Carbohydrate Research, 41 (1975) 93–104

COMPLEXATION OF REDUCING AND NONREDUCING CARBOHYDRATES WITH HYDROXIDES OF SOME ALKALI AND ALKALINE-EARTH METALS

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(Received November 6th, 1974, accepted for publication, December 19th, 1974)

ABSTRACT

Complexation of D-arabinose, D-fructose, D-glucitol, D-glucose, D-mannitol, L-sorbose, D-xylose, sucrose, and amylose with LiOH, NaOH, KOH, $Ba(OH)_2$, $Ca(OH)_2$, and $Sr(OH)_2$ has been studied conductometrically D-Glucitol and D-mannitol do not bind with any of the bases used Molecular complexes (1 1) of the other carbohydrates are formed in solution Reducing sugars bind more strongly than nonreducing ones Stability constants for the complexes have been determined, the free-energy change is of the order of hydrogen bonding The association process has been observed to depend significantly on the polarity of the medium

INTRODUCTION

Formation of adducts of certain carbohydrates with salts and hydroxides of alkali and alkaline-earth metals is known[1] In several recent studies, the compositions of such adducts with the hydroxides of barium, calcium, magnesium, and strontium have been established[2–4] through the formation of definite, solid compounds The strength of binding in solution, on the other hand, has not been determined, because of lack of a suitable method[1] In two recent publications[5 6], we have shown from spectral studies that ethylenediamine can act as an acceptor of a proton from the donating, reducing end of a carbohydrate moiety, and the binding strength is of the order of hydrogen bonding It has also been reported[7] that reducing sugars can affect the conductance of aqueous solutions of the hydroxides of barium and calcium Very recently, interactions of carbohydrates with salts have been estimated conductometrically[8], and in another publication[9], determination of stability constants of polyol–cation complexes has been reported

In the present paper, results of conductometric examination of the interactions of LiOH, NaOH, KOH, $Ba(OH)_2$, $Ca(OH)_2$, and $Sr(OH)_2$ with several reducing and nonreducing carbohydrates are presented. A quantitative estimation of the binding capabilities has been made on the basis of a simple, theoretical model

THEORETICAL ASPECTS

In previous papers[8,10,11], hindrance to ionic migration under an applied electric field was considered to be due to the obstruction of ions by the carbohydrates, as well as to the complexation of ions with them The obstruction effect should be significant in appreciable concentrations of carbohydrate In the present work, only very dilute solutions of carbohydrates were employed, and the obstruction effect was considered to be absent Any change in conductance would then be assigned to the interaction of ions with the carbohydrate moieties

For a 1 1 complex, the following scheme was considered

$$\underset{(a-x)}{\text{Carbohydrate}} + \underset{(b-x)}{\text{base}} \overset{K_A}{\rightleftharpoons} \underset{x}{\text{complex}}, \tag{1}$$

where a, b, and x are the concentrations of the carbohydrate, the base, and the complex, respectively, and K_A is the thermodynamic association constant This constant is given by equation *2*,

$$K_A = a_x/(a_c - a_x)(a_b - a_x), \tag{2}$$

where a_c, a_b, and a_x are the activities of the carbohydrate, the base, and the complex, respectively In dilute solutions of a base, the activity can be taken to be equal to its concentration The activity of the non-electrolytic carbohydrate does not usually deviate much from its concentration, which should not then deviate in dilute solutions From these considerations,

$$K_A = x/(a-x)(b-x) \tag{3}$$

When $x \ll a$,

$$K_A = x/a(b-x) \tag{4}$$

For dilute solutions, the specific conductance of the base can be represented[8] by

$$k = \bar{C}b \tag{5}$$

The conductance of the base at concentration $(b-x)$ is then given by

$$k = \bar{C}(b-x), \tag{6}$$

where $\bar{C}$ is the proportionality constant

From equations *4*, *5*, and *6*, it can be shown that[8]

$$k = \bar{k}(1 + K_A a), \tag{7}$$

or, $$\bar{k}/k = 1 - K_A(\bar{k}a/k). \tag{8}$$

If the concentration is expressed in g/ml, then

$$a = 1000\,C/\mathrm{M}, \tag{9}$$

where C is the concentration of the carbohydrate expressed in g/ml, and M is its molecular weight.

Equation *8* then takes the form

$$\bar{k}/k = 1-(1000K_A/\mathrm{M})(\bar{k}C/k) \qquad (10)$$

This linear equation may be used for determining the association constant of a carbohydrate–base complex in solution The simple method of conductance measurements can thus be made meaningful Under the conditions of the present work, the obstruction-cum-complexation equation derived earlier[8] can also be reduced to equation *10*

EXPERIMENTAL

Materials — All of the carbohydrates used were of either E Merck pro analysi or BDH Analar grades Fresh samples of carbonate-free hydroxides (also of E Merck, pro analysi grade) were used Strontium oxide was prepared by dissolving $SrCO_3$ in nitric acid, and igniting the crystallized $Sr(NO_3)_2$ to the oxide until it was free from nitrate The oxide was dissolved in water to produce the hydrate

Preparation of samples was performed in thoroughly boiled conductivity water (specific conductance, 2 μmho cm^{-1} at 30°) protected against unnecessary exposure to the atmosphere The solutions were stored in well-stoppered containers in a vacuum desiccator

The solutions of $Ba(OH)_2$, $Ca(OH)_2$, and $Sr(OH)_2$ were prepared by shaking the respective hydroxide with conductivity water in a stoppered container, and rapidly filtering the suspension The concentrations of all of the solutions were determined by titration of aliquots with standard HCl The concentration of each base used was 20μM, if not otherwise stated

Method — The general method used for measurements has been described[8] Exposure to the atmosphere during experimentation was avoided as far as possible

Prior to each measurement, the conductance of the carbohydrate solution was checked for any contamination by a salt If the order was more than 1 μmho cm^{-1}, the solution was rejected. The conductance of a carbohydrate of this desired order was observed to stay constant for a period of several hours at the temperature of the measurements (30 ±0 2°) At a temperature of ~60°, the conductance of solutions of D-glucose was found to increase with time Degradation of this sugar at higher temperatures was thus anticipated

RESULTS

Susceptibility of carbohydrates to the bases — Reducing carbohydrates are known to be susceptible to the action of bases[12] Apart from conformational changes[13] (alkaline transformations), alkalies degrade them The process of the Lobry de Bruyn–Alberda van Ekenstein alkaline degradation[14,15] has been well studied In a recent study[6], we anticipated occurrence of complexation prior to any degradation, at least in dilute basic solutions The remarkable change in conductance of a solution of a base[7] in the presence of a carbohydrate also led us to presume occurrence of complexation To corroborate this, carbohydrate solutions (15–68mM) at ~30° were treated with solutions (20μM) of various bases, and the content of base just after mixing and after an interval of 2 h was determined by titrating with a standard solution of hydrochloric acid The same procedure was followed for samples that had been heated for 1 5 h at ~75° It was observed that no base was consumed by the carbohydrates kept at 30° (the titers of HCl just after mixing were, within the limits of experimental error, exactly equal to those after 2 h) The heated samples consumed part of the base, depending on the carbohydrate, the titers of HCl were significantly lower The solutions also became straw colored, owing to the formation of polymeric, degradation products These results are given in Table I We also found that use of a concentrated solution of a base greatly lessens the time needed for degradation The results in Table I reveal that, in the working period of 1 h, alkaline

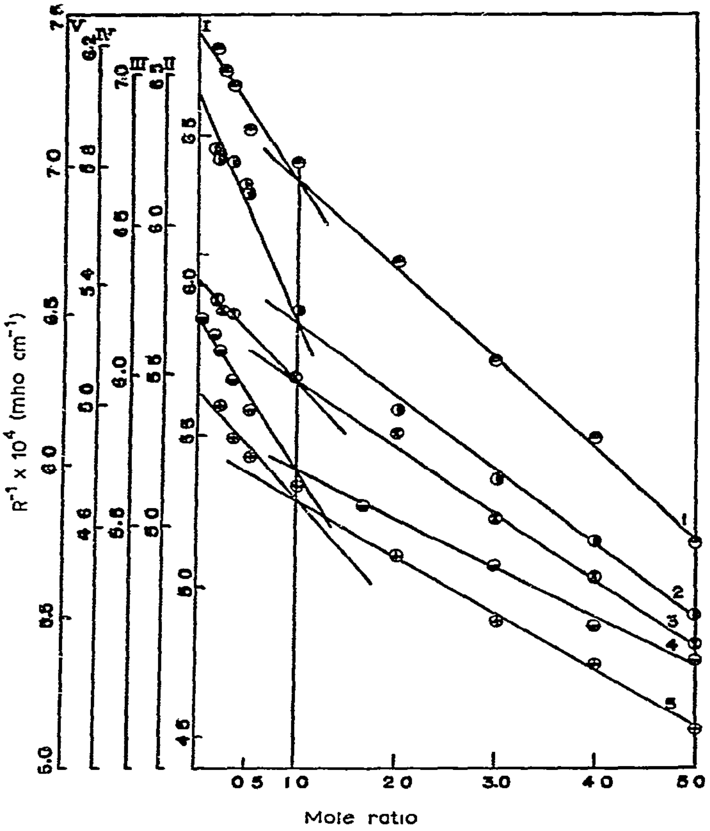

Fig 1 Plot of conductance of 20μM KOH *versus* mole ratio of carbohydrates [Key curves 1–5, L-sorbose, D-fructose, D-xylose, D-glucose, and D-arabinose]

TABLE I

REACTIONS OF BASES WITH CARBOHYDRATES[a]

Carbohydrate		*Base (millimoles[b])*							
Sugar	*Millimoles[b]*	*NaOH*		*KOH*		*Ba(OH)₂*		*Ca(OH)₂*	
		Added	*Consumed*	*Added*	*Consumed*	*Added*	*Consumed*	*Added*	*Consumed*
D-Arabinose	15.00	12.00	6.20	3.00	1.35	4.20	3.20	3.30	1.30
D-Fructose	22.50	12.00	7.00	3.30	2.10	4.20	2.30	3.30	2.10
D-Glucose	68.00	12.00	6.00	3.30	1.35	4.20	2.40	3.30	1.35
L-Sorbose	26.40	12.00	6.60	3.30	2.20	4.20	1.23	3.30	3.20
D-Xylose	16.70	12.00	6.40	3.30	2.10	4.20	1.30	3.30	2.00
Sucrose	39.00	12.00	Nil	3.30	Nil	4.20	Nil	3.30	Nil

[a] Temperature of reaction, ~75°, heating time, 1.5 h [b] Per liter

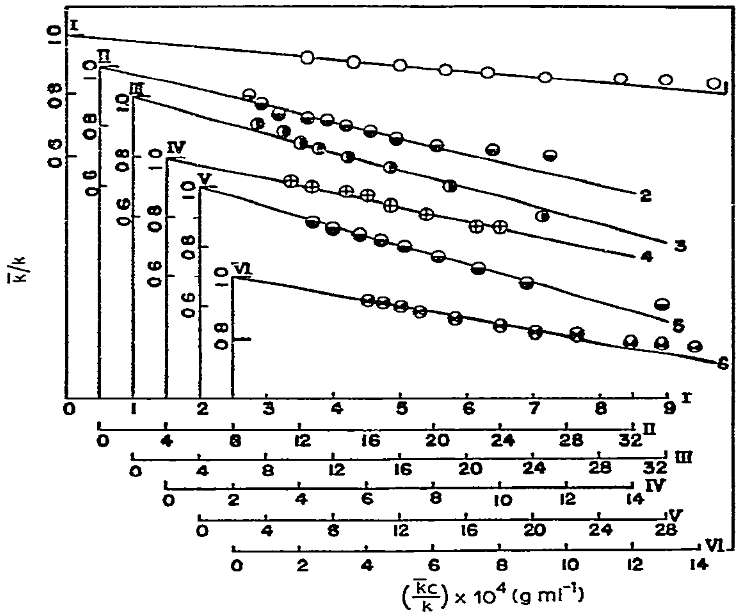

Fig 2 Plots of $\bar{k}/k$ *versus* $\bar{k}C/k$ for various carbohydrates in NaOH [Key curves 1–6, sucrose D-glucose, D-fructose, D-arabinose, L-sorbose, and D-xylose]

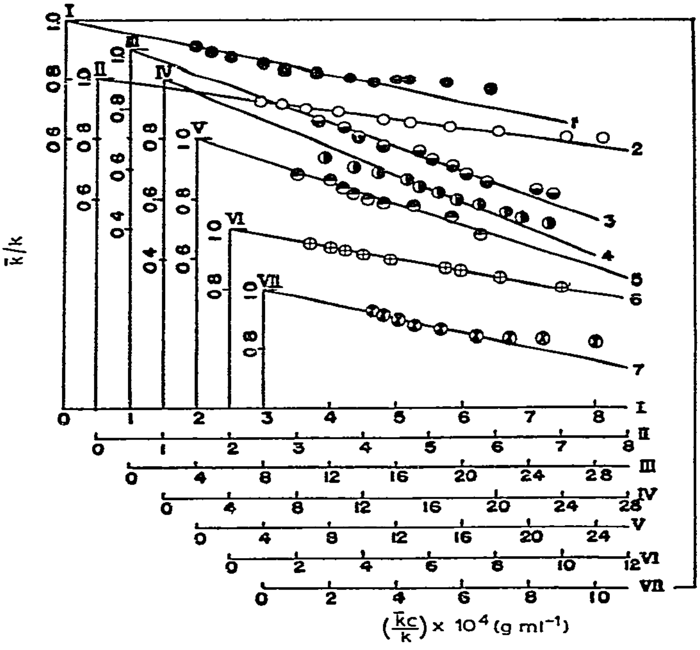

Fig 3 Plots of $\bar{k}/k$ *versus* $\bar{k}C/k$ for various carbohydrates in KOH [Key curves 1–7, amylose, sucrose, D-glucose, D-fructose, L-sorbose, D-arabinose, and D-xylose]

degradation leading to consumption[6] of base was not noticeable In the presence of a small proportion of either 1,4-dioxane (5–10%, v/v) or ethyl alcohol (10%, v/v), this degradation was small, even at the higher temperature On such occasions, estimation of the base by conductometric titration was adopted, keeping in mind that the color change of the tautomeric forms of phenolphthalein or other indicator may be significantly influenced in a medium of low dielectric constant (particularly 1,4-dioxane)

Composition of the complex — A 1 1 adduct of certain carbohydrates with certain bases was reported earlier[2–4] Under some conditions, adducts of other compositions were also found[1 4] Identification and determination of composition are both difficult in practice, owing to the high degree of instability of the isolated adducts In the present analysis, the conductance method of determination was used In a number of samples, the proportion of the carbohydrate was varied, but the overall concentration of the base was kept constant, these samples were allowed to stand for 0 5 h and their conductances were measured, taking care to avoid unnecessary exposure to the atmosphere The reciprocals of the resistances of these solutions were then plotted against the mole ratio of the carbohydrate The results are depicted in Fig 1 The several examples given in this Figure show a break in all of the curves at the 1 1 composition, this supports our early observations of 1 1 composition in isolated adducts, and implies formation of similar molecular complexes in solution

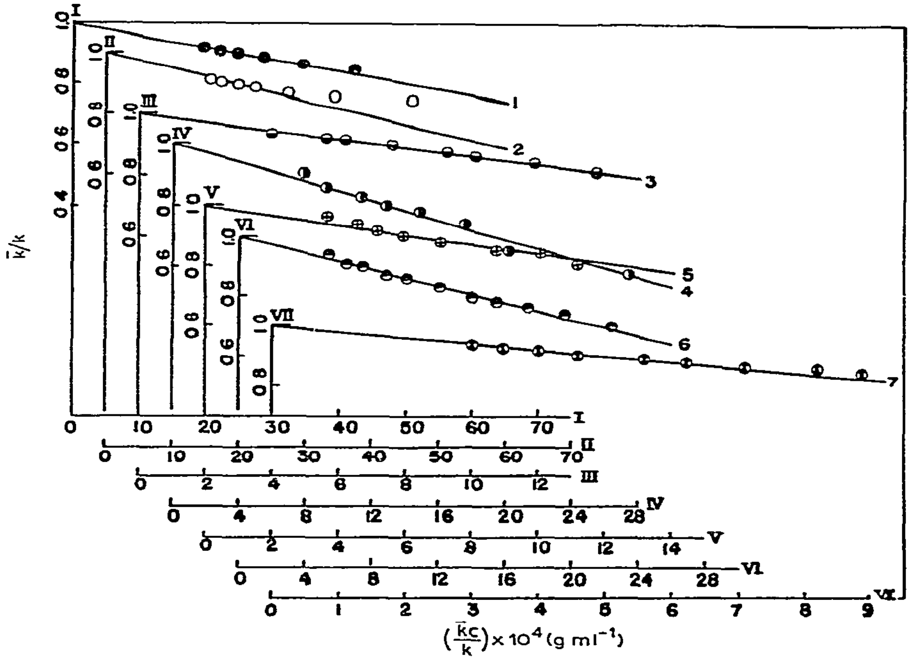

Fig 4 Plots of $\bar{k}/k$ *versus* $\bar{k}C/k$ for various carbohydrates in Ca(OH)$_2$ [Key curves 1–7, amylose, sucrose, D-glucose, D-fructose, D-arabinose, L-sorbose, and D-xylose]

Determination of the association constant — The experimental procedure employed for this purpose was that reported earlier[8]. Plots were made according to equation *10*, and the results are depicted in Figs 2–5 To ascertain the significance of equation *10*, the results of 10 experiments (chosen at random) were processed for a linear regression equation In all cases, such an equation gave values for the intercepts within the range of 0 97–1 03 From this sample analysis, it can reasonably be assumed (with little error) that the intercepts should be almost equal to 1 $\pm$0 03 On this assumption, mean curves were plotted, taking the intercept as equal to unity, and the standard deviations of the slopes were calculated and attributed to the values of K_A These results are given in Table II, from which it may be seen that the strengths of association are, energetically, more or less equal for the reducing sugars studied, and are essentially independent of the conformational differences between them A nonreducing carbohydrate, such as sucrose, binds less strongly The activity of amylose could not be made quantitative, due to its unknown molecular weight, the polymeric character of this species would suggest much weaker binding than that to the "dimeric" sucrose molecule The fact that the molecular weight was unknown prevented determination of the composition of the amylose–base complex

Effects of cosolvents — The effects of cosolvents were studied by using ethyl alcohol and 1,4-dioxane as polar and nonpolar solvents, respectively Determination of association constants was performed as usual The results are given in Fig 6 and

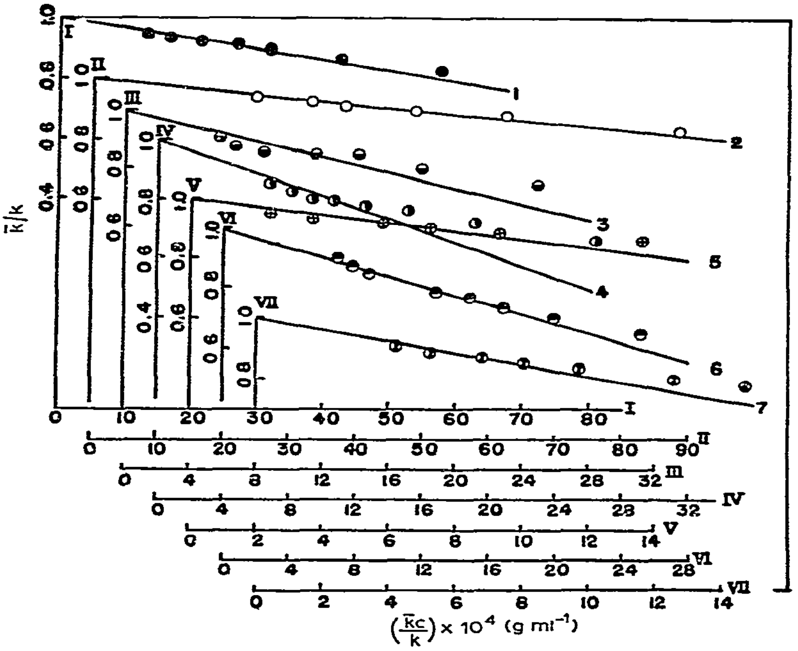

Fig 5 Plots of $\bar{k}/k$ *versus* $\bar{k}C/k$ for various carbohydrates in Ba(OH)$_2$ [Key curves, 1–7, amylose, sucrose, D-glucose, D-fructose, D-arabinose, L-sorbose, and D-xylose]

TABLE II

K_A AND ΔG VALUES FOR THE COMPLEX[a]

Base	D-*Arabinose*		D-*Fructose*		D-*Glucose*		L *Sorbose*		D-*Xylose*		*Sucrose*	
	K_A (*liter mol^{-1}*)	$-\Delta G$ (*kjoules· mol^{-1}*)	K_A (*liter· mol^{-1}*)	$-\Delta G$ (*kjoules· mol^{-1}*)	K_A (*liter· mol^{-1}*)	$-\Delta G$ (*kjoules· mol^{-1}*)	K_A (*liter· mol^{-1}*)	$-\Delta G$ (*kjoules· mol^{-1}*)	K_A (*liter· mol^{-1}*)	$-\Delta G$ (*kjoules· mol^{-1}*)	K_A (*liter mol^{-1}*)	$-\Delta G$ (*kjoules· mol^{-1}*)
LiOH	24.30	8.07	33.60	8.41	32.60	8.77	34.80	9.01	29.80	8.58	8.60	5.45
	±1.00	±0.10	±0.29	±0.10	±1.80	±0.07	±1.70	±0.54	±5.00	±0.02	±0.09	±0.04
NaOH	34.20	8.53	25.70	8.40	23.20	7.96	29.70	8.60	29.50	8.38	6.80	4.86
	±3.20	±0.25	±3.10	±0.28	±2.40	±0.26	±1.20	±0.13	±2.60	±0.03	±0.04	±0.013
KOH	29.80	8.58	40.50	10.42	36.90	9.14	32.50	8.88	37.50	9.18	10.50	5.97
	±2.10	±0.17	±2.50	±0.63	±1.50	±0.08	±2.60	±0.21	±3.80	±0.25	±0.04	±0.01
$Ba(OH)_2$	21.10	7.79	36.00	9.08	27.40	9.18	28.70	8.28	29.40	8.50	7.00	4.91
	±1.70	±0.26	±3.30	±0.21	±5.90	±0.70	±2.60	±0.29	±3.40	±0.24	±0.70	±0.25
$Ca(OH)_2$	23.30	7.97	27.80	8.44	25.20	8.18	25.20	8.18	29.70	8.61	17.80	7.30
	±1.50	±0.17	±1.30	±0.06	±0.06	±0.05	±0.90	±0.08	±1.00	±0.10	±1.10	±0.15
$Sr(OH)_2$	7.10	4.96	5.00	4.08	5.00	4.08	1.80	4.31	5.50	4.23	3.30	2.76
	±0.03	±0.02	±0.27	±0.01	±0.40	±0.02	±0.36	±0.19	±0.40	±0.18	±0.30	±0.25

[a] At 30 ±0.2°

Table III At equal volume-percent, 1,4-dioxane influenced the interaction far more than ethyl alcohol The K_A value was thus observed to be fairly susceptible to the polarity of the solvent. At a dielectric constant of ~65, aqueous 1,4-dioxane almost completely checked formation of a complex, which, at this isodielectric condition, in aqueous alcohol, was only lowered to 30% of that in water

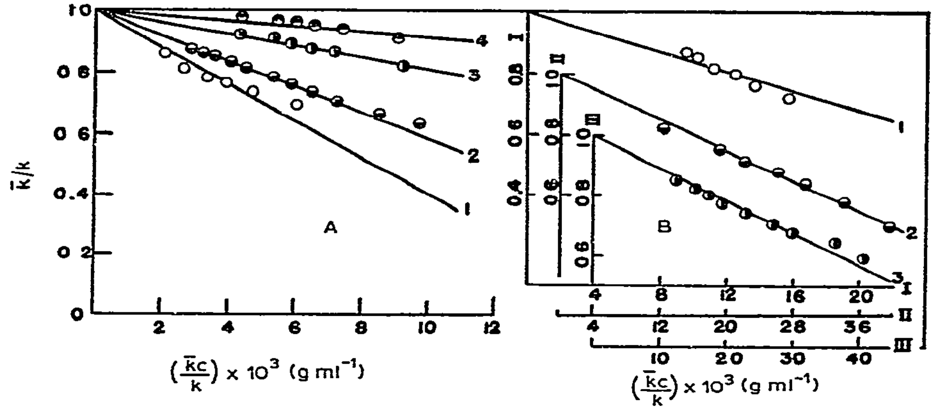

Fig 6 Plots of $\bar{k}/k$ *versus* $\bar{k}C/k$ for D-glucose–KOH system in aqueous 1,4-dioxane and aqueous alcoholic media. [Key A, curves 1–4, 1%, 2%, 5%, and 10% 1,4-dioxane B, curves 1–3, 40%, 20%, and 5% ethyl alcohol]

TABLE III

K_A AND ΔG VALUES FOR D-GLUCOSE–KOH COMPLEX IN AQUEOUS ETHANOL AND AQUEOUS 1,4-DIOXANE[a]

1,4-Dioxane (%, *v/v*)	*Dielectric constant*	K_A (*liter mol*$^{-1}$)	$-\Delta G$ (*kjoules mol*$^{-1}$)	*Ethyl alcohol* (%, *v/v*)	*Dielectric constant*	K_A (*liter mol*$^{-1}$)	$-\Delta G$ (*kjoules mol*$^{-1}$)
10 0	65 0	1 4 ±0 3	1 094 ±0 25	40 0	56 8	20 8 ±0 3	6 033 ±0 084
5 0	71 0	3 5 ±0 3	2 950 ±0 21	20 0	67 3	23 3 ±0 4	7 966 ±0 017
2 0	74 3	7 5 ±1 6	5 107 ±0 48	5 0	74 5	21 9 ±0 4	8 541 ±0 033
1 0	75 0	10 1 ±1 0	5 856 ±0 21				

[a] At 30 ±0 2°

DISCUSSION

Alkaline degradation of reducing sugars has been known for a long time[12–15] Mechanisms have been suggested for the process in basic environments[15], these do not, however, introduce the concepts of association or complexation of the base with the carbohydrate On the other hand, the possibility of adduct formation between the two types of compound has been studied[1–4] An interaction of this kind can be considered to be electrostatic in nature, where the carbohydrate acts as the center of positive charges That ethylenediamine (a proton-withdrawing agent) can act efficiently in combining with both reducing and nonreducing sugars[5 6] means that the interaction consists, most probably, in hydrogen bonding The hydrogen atom of the hydroxyl group on C-1 of a cyclic form of an aldose is bonded to the nitrogen atom of the amine In all probability, salts also bind at this center[8] A strong proton-withdrawing agent such as ethylenediamine may also activate other centers of a reducing sugar, as well as some centers of a nonreducing sugar, facilitating binding of different kinds[4,6].

That the binding is weak is supported by the possibility of quantitative determination of the base in the presence of a sugar by titration with a strong acid The complex formed significantly lessens the conductance of the base, but the adduct is broken by the addition of a strong acid The high mobility of hydroxyl ions makes study possible for low concentrations A true chemical reaction that involves all or part of the base is unlikely, this was also indicated in our previous studies[5 6]

As regards the postulation of weak binding with the reducing end of a carbohydrate, binding to sucrose and to amylose constitute exceptions, and it is difficult to surmise which are the active centers in these compounds Starch and amylose are known to give adducts with salts of alkali and alkaline-earth metals[1], the comparatively weak binding for sucrose and amylose parallels the rather weak binding of ethylenediamine to nonreducing sugars[6] The role of conformational differences has been observed to be of no significance, supporting our observations[6]

In earlier work[16], D-glucitol and D-mannitol were reported to form complexes No evidence for such has been adduced by the present method of conductometric experimentation The salts examined have been found not to bind to D-glucitol and D-mannitol[8], this is in contrast to the recent reports of binding of alditols with metal cations[9,17]

This electrostatic association primarily depends on the polarity of the medium[6] At equimolar concentrations, 1,4-dioxane is, therefore, more effective than alcohol as an inhibitor of complex-formation The profound, decomplexing activity of 1,4-dioxane under isodielectric conditions may indicate the necessity for presence of hydroxylic solvents in order to ensure efficient complex-formation

Finally, we have found that the conductance method cannot be used when ammonia is the weak base Addition of a sugar was observed to increase the conductance, which, for strong bases, always decreased This may result from an increased dissociation of NH_4OH in the presence of a carbohydrate, or from chemical reaction of reducing sugars with ammonia[18] The analogous phenomenon of an increase in the dissociation constant of acetic acid in the presence of urea has been noted[19]

ACKNOWLEDGMENTS

We thank Professor Mihir N Das, Head of the Physical Chemistry Section, for laboratory facilities We also thank Dr R Stuart Tipson for helpful suggestions and for taking a keen interest in our work

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