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REACTION OF GLYOXAL WITH BORIC ACID AND BORATE ION

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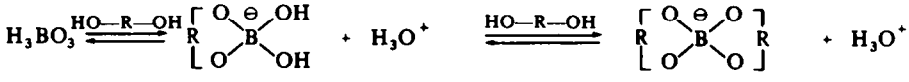
Abstract—Like many *cis*-dihydroxy compounds, glyoxal promotes the ionization of boric acid, apparently by withdrawing borate ions from solution. The association constant of glyoxal with borate ion is $2{\cdot}8 \times 10^5$. The conductivity increment, 1032 μ-mhos in 0·500M glyoxal plus 0·500M boric acid at 25°, is unusually high. The data give an independent confirmation of the polycyclic structure of aqueous glyoxal. Salts of the new acid have not been isolated. Two different methods used to determine the ionization "constants" gave different results which could be partially reconciled by assuming that glyoxal reacts with borate ion in preference to boric acid. The constants correspond to molar ratios of glyoxal to borate ion of 3·2 and 2·7 at 25°. The latter number is probably the average degree of polymerization of glyoxal in solution.

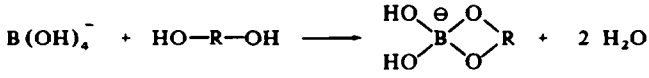
DISCUSSION

ALTHOUGH glyoxal is known to exist in hydrated form in water, its known reactions have largely been those of a dialdehyde.[1] The discovery that borax increases the acidity of aqueous glyoxal solutions was therefore unexpected.

A review of the behaviour of boric acid with bidentate ligands shows many instances of increased acidity, conductivity, and ionophoretic mobility.[2] Coordination compounds which show such properties are derived from polyhydric alcohols, and phenols, hydroxy acids, and dibasic acids. Increases in acidity in boric acid solutions have generally been attributed to the following reaction:



although it has previously been observed that much of the chemistry of the coordination compound of glycols, at least in aqueous medium, does not involve boric acid as such, but rather its conjugate base, $B(OH)_4^-$ (Ref. 2, p. 628)
thus



gives a better representation of the reaction.

Glyoxal causes a greater conductivity increase in boric acid than any commercial, aliphatic diol. A few conductivity increments, selected from Steinberg's text, are presented in Table 1.

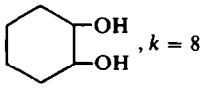
It has been stated that the primary requirement for enhancement of the conductivity of boric acid is a *cis* configuration and a planar O—C—C—O conformation.[3,4] This is vividly illustrated by the fact that *cis*-1,2-cyclopentanediol, in which the OH groups are almost eclipsed, enhances the acidity of boric acid ($\Delta = 149$) while *cis*-1,2-

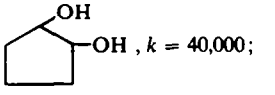
cyclohexanediol in which the hydroxyl groups assume an equatorial-axial position, does not ($\Delta = 0$).* This difference between these two cyclic diols is further emphasized

TABLE 1. CONDUCTIVITY INCREMENT OF TYPICAL LIGANDS
(Ref. 2)
(Ligand and boric acid each at 0·500M, 25·0°)

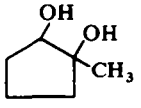
Polyol	Δ
Ethylene glycol	0
Glycerol	9
Mannitol	685
cis-1,2-Cyclohexanediol	0
Catechol	516
Hydroxy acid	
Glycolic acid	441
(Glyoxal	1032)

when we consider the 5000-fold difference in their rates of reaction with lead tetra-acetate which also involves a cyclic intermediate

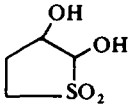

, $k = 8$


, $k = 40{,}000$;

However, other factors are important in determining the degree of conductivity enhancement. There is an appreciable inductive effect. Electron donating groups on the carbons holding the OH groups reduce the enhancement (*cis*

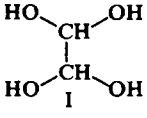


$\Delta = 114$) while electron withdrawing groups increase the enhancement (*cis*



$\Delta = 494$). Increased functionality also enhances conductivity as evidenced by the series glycerol ($\Delta = 9$), erythritol ($\Delta = 64$) and sorbitol ($\Delta = 794$). Furthermore, increased acidity enhances the conductivity as the high values for catechol ($\Delta = 516$) and the α-hydroxy acids (ϕ—CHCOOH, $\Delta = 19{,}303$) indicate. It is quite probable

that all of these factors contribute to the enhancement of the acidity of boric acid by aqueous glyoxal.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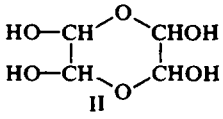
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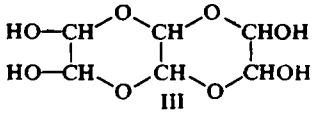

III

* The conductivity increment, Δ, is the difference between the conductivity of the borate-glycol solution and the sum of the conductivities of the components, usually at 0·500M concentration.

The planar O—C—C—O structure would not be expected to exist in the monomeric hydrate (I), but would exist in the hydrated dimer or trimer (II, III) if the dioxane ring assumes a "boat" form. The fact that the conductivity increment is very large (see Table 1) suggests that a large portion of the glyoxal exists in the dimer or trimer form. On the basis of the isolation of a derivative of the trihydrate, Raudnitz proposed that hydrated glyoxal exists as a trimer in aqueous solution.[5] Simple glycols do not react with boric acid[3] presumably because repulsion between adjacent hydroxyl groups in simple glycols gives a skewed conformation. In glyoxal, which in its aqueous monomeric form may be thought of as 1,1,2,2-ethanetetrol (I), adjacent hydroxyl groups would still be expected to assume an unfavourable, skew conformation. The reduction of dissociation constants when aqueous glyoxal is diluted, suggests that, at least in the presence of boric acid, both the cyclic and monomeric forms exist.

DETERMINATION OF CONDUCTIVITY INCREMENT

The increase in conductivity of 0·005M boric acid due to complex formation with glyoxal is shown in Table 2 which also shows that the conductivity increment (Δ) drops off after initial mixing. The value becomes constant after about 6 hr which is attributed to changes in the degree of polymerization of glyoxal on dilution. When a stock solution of 5·73M glyoxal was mixed with a stock solution of boric acid to give 0·500M glyoxal in 0·500M boric acid at 25·0°, the conductivity increment was 1642 μ-mhos immediately after mixing and 1032 μ-mhos in 64 hr. The decrease in conductivity would be expected if part of the dimer or trimer depolymerized to the monomeric form which should have a lower conductivity increment because of its conformation. To determine whether glyoxal or boric acid was responsible for the change in conductance with time, solid glyoxal (80% glyoxal–20% water) was dissolved and diluted to a concentration of 0·5M in water and allowed to equilibrate for several days at 25°. Then solid recrystallized boric acid containing 13·0% water was added to prepare a solution containing 0·5M glyoxal in 0·5M boric acid. The boric acid was dissolved as quickly as possible (in a period of about 3 min) and specific conductances were measured with time at 25°. The initial specific conductance, 1050 μ-mhos, rose slightly to 1090 μ-mhos in several hours. The dilution and subsequent equilibration of

TABLE 2. CONDUCTIVITIES OF PURIFIED GLYOXAL AND BORIC ACID (25·0°)

Molarity of glyoxal*	Glyoxal alone conductance†	Glyoxal +0·50M Boric Acid freshly mixed‡		Glyoxal + 0·50M boric acid after 64 hr		
		Conductance	pH	Conductance	Δ	pH
1·00	57·2	—	—	—	—	—
0·83	52·0	3400	2·0	2820	2741	—
0·50	41·3	1710	2·4	1100	1032	2·6
0·25	29·1	940	2·7	450	394	2·9
0·125	19·4	480	2·9	185	139	3·1
0·063	12·7	254	3·2	92	52	3·3
0·031	7·7	139	3·5	60	35	3·4

* Molecular weight of glyoxal taken as 58·04. The sample contained 0·06 per cent acid as acetic acid.

† Specific conductance in μmhos.

‡ Specific conductance of 0·50M boric acid = 26·7 μmhos.

the glyoxal and not the dilution of the boric acid is responsible for the large decreases in conductivity reported in Table 2.

In an effort to determine the ratio in which glyoxal complexes with boric acid, solutions of boric acid were titrated with glyoxal and vice versa, and conductivities were determined and plotted. No conclusions about combining ratios could be reached from these curves because no sharp breaks occurred. It was therefore necessary to turn to more sophisticated techniques.

DETERMINATION OF "IONIZATION CONSTANTS"

With these boric acid complexes, the "ionization constant" is by no means constant because as the ratio of the boric acid to the mono- and di-ligand adduct changes with the changing ligand concentration, the ionizing species changes. This is further complicated by the apparent depolymerization of the glyoxal itself and the slow decrease in conductivity which occurs after the boric acid and glyoxal are mixed.

The theory of formation of new acids by association of boric acid and glycols has been discussed by P. J. Antikainen[6] who found that the "ionization constants" of such acids often obey an equation of the following form:

$$K^{**} = C_2^n K_1 K_n + K_1$$

The "ionization constant", K^{**}, varies with the concentration of the ligand (C_2), and is independent of the concentration of the boric acid at concentrations below about 0·1M. K_n is the association constant of the boric acid and glycol, and K_1 is the first ionization constant of boric acid.

"Ionization constants" were determined by two different methods: the buffer capacity method of Kilpi[7a] and van Slyke,[8] and the half-neutralization or approximate EMF method.[9] Attempts to determine the ionization constant by conductivity methods failed to yield clear results.

The "ionization constants" were first determined using the buffer capacity method.

TABLE 3. IONIZATION CONSTANTS OF BORIC ACID–GLYOXAL (25°)

					By half neutralization				
	(0·05M H_3BO_3)				(0·05M H_3BO_3, 0·1M KCl)				
M_G	$-\log M_G$	CM_G	$-\log CM_G$	pK^{**}	M_G	$-\log M_G$	CM_G	$-\log CM_G$	pK^{**}
0·000	∞	0·000	∞	9·25	0·000	∞	0·00	∞	9·22
0·100	1·000	0·040	1·40	7·26	0·098	1·080	0·035	1·45	7·17
0·200	0·697	0·14	0·85	6·21	0·195	0·708	0·13	0·88	6·25
0·400	0·397	0·34	0·47	5·05	0·390	0·408	0·33	0·49	5·12
0·600	0·221	0·54	0·27	4·40	0·650	0·186	0·59	0·23	4·34
0·800	0·096	0·74	0·13	3·97	—	—	—	—	—
1·000	0·000	0·94	0·03	3·66	0·975	0·080	0·91	0·04	3·78

M_G = Molarity of original glyoxal solution.
M_{Gi} = Molarity of glyoxal at inflection point.
CM_G = Corrected molarity, obtained by assuming 2·5 moles glyoxal react with 1·0 mole of borate—see text.
pK^{**} = pH of solution at half neutralization.
P_i = Obtained graphically (see reference 8).

This procedure is easier to carry out in the presence of salt which reduces polarization of the electrodes of the pH meter and improves the precision of the reading, but the determination was also carried out in the absence of salt. The results are presented in Tables 3 and 4.

In the absence of salt, the association constant, K_n, is $2{\cdot}8 \times 10^5$ which is obtained by plotting pK^{**} against the negative logarithm of the glyoxal concentration and solving for K_n in the straight line equation—$\log (K^{**} - K_1) = -n \log C_2 - \log K_1 K_n$. The slope of the line gives a value for n of 2·73, indicating the number of molecules of glyoxal associated with each boric acid molecule. These values were significantly affected by addition of 0·1M potassium chloride, which yielded K_n of $3{\cdot}6 \times 10^5$ and $n = 2{\cdot}5$. Thermodynamic equilibrium constants must be determined in solutions of ionic acitivity approaching zero. Determination of the dissociation constant by the buffer capacity method in the absence of salt requires the addition of some acid followed by back titration, resulting in an ionic strength about 0·003 units higher than that resulting from $B(OH)_4^-$ and H_3O^+ alone. The amount of correction for the pK^{**} value was only of the order of 0·2 to 0·4 per cent and was not applied.

The "ionization constants" were next determined by measuring the pH of the half neutralized glyoxal–boric acid adduct (see Table 3). This value should be pK^{**}, and plotting pK^{**} against the log of the glyoxal concentration should yield K_n, the association constant, and n, the number of moles of glyoxal associated with each mole of borate ion. The results with 0·05 and 0·10M boric acid as first calculated, differed greatly. It is apparent, however, that because of the high degree of association between borate ion and glyoxal, as the titration proceeds, generating borate ion, the glyoxal concentration is reduced. Data obtained in the buffer capacity method permitted a simple first approximation correction for the reduced amount of glyoxal, bringing the values obtained at the two different concentrations into reasonable agreement. The corrected data yield a line whose intercept corresponds to an association constant, K_n of $4{\cdot}3 \times 10^5$ while the slope yields a value for n of 3·2, corresponding to 3·2 moles

					By buffer capacity			
(0·1M H_3BO_3)					(0·05M H_3BO_3, 0·1M KCl)			
M_G	$-\log M_G$	CM_G	$-\log CM_G$	pK^{**}	M_{Gl}	$-\log M_{Gl}$	$P_i \times 10^4$	pK^{**}
0·00	∞	0·00	∞	9·21	0·000	∞	0·360	8·91
0·10	1·000	0·017	1·77	7·55	0·100	1·00	8·245	6·18
0·20	0·697	0·074	1·13	6·68	0·199	0·697	20·68	5·39
0·40	0·397	0·27	0·56	5·36	0·398	0·397	48·00	4·66
—	—	—	—	—	0·665	0·175	80·95	4·18
0·80	0·096	0·67	0·17	4·11	—	—	—	—
1·00	0·000	0·87	0·06	3·75	0·995	0·002	141	3·67

of glyoxal per mole of borate ion. As anticipated, addition of 0·1M potassium chloride made no significant difference.

Data obtained by the buffer capacity method are believed to be more valid. In the first place, no correction is required to account for ligand removal from solution by the borate, and in the second place, glyoxal is more stable at the lower pH used in the buffer capacity determination. Both methods have been used to determine data in the literature, and authors using one method frequently disagree with authors using the other. Furthermore, data sometimes fail to yield straight lines.[10]

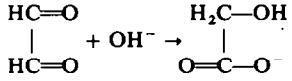
TABLE 4. IONIZATION CONSTANTS BY BUFFER CAPACITY METHOD, BORIC ACID–GLYOXAL COMPLEX, NO ADDED SALTS (25·0°)

Solution	1	2	3	4	5	6
H_3BO_3, Molarity	0·0500	0·0500	0·0500	0·0500	0·100	0·0100
Glyoxal, molarity	0·000	0·0993	0·199	0·993	0·199	0·199
−log Glyoxal molarity		1·002	0·700	0·002	0·700	0·700
$P_i \times 10^4$	0·307	5·71	14·8	124	20·9	8·36
K^{**}	$8·86 \times 10^{-10}$	$3·08 \times 10^{-7}$	$2·06 \times 10^{-6}$	$1·67 \times 10^{-4}$	$2·06 \times 10^{-6}$	$3·30 \times 10^{-6}$
pK^{**}	9·05	6·51	5·69	3·78	5·69	5·48

P_i determined graphically,
$-\log K_1 = 9·24$, $K_1 = 5·75 \times 10^{-10}$

The strong effect of borate concentration on the "ionization constant" is not seen with free boric acid. Table 4 shows that the ionization is independent of boric acid concentration when determined by the buffer capacity method (experiments 3, 5 and 6). This is further confirmation of the observation that the coordination occurs with $B(OH)_4^-$ rather than H_3BO_3.

Glyoxal can be used to sharpen the end point in titration of boric acid. Invert sugar or mannitol is usually used for this purpose but glyoxal gives a sharper end point. Because of the internal Cannizzaro reaction,



the pH of neutralized glyoxal drops spontaneously to about pH 5 in a few hours. A trace of acid in the commercial material prevents this reaction. This behaviour makes it necessary to neutralize glyoxal to pH 7 immediately before titrating glyoxal–boric acid mixtures. The titration should be carried out rapidly to avoid interference by the Cannizzaro reaction. The neutralized commercial glyoxal is satisfactory to sharpen the end point.

The dependence of pH on glyoxal concentration permits the use of glyoxal and boric acid to prepare multi-range buffers. Fig. 1 illustrates the use of the buffers covering pH ranges of 3 to 4, 4 to 6, 5 to 7, and 6 to 8 prepared simply by changing the glyoxal concentration. Several solutions of half neutralized boric acid and glyoxal were aged to determine the stability of pH with time. The pH shifts by as much as 0·1 unit during the first 24 hr but remains stable afterwards. Decomposition of the glyoxal at the higher pH limits the stability of the buffer system.

Attempts to isolate copper, iron, barium, silver, pyridine, and ammonium salts were unsuccessful. Evaporation of stoichiometric solutions of glyoxal–boric acid and selected metal salts or bases yielded boric acid crystals initially and no boric acid–glyoxal salts.

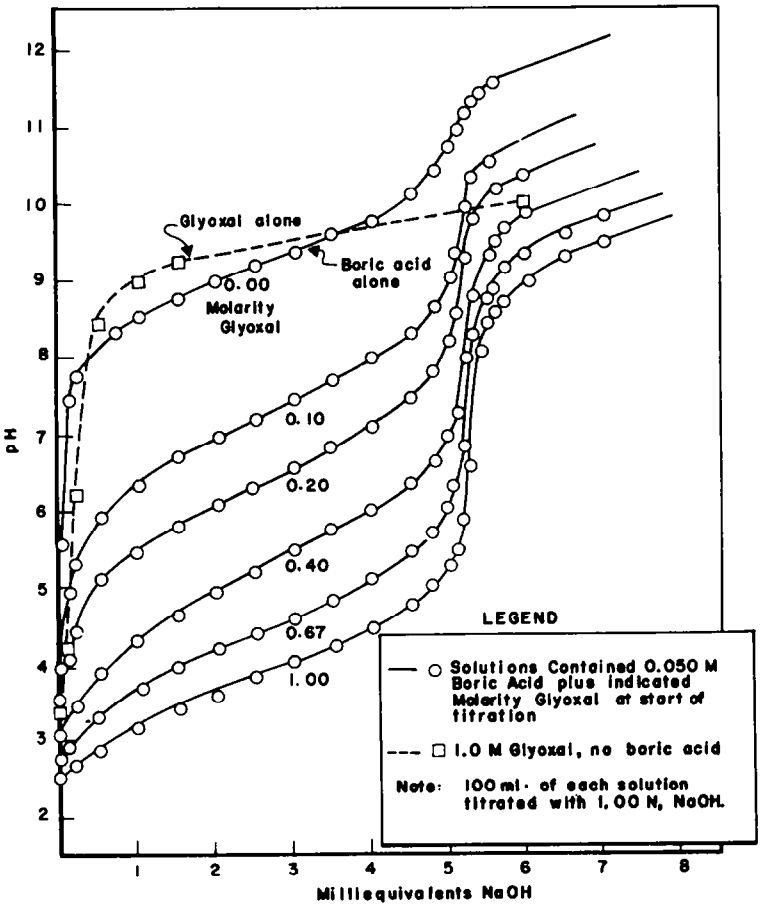


FIG. 1. Titration of boric acid and glyoxal with base (25°).

OTHER ALDEHYDES

Glutaraldehyde and α-hydroxyadipaldehyde were investigated to determine whether these materials combined with boric acid to enhance its acidity. Commercial samples of aqueous glutaraldehyde and α-hydroxyadipaldehyde having pH's of 2·9 and 2·8, respectively, were used. At 0·5M concentration in 0·5M H_3BO_3 both materials had a conductivity increment of −30μ-mhos which indicated no complexing. The negative values were probably due to the free acid in the aldehydes which decreased the ionization of the boric acid and reduced its contribution to conductivity in the mixture. It has been found in our laboratories[11] that glyoxal has a greater affinity for cellulose than does glutaraldehyde or α-hydroxyadipaldehyde. Glyoxal also is more strongly hydrated by water.

EXPERIMENTAL

Determination of ionization constants. The method of Kilpi[7b] was used to determine ionization constants by the minimum buffer capacity or differential potentiometric method. This method has the advantage of requiring very small additions of acid and base thereby causing a minimum disturbance in the equilibria between hydrated glyoxal monomer and polymer and between glyoxal hydrate and boric acid. Thus to 250 ml of equilibrated 0·01M boric acid and 0·2M glyoxal was added 0·1 ml of 0·1N hydrochloric acid and the minimum buffer capacity was determined by addition of 10·0μl increments of 0·100N sodium hydroxide.

A plot of incremental change in pH vs. the increment of acid or base added yields the maximum pH change denoted by $\Delta(\mathrm{pH})_i$. Näsänen (12) determined this value with a mathematical equation. The minimum buffer capacity is then calculated from the following equation:

$$P_i = \frac{(\Delta V)(B)}{(V_i)[\Delta(\mathrm{pH})_i]} \quad \text{and} \quad P_i = 4{\cdot}606\sqrt{(K^{**}C_0)}$$

where ΔV is the incremental volume of base added, B is the normality of the base, V_i is the volume of solution being titrated at the minimum buffer capacity. K^{**} is the "ionization constant", and C_0 is the initial concentration of acid. K^{**} is calculated by successive approximations.

Ionization constants were also determined by measuring the pH of the half neutralized glyoxal–boric acid adduct as described by Glasstone.[9] Solutions containing various amounts of glyoxal with 0·05M and 0·10M boric acid and with 0·10M boric acid containing 0·1M KCl were titrated with 1·0N sodium hydroxide, recording the pH after each incremental addition of base. Solutions of glyoxal and boric acid were allowed to stand at least 16 hours before titration and were purged with nitrogen to remove carbon dioxide. This method gave pK values for the ionization of boric acid of 9·25, 9·22, 9·21 (see Table 3) which are in good agreement with the literature. The buffer capacity method is difficult to apply to boric acid because of interference of carbon dioxide. It is more suitable for use with stronger acids such as the boric acid–glyoxal complexes described here.

In many cases minimum buffer capacities are not easily determined during the titration. Addition of salts such as KCl and NaCl accentuates the point of minimum buffer capacity and generally increases the dissociation constant.

Thermodynamic constants cannot be determined directly in the presence of salts. To obtain the thermodynamic constants from data obtained in the presence of salts, the effect of salt concentration on ionization constants is determined and the thermodynamic equilibrium constant is obtained by plotting dissociation constants as a function of the square root of the ionic strength and extrapolating to zero ionic strength. Constants in the Debye–Hückel equation can then be determined.[6,9]

Boric acid purification and analysis. Boric acid (Mallinckrodt AR grade) was recrystallized prior to use by dissolving 106 g of boric acid in 300 g of hot deionized water, then cooling. The crystals were filtered and washed several times with cold deionized water. Conductivity of 0·500M boric acid in deionized water before purification was 38·5 μ-mhos, and after recrystallization it was 27·5 μ-mhos. Correction for conductivity of the water (0·8) leaves a value of 26·7 for boric acid. Boric acid analyses were made by standard techniques using neutralized invert sugar to enhance the end point and phenolphthalein as an indicator.

Conductivity of the 0·500M glyoxal was 41·3 μ-mhos, and conductivity of the solution of 0·500M boric acid in 0·500M glyoxal was 1710 when freshly mixed and 1100 after standing 64 hr. The conductivity increments thus became

$$1710 - (41 + 27) = 1642$$

and

$$1100 - (41 + 27) = 1032$$

Glyoxal purification and analysis. Glyoxal 40% solution from Union Carbide Corporation was purified by treatment with ion exchange resins and decolorizing carbon. This increased the pH from 2·3 to 3·1 and reduced the acidity from 0·5 to 0·06%, calculated as acetic acid.

Glyoxal content is best determined by neutralizing the sample to phenolphthalein, adding excess standard base, allowing the solution to react for 15 min at room temperature, then back titrating to the phenolphthalein end point.[1]

Crystallized glyoxal can be prepared by concentrating Glyoxal 40% to about 60% solids by warming to 60° *in vacuo*, then allowing the syrup to stand at room temperature for a few weeks. The crystals are filtered and dried. The product analyzes about 80% glyoxal, corresponding to the trimeric hydrate.[13]

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