed for the reaction mechanism.

From Scheme 2,

$$\text{rate} = k_5 [X'] \tag{17}$$

[NBS]$_t$ represents total [NBS] in solution, then

$$[\text{NBS}]_t = [\text{RNH}^+\text{Br}] + [\text{RNBr}] + [\text{HOBr}] + [X] + [X'] \tag{18}$$

From equilibrium steps (i), (ii), (iii) and (iv) of Scheme 2 and solving for $[X']$, we have:

$$[X'] = \frac{K_1 K_2 K_3 K_4 [\text{NBS}]_t [\text{THM}][C_1][\text{H}_2\text{O}]}{[\text{RNH}][\text{Cl}^-]\{K_1 + [\text{H}^+]\} + K_1 K_2 [\text{H}_2\text{O}][\text{Cl}^-]} \tag{19}$$
$$+ K_1 K_2 K_3 [C_1][\text{H}_2\text{O}]\{1 + K_4[\text{THM}]\}$$

By substituting for $[X']$ from Eq. (19) in Eq. (17) the following rate law (Eq. (20)) is obtained:

$$\text{rate} = \frac{K_1 K_2 K_3 K_4 k_5 [\text{NBS}]_t [\text{THM}][C_1][\text{H}_2\text{O}]}{[\text{RNH}][\text{Cl}^-]\{K_1 + [\text{H}^+]\} + K_1 K_2 [\text{H}_2\text{O}][\text{Cl}^-]} \tag{20}$$
$$+ K_1 K_2 K_3 [C_1][\text{H}_2\text{O}]\{1 + K_4[\text{THM}]\}$$

The rate expression (20) clearly demonstrates the retarding effect of added Cl$^-$ on the rate, and is in good agreement with the experimental results.

In Schemes 1 and 2, X and X' represents the complex intermediate species whose structures are shown in Scheme 3, where a detailed mechanism of Ru(III)-catalyzed oxidation of THM with NBS in HCl medium is illustrated. An initial equilibrium involves hydrolysis of RNBr forming an active oxidizing species of NBS (HOBr). In the next step, the oxygen atom of the active species is coordinated to the metal centre of the active catalyst species to form loosely bound metal complex, X and Cl$^-$ [step (ii) of Scheme 2] trapped in a solvent cage. Then follows neucleophilic attack of oxygen on methylene group of thiamine to form intermediate X', Y and releasing [RuCl$_5$(H$_2$O)]$^{2-}$ [step (iii)]. Then reorganization of the intermediate (X') to form products with the release of HCl and HBr.

The effect of varying solvent composition and dielectric permittivity of the medium (D) on the rate has been described in several studies. For the limiting case of zero angle of approach between two dipoles or an ion-dipole system, Amis [32] has shown that plot of $\log k'$ versus $1/D$ gives a straight line with negative slope for a reaction between two dipoles and positive slope for a reaction between ion and a dipole. However, it is to be noted that a clear concept of the influence of dielectric constant on the rate of reaction in solution has not been put forward so far. The negative dielectric effect in the present studies supports the suggested mechanisms.

The mechanism is further supported by the high values of activation energy and other thermodynamic parameters. The fairly high positive values of Gibbs free energy of activation and enthalpy of activation indicate that the transition state is highly solvated. The

reduction product, RNH retards the reaction rate indicating the involvement of RNH in pre-equilibrium step prior to the rate determining step. Addition of chloride ion decreases the rate showing that chloride ions are formed in the reaction.

5. Conclusions

Oxidative cleavage of THM with NBS in hydrochloric acid medium has been studied in the presence of RuCl$_3$ catalyst. The stoichiometry of the reaction was found to be 1:1 and the oxidation products of THM were identified by spectral studies. Oxidation of THM with NBS in acid medium will become facile in presence of micro-quantities of ruthenium (III) catalyst. HOBr was found to be the reactive oxidizing species. Activation parameters were computed from the Arrhenius plot. The observed results have been explained by plausible mechanisms and the related rate laws have been deduced.

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