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N-Bromosaccharin oxidation of some aldoses: A kinetic study

P. C. Shukla, P. S. Tiwari and Deepa Khare*
1, Department of Chemistry, Degree College, Sirmour, Rewa, (M.P.) - India
2, Department of Chemistry, Govt. M.V.L. College, Bhopal, (M.P.) - India
3, Department of Chemistry, Janata PG College, Rewa, (M.P.) - India

Abstract
Kinetics of oxidation of some aldoses viz. D- ribose, D- xylose, L – arabinose and D- glucose by N- bromosaccharin in aqueous acetic medium in the presence of mercuric acetate as a scavenger for Br-, exhibits first order dependence in [NBSA] and [HC1O4]. The order with respect to aldose varies from 1 to 0. The reaction rate is retarded by the addition of saccharin. Effect of variation of composition of acetic acid-water binary mixture was also studied. Various activation parameters have been computed. These results points to a polar mechanism involving the formation of hypobromite ester in pre- equilibrium step which disproportionates into products via rate limiting attack of water molecule.

Key-Words: Kinetics and mechanism/ aldoses/ N-bromosaccharin

Introduction
Oxidation kinetics of aldosugars with different oxidants have been given a great deal of attention in past years[1-8]. In continuation of our earlier work9, we report herein the oxidation kinetics s of some aldoses viz. D- ribose, L-arabinose, D-xylose and D- glucose with N-bromosaccharin in aqueouracetic acid medium in the presence of mercuric acetate as scavenger for Br N-Bromosaccarin is bromoimide of orthosulphobenzoic acid and has been utilized as effective oxidant for the oxidation of various functional groups in last few decades.

Material and methods
N-bromosaccharin (NBSA) was prepared[10] and its acetic acid solution was standardized iodometrically[11]. A fresh aqueous solution of D-glucose (ARBDH), L-arabinose (BDH), D-xylose (Loba chemie) and D-ribose (BDH) was employed for kinetic studies. Mercuric acetate was prepared in 1:1 (v/v) acetic acid-water mixture. Other chemicals used were of standard grade. The reaction mixture was allowed to attain the desired temperature by keeping it in a thermostat (±0.5°C) and progress of the reaction was followed, at regular intervals, by estimating unconsumed NBSA iodometrically.

* Corresponding Author

Stoichiometry and product analysis
The stoichiometry of the reactions was determined in duplicate by estimating the unconsumed oxidant till the completion of the reaction, in a reaction mixture containing the excess of oxidant over carbohydrate. The results show that 1 mol all of NBSA consumes 1 all of substrate.

$$R\,CHO + C_6H_4COSO_2NBr + H_2O \longrightarrow R\,COOH + C_6H_4COSO_2NH + HBr$$

Where R = $C_5H_{10}O_5$ for hexose and $C_4H_9O_4$ for pentose

Acids
The product aldonic acid[5] were identified by paper chromatography[12]. This is in agreement with the observation that the aldonic acid invariably remains in equilibrium with corresponding r and s lactones in acid medium[13,14]. Saccharin, the reduction product of N-bromosaccharin, was also identified qualitatively.

Results and Discussion
Under the conditions [aldose] and [$Hg(OAc)_2$] >> [NBSA], the disappearance of [NBSA] with time followed first order kinetics as evidenced by the linear plots of log (a-x) versus time for different initial concentrations of oxidant in case of each aldose. Further the pseudo first order rate constant evaluated from the slope of the plot (a-x) versus time are fairly constant for each reaction (Table 1). The dependence of rate on substrate concentration was obtained by varying its concentration for nearly five folds. The plot

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k_1 versus [aldose] is linear initially and then bends towards X-axis (Fig. 1). This suggests that order with respect to substrate varies from 1 to 0. Further the reciprocal plot of k_1 versus [aldose], for each aldose, is linear with positive intercept on Y-axis indicating the formation of intermediate complex prior to the rare limiting step (Fig. 2).

The reactions are acid catalyzed (Table 2). The plots of k_1 versus [$HClO_4$] are linear with a positive intercept suggesting that each reaction follows two paths: acid dependent and acid independent. The nearly unit slope values of the linear log – log plot between k_1 versus [$HClO_4$] suggests that the reactions are first order in perchloric acid.

The effect of variation of the composition of acetic acid-water binary mixture shows that the reaction rate increases with decrease in dielectric constant of the medium. Addition of sodium perchlorate shows marginal positive effect. The oxidation rate of each aldose decreases with the addition of saccharin to the reaction mixture (Table 3). The plots of inverse of k_1 and [saccharin] are linear. Mercuric acetate has no effect on reaction rate which leads to the conclusion that it acts as a trapping agent for Br-. The reactions were also studied at different temperatures and various activation parameters were evaluated from Arrhenius and Eyring plots (Table 4).

Mechanism and Rate law

N-Bromosaccharin in aqueous-acetic acid medium is hydrolysed to HOBr as:

$$HBSA + H_2O \longrightarrow HOBr + Saccharin$$

Retardation of reaction rate by the added saccharin in NBSA oxidation of aldoses can be explained by shifting of above prehydration equilibrium to the left and it also postulated HOBr as oxidant. The plot of inverse of k_1 against [saccharin] is linear for each aldose supporting HOBr as active oxidant.

Oxidant of each aldose by NBSA is acid catalysed hence the involvement of protonated species in rate determining step may be postulated. The protonated oxidant is H_2O^+Br, hypobromous acidium ion, formation of which may be formulated in two different ways:

$$NBSA + H^+ \longrightarrow NBSAH^+ \cdots\cdots (A)$$

$$NBSAH^+ + H_2O \longrightarrow H_2O^+Br + Saccharin \ldots (B)$$

$$NBSA + H_2O \longrightarrow HOBr + Saccharin \ldots\ldots (C)$$

$$HOBr + H^+ \longrightarrow H_2O^+Br + Saccharin \ldots (D)$$

The choice between the two possibilities i.e. prior protonation of NBSA followed by nucleophilic attack by water or protonation of hydrolytic product is kinetically difficult. One can not ignore Br^+ as active oxidant, the formation of which may be formulated as:

$$NBSA + H^+ \longrightarrow BR^+ + Saccharin \quad \ldots (E)$$

Formation of bromonium ion explains acid catalysis as well as retarding effect of added saccharin but all it has been proved that H2O+Br is more powerful electrophile and hence preferred one.

In aqueous acidic solution D(+)- glucose predominantly exists in equilibrium between α and β-pyranose forms with free aldehydic form as intermediate besides the furanoid forms[15] which are too low in concentration to make any impact towards competing for oxidation with above intermediates. According to Mehrotra[4] et. Al. the rate of maturation is many times greater than the rate of oxidation. Hence the D-glucose oxidation is sum total of contribution from α and β-pyranose forms in addition to the free aldehyde form. The confirmation present in aqueous solution for D-glucose has anomeric proton equatorial in α-pyranose and axial in β-pyranose[16] and therefore β-anomer should be more reactive than α-anomer.

So with a view to determine where the oxidation of sugars is occurring through the ring form or through the aldehyde form and ring form graphical method[4] was utilized. The plot between second order rate constant k_2 and [aldehyde sugar] is linear with an intercept on rate axis. This suggests that observed rate is sum total of the rate contributed by the pyranose form together with the contribution from very small concentration of sugar present in aldehyde form.

The dependence of rate on [aldose] points to hypobromite ester formation between the oxidant species and sugar molecule in pre-equilibrium step. The medium effect studies i.e. positive slope for linear plot between log k_1 and inverse of dielectric constant and marginal salt effect suggest an interaction between positive ion and dipole or between dipoles. The acid catalysis suggests protonation of either oxidant or substrate species. It is likely that protonation of either oxidant is a dominant factor as unprotonated aldose is more nucleophilic than protonated aldose. Further the reactions follow an acid dependent and independent path. Accordingly in the presence of perchloric acid H_2O^+Br is the active oxidant while in the absence it is the HOBr. The slope value of Bunnett-Olsen plot (φ) (Xylose = 1.18, arabinose = 1.35, ribose = 1.28, glucose =1.22 and glucose = 1.36) suggests the participation of water molecule as proton abstracting agent in the slow step.

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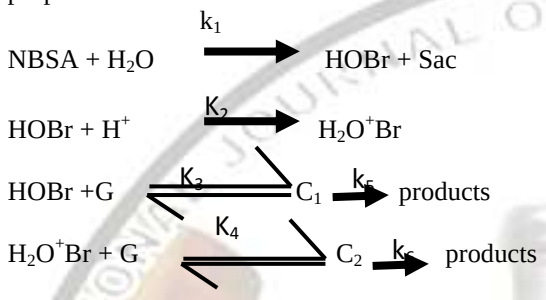
All the reactions understudy failed to induce polymerization of acrylonitrile ruling out free radical formation as reaction intermediates. Based on the above kinetic results a probable mechanism may be proposed as:



Rate $= k_5 [C_1] + k_6 [C_2]$ …(1)

Applying the principle of material balance to obtain $[C_1]$ and $[C_2]$

$$[C_1] = \frac{K_1K_3 [G] [NBSA]_T}{[S] + K_1 + K_1 K_3[G] + K_1K_2[H^+] (1+K_4[G])}$$

…(2)

AND

$$[C_2] = \frac{K_1K_2 K_4 [G] [NBSA]_T [H^+]}{[S] + K_1 + K_1K_3[G] + K_1K_2[H^+] (1+K_4[G])}$$

…..(3)

Substituting the value of $[C_1]$ and $[C_2]$ in equation (1)

Assuming $[G] >> [NBSA]_T$ we get:

$$k_{obs} = \frac{K_1[G]\{K_3k_5 + K_2K_4k_6 [H^+]\}}{[S] + K_1 + K_1K_3[G] + K_1K_2[H^+] (1 + K_4[G])}$$

…(4)

IF $K_1K_2[H^+] (1 + K_4[G]) << [S] + K_1K_3[G]$

$$k_{obs} = \frac{K_1[G](K_3k_5 + K_2K_4k_6 [H^+])}{[S] + K_1(1 + K_3[G])}$$

….(5)

Thus the equation (5) explains all the experimental results.

In the formation of hypobromite ester or conjugate acid of hybromite, the attack of electrophilic oxidant on equatorial –OH group is more accessible. Further this conformation facilitates elimination of proton and bromide ion as the hypobromite group can adopt the configuration required for trans elimination. In α-isomer such elimination will be highly strained because of non bonded interactions between bromine and the two axial hydrogen atoms at C-3 and C-5. Elimination will be assisted by the electrostatic repulsion between the incipient bromine ion and the C-2 hydroxyl group and ring oxygen atom[17].

The observed order of reactivity of aldoses under study is D-ribose > L-arabinose > D-xylose > D-galactose > D-glucose. For hexose series the order galactose > glucose is well in accordance with the percentage of β-pyranose as well as aldehydic form and in aldopentose series the relative amount of open chain form decrese[5] in the order D-ribose > L-arabinose > D-xylose[18,19] and interestingly the order of reactivity of pentose series is similar (Table 5). For ribose the concentration of furanoid from is considerable and highest and hence cannot be ignored and may account for highest rate of oxidation in pentoses.

The value of ΔG* for NBSA-aldose system is more or less constant suggesting that similar mechanism is operative for each aldose. The isokinetic temperature β = 357 K (Fig.) is higher than the experimental temperature hence the reactions are enthalpy controlled.

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Table 1: Effect of varying [NBSA] on the reaction rate
10^2 [Aldose] M = 3.33(1,2),2.5(4,5), 10^2 [$Hg(OAc)_2$] M = 1.0;
%(v/v) HOAc = 30(1), 20(2-4), temp. = 60°C.

[NBSA] 10^3 M	**Glucose 1**	**Xylose 2**	**Arabinose 3**	**Ribose 4**
2.0	11.53	19.44	16.25	20.76
2.5	11.62	19.44	16.84	20.26
3.33	11.67	19.57	16.56	20.54
5.0	11.56	19.67	16.71	20.67
10.0	11.60	19.77	16.63	20.54

Table 2: Effect of [$HClO_4$] on the reaction rate
10^3[NBSA]M=2.5; 10^2 [Aldose] M=10.0(1),3.33(2,3,4);
10^2 [$Hg(OAc)_2$ M=1.0, %(v/v) HOAc =30(1),20(2-4), temp. = 60°C.

[$HClO_4$] 10^3 M	**Glucose 1**	**Xylose 2**	**Arabinose 3**	**Ribose 4**
1.0	32.08	← 26.65 10^3 k_1 min^{-1}	→ 34.34	36.46
2.0	39.95	32.45	40.05	42.21
3.0	50.21	38.61	46.57	49.45
4.0	57.52	42.42	58.84	60.11
5.0	65.21	49.21	71.25	72.52

Table 3: Effect of [Saccharin] on the reaction rate
[NBSA] = 2.5 x 10^3M
10^2 [Aldose] M, 3.33 (1,3), 2.5(2,4);

[Sacchrin] 10^3 M	**Glucose 1**	**Xylose 2**	**Arabinose 3**	**Ribose 4**
0.0	11.62	← 14.55 10^3 k_1 min^{-1}	→ 24.59	20.26
1.25	-	10.12	22.98	19.08
1.43	10.11	9.77	22.18	18.41
1.66	9.12	9.21	20.61	16.78
2.0	8.51	8.29	18.11	14.94
2.5	7.65	7.34	16.09	12.91
3.33	6.47	-	-	-

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Table 4: Activation parameters

Aldose	Ea K J mol^{-1}	A Sec^{-1}	ΔH* K J mol^{-1}	ΔG* k J mol^{-1}	-ΔS* J K mol^{-1}
D-Glucose	74.11	8.17×10^{7}	72.84	96.67	71.1
D-Xylose	51.01	3.33×10^{9}	48.97	95.07	137.4
L-Arabinose	43.17	2.41×10^{8}	42.09	94.47	156.1
D-Ribose	33.41	7.62×10^{5}	31.22	94.34	188.1

Table 5: The percentage concentration of Free Aldehyde Sugars and α and β Sugars in aqueous solution.

	Aldehyde	% Pyranose From		% Furanose From	
	Sugar	α	β	α	β
Glucose	0.022	38	62	0.1	< 0.2
Galactose	0.085	29	64	3	4
Ribose	8.5	21	59	6	14
Xylose	0.13	36.5	63	-	-
Arabinose	0.22	63	34	2.5	2