SOME
NUCLEOPHILIC DISPLACEMENT REACTIONS
ON
ORGANIC SULPHITES

BY

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ABSTRACT

The acid catalysed hydrolysis of several Organic sulphites has been investigated. The rate of hydrolysis is found to be directly proportional to the acid concentration below 0.5 molar acid. Above this, deviations from linearity occur. These are attributed to an ionic strength effect.

The effect of added salts on the acid catalysis has also been investigated. In this case also added salts, the anion of which are nucleophilic reagents, show a specific catalysing action. This is attributed to bimolecular attack of the anion of the salts or acid on the sulphur atom of the protonated ester, a reaction which proceeds concurrently with, and competes with, the normal hydrolysis which involves attack by a water molecule on the same species.

Evidence is produced that the first step in the acid-catalysed hydrolysis is a fast non-rate-determining proton transfer and that the rate-determining step involves a water molecule. The effect of added salt is found to be a linear function of the salt concentration.

From the proceeding survey of the Chemistry of Organic

sulphites it may be seen that it might be possible to change the point of bond fission from sulphur-oxygen which is the preferred mode of fission in hydrolysis to carbon-oxygen for reactions in non-aqueous solvents with sodium alkoxides.

A detailed study has therefore been made of the reaction of a number of cyclic and open-chain sulphites with sodium methoxide and sodium ethoxide. The rates of reaction have been measured and the stoicheiometry of the process have been determined. The structural effects have been interpreted in terms of a normal steric effect.

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SECTION I

THE HYDROLYSIS OF ESTERS

For an uncatalysed reaction in dilute solution of the form $A \longrightarrow B$ the rate law is:-

$$\frac{-d[A]}{dt} = k[A]$$

where k is a function solely of the temperature and the solvent. If the same reaction is catalysed by a substance C the corresponding law is:-

$$\frac{-d[A]}{dt} = k_C[A][C]$$

where k_C is now a function of the temperature, the solvent and the catalyst.

The reaction will be kinetically of the first order in concentration of A with a rate constant $k = k_C[C]$.

The catalytic constant of C, k_C, is a measure of the effectiveness of the catalyst.

The hydrolyses of many esters are catalysed by both acids and bases and the rate may then be expressed in the general form:-

$$k_h = k_a[\text{acid}] + k_b[\text{base}] + k_n$$

where $k_h = \frac{-d[\text{ester}]}{dt}$ and k_a and k_b are the acidic and basic catalytic constants and k_n the neutral hydrolysis constant.

SECTION II

THE MECHANISMS OF CARBOXYLIC ESTER HYDROLYSIS

Day and Ingold[1] classified the hydrolyses of carboxylic acid esters into three groups: acid, alkaline and neutral. In both alkaline and neutral hydrolyses, the carboxylic form which undergoes reaction is the ester molecule R^1CO_2R, while in acid hydrolysis it is the conjugate acid of the ester, i.e.

$$R^1CO_2R + OH^- \longrightarrow R^1COO^- + ROH \qquad \text{Basic}$$

$$R^1CO_2R + H_2O \longrightarrow R^1COOH + ROH \qquad \text{Neutral}$$

$$R^1CO_2HR^+ + H_2O \longrightarrow R^1CO_2{}^+H_2 + ROH \qquad \text{Acidic}$$

Fission of the carboxylic ester may occur at either of two different points:-

(1) $R'CO - \vdots - OR$ (acyl-oxygen fission - denoted Ac)

(2) $R'CO - O - \vdots R$ (alkyl oxygen fission - denoted Al)

Finally the molecularity of the rate-determining step is designated 1 or 2 depending on whether it is uni- or bi-molecular.

The various possibilities are set out below:-

	Fission	
Type of Mechanism	Acyl	Alkyl
Basic	$B_{Ac}2$	$B_{Ac}1$
	$B_{Ac}1$	$B_{Ac}2$
Acidic	$A_{Ac}2$	$A_{Al}1$

Acid-Catalysed Hydrolysis

The most common method for the esterification of a carboxylic acid is to heat the acid with an excess of alcohol in the presence of a small amount of strong acid such as perchloric, sulphuric, or hydrochloric acid as a catalyst. It is well known that the reaction is reversible and hence identical mechanisms will operate in both esterification and hydrolysis reactions. The unimolecular ($A_{Al}1$) mechanism may be formulated thus:-

$$\text{(i)} \qquad R'.CO.OR + H^+ \rightleftharpoons R'.CO.O^+HR$$

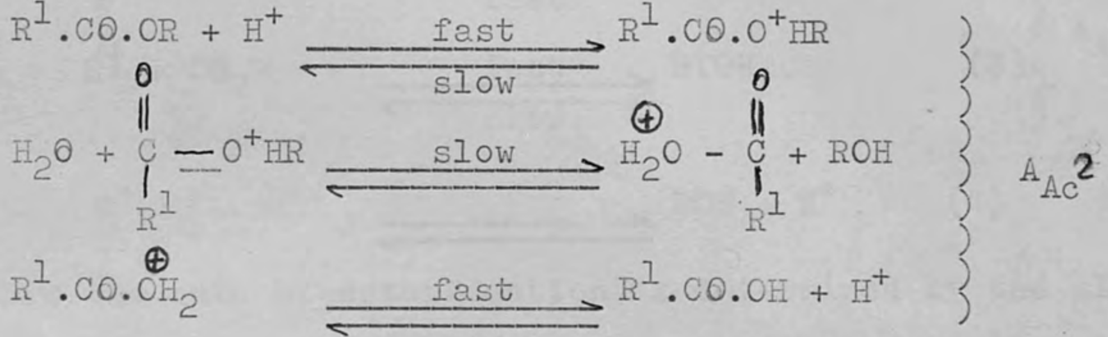
$$\text{(ii)} \qquad R'.CO - \overset{+}{O}HR \underset{\text{fast}}{\overset{\text{slow}}{\rightleftharpoons}} R'.\overset{+}{C}O + HOR \text{ --- (1)}$$

$$\text{(iii)} \qquad R'.CO^{\oplus} + H_2\overset{+}{O} \underset{\text{slow}}{\overset{\text{fast}}{\rightleftharpoons}} R'.CO - \overset{+}{O}H_2 \text{ --- (2)}$$

A-1

$$\text{(iv)} \qquad R'.CO - \overset{+}{O}H_2 \rightleftharpoons R'.CO.OH + H^+$$

Fission of the alkyl oxygen bond cannot occur without the instance of stages (1) and (2). In the $A_{Ac}2$ mechanism these stages become telescoped into a synchronous process, and the mechanism will become bimolecular.



$$\left.\begin{array}{l} R^1.CO.OR + H^+ \underset{slow}{\overset{fast}{\rightleftharpoons}} R^1.CO.O^+HR \\ H_2O + \overset{\overset{O}{\|}}{\underset{\underset{R^1}{|}}{C}}—O^+HR \overset{slow}{\rightleftharpoons} \overset{\oplus}{H_2O} - \overset{\overset{O}{\|}}{\underset{\underset{R^1}{|}}{C}} + ROH \\ R^1.CO.\overset{\oplus}{O}H_2 \overset{fast}{\rightleftharpoons} R^1.CO.OH + H^+ \end{array}\right\} A_{Ac}2$$

This mechanism was suggested by Ingold and Datta[2] and is similar to the mechanism which was suggested by Watson[3].

If as in the $B_{Al}1$ mechanism R in the ester $R^1.CO.OR$ has a definite tendency to ionise as cation R^+, this tendency will be greatly enhanced when, in an acid medium, the ester is converted into its conjugate acid $R^1.CO.O^+HR$, similarly the corresponding alcohol is also converted into its conjugate acid $R.O^+H_2$, from which R may readily ionise as a cation. The reversible esterfication and hydrolysis in acid media may then be expressed as follows :-

$$\left.\begin{array}{llll} R^1.CO.OR + H^+ & \rightleftharpoons & R^1.CO.O^+HR & (1) \\ R^1.CO.O^+HR & \underset{fast}{\overset{slow}{\rightleftharpoons}} & R^1.CO.OH + R^+ & (2) \\ R^+ + OH_2 & \underset{slow}{\overset{fast}{\rightleftharpoons}} & R^+OH_2 & (3) \\ R^+OH_2 & \rightleftharpoons & ROH + H^+ & (4) \end{array}\right.$$

$$\left.\begin{array}{l} (2) \\ (3) \end{array}\right\} A_{Al}1$$

Here the rate of esterfication is determined by the slow stage of reaction (3) and that of hydrolysis by the slow stage of reaction (2). The $A_{Al}2$ reaction may be formulated as follows:-

$$\begin{array}{lll} R^1.CO.OR + H^+ & \rightleftharpoons & R^1.CO.O^+HR \\ R^1.CO\ OH^+R + H_2O & \rightleftharpoons & R^1.CO.OH+R.OH_2^+ \ - \ A_{Al}2 \\ R.OH_2^+ & \rightleftharpoons & ROH + H^+ \end{array}$$

Method of determining the Point of Bond Fission

Several different methods have been used to determine the point of bond fission, the only unambiguous method, however, is that using isotopic tracer techniques.

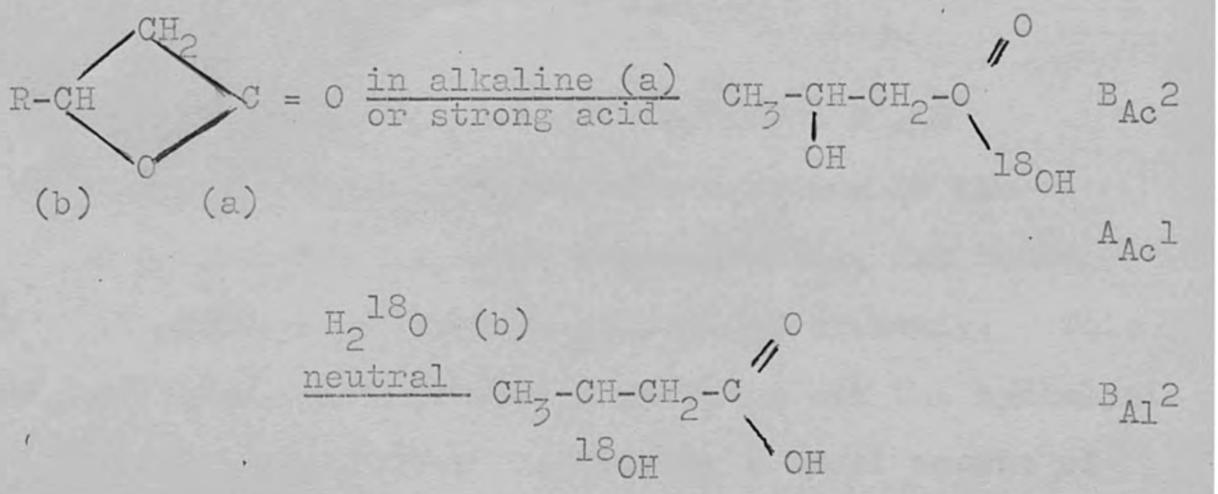
The Tracer Method In this method the ester is hydrolysed in water which is enriched in ^{18}O. It can be seen from the following reaction sequence that in alkyl-oxygen fission the isolated alcohol will be enriched in ${}^{18}O$ while in acyl-oxygen fission it will be normal.

$$\text{acyl}\quad R.CO \,\vdots\!\!-\!\!-\; O \;-\!\!-\; R' + H_2{}^{18}O \longrightarrow R.C.O.{}^{18}OH + R'OH$$

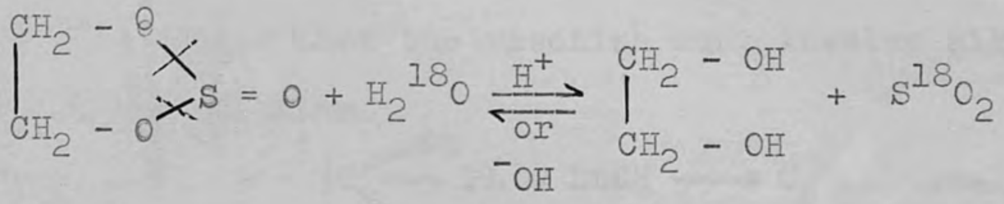
$$\text{alkyl}\quad R.CO \;-\!\!-\; O \;-\!\!\vdots\!\!-\; R' + H_2{}^{18}O \longrightarrow R.COOH + RO^{18}H$$

The alcohol or acid formed is extracted and examined mass-spectrometrically. Blank experiments must be performed to avoid the possibility of extraneous exchange between the solvent and products, also in order to obtain unambiguous results, special care must be taken to ensure that the alcohol or acid extracted is perfectly dry and free from enriched solvent before examination for the presence of ${}^{18}O$.

The mechanism of β-lactone hydrolysis, first investigated by kinetic and optical methods by Hughes *et al*[4] and by Olsen and Miller[5] has been confirmed by Olsen and Hyde[6] using the tracer technique:



It has been shown by Bunton *et al*[7] using the ${}^{18}O$ tracer technique that both the acid and alkaline hydrolyses of simple organic sulphites proceed entirely with S-O bond fission, e.g. for ethylene sulphite



$$\begin{array}{l} CH_2 - O \\ | \\ CH_2 - O \end{array} \!\!> S = O + H_2{}^{18}O \xrightleftharpoons[{}^{-}OH]{H^+ \text{ or}} \begin{array}{l} CH_2 - OH \\ | \\ CH_2 - OH \end{array} + S^{18}O_2$$

<u>Determination of Molecularity</u>

The second feature which has to be determined is the molecularity of the rate determining step.

In alkaline hydrolysis, where the net reaction is

$$R.COOH^1 + OH^- \longrightarrow R.COO^{\ominus} + R^1.OH$$

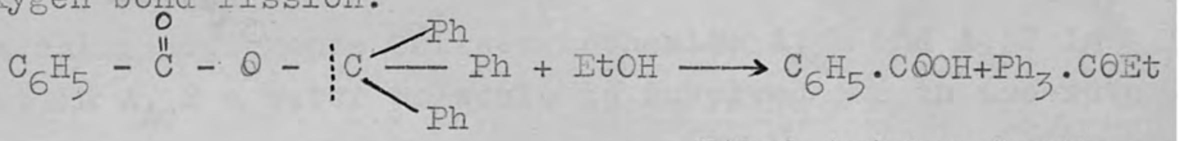
the molecularity is the same as the order of the reaction, and so may be determined directly. Those reactions which are unimolecular in dilute alkali, i.e. those in which the rate is independent of the reagent and the neutral hydrolysis are also unimolecular.

In acid the net reaction is

$$R.CO_2R^1 + H_2O \longrightarrow R.COOH + R^1.OH$$

Here water is always present in excess and so the dependence of rate on water concentration, and hence the molecularity, cannot be determined directly. This difficulty may be overcome by carrying out the hydrolysis in a non-aqueous solvent containing a small amount of water.

Hammond and Rudesill[8] investigated the reaction of ethyl-benzoate with a mixed solvent of ethanol and methyl ethyl ketone and by examination of the products showed that the reaction must involve alkyl-oxygen bond fission.



$$C_6H_5 - \overset{\overset{O}{\|}}{C} - O - \vdots\, C\left\langle\begin{smallmatrix}Ph\\Ph\\Ph\end{smallmatrix}\right. + EtOH \longrightarrow C_6H_5.COOH + Ph_3.COEt$$

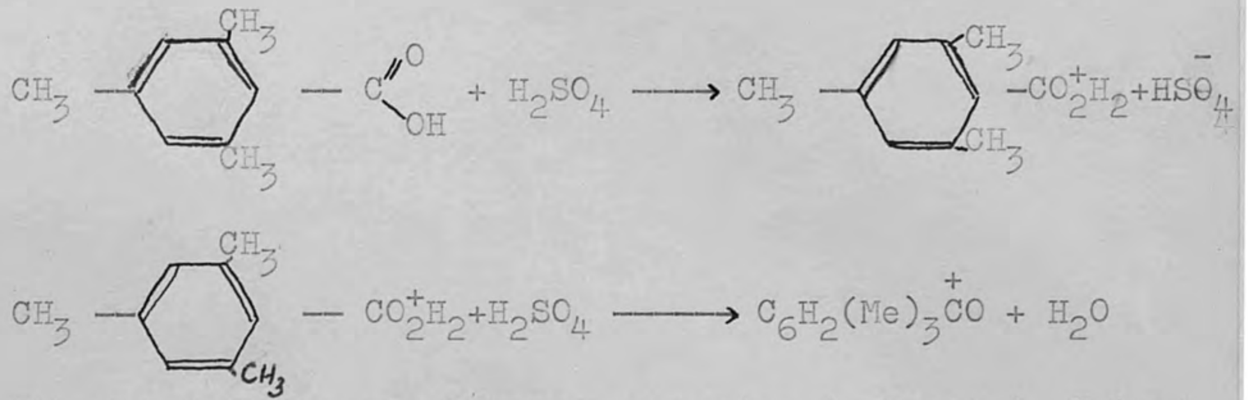
Ethyl triphenyl ether

They found the reaction was strictly first order, unaccelerated by added sodium chloride, apart from a small salt effect, and therefore they concluded that it must be unimolecular, i.e. involving the mechanism $B_{Al}1$

$$C_6H_5.COO.CPh_3 \rightleftharpoons C_6H_5CO_2^{\ominus} + \overset{+}{C}Ph_3 \xrightarrow[EtOH]{rapid} Ph_3CO.Et + C_6H_5COOH$$

The Molecularity of Acid-Catalysed Reactions

The rate of hydrolysis by mechanism $A_{Ac}1$ should be independent of water concentration. The first evidence of the existence of mechanism $A_{Ac}1$ was produced by Treffers and Hammett[9]. They found that mesitoic acid dissolved in sulphuric acid produced a four-fold depression of the freezing point, which can only be due to the production of the mesitoylium ion:-



The chief difference between mechanism $A_{Ac}1$ and $A_{Ac}2$ is that in $A_{Ac}2$ a water molecule is involved and in the rate determining step, whereas in $A_{Ac}1$ it is not. For any acid-catalysed ester-hydrolysis it is assumed that the first stage is a proton transfer.

$$S + H_3\overset{+}{O} \rightleftharpoons S^{+}H + H_2O$$

where S is the ester molecule.

If the proton transfer is a fast non-rate-determining step and involves H_3O^+, i.e. specific hydrogen ion catalysis, then for the next step there are two possibilities:-

$$(1)\quad \overset{+}{SH} \xrightarrow{\text{slow}} \text{Intermediate} \xrightarrow[\text{fast}]{+\text{ water}} \text{Products} \quad (A\text{-}1)$$

$$(2)\quad \overset{+}{SH} \xrightarrow[+\text{ water}]{\text{slow}} \text{Products} \quad (A\text{-}2)$$

The first involves unimolecular breakdown of the protonated ester to some intermediate which will react rapidly with water to give products; the second involves a bimolecular step, with a direct rate determining attack on the conjugate acid by a water molecule.

A solution to this problem was proposed by Hammett[10], when he introduced the acidity function H_o defined as:-

$$H_0 = -\log\left(\frac{a_{H^+} f_B}{f_{BH^+}}\right)$$

where a_{H^+} is the activity of hydrogen ion in the solution and f_B/f_{BH^+} is the ratio of the activity coefficient of a neutral base to that of its conjugate acid BH^+.

If we consider the dissociation of an acid BH^+

$$BH^+ \rightleftharpoons B + H^+$$

$$pK_a = -\log\frac{a_B . a_{H^+}}{a_{BH^+}}$$

$$\text{i.e. } pK_a = -\log\frac{a_{H^+} f_B}{f_{BH^+}} - \frac{C_B}{C_{BH^+}}$$

$$H_0 = pK_a + \log\frac{C_B}{C_{BH^+}} \qquad \text{..........(a)}$$

where $a_B = f_B . C_B$ etc.

It is also convenient to define a function ho as

$$h_0 = \frac{a_{H^+} . f_B}{f_{BH^+}}$$

Thus the Hammett acidity function is a measure of the tendency of a solvent to transfer a proton to a base (B). The ratio C_B/C_{BH^+} may be measured spectrophotometrically and knowing the pK_a's of bases the value of H_0 for a particular solution may be calculated from equation (a). Consider first the scheme:

$$\text{(i)} \quad S + \overset{+}{H_3}O^+ \underset{k_2}{\overset{k_1}{\rightleftharpoons}} SH^+ + H_2O$$

$$SH^+ \longrightarrow \text{Intermediate} \xrightarrow[\text{fast}]{+H_2O} \text{Products}$$

where S is an ester.

From the Brönsted equation we have:

$$v = k_2 . C_{SH^+} . \frac{f_{SH^+}}{X^*} \quad \text{..................(1)}$$

$$\text{and } K = \frac{C_{SH^+} . f_{SH^+} . a_{H_2O}}{C_S . C_{H_3O^+} \, f_S \, f_{H_3O^+}}$$

$$\text{i.e. } C_{SH^+} = \frac{K . C_S . C_{H_3O^+} \, f_S . f_{H_3O^+}}{a_{H_2O} \, . \, f_{SH^\oplus}} \quad \text{.........(2)}$$

$$\text{From (1) and (2) } v = \frac{k_2 K \, C_S . a_{H_3O^+}}{a_{H_2O}} \, . \, \frac{f_S}{f_{X^*}}$$

$$\text{i.e. } v = k_2 . K \, C_S . \left(\frac{a_{H^+} f_S}{f_{X^*}} \right)$$

$$\text{Now rate} = k_1 C_S$$

$$\therefore \quad k_1 = k_2 K . \left(\frac{a_{H^+} f_S}{f_{X^*}} \right)$$

and assuming that $f_{X^*} = f_{SH^+}$

$$\text{where } k_1 = k_2 \, K \, \frac{a_{H^+} f_S}{SH}$$

$$\therefore \quad \underline{k_1 \propto h_0}$$

Thus if the rate is proportional to h_0 we can assume a slow unimolecular breakdown of the protonated ester to give an intermediate which will give products by reaction with water. Cases of this type include the hydrolyses of sucrose[cf.11] and β-propiolactone[12].

Now let us consider the other possible scheme:

$$\text{(ii)}\quad S + H_3^+O \rightleftharpoons \overset{+}{SH} + H_2O \quad \text{Fast}$$

$$\overset{+}{SH} + H_2O \xrightarrow{\text{slow}} \text{Products}$$

From the Brönsted equation:

$$\text{Rate} = k_2 C_{SH} C_{H_2O} \frac{f_{SH^+} \cdot f_{H_2O}}{f_{X^*}} \quad \text{- - - - - - - - (3)}$$

$$\text{Now } K = \frac{k_{-1}}{k_1} = \frac{C_{SH^+}}{C_S \cdot C_{H_3O^+}} \quad \frac{f_{SH^+}}{f_S \cdot f_{H_3O^+}} \cdot a_{H_2O}$$

$$C_{\overset{\oplus}{SH}} = K \frac{C_S \cdot C_{H_3O} \cdot f_S f_{H_3^+O}}{a_{H_2O} \cdot f_{SH^+}}$$

Substituting in (3) for C_{SH^+} we have

$$\text{Rate} = \frac{k_2 \cdot f_{SH^+} \cdot f_{H_2O}}{f_{X^*}} \quad C_{H_2O}^{\,+} \quad \frac{K . C_S . C_{H_3^+O} \cdot f_S \cdot f_{H_3^+O}}{a_{H_2O} \cdot f_{SH^+}}$$

$$\text{Now Rate} = k_1 C_S$$

$$k_1 = k_2 . K . C_{H_3^+O} \frac{f_S \, f_{H_3^+O}}{f_{X^*}}$$

$$\text{If we assume that } \frac{f_S \cdot f_{H_3^+O}}{f_{X^*}} = 1$$

$$\text{then } k_1 = k_2 K . C_{H_3^+O}$$

$$\text{i.e.}\quad \underline{k_1 \propto C_{H_3^+O}}$$

If then the rate is found to be proportional to acid concentration the rate determining step is bimolecular and involves a water molecule. Examples of this type include the hydrolysis of γ-butyro-lactone[13], the enolisation of acetophenone[14], and the hydrolysis of ethyl acetate[15] and of methyl formate[15]. Thus if the rate is proportional to the stoicheiometric concentration of acid, then the mechanism operating is A-2.

Earlier it was assumed that the proton transfer was a fast non-rate determining step. This can be established by comparing the rate of hydrolysis in ordinary water, with that in deuterium oxide using the Bonhoeffer-Reitz Criterion[16]. Once again two alternatives present themselves:-

$$\text{either } S + H_3O^{\oplus} \underset{\text{fast}}{\overset{\text{fast}}{\rightleftharpoons}} \overset{\oplus}{S}H + H_2O$$

$$\overset{\oplus}{S}H \xrightarrow{\text{slow}} \text{Products}$$

or the proton transfer may be slow and rate-determining:-

$$S + H_3\overset{\oplus}{O} \xrightarrow{\text{slow}} \overset{\oplus}{S}H + H_2O$$

$$\overset{\oplus}{S}H \xrightarrow{\text{fast}} \text{Products}$$

If we compare the equilibria in water and D_2O we have :

$$S + H_3O^{\oplus} \rightleftharpoons SH^{\oplus} + H_2O$$

$$S + D_3{}^{\oplus}O \rightleftharpoons SD^{\oplus} + D_2O \qquad (4)$$

and for the second step:

$$SH^+ \longrightarrow \text{Products}$$
$$SD^+ \longrightarrow \text{Products} \qquad (5)$$

If step (4) and (5) are considered together it can be shown that if $\frac{k_1(D_2O)}{k_1(H_2O)} > 1$, the reaction must involve specific hydrogen ion catalysis. If on the other hand $k_1(D_2O)/k_1(H_2O) < 1$ no clear conclusion can be reached.

The following results for acid-catalysed hydrolyses illustrate the values which have been obtained:

Substrate	k_1D_2O/k_1H_2O
Methyl-Acetate[17]	1.68
Acetal[17]	2.66
Ethyl ortho formate[17]	2.05

Long and Pritchard[18] suggested that the value of k_1D_2O/k_1H_2O could be used as a further indication of the mechanism of reaction. Thus, whereas the value of k_1D_2O/k_1H_2O for an A-1 process is often in the range 1.9 - 2.6, the values for A-2 processes are often less and usually lie in the range 1.3 - 1.7.

Entropy of Activation Long, Pritchard and Stafford[18] suggested that a more positive entropy of activation would be expected for a unimolecular reaction, whereas the corresponding bimolecular reaction will show a relatively large negative entropy. Some idea of the spread of values obtained is given below:-

Substrate	Mechanism	ΔS(e.u.)	Reference
Diethyl sulfite	A-1	-9.14	19
Diethyl sulfite (60% Dioxane)	A-1	-22.0	19
Catechol sulfite (60% Dioxane)	A-1	-34.10	19
Ethyl formate	A-1	+5.8	20
Sucrose	A-1	+7.9	21
Ethylal	A-1	+7.3	22
Methyl Acetate	A-2	-23.0	23
γ-valerolactone	A-2	-24.6	24
γ-butyrolactone	A-2	-20.9	25

Whalley[26] has shown, however, that whereas this criterion may in certain cases give fortuitously correct results, it is not reliable in general as an unambiguous criterion of mechanism.

The use of the Zucker-Hammett hypothesis as a criterion of mechanism has been severely criticised in recent years. It is in-fact not surprising that the underlying assumptions have been found in some cases, to be invalid. It can still be of use, however, if considered in conjunction with other criteria.

More recently Bunnett has proposed an extension of the acidity function theory[27]. He showed that plots of $\log(k_1 + H_o)$ against $^{a}H_2O$ (where k_1 is the observed first order rate coefficient) gave linear plots with slopes (w) ranging from about -2 to +7. He then subdivided the range plots, $w < o$ implies an A-1 process,

$+1.2 < w > +3.3$ indicates water acting as a nucleophilic (A-2 process) and $w > +3.3$ indicates water acting as a proton transfer agent. In fact, however, anomalous values of w have been found for reactions of known mechanism. For the acid catalysed hydrolysis of sulphites, value of w in the range -1.00 → +4.33 have been found.

SECTION III

THE HYDROLYSIS OF NONCARBOXYLIC ACID

Dostrovsky and his co-workers[28] have investigated the point of bond fission of a variety of inorganic oxy-acids using ^{18}O tracer experiments. Triphenylmethyl hypochlorite, chlorate, bromate and iodate hydrolyse by X-O bond fission where X is the central atom of the oxy-acid. The corresponding perchlorate, however, hydrolyses by carbon-oxygen bond fission.

Tert-butyl hypochlorite and hypobromite hydrolyse by X-O bond fission as do nitrites such as n-butyl, tert-butyl and triphenyl methyl. The hydrolysis of n-butyl and n-octyl nitrates involves a mixture of both types of bond fission, whereas tert-butyl and triphenyl-methyl nitrates hydrolyse exclusively with X-O bond fission.

The hydrolysis of organic nitrates is complicated by the possibility of concurrent reactions occuring but has been elucidated chiefly by Baker and Easting[29] and a mixture of mechanisms is observed.

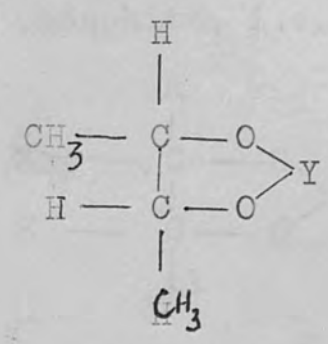
Allen[30] has made a detailed study of the hydrolysis of n-propyl, tert-butyl and diphenylmethyl nitrates and has shown that entire nitrosyl-oxygen bond fission occurs, He concluded that hydrolysis proceeds in the alkaline case by nucleophilic attack of hydroxide ion on the nitrogen atom. He found, however, that neutral alcoholysis of triphenylmethyl nitrite involves some carbon-oxygen bond fission.

The alkaline hydrolysis of trimethyl phosphate, has been shown to proceed entirely by phosphorous-oxygen bond fission.[31] Neutral solvolysis, however, proceeds[32] with entire alkyl-oxygen fission.

Bunton and his co-workers[33] have examined the alkaline hydrolysis of phenyl-toluene-p-sulphonate in aqueous dioxane and showed that the reaction involves bimolecular attack of hydroxide ion on the sulphur atom with fission of the sulphur-oxygen bond.

The hydrolysis of optically active sec-butyl hydrogen-phthalate has been studied by Burwell and Holmquist[34]. Alkaline hydrolysis involves complete inversion of configuration i.e. carbon-oxygen bond fission must occur.

The hydrolysis of cyclic esters of d(-) - 2,3 - butane diol has been described by Lucas and Garner[35].



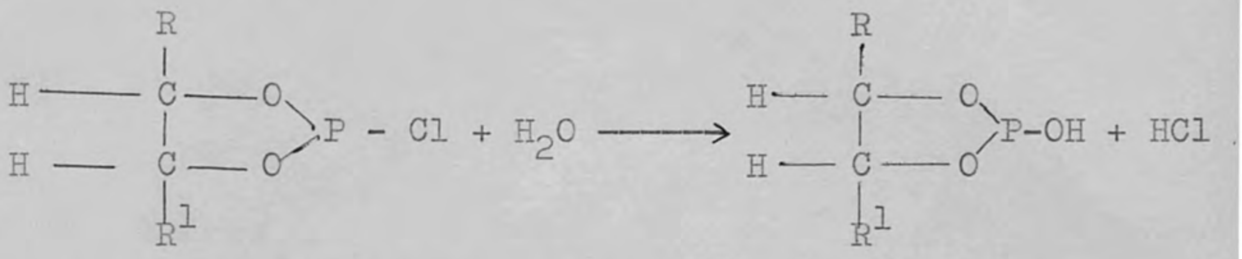
They found that hydrolysis of the formal (Y is CH_2) acetal (Y is $CH-CH_3$), carbonate (Y is C=O), sulphite (Y is S=O), chlorophosphite (Y is P-Cl), and borate proceed with complete retention of configuration.

The cyclic sulphate (Y = SO_2), however, shows anomalous behaviour. In acid solution the meso-diol was obtained, whereas in basic solution mainly the <u>dl</u>-diol is formed.

Thus except for cyclic sulphates all the cyclic esters studied by these workers hydrolyse by X-O bond fission.

Hydrolysis of the cyclic sulphate must involve some carbon-oxygen bond fission. The borate prepared was the so-called "neutral borate" of Morell and Lalthrop[cf.36] which on dissolving in water or in a solution of pH between one and thirteen immediately completely hydrolyses.

Lucas, Mitchell and Scully[37] have prepared cyclic phosphites of ethane diol, 1,2- and 2,3-butane diol. The diol chlorophosphites, hydrolyse under close control to give 95% yields of cyclic hydrogen phosphite, i.e.:-



These diol hydrogen phosphites react like dialkyl phosphites and are readily soluble in water giving a neutral solution which gradually becomes more acid due to hydrolysis to the mono-alkyl phosphite. Overend and Co-workers[38] have recently investigated the hydrolysis of cyclic sulphites and sulphates of <u>cis</u>- and <u>trans</u>-cyclohexane- 1,2-diol.

Trans-cyclo-hexanediol cyclic sulphite in acid and alkaline conditions hydrolyses to give the trans diol i.e. sulphur-oxygen fission must occur. Under acid conditions the <u>cis</u>-isomer gives the cis diol, but in alkaline hydrolysis the chief product is the trans-diol and a little cis diol, indicatingextensive carbon-oxygen bond fission.

Garner and Lucas[35] showed that basic hydrolysis of d(-) - 2:3-butylene cyclic sulphate yields 85% of dl-butane diol and suggested that this was due to the formation of an epoxide intermediate.

Overend, <u>et.al</u>[38] have postulated a similar intermediate for the trans-cyclohexane 1,2-diol cyclic sulphate.

This is supported by Burwell and Holmquist's evidence[34] that sodium (+) butan-2-ol sulphate is resistant to basic hydrolysis but eventually yields (-) butan-2-ol.

The fact that acid hydrolysis of the cis-cyclohexane-diol-sulphate yields the *trans*-diol is to be expected from Garner and Lucas' observation that d(-) 2,3-butylene cyclic sulphate yields meso-butan-2,3-diol under similar conditions.

The behaviour of the trans isomers on acid hydrolysis is not in accord with Garner and Lucas' observations[35] which would predict the cis-diol as the product where as in fact the major product is the *trans*-diol together with a small quantity of cis-diol.

The most detailed investigation of non-carboxylic esters other than in organic sulphites have been made on the organic phosphates mainly by Westheimer and his co-workers[39]. With the phosphates the position of the bond fission varies considerably with structure and in many cases hydrolysis with both C-O and P-O bond fission proceeds concurrently, whereas the hydrolysis of organic sulphites have been found to proceed only with S-O bond fission.

SECTION IV

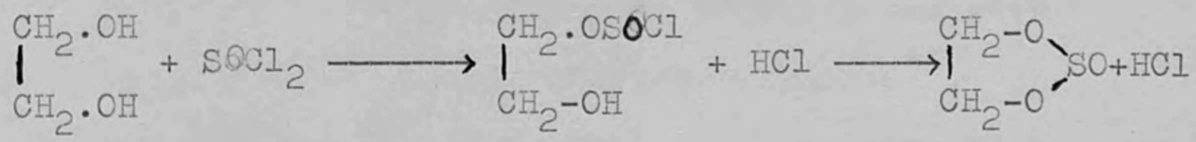
INTRODUCTION TO THE CHEMISTRY OF ORGANIC SULPHITES

The reaction of thionyl chloride with diols to form cyclic sulphites is well known[40,41,42].

Five-membered cyclic sulphites are readily prepared in good yield (70%) by reaction at room temperature. Six-membered ring sulphites are less readily prepared. The thionyl chloride has to be added slowly to the ice-cooled diol, yields are usually of the order of 30%. Szmant and Emerson have reported[42] the preparation of 1,4-butane-diol sulphite by a modification of the standard method using carbontetrachloride as solvent. The yield reported in this case was 10%.

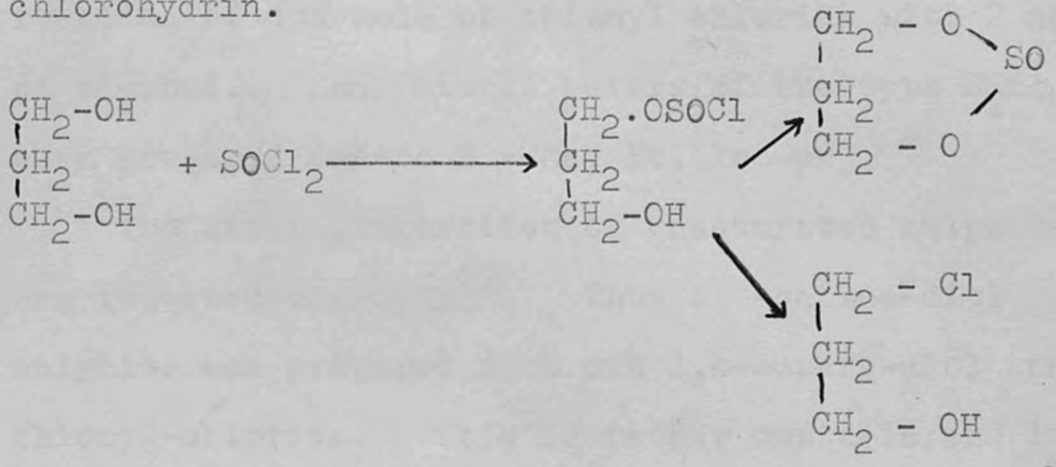
The poorer yields as the ring size increases are due to the fact that the intermediate chlorosulphinate which is formed first has available two reaction paths.

With ethylene glycol, sulphite formation is predominant.

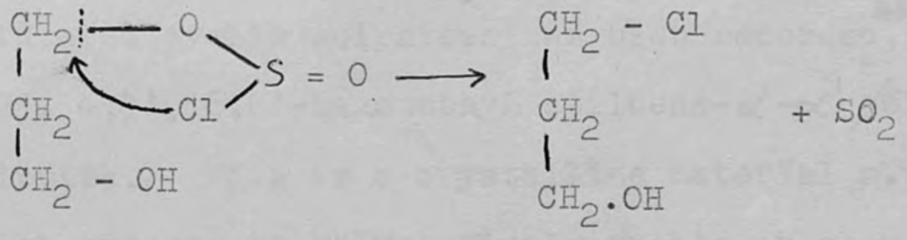


$$\begin{matrix} CH_2.OH \\ | \\ CH_2.OH \end{matrix} + SOCl_2 \longrightarrow \begin{matrix} CH_2.OSOCl \\ | \\ CH_2\text{-}OH \end{matrix} + HCl \longrightarrow \begin{matrix} CH_2\text{-}O \\ | \\ CH_2\text{-}O \end{matrix} \!\!> SO + HCl$$

With 1,3-diols, however, the yield of cyclic sulphite is reduced by the concurrent formation of the chlorohydrin.



The chlorohydrin being formed by internal S_Ni displacement of the chlorosulphinate viz.:

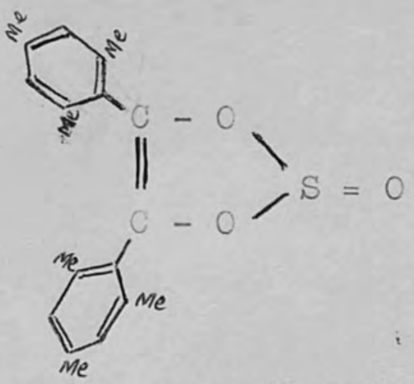


In fact this reaction is quoted in the literature[43] as being a standard method for the preparation of trimethylene chlorohydrin. Presumably this reaction competes even more strongly in the reaction of a 1,4-diol.

Aromatic cyclic and open-chain sulphites have also been prepared. Catechol sulphite has been prepared in good yield from catechol and thionyl chloride in benzene as solvent[44]. Diphenyl sulphite has been prepared by the refluxing solvent technique[45].

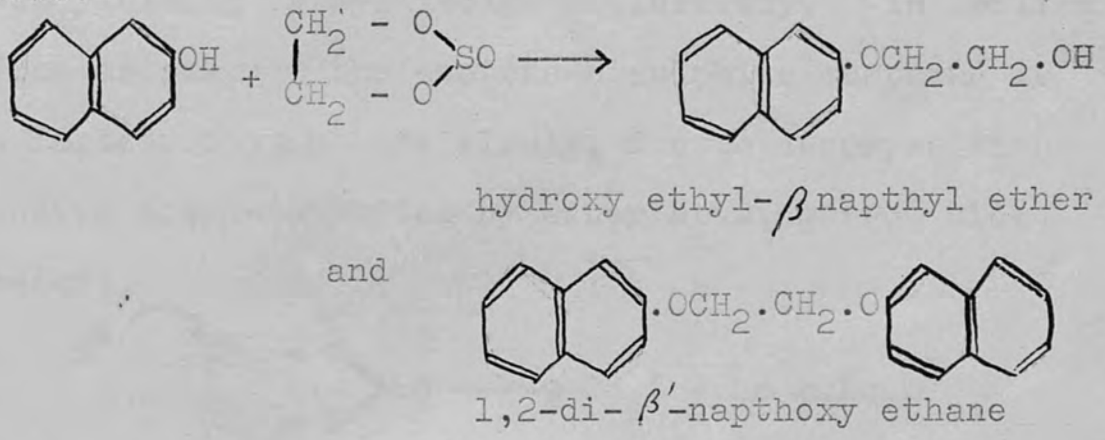
The preparation of dialkyl sulphites has been known for many years[46], and these are readily prepared by direct reaction of one mole of thionyl chloride with 2 moles of alcohol. Many simple esters of the type R_2SO_3 have been prepared (where R = Me, Et, Iso-pr).

The first preparation of unsaturated sulphites was reported recently[47]. Thus 1,4-butene-diol sulphite was prepared from cis 1,4-butene-diol and thionyl-chloride. This is rather unstable and its hydrolytic stability proved difficult to determine. Since then the preparation of more heavily substituted unsaturated cyclic sulphites has been recorded[48], e.g. cis-2,2', 4,4', 6,6'-hexamethyl stilbene-α-α'-diol sulphite. This is a crystalline material m.p. 175-178° which appears to be relatively stable at room temperature.



No measurement on the rate of hydrolysis of these materials has yet been reported.

There have been three main investigations relating to the point of bond fission in the hydrolysis of cyclic sulphites. As has been previously mentioned, Garner and Lucas[49] showed that the acid hydrolysis of levo-2,3-butylene Sulphite proceeds with complete retention of configuration, which indicates acyl-oxygen bond fission, since the bond attached to the asymmetric carbon atom has remained intact. Carlson and Cretcher[50], however, found that ethylene sulphite could be used as hydroxyethylating agent in a non-aqueous media such as toluene. This process must involve alkyl-oxygen (C-O) bond fission. The reaction with β-napthol proceeds as follows:-



hydroxy ethyl-β napthyl ether

1,2-di-β'-napthoxy ethane

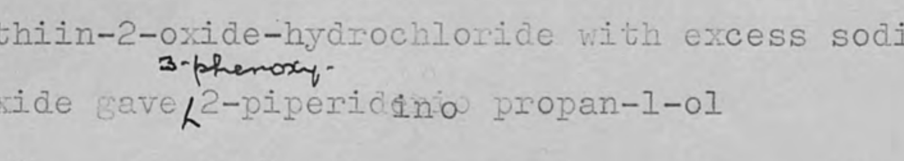
Thus the hydrolysis of sulphites in aqueous solution proceeds with sulphur-oxygen bond fission. Under non-aqueous conditions, however, it appears that carbon-oxygen bond fission may be observed.

Besides the O-alkylation achieved with sodium phenolates or alcoholates the products of N-alkylation are observed when dialkyl sulphites are heated with aniline. Thus with dimethyl sulphite and aniline the product consists of dimethyl aniline in 96% yield[46].

The alkylation of amines has also been carried out with iodides and bromides. When cyclic sulphites of 1,3-glycols are refluxed in acetone with sodium iodide, sodium iodoalkyl sulphites are formed, easily hydrolysable to the corresponding iodohydrins[51].

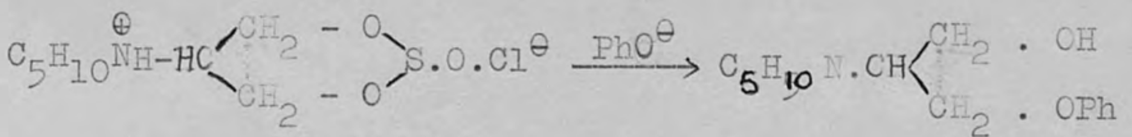
Foster, Hancock, Overend and Robb[52] investigated the reaction for a number of dialkyl sulphites and methyl sulphites of carbohydrates derivatives, the latter yielding methyl iodide exclusively. In boiling acetone as solvent the acetone-bisulphite compound is also formed, though more slowly, due to decomposition of sodium alkyl-sulphites by water arising from side reactions.

i.e.



$$I^{\ominus}\ \begin{matrix} CH_3 - O \\ CH_3 - O \end{matrix}\!\!>SO \longrightarrow CH_3I + Me\ O.So.O^{\ominus}$$

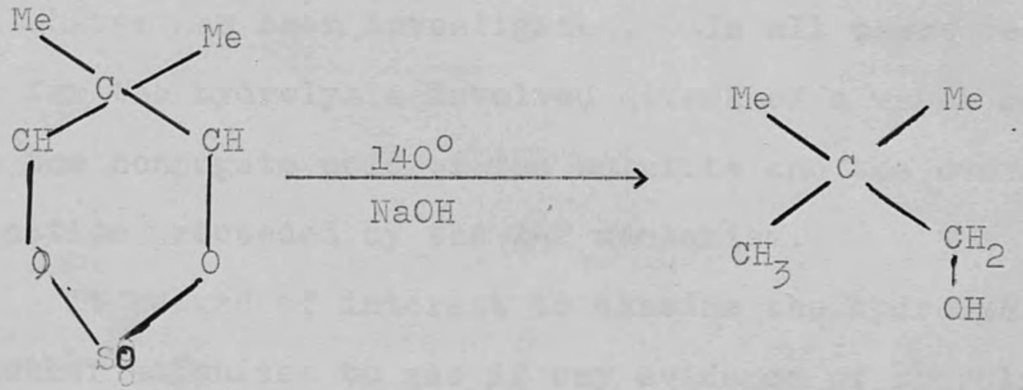
More recently Chapman, Isaacs and Parker[54] have shown that treatment of dihydrochloro-5-piperidino-1,3,2-dioxathiin-2-oxide-hydrochloride with excess sodium phenoxide gave 3-phenoxy-2-piperidino propan-1-ol



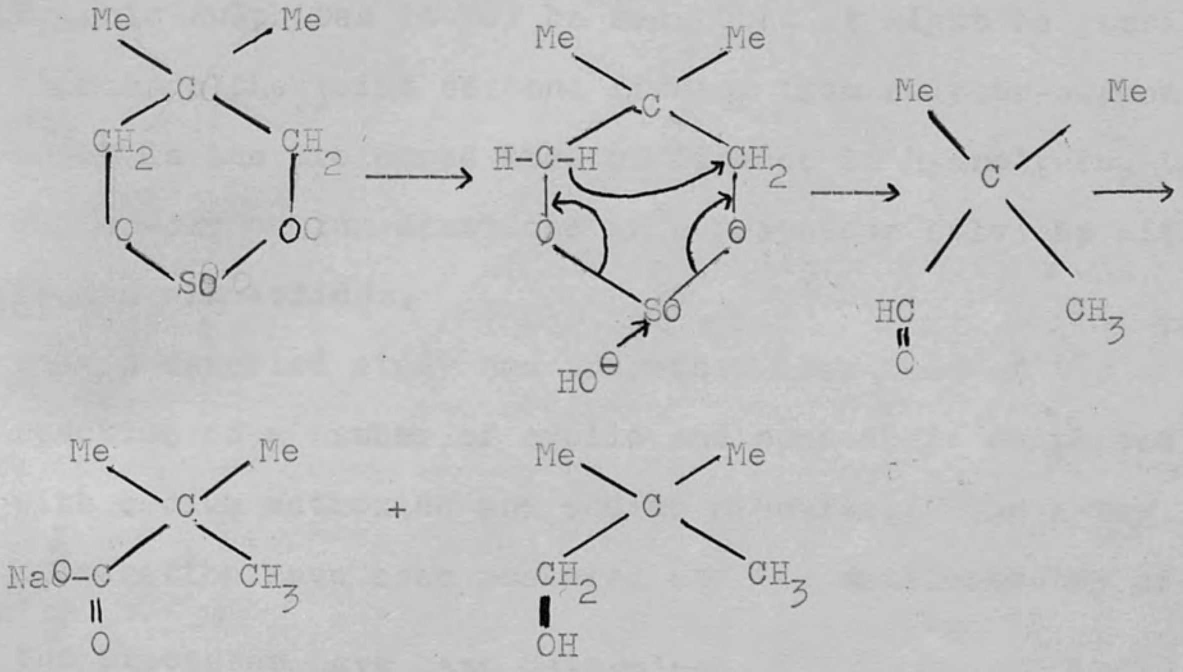
$$C_5H_{10}\overset{\oplus}{N}H-HC\begin{matrix} CH_2 - O \\ CH_2 - O \end{matrix}S.O.Cl^{\ominus} \xrightarrow{PhO^{\ominus}} C_5H_{10}N.CH\begin{matrix} CH_2\ .\ OH \\ CH_2\ .\ OPh \end{matrix}$$

A reaction of a different type which again involves

S-O bond fission is the rearrangement of 6-membered ring cyclic-sulphites reported by Crowdle <u>et al</u>.[55]. Thus in the presence of strong base the following reactions occur:



Apparently this is an extremely interesting example of a 1,3-hydride shift concurrent with elimination of an OH group. The resulting aldehyde, although not isolated among the products would be expected to undergo the Cannizzaro reaction in the strongly basic medium to yield the observed product, the monoalcohol.



THE AIMS AND OBJECTS OF THE INVESTIGATION

The acid-catalysed hydrolysis of several organic sulphites has been investigated. In all cases recorded so far the hydrolysis involved attack of a water molecule on the conjugate acid of the sulphite and the overall reaction proceeded by the A-2 mechanism.

It seemed of interest to examine the hydrolysis of further sulphites to see if any evidence of hydrolysis proceeding by an A-1 process could be found and at the same time to provide further information regarding the effect of ring size on the reactivity of the cyclic sulphites and to extend the measurements on open-chain aliphatic sulphites to cyclohexyl and aromatic systems.

From the proceeding survey of the chemistry of organic sulphites it may be seen that it might be possible to change the point of bond fission from sulphur-oxygen which is the preferred mode of fission in hydrolysis, to carbon-oxygen for reactions in non-aqueous solvents with sodium alk-oxides.

A detailed study has therefore been made of the reaction of a number of cyclic and open-chain sulphites with sodium methoxide and sodium ethoxide. The rates of reaction have been measured and the stoicheiometry of the processes have been determined.

SECTION V

EXPERIMENTAL WORK

Preparation of Sulphites:

1,4-Butane diol Sulphite: The preparation of 1,4-butane diol cyclic sulphite was described by Szmant and Emerson[56]. They reported the yield as only 10%.

Riemschneider and Ernst[57] prepared the rather unstable unsaturated 1,4-butene diol sulphite in 75% yield by heating cis 2-butene diol with dimethyl sulphite. Using the same method we prepared 1,4-butane diol sulphite in 90% yield. It was fractionated through an efficient column and had b.p. 72°/m.m., n_D25 1.4651 [Lit, n_D25 1.4631]. The analysis of this compound was (Found: C, 35.1; H, 5.9; O, 35.1; S, 23.4 Calculated for $C_4H_8O_3S$: C, 35.3; H, 5.9; O, 35.3; S, 23.5.)

Diphenyl Sulphite: The substance tends to decompose on heating and attempts to fractionate the impure material often lead to decomposition.

The various methods of preparation have been compared[58]. We finally adopted the following procedure:

To a mixture of phenol (18.8g.) and pyridine (15.8g.) in carbon tetrachloride (100 ml) in a three-necked flask equipped with water condenser and mechanical stirrer was added thionyl chloride (11.9 g. in 30 ml Ccl_4) over a period of 6 to 7 hours. An excess of pyridine was avoided because pyridinium salts dissolve in pyridine. Similarly, cooling of the carbon tetrachloride is best omitted because the precipitate is thicker at higher temperatures (40-45°) and is easier to wash. After filtering the pyridinium salts, the carbon tetrachloride was removed by pumping (12/15m.m.) whilst heating on a water bath at 30°, for two hours with regular stirring. A pale yellow liquid remained in the flask. This liquid was distilled under reduced pressure. After the fractionation in a fractionating column the yield was 60%, b.p. 185°/5m.m. and n_D25 1.5718 (Found: C, 16.4; H, 4.36; O, 20.35; S, 13.43 Calculated for $C_{12}H_{10}O_3$: C, 16.5; H, 4.27; O, 20.5; S, 13.6).

<u>Dicyclo-hexyl Sulphite</u>: This was prepared according to the method of Kyrides[59]. After fractionation it had b.p. 182°/19m.m., n_D25 1.4836 (Found: C, 58.50; H, 8.3; O, 19.70; S, 12.99 Calculated for $C_{12}H_{22}O_3S$: C, 58.50; H, 8.90; O, 19.5; S, 13.00).

<u>Other Sulphites</u>: The sulphites required for this investigation were prepared by standard methods, their physical properties are as follows :

Sulphite	b.p./m.m.	n_D^{25}
Ethylene[60]	88°/52	1.4450
Trimethylene[61]	74°/22	1.4509
1,2-propane diol[62]	58°/9	1.4359
2,3-butane diol (meso)[63]	73°/8	1.4380
Pinacol[64]	172.8°/760	solid
Diethyl[65]	158°/760	1.4130
Dimethyl[66]	126°/760	1.4070

SECTION VI

ACID CATALYSED HYDROLYSIS

The acids were of analytical reagent quality. Their concentrations were determined by titration with standard alkali. Sodium perchlorate was dried at 120° and was free from chloride ion.

Kinetic Procedure

The rate of hydrolysis at 25° and above was determined by a conventional sealed tube method. The conversion of organic sulphite into sulphur dioxide was determined at intervals by breaking samples under excess of iodine solution (or KIO_3) which was then back-titrated with sodium thiosulphate. The runs at 0° were carried out in stoppered flasks. Aliquot portions (usually 5.0 ml) were withdrawn at intervals and quenched in a large excess (200 ml) of ice-cold water containing excess of iodine which was then back titrated as above.

The following are examples of typical runs:

RUN NO. 129 Acid Catalysis Hydrolysis of 1,4-Butane Diol Sulphite in water at 45.01°

$[HClO_4]$ = 0.500M

Time (min)	Thio litre Excess KIO_3	Thio litre SO_2	x (ml)	a-x (ml)	log (a-x)	log $\frac{a}{a-x}$	$10^{+2}k_1$ (min^{-1})
0.00	26.95	0.60	--	38.83	1.5891	--	--
20.00	16.02	11.53	10.93	27.90	1.4456	0.1435	1.65
34.00	10.02	17.54	16.94	21.89	1.3403	0.2488	1.68
56.66	3.13	24.42	23.82	15.01	1.1776	0.4116	1.67
62.00	26.36	25.92	25.32	13.50	1.1306	0.4585	1.68
80.00	26.36	28.74	28.14	10.69	1.0289	0.5602	1.61
90.00	24.81	30.28	29.68	9.15	0.9614	0.6277	1.60
100.00	23.21	31.98	31.38	7.45	0.8774	0.7127	1.64
∞	15.67	39.43	38.83	--	--	--	--

Mean k_1 = 0.0164 min^{-1}

RUN NO. 118 Acid Catalysed Hydrolysis of 1,4-Butane Diol Sulphite in 30% dioxane water at 25°

$[HClO_4]$ = 0.250M

Time (min)	Thio titre Excess KIO_3	Thio litre SO_2	x (ml)	a-x (ml)	log (a-x)	log $\frac{a}{a-x}$	$10^{+2}k_1$ (min^{-1})
0.00	25.55	1.46	--	34.78	1.5413	--	--
31.55	21.67	5.38	3.88	30.90	1.4900	0.0513	0.375
63.00	18.20	8.81	7.35	27.43	1.4383	0.1030	0.384
91.00	15.51	11.50	10.04	24.74	1.3934	0.1479	0.378
120.00	12.75	14.26	12.80	21.98	1.3473	0.1990	0.381
150.00	10.43	16.59	15.13	19.65	1.2934	0.2479	0.370
180.00	9.37	17.62	16.12	18.66	1.2709	0.2709	0.345
∞	17.78	36.24	34.78	--	--	--	--

Mean k_1 = 0.00372 min^{-1}

RUN NO. 94 Effect of added Salt on the acid Catalysed hydrolysis of 1,4-Butane Diol sulphite in water at 25°

$[HClO_4] = 1.00M$

$[NaClO_4] = 1.00M$

Time (min)	Thio titre Excess KIo_3	Thio litre SO_2	x (ml)	a-x (ml)	log (a-x)	log $\frac{a}{a-x}$	$10^{+2}k_1$ (min^{-1})
0.00	26.80	0.25	--	33.76	1.5289	--	--
15.63	24.42	2.63	2.38	31.38	1.4966	0.0317	0.468
45.00	20.41	6.64	6.39	27.37	1.4373	0.0911	0.467
77.00	16.77	10.36	10.11	23.65	1.3738	0.1546	0.462
108.90	13.28	13.77	13.52	20.24	1.3062	0.2222	0.460
135.0	10.28	16.77	16.52	17.24	1.2610	0.2674	0.469
170.0	8.15	18.90	18.65	15.11	1.1793	0.3491	0.468
∞	20.09	34.01	33.76	--	--	--	--

Mean $k_1 = 0.00465\ min^{-1}$

RUN NO. 16 Acid Catalysed Hydrolysis of Dicyclohexyl Sulphite in 60% Dioxane water (v/v) at 25°

$[HClO_4] = 3.00M$

Time (min)	Thio litre Excess KIO_3	Thio litre SO_2	x (ml)	a-x (ml)	log (a-x)	log $\frac{a}{a-x}$	$10^{+2}k_1$ (min^{-1})
0	21.34	0.68	--	22.68	1.3557	--	--
10	15.80	6.22	5.45	17.14	1.2340	0.1217	2.682
20	11.72	10.30	9.64	13.04	1.1152	0.2405	2.968
30	8.75	13.27	12.59	10.08	1.0033	0.3524	2.760
40	5.63	16.39	15.71	6.97	0.8432	0.5125	2.951
50	3.83	18.19	17.51	5.17	0.7135	0.6422	2.960
60	25.68	18.69	18.01	4.67	0.6693	0.6822	2.631
∞	20.68	23.36	22.68	--	--	--	--
Blank	22.02						

Mean $k_1 = 0.0282\ min^{-1}$

RUN NO. 59 Acid catalysed Hydrolysis of Diphenyl Sulphite in 60% Dioxane water (v/v) at 0°

$[HClO_4] = 1.000M$

Time (min)	Thio litre Excess KIO_3	Thio litre SO_2	x (ml)	a-x (ml)	log (a-x)	log $\frac{a}{a-x}$	$10^{+2}k_1$ (min^{-1})
0.00	24.70	0.30	--	33.47	1.5243	--	--
60.33	24.10	0.90	0.60	32.87	1.5168	0.0075	0.0286
123.75	23.32	1.68	1.38	32.09	1.5063	0.0180	0.0265
180.00	23.00	2.00	1.70	31.77	1.5021	0.0222	0.0285
240.00	22.65	2.35	2.05	31.42	1.4971	0.0271	0.0261
300.08	21.99	3.07	2.47	31.00	1.4914	0.0329	0.0252
366.06	20.99	4.01	3.41	30.06	1.4780	0.0463	0.0292
∞	16.23	33.77	33.47	--	--	--	--
Blank	25.00						

Mean $k_1 = 0.000273\ min^{-1}$

SUMMARY OF KINETICS RUNS

The Acid Catalysed Hydrolysis of 1,4-Butane Diol Sulphite

Table I Acid Catalysis at 25°

(a)

Run No.	Acid	$[\text{Acid}]$ (mole.l^{-1})	$10^{+2}k_1$ (min^{-1})
92	$HClO_4$	0.500	0.147
31	"	0.750	0.259
6	"	1.000	0.350
87	"	1.500	0.559
5	"	2.000	0.836
86	"	2.500	1.250
131	H_2SO_4	0.500	0.198
132	"	1.000	0.468
134	HCl	0.500	0.441
133	"	1.000	1.350

(b) Acid Catalysis at 35.01° using $HClO_4$

125		0.500	0.452
124		1.000	1.250

(c) Acid Catalysis at 45.01° using $HClO_4$

129		0.500	1.64
130		1.000	4.24

(d) Acid Catalysis at 0° using $HClO_4$

126		1.000	0.134

(e) Effect of Added Salts on Acid Catalysis

Run No.	$[HClO_4]$ (mole l^{-1})	$[NaClO_4]$ (mole l^{-1})	$10^{+2}k_1$ (min^{-1})
95	0.500	1.500	0.254
94	1.000	1.000	0.465
93	1.500	0.500	0.679

(f) Acid Catalysis in 60% Dioxane water using $HClO_4$ at 25°

Run No.	[Acid] (mole l^{-1})	$10^{+2}k_1$ (min^{-1})
134	0.500	0.124
133	1.000	0.343
108	1.500	0.520
107	2.000	0.821

(g) Acid Catalysis in Dioxane water solvent at 25° using $HClO_4$ = 1.00M

Run No.	%Dioxane (V/v)	$10^{+2}k_1$ (min^{-1})
119	10%	0.335
111	20%	0.345
118	30%	0.372
112	40%	0.357
120	50%	0.349
133	60%	0.343
121	70%	0.336
122	80%	0.328
123	90%	0.347

Table II The Acid Catalysed Hydrolysis of Dicyclohexyl Sulphite in 60% Dioxane v/v

Acid Catalysis at 0°

Run No.	Acid	[Acid] (mole l^{-1})	$10^{+2}k_1$ (min^{-1})
18	$HClO_4$	1.000	0.102
12	"	2.000	0.518
16	"	3.000	2.850
20	"	4.000	1.340
25	HCl	0.500	0.149
27	"	1.000	0.735
29	"	1.500	0.962

Table III Acid Catalysed Hydrolysis of Diphenyl Sulphite in 60% Dioxane Water (v/v)

Acid Catalysis at 0° using $HClO_4$

Run No.	[Acid] (mole l^{-1})	$10^{+2}k_1$ (min^{-1})
59	1.000	0.0269
43	2.000	0.248
56	3.000	0.929
62	3.500	1.300
49	4.000	2.73

SECTION VII

REACTION IN NON-AQUEOUS SOLVENTS

Methyl and ethyl alcohol were dried using Lund and Bjerrum's method. The alk-oxide solutions were freshly prepared and standardised by addition to water and titrated against standard acid before use. The rate of reaction of methoxide and ethoxide with organic sulphite was followed in two different ways (a) by quenching in water containing excess iodine in acid followed by titration with sodium thiosulphate or (b) by quenching in water containing excess acid alone and back-titrating with standard alkali.

Typical Procedure: Ethylene sulphite (10 ml of 0.300M soln in MeOH) was added to 100ml of NaOMe (0.25M) in an automatic pipette, the apparatus being previously flushed out with nitrogen to remove water vapour. Samples (5.47ml) were pipetted out rapidly into reaction tubes again previously flushed with nitrogen and temporarily corked, and the tubes cooled in solid Co_2-MeOH mixture, and rapidly sealed. Tubes were withdrawn at intervals and stored in Dricold until analysed by either of the above methods indicated.

Rate constants were calculated by the usual second order rate expression:

$$k_2 = \frac{2.303}{t(b-2a)} \cdot \log \frac{a(b-2x)}{b(a-x)}$$

where a and b are the initial concentrations of sulphite and alkyloxide respectively.

The following are examples of typical runs:

RUN NO. 7 ALKALINE HYDROLYSIS OF ETHYLENE SULPHITE IN ETHOXIDE AT 60.04°

$[\text{Eto}] = 0.250\text{M}$

$[\text{E.S}] = 0.030\text{M}$

Time (min.)	Thio Equi of KIo_3	Thio Equi of SO_2	N of SO_2	M of SO_2	10^3x	$10^3(a-x)$	$10^3(2x)$	$10^3(b-2x)$	logY*	10^2k_2 l.mole^{-1} min^{-1}
0	--	--	--	--	--	27.2	—	227.2	--	--
3	23.26	2.30	.0042	.0021	2.1	25.1	4.2	223.0	.0268	11.9
6	20.96	4.60	.0084	.0041	4.1	23.0	8.4	218.8	.0758	12.5
9	18.86	6.70	.0122	.0061	6.1	21.1	12.2	215.0	.0863	12.7
12	17.96	8.10	.0150	.0075	7.5	19.7	15.0	212.2	.1104	12.2
15	15.55	10.01	.0184	.0092	9.2	18.0	18.4	208.8	.1427	12.6
18	13.89	11.67	.0214	.0107	10.7	16.5	21.4	205.8	.1742	12.8
21	11.71	13.85	.0240	.0120	12.0	15.2	24.0	203.2	.2043	12.9
28	10.92	14.64	.0255	.0127	12.7	14.5	25.0	201.7	.2215	12.3

Mean $k_2 = 0.124$ l.mole^{-1}.min^{-1}

$b = 0.2272$

$a = 0.0272$

$(b-2a) = 0.1728$

$$^*\log Y = \frac{a(b-2x)}{b(a-x)}$$

RUN NO. 2 ALKALINE HYDROLYSIS OF ETHYLENE SULPHITE IN METHOXIDE AT 60.04°

$[\overline{\text{Me}}\text{o}] = 0.250\text{M}$

$[\text{E.S}] = 0.030\text{M}$

Time (min.)	Thio Equi of KIO_3	Thio Equi. of SO_2	N of SO_2	M of SO_2	10^3x	$10^3(a-x)$	$10^3(2x)$	$10^3(b-2x)$	logY*	10^2k_2 l.mole^{-1} min^{-1}
0	--	--	--	--	--	27.2	--	227.2	--	--
15	24.02	2.43	.0044	.0022	2.2	25.0	4.4	222.8	.0282	2.49
30	21.59	4.80	.0088	.0044	4.4	22.8	8.8	218.4	.0596	2.63
45	19.96	6.49	.0119	.0058	5.8	21.4	11.9	215.3	.0935	2.75
60	18.34	8.1	.0148	.0078	7.8	19.4	14.8	212.4	.1155	2.65
75	16.20	10.2	.0188	.0094	9.4	17.8	18.8	208.4	.1487	2.62
90	14.56	11.89	.0218	.0104	10.4	16.8	21.8	206.4	.1676	2.46
105	13.24	13.21	.0241	.0120	12.0	15.2	24.1	203.1	.1959	2.46
120	12.10	14.35	.0261	.0130	13.0	14.2	26.1	201.1	.2293	2.53

Mean $k_2 = 0.0257$ l.mole^{-1}.min^{-1}

b = .2272
a = .0270
(b-2a)= .1728

$$*\log Y = \frac{a(b-2x)}{b(a-x)}$$

RUN NO. 9 Reaction of Trimethylene Sulphite with Sodium Methoxide at 60°

[MeO̅] = .100M

[T.M.S] = .03M

Time	Thio Equi To kIo_3	Thio Equi To SO_2	N of SO_2	M of SO_2	10^3x	$10^3(a-x)$	$10^3(2x)$	$10^3(b-2x)$	logY*	10^2k_2 (l.mole^{-1}. min^{-1})
	--	--	--	--	--	27.2	--	90.9	--	--
30	23.71	1.13	.0020	.0010	1.0	26.2	2.0	88.9	.0076	1.50
60	23.10	1.74	.0032	.0016	1.6	25.6	3.2	87.7	.0108	1.13
90	22.20	2.60	.0052	.0026	2.6	24.6	5.2	85.7	.0181	1.26
120	21.82	3.92	.0072	.0036	3.6	23.6	7.2	83.7	.0258	1.28
154	20.26	4.58	.0084	.0042	4.2	23.0	8.4	82.5	.0312	1.28
180	18.67	5.07	.0092	.0046	4.6	22.2	10.1	80.8	.0370	1.29
210	19.57	6.27	.0114	.0057	5.7	21.5	11.4	79.5	.0440	1.30
240	18.23	6.61	.0120	.0060	6.0	21.2	12.0	78.9	.0468	1.23

Mean k_2 = .0128 l.mole^{-1}min^{-1}

b = .09090

a = .0272

(b-2a) = .0365

$$*\log Y = \frac{a(b-2x)}{b(a-x)}$$

RUN NO. 22 Reaction of 1,4-Butane Diol Sulphite with Sodium Ethoxide at 60°

[Eto] = .500M

[1,4-B.DS] = .150M

Time (min)	Thio Equi to kIo_3	Thio Equi to SO_2	N of SO_2	M of SO_2	10^3x	$10^3(a-x)$	$10^3(2x)$	$10^3(b-2x)$	log Y*	10^2k_2 $l.mole^{-1}min^{-1}$
--	--	--	--	--	--	100.0	--	333.3	--	--
3.0	22.78	1.56	.0028	.0014	1.4	98.6	2.8	330.5	.0043	2.47
6.0	19.22	5.12	.0091	.0045	4.5	95.5	9.0	324.3	.0081	2.32
9.0	17.09	7.25	.0133	.0066	6.6	93.4	13.2	320.1	.0121	2.30
12.6	14.15	10.19	.0185	.0092	9.2	90.8	18.4	315.9	.0181	2.54
15.0	12.00	12.34	.0226	.0113	11.3	88.6	22.6	310.7	.0224	2.58
18.0	10.18	14.16	.0250	.0125	12.5	87.5	25.0	308.3	.0242	2.30
21.0	8.56	15.78	.0288	.0144	14.4	85.6	28.8	304.5	.0278	2.28
24.0	6.27	18.07	.0331	.0165	16.5	83.5	33.0	300.3	.0330	2.37

Mean k_2 = .0238 $l.mole^{-1}.min^{-1}$

b = 0.3333
a = 0.1000
(b-2a) = 0.1333

$$*\log Y = \frac{a(b-2x)}{b(a-x)}$$

RUN NO. 25 Reaction of Diethyl Sulphite with Sodium Methoxide at 60°

[Meo] = 0.5M

[O.E.S] = 0.15M

Time (min)	Thio Equito kIO_3	Thio Equito SO_2	N of SO_2	M of SO_2	10^3x	$10^3(a-x)$	$10^3(2x)$	$10^3(b-2x)$	log Y*	10^2k_2 $l.mole^{-1}min^{-1}$
--	--	--	--	--	--	100.0	0	333.3	--	--
5.0	19.03	3.43	.0063	.0031	3.1	96.9	6.2	327.1	.0055	1.89
10.1	15.79	6.72	.0125	.0064	6.4	93.6	12.8	320.5	.01170	1.96
15.2	12.36	10.15	.0187	.0093	9.3	90.7	18.6	315.7	.0175	1.98
20.2	9.30	13.21	.0242	.0121	12.1	87.4	24.2	309.1	.0233	1.99
25.0	7.14	15.37	.0283	.0141	14.1	85.9	28.2	305.1	.0276	1.90
30.0	3.60	18.91	.0346	.0173	17.3	82.7	34.6	298.7	.0349	2.00
35.0	1.59	20.92	.0387	.0193	19.3	80.6	38.6	294.7	.0402	1.98

b = .3333
a = .1000
(b-2a) = .1333

$$*\log Y = \frac{a(b-2x)}{b(a-x)}$$

Mean k_2 = .0195.l.mole^{-1}.min^{-1}

RUN NO. 42 Reaction of Pinacol Sulphite with Sodium Ethoxide at 60°

[EtO] = 0.25M

[Pin.S] = 0.03M

Time (min)	Thio Equi to kIO_3	Thio Equi to SO_2	N of SO_2	M of SO_2	10^3x	$10^3(a-x)$	$10^3(2x)$	$10^3(b-2x)$	log Y*	10^2k_2 $l.mole^{-1}min^{-1}$
--	--	--	--	--	--	27.2	--	227.2	--	--
12.4	16.25	7.35	.0134	.0067	6.7	20.5	13.4	213.8	.0707	7.60
30.0	11.80	11.80	.0214	.0102	10.2	17.0	21.4	205.8	.1713	7.63
46.0	9.15	14.45	.0264	.0132	13.2	14.0	26.4	200.8	.2348	7.72
50.2	7.25	16.35	.0299	.0149	14.9	12.3	29.1	198.1	.2852	7.57
60.0	5.25	18.36	.0335	.0167	16.7	10.6	33.5	193.7	.3401	7.55
70.0	4.01	19.59	.0356	.0178	17.8	9.4	35.6	191.6	.3874	7.33

Mean k_2 = .0756 $l.mole^{-1}.min^{-1}$

b = .2272
a = .0272
(b-2a) = 0.1728

$$*\log Y = \frac{a(b-2x)}{b(a-x)}$$

RUN NO. P5 REACTION OF ETHYLENE SULPHITE WITH SODIUM ETHOXIDE AT 60°
Simultaneous Determination by Acid Base and Iodometric Methods

Time (min)	Thio Equi to kIO_3	Thio Equi to SO_2	N of SO_2	M of SO_2	10^3x	ml of NaOH	[NaOEt]	$10^3x'$	10^2k_2* $l.mole^{-1}min^{-1}$
3.0	21.05	2.41	.0044	.0022	2.2	12.84	0.2225	4.7	12.5
6.0	18.70	4.76	.00872	.00436	4.4	13.01	0.2193	8.9	12.9
9.0	16.57	6.89	.0126	.0063	6.3	13.29	0.2141	13.1	13.0
12.0	15.05	8.41	.0152	.0076	7.6	13.46	0.2106	16.6	11.6
15.0	13.39	10.07	.0184	.0092	9.2	13.58	0.2087	18.5	12.6
18.4	11.36	12.10	.0221	.0110	11.0	13.88	0.2051	22.1	13.3
21.4	10.28	13.18	.0240	.0120	12.0	13.92	0.2025	24.7	12.4

*Calculated from formula $k_2 = \frac{2.303}{t(b-2a)} \cdot \log \frac{a(b-2x)}{b(a-x)}$

RUN NO. P6 REACTION OF TRIMETHYLENE SULPHITE WITH SODIUM ETHOXIDE AT 60°

Simultaneous Determination of Acid Base and Iodometric Methods

Time (min)	Thio Equi To kIO_3	Thio Equi To SO_2	N of SO_2	M of SO_2	10^3x	ml of NaOH	[NaOEt]	$10^3x'$	10^2k_2* $l.mole^{-1}min^{-1}$
0	--	--	--	--	--	--	0.2272	0	0
10.0	22.32	1.88	.0034	.0017	1.7	12.78	0.2242	3.0	2.86
20.0	20.71	3.43	.00638	.0032	3.2	12.98	0.2207	6.5	2.79
30.0	19.11	5.08	.00930	.0061	4.6	13.10	0.2176	9.6	2.77
40.0	17.41	6.78	.0123	.0061	6.1	13.27	0.2144	12.8	2.85
50.0	15.93	8.26	.0145	.0072	7.2	13.35	0.2130	14.2	2.90
60.0	14.66	9.53	.0174	.0087	8.7	13.45	0.2103	16.9	2.79
70.0	14.09	10.10	.0198	.0099	9.9	13.66	0.2073	19.9	2.75

*Calculated from formula $k_2 = \frac{2.0303}{t(b-2a)} \cdot \log \frac{a(b-2x)}{b(a-x)}$

RUN NO. P11 REACTION OF DIMETHYL SULPHITE WITH SODIUM METHOXIDE AT 60°

Simultaneous Determination of Acid Base and Iodometric Methods

Time (min)	Thio Equi to kIO_3	Thio Equi to SO_2	N of SO_2	M of SO_2	10^3x	ml of NaOH	[NaOEt]	$10^3x'$	10^2k_2 $l.mole^{-1}min^{-1}$
66	--	--	--	--	--	--	0.3333	--	--
3.0	22.00	2.19	.0040	.0020	2.0	32.05	0.3282	5.1	2.00
6.0	20.34	3.85	.0076	.0038	3.8	32.26	0.3243	9.0	1.90
9.0	18.61	6.58	.0120	.0060	6.0	32.34	0.3228	10.5	1.98
12.0	16.15	8.05	.0147	.0073	7.3	32.56	0.3189	14.4	1.96
15.0	14.15	10.04	.0183	.0091	9.1	32.80	0.3135	19.8	1.95
18.0	12.60	11.59	.0211	.0105	10.5	32.92	0.3124	20.9	1.91
21.0	11.14	13.05	.0247	.0123	12.3	33.14	0.2889	24.4	2.00

*Calculated from formula $k_2 = \frac{2.303}{t(b-2a)} \cdot \log \frac{a(b-2x)}{b(a-x)}$

RUN NO. P10 REACTION OF DIETHYL SULPHITE WITH SODIUM METHOXIDE AT 60°
Simultaneous Determination by Acid Base and Iodometric Methods

Time (min)	Thio Equi To kIO_3	Thio Equi To SO_2	N of SO_2	M of SO_2	10^3x	ml of NaOH	[NaOEt]	$10^2x'$	10^2k_2* $l.mole^{-1}min^{-1}$
0	--	--	--	--	--	32.19	0.3333	--	--
5.0	20.19	3.48	.0063	.0031	3.1	32.10	0.3119	8.8	6.90
10.0	17.36	6.88	.0124	.0062	6.2	32.45	0.3208	12.5	6.96
15.0	14.10	10.09	.0183	.0091	9.1	33.71	0.3161	17.2	7.54
21.0	11.05	13.14	.0250	.0125	12.5	33.15	0.3078	25.5	7.46
25.0	8.79	16.40	.02180	.01490	14.9	33.38	0.3038	29.5	7.36
30.0	5.65	18.54	.0338	.0169	16.9	33.58	0.3002	33.1	7.40
35.0	3.17	21.02	.0384	.0142	14.2	33.80	0.2952	38.1	7.65

*Calculated from formula $k_2 = \frac{2.303}{t(b-2a)} \cdot \log \frac{a(b-2x)}{b(a-x)}$

RUN NO. P8 REACTION OF PINACOL SULPHITE WITH SODIUM ETHOXIDE AT 60°

Simultaneous Determination of Acid Base and Iodometric Methods

Time (min)	Thio Equi to kIO_3	Thio Equi to SO_2	N of SO_2	M of SO_2	10^3x	ml of NaOH	[NaOEt]	$10^3x'$	10^2k_2* $l.mole^{-1}min^{-1}$
0	--	--	--	--	--	--	0.2272	--	--
5.0	21.34	2.84	.00547	.0027	2.7	12.79	0.2233	3.9	6.90
10.0	19.85	4.34	.00795	.0039	3.9	12.99	0.2196	7.6	6.96
15.0	18.64	6.55	.0119	.0059	5.9	13.20	0.2152	12.0	7.54
20.0	15.79	8.40	.0151	.0075	7.5	13.38	0.2124	14.8	7.46
25.0	13.04	10.15	.0185	.0092	9.2	13.51	0.2191	18.1	7.36
30.0	12.64	11.55	.0208	.0104	10.4	13.72	0.2058	21.9	7.40
35.0	11.34	12.85	.0235	.0117	11.7	13.82	0.2038	23.4	7.65

*Calculated from formula $k_2 = \frac{2.303}{t(b-2a)} \cdot \log \frac{a(b-2x)}{b(a-x)}$

The Reaction of Sulphites with Sodium Methoxide and Ethoxide at 60°

1. Ethylene Sulphite with Sodium Methoxide

Run No.	[MeO] (mole. l^{-1})	[Sulphite] (mole. l^{-1})	$10^2 k_2$ (mole. l^{-1})
1	.150	.03	--
2	.250	.03	2.65
3	.500	.03	2.58
4	.100	.03	2.59
5	.250	.15	2.61
P_1	.500	.03	2.35*
P_2	.500	.03	2.83*
P_{13}	.500	.03	2.48*
P_{15}	.500	.03	2.51*

2. Ethylene Sulphite with Sodium Ethoxide

Run No.	[Eto] (mole.l^{-1})	[Sulphite] (mole.l^{-1})	10^2k_2 (mole.l^{-1})
6	.180	.03	12.5
7	.250	.03	12.4
P_3	.500	.03	11.50*
P_4	.250	.03	12.7*
P_5	.250	.03	12.5*

3. Trimethylene Sulphite with Sodium Methoxide

9	.100	.03	1.27
10	.250	.03	1.21
11	.500	.03	1.23
12	.250	.15	1.26
13	.500	.15	1.17
P_{12}	.500	.03	1.25*

4. Trimethylene Sulphite with Sodium Ethoxide

Run No.	[Ēto] (mole.l^{-1})	[S̄ulphite] (mole.l^{-1})	10^2k_2 (l.mole^{-1}min^{-1})
14	.100	.03	2.74
15	.250	.03	2.71
16	.500	.15	2.50
17	.250	.15	2.60
18	.500	.03	2.50
P_6	.250	.03	2.80*

5. 1,4-Butane Diol Sulphite with Sodium Methoxide

Run No.	[M̄eo] (mole.l^{-1})	[S̄ulphite] (mole.l^{-1})	10^2k_2 (l.mole^{-1}min^{-1})
19	.500	.15	1.14
23	.250	.03	1.24
24	.250	.15	1.24

6. 1,4-Butane Diol Sulphite with Sodium Ethoxide

Run No.	[Ēto] (mole l^{-1})	[S̄ulphite] (mole l^{-1})	10^2k_2 (l.mole^{-1}min^{-1})
20	.250	.03	2.28
21	.250	.15	2.14
22	.500	.15	2.38

7. Diethyl Sulphite with Sodium Methoxide

Run No.	[Meo] (mole. l^{-1})	[Sulphite] (mole. l^{-1})	10^2k_2 ($l.mole^{-1}min^{-1}$)
25	.500	.150	1.95
26	.250	.150	1.93
P_{10}	.500	.150	1.95

8. Diethyl Sulphite with Sodium Ethoxide

Run No.	[Eto] (mole. l^{-1})	[Sulphite] (mole. l^{-1})	10^2k_2 ($l.mole^{-1}min^{-1}$)
27	.500	.150	1.92
28	.250	.150	1.94
P_7	.500	.150	1.93

9. Dimethyl Sulphite with Sodium Methoxide

Run No.	[Meo] (mole l^{-1})	[Sulphite] (mole. l^{-1})	10^2k_2 ($l.mole^{-1}min^{-1}$)
29	.500	.150	1.92
30	.250	.150	1.94
P_{11}	.500	.150	1.96

10. Dimethyl Sulphite with Sodium Ethoxide

Run No.	[Eto] (mole l^{-1})	[Sulphite] (mole l^{-1})	10^2k_2 ($l.\text{mole}^{-1}\text{min}^{-1}$)
31	.500	.150	1.92
32	.250	.150	1.94
P_9	.500	.150	1.94*

11. 1,2-Propane Diol Sulphite with Sodium Methoxide

Run No.	[Meo] (mole l^{-1})	[Sulphite] (mole l^{-1})	10^2k_2 ($l.\text{mole}^{-1}\text{min}^{-1}$)
33	.100	.03	2.60
34	.250	.03	2.32
P_{14}	.250	.03	2.31*

12. 1,2-Propane Diol Sulphite with Sodium Ethoxide

Run No.	[Eto] (mole l^{-1})	[Sulphite] (mole l^{-1})	10^2k_2 ($l.\text{mole}^{-1}\text{min}^{-1}$)
35	.100	.03	11.82
36	.250	.03	12.0

13. 2,3-Butane Diol Sulphite with Sodium Methoxide

Run No.	[Meo] (mole l^{-1})	[Sulphite] (mole l^{-1})	10^2k_2 ($l.\text{mole}^{-1}\text{min}^{-1}$)
37	.100	.03	1.82
38	.250	.03	1.84

14. 2,3-Butane Diol Sulphite with Sodium Ethoxide

Run No.	$[\overline{\text{E}}\text{tO}]$ (mole l^{-1})	$[\overline{\text{S}}\text{ulphite}]$ (mole. l^{-1})	10^2k_2 ($\text{l.mole}^{-1}\text{min}^{-1}$)
39	.100	.03	9.32
40	.250	.03	9.41

15. Pinacol Sulphite with Sodium Methoxide

Run No.	$[\overline{\text{E}}\text{tO}]$ (mole. l^{-1})	$[\overline{\text{S}}\text{ulphite}]$ (mole l^{-1})	10^2k_2 ($\text{l.mole}^{-1}\text{min}^{-1}$)
41	.100	.03	7.19
42	.250	.03	7.57
P_8	.250	.03	7.41*

16. Pinacol Sulphite with Sodium Ethoxide

Run No.	$[\overline{\text{M}}\text{eO}]$ (mole. l^{-1})	$[\overline{\text{S}}\text{ulphite}]$ (mole. l^{-1})	10^2k_2 ($\text{l.mole}^{-1}\text{min}^{-1}$)
43	.100	.03	1.86
44	.250	.03	1.58
P_8	.250	.03	7.41

Footnote:
The values of k_2 were obtained from the acid-base titrations. The values calculated using the iodate measurements are identical*. The runs were analysed both by acid-base and iodate methods.

PRODUCT ANALYSES

Experimental Procedure

The sulphite (1.0 mole) was dissolved in the sodium alkoxide solution (100 ml, 0.5 or 1.0 mole). After refluxing for eight hours the resulting solution was allowed to cool and was then centrifuged. The supernatent liquid was decanted off and the remaining solid dried in the air with gentle warming.

Ethylene Sulphite with Sodium Methoxide

		Found			
Expt.No.	[E.S]/[NaOMe]	%C	%H	%S	%Na
E 1	1:2	0.56	0.56	22.18	32.06
E 9	1:1	2.83	0.61	31.25	21.90

Ethylene Sulphite with Sodium Ethoxide

	[E.S]/[NaOEt]				
E 4	1:2	1.55	1.19	22.03	31.87
E 10	1:1	2.50	1.17	21.52	31.06

Dimethyl Sulphite with Sodium Methoxide

	[D.M.S]/[NaOMe]				
E 6	1:2	1.27	0.20	24.88	35.76
E 13	1:1	2.23	0.51	23.03	33.02

Dimethyl Sulphite with Sodium Ethoxide

		Found			
Expt. No.	[D.M.S.]/[NaOMe]	%C	%H	%S	%Na
E 8	1:2				
E 14	1:1	1.25	0.51	22.29	32.03

Diethyl Sulphite with Sodium Methoxide

	[D.E.S.]/[NaOMe]				
E 7	1:2	1.01	0.22	25.02	35.65
E 11	1:1	2.03	0.63	23.22	33.03

Diethyl Sulphite with Sodium Ethoxide

	[D.E.S]/[NaOEt]				
E 3	1:2	1.06) 1.04)	0.20) 0.11)	23.00	23.98
E 5	1:2	0.90	0.11	22.61	32.60
E 12	1:1	2.02	0.21	22.25	31.25

DISCUSSION

THE ACID CATALYSED HYDROLYSIS

The Position of Bond Fission

Garner and Lucas[67] showed that the acid or alkaline-catalysed hydrolysis of 2,3-butane diol sulphite proceeds with retention of configuration. They concluded that these hydrolyses proceeded entirely with sulphur-oxygen bond fission. Subsequently Bunton et al[68] showed that sulphur-oxygen bond fission was the preferred mode of fission under both acid and alkaline conditions for a number of aliphatic sulphites, i.e. for ethylene sulphite:

$$\begin{array}{l} CH_2 - O \\ | \qquad\quad > SO \\ CH_2 - O \end{array} + H_2{}^{18}O \longrightarrow \begin{array}{l} CH_2 - OH \\ | \\ CH_2 - OH \end{array} + H_2S^{18}O_3$$

We have therefore assumed in the present investigation that under acid conditions, 1,4-butane diol sulphite, diphenyl sulphite and dicyclohexyl sulphite hydrolyse entirely by sulphur-oxygen bond fission.

The Acid-Catalysed Hydrolysis of 1,4-Butane Diol Sulphite

The results for 1,4-butane diol sulphite from Table II are represented graphically in the four first figures.

Correlation of Rate with Hammett Acidity Function

The values of log k_1 for 1,4-butane diol sulphite plotted against the values of the Hammett acidity function are shown in Figure I.

We used three acids as catalysing agents: perchloric, sulphuric, and hydrochloric acid. The concentration of the acids varied from 0.5 - 2.00 Molar. Consider first the effect of variation in the concentration of perchloric acid on the rate. The points lie on a straight line of slope 0.69. The points of hydrochloric acid, sulphuric acid and the mixture of sodium perchlorate and perchloric acid (not shown) lie on different straight lines. The slope for perchloric acid itself is rather low for the Hammett slope of an acid-catalysed reaction proceeding by the A-1 mechanism and it might in fact arise from either a bimolecular reaction, or from a unimolecular reaction which exhibits a large negative salt effect.

The addition of sodium perchlorate to perchloric acid increases the acidity of the solution as measured by H_0. The rate of the acid-catalysed hydrolysis of ethylene sulphite is not increased to the same extent[69]. The above results indicate that the reaction is not Hammett dependent, neither is the rate directly proportional to the concentration of the acid. When the reaction is carried out with the concentration of s

ACID CATALYSED HYDROLYSIS OF 1,4-BUTANE DIOL SULPHITE IN WATER AT 25°

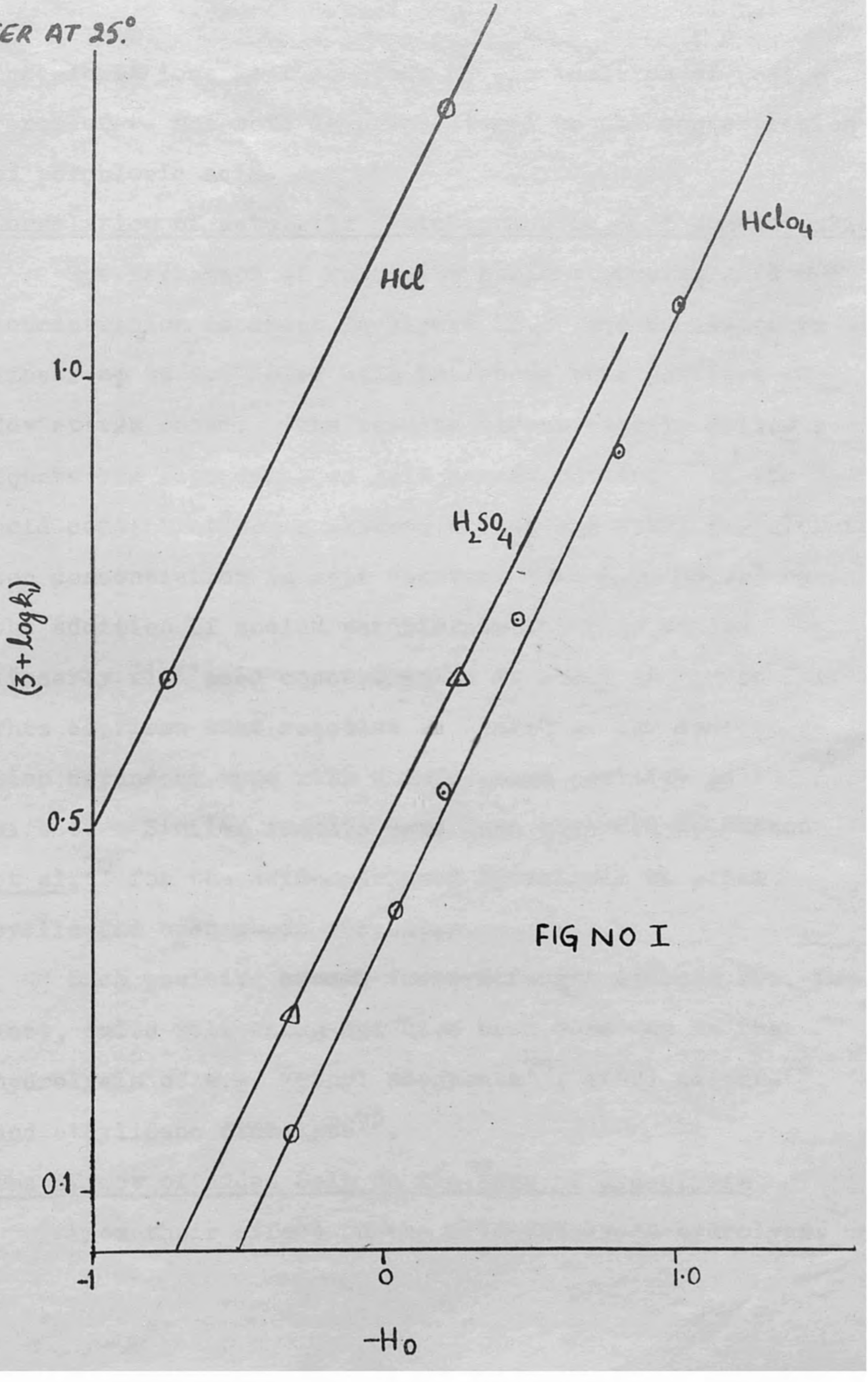


FIG NO I

perchlorate ions kept constant by the addition of sodium perchlorate the rate is proportional to the concentration of perchloric acid.

Correlation of Rate with Stoicheiometric Acid Concentration

The variation of rate with stoicheiometric acid concentration is shown in Figure II. The variation is linear up to 0.5 Molar acid but above this positive deviations occur. The results almost exactly follow a square law dependence on acid concentration. If the acid concentration is altered whilst the total perchlorate ion concentration is kept constant (μ= 2.00 Molar) by the addition of sodium perchlorate the rate varies linearly with acid concentration as shown in Figure III. This confirms that reaction is indeed of the concentration dependent type with a superposed positive salt effect. Similar results have been observed by Bunton et al.[70] for the acid-catalysed hydrolysis of other cyclic and open-chain sulphites.

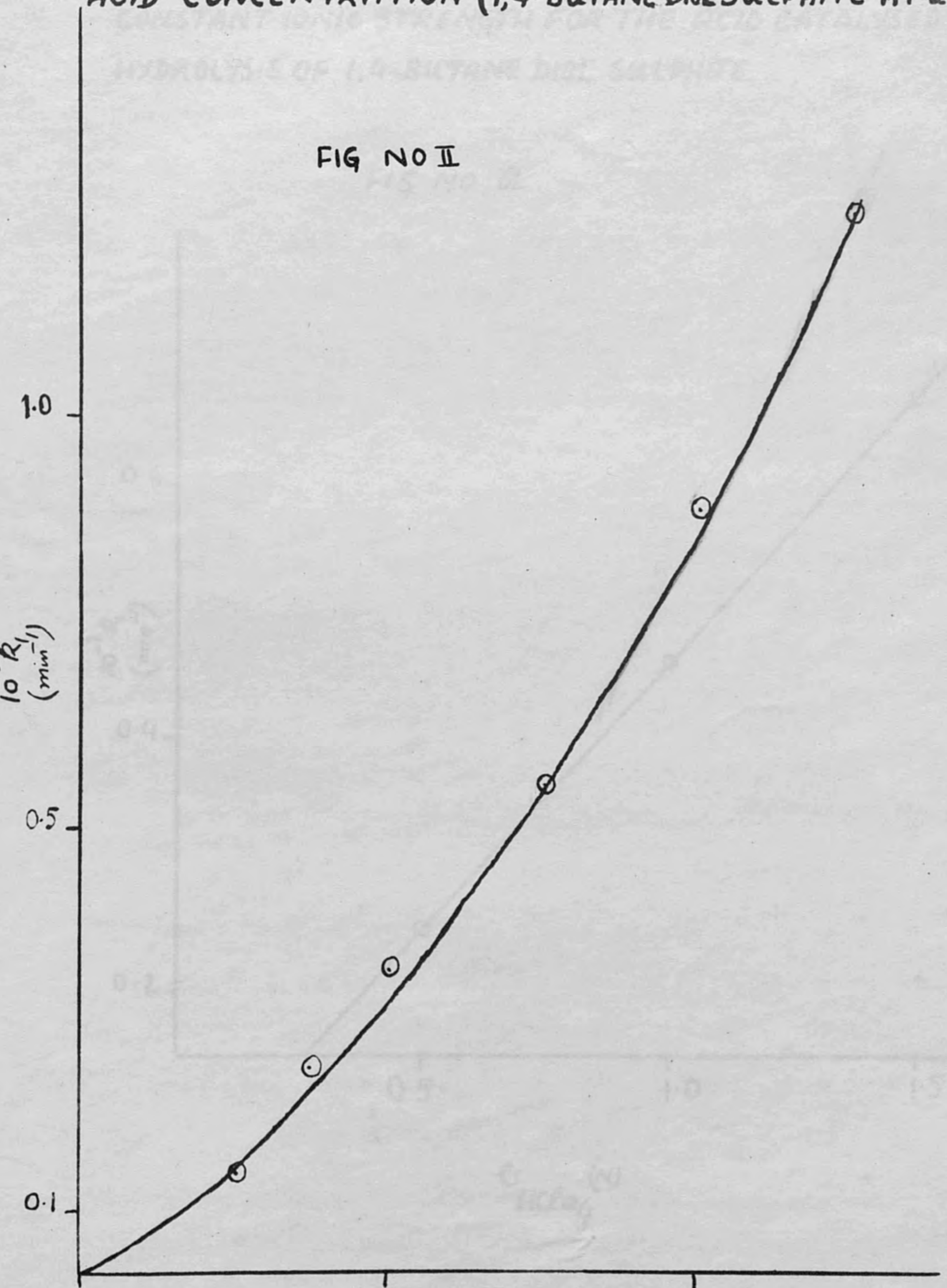
Such positive [redacted] ionic strength effects are, in fact, quite well known and have been observed in the hydrolysis of e.g. methyl phosphate[71], ethyl acetate[72], and ethylidene diacetate[73].

The Effect of Added Salt on the Rate of Hydrolysis

From their effect on the acid-catalysed hydrolyses

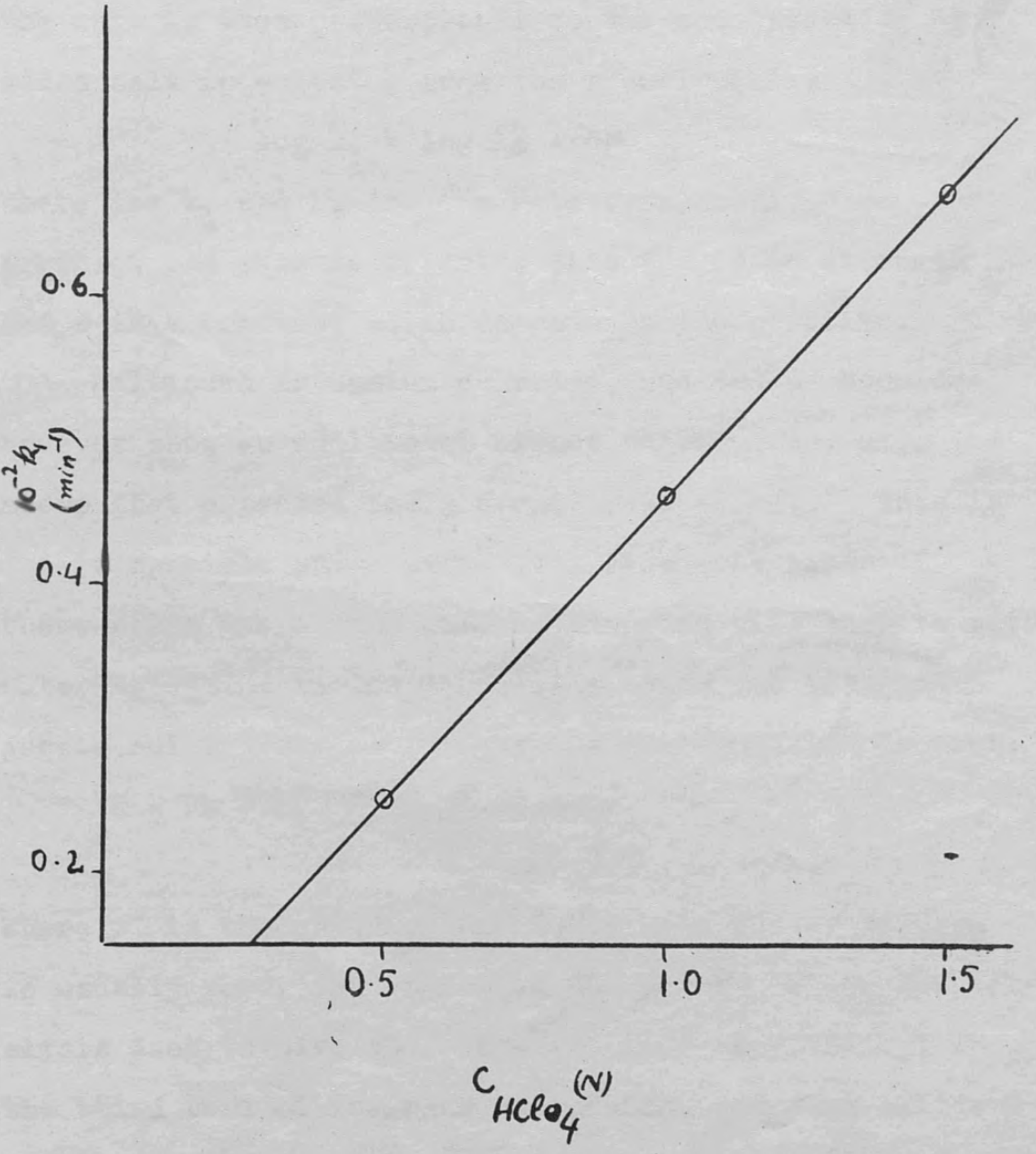
THE VARIATION OF RATE WITH STOICHEIOMETRIC ACID CONCENTRATION (1,4-BUTANE DIOL SULPHITE AT 25°)

FIG NO II



THE VARIATION OF RATE WITH ACID CONCENTRATION AT CONSTANT IONIC STRENGTH FOR THE ACID CATALYSED-HYDROLYSIS OF 1,4-BUTANE DIOL SULPHITE.

FIG NO III



of organic sulphites, salts may be divided into two classes.

Sodium perchlorate and sodium p- toluene sulphonate have merely an ionic strength effect and increase the rate. The rate is then proportional to the concentration of added salt as expected from the reactionship:

$$\log k_1 = \log k_0 + B\mu$$

Where log k_1 and k_0 are the rate constant in the presence and absence of salt, μ is the ionic strength and B is a constant which depends on the reaction.

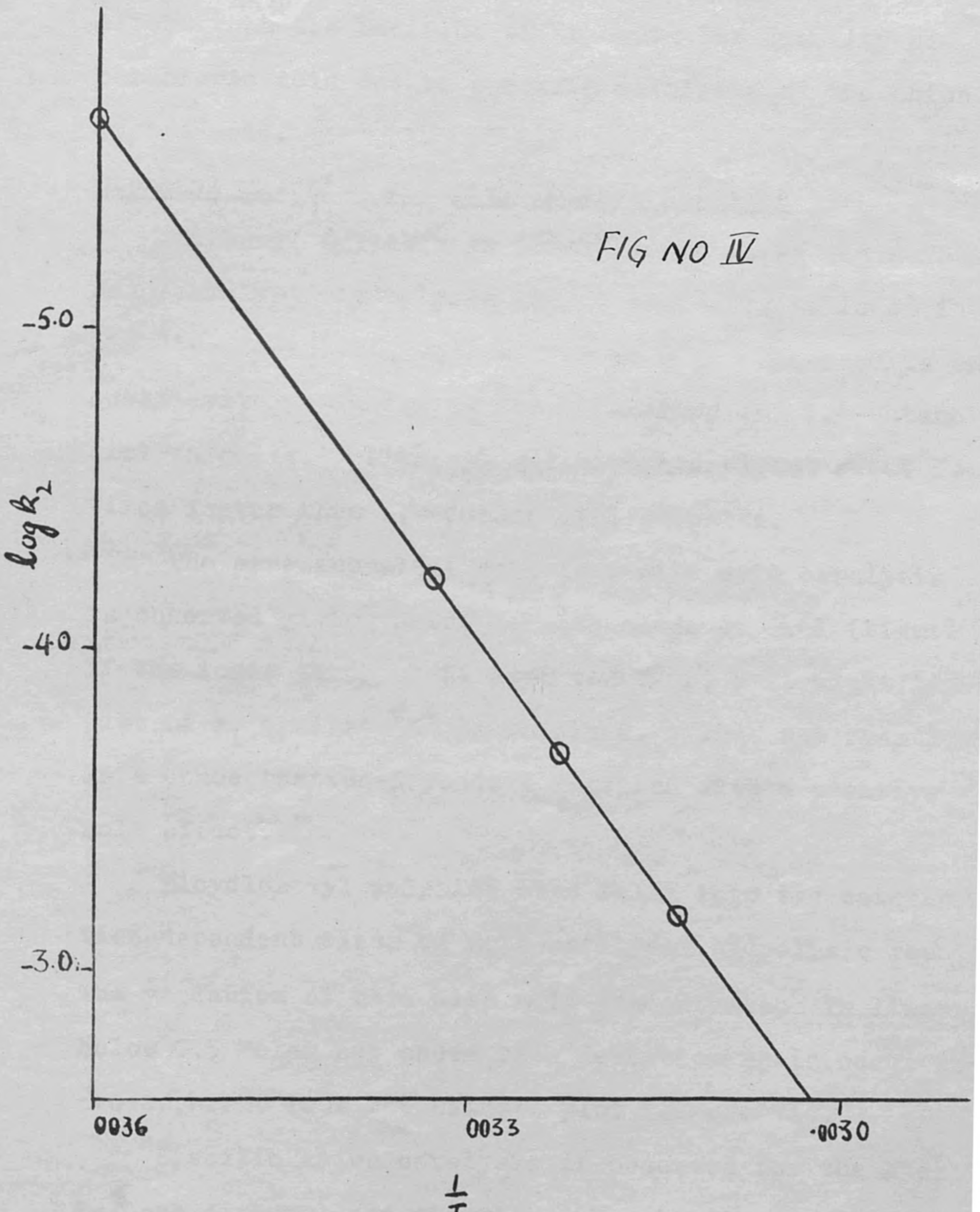
Salts such as sodium chloride, and sodium bromide however show an additional effect on the rate, over and above that expected for a normal salt effect. This is due to specific anion catalysis, since the anion of these salts are strong nucleophiles and will compete with water molecules in the transition state for the conjugate acid. The overall rate expression then becomes:

$$k = k_0 + k_{H}^{+} [H^+] [\text{Sulphite}] + k_{x^-} [H^+][\text{Sulphite}][x^-]$$

Where x^- is the anion of the added salt (Cl or Br), k_0 is usually zero, and it can be shown that halide ion catalysis does involve the conjugate acid as indicated in the third term of the rate expression, and that halide ion catalysis of the neutral reaction does not occur.

ARRHENIUS PLOT FOR THE ACID CATALYSED HYDROLYSIS OF 1,4-BUTANE DIOL SULPHITE

FIG NO IV



Thus for 1,4-butane diol sulphite, the addition of sulphuric acid or hydrochloric acid as shown in Figure I has a larger effect than the addition of an equimolar quantity of perchloric acid due to specific catalysis by the anion of the acid.

Diphenyl Sulphite and Dicyclohexyl Sulphite

Diphenyl Sulphite is insoluble in water and so its acid-catalysed hydrolysis was conveniently followed in 60% dioxane-water (v/v) solvent at 0°. The results are qualitatively similar to those obtained for 1,4-butane diol sulphite. Diphenyl sulphite hydrolysed about four times faster than 1,4-butane diol sulphite.

The same anomalous behaviour with acid catalysis is observed giving a low Hammett slope of 0.61 (Figure V). If the ionic strength is kept constant, a straight line plot of k_1 against C_{H^+} is obtained. Thus the reaction is a concentration-dependent reaction with a positive salt effect.

Dicyclohexyl sulphite also falls into the concentration-dependent class of acid-catalysed hydrolysis reactions The variation of rate with acid concentration is linear below 0.5 Molar but above this deviations again occur as are apparent from the Hammett plot (Figure VI).

Specific anion catalysis is observed for the hydrolysis of both diphenyl and dicyclohexyl sulphites.

ACID CATALYSED HYDROLYSIS OF DIPHENYL SULPHITE IN 60% DIOXANE WATER (V/V) AT 0°

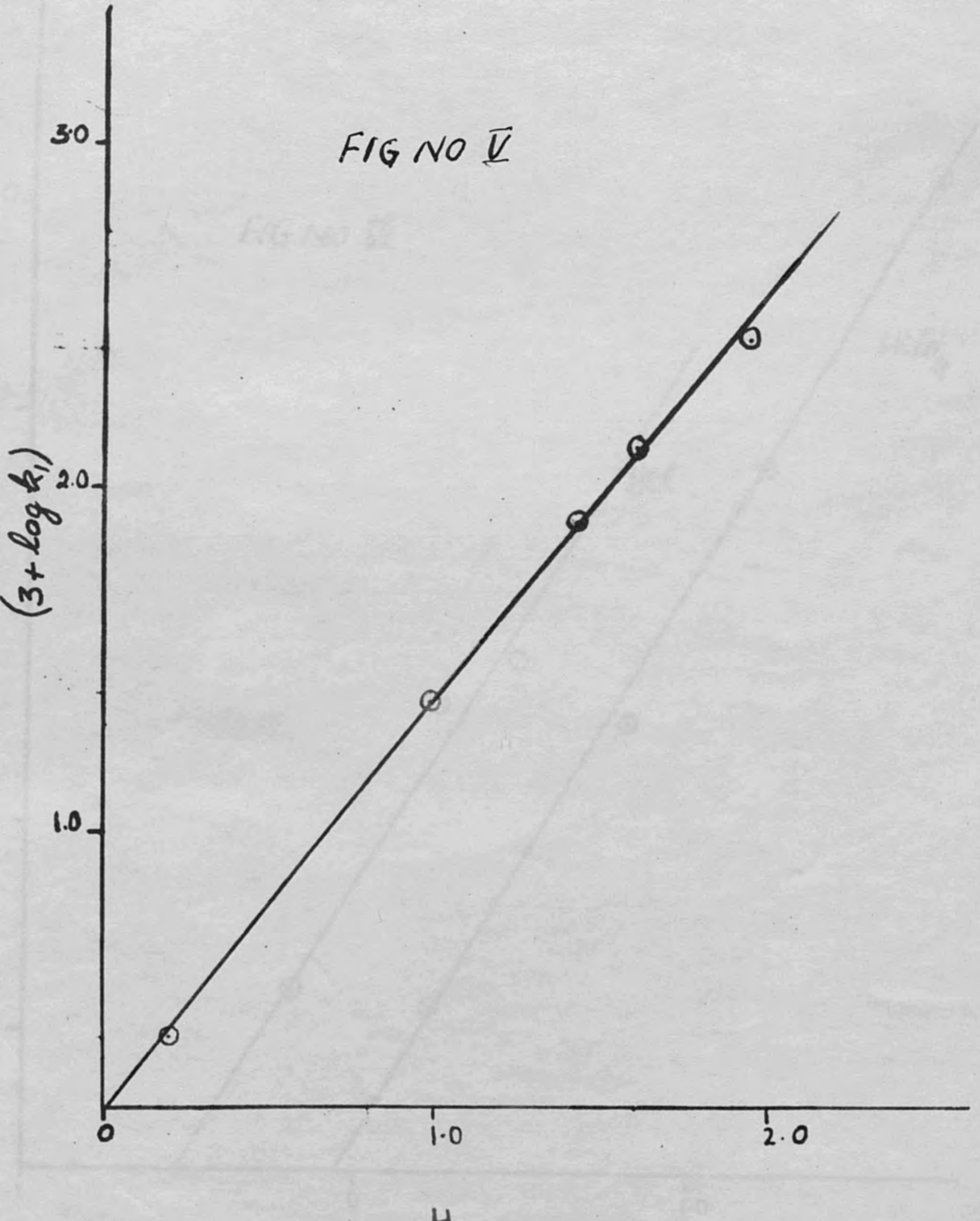
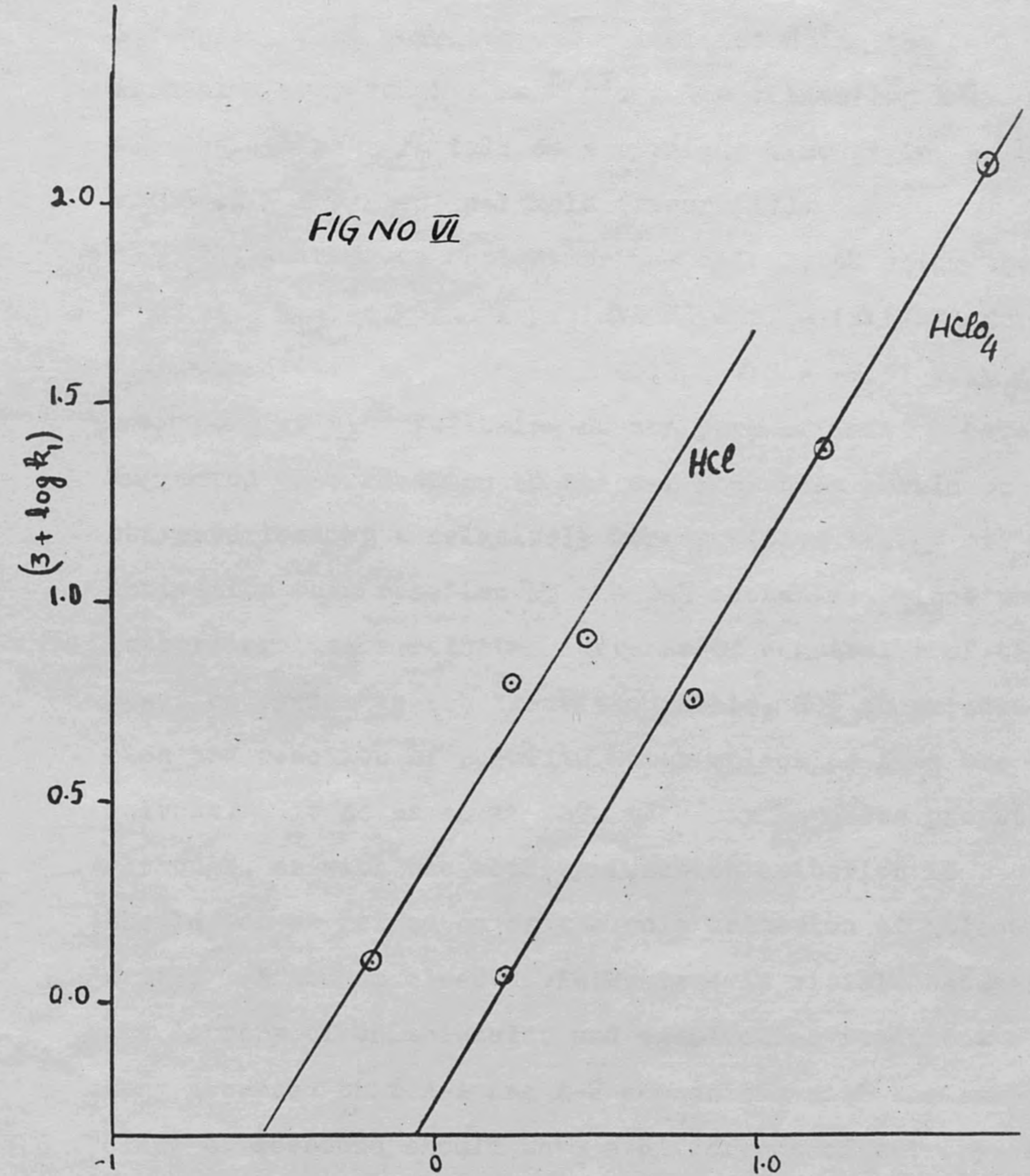


FIG NO V

ACID CATALYSED HYDROLYSIS OF DICYCLOHEXYL SULPHITE
IN 60% DIOXANE WATER (V/V) AT 0°

FIG NO VI



Other correlations

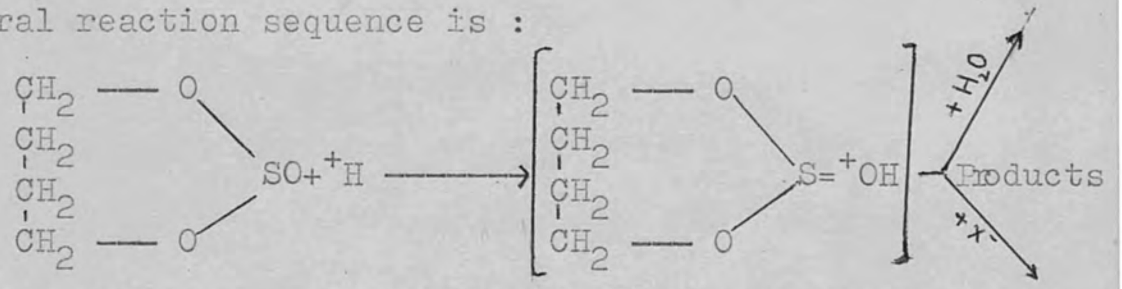
The energy of activation for the hydrolysis of 1,4-butane diol sulphite was calculated using the Arrhenius equation $k = Ae^{-E/RT}$. The values of log k plotted against $^1/_T$ fall on a straight line giving a value of $E = 21.0$ cal/mole (Figure IV).

The entropy of activation was calculated using the formula - $k = (e.kT/h) \exp. (\Delta S/R) \exp. - (\Delta E/RT)$; for 1,4-butane diol sulphite in IM$HClO_4$, $\Delta S = -8.51$ e.u.

Long et al[74] following on the work of Taft[75], have suggested that reaction by the A-1 mechanism should be characterised by a relatively more positive energy of activation than reaction by the A-2 mechanism, since the latter involves a relative increase of constraint of the reaction system in the transition state, due to orientation and reaction of specific water molecules from the solvent. It seems as if this idea may be quite profitable although, as with the acidity function criterion it should not be relied on as the sole criterion of molecularity, Since no clear dividing line is visible between the entropy of unimolecular and bimolecular reactions. Long proposed that A-1 and A-2 mechanisms with the same class of compound should have a difference of entropy of 20 - 30 e.u.

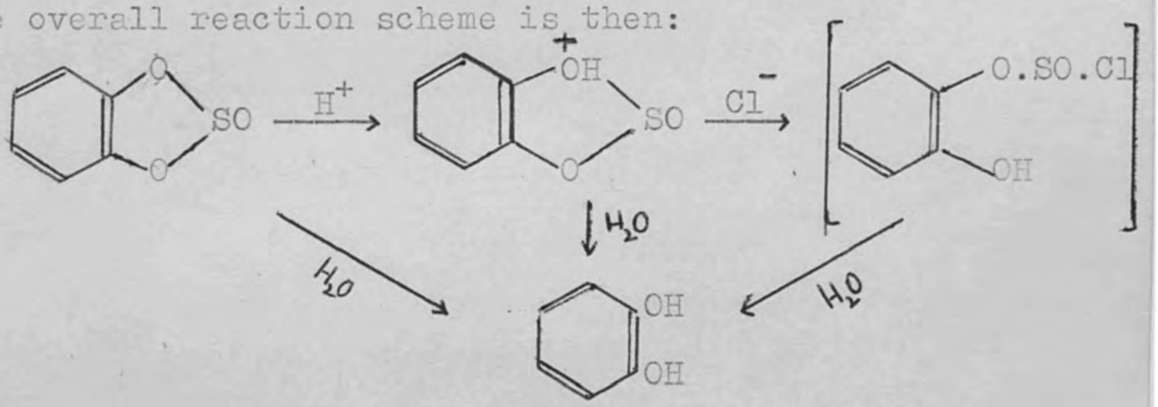
Both for the cyclic sulphites and open chain sulphites, hydrolysis could in principle proceed either by the bimolecular (A-2) mechanism in which a water molecule participates covalently in the rate determining attack on sulphur or by the A-1 mechanism in which the first stage is unimolecular, followed by a fast non-rate determining step.

From the effect of added salts it seems probable that the rate determining step involves some nucleophilic reagent which for normal hydrolysis is a water molecule, and in the presence of halide ions the most probable general reaction sequence is :



In the presence of halide ion (x^-), the conjugate acid is competed for by all the nucleophiles present which would be water molecules and halide ions. The effect of halide ions is probably to convert the conjugate acid into an intermediate halosulphinate which in fact then rapidly decomposes under the influence of water to give the products. This latter decomposition is more rapid than the direct decomposition of the conjugate acid with water molecules as nucleophiles and this accounts for the enhanced rate on the addition of halide ions.

The halide catalysis of catechol sulphite has been explained[76] by a similar mechanism involving the formation of a readily hydrolyzable chlorosulphinate intermediate. The general reaction sequence is more complicated, however, because there is also a high neutral rate of hydrolysis. The overall reaction scheme is then:



The intermediate chlorosulphinate is a probable intermediate in the formation of catechol sulphite from catechol and thionyl chloride. Subsequently Bunton and Hendy[77] have found similar nucleophilic catalysis by halide ion on a sulphur atom in the acid-catalysed hydrolysis of methyltoluene-p-sulphinate in aqueous dioxane, i.e.

$$C_7H_7SO_2Me + H^+ \rightleftharpoons C_7H_7SO_2\overset{+}{H}Me$$

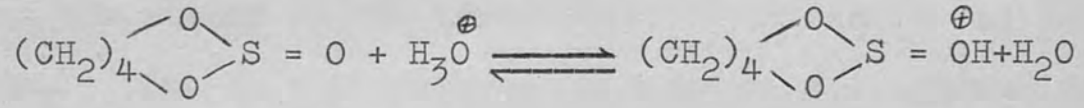
$$\begin{tikzcd}
C_7H_7SO_2{}^+HMe+H_2O \arrow[r, "slow"] \arrow[d, "Cl^-", "slow"'] & C_7H_7SOO^+H_2+MeOH \\
C_7H_7SOCl+MeOH \arrow[ur, "very\ fast", "H_2O"'] &
\end{tikzcd}$$

In this case the intermediate can be prepared independently

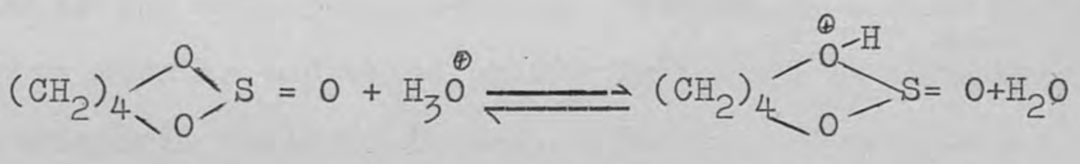
Its rate of hydrolysis is initially neutral aqueous dioxane was found to be too fast to measure by dilatometry and is therefore considerably faster than the ester hydrolysis.

Detailed Mechanism of Hydrolysis of 1,4-Butane Diol Sulphite in Perchloric Acid

The first step involves protonation to give the conjugate acid of the ester. Protonation may occur on either the exocyclic oxygen atom or one of the ring oxygens.

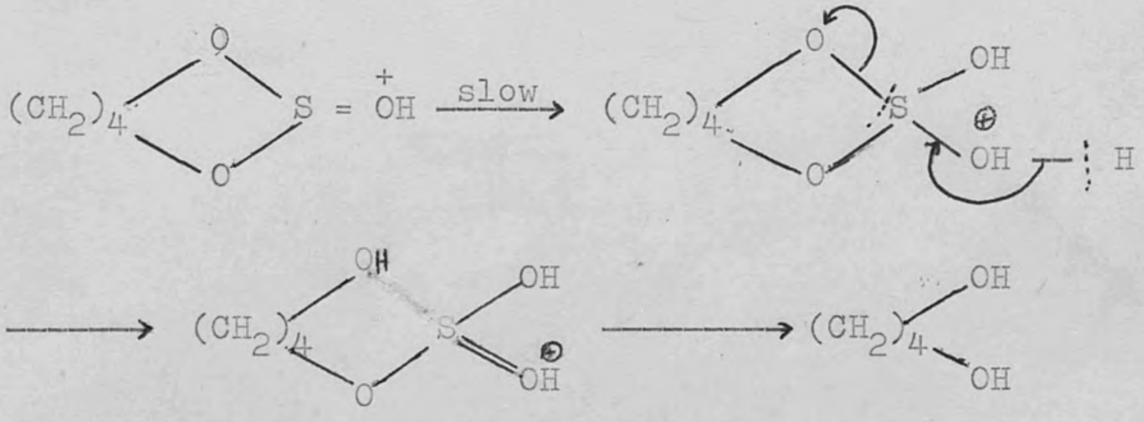
(1)


or

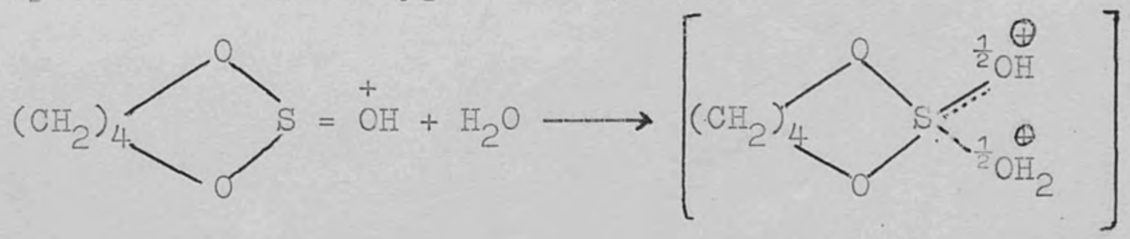
(2)


At present we are not able to distinguish between these two formal possibilities. The polar nature of the sulphur-oxygen bond in the sense S = O may favour protonation of the exocyclic oxygen atom as indicated in No. (1). By analogies with results for other sulphites of comparision of rates in normal and deuterated water we assume that this is a rapid pre-equilibrium proton transfer and therefore non rate-determining.

The subsequent stages consist of a slow rate-determining attack of a water molecule on the sulphur atom of the conjugate acid followed by a number of rapid steps leading to the observed products.

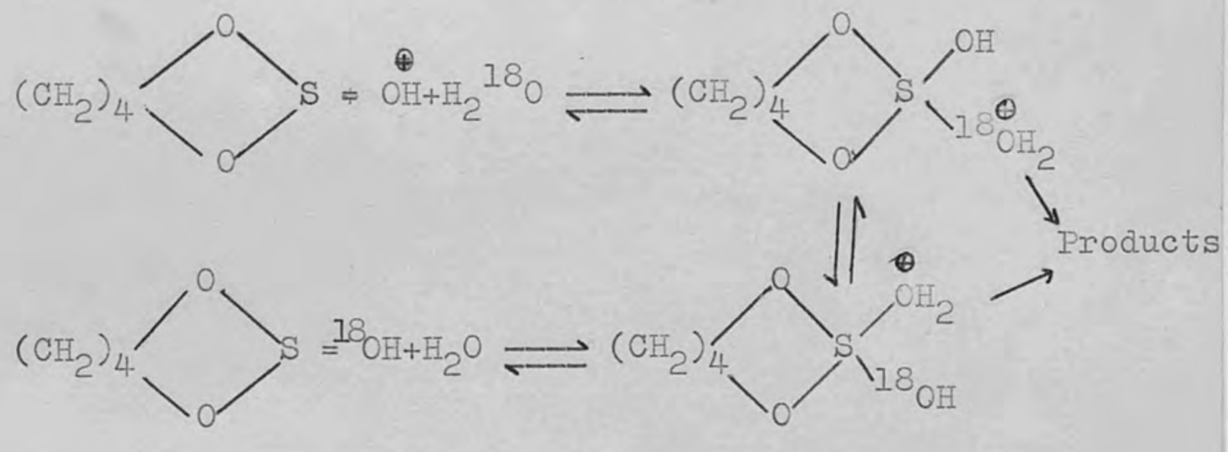


It has been established in the case of ethylene sulphite[78] that the attack by the nucleophile is indeed on the sulphur atom. Thus in the presence of concentrated hydrochloric acid as the catalysing acid no evidence of attack on the carbon atom as indicated by the formation of ethylene chlorohydrin could be formed. The attack of a water molecule can then be pictured as proceeding through a transition state in which the water molecule is practically bonded to the sulphur atom and the positive charge is spread over both oxygen atoms, viz.:



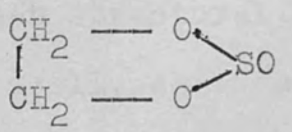
THE REPRESENTATION OF THE HYDROLYSIS MECHANISM

In Appendix I ([redacted]) the carbonyl-addition and nucleophilic substitution models for this process are discussed. In principle it ought to be possible to show by partial hydrolysis studies in $H_2{}^{18}O$ that an actual intermediate is formed involving a water molecule covalently bond to the sulphur atom of the conjugate acid. Thus for the hydrolysis of 1,4-butane diol sulphite in $H_2{}^{18}O$ we can write the formal exchange scheme:

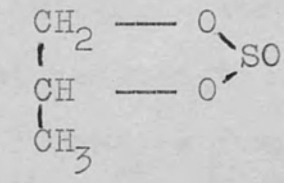


Such experiments involving extraction of the enchanged sulphite after partial hydrolysis have been carried out on ethylene and trimethylene sulphite under both acid and alkaline conditions.[79] No evidence of ^{18}O exchange has been observed. This does not mean, however, that such exchange does not occur for the reasons set out in Appendix I. And in fact we consider that the reaction does not involve such a tetrahedral intermediate as indicated previously for 1,4-butane diol sulphite.

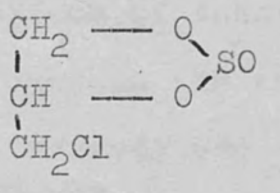
STRUCTURAL EFFECTS



1



1



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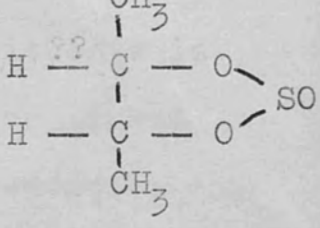
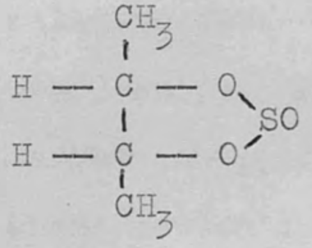
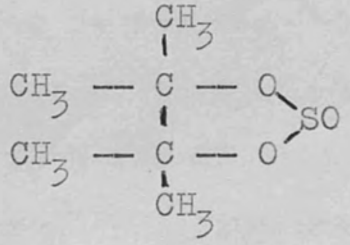


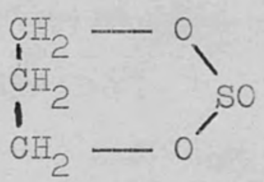
1.2



0.8



0.7



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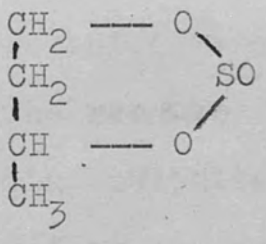
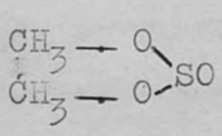


2.4



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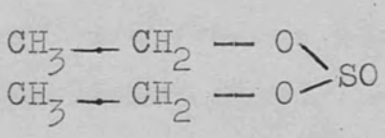

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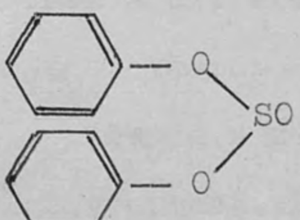
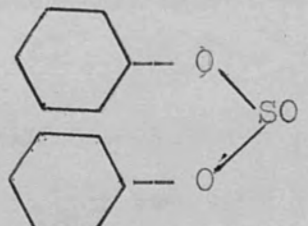
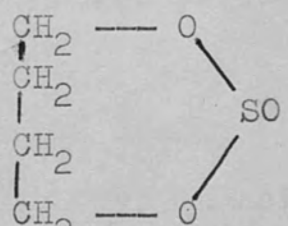


1.17



4.45



5.85

Rates Relatve To Ethylene Sulphite =1

The rates of acid hydrolysis do not vary very much with structural change. The effect of substituents is small, as might be expected, because the substituent groups are well removed from the reaction centre. Changes in ring size have a small effect. Thus the relative rates for 5-, 6-, and 7-membered ring (unsubstituted) sulphites are 1:4:5.85. This small effect is in marked contrast with the situation in alkaline hydrolysis where not only are the differences more marked but the relative order of reactivity is reversed. Thus for alkaline hydrolysis we have the reactivity sequence 5-membered ring > 6-membered by a factor of ca. 1000. The reason for the higher reactivity of the 7-membered ring sulphite are not clear. It is not known whether this difference arises from a difference in basicities of the esters or from a difference in the relative reactivities of their conjugate acids.

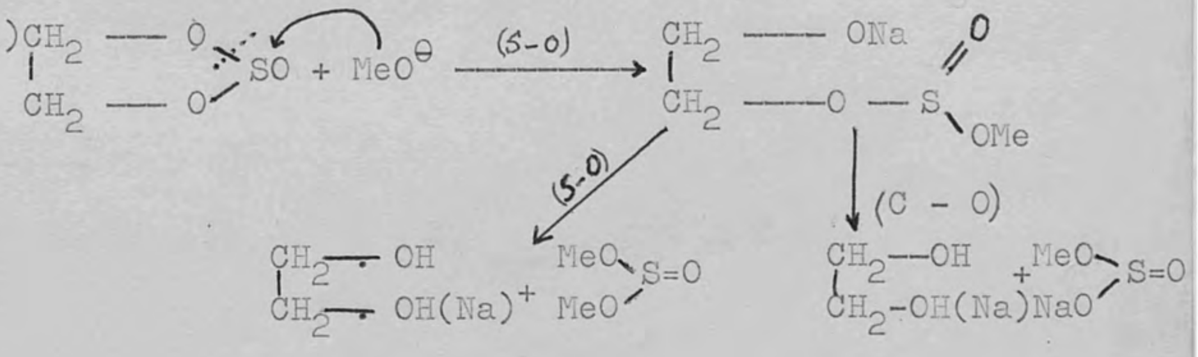
There is a considerable difference between the relative reactivities of sulphites and phosphates in acid and alkaline solution. The high reactivity of ethylene hydrogen phosphate (relative to the dialkyl hydrogen phosphates) appears in acids as well as alkaline hydrolysis The 5-membered ring phosphate being the more reactive under both sets of conditions. This is clear by not so for organic sulphites. It has been shown that the high reactivity of the 5-membered ethylene phosphate has been due primarily to ring strain[80]. Furthermore such strain has been shown to be absent in organic sulphites by thermochemical measurements[81]. It is not surprising therefore that structural effects in acid hydrolyses are small. The exact reason for the difference in reactivity in alkaline hydrolysis is still not clear. Preliminary measurements[82] indicate that entropy effects play an important role in this reaction.

The relative rates of hydrolysis of dicyclohexyl and diphenyl sulphite differ only by a factor of ca.4. This would seem to indicate that there is no fundamental difference in the mechanism of hydrolysis of the two sulphites.

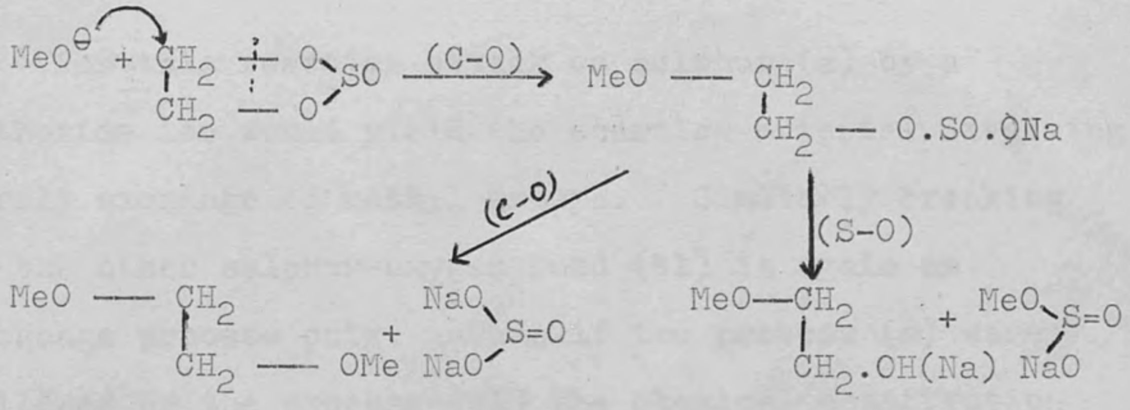
THE REACTION OF ORGANIC SULPHITES WITH SODIUM ALKOXIDES

The rate of reaction of sodium methoxide and ethoxide with organic sulphites in alcohol as a solvent was followed in two different ways. Both the disappearance of alkoxide and the appearance of sulphur dioxide were followed simultaneously after quenching in water. In all the cases studied (Table1-16) it is apparent that one mole of sulphite reacts with two moles of sodium alkoxide. By analogy with the established mechanism of the alkaline hydrolysis of organic sulphites in water the most likely reaction scheme is a two-stage process. Each step may proceed with either carbon-oxygen or sulphur-oxygen bond fission. The formal possibilities for the reaction of ethylene sulphite and sodium methoxide are outlined below:

(1)

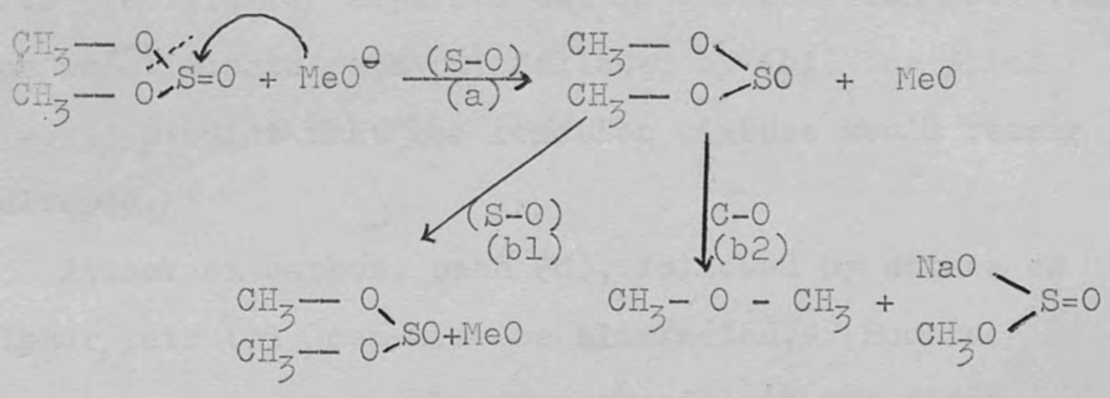


(2)

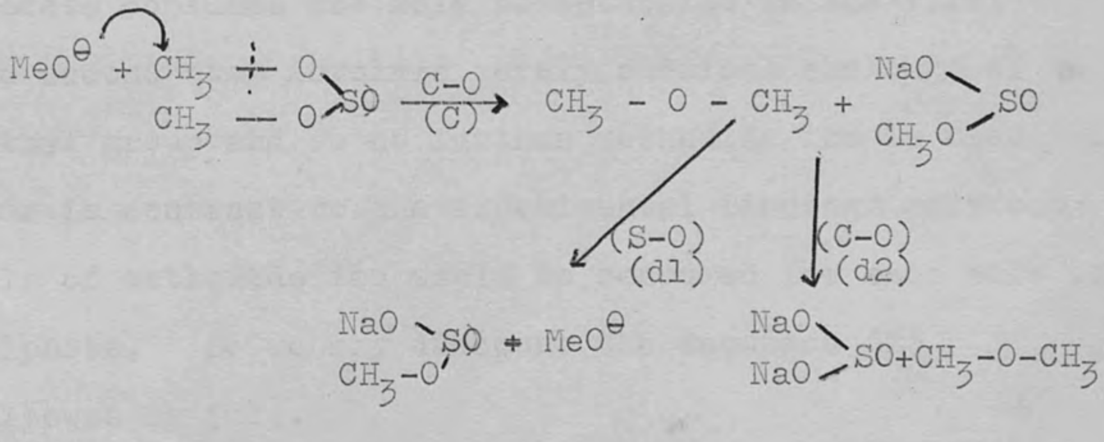


Since two moles of alkoxide are consumed the reaction must proceed through to one of the products of the second stages. Some of the formal possibilities may be eliminated by considering the analogous reaction between dimethyl sulphite and sodium methoxide. The possible reaction sequences are:

(1)



(2)

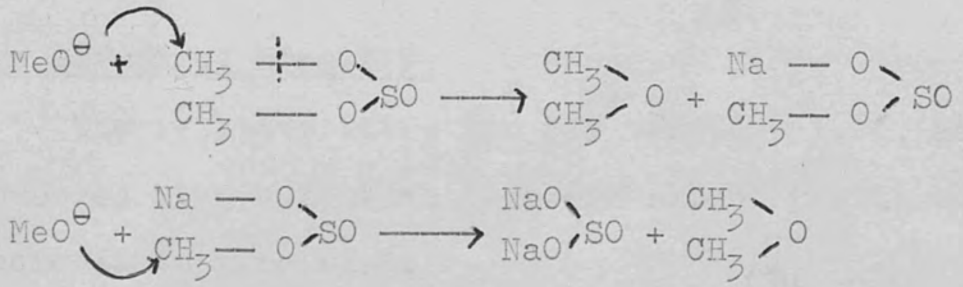


For this reaction attack on sulphur (a) by a methoxide ion would yield the starting material involving merely exchange of methyl groups. Similarly breaking of the other sulphur-oxygen bond (bl) is again an exchange process only. Thus if the process (a) were followed by the process (bl) the chemical constitution of the reaction mixture would remain unchanged and the concentration of sodium methoxide and dimethyl sulphite would remain unaltered. In fact, however, the concentrations of both these components have been found to alter with time, i.e. a reaction is occuring, and in due course a white precipitate separate out in the reaction solution. Thus we may eliminate path (a) followed by (bl) for which we would predict that the reaction mixture would remain unaltered.

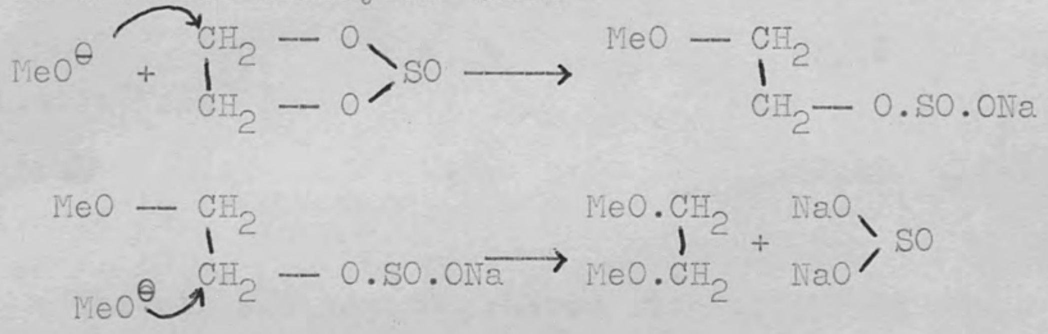
Attack on carbon, path (C), followed by attack on sulphur, path (dl), can also be eliminated. Such a process consumes one mole of methoxide in the first step. The second step involves merely chemical exchange of a methyl group and so no further methoxide ion is used up. Thus in contrast to the experimental findings only one mole of methoxide ion would be consumed for each mole of sulphite. So we may discount the sequence (C) followed by (dl).

This leaves two formal possibilities path (a) followed by path (b2) and path (C) followed by path (d2). Both of these schemes yield dimethyl ether as one of the products. Separation and purification of the white solid produced in all of these reactions is difficult. It often comes down in solution in a flocculent mass and passes through a filter paper or a sintered glass funnel. Usually it was separated by centrifuging and the supernatant liquid was then decanted. The solid was allowed to dry in the air with gentle heating. Any remaining volatile material was removed by pumping with Hyvac pump.

We consider that the white product in all the reactions studied is, in fact, sodium sulphite. The analyses of the products conform reasonably well with this hypothesis, allowing for possible contamination by remaining solvents and sodium alk-oxide. (Calc. for Na_2SO_3 : S, 25.80; Na, 37.09%). This indicates therefore that the most possible reaction sequence is path (C) followed by path (d2), i.e. the reaction proceeds entirely by carbon-oxygen bond fission and is :



The corresponding scheme for the reaction of ethylene sulphite and sodium methoxide which we assume by analogy is the most likely is then:



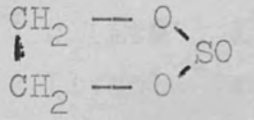
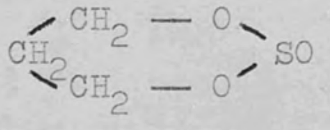
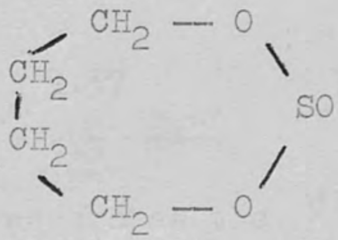
Further confirmation that attack of the methoxide is indeed on the carbon atoms rather than sulphur is provided by the influence of structural effects in these reactions, which are summarised below:

Values of the 2nd order Rate Coefficient (l.mole^{-1}.min^{-1}) at 60°

Sulphite	MeO$^{\ominus}$	Eto$^{\ominus}$
Ethylene	2.6	12.5
Trimethylene	1.24	2.6
1,4-Butane diol	1.18	2.25
Dimethyl	1.94	1.94
Diethyl	1.93	1.93
1,2-Propane diol	2.32	12.00
2,3-Butane diol	1.82	9.37
Pinacol	1.74	7.41

The Effect of Ring Size

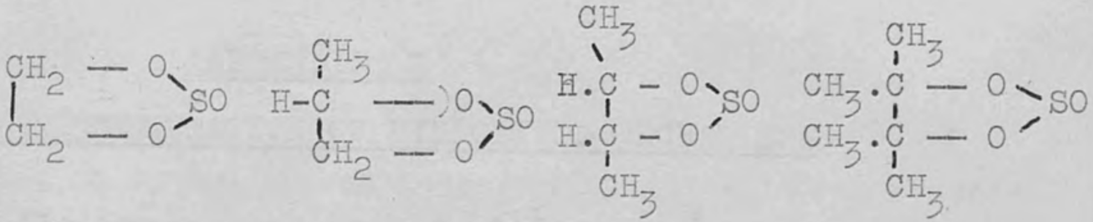
The relative rates for the simplest 5, 6, and 7-membered ring sulphites decrease slightly with the increase in ring size:

			
$k_2(MeO^{\ominus})$ $(l.mole^{-1}min^{-1})$	2.6	1.24	1.18
$k_2(EtO)$ $(l.mole^{-1}min^{-1})$	12.5	2.60	2.25

The six and seven-membered ring sulphites react with both methoxide and ethoxide at approximately the same rate. Ethylene sulphite appears to be more reactive with either reagent. The other five-membered ring sulphites which were studied also react more rapidly with either reagent than the six- and seven-membered ring compounds.

Structural Effects in Five-Membered Ring Sulphites

Structural effects were confined for convenience to the gradual replacement of all the hydrogen atoms in ethylene sulphite by methyl groups:



$k_2(MeO^{\ominus})$ (l.mole^{-1}min^{-1})	2.6	2.32	1.83	1.74
$k_2(EtO^{-})$ (l.mole^{-1}min^{-1})	12.5	12.0	9.37	7.41

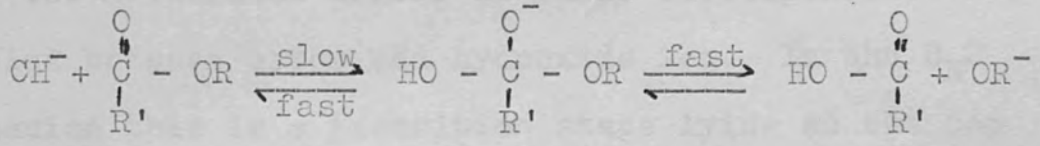
A gradual decrease in rate occurs as the hydrogen atoms are successively replaced by methyl groups. This is to be expected if the incoming methoxide ion is attacking the carbon atom because successive replacement of this type increasingly surrounds the carbon atoms by bulkier groups thus making difficult the close approach of the methoxide ion to the carbon atom, such close approach being necessary for covalent bond formation. So this, therefore, is a normal steric effect. Even bulkier groups would be expected to slow the rate down still further. The relative rates with methoxide and ethoxide seem to vary slightly with substrate. The greater reactivity of ethoxide as compared to methoxide is in keeping with the greater nucleophilic power of the former reagent.

APPENDIX I

THE REPRESENTATION OF HYDROLYSIS MECHANISMS

The commonest mode of alkaline hydrolysis of a carboxylic ester, mechanism $B_{Ac}2$, can be represented in two different ways:

(a) Carbonyl addition model



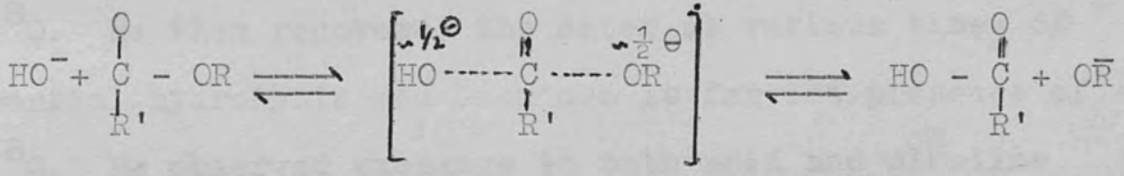
$$CH^- + \underset{R'}{\overset{O}{C}} - OR \underset{fast}{\overset{slow}{\rightleftharpoons}} HO - \underset{R'}{\overset{O^-}{C}} - OR \overset{fast}{\rightleftharpoons} HO - \underset{R'}{\overset{O}{C}} + OR^-$$

This is followed by rapid proton capture.

$$R'.COOH + OR' \xrightarrow{fast} R'.CO\bar{O} + ROH$$

This process is in principle reversible but in practice is driven completely to the right hand side by the final proton transfer.

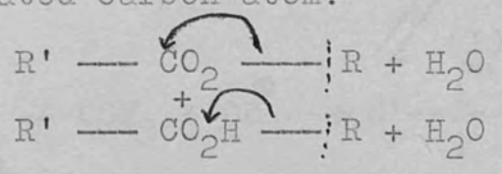
(b) Nucleophilic Substitution Model



$$HO^- + \underset{R'}{\overset{O}{C}} - OR \rightleftharpoons \left[\overset{\sim\frac{1}{2}\ominus}{HO} \cdots\cdots \underset{R'}{\overset{O}{C}} \cdots\cdots \overset{\sim\frac{1}{2}\ominus}{OR} \right] \rightleftharpoons HO - \underset{R'}{\overset{O}{C}} + O\bar{R}$$

$$R'.COOH + OR^- \longrightarrow R'.CO\bar{O} + ROH$$

Any mechanism involving alkyl-oxygen fission will tend to be similar to a substitution since it involves reaction at a saturated carbon atom:-

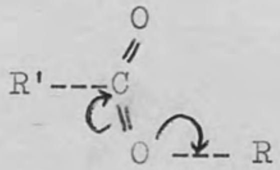


$R' — CO_2 —⁞ R + H_2O$ B_{al}

$+$

$R' — CO_2H —⁞ R + H_2O$ A_{al}

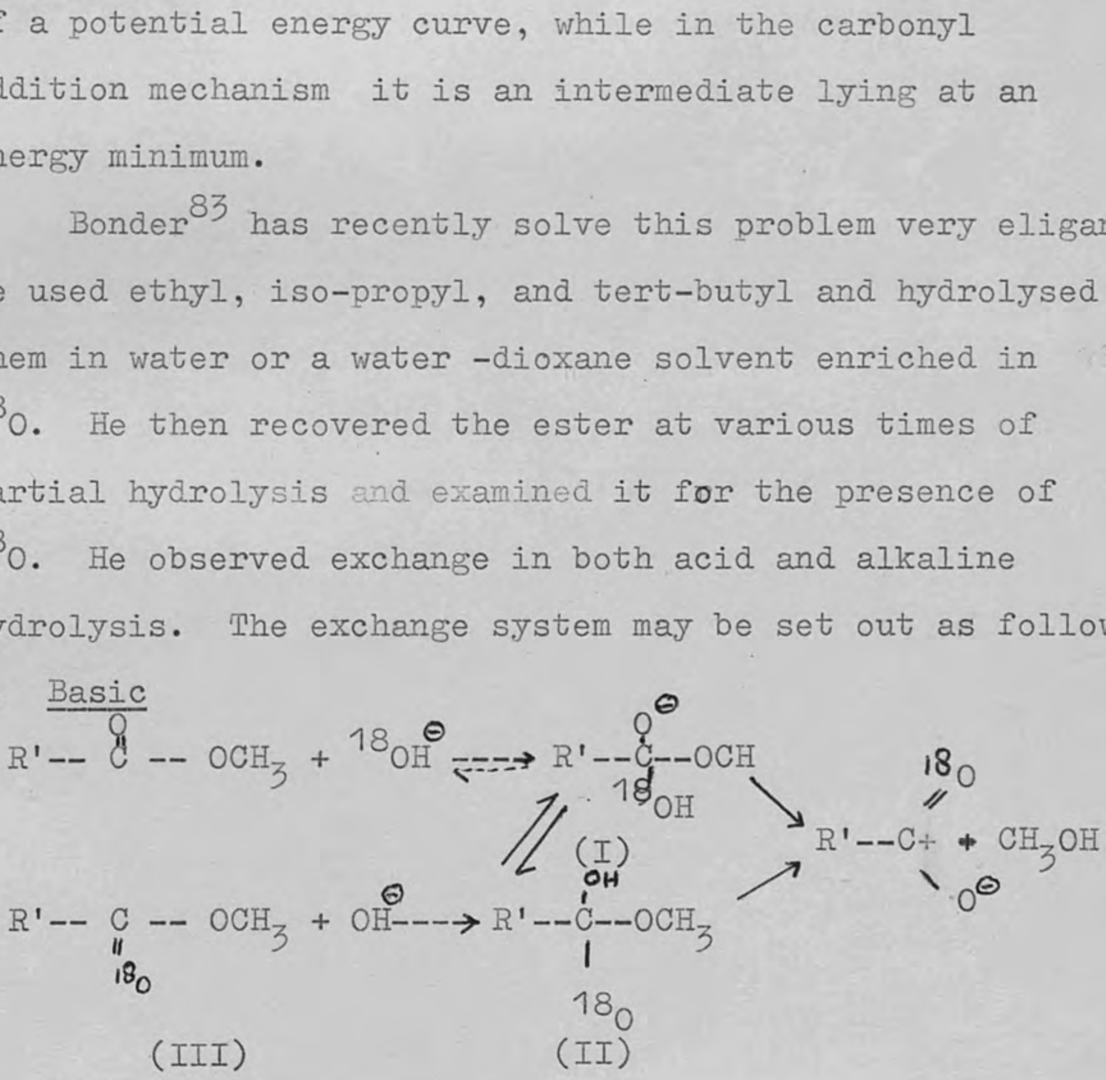
But in acyl-oxygen fission the carbon centre has the properties of a carbonium ion and the reaction might be expected to be analogous to a carbonyl addition mechanism:-



The mechanisms differ in their description of the complex between ester and hydroxide ion. In the S_N2 mechanism this is a transition state lying at the top of a potential energy curve, while in the carbonyl addition mechanism it is an intermediate lying at an energy minimum.

Bonder[83] has recently solve this problem very eligantly. He used ethyl, iso-propyl, and tert-butyl and hydrolysed them in water or a water -dioxane solvent enriched in ^{18}O. He then recovered the ester at various times of partial hydrolysis and examined it for the presence of ^{18}O. He observed exchange in both acid and alkaline hydrolysis. The exchange system may be set out as follows:-

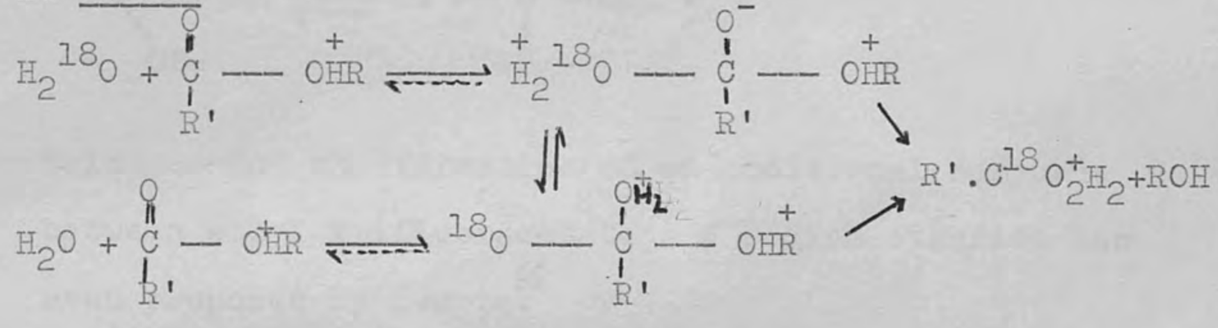
1. Basic



The argument is that if (I) exists for a sufficiently long time, then the proton will equilibrate, i.e. I ⟶ II. Then if the chance of OCH_3 splitting off from the intermediate is not too large compared with that of OH, then the reverse reaction to III should occur.

Similarly for the acid Case:

2. Acidic



Three conditions may be laid down for this type of exchange to be observable:

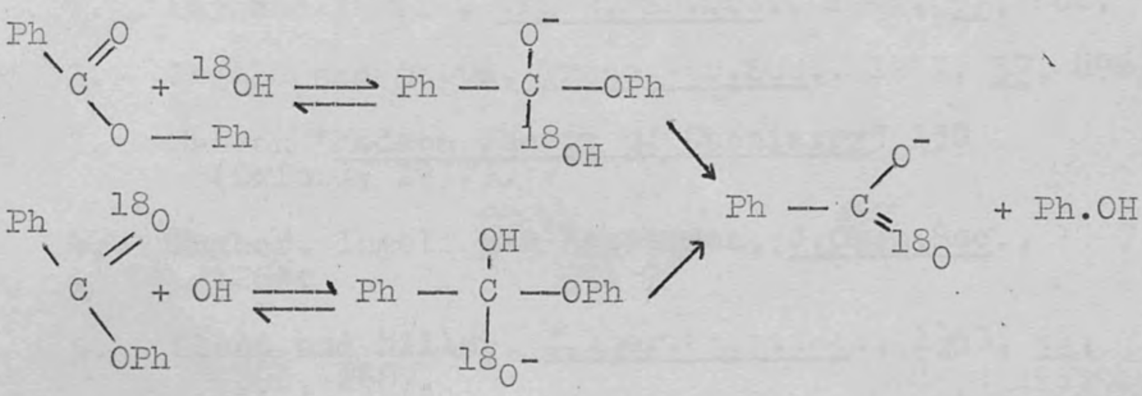
1. The intermediate must be sufficiently long-lived for proton equilibrium to occur.

2. The probability of OR^- splitting off from the intermediate must be not much greater than that of $O\bar{H}$.

3. It has to be assumed that proton transfers cannot take place during the lifetime of the transition state.

If, however, exchange is not observed this does not prove that an intermediate is non-existent since any of the above conditions might not be satisfied.

For example, in the case of phenyl benzoate no enrichment of the original ester after partial hydrolysis was observed;[84] the following sequence may or may not occur depending on the factors involved:



Evidence for the formation of an additional compound between ethyl trifluoracetate and sodium ethoxide has been proposed by Swarts.[85]

$$CF_3 \ . \ CO_2 \ . \ Et + Na.OEt \rightleftharpoons \left. CF_3 - \overset{OEt}{\underset{OEt}{C}} - O^- \right\} Na^+$$

Bender[86] has confirmed and attended this observation by infra-red measurements and pointed out that it supports the carbonyl addition mechanism.

Consequent upon the support for this type of mechanism it has been used where possible to indicate the course of hydrolysis although it has never been observed for sulphur.

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