Kinetics and Mechanisms of the Acid Degradation of the Aldopentoses to Furfural

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Abstract □ The acid degradation of the aldopentoses to furfural and the degradation of furfural were followed spectrophotometrically and are first-order functions of HCl and pentose concentration. The aldopentose is largely transformed to furfural with small parallel reactions (7–25%). The furfural is subsequently degraded by specific hydrogen ion-catalyzed solvolysis to nonchromophoric products. The heats of activation were the same for the aldopentoses, 30 kcal./mole. The order of reactivities were ribose > xylose ~ lyxose > arabinose and in the ratio 5.4:2.2:2.2:1. The steric positioning of the hydroxyls in the reactive forms were the controlling factor. Free rotation of the hydroxyls in the open-chair form negates any steric requirements for this form. No correlation between steric factors and observed reactivities could be found for the furanose forms. The most plausible explanation of the order and magnitudes of the reactivities is that the rate-determining step is dehydration of the 3-OH, 2H or 4-OH, 5-H in those pyranose conformers amenable to axial-axial dehydration. The relative rates of dehydration are functions of the equilibrium concentrations of these reactive conformers and a specific reactivity which is a stereochemical function of the numbers of axial hydroxyls of such conformers. This explanation and the data are consistent with a positive entropic effect which implies that the transition state involves ring opening.

Keyphrases □ Furfural formation—aldopentose acid degradation □ Aldopentose acid degradation—kinetics, mechanism □ UV spectrophotometry—aldopentoses, furfural degradation monitoring □ Heats of activation—aldopentoses □ Hydroxyl steric position—reaction effect.

The thermal degradation of the aldopentoses (ribose, xylose, lyxose, and arabinose) by mineral acids yields furfural (1–4). The UV spectrophotometric absorbance of furfural (5) or of the colored compounds formed on its reaction with other reagents (6) have served as bases for analysis of these aldopentoses as well as compounds that contain them.

A sensitive analytical technique for the determination of ribose has recently been developed in these laboratories (5). This method depends on the UV absorbance of furfural produced from degrading solutions of ribose under well-defined conditions of acidity, temperature, and time.

The purposes of this investigation were to determine the rate constants and their dependencies for the acid degradation of the aldopentoses to furfural, to ascertain the possible stereochemical effects of the hydroxyl positions on these kinetics, and to develop a mechanism consistent with these effects.

EXPERIMENTAL

Materials and Apparatus—D-Ribose, D-xylose, and D-lyxose,[1] (analytical reagent grade), D-arabinose (reagent grade)[2] and furfural[3] (reagent grade) were all used. All other chemicals used were of analytical grade. Spectrophotometric readings were taken on a spectrophotometer,[4] slit width 0.1 mm. Complete absorption spectra were obtained on a recording spectrophotometer.[5] Matched quartz cells (1.00 cm.) were used for all measurements. Constant-temperature baths were maintained to within ±0.1° of the temperature of study. The computer curves were obtained and recorded by the use of an analog computer[6] and a recorder.[7]

Kinetic Procedures—A master solution was prepared for each of the sugars under study by weighing out 1×10^{-3} mole in a 100-ml. volumetric flask, and then bringing the volume up to 100 ml. with distilled water. Samples were withdrawn from this 10^{-2} *M* master solution and added to flasks containing the appropriate HCl solutions such that the final concentrations of HCl ranged from 0.25 to 1.00 *M*. The flasks had been pre-equilibrated at the temperatures of the studies. Aliquots were withdrawn at various time intervals, cooled, and the absorbances read at 277 mμ and recorded. The master solution of furfural was prepared by weighing 1×10^{-3} mole on a gram electrobalance[8] and transferring this quantity to a 100-ml. volumetric flask. The solution was then brought up to 100 ml. with distilled water. The procedures for the studies on furfural were the same.

Possible Furfural Accelerated Degradation of the Aldopentoses—To determine if furfural accelerated the degradation of the aldopentoses, four solutions of ribose, 5×10^{-4} *M*, in 1.00 *M* HCl were prepared. Different concentrations of furfural (1.32×10^{-4} *M*, 2.64×10^{-4} *M*, and 6.6×10^{-4} *M*) were added to three of these and the solutions were then degraded at 80.0°. Aliquots were withdrawn with time and read at 277 mμ against a 1.00 *M* HCl blank as well as against the solution which contained only ribose. From the differences in the absorbances, the absorbance due to the furfural produced was determined.

RESULTS AND DISCUSSION

When the pentoses are degraded in 1.0 *M* HCl at 80°, a chromophore with a $\lambda_{max.}$ at 277 mμ is generated (Fig. 1). The UV spectra of the degraded solutions are identical with that of furfural in 1.0 *M* HCl. The molar absorptivity (ε) of furfural was determined to be 15,200 in agreement with the literature value of 14,800 (7). In the time interval 0 to 24 hr., the rate of increase in absorbance at 277 mμ is linear with time, an apparent zero-order process. Typical examples of such plots are shown in Fig. 2 for xylose.

The apparent zero-order process that is initially observed, is for less than one apparent half-life. The overall production of furfural at constant acid concentration has been shown to be first-order with respect to pentose (8). The typical plots of furfural concentration against time for a given acid concentration and temperature for the various pentoses (Fig. 3) imply a sequential reaction where furfural appears to be generated and decomposed by sequential first-order processes.

These linear slopes (dA/dT) of the initial plots of absorbance at 277 mμ (of the degraded pentose solution) *versus* time (Fig. 2) were divided by the ε value for furfural to obtain the initial rates of furfural production, dF/dt, which were plotted against the initial pentose concentration. The apparent first-order rate constant for the production of furfural was obtained from the slopes of these

[1] Calbiochem.
[2] Eastman Organic Chemicals.
[3] Fisher Scientific Co.
[4] Beckman model DU-2.
[5] Cary, model 15.
[6] Pace TR-10, Electronic Associates, Inc.
[7] Moseley Autograf model 2D-2-X-Y, Hewlett-Packard, Inc.
[8] Cahn.

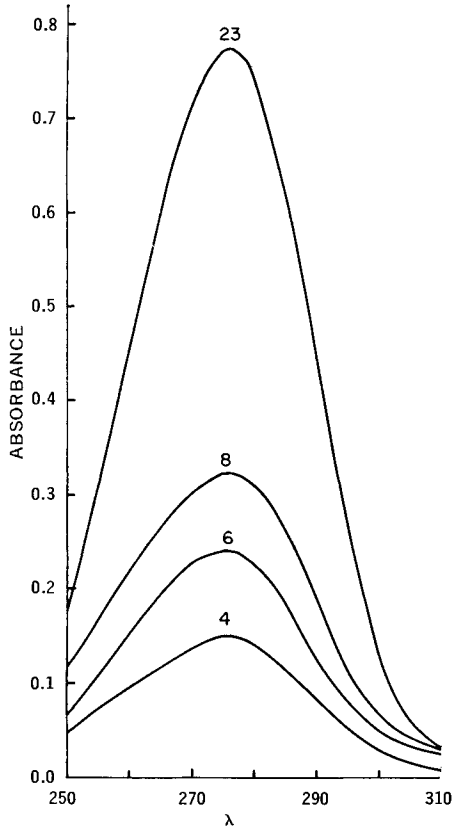


Figure 1—*Typical UV spectra (ribose, 80.0°, 1.00 M HCl) of the degrading aldopentoses. The curves are labeled as to hours after the start of the reaction. The spectrum of furfural under the same conditions is similar except the absorbance decreases with time.*

plots according to:

$$\frac{dA/dt}{\epsilon} = d[F]/dt = k_1[P]_0 = k_{HCl}[HCl][P]_0 = k_{a_{H+}}a_{H+}[P]_0 \quad \text{(Eq. 1)}$$

where k_1 is the apparent first-order rate constant for the production of furfural, k_{HCl} and $k_{a_{H+}}$ are the bimolecular rate constants in terms of acid concentration and hydrogen-ion activity, respectively, and $[P]_0$ is the initial pentose concentration (Fig. 4 and Table I).

A single concentration of each pentose (1×10^{-3} *M*) was degraded at various HCl concentrations and selected temperatures. From this data and from the apparent rate constants obtained by

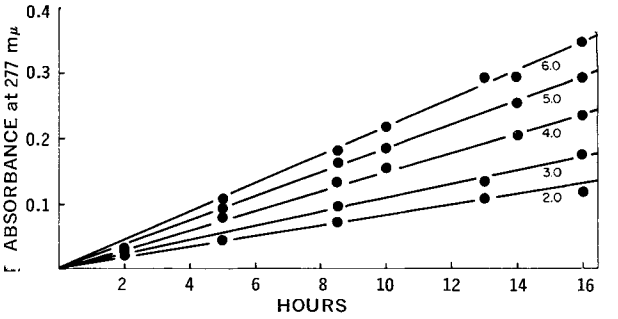


Figure 2—*Degradation of xylose, 80.0°, 1.00 M HCl, as followed by the absorbance at 277 mμ with time. The curves are labeled in terms of 10^4 M xylose.*

use of Eq. 1, the energies of activation and log *P* values for the production of furfural from the pentose were determined in accordance with:

$$\log k = -(\Delta H_a/2.303R)(1/T) + \log P \quad \text{(Eq. 2)}$$

where $R = 1.987$ cal./mole °K. and T is the temperature in °K. (Fig. 5 and Table I). The dependency of the apparent first-order rate constants for the production of furfural (k_1 from Eq. 1) on acid concentration and hydrogen-ion activity were determined from the slopes of the plots of *dF/dt versus* [HCl] and a_{H+} at constant temperature and sugar concentrations (Table I, Fig. 6) according to:

$$k_1 = k_{HCl}[HCl] = k_{a_{H+}}a_{H+} \quad \text{(Eq. 3)}$$

The hydrogen-ion activities were calculated for HCl at 80° by use of the data obtained from the literature (9).

The degradation of furfural was carried out in aqueous acidified solutions at the same acid concentrations and temperatures used for the aldopentoses. The degradation proceeded by an apparent first-order process (Fig. 7) and the apparent first-order rate constant for the degradation of furfural was obtained from the slope of the plots of:

$$\log (A - A_\infty) = k_3t/2.303 + \log (A_0 - A_\infty) \quad \text{(Eq. 4)}$$

where k_3 is the apparent first-order rate constant for the degradation of furfural, and was determined to be 0.582×10^{-6} sec.$^{-1}$. The bimolecular rate constants $k_{a_{H+}}$ and k_{HCl} as well as the ΔH_a and log *P* values were obtained for furfural according to Eqs. 1–3. These values were $k_{a_{H+}} = 0.79 \times 10^{-6}$ l./mole-sec., $k_{HCl} = 0.58 \times 10^{-6}$ l./mole-sec., $\Delta H_a = 21.3$ Kcal./mole, and log $P = 7.9$.

The acid degradations of the aldopentoses were carried out to completion and the maximum yields of furfural determined. As seen from the partial plots of the data in Fig. 3, these yields varied with the aldopentose.

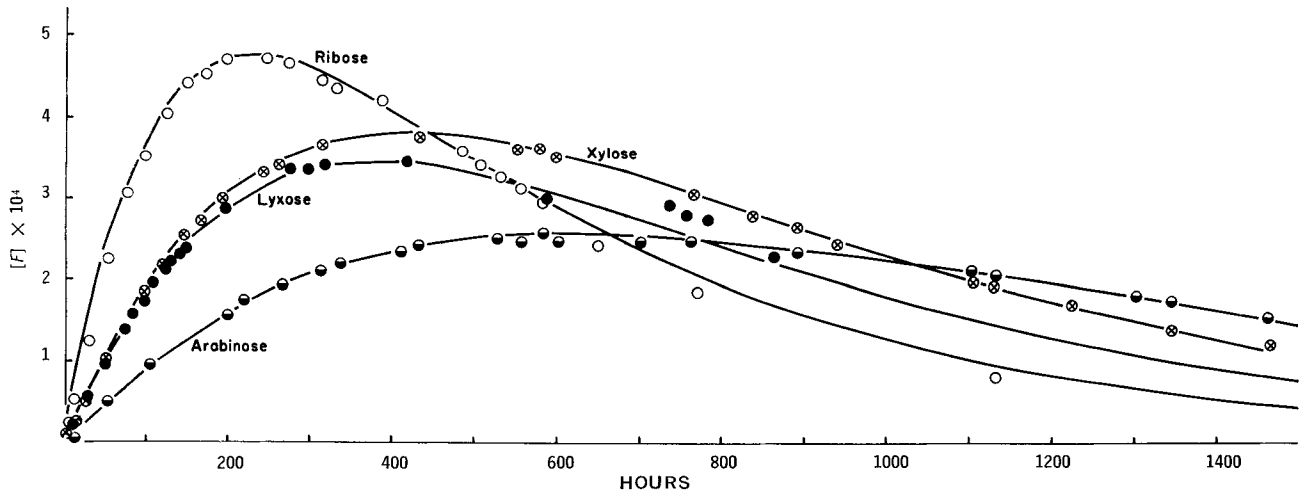


Figure 3—*Acid degradation of the aldopentoses (10^{-3} M) to furfural as followed by the absorbance appearing at 277 mμ as a function of time, 1.00 M HCl, 80.0°. The solid lines are the curves drawn by the analog computer programmed with the appropriate model.*

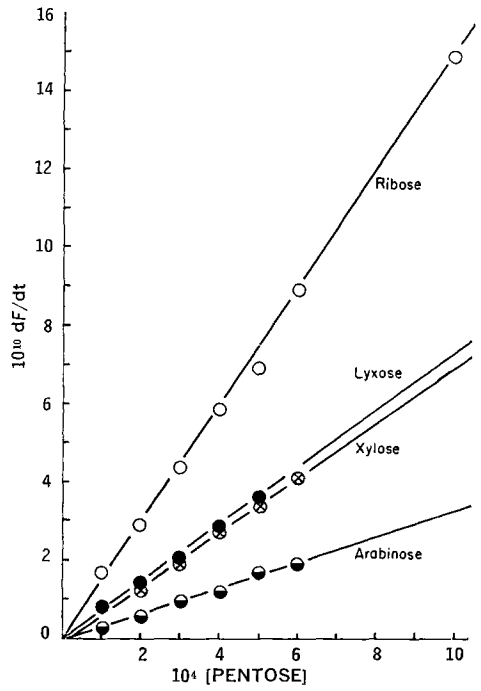


Figure 4—*Instantaneous rate of furfural production* (dF/dt) versus *initial pentose concentration, 80.0°, 1.00* M *HCl.*

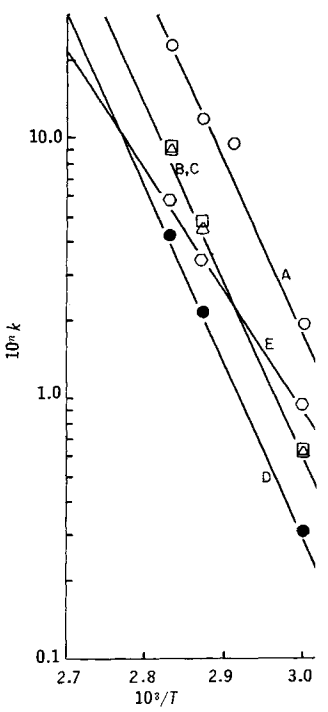


Figure 5—*Arrhenius plots for* A, *ribose;* B, *xylose;* C, *lyxose;* D, *arabinose; and* E, *furfural in 1.00* M *HCl.* k *is in absorbance units-l.²/mole²-sec. and* n = 6 *for* A-D, n = 7, *and* k *is in absorbance units/sec. for* E.

The differences in the observed maximum yield of furfural may depend on the relative rates of furfural degradation to its formation under the same conditions. On the basis of this assumption, the following model has been proposed (8)

$$\text{pentose} \xrightarrow{k_1} \text{intermediate(s)} \xrightarrow{\text{fast}} \text{furfural} \xrightarrow{k_2} \text{destruction products} \quad \text{(Eq. 5)}$$

If the formation of the intermediate(s) is slow and the formation of furfural from the intermediate(s) is fast, the above model may be simplified to

$$\text{pentose} \xrightarrow{k_1} \text{furfural} \xrightarrow{k_2} \text{destruction products} \quad \text{(Eq. 6)}$$

This model (Eq. 6) was programmed into the analog computer along with the experimentally determined rate constants k_1 for formation of furfural and k_2 for destruction of furfural. The generated curves yielded values for furfural concentration greater than those experimentally observed.

Table I—Rates of Production of Furfural Absorbance at 277 mμ,[a] Rate Constants, and Arrhenius Parameters, from Acidic Solutions of the Aldopentoses

Sugar	10^6 dA/dt[b] in 1.00 M HCl at 80.0°: 10^4[Pentose] 1	2	3	4	5	6	7	10	$10^6k^c_{1_{exptl.}}$	$10^6k^d_{1_{compt.}}$	$10^6k_{2_{compt.}}$
Ribose	2.59	4.39	6.64	8.96	10.6	13.63	—	22.69	1.54	1.67	0.545
Xylose	1.28	2.08	2.97	4.12	5.20	6.11	—	8.89	0.678	0.699	0.112
Lyxose	1.17	2.10	3.12	4.38	5.55	6.25	—	9.21	0.711	0.677	0.292
Arabinose	0.48	0.94	1.42	1.85	—	2.61	3.03	4.81	0.310	0.312	0.028

Sugar	10^6 dA/dt[b] at 1 × 10^{-3} M Pentose, 80.0°: [HCl] 0.125	0.25	0.375	0.50	0.75	1.00	k_{HCl}[e] 10^6	$k_{a_{H^+}}$[f] 10^6
Ribose	—	4.41	—	11.83	16.77	22.69	1.94	1.49
Xylose	0.916	1.25	3.47	3.89	5.69	8.89	0.736	0.539
Lyxose	—	1.81	—	4.23	6.73	9.21	0.808	0.597
Arabinose	—	0.90	—	2.33	2.70	4.81	0.354	0.314

Sugar	10^6 dA/dt[b] at 1 × 10^{-3} M Pentose, 1.00 M HCl: °C 80.0	75.0	70.0	60.0	ΔH_a[g]	log P[g,h]	ΔS_a[g,i]
Ribose	22.69	11.75	9.54	1.96	30.9	17.5	21.2
Xylose	8.89	4.48	—	0.60	30.3	17.0	18.9
Lyxose	9.21	4.83	—	0.63	30.3	17.0	18.9
Arabinose	4.27	2.24	—	0.31	30.8	16.7	17.5

[a] Determined between 5 and 20 hr. after initiation of reaction. [b] dA/dt determined from the initial slope of absorbances at 277 mμ *versus* time for each of the pentoses at various concentrations where dA/dt is in absorbance units/sec. [c] $k_{1_{exptl.}} = [(dA/dt)/\epsilon]$/[pentose] where ϵ = 15,000 absorbance units-l./mole and k_1 is in units of sec.$^{-1}$. [d] $k_{1_{compt.}}$ was read off the analog computer when a fit of the experimental data was obtained. [e] $k_{HCl} = [(dA/dt)/\epsilon]$/[HCl][pentose] where ϵ = 15,000 absorbance units-l./mole, [pentose] = 1 × 10^{-3} M, and k_{HCl} is in units of l./mole-sec. [f] $k_{a_{H^+}} = [(dA/dt)/\epsilon]/(a_{H^+})$ [pentose] where ϵ = 15,000 absorbance units-l./mole, [pentose] = 1 × 10^{-3} M and a_{H^+} is calculated for HCl at 80.0° by use of the data obtained from (9). k_{aH^+} is in l./mole-sec. [g] ΔH_a and log P obtained from log $k = (-\Delta H_a/2.303R)(1/T)$ + log P, where R = 1.987 cal./mole °K., T is in °K., and k is the second-order rate constant for the degradation of the sugars at the different temperatures as obtained from (dA/dt)/[pentose] [HCl] where [pentose] = 1 × 10^{-3} M and [HCl] = 1.00 M. ΔH_a is in Kcal./mole. Within experimental error all ΔH_a's can be considered to be the same. Log P values were determined using a common ΔH_a of 30.8 Kcal./mole. [h] The order of log P followed the reactivities of the sugars. [i] $\Delta S_a = 2.303\ R\ [\log P - (\log \bar{k}T/h)]$. $\bar{k}$ is the Boltzmann constant, h the Planck constant, T the temperature in °K. Log P was determined from the Arrhenius expression, ΔS_a is in cal./mole-°K.

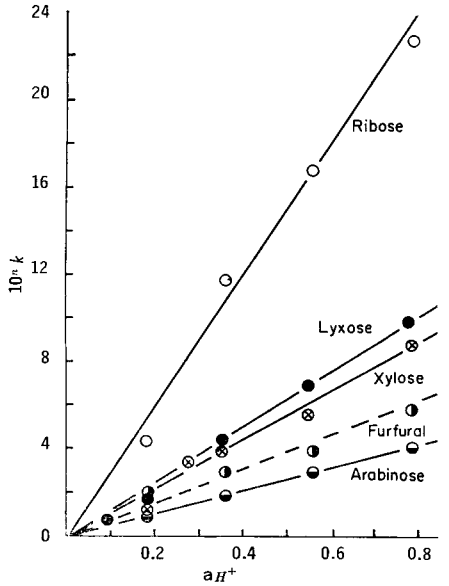


Figure 6—*Dependence of the apparent first-order rate constants for the production and degradation of furfural* versus *hydrogen-ion activity, 80.0°.* n = *3 for the aldopentoses,* n = *7 for furfural.*

The higher theoretical concentrations could be rationalized by postulating a yield-reducing side reaction. The possible side reactions may be caused by the reaction of the intermediate(s) with some of the furfural being formed (Eq. 7) or by a parallel reaction (Eq. 8) where the pentose proceeds to a nonchromophoric product

$$\text{pentose} \xrightarrow{k_1} \text{intermediate(s)} \xrightarrow{\text{fast}} \text{furfural} \xrightarrow{k_3} \text{destruction products}$$

$$\text{intermediate(s)} + \text{furfural} \xrightarrow{k_2} \text{other products} \quad \text{(Eq. 7)}$$

$$\text{pentose} \xrightarrow{k_1} \text{furfural} \xrightarrow{k_3} \text{destruction products}$$
$$\xrightarrow{k_2} \text{other products} \quad \text{(Eq. 8)}$$

It has been stated in the literature (8, 10) that under conditions of high acidity, temperature, and/or pressure, intermediates react with furfural and promote its destruction (Eq. 7). A single concentration of ribose was degraded in the presence of various furfural concentrations. If the model in Eq. 7 is correct, a change in the rate of furfural production and the maximum observed yield of furfural was expected. The results of this experiment showed no change whatsoever in either of these two parameters (Fig. 8). Thus under

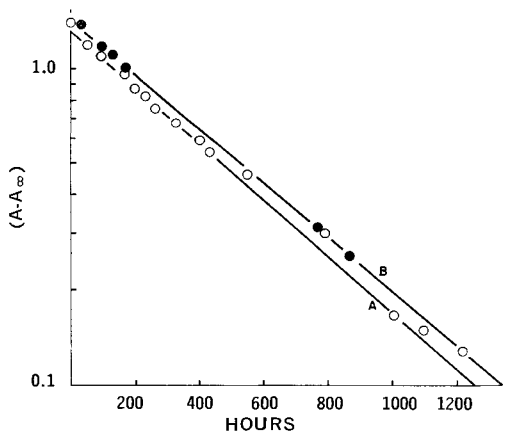


Figure 7—*Typical first-order plots for the degradation of furfural, 80.0°, 1.00* M *HCl. Curve* A *is 0.021* × 10^{-4} M *and* B *is 0.944* × 10^{-4} M *in furfural.*

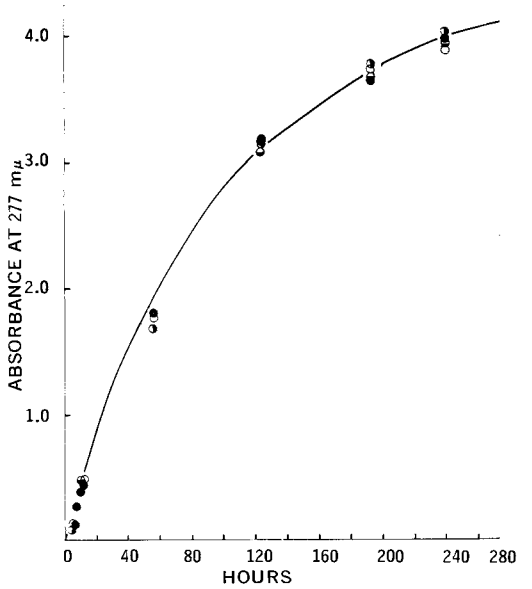


Figure 8—*Absorbance of furfural produced from degrading solutions of ribose (5* × 10^{-4} M*) and furfural at 80.0° in 1.00* M *HCl. The data are corrected for the absorbance contributions of the furfural initially present.* ○, *Control, no furfural added;* ●, *1.32* × 10^{-4} M F; ◒, *2.64* × 10^{-4} M F; ◑, *6.6* × 10^{-4} M F.

these conditions of acidity and temperature it is more reasonable to postulate the acidic transformation of the aldopentoses by parallel reactions (Eq. 8) to furfural and other nonchromophoric products.

To determine if this was the model for conditions in this laboratory, Eq. 8 was programmed into the analog computer. The k_3 experimental values were used and values of k_1 and k_2 adjusted for optimum fit of the plots of concentration of furfural *versus* time (Fig. 3). The computer values for the rate constants k_1 and k_2 are given in Table I. The excellent agreement between the computer-obtained values of $k_{1_{compt.}}$ and the experimental $k_{1_{exptl.}}$ (Eq. 1) is well demonstrated. The $k_{1_{compt.}}$ value for ribose was the same as that previously obtained experimentally (5).

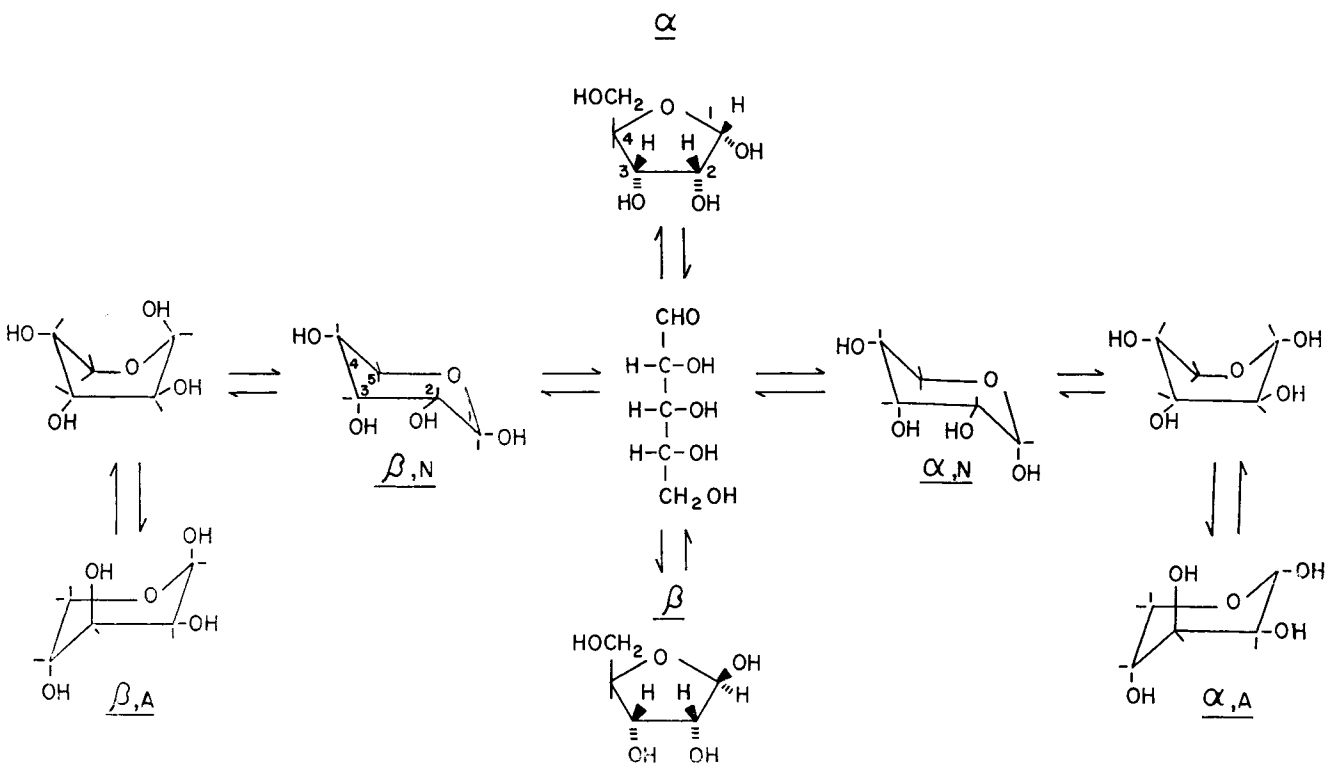
A Consistent Mechanism of Furfural Formation—The aldopentoses studied differ mainly in the steric positioning of the hydroxyl functions. Thus, the differences in their rates of furfural production should be explicable on the basis of their stereochemistry.

In aqueous solution, reducing sugars are present as complex mixtures of isomeric forms (11, 12*a*). The physical and chemical properties of equilibrated sugars in solution will depend on the composition at equilibrium of these mixtures.

The aldopentoses can take three forms in aqueous solution. These are (*a*) open chain; (*b*) furanose; and (*c*) pyranose. The furanose form has two possible anomers, α and β. The pyranose form has two possible anomers α and β, each having an A or N conformer in the chair form as well as an intermediate boat conformer (12*a*) (Scheme I).

Los *et al.* (11) have shown that an equilibrium solution of glucose contains only very minor amounts of the open-chain aldehyde form. This has been stated to be the case for all aldehyde sugars including the pentoses (12*a*, 13). Also, there is free rotation of hydroxyls in the open-chain aldehyde form so that steric effects cannot be rationalized as a cause for preferential dehydration from these forms. Thus it is argued that the dehydration of the open-chain form of the aldopentoses are not kinetically significant in the acid degradation of these sugars to furfural.

Bishop and Cooper (14) have studied the glycosidation of pentoses in methanolic hydrogen chloride by means of gas chromatographic quantification of products. The equilibrium constants and the derived free energies for the furanoside-pyranoside equilibria reflect the relative fractions of the equilibrated forms in solution, and show that the fractions as α and as the sum of the α and β furanoside decrease in the order arabinose > ribose > xylose > lyxose; for relative fractions as β furanoside, the order is ribose > arabinose > xylose > lyxose.



Scheme I—Typical multiple equilibria of the aldopentoses in solution for the example of ribose.

If the furanose conformers are the reactive species in our system and if the relative amounts of furanose forms in our aqueous HCl are similar to those in methanolic HCl (13, 14), the rate of formation of furfural may be proportional to the fraction present as the furanose forms. However, this was not observed. The order of reactivity is ribose > xylose ~ lyxose > arabinose (Table I).

Further argument against the furanose forms as the reactive species in the dehydration to furfural can be found in their stereochemistry (Scheme I).

Elimination of the 1-OH, 2-H cannot be the rate-determining step since the 1-OH is the enolic form of the aldehyde function which must be regenerated to form furfural (16). Elimination of the 3-OH, 4-H or the 2-OH, 1-H would introduce double bonds into such positions that allylic rearrangement or rehydration and subsequent dehydration would be necessary to yield furfural. Only dehydration of the 2-OH, 3-H or 3-OH, 2-H would give an intermediate which would yield furfural.

The hydroxyls on carbon 2 and 3, in the furanose forms, are *cis* for ribose and lyxose and are *trans* for arabinose and xylose. Generally, *trans*-elimination, which occurs with the *cis*-configuration is more facile than *cis*-elimination which occurs with the *trans*-configuration (15). These two criteria are consistent with the ease of dehydration: ribose > xylose and lyxose > arabinose but not with ribose > lyxose, lyxose ~ xylose, or xylose > arabinose on the assumption of equal fractions of furanose forms. Even consideration of different fractions of furanose forms, based on the data of Bishop and Cooper (14), did not give any correlation to the experimentally observed relative rates.

The pyranose forms (Scheme I) can exist as two conformers, chair and boat. The chair form, is the more stable of the two conformers in cyclohexane since it is free of angle, torsional (Pitzer), and van der Waals strains (12*b*). Also, the chair forms can exist in two distinct conformations, each capable of being converted into the other by the flipping of the ring (Scheme I).

The pyranose forms of the sugars are conformationally similar to cyclohexane (12*a*). In the boat form (Scheme I) the substituents on carbons 2, 3, and 5 are *cis-trans*, while those on 1 and 4 may be thought of as axial-equatorial. To a first approximation, the steric positioning of the hydroxyls are similar to those on the furanose ring. Also, Reeves after a careful study of various pyranosides, came to the conclusion that the boat form plays no significant role in the equilibrium of sugar conformations (12*a*).

The chair forms exist in two anomeric configurations, α and β. Either configuration may exist as two conformers, designated normal, N, or alternate, A, dependent on whether or not the hydroxyl on the anomeric carbon is equatorial if it were in the β-anomeric configuration (12*a*) (Scheme I).

If one assumes that the rate of protonation of the aldopentose hydroxyls in the pyranose configuration is much faster than the subsequent elimination of water, the observed dependency on hydrogen ion (Fig. 6) must signify that the rate-determining step occurs after protonation. This leads to the conclusion that the rate-determining step in the acid-catalyzed transformation of the aldopentoses to furfural is the elimination of a water molecule (dehydration).

The overall acid-catalyzed transformation of aldopentose to furfural involves the loss of three molecules of water. If it is argued that the rate-determining step in the acid-catalyzed transformation of aldopentose to furfural is the initial dehydration in the pyranose form (I), the possible dehydrations may be of the following pairs: 3-OH, 2-H (II); 4-OH, 5-H (III); 2-OH, 3-H (VII); 2-OH, 1-H (VIII); 1-OH, 2-H (IX); 3-OH, 4-H (X); or 4-OH, 3-H, (XI) (Scheme II).

VII, VIII, IX, X, and XI, may be ruled out since dehydration to any of these species cannot produce furfural without a subsequent rehydration step. The 2-OH, required for the final closure to the furanose ring, has been eliminated in VII and VIII (see IV → V). The 1-OH, the enolic form of the aldehyde function which must be regenerated to form furfural (16) does not appear in IX. The dehydrations to X and XI would introduce double bonds into such positions that an allylic rearrangement or rehydration and subsequent dehydration would be necessary to yield the furfural structure (see IV → V).

This analysis also permits exclusion of any further dehydrations of VII, VIII, IX, X, and XI as being rate determining. Dehydration to VI may also be excluded as rate determining since it is analogous to the argument presented againt VII and VIII. There is free rotation about the 3 and 4 carbon atoms in IV and thus dehydration of IV to V may also be excluded as rate determining since steric factors are of no importance. This leaves the possibilities that either the initial dehydration to II or III, or the second dehydration II or III to IV may be rate determining. These routes are consistent with the premises that the steric and conformational attitudes of the several aldopentoses should be related to the ease of dehydration.

The rates of reactions occurring at ring positions may be affected by two factors, stereoelectronic and steric. Stereoelectronic factors

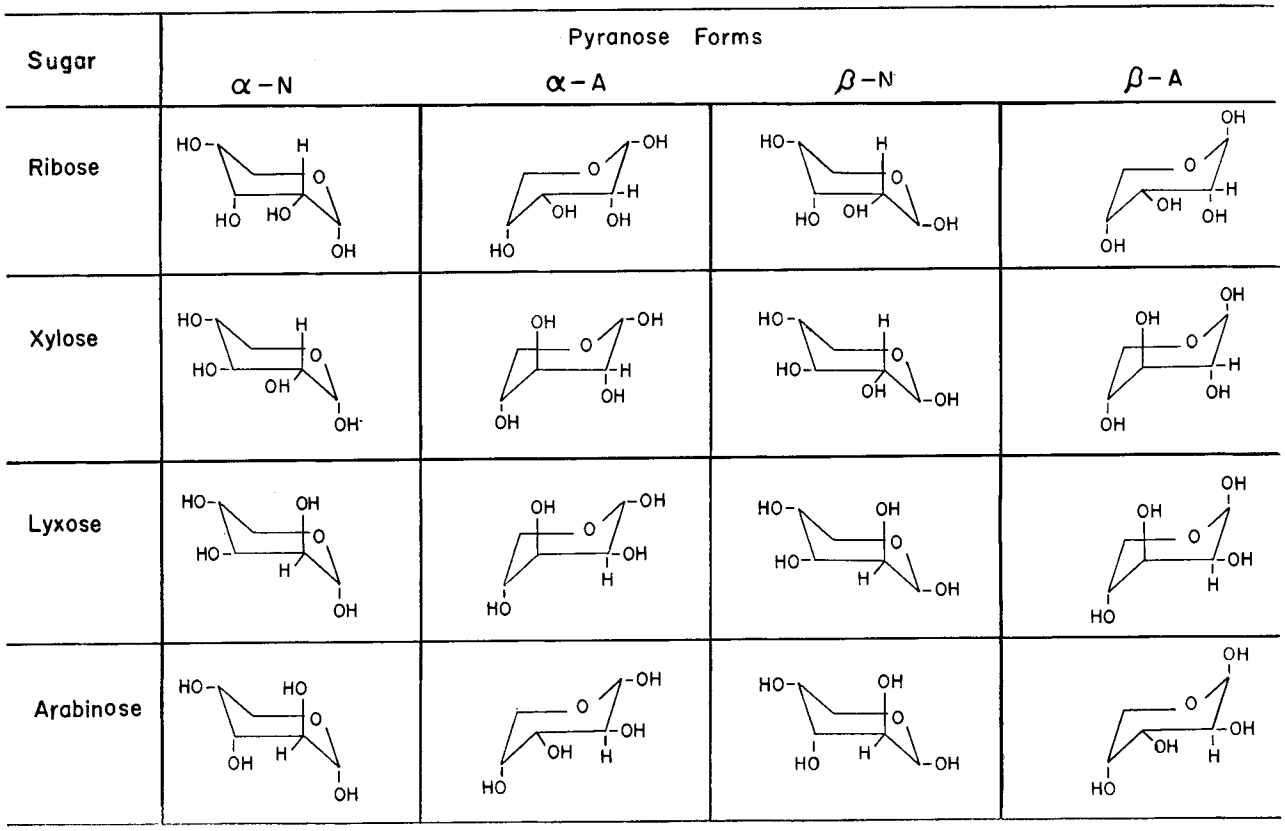


Figure 9—*Structures of the various conformers of the aldopentoses in the pyranose form.*

are due to the more or less favorable arrangement of the bonding electrons toward the preferred geometry of the transition state. Such factors in bimolecular elimination reactions favor the removal of atoms or groups when they are *trans* and diaxial (A-A) (15, 17*a*, 12*d*). Diequatorial eliminations (E-E) are slower than A-A eliminations but are more facile than axial-equatorial (A-E) eliminations (15, 17*a*). This latter type of elimination occurs with great difficulty, if at all (17*b*). The rate differences due to stereoelectronic causes are of the order of several powers of 10 (10^2 or greater) (12*d*). However, the observed rate differences (Table I) were much smaller than would be expected if attributable to stereoelectronic causes. This leads to the conclusion that the degradation of the aldopentoses all proceed by the same type of elimination.

The structures of the aldopentoses in the various pyranose forms are given in Fig. 9. Either A-A, E-E, or A-E elimination is possible for all the sugars. Thus, it may be concluded that the degradation of the aldopentoses all proceed by the facile A-A elimination.

The rate of dehydration may not only be dependent on the necessity of axial-axial elimination but the fracton of the sugar in those conformers amenable to A-A elimination. This may indicate that steric factors affect the rate of dehydration by affecting concentrations of reactive conformers. Those with the greatest number of nonhydrogen equatorial substituents should be preferred because of less steric crowding in the ground state (17*b*). The interaction energies for each conformer (Table II) (12*c*) indicate the percentage of each aldopentose in each conformer and reflect this statement. Consistent with the present authors' data (Table I), is the fact that the rate differences assignable to such causes are of the order of magnitude of 2 to 60 times (12*d*).

If one assumes that the rate constant for A-A elimination is the same for all the aldopentoses, then the degradation of ribose should be favored since all its possible pyranose forms are amenable to A-A elimination (Fig. 9) either by I to II or III (Scheme II). Lyxose degradation should proceed at a slower rate than ribose since only the A forms (Fig. 9) are amenable to A-A elimination (I → II, and III) (Scheme II). To a first approximation one may state that since the A and N forms have similar interaction energies (Table II) they should be present 1:1 in an equilibrium solution. The percent of lyxose and ribose present in an equilibrated solution differs only slightly (Table II) but since only the A forms of lyxose can eliminate A-A, the overall rate of degradation of lyxose to furfural may be expected to be one-half that for ribose. This is in agreement with the data (Table I). Of course, these arguments are made on the premise that the estimates of fractions amenable to axial-axial dehydration which were made at 25° are valid for our reacting conditions at 60–80°.

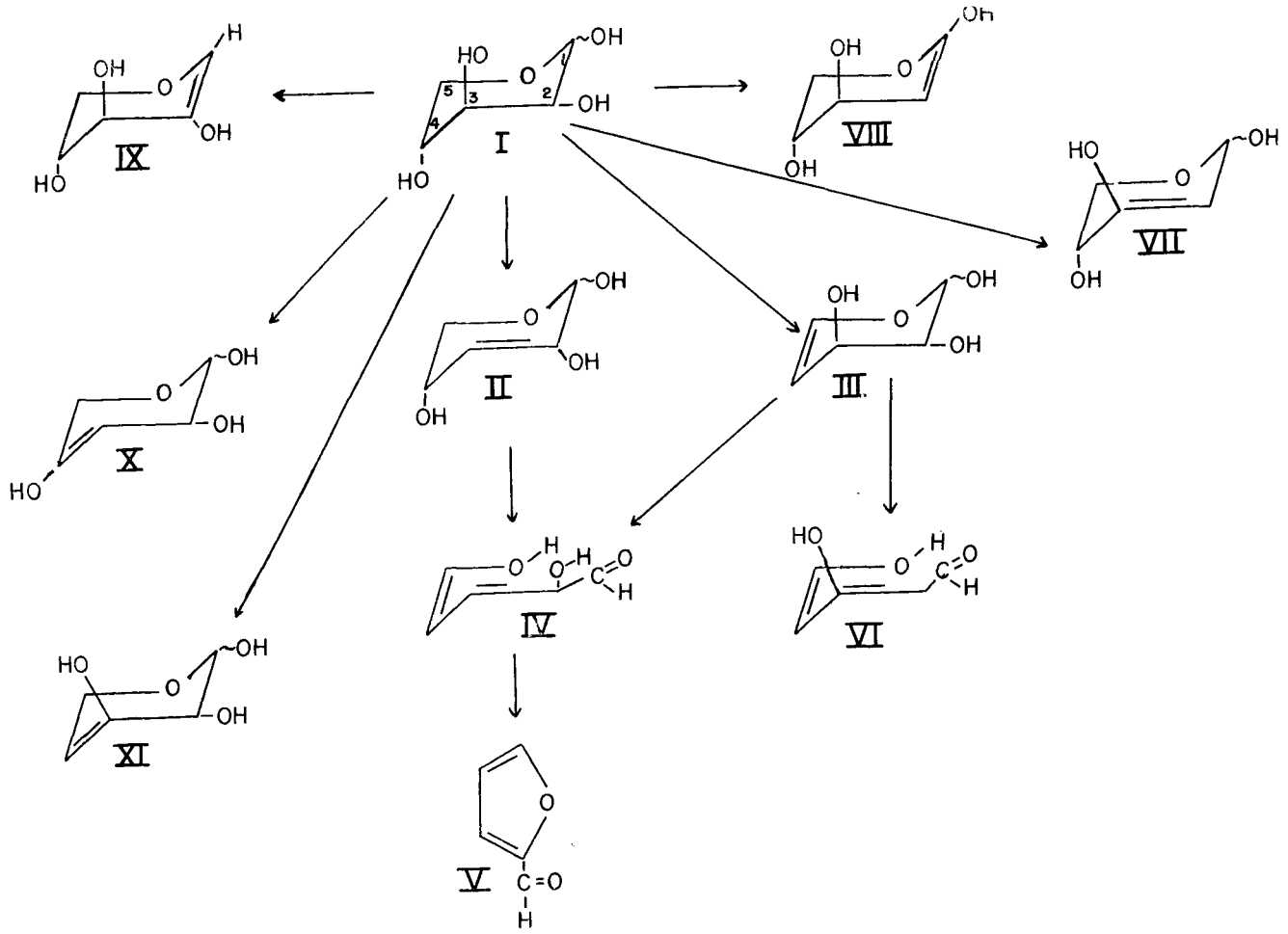
Similar analysis of the data for xylose and arabinose (Fig. 9 and Table II) predicts that the relative degradation reactivities of these two sugars should be the reverse of the observed fact that xylose degradation was almost twice that of arabinose. Thus the hypothesis that the relative dehydrations are dependent only on a constant rate of axial-axial elimination of those fractions of sugars in conformers amenable to such eliminations is inconsistent with the facts.

An alternative hypothesis is that the steric influence on relative reaction rate is effected through sterically modified rates of axial-axial dehydration. It may be postulated that axial-axial dehydration to furfural of the conformer with the greatest number of nonhydrogen axial substituents proceeds at faster rates. An interesting relationship between reactivities and numbers of axial hydroxyls does exist. The relative rate constant for furfural formation, k_r, is assumed to be proportional to the sums of the products of the fraction of sugar in the reactive forms amenable to axial-axial dehydration to furfural, f_r, and the total number of axial hydroxyls on each of these reactive forms,

$$k_r = \alpha (f_1 s_1 + f_2 s_2 + f_3 s_3 + f_4 s_4) \qquad \text{(Eq. 9)}$$

where the f_i and s_i are the fractions of conformers amenable to axial-axial dehydration to furfural and their sums of axial hydroxyls, respectively. The value α is the proportionality constant. The ratios of the obtained k_r are 5.6:2.5:2.6:2 = ribose:xylose:lyxose:arabinose where the experimentally obtained values are 5.4:2.2:2.2:1.

Considering that the data available for the calculation of the f_i values (Table II) are estimated based on theoretical consideration of interaction energies (12*c*) in aqueous solution at 25°, the ranking of relative reactivities derived from Eq. 9 is sufficiently in agreement with the actual relative reactivities obtained at 60–80° (Table I)



Scheme II—Possible intermediates resulting from the dehydration of the pyranose forms of the aldopentoses for the example of lyxose.

to implicate the steric enhancement of axial-axial dehydration as a function of the number of nonhydrogen axial substituents on the reacting conformers.

Steric factors may thus influence the dehydration rate in two ways. One affects the fraction of conformer available for A-A dehydration and the other enhances the reactivity at the dehydration sites. Since the dehydration of all aldopentoses involves similar heats of activation (Table I), the enhancement of reactivity appears to be due to entropic factors.

The absolute rate theory (19) states that

$$k = \frac{\bar{k}T}{h} e^{\Delta Sa/R} e^{-\Delta Ha/RT} \qquad \text{(Eq. 10)}$$

where k is the overall rate constant, $\bar{k}$ is the Boltzmann constant, h is the Planck constant, T is the temperature in °K., ΔS_a is the entropy of activation, R is the gas law constant, and ΔH_a the heat of activation.

The entropy term may be calculated by equating the logarithm of Eq. 10 and Eq. 2 which upon rearrangement yields

$$\Delta S_a = 2.303\, R[\log P - \log \bar{k}T/h] \qquad \text{(Eq. 11)}$$

The values for the calculated ΔS_a are given in Table I.

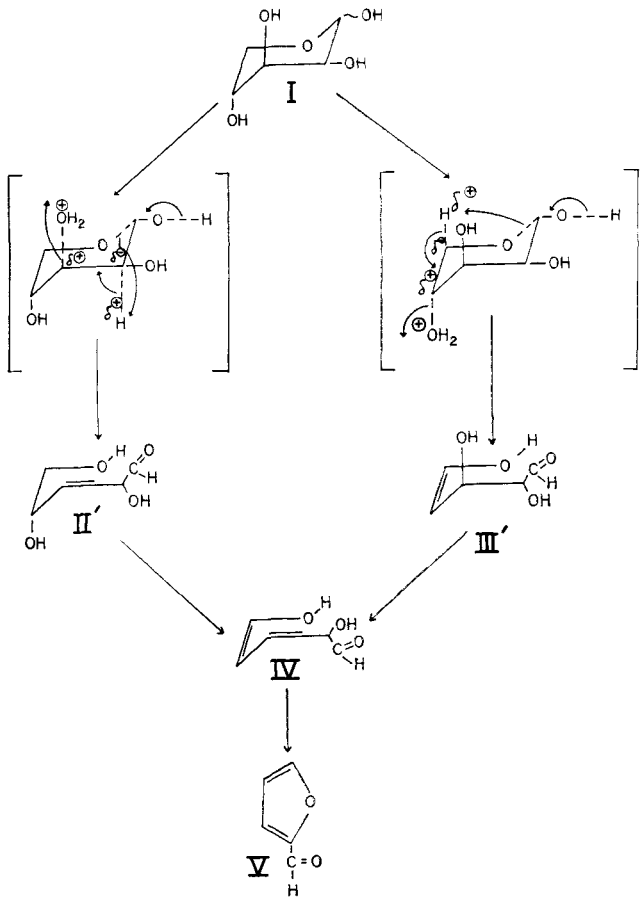
The positive nature of the entropy values are indicative of a process where there is a gain in degrees of freedom from the ground state to the transition state. This may be rationalized by assuming that the transition state for dehydration includes a partial or complete ring opening.

This implies that the hypothesis of dehydrations to II and III (Scheme II) occurring with retention of the cyclic conformation may not be valid. The product of the rate determining initial dehydration as given in Scheme III for the example of lyxose may be postulated as II′ or III′ proceeding through the possible transition state where the leaving positively charged hydrogen is immediately implicated in ring opening.

Table II—Percent of Aldopentose as Pyranose in an Equilibrated Solution, as Reactive Forms and Interaction Energies of the Various Forms

Sugar	Percent Pyranose in Solution[a]	Interaction Energies[b] (Kcal.) and Percent of Reactive Form Present in an Equilibrated Solution[c]			
		α		β	
		A	N	A	N
Ribose	~ 80	4.85 (44)	3.85 (55)	4.4 (36)	2.5 (64)
Xylose	~100	5.05 (28)	1.95	5.6 (22)	1.6
Lyxose	~100	3.05 (45)	2.5	4.4 (40)	2.95
Arabinose	~ 70	2.5 (62)	4.05	2.85 (55)	3.5

[a] Estimated from the data in the literature (13, 14). [b] Taken from the literature (12c) for aqueous solution at 25°. [c] Estimated relationship 100-A/N where A and N are the interaction energies for the reactive forms based on the assumption that only those forms which eliminate the 3-OH, 2H or 4-OH, 5H diaxially are reactive.



Scheme III—Proposed mechanism for the acid degradation of the aldopentoses to furfural for the example of lyxose.

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