

Reactivities of some sugar phosphates towards permanganate in perchloric acid medium and mechanism of the oxidation processes

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The reactivities of some sugar phosphates towards permanganate have been examined in perchloric acid medium. The reactions are first order in [sugar phosphate] and $[\text{MnO}_4^-]$. The rate increases with increase in $[\text{H}^+]$. The reactivities follow the order: erythrose 4-phosphate > ribose 5-phosphate > fructose 1,6-diphosphate > glucose 6-phosphate > glucose 1-phosphate. The mechanism of the reactions is discussed.

Phosphorus compounds play an important role in life processes. Many of the biologically important phosphorus compounds are orthophosphates. Of the different orthophosphates sugar phosphates play a major role in photosynthesis¹ and in metabolism². Recently oxidative behaviours and relative reactivities of glycerophosphates by HOSO_5^- (ref. 3), IrCl_6^{2-} (ref. 4), $[\text{Cu}^{\text{III}}(\text{H}_2\text{TeO}_6)_2]^{5-}$ (ref. 5), $[\text{Ag}^{\text{III}}(\text{H}_2\text{TeO}_6)_2]^{5-}$ (ref. 6), HCrO_4^- (ref. 7) and MnO_4^- (ref. 8) have been studied. There is no literature data involving the oxidations of sugar phosphates by acid permanganate. The oxidation of some sugar phosphates by permanganate in perchloric acid medium have been studied and the results are given in this note.

Experimental

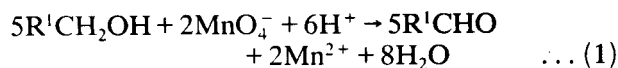
Sodium salts of the sugar phosphates (Sigma) were used. Potassium permanganate (GR, E. Merck), sodium fluoride (Loba) and perchloric acid (GR, E. Merck) were used. The other materials employed were of the highest purity available. All solutions were prepared in doubly distilled water.

The reactions were carried out under the conditions at which [sugar phosphate] and $[\text{H}^+]$ were much higher than that of $[\text{MnO}_4^-]$. Since in permanganate oxidation reactions intermediate valence states of manganese introduce many complica-

tions, the present investigations were carried out in the presence of large excess of fluoride ions⁹. Fluoride ions are known to suppress the reactivities of Mn(III) and Mn(IV) by complexation. Solutions of the permanganate and the mixture containing sugar phosphate, perchloric acid and sodium fluoride were separately thermally equilibrated ($\pm 0.1^\circ$) for nearly 1 h. Each reaction was started by adding the permanganate to the mixture. Aliquots of the reaction mixtures were quenched in excess of potassium iodide solution under a blanket of carbon dioxide and the liberated iodine was titrated with sodium thiosulphate solution using starch as indicator. The pseudo-first order rate constants (k_{obs}) were calculated from the slopes of $\log [\text{MnO}_4^-]$ against time plots ($r > 0.99$). Duplicate measurements were reproducible to within $\pm 3\%$.

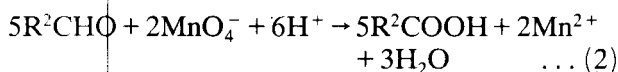
All the sugar phosphates were oxidised by permanganate under kinetic conditions. After the reactions were completed the oxidation products were divided into two parts. In one part a ferric chloride solution coloured violet with phenol was added. The immediate appearance of yellow colour with the products obtained in the oxidations of glucose-6-phosphate, ribose-5-phosphate and erythrose-4-phosphate indicated that these sugar phosphates were oxidized to the respective phosphoaldonic acids¹⁰. On the other hand, when 2,4-DNP was added to other parts, yellow precipitation of 2,4-dinitrophenylhydrazone derivatives appeared only with the products obtained from glucose-1-phosphate and fructose 1,6-diphosphate. This indicated that $-\text{CHOH}$ group of the sugar phosphates were not oxidised to $\text{C}=\text{O}$; rather $-\text{CH}_2\text{OH}$ group of glucose-1-phosphate was oxidised to $-\text{CHO}$ group. On the other hand, since both C_1 and C_6 of fructose 1,6-diphosphate are blocked by the phosphate group, $\text{C}-\text{C}$ bond of this compound was cleaved leading to the formation of aldehyde compound which reacted with 2,4-DNP to give 2,4-dinitrophenylhydrazone derivatives.

Since the reactions were studied in excess [substrate] the oxidation of glucose-1-phosphate and glucose-6-phosphate may be expressed respectively as shown in Eqs 1 and 2.



Substrate	ΔH^\ddagger (kJ mol ⁻¹)	ΔS^\ddagger (JK ⁻¹ mol ⁻¹)
Glucose-1-phosphate	156	235
Glucose-6-phosphate	132	164
Ribose-5-phosphate	125	150
Erythrose-4-phosphate	109	122
Glyceraldehyde-3-phosphate	101	51
Fructose 1,6-diphosphate	72	-27

where $R^1 = \text{H}_2\text{O}_3\text{POHOCH}(\text{CHOH})_4^-$



where $R^2 = \text{H}_2\text{O}_3\text{POH}_2\text{C}(\text{CHOH})_4^-$

However, when the reaction mixture containing glucose-1-phosphate and excess permanganate in perchloric acid medium were allowed to react for several hours further oxidation of the $R^1\text{CHO}$ occurs.

Results and discussion

The pseudo-first order rate constants at 35°C ($10^4 k_{\text{obs}}$) determined at different $[\text{MnO}_4^-]$ in the region $(3.33-33.3) \times 10^{-4} \text{ mol dm}^{-3}$ but a constant [substrate], $[\text{HClO}_4]$ and $[\text{NaF}]$ of 8×10^{-3} , 1.0 and $2 \times 10^{-2} \text{ mol dm}^{-3}$ for glucose-1-phosphate, glucose-6-phosphate, ribose-5-phosphate, erythrose-4-phosphate and fructose-1,6-diphosphate are 2.71 ± 0.6 , 7.36 ± 0.2 , 21.5 ± 0.5 , 320.0 ± 0.1 and $12.8 \pm 0.3 \text{ s}^{-1}$ respectively. The results indicate that the order in $[\text{MnO}_4^-]$ is unity. The pseudo-first order rate constants were determined at different sugar phosphate concentrations but at constant concentration of other reagents. The pseudo-first order rate constant increases linearly with the increase in [sugar phosphate] with zero intercept indicating that each reaction is first order in [sugar phosphate]. The second order rate constants at $[\text{HClO}_4] = 1.0 \text{ mol dm}^{-3}$ and at 35°C for the oxidation of glucose 1-phosphate, glucose 6-phosphate, ribose 5-phosphate, erythrose 4-phosphate and fructose 1,6-diphosphate are 3.39×10^{-2} , 9.23×10^{-2} , 26.87×10^{-2} , 400×10^{-2} and $16 \times 10^{-2} \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$ respectively. The reducing abilities of the sugar phosphates follow the order: erythrose 4-phosphate > ribose 5-phosphate > fructose 1,6-diphosphate > glucose 6-phosphate > glucose 1-phosphate. The results indicate that the compounds existing in either acyclic or furanoid forms react faster than those existing in pyranoid form. Again of the two different sugar phosphates

which exist in pyranoid form, glucose 6-phosphate react at faster rates than glucose 1-phosphate. This is due to the fact that oxygen atom of the ring exerts-I effect which is more pronounced on the nearer C_1 position than C_6 .

The reactions were also studied at different $[\text{H}^+]$ in the range $(0.2-2.0 \text{ mol dm}^{-3})$. The acidity was varied by the addition of perchloric acid to the reaction mixture. Since the rates increase to the extent of 68, 50, 51 and 75% in $2.0 \text{ mol dm}^{-3} [\text{NaClO}_4]$ from those in the absence of salt in the oxidations of glucose 1-phosphate, glucose 6-phosphate, ribose 5-phosphate and erythrose 4-phosphate respectively, the ionic strength of each experiment was maintained constant by the addition of sodium perchlorate. The pseudo-first order rate constant increases with the increase in $[\text{H}^+]$. The slopes of the $\log k_{\text{obs}}$ versus $\log [\text{H}^+]$ plots have been calculated to be (0.9 ± 0.1) .

The second order rate constant (k_2) for the oxidation of sugar phosphates by acid permanganate were determined at different temperatures. The enthalpy of activation (ΔH^\ddagger) for the reactions were calculated from the least squares plots of $\log k_2/T$ against $1/T$ followed by entropy of activation (ΔS^\ddagger) using the relation,

$$k_2 = \frac{kT}{h} \exp\left(-\frac{\Delta H^\ddagger}{RT}\right) \exp\left(\frac{\Delta S^\ddagger}{R}\right) \quad \dots (3)$$

where k and h are Boltzmann and Planck constants. The average error limits in the values of ΔH^\ddagger and ΔS^\ddagger are $\pm 8 \text{ kJ mol}^{-1}$ and $\pm 27 \text{ JK}^{-1} \text{ mol}^{-1}$ respectively. All the reactions except that of fructose 1,6-diphosphate are characterized by higher activation parameters (Table 1). These are similar to those observed¹¹ in the hydrolyses of some glycosides in acid medium. The higher activation parameters are not unexpected since all the sugar phosphates are oxidized via C-H bond fission whereas fructose 1,6-diphosphate is oxidized via C-C bond cleavage.

Sodium salts of the sugar phosphates exist as negative ions in aqueous solutions but under acidic condition ($> 1.0 \text{ mol dm}^{-3}$) the respective anions are completely protonated. Again the apparent ionisation constants of some sugar phosphates are known. The pK_1 values¹² of glucose-1-phosphate, glucose-6-phosphate and fructose 1,6-diphosphate are 1.10, 0.94 and 1.48 whereas the pK_2 values¹² for the respective compounds are 6.13, 6.11 and 6.32. D-glucopyranose-1-phosphate is believed to exist as β conformation and the pK values indicate the formation of hydrogen bond

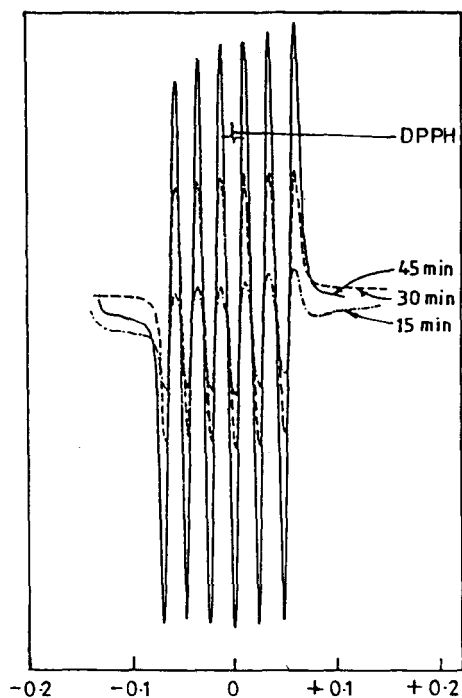


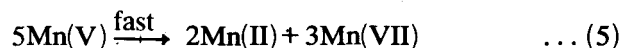
Fig. 1—The EPR spectra of the reaction mixture involving permanganate and glucose-1-phosphate at different time intervals and at 9.45 GHz.

between the ring oxygen of the sugar moiety in β -conformation¹³ and the second acid hydrogen of the phosphate group of the sugar phosphates. D-glucose-6-phosphoric acid exists mainly as the β -pyranoid chair form. Since the second hydrogen atom of the phosphate group is bonded to the ring oxygen of the sugar moiety and the medium is strongly acidic, protonation of the ring oxygen atom is not feasible owing to intramolecular hydrogen bonding. Likewise protonation of the ring oxygen atom with D-ribose-5-phosphoric acid which exists mainly as α -furanoid form¹⁴ seems unlikely. Since the rate increases linearly with increase in $[H^+]$, protonation of permanganate anion to give permanganic acid¹⁵ occurs which then reacts with the substrates.



The reaction occurs through the formation of an unstable intermediate (fast) which then decomposes to give products via C-H bond rupture (slow) in the oxidations of sugar phosphates unlike fructose 1,6-diphosphate. The formation of phosphoaldonic acids clearly indicates that C-H bond breakage occurs in the rate determining step although it is not clear whether the slow step involves hydride ion transfer or hydrogen atom ab-

straction. It has been shown⁹ in the permanganate oxidation of some organic compounds that hydride ion is transferred from substrates to oxidant. Since addition of acrylonitrile to the reaction mixtures failed to give polymer the possibility of hydride ion being transferred from the substrates to acid permanganate cannot be ruled out. Fructose 1,6-diphosphate, however, is oxidized by C-C bond cleavage. During reactions manganese (VII) is reduced to manganese(V) which decomposes in a fast step to give manganese(II) and manganese(VII) as shown below.



The existence of manganese(V) as a short lived intermediate has been shown¹⁶ in the oxidation of unsaturated compounds by permanganate whereas manganese(VII) is reduced to manganese(IV)¹⁷ in neutral solution. Since the reaction mixtures were found to be transparent in the present reactions, the formation of manganese(IV) has been ruled out. The EPR spectra of the reaction mixtures were recorded (Fig. 1) at different time intervals. The peak intensity increases with an increase in time thus indicating that paramagnetic species are generated during the reactions. The absence of the formation of polymer when vinyl compounds were added to the reaction mixtures suggest that free radical does not intervene and paramagnetic behaviour of the reaction mixture may be due to the formation of manganese(II) species. The experimentally obtained order with respect to each reagent and the products identified in each reaction corroborate the suggested steps.

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