

Thermodynamics of the Conversion of Aqueous Glucose to Fructose

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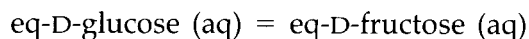
ABSTRACT

The thermodynamics of the conversion of aqueous glucose to fructose has been investigated using both heat conduction microcalorimetry and high pressure liquid chromatography (HPLC). The reaction was carried out in both aqueous Tris/HCl buffer and in aqueous phosphate buffer in the pH range 7–8 using the enzyme glucose isomerase and the cofactors CoCl_2 and MgSO_4 . The temperature range over which this reaction was investigated was 298.15–358.15 K. We have found that the enthalpy of reaction is independent of pH over the range investigated. A combined analysis of both the HPLC and microcalorimetric data leads to the following results at 298.15 K: $\Delta G^\circ = 349 \pm 53 \text{ J mol}^{-1}$, $\Delta H^\circ = 2.78 \pm 0.20 \text{ kJ mol}^{-1}$, and $\Delta C_p^\circ = 76 \pm 30 \text{ J mol}^{-1} \text{ K}^{-1}$. The stated uncertainties are based upon an analysis of both the random and systematic errors inherent in the measurements. Comparisons are made with literature data. The percent conversion of glucose to fructose has been calculated for the temperature range 300–373.15 K.

Index Entries: Calorimetry, of the glucose to fructose conversion; enthalpy, of the glucose to fructose conversion; enzyme catalyzed reactions; equilibrium constants, of the glucose to fructose conversion; fructose, conversion from glucose; glucose isomerase, and the conversion to fructose; heat capacity, of the glucose to fructose conversion; high pressure liquid chromatography, in glucose to fructose conversion; thermodynamics, of the glucose to fructose conversion; xylose isomerase, and the glucose to fructose conversion.

INTRODUCTION

There have been several reviews on the conversion of aqueous glucose to fructose that uses the enzyme, glucose isomerase (1-3). An important aspect of this conversion is the thermodynamics of the reaction itself,



The prefix "eq" denotes that there is an equilibrium mixture of the α and β forms of glucose and fructose. Fructose also exists as furanose and pyranose structures. Although equilibrium constants (K) for this reaction have been reported in the literature (4-12), the data show a considerable amount of discord. Also, there are no calorimetric data in the literature on this reaction. Because the maximum product yield at a given temperature can be calculated from the equilibrium constant at that temperature, there is considerable industrial interest in this information.

METHODS

We report herein the results of an experimental study that used both high pressure liquid chromatography (HPLC) and heat conduction microcalorimetry for the measurement of equilibrium constants and enthalpies (ΔH°) of reaction, respectively, as a function of temperature (T). The details of the measurements and the analysis of the data are being reported elsewhere (13).

TABLE 1
Summary of Results from HPLC and
Microcalorimetric Measurements

HPLC Results		Microcalorimetric results	
T , K	K	T , K	ΔH° , J mol ⁻¹
298.15	0.866	298.15	2755
306.15	0.892	313.25	4007
313.15	0.936	331.85	5213
322.15	0.964	344.15	6343
331.85	1.004		
344.15	1.094		
353.15	1.157	$\Delta H^\circ = 2.78 \pm 0.20 \text{ kJ mol}^{-1}$	
358.15	1.199	$\Delta C_p^\circ = 76 \pm 30 \text{ J mol}^{-1} \text{ K}^{-1}$	

^a $\Delta G^\circ = 0.404 \pm 0.073 \text{ kJ mol}^{-1}$; $\Delta H^\circ = 4.79 \pm 0.79 \text{ kJ mol}^{-1}$; ΔC_p° set equal to $0.0 \text{ J mol}^{-1} \text{ K}^{-1}$.

^b $\Delta G^\circ = 0.349 \pm 0.053 \text{ kJ mol}^{-1}$; $\Delta H^\circ = 2.59 \pm 0.32 \text{ kJ mol}^{-1}$; ΔC_p° set equal to $76.0 \text{ J mol}^{-1} \text{ K}^{-1}$.

EXPERIMENTAL RESULTS

The results of the HPLC and the calorimetric measurements are summarized in Table 1. The reaction was carried out in both aqueous Tris/HCl buffer and in aqueous phosphate buffer in the pH range 7–8 using the solubilized enzyme glucose isomerase obtained from *olivaceus* bacteria and the cofactors CoCl_2 and MgSO_4 . We have found that the

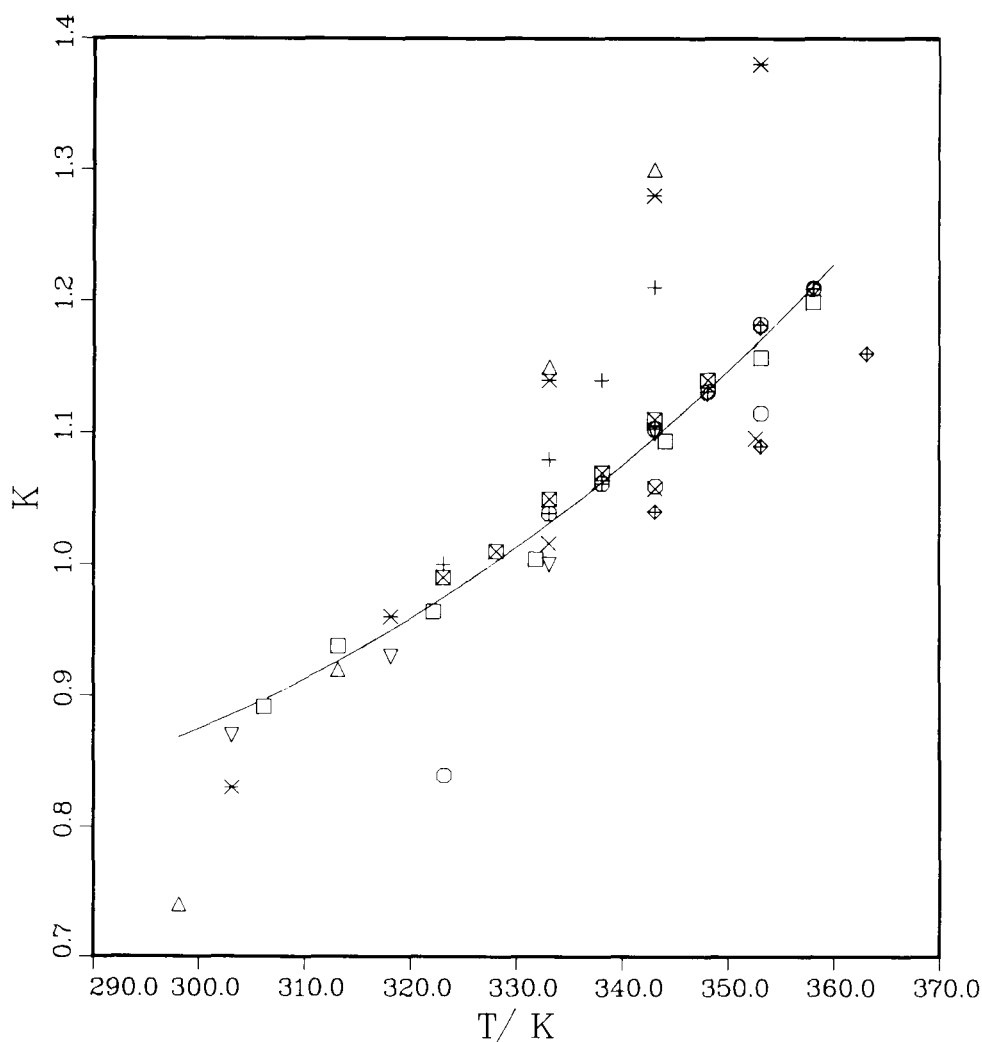


Fig. 1. Equilibrium constants for the conversion of glucose to fructose as a function of temperature. The data sets are: (□) this investigation; (◇) Clinton Corn Research; (×) Havewala and Pitcher; (+) Lantero; (●) Lloyd and Khaleeluddin; (○) McKay and Tavlarides; (◆) Scallet; (*) Sproull; (f) Takasaki; (△) van Tilburg; and (⊠) Lloyd and Chan. The line was calculated using the values $\Delta G^\circ = 349 \text{ J mol}^{-1}$, $\Delta H^\circ = 2780 \text{ J mol}^{-1}$, $\Delta C_p^\circ = 76 \text{ J mol}^{-1} \text{ K}^{-1}$.

TABLE 2
Equilibrium Constants for the Conversion of Glucose to Fructose from the Literature and Values of ΔG° and ΔH Calculated from These Investigations Using the Model of Clarke and Glew (14)

Worker(s)	T, K	K	ΔG° , kJ mol ⁻¹	$\Delta^\circ H$, kJ mol ⁻¹	Method	Enzyme	Cofactor(s)	Buffer
Clinton Corn (6)	348.15	1.13	0.71 \pm 2.0 ^a	7.1 \pm 13. ^a	?	?	?	?
	353.15	1.18	0.37 \pm 2.3 ^b	2.9 \pm 15. ^b				
	358.15	1.21						
Havewale and Pitcher (7)	333.15	1.016	0.36 \pm 0.15 ^c	3.8 \pm 0.41 ^a	Polarimetry	Streptomyces (soluble) and immobilized	MgSO ₄ , 20 mM CoCl ₂ , 1 mM	Sodium maleate
	343.15	1.058	0.14 \pm 0.55 ^b	0.42 \pm 3.1 ^a				
	352.65	1.096						
Lantero (8)	323.15	1.00	0.69 \pm 0.38 ^c	8.6 \pm 3.4 ^a	?	Streptomyces olivaceus	Mg ²⁺ , 22 mM Co ²⁺ , 0.5 mM	? pH = 7.8
	333.15	1.08	0.554 \pm 3.0 ^b	6.0 \pm 1.8 ^a				
	338.15	1.14						
	343.15	1.21						
Lloyd and Chan (12)	333.15	1.039	0.58 \pm 0.11 ^c	6.25 \pm 0.82 ^a	HPLC	Bacillus stearo-thermophilus and Bacillus licheniformis	Mg ²⁺ , 5 mM Co ²⁺ , 0.2 mM	Sodium sulfite/bisulfite, pH = 7.0
	338.15	1.062	0.33 \pm 0.10 ^b	2.67 \pm 0.73 ^b				
	343.15	1.103						
	348.15	1.131						
	353.15	1.182						
Lloyd and Khaleeluddin (4)	358.15	1.209			Polarimetry and HPLC	Streptomyces GI	MgSO ₄ , 5 mM	Phosphate, pH = 7.3
	303.15	0.87	0.46 \pm 0.28 ^c	4.86 \pm 3.1 ^a				
	318.15	0.93	0.41 \pm 0.18 ^c	3.05 \pm 2.0 ^a				
	333.15	1.00						

enthalpy of reaction is independent of pH over the range investigated. From the enthalpy data we calculate $\Delta H^\circ = 2780 \pm 200 \text{ J mol}^{-1}$ and a heat capacity change (ΔC_p°) of $76 \pm 30 \text{ J mol}^{-1} \text{ K}^{-1}$ at 298.15. By fixing ΔC_p° at this value, we calculate from the equilibrium constants a value of the Gibbs energy change (ΔG°) of $349 \pm 53 \text{ J mol}^{-1}$ and a value of ΔH° equal to $2590 \pm 320 \text{ J mol}^{-1}$ at 298.15 K. The uncertainties in ΔH° and ΔC_p° obtained from the calorimetric data includes both random error and an allowance for possible systematic errors. The uncertainties in the values of ΔG° and ΔH° obtained from the HPLC measurements are purely statistical and refer to 95% confidence limits.

The equilibrium constants reported in the other investigations are summarized in Table 2 and are shown together with our results in Fig. 1. In Table 2 we also give the values of ΔG° and ΔH° at 298.15 K that have been calculated from the equilibrium constants by fixing ΔC_p° either at zero or $76 \text{ J mol}^{-1} \text{ K}^{-1}$. Our measurements are in excellent agreement with the data of van Tilburg (3), of Lloyd and Khaleeluddin (4), and of Lloyd and Chan (12). Our measurements overlap the data of Sproull et al. (5) within the stated uncertainties. The agreement of our data with the measurements of Clinton Corn Research (6), Havewala and Pitcher (7), Lantero (8), McKay and Tavlarides (9), and Scallet (10), arises from the large statistical uncertainties associated with their measurements. Our measurements are not in agreement with those of Takasaki (11).

DISCUSSION

There are several factors that lead us to believe that our equilibrium measurements are accurate. Firstly, the equilibrium constants were measured in separate experiments in which equilibrium was approached starting from both pure glucose and pure fructose. The agreement of the equilibrium constants determined *via* these two independent experiments is excellent evidence that equilibrium has been attained. Secondly, we have found a material balance between the amounts of starting material (glucose or fructose) and the amounts of the carbohydrates at equilibrium. This fact, together with the absence of any observed side products in the chromatograms, mitigates against the possibility of side reactions. Finally, the value of the enthalpy change calculated from the temperature dependency of the equilibrium constants is in excellent agreement with the calorimetrically determined enthalpy change.

Values of the equilibrium constant for the conversion of glucose to fructose as a function of temperature can be calculated using the relationship

$$-RT \ln K = \Delta G_T^\circ = \Delta H_T^\circ - T\Delta S_T^\circ \quad (1)$$

where R is the gas constant ($8.31441 \text{ J mol}^{-1} \text{ K}^{-1}$) and

TABLE 3
The Equilibrium Constant and the Percent Conversion of
Aqueous Glucose to Fructose as a
Function of Temperature

T, K	Percent conversion	Equilibrium constant
300	46.7	0.875
310	47.7	0.913
320	49.0	0.959
330	50.3	1.013
340	51.8	1.075
350	53.4	1.147
360	55.1	1.227
373.15	57.4 ^a	1.348 ^a

^aExtrapolated value.

$$\Delta H_T^\circ = \Delta H_{298.15}^\circ + \Delta C_p(T - 298.15) \quad (2)$$

The entropy change (ΔS°) is given by

$$\Delta S_T^\circ = \Delta S_{298.15}^\circ + \Delta C_p \ln (T/298.15) \quad (3)$$

where

$$\Delta S_{298.15}^\circ = (\Delta H_{298.15}^\circ - \Delta G_{298.15}^\circ)/298.15 \quad (4)$$

The above equations assume that ΔC_p° is independent of temperature. If it is not, the appropriate equation is

$$\Delta G_T^\circ = \Delta H_{298.15}^\circ + \int_{298.15}^T \Delta C_p dT - T[\Delta S_{298.15}^\circ + \int_{298.15}^T (\Delta C_p/T) dT] \quad (5)$$

The percent conversion of glucose to fructose is given by $100K/(K + 1)$. We use the values $\Delta G^\circ = 349 \text{ J mol}^{-1}$, $\Delta H^\circ = 2780 \text{ J mol}^{-1}$, and $\Delta C_p^\circ = 76 \text{ J mol}^{-1} \text{ K}^{-1}$ to calculate the values of the equilibrium constants and the percent conversion of glucose to fructose given in Table 3. These values can be used for the optimization of the product yield of fructose over this temperature range. Clearly two ways of improving product yield are to go to higher temperatures and/or to remove the fructose continuously as it is produced. We have extrapolated the data to 373.15 K to obtain a percent conversion of 57.4% at that temperature.

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