

BASE-CATALYZED, PYROLYTIC REARRANGEMENT OF SOME MONOSACCHARIDES

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ABSTRACT

Thermal reactions of D-glucose, D-mannose, D-fructose, D-allose, and D-altrose, in the presence of a basic catalyst, have been investigated and compared with transformations in aqueous alkali. G.l.c. analysis of products formed near the melting point of these sugars showed that melting is accompanied by drastic chemical reactions involving C-3 epimerization in addition to the C-2 epimerization observed in aqueous solution.

INTRODUCTION

Treatment of carbohydrates with aqueous acid or alkaline reagents results in a variety of reactions ranging from mutarotation of the free sugars to extensive rearrangement and degradation of the molecules^{1,2}. Recent studies³⁻⁶ have shown that the same types of transformation also take place when sugars are heated in a dry state. For instance, heating of α -D-xylopyranose^{3,4} results in thermal anomerization of the molecule when it melts; pyrolysis of 1,6-anhydro- β -D-glucopyranose^{5,6}, especially in the presence of alkali, results in opening of the oxygen-containing rings, dealdolization, dehydration, and rearrangement of the molecule; and pyrolysis of glycosides results in cleavage of the glycosidic group and formation of furan derivatives^{3,4,7,8}. We now report on the pyrolytic epimerization of several free sugars.

RESULTS AND DISCUSSION

The sequence of physical and chemical transformations which take place on heating a sample of β -D-glucopyranose mixed with 5% of calcium hydroxide was first investigated by thermal-analysis methods. The resulting thermograms (Fig. 1) show two major, endothermic peaks at 142° and 186°. The first endotherm, which corresponds with the melting point of the sugar, is much wider than the melting-point endotherm of β -D-glucopyranose (Fig. 2) and indicates the simultaneous occurrence of extensive transformations. The second endotherm is accompanied by a sharp loss in weight (t.g.a.), and a d.t.g. peak which signals the decomposition of the sugar.

TABLE I

BASE-CATALYZED THERMAL REARRANGEMENTS OF SOME HEXOSES

Starting material		Condition		Products									
Hexose	Catalyst	Temp. (degrees)	Time (min)	1	2 + D-ribo-hexulose	β -D-Manno-pyranose	3 + D-ribo-hexulose	4 + α -D-allo-pyranose	β -D-Allo-pyranose	D-Allo- and D-pyranose	D-Allo- and D-furanose	Decomposition products ^a	
β -D-Gluco-pyranose (1)	Ca(OH) ₂	130	0	95.8	4.2	0.5	3.7	2.8	T ^b			9.7	
			3	75.0	8.3	0.5	4.1	4.6	T			16.4	
			6	60.3	14.1	0.5	5.5	6.2	T		T	25.8	
			8	40.5	21.5	0.5	5.8	6.4	1.9		0.8	54.4	
			15	15.6	14.5	0.6	7.8	7.5	3.6	T	1.3	53.8	
			20	11.6	13.4	1.0	2.3	1.9	1.3	T	0.5	88.9	
α -D-Gluco-pyranose (2)	Na ₂ CO ₃	110	0	5.6	94.4								
			15	9.7	75.0	1.1	4.5	4.3	2.3		0.8	2.3	
			20	11.8	63.5	1.1	5.5	7.2	3.3	T	1.6	6.0	
			41	15.5	52.0	1.3	8.2	10.0	4.8	T	2.2	6.0	
			51	19.0	44.3	1.6	8.0	9.0	5.1	T	1.0	12.0	
			60	18.5	41.0	1.6	8.1	10.2	4.4	T	1.5	14.7	
α -D-Manno-pyranose (3)	Na ₂ CO ₃	110	80	18.2	35.2	1.4	8.5	11.8	3.2	T	1.8	19.9	
			120	14.5	33.0	1.3	8.6	9.4	3.4	T	1.8	28.0	
			0			3.8	96.2						
			5	6.9	7.1	16.4	58.2	7.6	4.2		T		
			10	7.3	10.9	20.9	40.8	13.7	5.6		2.5		
			15	9.6	13.6	15.5	33.2	18.1	8.3		4.1		8.4
D-Fructose (4)	Na ₂ CO ₃	90	20	8.6	13.5	13.5	28.1	17.2	7.1		3.6	11.6	
			32	8.8	13.0	11.2	27.8	16.7	6.8		4.1	28.9	
			60	5.5	12.6	7.8	16.1	17.8	7.0		4.3		
			0		5.7			94.3					
			10	2.7	7.6	2.1	21.1	59.5	T		T	7.0	
			20	8.8	13.8	3.4	25.4	34.5	5.0	T	4.2	4.9	
			30	13.2	18.3	4.2	27.1	17.6	7.2		3.6	8.8	
			50	11.3	14.6	3.5	23.5	13.0	6.9		3.0	24.2	

^aObtained by difference. ^bT, a small shoulder indicating trace amounts.

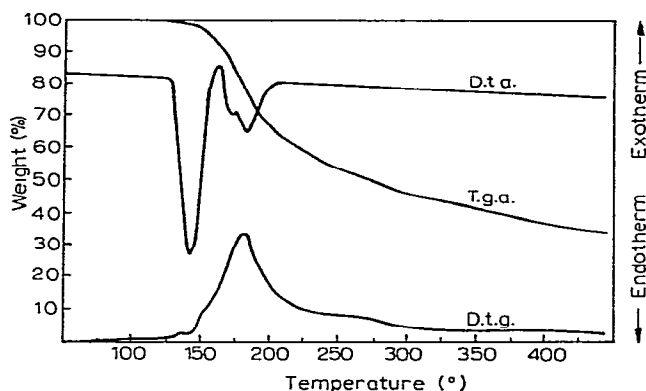


Fig. 1. Thermogram of β -D-glucopyranose + 5% of $\text{Ca}(\text{OH})_2$.

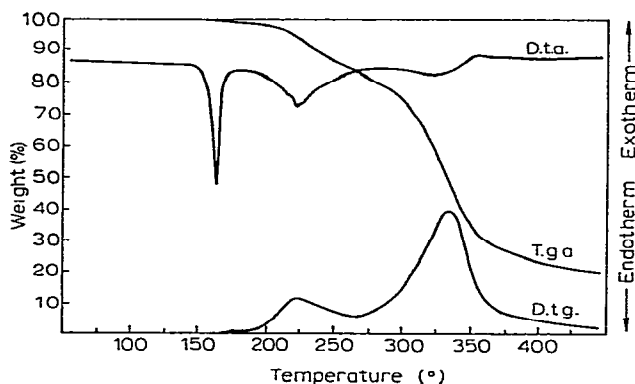


Fig. 2. Thermogram of β -D-glucopyranose.

In the absence of the basic catalyst, the principal thermal reaction of a free sugar in the melting-point region has been shown to be anomerization and equilibration of α and β forms^{3,4,9}. However, in the presence of alkali, the situation is more complicated because of the possibility for epimerization of the free sugar in addition to its anomerization. This possibility was investigated by isothermal heating of the alkali-treated sugar at 130° (near the beginning of the endotherm) for different periods of time to obtain a series of products corresponding to different stages in the development of the endothermic reactions. The products obtained were trimethylsilylated and analyzed by g.l.c.¹⁰. The resulting data, presented in Table I, show the transformation of β -D-glucopyranose to the α -D-anomer as well as D-mannose, D-fructose, D-allose, and trace amounts of D-altrose, which are the products of C-2 and C-3 epimerization and rearrangement. There was also an increasing amount of decomposition as the isothermal heating was continued. It should be noted that the g.l.c. method gave overlapping peaks for α -D-glucopyranose and D-ribo-hexulose, α -D-mannose and another form of D-ribo-hexulose, D-fructose and α -D-allopyranose and the furanoid

forms of allose and altrose. Furthermore, it could not distinguish between the enantiomeric forms. Despite these limitations of the g.l.c. method, the isothermal data, summarized in Fig. 3, augment the results obtained by dynamic thermal analysis (Fig. 1) and show that the melting process is accompanied by rapid, chemical-transformation reactions involving anomerization, epimerization, and increasing decomposition of the sugar molecule.

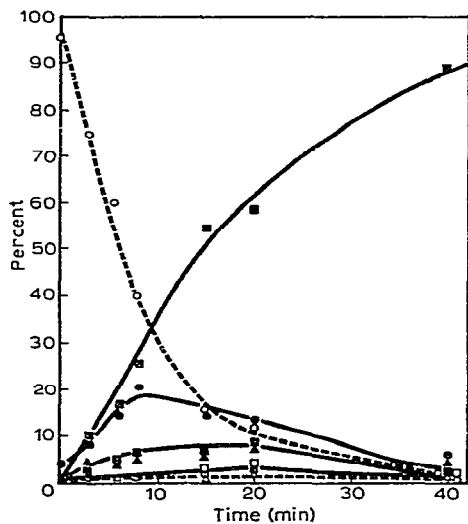


Fig. 3. Thermal rearrangements of β -D-glucopyranose + 5% of $\text{Ca}(\text{OH})_2$. O, β -D-Glucopyranose; ●, α -D-glucopyranose + D-ribo-hexulose; Δ , β -D-mannopyranose; ▲, α -D-mannopyranose + D-ribo-hexulose; ■, D-fructose + α -D-allopyranose; □, β -D-allopyranose; ○, D-allo- and D-altro-furanose; ⊠, decomposition products.

Similar data were also obtained by heating α -D-glucopyranose, α -D-mannopyranose, and D-fructose mixed with 5% of sodium carbonate, with analysis of the reaction mixture at different intervals (see Table I). These data may be compared with the recent results obtained by MacLaurin and Green¹¹ for the transformation of 2mM solutions of the sugars in M sodium hydroxide and the previous studies on Lobry de Bruyn-Alberda van Ekenstein transformations under aqueous conditions¹.

MacLaurin and Green did not detect any D-allose or D-altrose as the transformation products of the D-glucose, D-mannose, and D-fructose triangle, although treatments of D-fructose with dicyclohexylcarbodi-imide¹², secondary amines¹³, and potassium aconitate¹⁴ have been reported to produce D-ribo-hexulose. D-ribo-Hexulose has been also obtained by treatment of D-glucose with ammonia¹⁵. In this study, allose and traces of altrose were detected as the secondary epimerization products of D-glucose and D-mannose, which, in aqueous systems, has generally been considered as a remote possibility¹. The secondary thermal epimerization of hexoses was confirmed by the presence of small peaks for β -D-glucopyranose and a trace

TABLE II
BASE-CATALYZED THERMAL REARRANGEMENTS OF D-ALLOPYRANOSE AND D-ALTROPYRANOSE

Starting material	Temp. (degrees)	Products							
Hexose	Catalyst	β -D-Glucopyranose	α -D-Glucopyranose + D-ribohexulose	β -D-Mannopyranose	α -D-Mannopyranose + D-ribohexulose	D-Fructose + α -D-allopyranose	β -D-Allopyranose	D-Altropyranose and D-allofuranose	Decomposition products ^a
D-Allopyranose (5)	None	25					100		
	145					28.5	61.5	10.0	
	Na ₂ CO ₃	118	S ^b	S	5.5	9.4	70.0	13.0	
	125	0.2	10.0	S	8.5	20.5	40.5	1.3	12.2
	130	0.6	10.2	S	10.2	15.3	33.0	1.4	23.4
D-Altropyranose (6)	None	25						98.5	1.5
	113							83.0	17.0
	Na ₂ CO ₃	105	S	S	4.7	T	3.0	70.5	12.0
	111	S	11.3	S	13.5	6.5	5.2	54.0	8.3
	115	S	10.5	S	11.2	7.5	5.9	41.0	7.8
									16.1

^aObtained by difference. ^bS, a small peak.

amount of β -D-mannose among the products formed by heating β -D-allopyranose and β -D-altropyranose in the presence of 10% of sodium carbonate (Table II).

In comparison with the results obtained by MacLaurin and Green, which may be considered as the aqueous counterpart of this study, it is seen that, under pyrolytic conditions, in addition to decomposition and secondary epimerization there are considerable changes in the proportion of the major sugars in the reaction mixture. These differences confirm the existence of more than one mechanism for the alkaline transformations, as discussed by Gleason and Barker¹⁶, and indicate that the pyrolytic condition results in more-drastic rearrangements.

EXPERIMENTAL

Preparation of samples. — Samples of the sugar containing 5% of calcium hydroxide or sodium carbonate were prepared by grinding to a fine powder. The mixtures were then dried and kept under anhydrous conditions. D-ribo-Hexulose, used as a standard in the g.l.c. experiments, was prepared¹⁷ by hydrolysis of 1,2:4,5-di-O-isopropylidene- β -D-ribo-hexulose with Amberlite IR-120(H⁺) resin at 65° for 5 h.

Analysis. — Thermal analysis and g.l.c. were carried out by the instruments and methods described in previous reports^{4,7,10}.

Thermal rearrangements. — Known amounts of the base-treated samples (~5 mg) of D-glucose, D-mannose, and D-fructose were placed in small ampoules (5 ml) which were sealed under a nitrogen atmosphere and then heated at constant temperature for different periods of time, cooled rapidly in cold water, and opened. The reaction mixtures were trimethylsilylated and analyzed¹⁰ by g.l.c.; the results are given in Table I.

In experiments with D-allose and D-altrose, samples of base-treated sugars (1–2 mg) were placed in small, covered aluminum pans and heated at a rate of 10°/min in a Fisher-Johns melting-point apparatus. After reaching the given temperatures, the pans were cooled, and the mixtures were trimethylsilylated and analyzed as before. The results are given in Table II.

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