FIGURE 9d

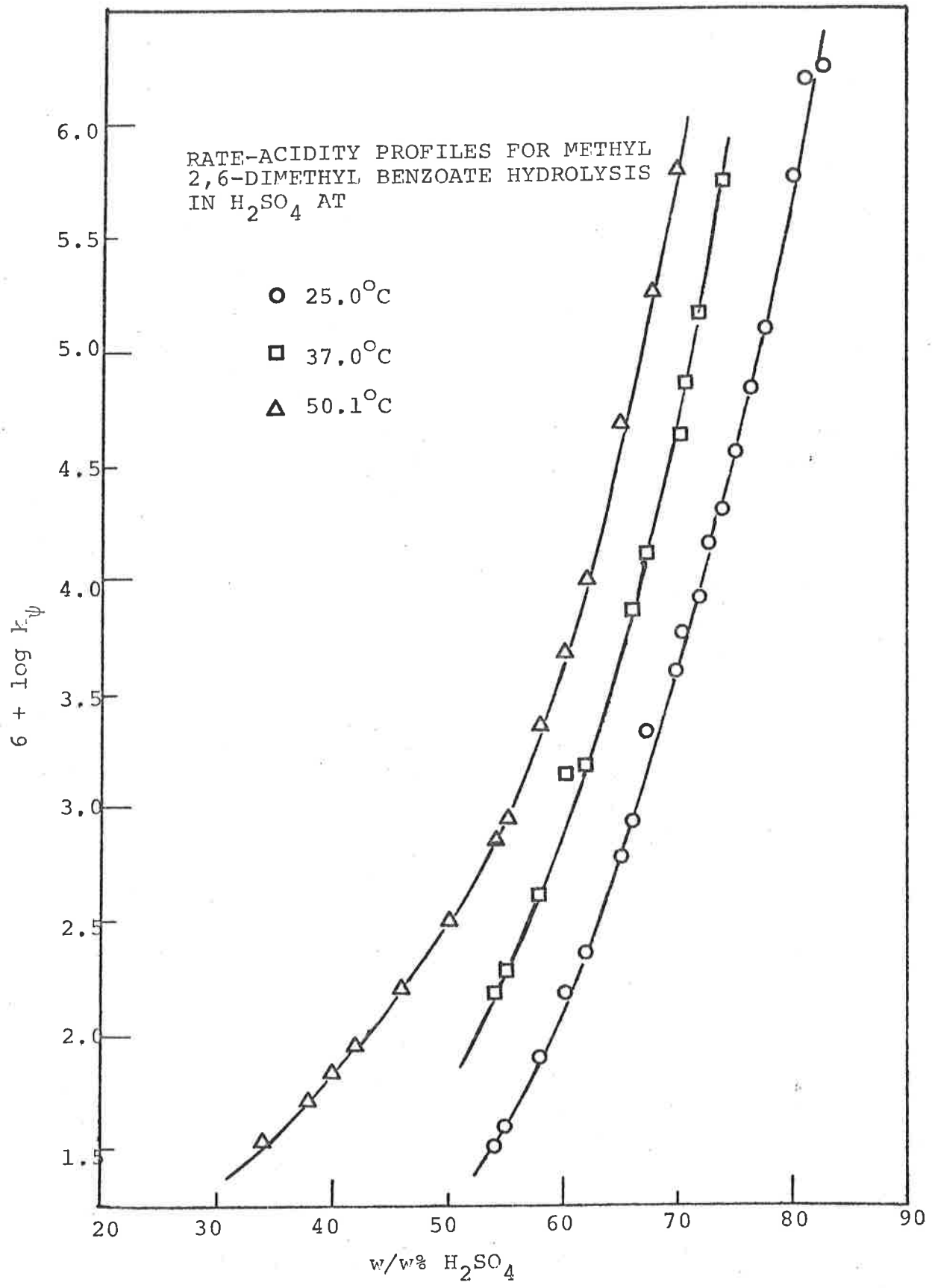

RATE-ACIDITY PROFILES FOR METHYL 2,6-DIMETHYL BENZOATE HYDROLYSIS IN H_2SO_4 AT
25.0°C
37.0°C
50.1°C
6 + log k_ψ
w/w% H_2SO_4
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
20
30
40
50
60
70
80
90

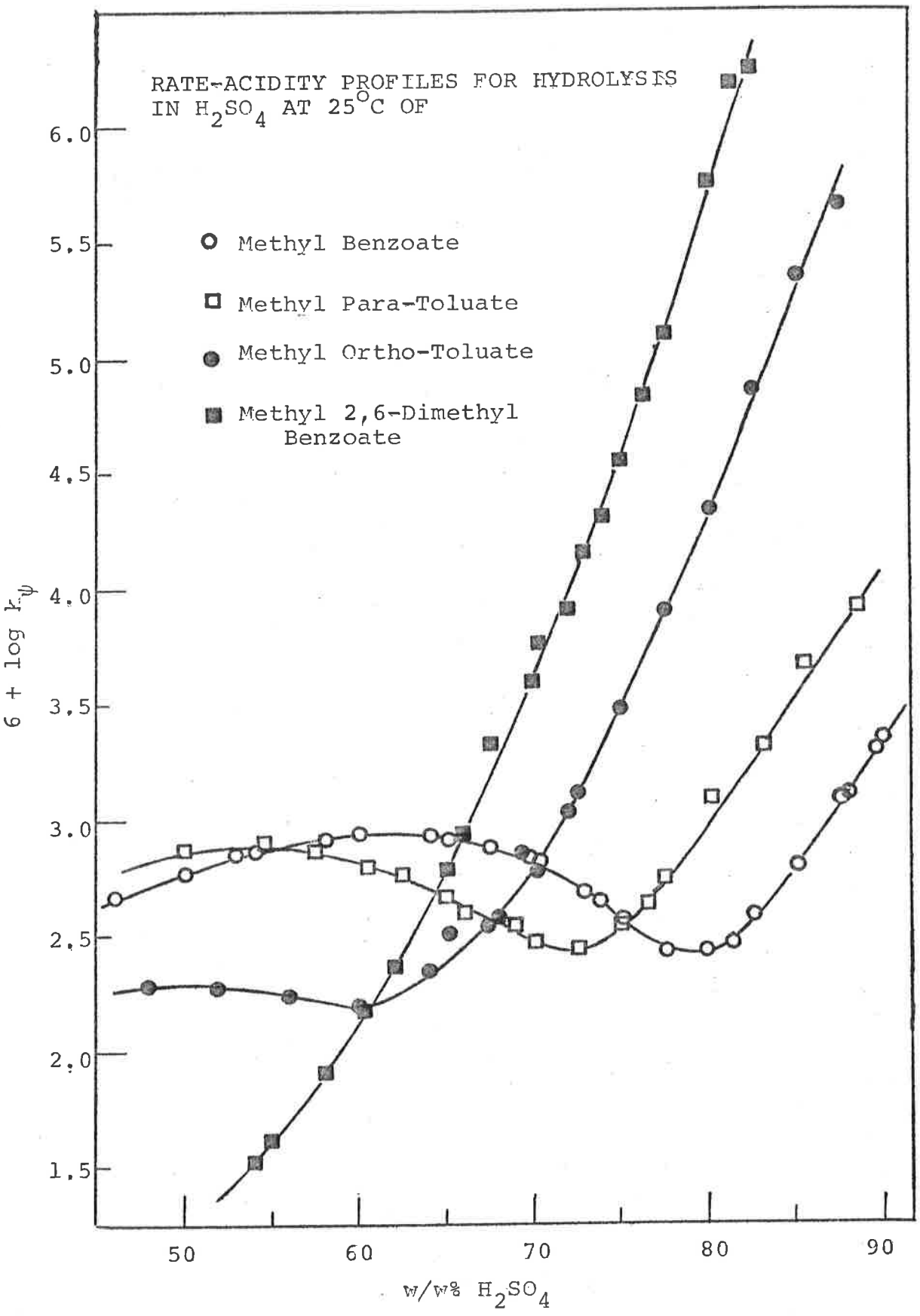
TABLE 9: PSEUDO-FIRST ORDER RATE CONSTANTS (MIN.$^{-1}$) FOR HYDROLYSIS OF BENZOATE ESTERS AT 25°C

MB[a]		MPT[b]		MOT[c]		2,6-MDMB[d]	
w/w% H_2SO_4	$\log k_\psi$[e]	w/w%	$\log k_\psi$[e]	w/w%	$\log k_\psi$[e]	w/w%	$\log k_\psi$[e]
42.04	2.53	40.0	2.55	40.0	2.16	40.0	0.40
46.0	2.66	45.0	2.75	44.0	2.24	46.0	0.83
50.0	2.79	50.0	2.87	48.0	2.28	51.04	1.24
54.0	2.86	52.5	2.90	52.0	2.27	55.0	1.61
58.0	2.92	55.0	2.90	56.0	2.24	60.16	2.19
62.0	2.94	60.0	2.80	60.0	2.20	62.0	2.37
65.03	2.91	62.58	2.76	64.0	2.35	65.03	2.79
67.39	2.88	66.03	2.59	67.39	2.55	68.0	3.26
69.76	2.84	68.93	2.55	70.29	2.78	70.29	3.77
72.88	2.69	72.5	2.43	72.45	3.23	72.88	4.16
75.09	2.57	75.0	2.53	75.09	3.48	75.09	4.56
77.61	2.43	76.53	2.64	77.61	3.90	76.53	4.84
80.0	2.43	80.19	3.09	80.28	4.35	77.61	5.10
81.41	2.46	83.13	3.32	82.68	4.87	80.28	5.76
82.68	2.58	85.58	3.67	85.16	5.35	81.41	6.19
85.16	2.80	85.59	3.92	87.67	5.66	82.68	6.25
87.67	3.08						
89.63	3.30						

[a]Methyl benzoate [b]Methyl para-toluate [c]Methyl ortho-toluate

[d]Methyl 2,6-dimethyl benzoate [e]Values given as 6 + log kψ

FIGURE 10


RATE-ACIDITY PROFILES FOR HYDROLYSIS IN H_2SO_4 AT 25°C OF
Methyl Benzoate
Methyl Para-Toluate
Methyl Ortho-Toluate
Methyl 2,6-Dimethyl Benzoate
6 + log k_ψ
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
50
60
70
80
90
w/w% H_2SO_4

As the acidity continues to increase and water-activity decreases, a minimum in the rate-acidity profile is often reached, followed by a new rate increase with higher acidity. This is indicative of a new mechanism, one in which water activity is not playing as important a role, and is a unimolecular reaction, either A_{Ac}-1 or A_{Al}-1. Both of the non-ortho substituted esters - methyl benzoate and methyl para-toluate - are exhibiting this 'typical' A-2 → A-1 behaviour in their rate-acidity profiles. Both the maximum and minimum for the para-toluate occur earlier in the acid region than those for the parent compound, methyl benzoate. Moreover, the rate is generally slower for MPT in the A-2 region and faster in the A-1 region than that for MB. These points will be elaborated upon later as the rate data for each ester are discussed in turn.

Methyl ortho-toluate also appears to be going through an A-2-type maximum even earlier than that for the para-toluate. But it is a very shallow maximum, and, at temperatures higher than 25°C (cf. Fig. (9c)), there is no longer a pronounced maximum. Nevertheless, activation parameters for the hydrolysis of this ester indicate that it, too, is undergoing a mechanistic change between the dilute and concentrated acid ends of the acidity range. Other evidence will be introduced later which further supports this change of mechanism.

The only ester which does not fit this general scheme is methyl 2,6-dimethyl benzoate. Its rate increases monotonically throughout the entire acid range studied (20-88% H_2SO_4) at all temperatures. The rate of this increase is not constant, however, being smaller in the dilute end and large in the concentrated acid region. For example, k_ψ at 80% H_2SO_4 ≃ 100 k_ψ at 70% at 25°C. This is reflected in the change of activation parameters between the two ends of the acid region.

It is difficult to say with certainty whether this ester undergoes A-2 hydrolysis in dilute H_2SO_4 or not. Most of the evidence that will be presented suggests that in acid less concentrated than ∿60% H_2SO_4, the A-2 reaction predominates in the hydrolysis of 2,6-MDMB, but there seems to be a competition with the A-1 reaction even in dilute acid. It should be noted, as well, that it was impossible to measure the rates of hydrolysis of this ester in <60% H_2SO_4 at 25°C, due to the very long half-lives of reaction (e.g. at 40%, $k_\psi^{calc.} \simeq 2.5 \times 10^{-6}$ min.$^{-1}$ → $t_{1/2} \simeq 6.4$ months). It was necessary therefore to measure the rates at several higher temperatures in the dilute acid region and extrapolate via the Arrhenius-type equation to 25°C. This enabled a rate profile to be obtained at this temperature for as wide an acidity range as possible.

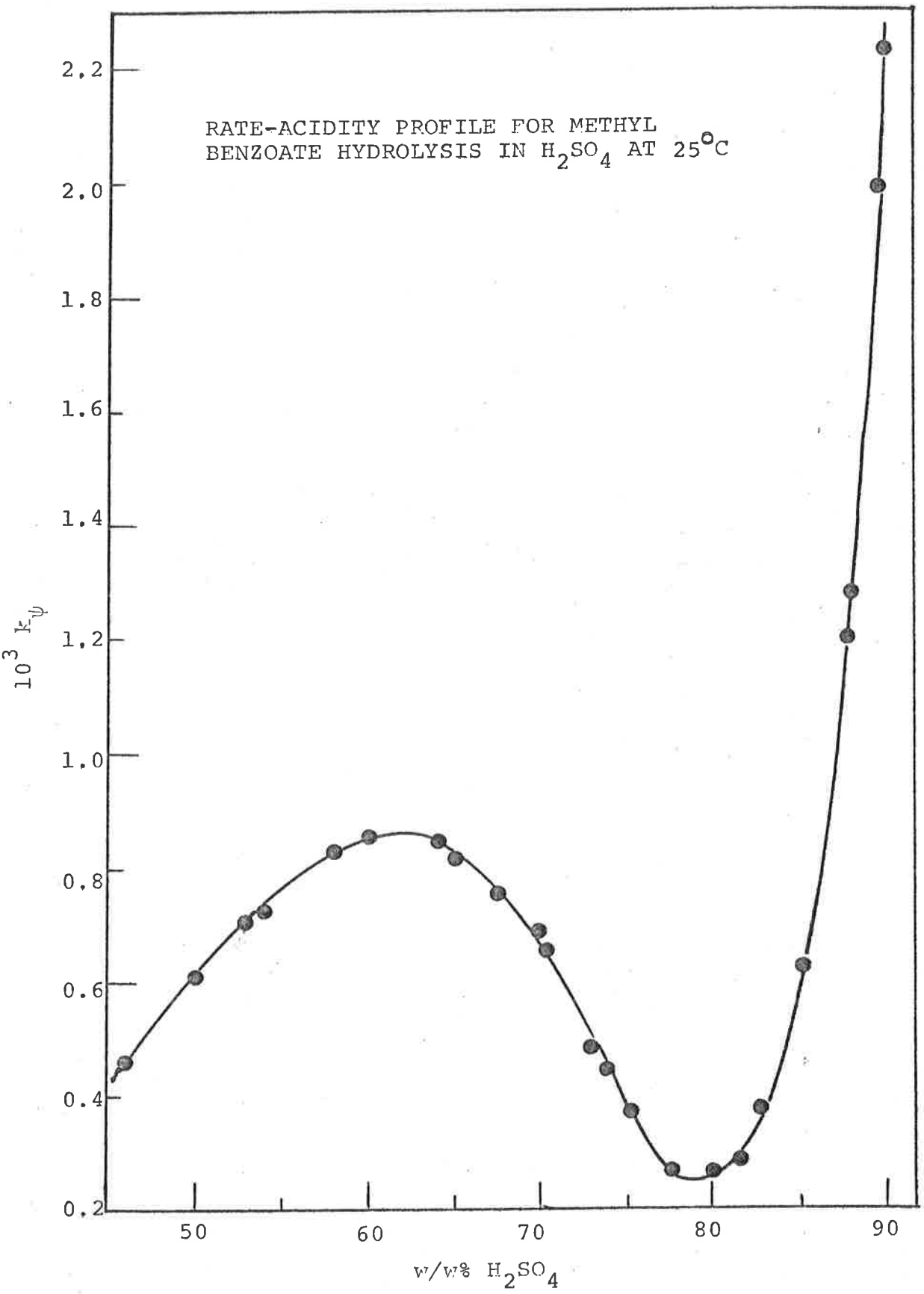
Since the behaviour of these esters varies greatly, they will be discussed individually in turn.

A. METHYL BENZOATE

The rate of hydrolysis of this ester increases, at 25°C, to a maximum at about 62% H_2SO_4 and then falls off rapidly to a minimum at ∿79% H_2SO_4, whereupon it rises again in the concentrated acid region. This is illustrated in the plot of k_ψ (25°C) vs. w/w% H_2SO_4, shown in Fig. (11). As the temperature is increased, the turning points occur at slightly less concentrated acid.

This behaviour is consistent with an A-2 reaction in the dilute to moderately concentrated acid range, which then switches over to an A-1 mechanism as the activity of water falls drastically in the concentrated acid region. This is supported by many pieces of evidence, including similarity to acetate ester hydrolysis,[13] activation parameter calculations,[104,105] O^{18}-exchange studies,[67] Hammett σρ correlations[73,106,107] and the various hydration parameter treatments which have been devised and successfully applied to various reaction mechanisms. These include the Bunnett 'ω' treatment,[29] the Yates-McClelland 'r' plots[13] and the more recently devised transition state activity coefficient treatment.[41] The earliest of these rate-

FIGURE 11


RATE-ACIDITY PROFILE FOR METHYL BENZOATE HYDROLYSIS IN H_2SO_4 AT 25°C
$10^3 k_\psi$
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
50
60
70
80
90
w/w% H_2SO_4

acidity correlations, the Zucker-Hammett hypothesis,[24] proposed a means of determining the molecularity of the reaction. This depended on whether the rate constant, k_ψ, was linearly related to the acid concentration, $C_{H_3O^+}$, or the acidity function, h_o. However, as a serious criterion of mechanism, it has been strongly criticised in recent years,[68] and consequently has not been used to treat the data in the present study.

(i) ACTIVATION PARAMETERS

Timm and Hinshelwood[106] studied the acid-catalysed hydrolysis of ethyl esters of a number of substituted benzoic acids in ethanol-water and in acetone-water solvents at various temperatures. From other evidence these are known to be A-2 reactions and they found for the Arrhenius energy of activation, E_a, a range of values from 17.5 to 21.0 kcals/mole. Values for the entropy of activation, $\Delta S^{\ddagger}$, obtained were in the range of -32 to -24 e.u. at 100°C. This was in contrast to the alkaline hydrolysis of the same series of esters in alcohol-water for which the $\Delta S^{\ddagger}$ was relatively constant (~-16.0 e.u. at 25°C), while the activation energy changed from 16.7 to 20.0 kcal/mole. They therefore concluded that changes in the rate constant for alkaline hydrolysis were dependent mainly on the change in E_a. This is not the case for acid-catalysed hydrolysis.

Furthermore, Taft[105] concluded that hydrolyses proceeding by the A-1 mechanism should have more positive entropies of activation than those reacting by an A-2 mechanism. This is due, in the A-2 reaction, to greater constraint in the transition state because of the orientation and participation of one or more water molecules from the solvent shell. Finally, Long and co-workers[108] calculated $\Delta S^{\ddagger}$ values at 25°C for a number of acid-catalysed ester hydrolyses whose mechanisms were well-known. They found that for an A-2 reaction, the $\Delta S^{\ddagger}$ values were in the range of -20.9 → -24.6 e.u., whereas for the A-1 reaction series, $\Delta S^{\ddagger}$ values ranged from +5.8 to +9.0 e.u., a total separation of ∿30 e.u. between the two reaction categories.

The acid-catalysed hydrolysis of methyl benzoate was studied over a wide range of sulphuric acid concentration. This was possible since the difference in rate constants between the fastest and slowest reactions at 25°C was only ∿ one order of magnitude. Kinetics were also studied at a number of different temperatures - 25°, 37°, 45°, 50°, 54.9°, 60.1°, 66.4° and 67.0°C.* The activation parameters for these reactions were then calculated at a number of different acids, using the Arrhenius-type equation based on transition state theory (cf. p. 86). The activation parameters, $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$,

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*The rate data at these temperatures are found in Table 8(a).

obtained from a plot of ln (k_ψ/T) versus 1/T, gave results for methyl benzoate hydrolysis shown for a selected number of acids in Table (10).

TABLE 10: ACTIVATION PARAMETERS FOR HYDROLYSIS OF METHYL BENZOATE IN SULPHURIC ACID

w/w% H_2SO_4*	$\Delta H^{\ddagger}$ (kcal/mole)	$\Delta S^{\ddagger}$ (e.u.)
40.0	20.18	-15.2
50.0	20.30	-13.3
60.0	20.09	-13.3
65.0	19.92	-14.0
70.0	20.27	-13.2
75.0	21.90	-8.85
78.0	23.98	-2.59
82.0	26.81	+7.33
86.0	28.29	+13.9
90.0	29.61	+20.5

*Rate constants obtained at integral H_2SO_4 concentrations from interpolations of appropriate rate-acidity profiles. Integral values, chosen for comparison with the other esters, since hydrolysis of different esters not always done at the same acid strengths.

The $\Delta S^{\ddagger}$ values appear to be about 7 e.u. more positive than those observed for acetate hydrolysis via an A-2 mechanism, probably due to a lower degree of hydration in the transition state for the benzoate ester series than for the acetates. This is supported by the transition-state activity coefficient behaviour and the slopes of the ionisation ratio plots for the two series of esters. The latter slope, 'm', is 0.62 for the primary alkyl acetates as compared to 0.90 for methyl

benzoate. Furthermore, the transition state activity coefficient, $f_{\ddagger}^{*}$, for methyl benzoate is slightly less salted-out than for isopropyl acetate. This last point will be discussed further later on.

On both counts, then, it can be seen that there is less solvation in the transition state of the protonated benzoate ester than for the acetate ester. This accordingly results in a somewhat more positive value of the entropy of activation for the A-2 hydrolysis of methyl benzoate. As further verification, Smith[109] has compared the $\Delta S^{\ddagger}$ values for acetamide hydrolysis in 0.1 M HCl with that for benzamide in 20-50% H_2SO_4. These are -17.4 e.u. and -14.8 e.u. respectively. Again, the difference is not large but it is in the same direction as that observed in this study, as well as putting the $\Delta S^{\ddagger}$ value in the same general vicinity for benzamide as for benzoate hydrolysis.

As the hydrolysis of methyl benzoate changes over from an A-2 to an A-1 mechanism, the activation parameters also change. Specifically, the $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ values both increase as the acid concentration increases. This parallel increase is quite commonly observed. For example, in the H_2SO_4-catalysed hydrolysis of ethyl acetate:[110a]

w/w% H_2SO_4	E_a (kcal/mole)	$\Delta S^{\ddagger}$ (e.u.)
71.8	18.8	-12.4
98.4	24.2	+2.3

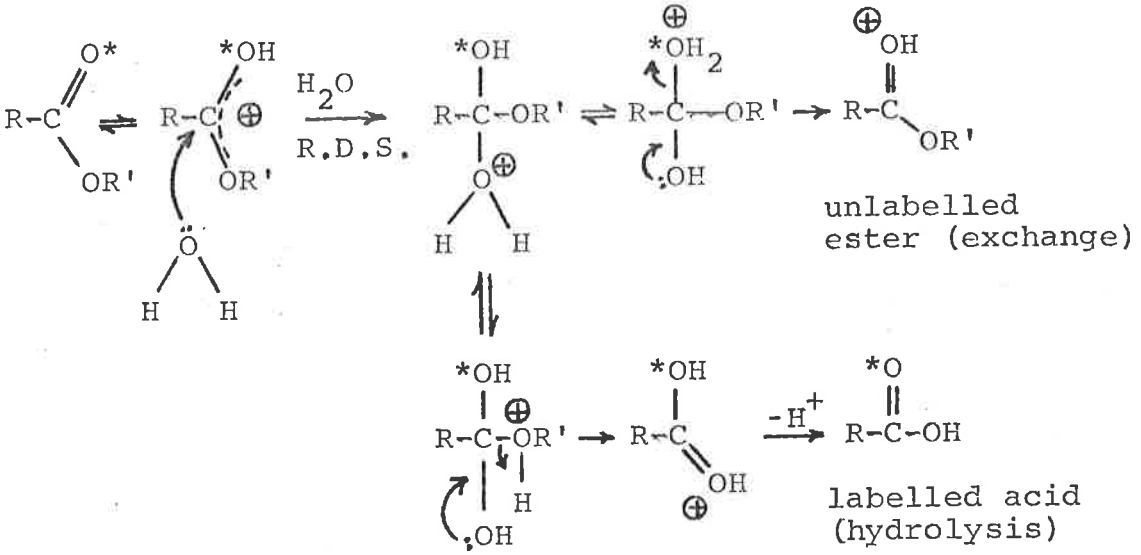
Thus, although a higher activation energy, typical of A-1 reactions, would serve to slow the rate down, the corresponding increase in the activation entropy counters this effect, and in the very concentrated acid range, appears to be the main factor determining the increase in rate.

(ii) O^{18}-EXCHANGE STUDIES

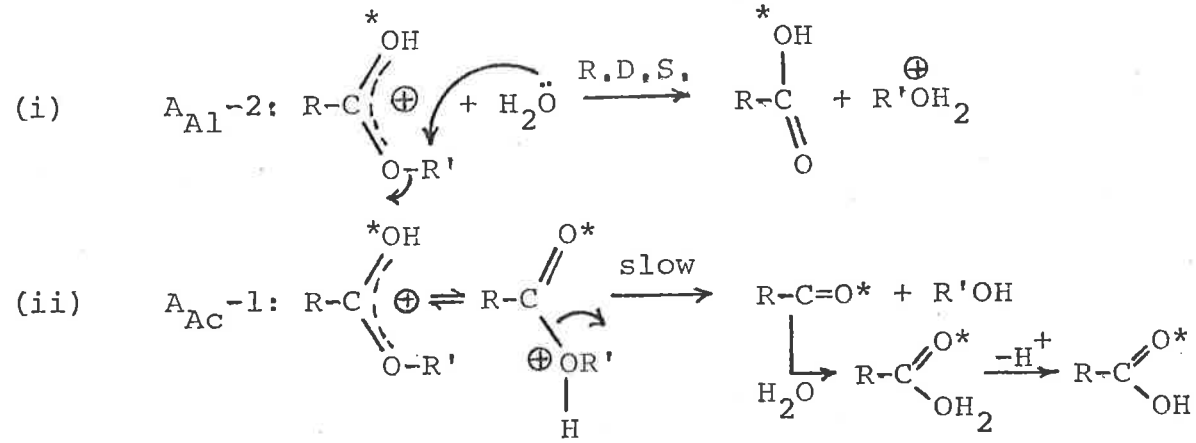
In an attempt to show the position of cleavage in A-2 ester hydrolysis, Bender[10] in 1951 used isotope exchange studies to show that a tetrahedral intermediate is formed in both the acid- and base-catalysed hydrolysis of ethyl benzoate. Specifically, he found that:

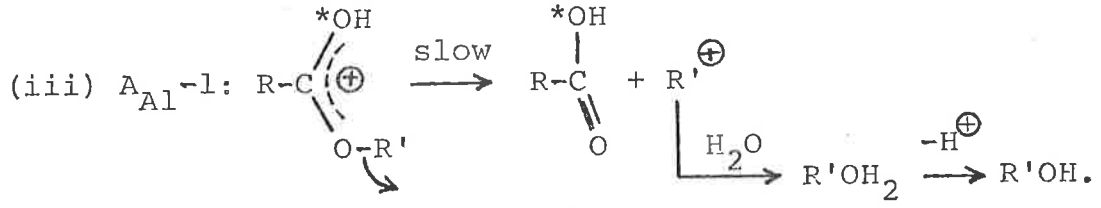
	ACID-CATALYSED	BASE-CATALYSED
$\frac{k_{hydrolysis}}{k_{exchange}}$	5.2	4.8

This implies an initial attack by the nucleophile on the isotopically-labelled carbonyl position of the ester, followed by formation of the tetrahedral adduct, which then partitions to go back to exchanged starting material or on to product:



McClelland[110e] found similar results for the acid catalysed A-2 hydrolyses of a number of acetates as did Lane et al.[35] for ethyl acetate. However, for n-propyl acetate in 96.1% H_2SO_4 and isopropyl acetate in 84.8% H_2SO_4, McClelland found virtually no isotope exchange. This is consistent only with the fact that the hydrolysis is no longer proceeding by means of an $A_{Ac}2$ mechanism. There remain, however, three possibilities:





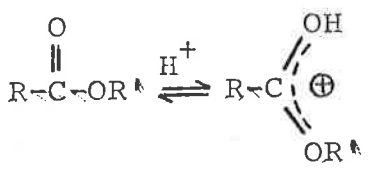
These three are indistinguishable on the basis of exchange results alone. They all yield products with the carbonyl-oxygen label unchanged. There are, however, other means for distinguishing between these. The 'r' hydration treatment was used by McClelland to show that, in fact, there are no longer two or more molecules of water involved in the transition state at these high acidities, as was the case for the dilute acid range. This effectively ruled out the A_{Al}-2 mechanism. Until lately in fact, this mechanism has not been observed in the acid-catalysed hydrolysis of carboxylic acid derivatives. McClelland, in a very recent paper,[43] provides evidence for an analogous mechanism in the H_2SO_4-catalysed hydrolysis of 2,6-dimethylbenzimidate esters from exchange studies, substituent effects and product studies. However, it is extremely unlikely that such a mechanism is operative in a simple acetate or benzoate system, especially in a region where the water activity is extremely low. The most direct means of choosing between the two unimolecular reactions involves examining substituent effects on the rate of the reaction. This is discussed below.

Unfortunately, no isotope exchange studies have been carried out on any of the esters in the present study. It is, nevertheless, possible to determine the position of cleavage of the ester in at least three of the substrates by other means. The one ester for which there remains some doubt, at the moment, is the 2,6-dimethyl benzoate, although exchange work is presently being done on that ester in these laboratories.

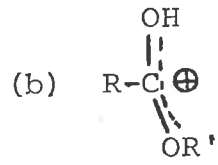
(iii) SUBSTITUENT EFFECTS

There is a great deal of information that can be derived about the mechanism of ester hydrolysis from the effect of substituents in the acid or alcohol moieties of the ester on the reaction rates. Moreover, depending on the class of σ constants with which the rate constants give a better correlation, some insight may be obtained as to the nature of the charge developing in the transition state.

For all the acid-catalysed mechanisms by which an ester may hydrolyse, there are two steps involved, each of which shows opposing effects due to the electronic nature of the substituents. These are a pre-equilibrium protonation step:

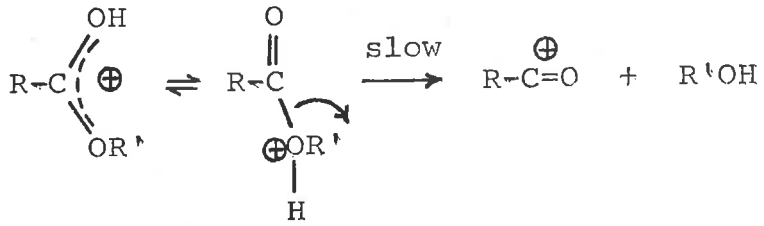
(a) 

followed by a rate-determining heterolysis step, which may or may not involve a water molecule explicitly as a nucleophile:



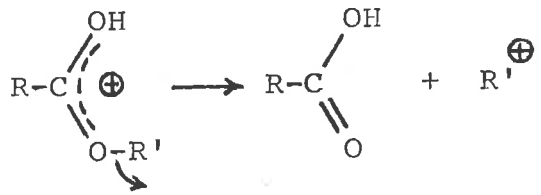
For an A_{Ac}-2 reaction, water is involved in the second step. In this case, electron-donating substituents in R, the acyl group, will accelerate the rate of the first step, but retard that of step (b). The same is true for substituents in R', but here their effect will be less pronounced, since they are removed from the reaction centre by at least one more atom, the ether oxygen, and are not in conjugation with it. Consequently, the ρ value is expected to be negative for step (a) and positive for step (b).

For an A_{Ac}-1 reaction, it can be assumed that protonation is either complete or at least well-advanced, since only methyl mesitoate has been previously shown to exhibit A_{Ac}-1 behaviour in any acid much less concentrated than about 60% H_2SO_4. Accordingly, the main effect is that for substituents on the heterolysis step.



Electron-releasing substituents in R will help to stabilise the incipient acylium cation, resulting in a negative ρ value, while the opposite is true for polar effects in R'.

In contrast to this, for the A_{Al}-1 mechanism, the effects of substituents in the heterolytic step are just the opposite.



A positive ρ is expected for substituents in R and a negative ρ for groups in R'. This is because both the position of bond cleavage and the carbon bearing the resulting positive charge are different for the A_{Al}-1 hydrolysis from those for the A_{Ac}-1.

A word of caution is in order at this point. Although the ρ values, especially their sign, are significant in deciding which mechanism is being followed for a reaction under a particular set of conditions, they serve only to corroborate other pieces of evidence about the reaction, rather than being definitive in themselves. This may be true for other evidence as well, particularly other linear free-energy relationships, but it is especially true here. The reasons for this are several, but mainly they involve two objections.

First of all, there is the problem of deciding what the ρ values mean if they are very small in magnitude, i.e. $|\rho| < 0.5$. This is quite clearly the case, e.g. for the acid-catalysed ester hydrolysis proceeding by the A_{Ac}-2 mechanism. The two steps of the reaction are each expected to show opposite signs for ρ. It has been widely assumed that these effects almost cancel one another, resulting in slightly positive ρ value of the order of ∿+0.1.

This result has been taken from data of Timm and Hinshelwood[106] who examined the acid-catalysed hydrolysis of a series of m- and p-substituted ethyl benzoates at 100°C in ethanol-water and acetone-water systems. A number of different workers have quoted various ρ values from the data in this paper, but unfortunately none of them agree. These include +0.03, +0.05,[110a,b] +0.106, +0.144[111] and ∿+0.3.[7a] Taft[112] used the lowest of these values, +0.03, to conclude that, unlike base-catalysed ester hydrolysis, the acid-catalysed bimolecular reaction shows little, if any, electronic effects from substituents in the acyl moiety.

A closer examination of the original data revealed why there was such disagreement between the ρ values. There was so much scatter in the plots that, at most, three points out of eight showed any correlation whatsoever. Depending on the solvent system, whether σ or σ^+ was chosen as the abscissa, and which points in

the set were used to determine ρ, ten (10) values of ρ ranging from +0.045 to +0.258 were calculated. However, even the conclusion that whatever the overall ρ value is, the effect on the heterolysis step (ii) is somewhat greater than that on the protonation step (i) cannot be made with absolute conviction.

In a study some years ago, Chapman and coworkers[113] compared the polar effects of substituents in acid- and base-catalysed hydrolysis of methyl benzoates. At 100.8°, in 80% v/v methanol-water, the m-substituted benzoates showed a ρ value of -0.23 for 3 of the 4 esters (r = 0.9996) for the acid-catalysed reaction. This can only mean that, for this reaction series at least, the protonation step shows the greater susceptibility to a change of the electronic environment on the aromatic ring.

The second, and perhaps major, objection to quoting ρ values as proof of mechanism is that in most cases, solvent systems and other reaction conditions are sufficiently different between two sets of data that meaningful conclusions as to mechanism are, at best, suspect. The worst example of this, is again the use to which Timm and Hinshelwood's data is put. Their reactions were carried out not only at highly elevated temperatures (∿100°) but in solvents which were essentially aqueous-organic in nature. Yet their results have been used many times as confirming the essential

lack of significant electronic effects in the acid-catalysed hydrolysis of esters proceeding by the A_{Ac}-2 mechanism. It is obvious that there is a significant difference between aqueous-organic and dilute to moderately concentrated aqueous acid reaction conditions.

A further example of this problem is the conclusion reached by Goering et al.[114] They studied the alkaline hydrolysis of para-substituted methyl 2,6-dimethyl benzoates in dioxan-water solvent at 80-175°C, and found ρ = +1.26 for this reaction. Realising that this was about half that found for unhindered benzoates saponifying in 88% ethanol at 30°[112] (ρ = +2,50) they searched the literature for a meaningful comparison. A value of 1.19 for benzenesulfonic ester hydrolysis in 30% ethanol at 25°[115 a] was then quoted and the authors concluded that the mechanism must be the same in both cases. That is, the 2,6-dimethyl benzoate esters must also be hydrolysing via alkyl-oxygen fission (B_{Al}-2). The only proviso they put on this conclusion was the possibility that the ortho-methyl groups were preventing the ester function from achieving coplanarity with the ring, thereby reducing the effects of the para substituents on the reaction rate. They suggested confirmation of this mechanism should await O^{18}-exchange results. The exchange work was subsequently studied by Bender and Dewey,[116] who refuted this mechanism by showing that the ester did indeed exchange with

O^{18}-enriched solvent, giving a k_h/k_e = 6.8 at 126°. This must necessarily mean that a tetrahedral intermediate is formed in this reaction and that the hydrolysis proceeds via the B_{Ac}-2, rather than the previously-proposed B_{Al}-2, mechanism.

Summarising the evidence then, it is clear that exact values of ρ must be viewed with caution in comparing two different sets of data in attempting to show mechanistic similarities. At best, the sign of ρ and its relative order of magnitude are the only significant bases for deriving mechanistic conclusions for various reaction series. Given these constraints, it is nonetheless meaningful to study the rates of hydrolysis of substituted benzoate esters in acid media to determine how changing mechanisms are reflected in changing ρ values as the strength of the acid medium is increased.

Hopkinson showed[111] that the acid-catalysed hydrolysis of methyl esters of a series of aliphatic acids in 76.88% H_2SO_4 at 25° had a ρ* value of +0.738.[a] Since these esters were known from other evidence to be undergoing A_{Ac}-2 hydrolysis, it is evident that the polar effect on the heterolysis step must be the more significant one here. This conclusion seems reasonable since the esters are already protonated to a significant

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[a]Deleting data for 4 of the 12 esters studied improved the correlation coefficient from 0.836 to 0.991, but did not significantly alter the ρ value (+0.756).

extent in this medium. Therefore the ρ value is expected to be considerably larger than that for the Timm -Hinshelwood set of data, though the mechanism is the same for both.

Other values relevant to the present study are ρ = -0.17 for benzyl acetates in 40-60% H_2SO_4,[110b] -0.19 for phenyl acetates in 50.2% H_2SO_4 and +0.49 for the same phenyl acetates in 74.1% H_2SO_4,[110c] all at 25°C. In the latter acid, the esters are hydrolysing by an A_{Ac}-1 mechanism, since electron-withdrawing substituents in the leaving group serve to enhance the rate of acyl-oxygen bond fission. Furthermore, the hydrolysis of m- and p-substituted benzamides has been studied at 95°C in 5.86-8.54 M $HClO_4$.[117] The ρ values obtained were +1.12 in 7.19 M acid and +1.19 in 8.54 M $HClO_4$. This compares with ρ = +0.12 for amide hydrolysis in very dilute acid, the difference being the result of effectively complete protonation of the amide substrates in the more concentrated acids. Thus the ρ value reflects only the electronic effect on bond fission, expected to be positive for that step in the A_{Ac}-2 reaction scheme.

Hence, one may conclude that for the A_{Ac}-2 hydrolysis of unhindered carboxylic acid derivatives, if the substrates are essentially unprotonated, the ρ values are quite small, in the -0.2 to +0.2 range. As the substrates become increasingly protonated, the

susceptibility of the heterolysis step to electronic effects outweighs that of the pre-equilibrium protonation step, resulting in a positive ρ value from ∿+0.5 to ∿+1.1.

The substituent effects are somewhat clearer in the very concentrated acid region where the mechanism has changed from A-2 to A-1. For A_{Ac}-1 ester hydrolysis, substituent changes in the acyl moiety are expected to yield a negative value of ρ, whereas those in the alcohol moiety will give a positive ρ. The reverse is true for the A_{Al}-1 reaction in which the positive charge is developing on the leaving carbonium ion. The hydrolysis of several m- and p-substituted methyl benzoates have been examined in concentrated acid by a number of workers. Kershaw and Leisten[73] found ρ = -3.21 for this series in 99.9% H_2SO_4 at 45°C. They also found a similar result for a series of ethyl benzoates, except that as the ring substituents became increasingly electron-withdrawing, a break in the σρ plot resulted. This was due to a change from the A_{Ac}-1 mechanism ($\rho < 0$) to the A_{Al}-1 mechanism ($\rho > 0$).

Van Bekkum et al.[107] obtained ρ = -3.64 for methyl benzoate hydrolysis in 95% H_2SO_4 at 25°C. In comparing the rates for the benzoate esters with those for analogous cyclohexanecarboxylate esters (the saturated ring), they observed that the rate for the aromatic system is at least ten times less than that for

the saturated analog. Although the aromatic ring gains some conjugation energy in going from the protonated ester to the transition state of hydrolysis, the inductive effect of the phenyl ring tends to oppose this possible enhancement of rate.

In general the rate of benzoate ester hydrolysis in dilute acid media is slower than that of aliphatic esters. The reasons for this are mainly three-fold:[119]

(i) Ground-state stabilisation of the ester due to resonance interaction between the benzene ring and the -COOR group;

(ii) Electron-withdrawing effect of the phenyl ring which, while increasing the susceptibility of the carbonyl carbon to attack, decreases the extent of protonation on the carbonyl oxygen; and

(iii) Steric inhibition by ortho-substituted groups to:

(a) ability of the ester group to protonate

(b) attack of the protonated ester by water

(c) solvation of the transition state.

The last two factors, (iii) (b) and (c) are affected even by ortho-hydrogens on the benzene ring. All these effects are predicated on the mechanistic necessity for the reaction to proceed via the protonated ester, however low in concentration this may be.

Hopkinson[72] studied a series of substituted methyl benzoates in a solvent system comprising $H[B(HSO_4)_4]$ in 100% H_2SO_4 at 64.8°C and obtained ρ = -0.825. This again indicates the need for caution in deriving mechanistic conclusions from ρ values for different solvent systems, unless the mechanism is known from other criteria. He also examined the hydrolysis of isopropyl benzoates in 98.7% H_2SO_4 at 0°C and found a ρ = +1.99, indicating a difference in mechanism. It is obvious from these results that unless there is a driving force towards the A_{Ac}-1 mechanism - which produces a relatively unstable benzoylium cation - the reaction prefers to proceed via A_{Al}-1 in concentrated acid if a more stable carbonium ion can be produced.

Hopkinson further studied the hydrolysis of methyl esters of a series of aliphatic monocarboxylic acids[111] in 95.88% H_2SO_4 at 25°, and obtained a ρ^* value of -3.71. This is in good agreement with the other ρ's for A_{Ac}-1 hydrolysis and confirms that methyl esters do not undergo A_{Al}-1 hydrolysis even with strongly electron-withdrawing substituents. It should be noted, however, that they did observe a break in the $\sigma^*\rho^*$ plot in going from negative σ^* values to positive ones ($\sigma^* > 0.38$), the latter (haloacetate esters) giving a ρ^* = +0.789 (r = 0.993). This was thought to indicate a change to the A_{Al}-1 mechanism but other evidence ruled that

conclusion out. The rates of the haloacetates decreased continuously from 76.88% to 99.5% H_2SO_4, with further increases in acidity giving charred reaction mixtures and negligible amounts of hydrolysis. Moreover, it was noted that Deno et al.[120] were unable to prepare a solution of the chloroacetyl cation ($ClCH_2C^{+}=O$) in 65% oleum, although the majority of carboxylic acids form acylium ions in 15-20% oleum. This all points to continued A_{Ac}-2 hydrolysis of these acetates even to very highly concentrated acid, and the ρ obtained (+0.789) is in good agreement with this assignment.

A general conclusion can thus be made for hydrolysis of substituted methyl benzoates in concentrated sulfuric acid solutions. That is, regardless of the extent to which polar groups on the aromatic ring withdraw electrons from the reaction centre, methyl esters of substituted benzoate systems will hydrolyse only by A_{Ac}-1, not A_{Al}-1, and conceivably may not change mechanism at all. The haloacetates, for example, hydrolyse by the A_{Ac}-2 pathway throughout the entire acidity range studied, whereas methyl mesitoate hydrolyses solely by the A_{Ac}-1 mechanism even in dilute H_2SO_4 media.

In light of this, it was considered worthwhile to examine the polar effects on the hydrolysis of methyl benzoates in 40.0% and 90.5% H_2SO_4 to provide additional confirmation of the presumed mechanisms of hydrolysis of

the parent member of the present series, methyl benzoate. It was also of interest to determine the manner in which the ortho-methyl substituents caused the hydrolytic rates of MOT and 2,6-MDMB to deviate from the linear free-energy relationships obtained in the two acid media investigated. The two acids were chosen since methyl benzoate is known to hydrolyse by different mechanisms in these different acid concentrations. The kinetics were measured at 50.1^{o} and 60.1^{o}C to determine the temperature effect on the ρ values obtained. The results are given in Table 11 and Fig. 12.

Although the number of esters used to obtain these results is small, the trends are readily apparent. There is more scatter in the data at 40.0% than at 90.5% H_2SO_4, as evidenced by the correlation coefficients. Furthermore, the latter also indicate that the fit is somewhat better using σ^+ values than σ values. However, since most literature values quoted for benzoate hydrolysis are obtained from correlations with σ rather than σ^+, and since the correlation coefficients are not that different for the two plots, it is the ρ values that should be used for comparison with the previously-quoted results.

Despite the reservations concerning the interpretation of ρ values made earlier, it can be seen that the values obtained in this study agree well with those

TABLE 11: RATE DATA FOR HYDROLYSIS OF METHYL 4-X-BENZOATES IN SULPHURIC ACID

w/w% H_2SO_4	T(°C)	X	log k_ψ [a]	σ [b]	σ^+ [b]
40.0	50.1	$-OCH_3$	1.577	-0.268	-0.778
		$-CH_3$	1.654	-0.170	-0.311
		-H	1.635	0	0
		-Cl	1.807	+0.227	+0.114
		$-NO_2$	1.776	+0.778	+0.790
	60.1	$-OCH_3$	1.917	-0.268	-0.778
		$-CH_3$	2.040	-0.170	-0.311
		-H	2.073	0	0
		$-NO_2$	2.082	+0.778	+0.790
90.5	50.1	$-CH_3$	4.335	-0.170	-0.311
		-H	3.150	0	0
		-Cl	2.168	+0.227	+0.114
	60.1	$-CH_3$	5.000	-0.170	-0.311
		-H	3.763	0	0
		$-NO_2$	1.253	+0.778	+0.790

HAMMETT ρ VALUES:

w/w% H_2SO_4	T(°C)	ρ [c]	r [d]	ρ^+ [e]	r [f]	N [g]
40.0	50.1	+0.167	0.950	+0.121	0.956	4
	60.1	+0.103	0.642	+0.096	0.832	4
90.5	50.1	-5.40	-0.991	-4.83	-0.979	3
	60.1	-3.73	-0.987	-3.36	-0.999	3

[a] Values given as 4 + log k_ψ ($min.^{-1}$)

[b] Obtained from Reference 115b.

[c] Plotted vs. σ values.

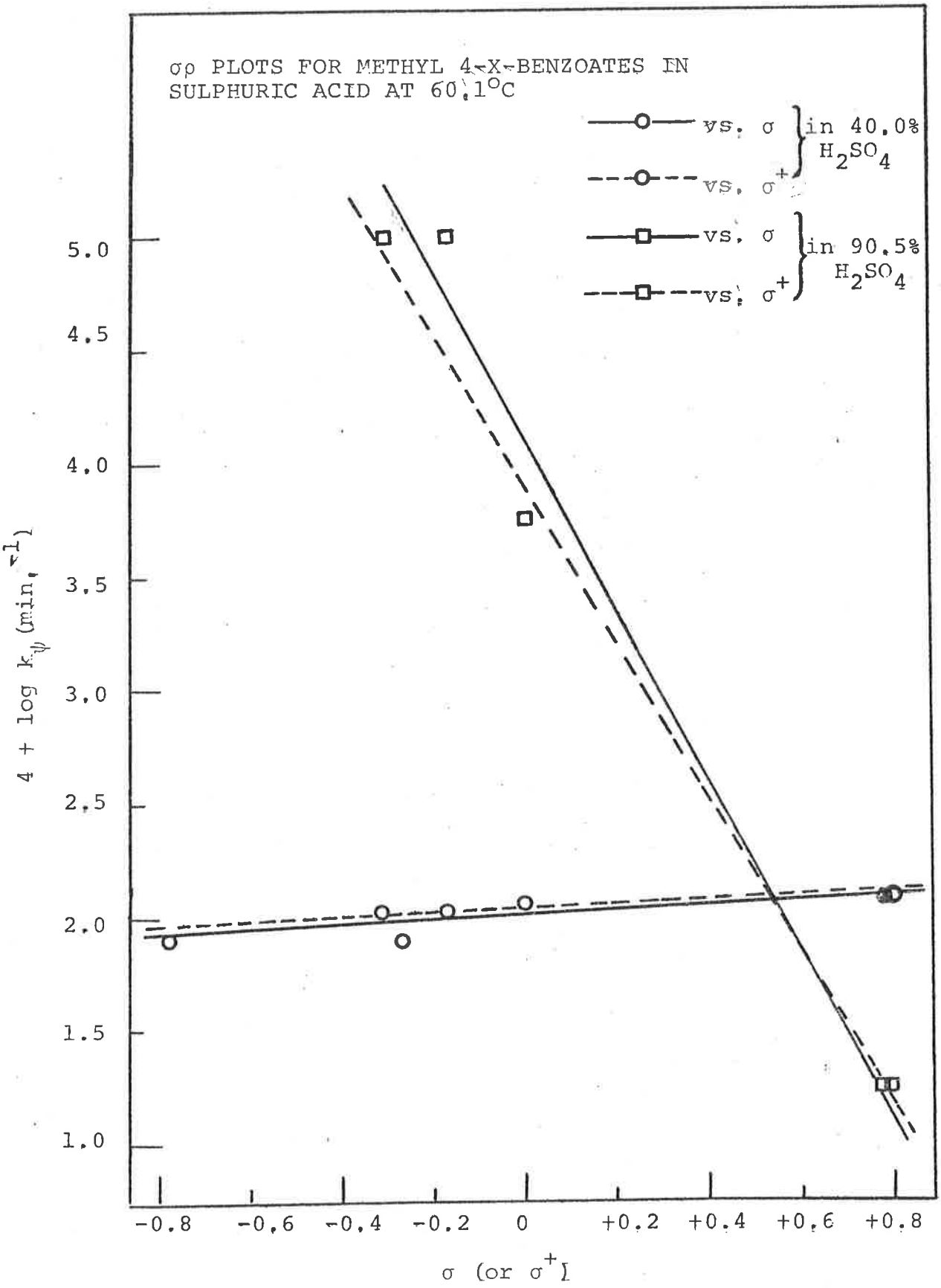
[d] Corr. coefft. for ρ.

[e] Plotted vs. σ^+ values.

[f] Corr. coefft. for ρ^+.

[g] Number of points used for correlation.

FIGURE 12


σρ PLOTS FOR METHYL 4-X-BENZOATES IN SULPHURIC ACID AT 60.1°C
vs. σ in 40.0% H2SO4
vs. σ+ in 40.0% H2SO4
vs. σ in 90.5% H2SO4
vs. σ+ in 90.5% H2SO4
4 + log kψ (min.-1)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
-0.8
-0.6
-0.4
-0.2
0
+0.2
+0.4
+0.6
+0.8
σ (or σ+)

obtained elsewhere for similar systems. It is clear that there is little net electronic effect in 40.0% H_2SO_4, in accord with the A_{Ac}-2 mechanism assigned for hydrolysis in this acid. Moreover, ρ decreases as the temperature is increased, as would be expected. In 90.5% H_2SO_4, the ρ values are large and negative in agreement with the A_{Ac}-1 mechanism proposed for reaction in this acid, and again the ρ-value decreases with increasing temperature.

One other piece of evidence is quite interesting. Although comparisons can only be made for two esters - methyl benzoate and methyl p-toluate - over the entire acidity range studied, the manner in which the ρ values change as the esters become increasingly protonated in the A_{Ac}-2 region is significant:

w/w% H_2SO_4	$\rho_{25°}$ (based on σ)	$\rho_{50°}$ (based on σ)
40.0	-0.52	-0.11
50.0	-0.49	+0.50
60.0	+0.78	+0.86
65.0	+1.42	+0.81
70.0	+2.06	+0.57
75.0	+0.31	-1.27
80.0	-3.45	-4.23

These results would appear to indicate, with the proviso that only the trend is meaningful rather than the actual values (since only two esters were used), that as the esters become more protonated, the heterolysis step in the A_{Ac}-2 mechanism shows the greater susceptibility to electronic effects, resulting in a

positive ρ value. As the activity of water continues to decrease, the sign of the ρ changes, indicating that a new mechanism (A_{Ac}-1) is taking over and this changeover occurs somewhat earlier as the temperature increases, as might be expected.

Finally, one of the reasons for studying the σρ behaviour of benzoate hydrolysis was to determine how the hydrolytic rates for the two ortho-substituted esters deviated from the σρ correlations at the two different acidities. The results are as follows:

T(°C)	w/w%	x	log k_ψ [a]	log k_ψ [b]	Rel. k_ψ [c]
50.1	40.0	p-CH_3	1.654	1.618	1.1
		o-CH_3	1.304	1.618	0.5
		2,6-dimethyl	-0.162	1.589	0.02
60.1	40.0	p-CH_3	2.040	2.002	1.1
		o-CH_3	1.711	2.002	0.5
		2,6-dimethyl	0.346	1.984	0.02
50.1	90.5	p-CH_3	4.335	4.237	1.3
		o-CH_3	>5.0[d]	4.237	>6
		2,6-dimethyl	>7.0[d]	5.155	>70
60.1	90.5	p-CH_3	5.000	4.728	1.9
		o-CH_3	>6.0[d]	4.728	>19
		2,6-dimethyl	>>7.0[d]	5.362	>43

[a] Values given as 4 + log k_ψ

[b] Values calculated from log k/k_o = σρ and given as 4 + log k_ψ where ρ values are taken from Table 11
σ = -0.17 (for o-CH_3 and p-CH_3)
= -0.34 (for 2,6-dimethyl)

[c] Relative k_ψ = k_ψ^a/k_ψ^b

[d] Too fast to be measured accurately

Because of the difficulty of obtaining the rate constants for the sterically-hindered esters in the concentrated acid medium at elevated temperatures, the following data at 25°C offers a further indication of the manner in which rates for the ortho-substituted esters differ from those for the unhindered esters in various acid media.

w/w H_2SO_4	ESTER	$4+\log k_\psi$ (min^{-1})	k_ψ^E/k_ψ^{MB} [a]
40.0	MB	0.465	1.0
	MPT	0.554	1.23
	MOT	0.155	0.49
	2,6-MDMB	-1.604	0.01
60.0	MB	0.932	1.0
	MPT	0.799	0.74
	MOT	0.202	0.19
	2,6-MDMB	0.135	0.16
80.0	MB	0.429	1.0
	MPT	1.015	3.9
	MOT	2.300	74
	2,6-MDMB	3.714	1930

[a] The ratio is the rate constant for the substituted ester relative to that for methyl benzoate itself.

From the data in these two tables, it is obvious that, regardless of acidity or mechanism, the rate constants for the esters substituted with methyl groups in one or both ortho positions are not mainly determined by their electronic effects on the reaction centre. There is quite clearly a steric effect operative for these esters causing them, in dilute acid, to hydrolyse more slowly and in the concentrated acid

range, much more rapidly, than the corresponding unhindered esters. The mechanisms of methyl ortho-toluate and methyl 2,6-dimethyl benzoate hydrolysis will be discussed more fully later.

(iv) HYDRATION TREATMENTS

In attempts to elucidate the reaction order of acid-catalysed ester hydrolysis with respect to water, several relations have been devised. Most of these are subject to various assumptions, particularly concerning the behaviour of activity coefficients of the different species present in solution. The two that have shown the most promise for hydrolysis reactions are the 'r' plots and the behaviour of transition state activity coefficients* as a function of changing acidity.

(a) 'r' PLOTS

For an ester which is partially protonated, the 'r' relation predicts that:

$$\log k_2 = \log k_\psi - \log \frac{h_o^m}{h_o^m + K'_{SH^+}{}^m} = r \log a_{H_2O} + \log k_o \qquad (24)$$

*This is truly not a hydration treatment but is included here as a useful relation between rates and acidity of the medium.

where: m = slope of the plot of log $[SH^+]/[S]$ vs. $-H_o$ and pK'_{SH^+} = the H_o value at which the substrate is half-protonated. The 'r' equation, as initially derived (equation (20), p. 29), requires a knowledge of the acidity function which the protonation of the substrate under investigation follows. To date, however, there has been no acidity function determined for aromatic esters, although one recently appeared[11] for aliphatic esters. This H_E function was not employed for the present study, since the ionisation of aliphatic esters is quite different from that of aromatic esters as seen from comparing the 'm' and pK'_{SH^+} values in the two cases. For this reason, the ionisation parameters specific for each benzoate ester studied were used for the 'r' plots, and equation (24), above, was used as the corresponding relation, rather than:

$$\log k_\psi + H_S = r \log a_{H_2O} + \log \frac{k_o}{K_{SH^+}} \qquad (20)$$

Moreover, the H_o[12,121] and $\log a_{H_2O}$[122] values at 25°C were obtained from the literature.

The results of this treatment for methyl benzoate hydrolysis in sulphuric acid at 25°C are shown in Table 12 and Fig. 13. The 'r' value of +2.30 for the relatively dilute acid region, 40-70% H_2SO_4, is in excellent agreement with that found by Lane et al.[35] of +2.25, although their value for m, 0.846, was slightly lower than that

TABLE 12. DATA FOR THE 'r' PLOT FOR HYDROLYSIS OF METHYL BENZOATE IN SULPHURIC ACID AT 25°C

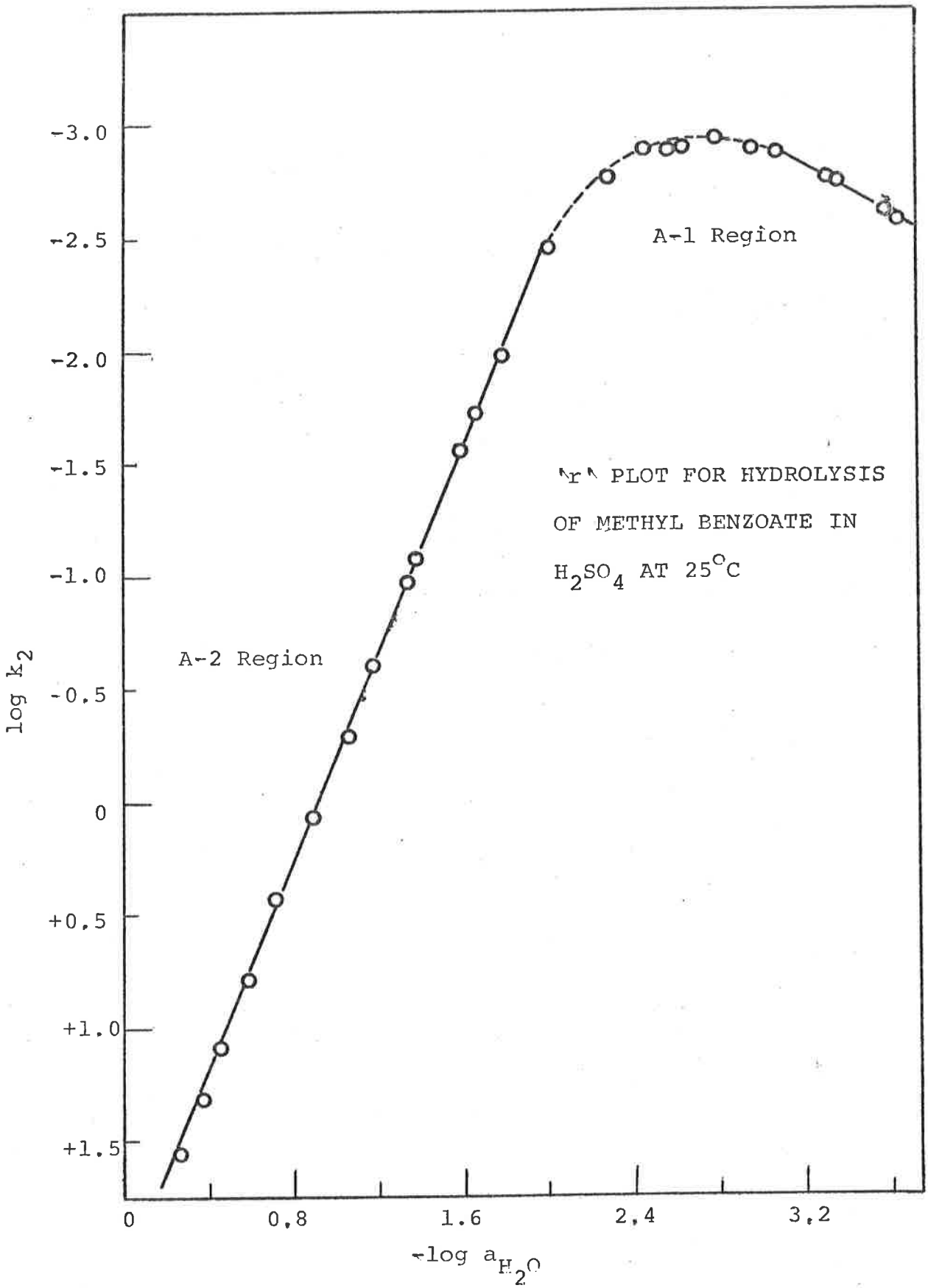
w/w% H_2SO_4	log k_2 [a]	-log a_{H_2O}
40.0	1.564	0.247
42.0	1.486	0.280
46.0	1.309	0.360
50.0	1.088	0.455
54.0	0.783	0.573
58.0	0.426	0.710
62.0	0.066	0.877
65.03	-0.298	1.03
67.39	-0.610	1.16
69.76	-0.973	1.33
70.29	-1.074	1.37
72.88	-1.545	1.58
73.75	-1.723	1.65
75.09	-1.977	1.76
77.61	-2.462	2.00
80.0	-2.761	2.27
81.41	-2.890	2.45
82.20	-2.882	2.55
82.68	-2.899	2.63
84.0	-2.935	2.79
85.16	-2.894	2.95
86.0	-2.873	3.07
87.67	-2.762	3.30
88.0	-2.750	3.35
89.63	-2.615	3.58
90.0	-2.572	3.63

[a] $\log k_2 = \log k_\psi - \log h_o^m/(h_o^m + K'^m_{SH^+})$

$m = 0.905$, $pK'_{SH^+} = -8.15$

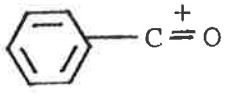
RANGE w/w% H_2SO_4	SLOPE = r	INTERCEPT = log k_o	CORR. COEFFT.	MECH.
40.0-77.61	2.299	2.096	0.9996	A_{Ac}-2
84.0-90.0	-0.435	-4.179	-0.984	A_{Ac}-1

FIGURE 13


-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0
+0.5
+1.0
+1.5
log k_2
A-1 Region
A-2 Region
'r' PLOT FOR HYDROLYSIS
OF METHYL BENZOATE IN
H_2SO_4 AT 25°C
0
0.8
1.6
2.4
3.2
-log a_{H_2O}

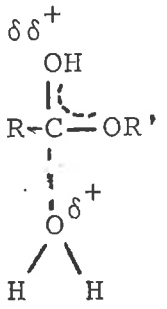
obtained in this study, 0.905. The concentrated acid region, 84-90% H_2SO_4, has an 'r' value = -0.435, more negative than the average value of -0.17 found for primary alkyl acetates and fortuitously coincidental with r = -0.43, the average value obtained for phenyl acetates,[110d] both of which hydrolyse by the A_{Ac}-1 mechanism in concentrated acid. This 'r' value also agrees well with that obtained by van Bekkum et al.,[107] r = -0.40, for methyl benzoate hydrolysis at 25°C in 85-95% H_2SO_4.

The reason for the more negative value for benzoate hydrolysis in concentrated acid than that for the primary alkyl acetates is the difference in solvation requirements for the transition states in the two reactions. It should be remembered that 'r' is actually a measure of the change in the number of water molecules of hydration between the protonated ester and the transition state of the reaction. If the latter is presumed to resemble, to some extent, an acylium cation, the reason for the more negative 'r' value for the benzoylium ion relative to that for the acetylium ion becomes clearer.

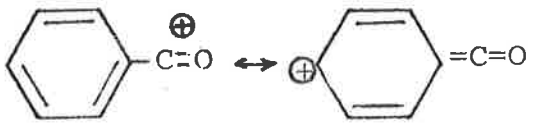
$CH_3-C^{\pm}=O$ vs. 

Both of these species will require less solvation than the corresponding transition states for the A_{Ac}-2

reaction,

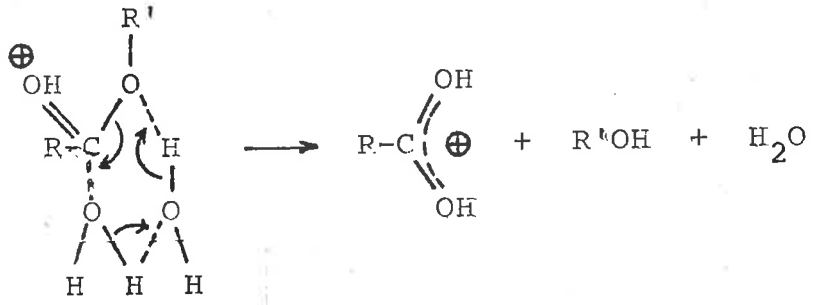


which is much more oxonium ion-like in character than the carbonium ion-like acylium ions. The better correlation of Hammett σρ plots with σ^+, rather than σ, values further attests to the developing carbonium ion nature of the A_{Ac}-1 transition state, allowing for such resonance contributors as



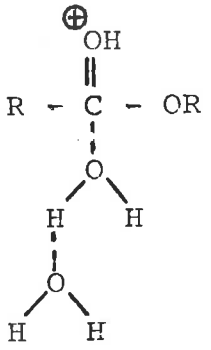
Because of this partial resonance stabilisation, the benzoylium ion will have less need for solvent stabilisation by water molecules in the concentrated acid medium than is the case for the acetylium ion. This results in the more negative 'r' value. The fact that 'r' is less than, and not equal to, zero in this acid range suggests that the transition state for the A_{Ac}-1 reaction is less hydrated than the protonated ester, whereas the opposite is true for the A_{Ac}-2 mechanism. This is a consequence of the different solvation requirements of the transition states in the two reactions.

An 'r' value of 1 would naively be expected for the A_{Ac}-2 mechanism on the basis that the only water molecule postulated for the second step, in addition to those acting as hydrating molecules, is the one acting as the direct nucleophile on the carbonyl carbon. That r = ∿2, instead, necessarily implicates an additional water molecule, thought to be involved as a proton transfer agent. This value of 'r' seems to be quite general for ester hydrolysis in dilute acid media, since McClelland found values from 1.65-2.30[110d] for acetate hydrolysis in the acid region. Lane et al.[35] proposed a cyclic mechanism employing both water molecules as a means of accomplishing all the proton transfers in one step through the cyclic hydrogen bonds:



(I)

This was proposed as an alternative to:



(II)

on the basis that, if II were the more "accurate" representation of the transition state, the rate of proton transfer must decrease in concentrated acid in order to explain the maximum in the hydrolysis rate profile. But the rates of such proton transfers from, e.g. methyl-oxonium ions, is known to be very rapid even in 70% H_2SO_4 at -20°C.[123] For this reason the authors[35] prefer (I) to (II).

However, since the rate decrease can be explained just as easily by the fact that the water activity is decreasing more rapidly in the 60-80% H_2SO_4 region than the concentration of the reactive, protonated, ester substrate is increasing, there is little to choose between these two proposed transition states. All other results of hydrolysis and exchange can be explained equally well by either. Suffice it to say that there is a second molecule to water involved in the $A_{Ac}-2$ mechanism of hydrolysis, and that it is probably acting as a proton transfer agent. This is also confirmed by Bunnett's 'ω' treatment[29] which indicates a value of 'ω' ≃ + 4 → +5, in the region (> +3.3) empirically determined for water acting as a proton-transfer agent.

(b) TRANSITION STATE ACTIVITY COEFFICIENTS

The various hydration parameter treatments give rise to a number of problems, particularly in their use

for interpreting reaction mechanisms. This is especially true for the Bunnett 'ω' and 'ϕ' relations. Even when these give linear plots, the best that Bunnett was able to do was relate the 'ω' or 'ϕ' values obtained with those resulting from reactions whose mechanisms were known. This was not always successful in giving satisfactory interpretations of mechanism and, in addition, many of his plots were curved.

Even the 'r' plots which work very well for ester hydrolysis, considering the assumptions involved, give rise to certain anomalous results, especially very large negative values for A-1 reactions. For example, t-butyl acetate hydrolysis in 10-30% H_2SO_4 shows an 'r' value of -8,91 at 25°C. This is explained by the fact that the water activity is effectively invariant in this acid region. As a result, any changes in rate will show a much greater dependence on water activity than the mechanism would justify. The development of the recent technique - an estimation of transition state activity coefficient behaviour in acid-catalysed hydrolyses - enabled a more satisfying physical understanding of mechanisms in sulphuric acid media to be obtained. This parameter, log $f_{\ddagger}^*$, is defined as:

$$\log \frac{f_{\ddagger}^*}{k_o} = -\log k_{\psi} (1+I) + \log K_{SH^+} + \log f_S + \log a^*_{H^+} \qquad (26)$$

where the asterisk indicates that those quantities are determined relative to the activity coefficient of the reference cation, tetraethyl ammonium cation. Log $f_{\ddagger}^*$ itself is obtained by a plot of equation (26) against w/w% H_2SO_4 and extrapolating back to 0% H_2SO_4 to determine log k_o. This value is then incorporated into the equation

$$\log f_{\ddagger}^* = \log \frac{f_{\ddagger}^*}{k_o} - (-\log k_o)$$

to obtain log $f_{\ddagger}^*$ directly.

The major advantage of this approach over the hydration treatments previously used is that no assumptions are made about the way in which activity coefficients cancel. For example, the 'r' relation assumes that $f_{SH^+_h} \simeq f_{\ddagger_h}$ and that $f_{S_h} \simeq f_{B_h}$, since the members of these pairs of hydrated species are expected to resemble one another in structure, charge and solvation characteristics. It can be seen, however, in Fig. 14 that, for the formal activity coefficients, $f^*_{SH^+}$[a] and $f_{\ddagger}^*$, in the case of methyl benzoate hydrolysis, there is a wide variation in the behaviour of the two species as the acidity is increased. $f^*_{SH^+}$

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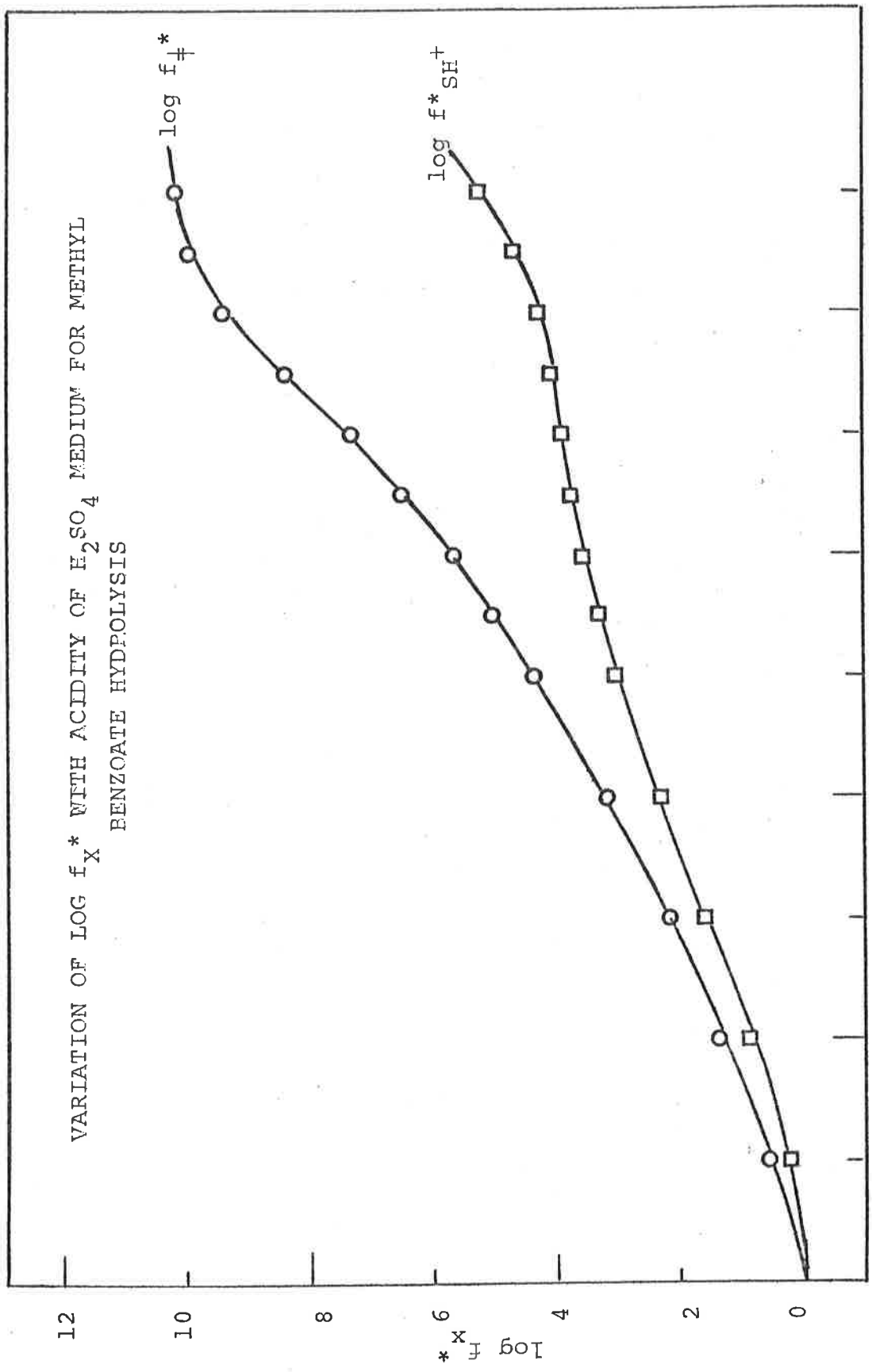
[a] log $f^*_{SH^+}$ calculated from: log $f^*_{SH^+}$ = log $a^*_{H^+}$ + log f_S + mH_o.

FIGURE 14


VARIATION OF LOG f_X^* WITH ACIDITY OF H_2SO_4 MEDIUM FOR METHYL BENZOATE HYDROLYSIS
log $f_{\neq}^*$
log $f^*_{SH^+}$
log f_X^*
w/w% H_2SO_4
0
2
4
6
8
10
12
10
20
30
40
50
60
70
80
90

and $f_{\ddagger}^{*}$ differ by less than one logarithmic unit up to ~40% H_2SO_4, but they diverge significantly as the acid concentration increases, so that by 90% H_2SO_4 the difference is about five logarithmic units. This shows that the protonated substrate, SH^+, is much more salted in than the transition state activated complex, $S^{\ddagger}$. Although these calculations were carried out using formal activity coefficients, the difference between the two is large enough that it seems reasonable to conclude that even for the hydrated activity coefficients, $f_{SH^+}{}_h / f_{\ddagger}{}_h \neq 0$.

In equation (26), the terms on the right-hand side of the equation are all potentially accessible by experiment. Log k_{ψ} and log K_{SH^+} have been obtained for each of the esters in this study as previously discussed. Values for log $a^*{}_{H^+}$ in sulphuric and other mineral acids have been recently published.[37-39] A short extrapolation of the log $a^*{}_{H^+}$-w/w% H_2SO_4 plot beyond 70% was necessary to treat the rate data in acid as concentrated as 90% H_2SO_4. The other quantity to be determined is f_S (or log f_S), the activity coefficient of the neutral substrate species in acid solution. These values have been previously obtained[95] for methyl benzoate and methyl mesitoate in 0-40% H_2SO_4 at 25°C. Log f_S values for the other benzoate esters under investigation in 0-70% H_2SO_4 at 25°C were determined in the course of the present studies. Again, a short extrapolation to 90%

H_2SO_4 permitted the calculation of log $f_{\ddagger}^*$ in the concentrated acid range. Although the acidity region for extrapolation is longer in the case of methyl benzoate, the contribution of log f_S to the total value of log $f_{\ddagger}^*$ is relatively minor. Even the most negative value of log f_S, for methyl benzoate in 90% H_2SO_4, is only 20% of the final value obtained for log $f_{\ddagger}^*$. It is for this reason that the extrapolation is considered justified.

The results of this treatment for methyl benzoate hydrolysis at 25°C are given in Table 13 and plotted in Fig. 15. The value for log k_o for the reaction in dilute acid, 2.43, is in reasonable agreement with that obtained from the 'r' plot, 2.10, considering the relative degrees of approximation in the two approaches. Fig. 15 shows that the value of log $f_{\ddagger}^*$ rises quite rapidly in 0-75% H_2SO_4, indicating a large salting-out (i.e. destabilising) effect on this activity coefficient, by about 9 logarithmic units relative to that for TEA^+. Instead, however, of continuing to rise at an increasingly rapid rate, the rate of increase of log $f_{\ddagger}^*$ begins to slow down beyond this acidity, indicating a change in the nature of the transition state and hence a change in mechanism.

TABLE 13. LOG $f_{\ddagger}^*$ VALUES FOR METHYL BENZOATE HYDROLYSIS IN H_2SO_4 AT 25°C

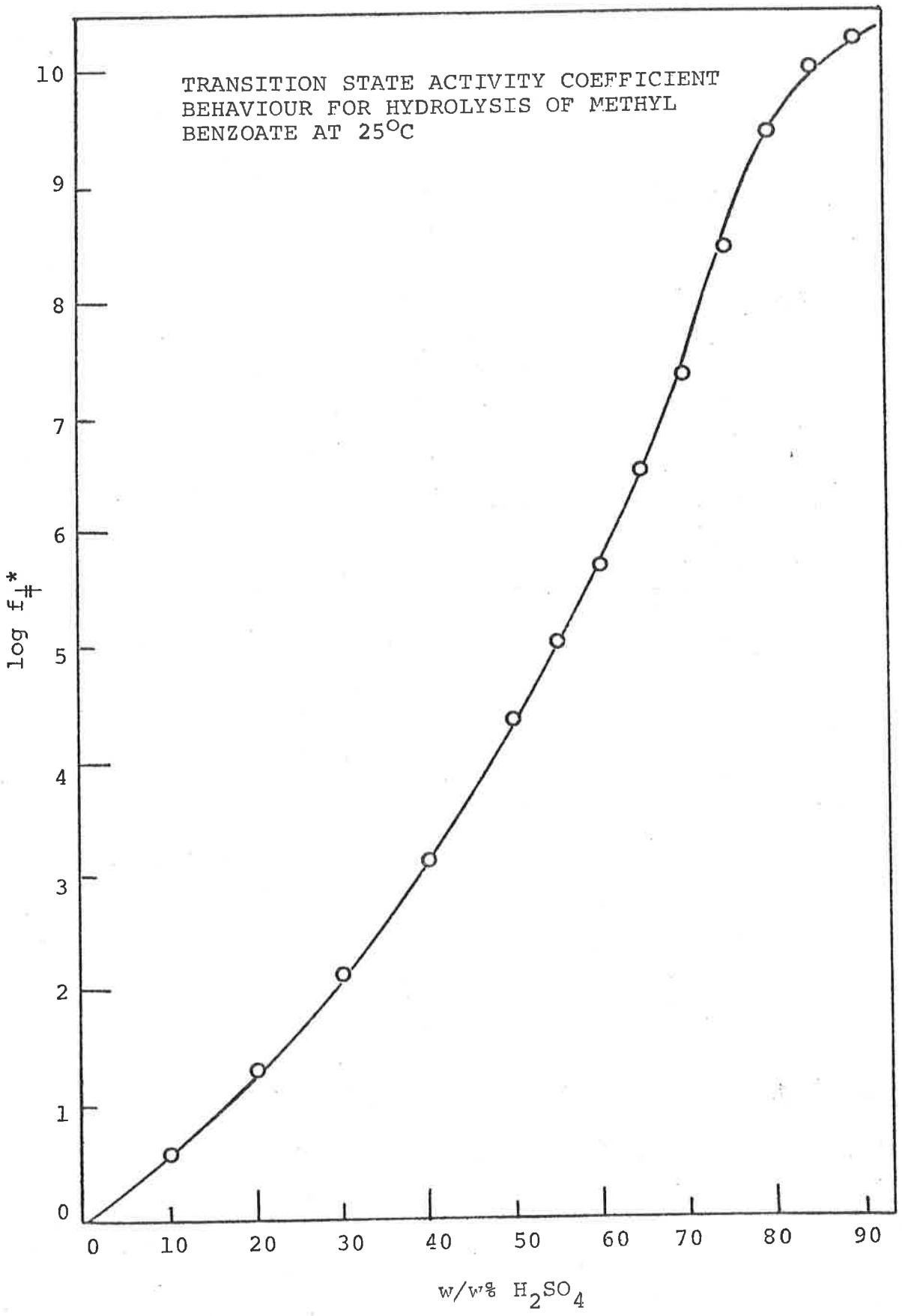
w/w% H_2SO_4	log k_2	$-H_o$	log f_S	log $a^*_{H^+}$	log $f_{\ddagger}^*/k_o$	log $f_{\ddagger}^*$
0	2.096	--	--	--	(-2.43)[a]	0.0
10	2.050	0.38	0.11	0.43	-1.85	0.58
20	1.969	1.03	0.23	1.55	-1.12	1.31
30	1.809	1.78	0.30	2.84	-0.28	2.15
40	1.564	2.52	0.20	4.34	+0.70	3.13
50	1.088	3.40	-0.05	6.13	+1.92	4.35
55	0.680	3.93	-0.22	7.07	+2.61	5.04
60	0.270	4.52	-0.43	8.05	+3.26	5.69
65	-0.298	5.07	-0.68	9.05	+4.08	6.51
70	-1.045	5.78	-0.97	10.08	+4.92	7.35
75	-1.970	6.56	-1.29	11.30	+6.04	8.47
80	-2.761	7.34	-1.61	12.52	+7.03	9.46
85	-2.900	8.11	-1.91	13.94	+7.59	10.02
90	-2.572	8.92	-2.23	15.56	+7.83	10.26

$\log f_{\ddagger}^*/k_o = -\log k_2 + mH_o + \log f_S + \log a^*_{H^+}$, where: m = 0.905

$\log f_{\ddagger}^* = \log f_{\ddagger}^*/k_o - (-\log k_o)$

[a]Obtained by extrapolating plot of $\log f_{\ddagger}^*/k_o$ vs. w/w% H_2SO_4 to 0% H_2SO_4

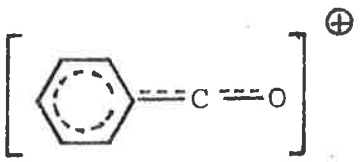
FIGURE 15


TRANSITION STATE ACTIVITY COEFFICIENT BEHAVIOUR FOR HYDROLYSIS OF METHYL BENZOATE AT 25°C
log $f_{\ddagger}^{*}$
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
w/w% H_2SO_4

The log $f_{\ddagger}$*-w/w% H_2SO_4 profile bears a strong resemblance to that found for benzyl acetate hydrolysis (cf. Fig. 1). It therefore seems likely that the initial large salting-out is indicative of an A_{Ac}-2 transition state. This species has a positively-charged oxonium ion on a carbon bearing two other electron-withdrawing oxygens and thus requires a great deal of solvent stabilisation from the water molecules in the acid media. As the acidity is increased, the water activity decreases and hence the water molecules are less able to provide this stabilisation. Thus the tetrahedral transition state complex becomes destabilised and this is observed as the large salting-out of the activity coefficient for this transition state. As the acidity is further increased, however, the transition state for the benzoylium cation, which is relatively unstable in dilute acid, becomes the predominant species in solution since it has less requirement for solvent stabilisation, resembling a carbonium ion, than the oxonium ion-like tetrahedral transition state. As a result, the mechanism, A_{Ac}-1, which produces the more stable transition state in concentrated acid becomes the major pathway of reaction.

The positive charge in the A_{Ac}-1 transition state is localised more on carbon than on oxygen as is the case for A_{Ac}-2 hydrolysis. Moreover, for the benzoate

esters, this charge can be stabilised internally by delocalisation through the aromatic ring system:



Hence, the solvation requirements for this transition state are much less than those for the A_{Ac}-2 oxonium ion transition state. This A_{Ac}-1 species is still salted-out much more than long-lived carbonium ions, but it is salted-in, i.e. more stable, in the concentrated acid range relative to the increasingly unstable tetrahedral A_{Ac}-2 activated complex.

Accordingly, the physical meaning for the manner in which the transition state activity coefficient varies with changing acid strength is readily understood and this method provides a clearer picture of why the mechanisms do change with increasing acid strength as well as the acidity range in which the mechanistic change is occurring. The activity coefficient behaviour is best explained as showing an A_{Ac}-2 transition state in dilute to moderately concentrated acid, which then changes to an A_{Ac}-1 transition state in the highly concentrated acid solutions. For methyl benzoate hydrolysis, this change occurs at ∿75-80% H_2SO_4. These results agree well with those from the 'r' plot hydration treatment, and exhibit behaviour very similar to that of acetate hydrolysis in sulphuric acid media.[110]

(V) SUMMARY: CONCLUSIONS RE MECHANISM OF HYDROLYSIS OF METHYL BENZOATE IN SULPHURIC ACID

All the data reported herein corroborate the conclusion that this ester hydrolyses by the A_{Ac}-2 mechanism in dilute acid and by the A_{Ac}-1 mechanism in concentrated sulphuric acid. The rate profile shows a maximum at about 62% H_2SO_4 at 25°C, followed by a minimum at ∿79% H_2SO_4, after which the rate begins to rise rapidly once more. The maximum in the profile is a common feature of many esters undergoing A_{Ac}-2 hydrolysis, and the minimum indicates a change in mechanism from one in which water is involved as a nucleophile in the rate-determining step to the A_{Ac}-1 reaction in which water acts only as hydrating species in the slow step of the reaction.

The activation parameters show that $\Delta S^{\ddagger}$ increases from about -15 e.u. at 40% H_2SO_4 to -2.6 e.u. at 78% to +20.5 e.u. at 90% H_2SO_4. Similarly, the enthalpy of activation decreases from 20.2 kcal/mole at 40% to 19.9 kcal/mole at 65% H_2SO_4 (consistent with a rate increase in this range), and then begins to increase steadily until $\Delta H^{\ddagger} \simeq 29.6$ kcal/mole at 90% H_2SO_4. The large value of $\Delta H^{\ddagger}$ at this acidity is opposed by the correspondingly high value of $\Delta S^{\ddagger}$, so that the reaction

continues to proceed at a measurable rate, albeit by a different mechanism.

Both the $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ values are consistent with an A-2 mechanism in dilute acid switching over to an A-1 mechanism in concentrated acid. The somewhat higher values of $\Delta H^{\ddagger}$ relative to those of aliphatic ester hydrolysis ($\Delta\Delta H^{\ddagger} \simeq 3.4$ kcal/mole) are due to steric hindrance to solvation and attack of the water molecules (even by the ortho-hydrogens) as well as the inductive effect of the benzene ring.

O^{18}-exchange studies on ethyl benzoate, hydrolysing in dilute acid, indicated that the acyl-oxygen bond, R-$\overset{O}{\overset{\|}{C}}$-OR', is the one being cleaved in this medium. Exchange studies on primary alkyl acetate systems gave similar results for dilute H_2SO_4, but no exchange is observed in sulphuric acid more concentrated than 84 w/w%. Although isotope exchange studies were not carried out in the present work, on the basis of similar behaviour in the hydrolysis of methyl and ethyl benzoate and that of the primary alkyl acetates, we are justified in concluding that similar results would be obtained here as well. That is, exchange would be observed in the dilute acid range indicating A_{Ac}-2 hydrolysis, and reaction in concentrated acid would give no exchange indicative of either A_{Ac}-1 or A_{Al}-1 mechanisms.

The fact that it must be acyl-oxygen (A_{Ac}-1) rather than alkyl-oxygen (A_{Al}-1) cleavage is shown most directly by the electronic effects of substituents on the reaction rate. Several independent studies of benzoate ester hydrolysis in >90% H_2SO_4 have shown that the ρ value for this reaction is -3.2 → -3.7, consistent only with an A_{Ac}-1 mechanism. Moreover, these studies have shown that when the ester is a methyl ester, only an A_{Ac}-1 mechanism is observed. This appears to be true regardless of how strongly electron-withdrawing the substituents on the phenyl ring are.

Finally, two further pieces of evidence support not only the assignment of which mechanism is operative in each acid, but also pinpoints fairly accurately the acid range in which the reaction mechanism is changing. The 'r' plots give r = +2.30 (log k_o = 2.10) for the dilute acid range and r = -0.435 (log k_o = -4.18) for acids >84% H_2SO_4. The acid strength where the two linear 'r' plots cross is 80% H_2SO_4. The transition-state activity coefficient behaviour reveals the same mechanistic information. The transition state is strongly salted out in the 0-70% H_2SO_4 range, followed by a much less pronounced salting-out in the 80-90% H_2SO_4 region, with the changeover occurring in 75-80% H_2SO_4.

All these data and results are consistent with an A_{Ac}-2 hydrolysis mechanism for methyl benzoate in 0 → ∿75% H_2SO_4, proceeding via an oxonium ion-like tetrahedral intermediate. As this species becomes increasingly unstable and the availability of water molecules much less (as indicated by the decreasing water activity), the hydrolysis undergoes a change in mechanism in 75-80% H_2SO_4. The ester then hydrolyses via an A_{Ac}-1 mechanism, characterised by a carbonium ion-like intermediate, the benzoylium cation, $\phi\text{-}C\overset{+}{=}O$.

B. METHYL PARA-TOLUATE AND METHYL ORTHO-TOLUATE

The rate profiles, Fig. 16 and 17, indicate that these two esters have quite different rate-acidity dependences. They are being discussed together, however, to compare the similarities and differences in behaviour resulting from placing a methyl group in different positions on the benzene ring. The fact that the position of the methyl group on the ring influences chemical reactivity differently is obvious from the pK_a's and pK_{SH^+}'s of benzoic, para-toluic and ortho-toluic acids as well as the pK'_{SH^+} values for their respective methyl esters.

FIGURE 16

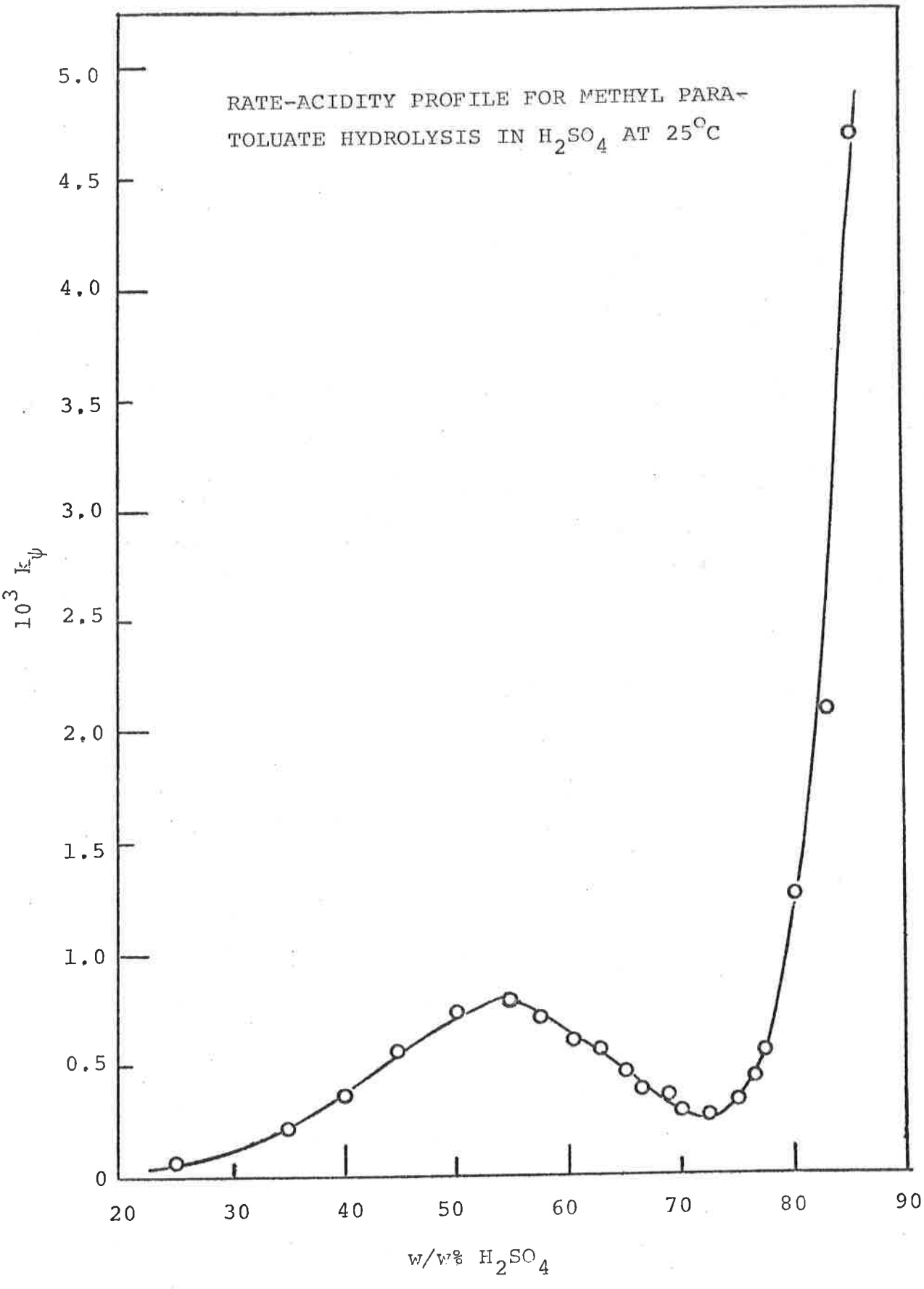
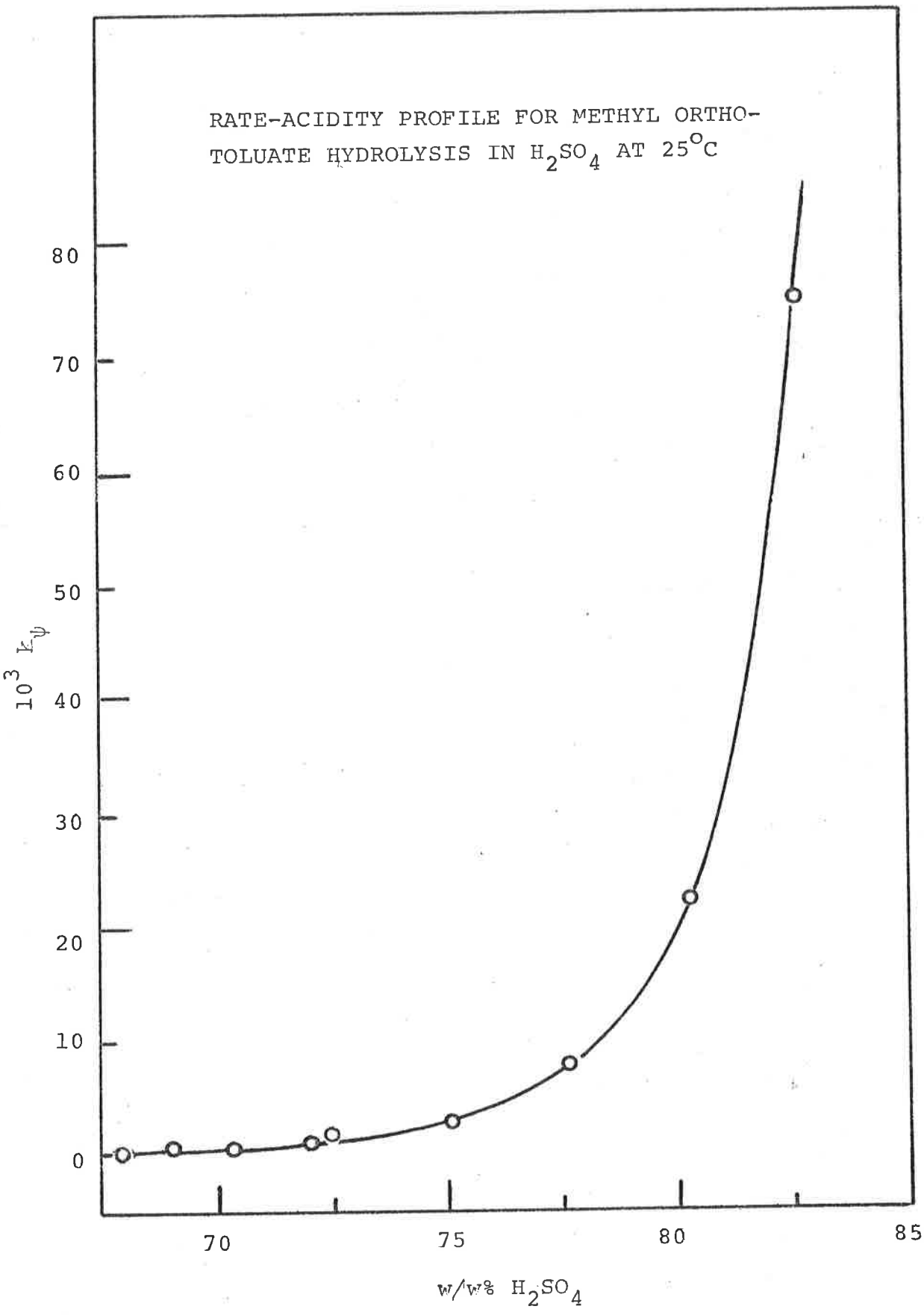

RATE-ACIDITY PROFILE FOR METHYL PARA-TOLUATE HYDROLYSIS IN H_2SO_4 AT 25°C
$10^3 k_\psi$
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
20
30
40
50
60
70
80
90
w/w% H_2SO_4

FIGURE 17


RATE-ACIDITY PROFILE FOR METHYL ORTHO-TOLUATE HYDROLYSIS IN H_2SO_4 AT 25°C
80
70
60
50
40
30
20
10
0
$10^3 k_\psi$
70
75
80
85
w/w% H_2SO_4

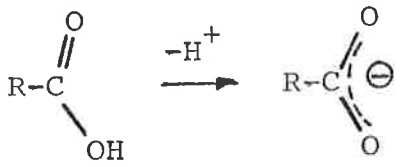
ACID	pK_a [a]	pK_{SH^+} [b]	pK'_{SH^+} [c]
BENZOIC ACID	4.21	-7.26	-8.15
PARA-TOLUIC ACID	4.37	-6.92	-7.60
ORTHO-TOLUIC ACID	3.91	-7.21	-7.95

[a] Reference 122a, p. 529.

[b] Reference 52,

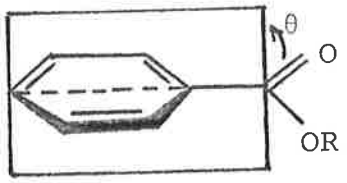
[c] This study; pK'_{SH^+} values for the methyl esters at 25°C.

The results all tend towards the same conclusion - that there are two opposing effects for the ortho-methyl substituent. One effect is an acid-weakening and base-strengthening factor due to the electronic nature of the methyl group. The other effect is a steric one as a result of the methyl group twisting the carboxylic acid or ester group out of the plane of the aromatic ring. This reduces the extent of conjugation with the ring, resulting in an acid-strengthening effect as the carboxylic acid gains some conjugative energy by proton loss,



If a plane of symmetry is considered drawn through the middle of the aromatic ring passing through the carboxylic group, and the angle subtended between the

carbonyl group and the plane is designated θ:



; R = H, CH_3

then for benzoic and para-toluic acids or their esters, θ ≃ 0^{o}. The carbonyl σ-bond is perpendicular to this plane and therefore the π-bond is parallel to it and in conjugation with the conjugated π-system of the benzene ring. The para-methyl group simply increases the displacement of electron density to the carbonyl centre, making it easier to protonate, and thus results in a less negative pK_{SH}^{+} value than for the parent benzoic acid or its methyl ester.

If the methyl group is in the ortho-position, however, the angle θ now becomes greater than 90^{o}. The π-bond of the carbonyl is no longer completely parallel with the conjugated π-system of the benzene ring. This causes the acid, or ester, to become more difficult to protonate than is the case of the para-isomer, since the electronic effect of the methyl group becomes reduced. The pK_{SH}^{+} results show that the electronic base-strengthening effect is still slightly greater than the steric base-weakening effect, resulting overall in a somewhat more positive pK_{SH}^{+} for the ortho-toluic acid than for the parent benzoic acid.

These two opposing effects were the reason for investigating the reactivity of the benzoate esters substituted in both the ortho and the para positions. In dilute acid the para-toluate exhibits enhanced spectral characteristics (longer λ_{max} and higher ε) over those for methyl benzoate and reacts somewhat slower than the parent ester. In concentrated acid, methyl para-toluate has greater reactivity than the unsubstituted benzoate. Methyl ortho-toluate has a lower ε_{max} value in its uv spectrum than either of the other two aromatic esters. In dilute acid, its hydrolysis rate is much slower and, in concentrated acid, much more rapid than that for the other two esters. The order of reaction rates is:

<60% H_2SO_4: MB > MPT > MOT

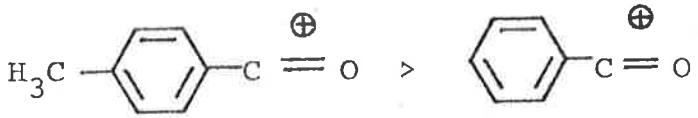
>70% H_2SO_4: MOT > MPT > MB.

(i) RATE PROFILES

Figures 16 and 17 show the rate-acidity dependences at 25°C for these two esters plotted with k_ψ (min^{-1}) as the ordinate. Fig. 10 (p. 147) shows the rate profiles for all four esters plotted using $6 + \log k_\psi$. Methyl para-toluate reacts at about the same rate as methyl benzoate until ~60% H_2SO_4 but then reacts more slowly until it changes mechanism at

about 73% H_2SO_4. It reaches a rate maximum at a slightly lower acidity than methyl benzoate, because of its more basic character. The ρ value of an A_{Ac}-2 reaction becomes more positive as the ester becomes protonated, as we have seen. Hence a slower rate of the para-toluate ester than for methyl benzoate is predicted for 60-75% H_2SO_4 and that is in fact what is observed.

In even higher acid concentration, the A_{Ac}-1 mechanism begins to take over from the A_{Ac}-2 reaction and does so earlier than is the case for methyl benzoate due to the greater internal stability of the resulting acylium ion,



Furthermore, methyl para-toluate hydrolyses more rapidly via the A_{Ac}-1 mechanism than the unsubstituted benzoate ester as a result of the electron-donating assistance of the para-methyl group.

The rate-acidity profile for methyl ortho-toluate hydrolysis, Fig. 17, exhibits quite different behaviour. It shows a shallow maximum (more easily seen in the log k_ψ plot of Fig. 9b) at ∿50% H_2SO_4. This must be considered an artifact since the data, Table 8b (p. 137) shows a rate maximum for this ester only at 25°, although this acid range shows only a shallow rise in the rate profiles at higher temperatures. The hydrolysis rates

for this ester were not easily measured at 25°C, due to their very long half-lives ($\tau_{1/2}$ at 40% ≃ 81 hr.). As a result, the rate profile for the ortho-toluate in the 40-65% H_2SO_4 region was constructed on the basis of activation parameters for the data obtained at higher temperatures. A consequence of this procedure was that a maximum was 'dictated' by the temperature dependence of the rates in this acid region. Thus it is not clear whether any physical significance can be attributed to this apparent maximum. Nonetheless, it will be shown that there is ample evidence that this ester is hydrolysing predominantly by an A_{Ac}-2 mechanism in <60% H_2SO_4.

In more concentrated acid (>65% H_2SO_4), the steric, rather than the electronic, effect of the ortho-methyl group plays the main role in determining the rate of the reaction. The water activity begins to significantly decrease and the bulk effect of the ortho-methyl makes it even more difficult for water to attack the protonated ester. Therefore, as the acid medium becomes more concentrated, the ease with which the acylium ion can form relative to the tetrahedral intermediate is greater, and the A_{Ac}-1 mechanism begins to take over, so that by ∿70% H_2SO_4, the rate of MOT hydrolysis is more rapid than that of either MPT or MB. The rate continues to increase more rapidly than that of the other two, because now the electronic and steric

effects of the ortho-methyl group are both working in the same direction instead of contrary to one another. That is, the inductive effect of the methyl helps stabilise the incipient acylium ion, and the release of steric strain also makes the A_{Ac}-1 reaction much more favourable than the A_{Ac}-2.

(ii) SPECTRAL BEHAVIOUR

The comparison of extinction coefficients in the ultraviolet spectra of variously-substituted benzoate esters provides a means for approximating the angle, θ, subtended between the ester group and the aromatic ring. Braude and coworkers[124] derived a relation between this angle and the ratio of the extinction coefficients of substituted and unsubstituted compounds, i.e.

$$\cos^2\theta = \frac{\varepsilon}{\varepsilon_o}$$

and applied it to the spectral changes observed in substituted benzaldehydes and acetophenones. ε is the extinction coefficient of a particular methyl-substituted derivative, and ε_o is the value of the unsubstituted compound. This latter value is augmented by the effect observed for a methyl group in the para-position (which is expected to exert only an electronic effect) multiplied by the number of methyl groups the substituted

compound has. The following table reveals the results they obtained for these two sets of compounds.

COMPOUND[a]	λ (nm)[b]	ε^b	ε_o	$\varepsilon/\varepsilon_o$	θ (°)
(1) Benzaldehyde	242	14000	14000	1.00	0
4-CH_3	251	15000	15000	1.00	0
2-CH_3	251	13000	15000	0.87	21.4
2,6-dimethyl	251	12500	16000	0.78	27.9
2,4,6-trimethyl	264	14500	17000	0.85	22.5
(2) Acetophenone	242	13000	13000	1.00	0
4-CH_3	252	15000	15000	1.00	0
2-CH_3	242	8500	15000	0.57	41.2
2,4-dimethyl	251	13000	17000	0.76	29.0
2,5-dimethyl	245	10000	17000	0.59	39.9
2,6-dimethyl	251	5500	17000	0.32	55.3
2,4,6-trimethyl	242	3500	19000	0.18	64.6

[a]Ref. 125.

[b]Spectra taken in hexane solution.

The results show the effect of the ortho-methyl groups in twisting the carbonyl function out of the plane of the ring (i.e. $\theta \neq 0^o$), and decreasing the effect of conjugation with the benzene π-system. The effects are, of course, greater with the acetophenones than with the benzaldehydes, since the steric strain will be more severe with the larger acetyl group.

Similar studies were made with different substituted benzoate esters in varying sulfuric acid

solutions to examine the effect of steric hindrance in this particular system. The results are as follows:

w/w% H_2SO_4	ESTER	λ (nm)	ε	ε_o	$\varepsilon/\varepsilon_o$	θ (°)
40.12	Methyl benzoate	231	11400	11400	1.00	0
	4-methyl	243	14000	14000	1.00	0
	2-methyl	233	8060	14000	0.58	40.7
	2,4-dimethyl	244	9760	16600	0.59	40.0
	2,6-dimethyl	235	2160	16600	0.13	68.9
70.83	Methyl benzoate	236	11900	11900	1.00	0
	4-methyl	247	14700	14700	1.00	0
	2-methyl	238	8940	14700	0.61	38.7
	2,4-dimethyl	249	11700	17400	0.67	34.8
	2,6-dimethyl	235	2540	17400	0.15	67.6
97.22	Methyl benzoate	262	17000	17000	1.00	0
	4-methyl	278	20000	20000	1.00	0
	2-methyl	266	15500	20000	0.77	28.4
	2,4-dimethyl	281	19600	23000	0.85	22.5
	2,6-dimethyl	269	5850	23000	0.25	59.7

These data clearly show that the main effect of methyl substitution is to alter the size of the extinction coefficient, with little effect on the position of λ_{max} in any given sulphuric acid solution. The results in 40.12% H_2SO_4, where the ester is essentially unprotonated, compare favourably with those for acetophenone in hexane.

SUBSTITUENT	θ_{ArCOCH_3}	$\theta_{ArCOOCH_3}$
2-methyl	41.2	40.7
2,4-dimethyl	29.0	40.0
2,6-dimethyl	55.3	68.9

The angles of twisting for the methyl benzoate system are expected to be somewhat larger than for the acetophenones, due to the presence of an additional oxygen atom in the side-chain function.

The other significant aspect of these results is the manner in which the angle θ varies with increasing acid strength. As the ester proceeds from the unprotonated state in 40% H_2SO_4 to the fully protonated form in 97% acid, the double-bond character of the carbonyl bond weakens as electron density is displaced towards the attached proton. This will tend to lengthen the bond and decrease the amount of steric interaction, hence the lower θ value. If the proton is on the ether oxygen, as must be the case for $A_{Ac}1$ hydrolysis to occur, the argument is even better.

The carbon-ether oxygen bond will also lengthen in preparation for heterolysis, allowing the carbonyl functional group to line up more favourably to interact with the conjugated π-system of the aromatic ring.

Once again, then, it becomes clear that the steric nature of the bulky methyl group in the ortho-position causes that ester to behave differently both physically and chemically from the para-methyl benzoate ester.

(iii) ACTIVATION PARAMETERS

The temperature dependence of the rates of hydrolysis for the two mono-methyl-substituted benzoates was investigated. The para-methyl ester was studied at 25°, 45°, 50.1°, 54.6°, 60.1°, 66.5°, 70° and 75°C at various acidities. The ortho-methyl ester was studied at 25°, 37°, 44.9°, 50.1°, 54.9°, 57.8°, 60.1°, 66.4°, 70°, 72.5° and 73.4°C. Arrhenius plots were constructed for each of the esters over a range of acidities and are shown in Table 14.

The results for methyl para-toluate are quite similar to those for methyl benzoate, although both the $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ are slightly less positive in the dilute acid range and more positive in the concentrated acid range than for the parent benzoate compound. The results for methyl ortho-toluate are strikingly different especially in the >60% H_2SO_4 region. The $\Delta H^{\ddagger}$ values increase earlier in the acid profile than for the other two esters, which partially explains the decreased reactivity of this ester, but the entropy of activation also starts becoming more positive simultaneously, indicating that the A_{Ac}-1 mechanism is taking over as soon as the stability of the resulting toluylium ion will allow. In fact, by 65% H_2SO_4, the activation parameters show that the A_{Ac}-1 mechanism is the main one

TABLE 14 ACTIVATION PARAMETERS FOR HYDROLYSIS OF METHYL PARA-TOLUATE AND METHYL ORTHO-TOLUATE IN SULPHURIC ACID

w/w% H_2SO_4	$\Delta H^{\ddagger}$ (kcal/mole)		$\Delta S^{\ddagger}$ (e.u.)	
	MPT	MOT	MPT	MOT
40.0	18.61	19.55	-20.0	-18.7
50.0	17.26	20.47	-23.1	-15.0
60.0	19.73	25.55	-15.1	+1.66
65.0	21.76	26.85	-8.95	+6.75
70.0	24.70	27.58	+0.01	+11.0
75.0	26.77	29.24	+7.22	+19.8
76.0	-	29.51	-	+21.5
77.5	26.99	-	+8.95	-
80.0	27.82	-	+13.0	-
85.0	29.85	-	+22.5	-

operating in the reaction scheme. Although this still gives a lesser rate of reaction than the A_{Ac}-2 mechanism does for the unhindered benzoates, the ortho-toluate quickly catches up so that by ∿70% H_2SO_4, it is reacting more rapidly than either of the other two esters, continuing to rise monotonically and more quickly in the concentrated acid range. This behaviour is very similar to that observed by McClelland[110f] for ortho-carboxy phenyl acetate relative to its para-isomer. The ortho-substituted acetate reacted only about 1/3 as fast as the para-acetate from 20-50% H_2SO_4, but started to increase rapidly beyond this point until it caught up at about 65% H_2SO_4 and by 72% acid, the ortho-isomer was reacting about 5 times as fast as the para isomer. The ortho-toluate reacts about 1/4 as fast as the para-toluate until 60% H_2SO_4, 1/2 as fast by 65%, twice as fast by 70% and ten times as fast by 76%. The effects are expected to be more pronounced for the benzoates than for the phenyl acetates, since the sterically hindering methyl group is closer to the reaction centre.

The activation parameters show a change from an A-2 reaction with a fairly negative entropy of activation to an A-1 reaction with a positive value for both methyl-substituted esters, the changeover coming at ∿70% for methyl para-toluate and at ∿60% for the methyl ortho-toluate.

(iv) "HYDRATION" TREATMENTS

(a) 'r' PLOTS

The rate data at 25° for these two mono-substituted esters was treated according to the 'r'-plot hypothesis in the same manner as for methyl benzoate. The data and plots are shown in Tables 15 and 16 and in Figs. 18 and 19. The m and pK_{SH}^+ parameters for each ester are those determined from the protonation behaviour studies as discussed earlier. The H_o and a_{H_2O} values were taken from the same references as those for methyl benzoate hydrolysis.

The plots give good straight lines in both the dilute and concentrated acid ranges with the change-over in mechanism occurring at different acid strengths, depending on the particular substrate.

The results in the concentrated acid region are as expected for an $A_{Ac}1$ mechanism. That is, the 'r' value for methyl para-toluate is slightly more negative than that for methyl benzoate (-0.474 and -0.435 respectively), with the ortho-toluate having an even more negative 'r' value = -0.678. These results are in agreement with the understanding that there is less chance for solvent stabilisation in the concentrated acid medium and that the resulting acylium is forced to rely

TABLE 15: DATA FOR THE 'r' PLOT FOR HYDROLYSIS OF METHYL PARA-TOLUATE IN SULPHURIC ACID AT 25°C

w/w% H_2SO_4	log $k_2{}^a$	-log a_{H_2O}
20.0	0.708	0.056
25.0	0.671	0.084
30.0	0.651	0.124
35.0	0.630	0.178
40.0	0.561	0.247
45.0	0.423	0.338
50.0	0.182	0.455
52.5	0.012	0.527
55.0	-0.204	0.605
57.5	-0.478	0.690
60.0	-0.767	0.788
62.5	-1.014	0.902
65.0	-1.327	1.02
66.03	-1.503	1.08
67.5	-1.699	1.17
68.93	-1.867	1.27
70.0	-2.073	1.35
72.5	-2.411	1.55
75.0	-2.584	1.75
76.53	-2.624	1.90
80.0	-2.564	2.27
82.5	-2.429	2.58
85.0	-2.242	2.93
85.58	-2.205	3.01
88.59	-2.018	3.44

$$^a\log k_2 = \log k_\psi - \log \frac{h_o^{\,m}}{h_o^{\,m} + K'_{SH^+}{}^m}; \quad m = 0.787,$$

$pK'_{SH^+} = -7.61$

w/w% H_2SO_4	SLOPE	INTERCEPT	CORR. COEFFT.	MECHANISM
45.0-70.0	2.539	1.298	0.9985	A_{Ac}-2
80.0-88.59	-0.474	-3.641	-0.9990	A_{Ac}-1

TABLE 16: DATA FOR THE 'r' PLOT FOR THE HYDROLYSIS OF METHYL ORTHO-TOLUATE IN SULPHURIC ACID AT 25°C

w/w% H_2SO_4	log k_2^a	-log a_{H_2O}
24.0	2.131	0.078
28.0	1.929	0.106
32.0	1.719	0.143
36.0	1.546	0.191
40.0	1.371	0.247
44.0	1.138	0.318
48.0	0.834	0.399
52.0	0.450	0.512
56.0	0.008	0.637
60.0	-0.506	0.788
64.0	-0.771	0.975
65.03	-0.721	1.03
67.39	-0.983	1.16
68.0	-1.071	1.21
70.29	-1.186	1.37
72.0	-1.191	1.51
72.88	-1.088	1.58
75.09	-1.183	1.76
76.0	-1.153	1.85
77.61	-1.118	2.00
80.0	-1.019	2.27
80.28	-1.005	2.31
82.68	-0.723	2.63
85.16	-0.434	2.95
87.67	-0.244	3.30

$$^a\log k_2 = \log k_\psi - \log \frac{h_o^m}{h_o^m + K'^m_{SH^+}}; \quad m = 0.962,$$

$$pK'_{SH^+} = -7.94$$

w/w% H_2SO_4	SLOPE	INTERCEPT	CORR. COEFFT.	MECHANISM
32.0-60.0	3.459	2.219	0.9999	A_{Ac}-2
76.0-87.67	-0.678	-2.489	-0.986	A_{Ac}-1

FIGURE 18

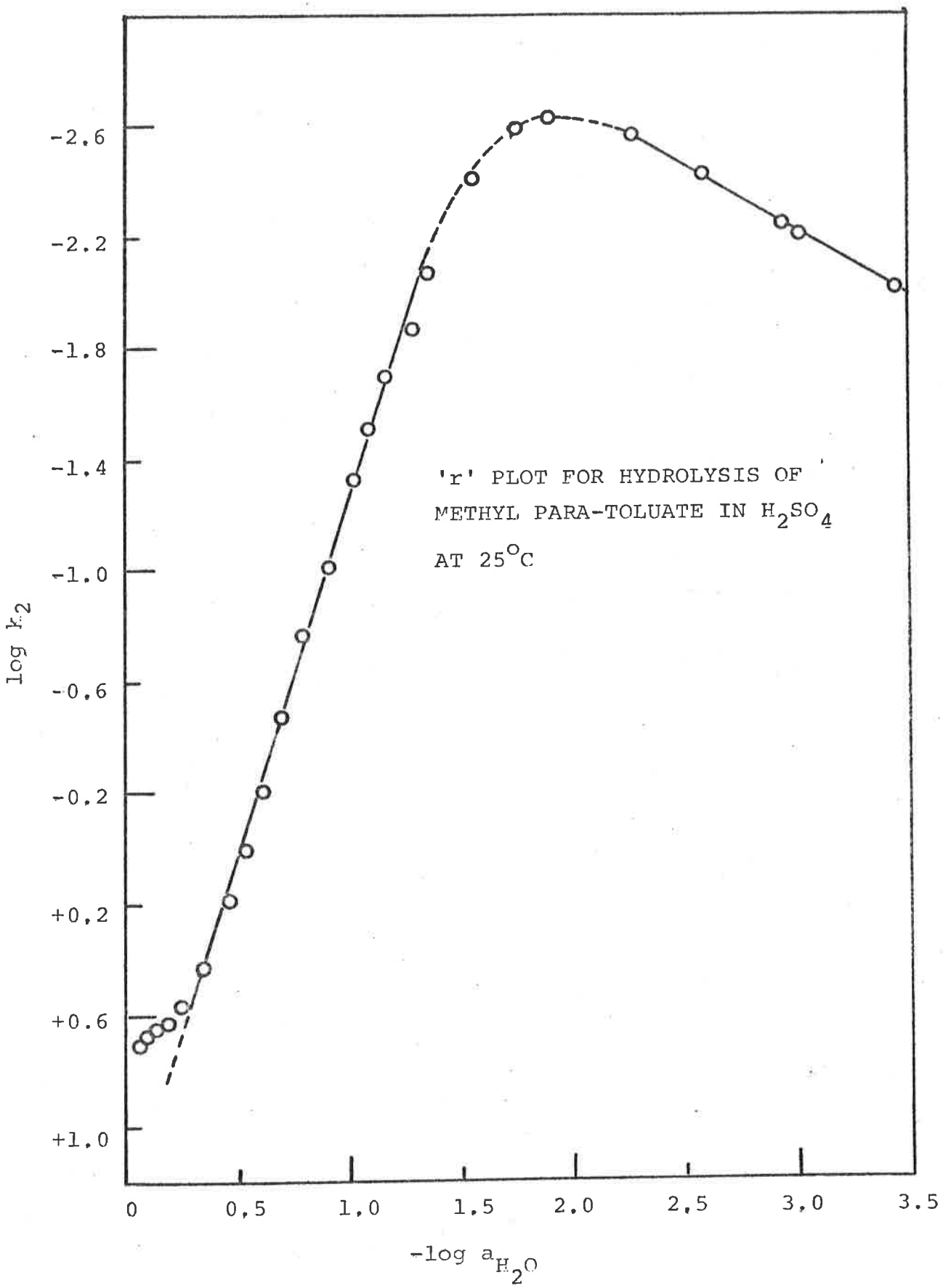
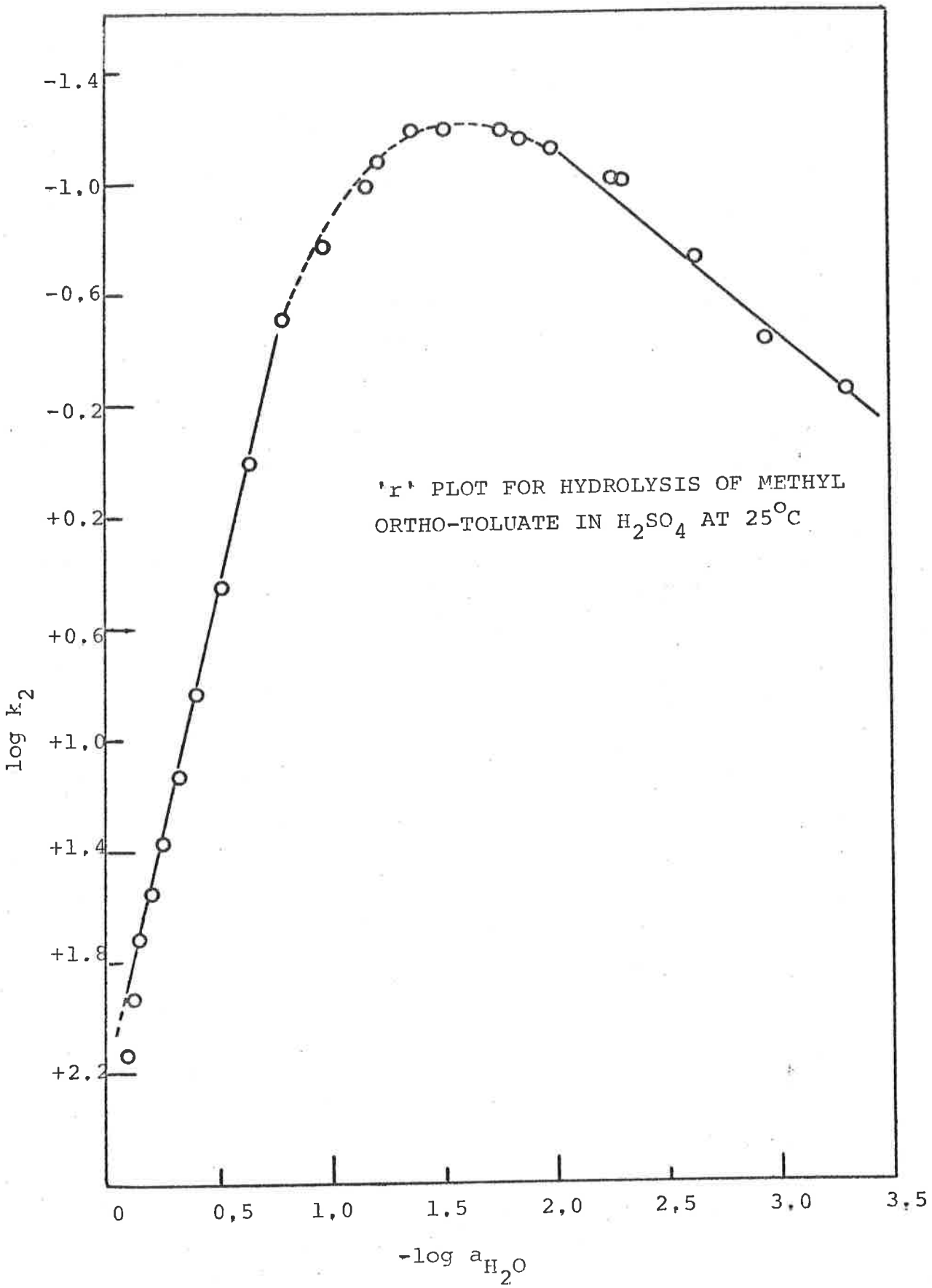

'r' PLOT FOR HYDROLYSIS OF METHYL PARA-TOLUATE IN H_2SO_4 AT 25°C
log k_2
-2.6
-2.2
-1.8
-1.4
-1.0
-0.6
-0.2
+0.2
+0.6
+1.0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
-log a_{H_2O}

FIGURE 19


'r' PLOT FOR HYDROLYSIS OF METHYL ORTHO-TOLUATE IN H_2SO_4 AT 25°C
log k_2
-1.4
-1.0
-0.6
-0.2
+0.2
+0.6
+1.0
+1.4
+1.8
+2.2
0
0,5
1,0
1.5
2,0
2,5
3,0
3,5
-log a_{H_2O}

on internal stabilisation. Also, the relief of steric strain is a strongly accelerating factor for the ortho-toluate and contributes to a greater negative dependence on the water activity.

The main reason, however, for the negative 'r' values is the change in solvation requirements in going from the protonated ester to the transition state. Methyl benzoate has already been shown to have a lower solvation need than the primary alkyl acetates due to its internal stabilisation of the benzoylium cation. With the addition of an electron-donating group, such as methyl, in the para position, the need for solvent stabilisation decreases even slightly further. When the methyl group is in the ortho-position, both the need and the opportunity of solvent water molecules approaching the acylium ion centre is decreased substantially, due to the steric crowding of the methyl group so close to the reaction centre, and this is reflected in the more negative 'r' value for the ortho-toluate relative to that for the para-toluate.

The results in the dilute acid region are somewhat more uncertain however. The value of 'r' for the para-toluate is +2,54 and for the ortho-toluate, +3.46. The largest value previously reported was +3.3 for the hydrolysis of benzamide.[33,126] One possible explanation for these anomalous results is that an additional water molecule is necessary to help stabilise the protonated

carbonyl in addition to the other waters acting as the nucleophile and the proton-transfer agent. But it is difficult to see why this should be so when an ortho-methyl group is acting, if anything, to prevent the approach of water molecules. The $\Delta S^{\ddagger}$ values, which are less negative, agree with this idea and predict a lower, not a higher, 'r' value. The less negative $\Delta S^{\ddagger}$ and the less positive 'r' values would both reflect the greater resistance to an A_{Ac}-2 hydrolysis mechanism for methyl ortho-toluate relative to the situation for an unhindered benzoate ester.

Nevertheless, it is clear that water molecules are involved in the rate-determining step in the dilute acid region for both the para- and ortho-toluates, and that a mechanistic change is occurring in the concentrated acid region to an A_{Ac}-1 reaction. The changeover occurs at ~74% H_2SO_4 for the para-toluate and at ~67% H_2SO_4 for the ortho-toluate, in good agreement with the conclusions derived from the rate profiles and the activation parameters. The para-toluate will change mechanism earlier than methyl benzoate due to the somewhat greater stability of the para-toluylium ion. The ortho-toluate changes even earlier because of the added steric hindrance to solvent stabilisation of the resulting acylium ion.

(b) TRANSITION-STATE ACTIVITY COEFFICIENTS

The log $f_{\ddagger}^{*}$ treatment was applied to these two esters in the same manner as that for methyl benzoate, with the exception that it was necessary to determine values for the activity coefficient of the neutral substrates, log f_S, since data for these two esters was previously unavailable. Ortho-toluamide had earlier[127] exhibited behaviour anomalous to that of benzamide itself. It was therefore felt advisable to see if the same were true for the toluate esters. The activity coefficients of the neutral esters - methyl para- and ortho-toluate and methyl 2,6-dimethyl benzoate - are given in Table 17 and Fig. 20. For the purpose of determining transition state activity coefficients at the same acidity values for the various esters, the data in Fig. 20 were interpolated to give log f_S values at common integral values of w/w% H_2SO_4. These data are shown in Table 18, together with those previously obtained for methyl benzoate and methyl mesitoate.

The behaviour of these esters appears to be normal, in that they exhibit an initial salting-out effect in the 0-30% H_2SO_4 range, followed by a pronounced salting-in in the more concentrated sulphuric acid media. There are two puzzling features about this activity coefficient behaviour, however. One is that

TABLE 17: log f_s VALUES FOR BENZOATE ESTERS IN H_2SO_4 AT 25°C

w/w% H_2SO_4	MPT	MOT	2,6-MDMB
10.02	0.12	-0.07	0.06
20.23	0.15	0.00	0.12
30.20	0.20	+0.03	0.18
40.94	0.16	+0.03	0.23
51.07	0.02	-0.04	0.16
60.44	-0.25	-0.19	0.04
68.92	-0.65	-0.50	-0.07

FIGURE 20

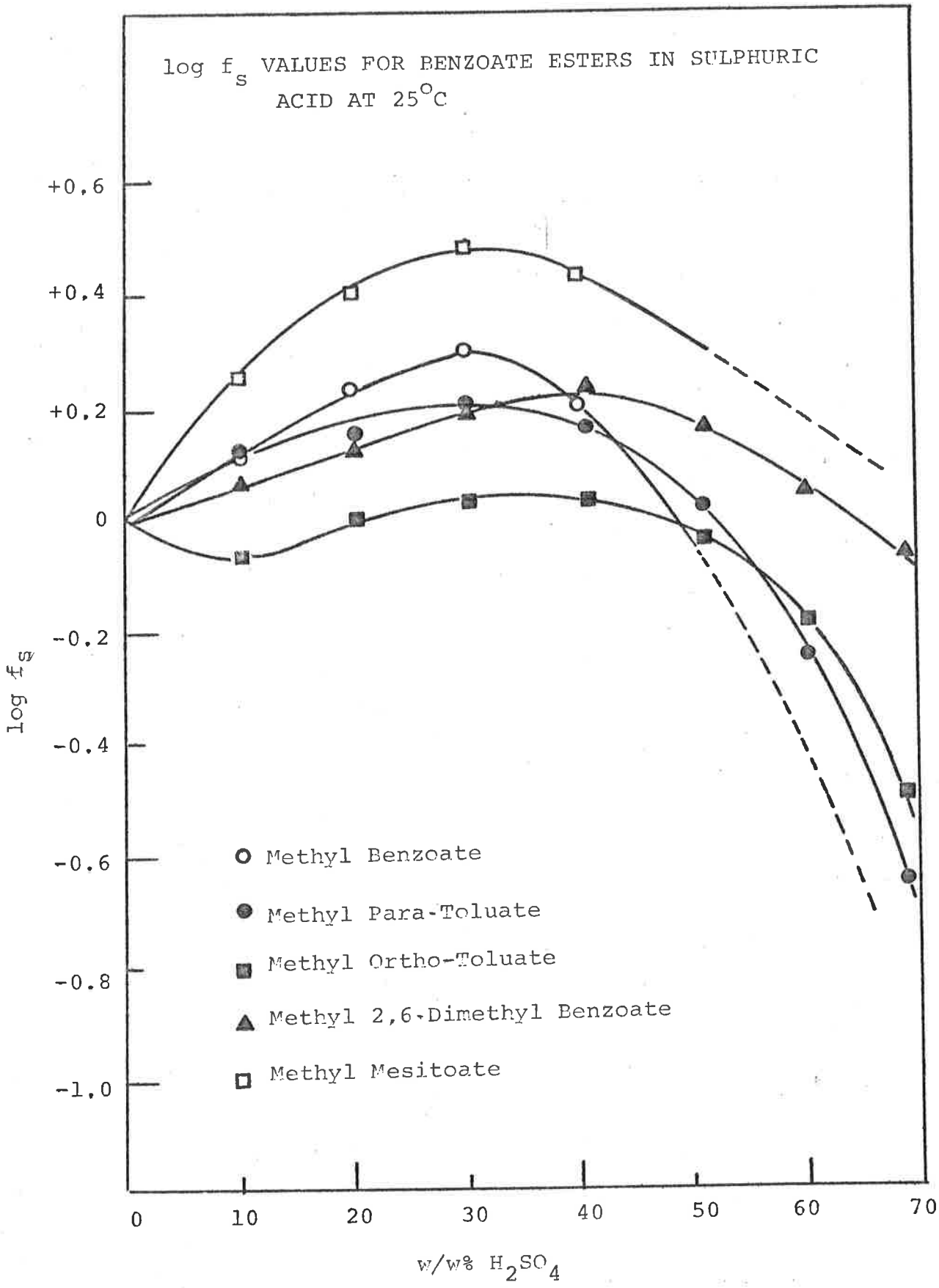

log f_s VALUES FOR BENZOATE ESTERS IN SULPHURIC ACID AT 25°C
+0.6
+0.4
+0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
log f_s
Methyl Benzoate
Methyl Para-Toluate
Methyl Ortho-Toluate
Methyl 2,6-Dimethyl Benzoate
Methyl Mesitoate
0
10
20
30
40
50
60
70
w/w% H_2SO_4

TABLE 18: log f_s VALUES FOR BENZOATE ESTERS IN H_2SO_4 AT 25°C

w/w% H_2SO_4	MB	MPT	MOT	MDMB	MM[b]
10	0.11	0.09	-0.07	0.06	0.25
20	0.23	0.17	0,0	0.13	0,40
30	0,30	0,20	+0.03	0.19	0.48
40	0,20	0,16	+0.03	0,22	0,43
50	-0,05[a]	0.04	-0.03	0.17	0.32[a]
55	-0.22[a]	-0.07	-0.09	0.11	0.25[a]
60	-0.43[a]	-0.24	-0.19	0.05	0.18[a]
65	-0.68[a]	-0.46	-0.34	-0,02	0.12[a]
70	-0.97[a]	-0.71	-0.55	-0,08	0.05[a]
75	-1.29[a]	-0.98[a]	-0,79[a]	-0.15[a]	
80	-1,61[a]	-1.30[a]	-1.05[a]	-0.21[a]	
85	-1,91[a]	-1.61[a]	-1.33[a]	-0.27[a]	
90	-2.23[a]	-1,91[a]	-1.61[a]	-0.35[a]	

[a]Extrapolated

[b]log f_s at 90°C

methyl ortho-toluate exhibits a small but significant salting-in effect in the 0-10% H_2SO_4 region, followed by the usual salting-out normally observed. The measurements from 0 and 10% H_2SO_4 were repeated several times with reproducible results, so it seems clear that this unusual behaviour is real. Nevertheless, as the contribution of the neutral activity coefficient to the values for log $f_{\ddagger}^*$ is small, this anomaly did not affect the interpretation of the transition state activity coefficient behaviour for this ester in the very dilute acidity region.

The second observation to be made about these values of log f_s is that although they salt-out and salt-in in the order expected on the basis of their relative molar volumes, they do not give values intermediate between those of methyl benzoate and methyl mesitoate as might be expected. This is the case for the dilute salting-out acid region. However the expected order is observed at >50-60% H_2SO_4. The discrepancy may arise from the fact that Bunton et al.[95] did not report any of their numerical data but merely presented graphical results. However, as the activity coefficients, f_s, of methyl benzoate and mesitoate were not determined in the course of the present study, the values of f_s were used as published. Any variation in the values would merely shift the log $f_{\ddagger}^*$-acidity plot up or down the necessary amount and would not significantly alter the overall value of log $f_{\ddagger}^*$. Nor would it affect the manner

in which $f_{\ddagger}^*$ changes its behaviour as the acidity is increased. A problem in interpretation would arise only in comparing log $f_{\ddagger}^*$ for the different esters.

The transition state activity coefficients for the hydrolysis in H_2SO_4 at 25°C of methyl para- and ortho-toluate were calculated according to equation (26) (p. 37) and are shown in Tables 19 and 20 and Figs. 21 and 22. These esters exhibit behaviour very similar to that for methyl benzoate. There is an initial strong salting-out of the transition state species up to ∿75% for the para-toluate and to ∿65% for the ortho-isomer. This is followed in turn by a lower degree of salting-out for methyl para-toluate and a relatively flat region for methyl ortho-toluate. Furthermore, since the pseudo-first order rate constant is inversely related to $f_{\ddagger}^*$, the greater the value of log $f_{\ddagger}^*$ the slower is the expected observed rate constant. From the rate profiles for these esters at 25°C (cf. Fig. 10), the order of rate constant is: <∿60%: MB ∿ MPT > MOT > MDMB

>∿75%: MDMB > MOT > MPT > MB,

with the 60-75% acid region exhibiting a variety of orders, where the mechanisms of the various esters are changing from A_{Ac}-2 to A_{Ac}-1 at different acidity values. Given that there are differences between the values for the other parameters for the two esters in

$$k_{\psi} = \frac{k_o}{K_{SH^+}} \cdot \frac{f_S a^*_{H^+}}{f_{\ddagger}^*}$$

TABLE 19: log $f_{\ddagger}^{*}$ VALUES FOR MPT HYDROLYSIS IN H_2SO_4 AT 25°C

w/w% H_2SO_4	log k_2	$-H_o$	log f_s	log $a^*_{H^+}$	log $f_{\ddagger}^{*}/k_o$	log $f_{\ddagger}^{*}$
0	1.298	-	-	-	(-0.77)	0.0
10	0.740	0.38	0.09	0.43	-0.52	0.25
20	0.708	1.03	0.17	1.55	+0.20	0.97
30	0.651	1.78	0.20	2.84	+0.99	1.76
40	0.561	2.52	0.16	4.34	+1.96	2.73
50	0.182	3.40	0.04	6.13	+3.31	4.08
55	-0.204	3.93	-0.07	7.07	+4.11	4.88
60	-0.767	4.52	-0.24	8.05	+5.02	5.79
65	-1.327	5.07	-0.46	9.05	+5.93	6.70
70	-2.073	5.78	-0.71	10.08	+6.89	7.66
75	-2.584	6.56	-0.98	11.30	+7.74	8.51
80	-2.564	7.34	-1.30	12.52	+8.01	8.78
85	-2.242	8.11	-1.61	13.94	+8.19	8.96
90	-1.920	8.92	-1.91	15.56	+8.55	9.32

$$\log f_{\ddagger}^{*}/k_o = -\log k_2 + mH_o + \log f_s + \log a^*_{H+};\ m = 0.787$$

TABLE 20: $\log f_{\ddagger}^*$ VALUES FOR MOT HYDROLYSIS IN H_2SO_4 AT 25°C

w/w% H_2SO_4	$\log k_2$	$-H_o$	$\log f_s$	$\log a^*_{H^+}$	$\log f_{\ddagger}^*/k_o$	$\log f_{\ddagger}^*$
0	2.219	-	-	-	(-2.50)	0.0
10	2.136	0.38	-0.07	0.43	-2.14	0.36
20	2.025	1.03	0.0	1.55	-1.47	1.03
30	1.790	1.78	+0.03	2.84	-0.63	1.87
40	1.371	2.52	+0.03	4.34	+0.57	3.07
50	0.645	3.40	-0.03	6.13	+2.18	4.68
55	0.126	3.93	-0.09	7.07	+3.07	5.57
60	-0.506	4.52	-0.19	8.05	+4.02	6.52
65	-0.818	5.07	-0.34	9.05	+4.65	7.15
70	-1.143	5.78	-0.55	10.08	+5.11	7.61
75	-1.195	6.56	-0.79	11.30	+5.39	7.89
80	-1.019	7.34	-1.05	12.52	+5.43	7.93
85	-0.521	8.11	-1.33	13.94	+5.33	7.83
90	-0.028	8.92	-1.61	15.56	+5.40	7.90

$\log f_{\ddagger}^*/k_o = -\log k_2 + mH_o + \log f_s + \log a^*_{H^+}$; m = 0,962

FIGURE 21

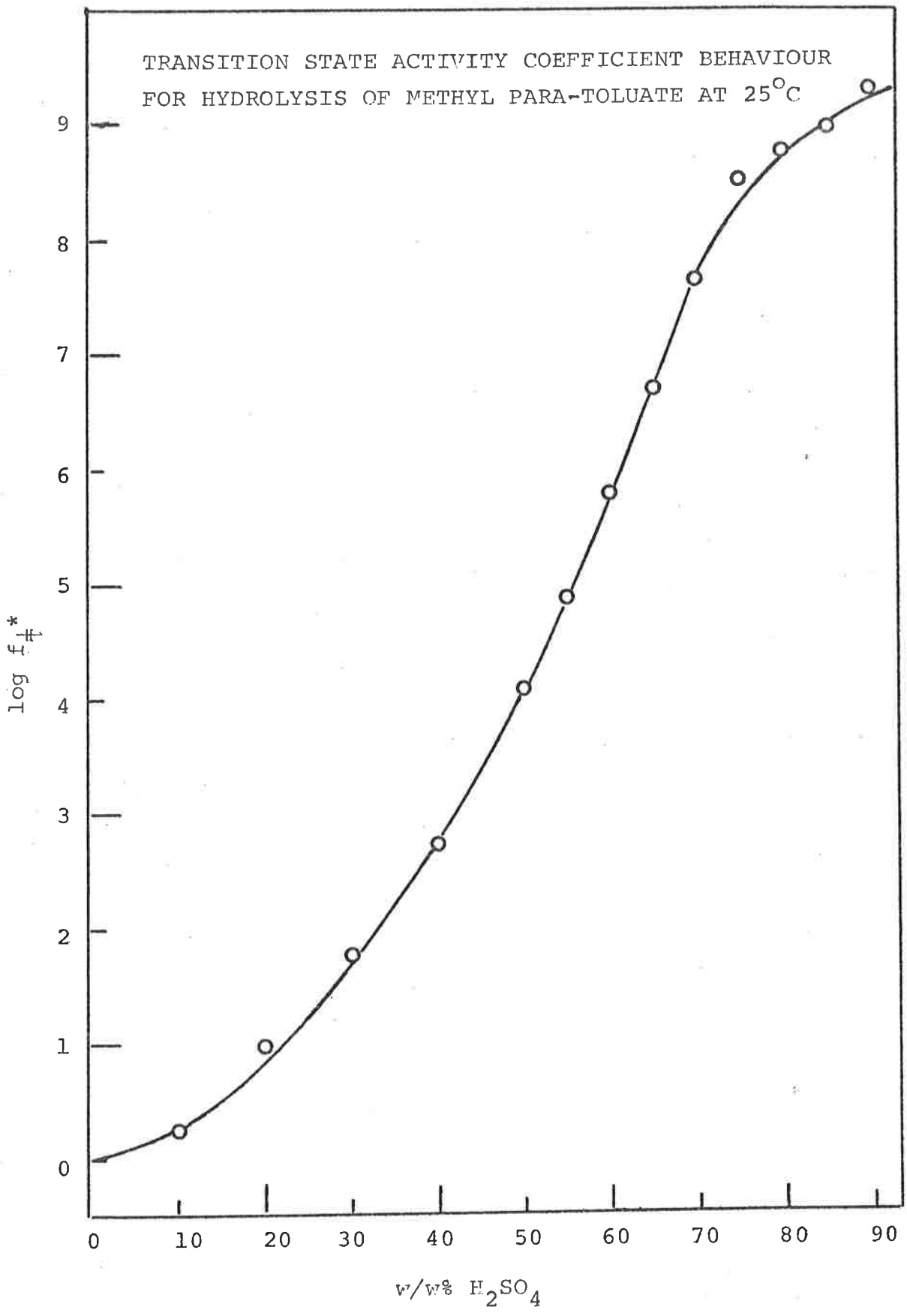
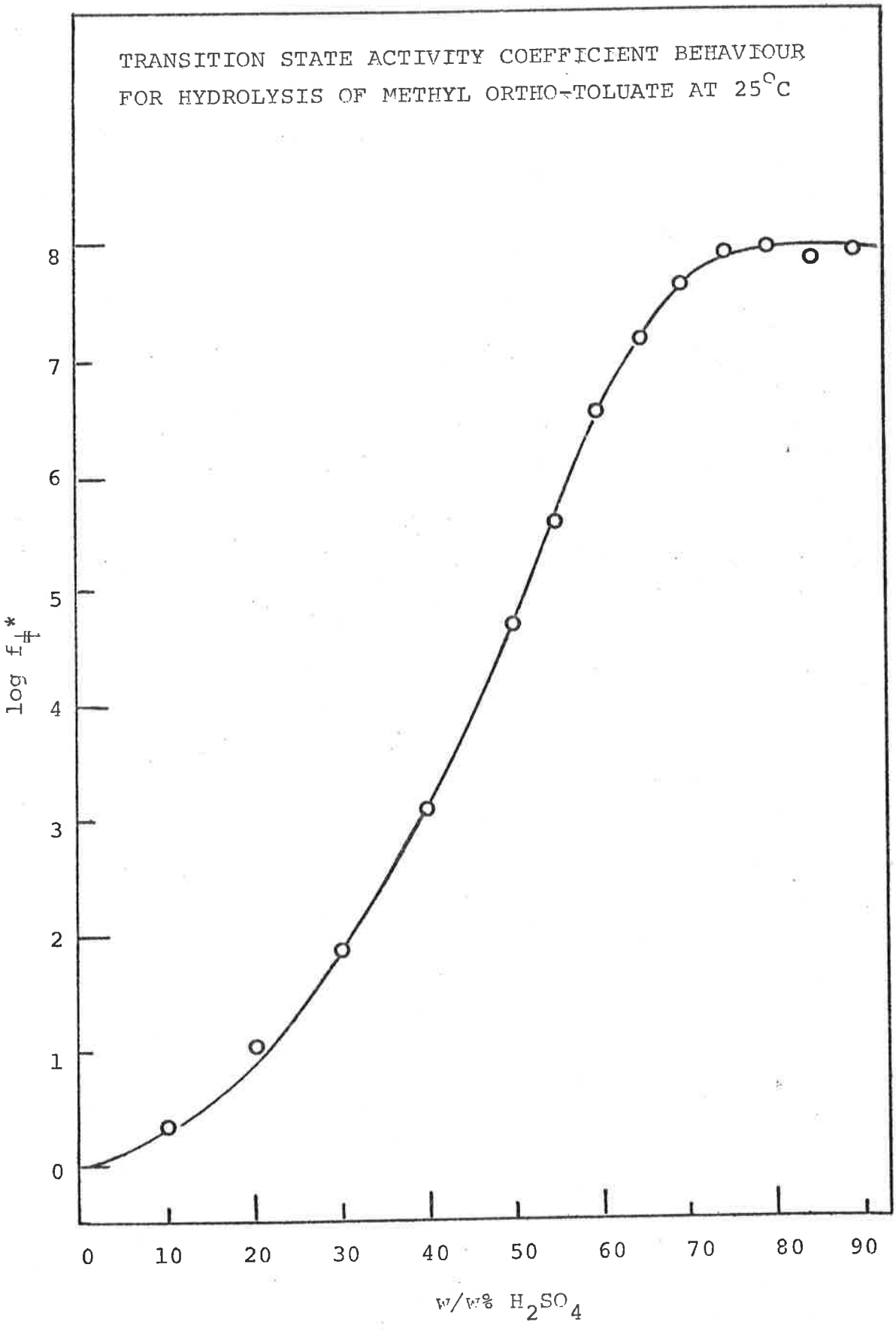

TRANSITION STATE ACTIVITY COEFFICIENT BEHAVIOUR
FOR HYDROLYSIS OF METHYL PARA-TOLUATE AT 25°C
log f‡*
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
w/w% H2SO4

FIGURE 22


TRANSITION STATE ACTIVITY COEFFICIENT BEHAVIOUR
FOR HYDROLYSIS OF METHYL ORTHO-TOLUATE AT 25°C
log $f_{\ddagger}^{*}$
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
90
w/w% H_2SO_4

nevertheless, for these two esters $f_{\ddagger}^*$ for MPT is less than that for MOT in the A-2 region, but the order is reversed at >70% H_2SO_4. At higher acidities, the A-1 mechanism takes over and produces an acylium ion in the ortho-toluate hydrolysis which is considerably more stable than that from the para-toluate, hence the faster rates and lower $f_{\ddagger}^*$ values for the ortho-toluate.

The region where the mechanism changes according to this treatment is in good agreement with the results obtained by the 'r' hydration approach. For methyl para-toluate, this comes at ∿70-75% H_2SO_4 and for methyl ortho-toluate, at 65-70% H_2SO_4.

SUMMARY: CONCLUSIONS CONCERNING THE MECHANISM OF HYDROLYSIS OF METHYL PARA-TOLUATE AND METHYL ORTHO-TOLUATE IN SULPHURIC ACID

All the evidence for these two esters points to an A_{Ac}-2 reaction proceeding in dilute sulfuric acid, followed by a change to an A_{Ac}-1 mechanism in the concentrated acid range.

The rate profiles show a maximum at 55% H_2SO_4 for the para-isomer and at 50% H_2SO_4 for the ortho-toluate. The rates then decrease to a minimum at ∿73% H_2SO_4 and at ∿60% H_2SO_4 for the two esters respectively, followed by a rapid increase in rates in the concentrated acid region, consistent with an A_{Ac}-1 mechanistic

assignment. The ortho-toluate hydrolyses more slowly in the dilute acid region than the para-toluate, consistent with, but not necessarily proving, an A_{Ac}-2 mechanism in this region for the ortho-toluate. But its rate rapidly approaches that of the para-toluate in the 60-70% acid range, and it hydrolyses much more rapidly than MPT at acid strengths greater than 70 w/w%. This behaviour agrees with what is expected on the basis of steric effects for the A_{Ac}-1 mechanism for these two esters.

The activation parameters are divided into two regions for both esters. For methyl para-toluate, $\Delta H^{\ddagger} \simeq$ 19 kcal/mole in <65% H_2SO_4 and ∿27-28 kcal/mole for the 75-85% H_2SO_4 range. Correspondingly, $\Delta S^{\ddagger} \simeq$ -15 → -20 e.u. at <65% and +7 → +22 e.u. in 75-85% H_2SO_4. These values agree well with an A-2 mechanism in dilute acid, followed by a changeover in the 65-75% acid range to an A-1 mechanism at even higher acidities.

The behaviour of methyl ortho-toluate is somewhat different, but here too the activation parameters can be grouped into two categories. At less than 50% H_2SO_4, $\Delta H^{\ddagger} \simeq$ 20 kcal/mole and at >60% H_2SO_4, $\Delta H^{\ddagger} \simeq$ 26-29 kcal/mole. The former value is slightly higher than that for the para-toluate in agreement with the greater difficulty in hydrolysing the ortho-substituted benzoate by an A_{Ac}-2 mechanism. The $\Delta S^{\ddagger}$ values in acid <50 w/w% are ∿-15 → -20 e.u. and in the 60-80% H_2SO_4 range, 0 → +22

e.u. The latter are also higher in any given acid than for methyl para-toluate. This is indicative, for the ortho-isomer, of the less constrained A_{Ac}-1 activated complex, the lesser degree of hydration and the consequent greater rate of hydrolysis in this acid region, relative to the para-toluate.

The 'r' plots provide additional evidence that the reactions are undergoing a change of mechanism between the two parts of the acidity range. The values for 'r' for both toluates are higher than expected in the dilute acid region - +2.54 for the para-toluate and +3.46 for the ortho-toluate. Nevertheless these plots are linear over a significant range of acidity, indicating that the behaviour is real. The 'r' values in concentrated acid are more readily understood, being -0.474 and -0.678 for the para- and ortho-isomers respectively. The degree of solvation is less for the ortho-toluate, hence its more negative value. The 'r' plots cross at 74% H_2SO_4 for methyl para-toluate and at 67% H_2SO_4 for methyl ortho-toluate.

The para-substituted ester is very similar in its 'r' plot behaviour to that for methyl benzoate. The changeover in mechanism occurs earlier due to the greater stability of the para-toluyl cation. The ortho-toluate is also exhibiting this type of behaviour, having a definite region in which it is undergoing A-2 hydrolysis and another in which it hydrolyses via the A_{Ac}-1

mechanism. But the 'r' values are more positive in the dilute acid region and more negative in concentrated H_2SO_4, due to its different solvation requirements. than is the case for methyl benzoate.

Finally, the transition state activity coefficient calculations give results in agreement with the other evidence cited. The plot of this parameter for both esters show that there is a wide acidity range for which the transition state is increasingly salted-out. As the acidity of the medium is further increased, however, the oxonium ion-like tetrahedral intermediate gives way to the para- or ortho-toluyl cations, the transition state species for the A_{Ac}-1 reactions. The acidity range in which the mechanism changes, 70-75% H_2SO_4 and 65-70% H_2SO_4 for MPT and MOT respectively, supports the results of the 'r' hydration treatment. Moreover, it is possible to give a physical interpretation to the $f_{\ddagger}^*$ values for these esters where it was difficult to do so for the 'r' values obtained. It is evident from the activity coefficient treatment that the toluate esters are more salted out than methyl benzoate, at least in the 50-70% H_2SO_4 region, and therefore require greater solvent stabilisation. At greater than 75% H_2SO_4, where the A_{Ac}-1 mechanism is taking over, the order is reversed,

$$f_{\ddagger}^*(MB) > f_{\ddagger}^*(MPT) > f_{\ddagger}^*(MOT)$$

This is easily explained on the grounds of greater stability of the acylium ions relative to their respective tetrahedral intermediates in the same order, and is further corroborated by the order of the rate constants in concentrated sulphuric acid media.

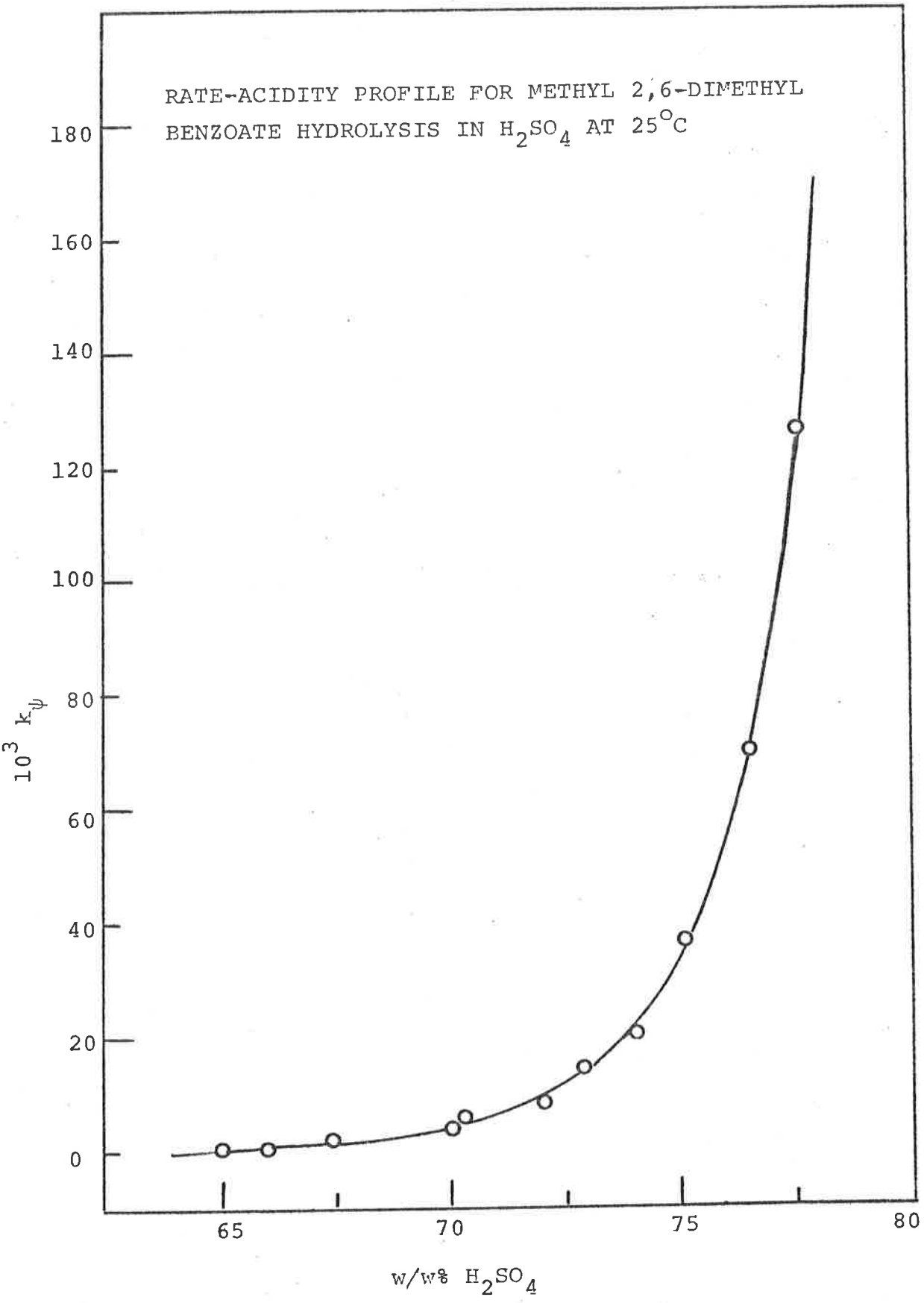
C. METHYL 2,6-DIMETHYL BENZOATE

The situation for this ester is not as clear as for the other three. None of the results obtained provide conclusive evidence for an $A_{Ac}2$ mechanism in dilute acid, although all of it indicates that the ester is hydrolysing via an $A_{Ac}1$ pathway in >60% H_2SO_4.

(i) RATE PROFILES

The rate-acidity data are given in Table 8d (p. 143) and Fig. 9d (p.145) at various temperatures, and at 25°C in comparison with the other esters in Fig. 10 (p.147). The rate data for hydrolysis at 25°C are plotted in Fig. 23, using k_ψ as ordinate. The rate profiles are monotonic throughout the entire acid range studied, having extremely slow rates in the dilute H_2SO_4 region ($\tau_{1/2}$ at 40% ≃ 6 months) and rising very rapidly in the moderately concentrated acid range, so that by 80% H_2SO_4, $\tau_{1/2}$ ≃ 80 sec., making further rate

FIGURE 23


RATE-ACIDITY PROFILE FOR METHYL 2,6-DIMETHYL BENZOATE HYDROLYSIS IN H_2SO_4 AT 25°C
180
160
140
120
100
80
60
40
20
0
$10^3 k_\psi$
65
70
75
80
w/w% H_2SO_4

measurements very difficult, if not, in fact, impossible. The rate data at the dilute end of the acid range represent the upper limit, since the rate constants at 25°C were determined via the activation parameter treatment, using only two or three temperatures in the 50-75°C range. It is difficult to estimate anything more than a good approximation of the rates at 25°C by this means, but if anything, the rates are probably somewhat less than those calculated. In any case, the steric effect of the two ortho methyl groups far outweighs their electronic effect, giving rise initially to very slow rates of hydrolysis.

This is further corroborated by both the pK_a and pK'_{SH^+} data for 2,6-dimethyl benzoic acid and its methyl ester respectively, and by the angle of twisting, θ, for this ester as discussed in the previous section.

ESTER	pK_a [a]	pK'_{SH^+} [b]	θ (°) [c]
Methyl Benzoate	4.21	-8.15	0
Methyl p-Toluate	4.37	-7.60	0
Methyl 2,6-Dimethyl Benzoate	3.25	-8.09	68.9

[a] Values given for the carboxylic acid.

[b] Values given for the methyl esters.

[c] Values given at 40.1% H_2SO_4.

Methyl substitution in the para-position results in an acid-weakening and base-strengthening effect, as

well as no significant angle of distortion of the carboxylic acid group from the plane of the ring. On the other hand, methyl substitution in both ortho positions gives the opposite effects, together with considerable twisting of the methyl ester out of the plane of the ring. It is therefore the steric effect of the ortho methyls which is the main factor in explaining the very slow rates of hydrolysis in dilute acid solution.

The A_{Ac}-1 mechanism for the hydrolysis of this ester may be operating even in dilute acid; this is known to be the hydrolysis mechanism of methyl mesitoate in 20-70% H_2SO_4, although the acylium ion formed in the latter case is stabilised by the additional para methyl group. The fact that a rate maximum, a common feature of the A_{Ac}-2 reaction, is not observed in the rate-acidity profile for this ester supports the view that the A_{Ac}-1 mechanism is becoming the major one before such a maximum is reached. This type of behaviour is observed for the rate profiles for phenyl and vinyl acetates which, while exhibiting no rate maxima, have been shown to have both A-2 and A-1 components. It would appear that similar behaviour is occurring here.

(ii) ACTIVATION PARAMETERS

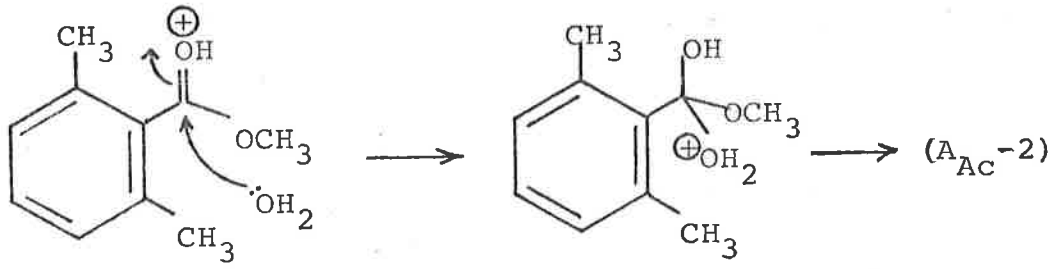
The rates of methyl 2,6-dimethyl benzoate hydrolysis were measured in different acidities at 25°, 37°, 45°, 50.1°, 60.25° and 75.1°C and Arrhenius plots were constructed from these data for the 40-75% H_2SO_4 range. The $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ values for these reactions are given in the following table:

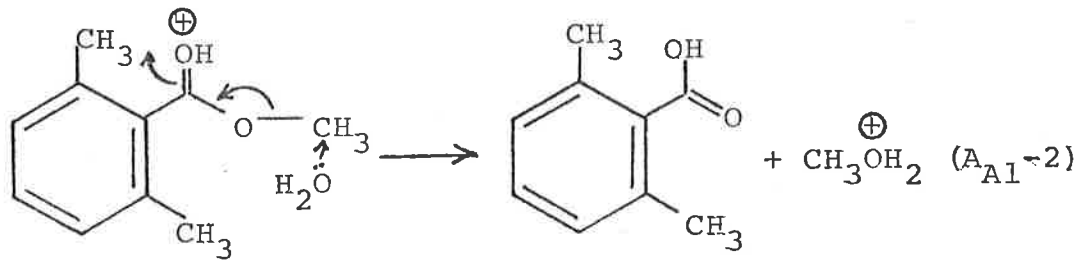
ACTIVATION PARAMETERS FOR HYDROLYSIS OF METHYL 2,6-DIMETHYL BENZOATE IN SULPHURIC ACID

w/w% H_2SO_4	$\Delta H^{\ddagger}$ (kcal/mole)	$\Delta S^{\ddagger}$ (kcal/mole)
40.0	24.60	-9.80
46.0	23.69	-10.9
50.0	23.19	-11.1
55.0	23.37	-8.36
60.0	25.97	+2.74
65.0	31.09	+22.7
68.0	34.54	+36.6
72.0	43.22	+68.8
75.0	52.70	+103

The behaviour of these parameters in the dilute acid region is generally what might be expected from a hydrolysis proceeding via an A-2 reaction, although the entropies of activation are somewhat more positive than those for a normal A_{Ac}-2 mechanism (-14 → -25 e.u.). They have, in fact, more in common with those observed

for the A_{Al}-2 hydrolysis of methyl and ethyl 2,6-dimethyl benzimidates in sulphuric acid solution.[43] These had an enthalpy of activation of ∿24-26 kcal/mole and $\Delta S^{\ddagger} \simeq -7 \rightarrow -9$ e.u. in 0-50% H_2SO_4. Both this $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ are intermediate between those expected for an A_{Ac}-2 reaction and those for an A_{Ac}-1 reaction and are very similar to the activation parameters for other known S_N2-type reactions. On the basis of steric hindrance to approach of water molecules, it seems reasonable to consider that an A_{Al}-2 mechanism would be more facile than an A_{Ac}-2 reaction.



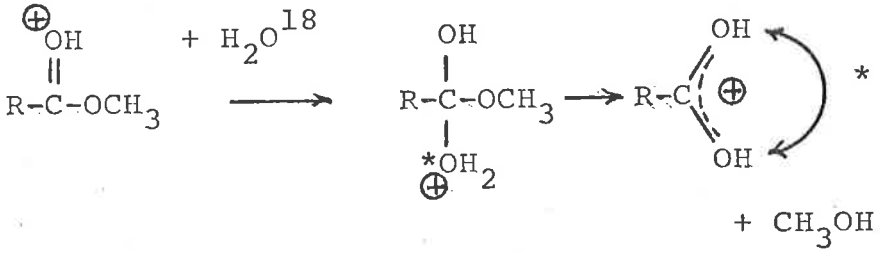


The factors favouring the A_{Al}-2 displacement reaction over an A_{Ac}-2 - A_{Ac}-1 competition include the

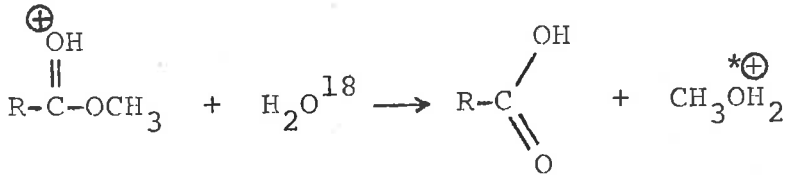
fact that the benzoylium ion formed via the A_{Ac}-1 pathway would not be sufficiently stable in dilute acid < ~60% H_2SO_4. The mesitoylium ion is known to be relatively stable even in 20% H_2SO_4, but this cation has the additional para-methyl group to lend further stability. Moreover, unlike the A_{Al}-1 reaction which would produce a methyl carbonium ion and is known to not occur for methyl esters, the A_{Al}-2 mechanism produces a methyloxonium ion. This is a considerably more stable species although it would not be present in very high concentrations in the acid range being considered. Nevertheless, its relatively minor abundance would also help to explain the extremely slow rates observed for this reaction in dilute acid. The main factor favouring such a proposed mechanism must remain however the severely sterically crowded A_{Ac}-2 transition state for this ester.

A definitive answer to this problem may be obtained from cleavage studies using O^{18}-enriched water. Such a reaction must give as products a labelled acid (and ester) if the mechanism is A_{Ac}-2 and the unlabelled acid, if A_{Al}-2.

A_{Ac}-2:



A_{Al}-2:



Unfortunately, these studies have not yet been made on this ester, although work is proceeding on them in our research group at the present time. At the moment, there remains the possibility that the intermediate values of the activation parameters in <60% H_2SO_4 arise from a competition between the A_{Ac}-2 and A_{Ac}-1 mechanisms.

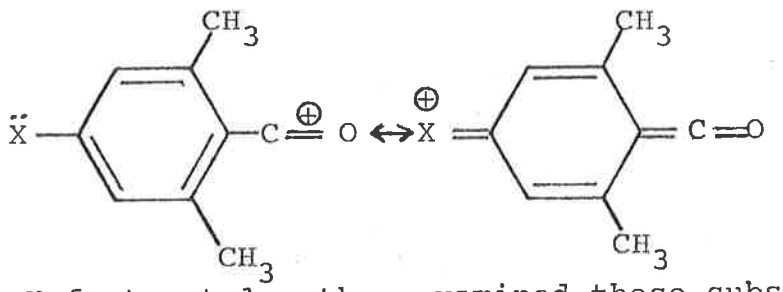
The activation parameters for the more concentrated acids are indicative of an A_{Ac}-1 mechanism. The $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ values are unusually high, however, in the 70-75% H_2SO_4 region. Previous results have indicated normal values of $\Delta H^{\ddagger} \simeq$ 27-31 kcal/mole and $\Delta S^{\ddagger} \simeq$ 0-+25 e.u. for the A_{Ac}-1 mechanism of benzoate ester hydrolysis. The only explanation one can give for a value such as $\Delta H^{\ddagger}$ = 43 kcal/mole and $\Delta S^{\ddagger}$ = 69 e.u. at, e.g. 72% acid is the same as that given for the rate data at 25°C in the low acid region. That is, the rates of these reactions were too fast to measure at >70% H_2SO_4 at temperatures higher than ∿40°C so that activation plots were constructed with data at only two temperatures, 25° and 37°C. Furthermore, rate constants were averaged to give smooth rate profiles, so that these figures probably represent an upper limit of the true activation parameters. What can be definitely concluded is that at some acid strength

close to 60% H_2SO_4 the A_{Ac}-1 reaction becomes the predominant mechanism via which the hydrolysis is proceeding.

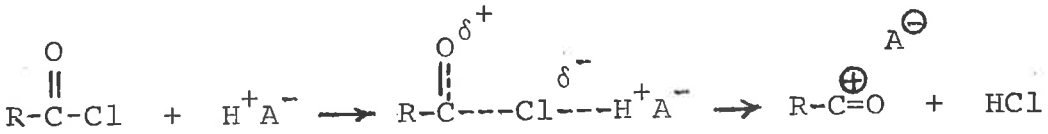
(iii) SUBSTITUENT EFFECTS

Bender and Chen[128] examined the effect of para-substitution on the rates of hydrolysis of a series of methyl 2,6-dimethyl benzoates in 9.70 M (~62.6%) H_2SO_4 at 25°C. Previous evidence was cited showing that methyl mesitoate, one of the compounds included in their study, hydrolysed only by the A_{Ac}-1 mechanism throughout the acidity range. They sought to prove this was generally true for a series of analogous hindered esters and to test the applicability of using the σρ-plots as a mechanistic criterion for reactions of hindered substrates.

They plotted their data against both σ and σ^+ and found a much better correlation with the σ^+ values (the former giving a curved plot) with ρ = -3.22, in good agreement with results previously obtained for A_{Ac}-1 benzoate ester hydrolysis. The better linearity using σ^+ values for the substituent effects is good indication that there is substantial positive charge build-up on the acyl carbon in the transition state, giving rise to resonance stabilising contributors, such as:



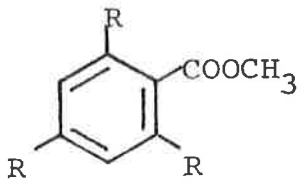
Unfortunately, they examined these substrates in an acid solution where the results of the present study also indicate an A_{Ac}-1 mechanism is the main one. Thus they shed no further light on the problem of the reaction mechanism in dilute acid. However, in a previous paper,[129] Bender and Chen examined the hydrolysis of 4-substituted-2,6-dimethyl benzoyl chlorides. They found evidence for the first time of acid-catalysed hydrolysis of acid chlorides in 99% CH_3CN-H_2O. Although the mechanism they proposed, based on the data obtained, is unimolecular (specific-acid-catalysed),



it suggests the possibility of a specific acid-general base catalysed A_{Al}-2 reaction for the hindered 2,6-dimethyl benzoate ester.

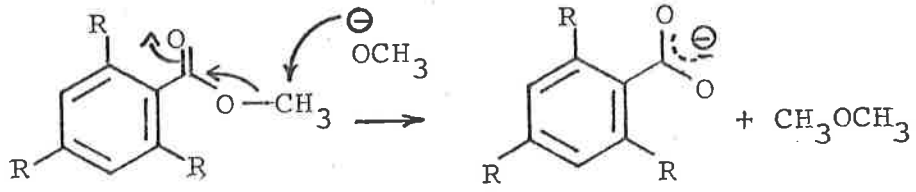
One piece of evidence that rules against an assignment of the S_N2-type displacement is the observation of O^{18}-exchange in the saponification of methyl mesitoate.[116] The ratio, k_h/k_e, equals 6.8 at 126°C. This requires the reaction to proceed by way of a tetrahedral intermediate and therefore acyl-oxygen cleavage.

Nevertheless, Bunnett and coworkers[130] found evidence, in an analogous reaction, to support a base-catalysed alkyl-oxygen fission - the B_{Al}-2 mechanism. When sodium methoxide was reacted with



; R=CH_3, H, Br

under anhydrous conditions at 100°C, they found that the order of reactivity was R = Br > H > CH_3, and more significantly they isolated dimethyl ether as the main product. This result can only arise from methoxide displacement at the alcoholic methyl group,



a reaction which is equivalent to the Williamson synthesis.

There are thus conflicting data for this reaction. The ρ value = +1.26 found for base-catalysed hydrolysis of a series of 4-substituted 2,6-dimethyl benzoates,[114] half that found for saponification of unhindered benzoates, could simply be due to the attenuating effect of the di-ortho methyls on the electronic contribution of the substituents to the reaction rate rather than indicative of a new mechanism. This is especially likely

since it is known that the ester group is significantly twisted out of line for resonance conjugation. This would lead one to conclude that it is the A_{Ac}-2, rather than A_{Al}-2, mechanism by which the ester hydrolyses in dilute acid. Certainly the rates would be very slow no matter which reaction mechanism is operative. On the other hand, under certain situations, a B_{Al}-2 mechanism has been shown to be the main reaction pathway, with the ortho substituents acting chiefly in terms of their electronic effects; and, therefore, one may postulate as reasonable an A_{Al}-2 mechanism analogously for the acid-catalysed reaction.

(iv) "HYDRATION" TREATMENTS

(a) 'r' PLOTS

The rate data at 25°C for methyl 2,6-dimethyl benzoate were treated according to the 'r' - hydration hypothesis as was done for the other three esters and the results are shown in Table 21 and Fig. 24. For the purposes of comparison, data for the hydrolysis of methyl mesitoate at 90°C were obtained from the literature for the 20-70% H_2SO_4 range and treated in the same manner, with the following difference: neither the 'm' value (slope of the ionisation plot) nor the pK_{SH}^+ for this ester have been determined. However, under conditions

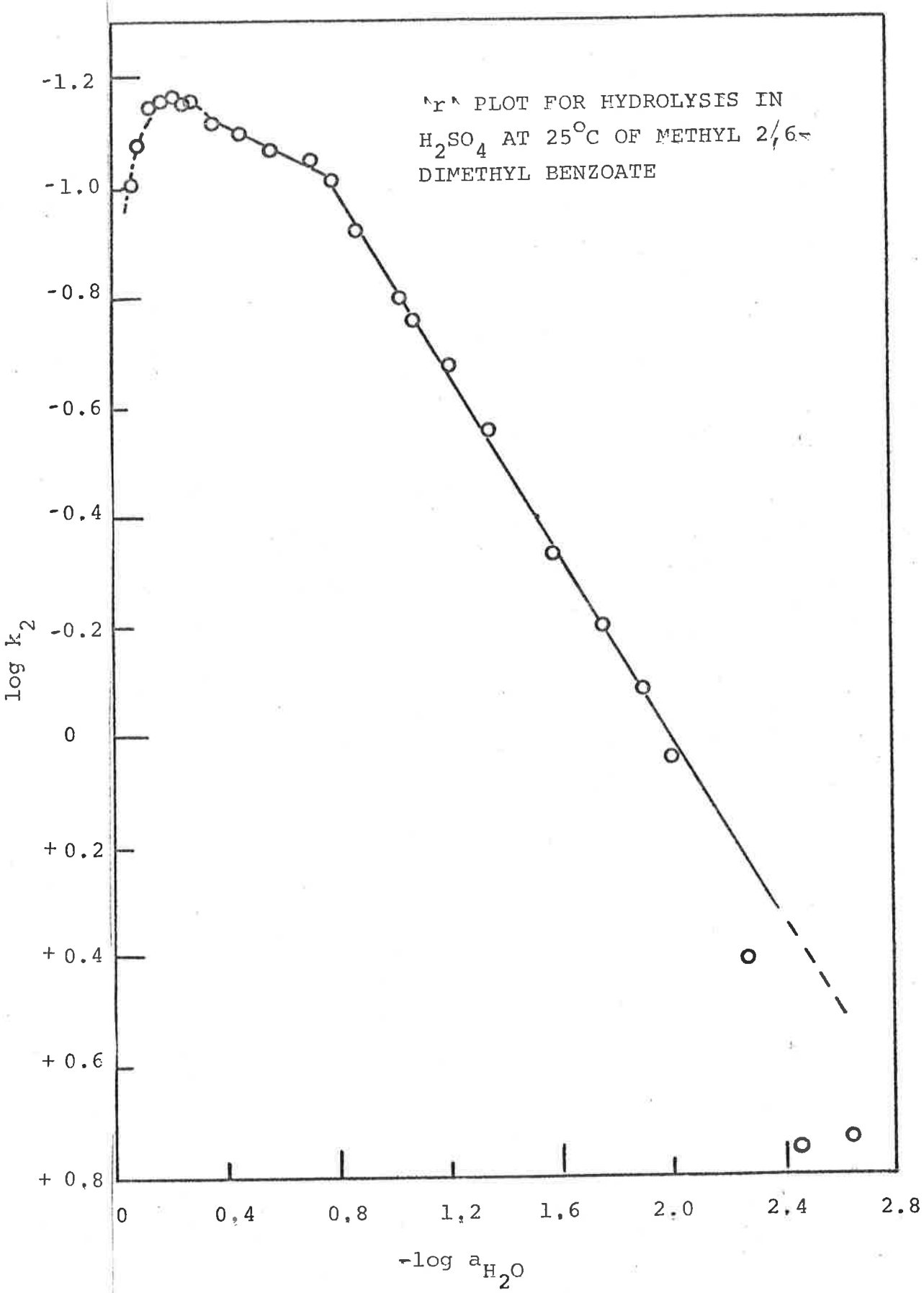
TABLE 21: DATA FOR THE 'r' PLOT FOR THE HYDROLYSIS OF METHYL 2,6-DIMETHYL BENZOATE IN SULPHURIC ACID AT 25°C

w/w% H_2SO_4	log k_2[a]	-log a_{H_2O}
22.0	-1.004	0.066
25.0	-1.074	0.084
30.0	-1.148	0.124
34.0	-1.153	0.166
38.0	-1.164	0.217
40.0	-1.150	0.247
42.0	-1.154	0.280
46.0	-1.116	0.360
50.0	-1.096	0.455
54.0	-1.066	0.573
58.0	-1.046	0.710
60.0	-1.010	0.788
62.0	-0.918	0.877
65.03	-0.796	1.03
66.0	-0.752	1.08
68.0	-0.671	1.21
69.03	-0.289	1.28
70.0	-0.553	1.35
71.60	-0.136	1.47
72.88	-0.329	1.58
75.09	-0.199	1.76
76.53	-0.080	1.90
77.61	+0.045	2.00
80.0	+0.410	2.27
81.41	+0.755	2.45
82.68	+0.733	2.63

[a] $\log k_2 = \log k_\psi - \log \frac{h_o^m}{h_o^m + k'_{SH^+}{}^m}$; m = 0.800, pK'_{SH^+} = -8.09

RANGE w/w% H_2SO_4	SLOPE	INTERCEPT	CORR. COEFFT.	MECHANISM
38.0-60.0	-0.256	-1.216	-0.9924	A_{Ac}-2
58.0-77.61	-0.833	-1.654	-0.9989	A_{Ac}-1

FIGURE 24


'r' PLOT FOR HYDROLYSIS IN
H_2SO_4 AT 25°C OF METHYL 2,6-
DIMETHYL BENZOATE
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0
+0.2
+0.4
+0.6
+0.8
log k_2
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
-log a_{H_2O}

of dilute acid, in which the ester is essentially in its neutral unprotonated form, the 'r'-relation can be simplified to

$$\log k_{\psi} + mH_o = r \log a_{H_2O} + \log \frac{k_o}{K'_{SH^+}{}^m}$$

Using this equation and choosing a value of m ≃ 0.8 (similar to that of methyl 2,6-dimethyl benzoate), the 'r' plots were calculated for methyl mesitoate and the results are shown in Table 22 and Fig. 25. The H_o values used were those at 25°C. However, log a_{H_2O} values were corrected for their temperature dependence in the manner derived by Smith as noted.

In the region of comparison (log a_{H_2O} = 0 → -0.8; w/w% H_2SO_4 = 0 → 60%), the behaviour of these two sterically-hindered esters is considerably different. Except for the first two or three points, the 2,6-dimethyl benzoate exhibits a shallow decline with slope (r) = -0.256 followed by a region of linearity with an even steeper slope, r = -0.833. Methyl mesitoate, however, has a slope = -2.59 in 0-60% H_2SO_4 and shows reasonably good linearity throughout the dilute to moderately concentrated acid region (correlation coefficient = -0.9990), indicating only one mechanism is operative in this region, namely A_{Ac}-1.

As with other evidence, the interpretation of these results for methyl 2,6-dimethyl benzoate in acid

TABLE 22: DATA FOR THE 'r' PLOT FOR THE HYDROLYSIS OF METHYL MESITOATE IN SULPHURIC ACID AT 90°C

w/w% H_2SO_4	log k_2 [a]	$-\log a_{H_2O}$ [b]
23.7	-0.278[c]	0.0598
25.4	-0.392	0.0685
30.3	-0.170[c]	0.1004
35.1	+0.248	0.1490
42.2	+0.147[c]	0.2164
42.9	+0.225[c]	0.2256
62.6	+1.437[c]	0.7191
68.9	+1.053	1.0036

[a] $\log k_2 = 4 + \log k_\psi$[e] $+ mH_o$; $m \simeq 0.8$; H_o values used were those at 25°C.

[b] $\log a_{H_2O}$ values were determined from those at 25°C, via the equation:[d]

$$\log a_w^{90^\circ} = \left(\frac{346.02}{363.15} - 0.162\right) \log a_w^{25^\circ}$$

[c] Points which were used in the correlation.

[d] $\log a_{H_2O}$ - Temperature relation determined by C. R. Smith, Reference 109, pp. 100-101.

[e] k_ψ data obtained from References 68 and 100.

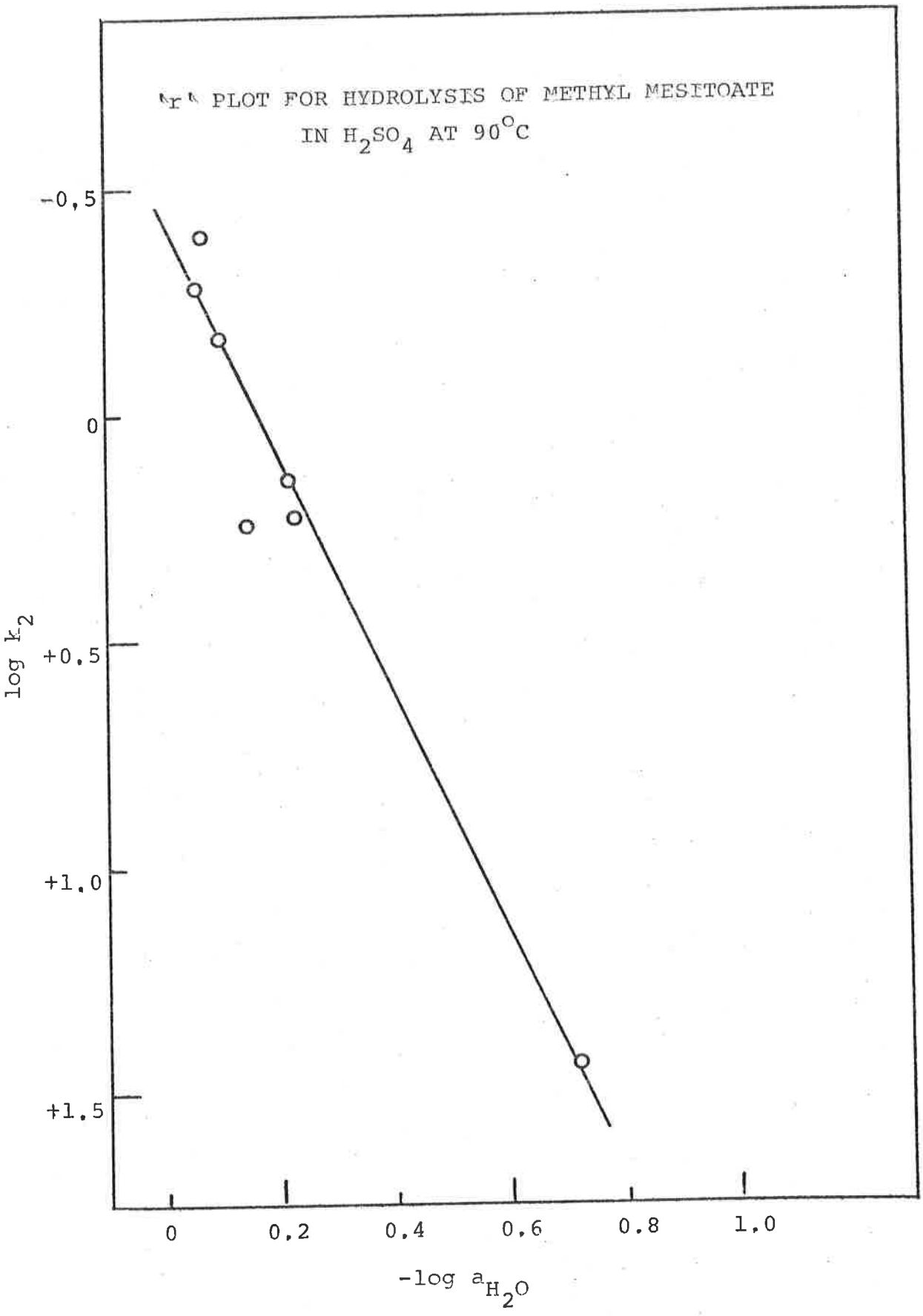
SLOPE = -2.59

INTERCEPT = $4 + \log k_o + pK'_{SH^+}{}^m$ = -0.411

CORR. COEFFT. = -0.9990

MECHANISM = A_{Ac}-1

FIGURE 25


'r' PLOT FOR HYDROLYSIS OF METHYL MESITOATE IN H_2SO_4 AT 90°C
-0,5
0
+0.5
+1.0
+1.5
log k_2
0
0.2
0.4
0.6
0.8
1.0
-log a_{H_2O}

<60% H_2SO_4 is difficult. The dependence on water activity is certainly not that which is normally observed for A_{Ac}-2 hydrolysis alone, although that may be the case up to ∿35% H_2SO_4 (log a_{H_2O} ≃ -0.18). However, it is also not similar to the behaviour observed for the sterically hindered benzimidates[43] which showed curved plots with small positive slopes in the 0 → 50% H_2SO_4 region. At best one can conclude that there is a considerable acidity range (35-60% H_2SO_4) over which the mechanism is dual (A-2 and A_{Ac}-1). In the more concentrated acid the A_{Ac}-1 reaction takes over completely with the stability of the 2,6-dimethyl benzoylium cation and the relief of steric strain playing the major role.

The 'r' plot in the concentrated acid region has a slope consistent with an A_{Ac}-1 mechanistic assignment and with a value reasonable on the basis of increasing steric hindrance for the benzoate esters.

ESTER	A_{Ac}-1 'r' VALUE
MB	-0.435
MPT	-0.474
MOT	-0.678
2,6-MDMB	-0.833
MM	-2.59

Furthermore, the changeover in mechanism comes earlier for the di-ortho-substituted ester than for the ortho-toluate → 59.3% and 66.9% H_2SO_4 respectively. This order

is consistent with the greater steric strain inherent in the 2,6-dimethyl benzoate, resulting in an effort to change mechanisms to one which will relieve this strain as soon as the stability of the consequent acylium ion in the acid medium will permit.

(b) TRANSITION STATE ACTIVITY COEFFICIENTS

The rate data for methyl 2,6-dimethyl benzoate at 25°C and for methyl mesitoate at 90°C were treated according to this hypothesis using the values of log f_S previously obtained and discussed. The calculation of log $f_{\ddagger}^*$ for these esters are given in Tables 23 and 24 and Fig. 26. Although the rate constants for methyl mesitoate are those for the reaction at 90°C, the values of log f_S and log $a^*_{H^+}$ needed for the calculations for this ester were obtained at 25°C. As a result, the actual log $f_{\ddagger}^*$ values may not be the true values for the reaction at 90°C, and they certainly are not those for the hydrolysis at 25°C. Nevertheless, the manner in which the activity coefficient of the transition state species in the hydrolysis of this ester changes with increasing acidity is significant.

The behaviour of log $f_{\ddagger}^*$ for 2,6-MDMB with changing acidity is similar to that observed for the other three esters. It exhibits an initial salting-out followed by a flattening-out of the curve in the more concentrated

TABLE 23: log $f_{\ddagger}^*$ VALUES FOR 2,6-MDMB HYDROLYSIS IN H_2SO_4 AT 25°C

w/w% H_2SO_4	log k_2	$-H_o$	log f_s	log $a^*_{H^+}$	log $f_{\ddagger}^*/k_o$	log $f_{\ddagger}^*$
0	-0.858	-	-	-	(+0.33)	0.0
10	-0.906[a]	0.38	0.06	0.43	1.09	0.76
20	-1.050[a]	1.03	0.13	1.55	1.91	1.58
30	-1.148	1.78	0.19	2.84	2.75	2.42
40	-1.150	2.52	0.22	4.34	3.69	3.36
50	-1.096	3.40	0.17	6.13	4.68	4.35
55	-1.061[a]	3.93	0.11	7.07	5.10	4.77
60	-1.010	4.52	0.05	8.05	5.49	5.16
65	-0.796	5.07	-0.02	9.05	5.77	5.44
70	-0.553	5.78	-0.08	10.08	5.93	5.60
75	-0.202	6.56	-0.15	11.30	6.10	5.77
80	+0.410	7.34	-0.21	12.52	6.03	5.70
82.68	+0.703	7.75	-0.24	13.25	6.10	5.77

[a]Interpolated from 'r' plot.

$\log f_{\ddagger}^*/k_o = -\log k_2 + mH_o + \log f_s + \log a^*_{H^+}$; m = 0.800.

TABLE 24: $\log f_{\ddagger}^*$ TREATMENT FOR METHYL MESITOATE HYDROLYSIS IN SULPHURIC ACID AT 90°C

w/w% H_2SO_4	$-\log k_2 + mH_o = -(4 + \log k_\psi)$ [a]	$\log f_S$ [b,c]	$\log a^*_{H^+}$ [b]	$\log f_{\ddagger}^*/k_o$ [d]	$\log f_{\ddagger}^*$
				(-0.21)	0.0
23.7	-0.778	0.42	2.04	1.69	1.90
25.4	-0.760	0.44	2.25	1.93	2.14
30.3	-1.270	0.48	2.90	2.11	2.32
35.1	-1.968	0.46	3.61	2.11	2.32
42.2	-2.283	0.42	4.75	2.88	3.09
42.9	-2.401	0.41	4.86	2.87	3.08
62.6	-5.261	0.22	8.55	3.51	3.72
68.9	-5.549	0.14	9.87	4.46	4.67

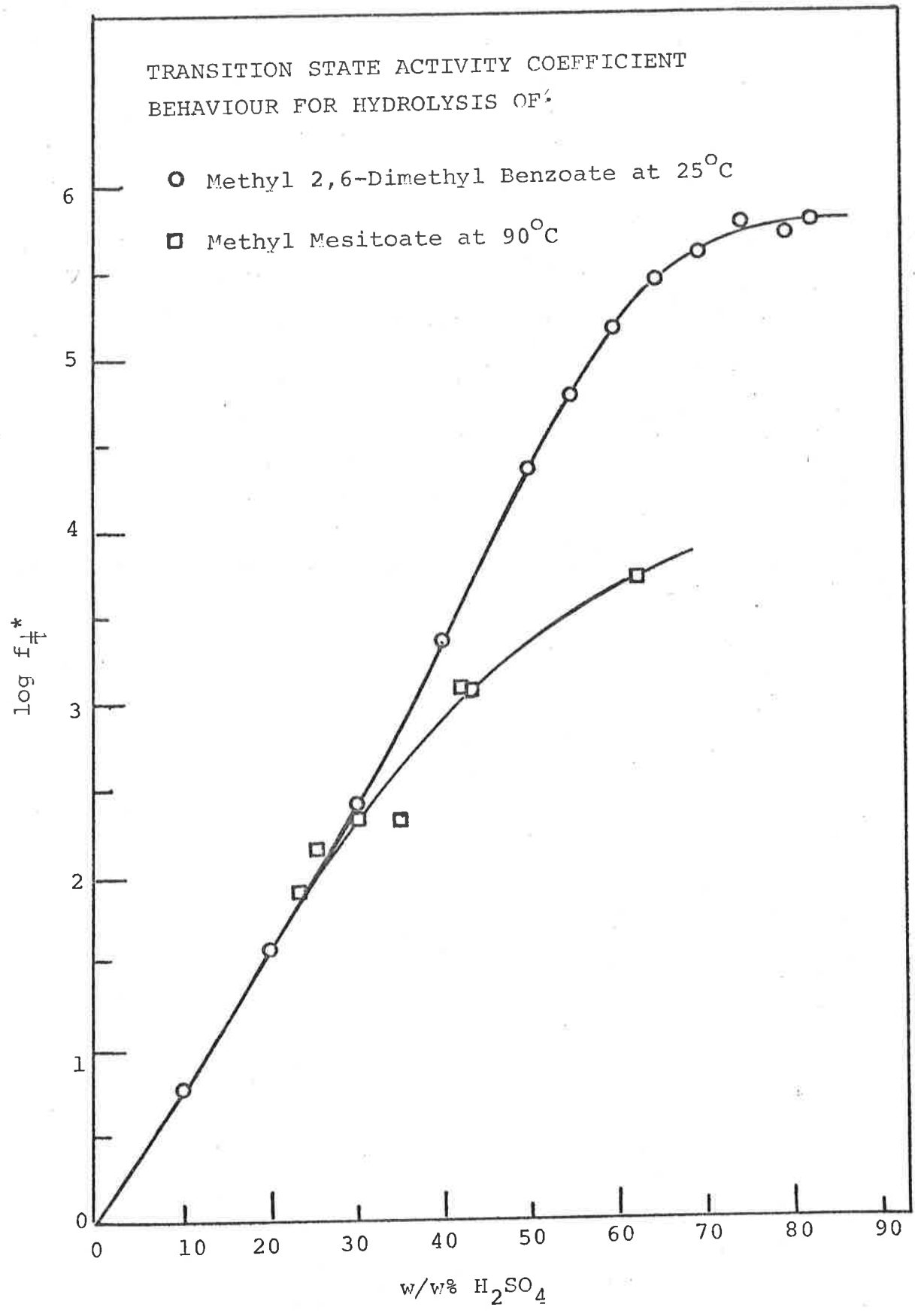
[a] At T = 90°C.

[b] At T = 25°C.

[c] From Reference 95.

[d] $\log f_{\ddagger}^*/k_o = -\log k_2 + mH_o + \log f_s + \log a^*_{H^+}$

FIGURE 26


TRANSITION STATE ACTIVITY COEFFICIENT
BEHAVIOUR FOR HYDROLYSIS OF:
O Methyl 2,6-Dimethyl Benzoate at 25°C
□ Methyl Mesitoate at 90°C
log f‡*
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
w/w% H2SO4

acids. This supports the view that, although the A-1 mechanism may be operating in part throughout the dilute to moderately concentrated acid range, it does not become the dominant mechanism until >60% H_2SO_4. The other interesting feature for the log $f_{\ddagger}^*$ variation of this ester is that the initial salting-out is greater than that of the other esters, as expected, but does not rise nearly as steeply as does log $f_{\ddagger}^*$ for the others. In fact, it is almost a linear function of w/w% H_2SO_4, up to ~40% H_2SO_4.

This is even more evident in the case of methyl mesitoate hydrolysis. Here the shape of the log $f_{\ddagger}^*$ vs. w/w% H_2SO_4 profile is convex rather than concave in the dilute acid region. This ester is known from other evidence to be hydrolysing only by the A_{Ac}-1 mechanism, even in dilute acid. The transition state activity coefficient behaviour supports that conclusion. It is very similar in shape to that of p-methoxybenzyl acetate, which also hydrolyses mainly by A-1 in >20% H_2SO_4.

For methyl 2,6-dimethyl benzoate, the values of log $f_{\ddagger}^*$ in the acid region in which the A-2 mechanism may be assumed to be operating are higher than any of the other esters included in this study. This agrees with the very slow rate of reaction in this acid range. On the other hand, in the concentrated acid region in which the acylium ion produced by the A_{Ac}-1 mechanism is the most stable of that produced by the four esters under

investigation, the $f_{\ddagger}^{*}$ values are at least two orders of magnitude lower than that of the next most stable species, the ortho-toluyl cation. These values are in agreement with the exceptionally fast rates of reaction for this sterically-hindered ester.

The changeover in mechanism for 2,6-MDMB occurs in the 55-60% H_2SO_4 region, giving the same result as that obtained by the 'r' plots, which showed the A_{Ac}-1 mechanism as being the predominant one in >60% H_2SO_4.

(v) SUMMARY: CONCLUSIONS RE THE MECHANISM OF HYDROLYSIS OF METHYL 2,6-DIMETHYL BENZOATE IN SULPHURIC ACID

All the evidence cited herein provide good indication that, in acid >60% H_2SO_4, this ester is hydrolysing by an A_{Ac}-1 mechanism. The activation parameters, although becoming unusually large, for reasons explained, are consistent with this mechanistic interpretation, as is the effect of para-substitution on the reaction rates, giving a $\rho = -3.22$. The order of rates for the four esters studied in the present work in the acid region where all are hydrolysing by the same mechanism is in agreement with this conclusion:

w/w% = 80% H_2SO_4

ESTER	4 + log k_ψ (min^{-1})
Methyl Benzoate	0.429
Methyl para-Toluate	1.015
Methyl ortho-Toluate	2.300
Methyl 2,6-dimethyl Benzoate	3.714

Similarly, the 'r' plots show a considerable negative slope in the 60-80% H_2SO_4 range, with 'r' = -0.833, consistent with an A_{Ac}-1 mechanism.

In the more dilute acid (<60% H_2SO_4), the mechanism is less well understood. The activation parameters give values intermediate between those for an A-2 and an A-1 reaction, suggesting either a competition between these two mechanisms, or an A_{Al}-2 mechanism, may be operating. The 'r' plots tend to support the former conclusion in that, except for the very dilute acid region (up to ∿35% H_2SO_4), there is a fairly wide range of acidity, 35-60% H_2SO_4, for which the 'r' plot has a slightly negative slope, -0.256. Although this value is typical for the A_{Ac}-1 hydrolysis of primary alkyl acetates, it is much less negative than the values observed for the benzoate esters included in the present study.

The transition state activity coefficient behaviour for methyl 2,6-dimethyl benzoate is more readily understood. The variation of log $f_{\ddagger}^*$ for this ester is

similar to that for the other three esters with the exception that the curve is more convex in the 0 → 60% acid region. In the more concentrated acid media, the log $f_{\ddagger}$*-acidity plot flattens out considerably and the value of log $f_{\ddagger}$* for 2,6-MDMB is ∿5 logarithmic units lower - i.e. more stable - than that for methyl benzoate. Moreover, the degree of flattening of the four substrates is in the order one would expect for the relative stabilities of the acylium ion-like transition state:

$$MB < MPT < MOT < 2,6\text{-MDMB}$$

III. EXAMINATION OF THE log $f_{\ddagger}$* AND 'r'-HYDRATION CONCEPTS

The role of water in acid-catalysed hydrolysis reactions has been one of the major areas of investigation in studying these systems. Several rate-acidity relations have been devised to try and determine how the changing water activity and/or medium acidity effect changes in mechanism. The best test of any hypothesis is its applicability to a variety of reactions in terms of its successes and failures. Of the number of correlations derived over the last 30-40 years, the two that have met with the greatest success to date in analysing ester hydrolysis are the 'r' hydration treatment and the transition state activity coefficient behaviour. Both

of these have been used to examine mechanistic changes in acetate ester hydrolysis as well as for the benzoate esters included in the present study.

For most of these esters, the 'r' plots give a slope of ∿+2 for reactions in dilute to moderately concentrated acids. In the very concentrated acid region, a break in the 'r' plot is observed resulting in a slope of -0.2 to -0.8. This is usually taken to indicate a change from an A-2 mechanism to A-1. There are at least two esters known, however, which hydrolyse by an A-1 mechanism even in very dilute H_2SO_4 media, t-butyl acetate and p-methoxybenzyl acetate. These show very large negative 'r' values - -8.9 and -4.1 respectively. It is difficult to ascribe any real physical significance to these values. The fact that water activity in these acid media is effectively invariant results in any rate changes showing a much greater dependence on water activity than the mechanism would justify. Furthermore, although the para-methoxybenzyl acetate is known to have some reaction proceeding via the A_{Ac}-2 pathway in <20% H_2SO_4, the 'r' plot for the hydrolysis of this ester shows no A-2 region.

In the case of the benzoate esters, the difficulties in interpretation also occur mainly in the dilute acid region. Both methyl para-toluate and methyl ortho-toluate have rather large values for 'r' in this region, +2.54 and +3.46 respectively. The latter value

is especially puzzling, since the steric hindrance near the reaction centre should preclude the ability of solvent water molecules to stabilise the protonated ester species. This would have the effect of lowering the 'r' value to less than 2. The opposite, in fact, is observed. Furthermore, the 'r' plots for methyl 2,6-dimethyl benzoate hydrolysis show no clear A-2 region at all, although the A_{Ac}-1 mechanism does not become the main one until >60% H_2SO_4. Instead, there is a region with a shallow negative slope (35-60%), 'r' = -0.26, followed by a much steeper region of the 'r' plot in acids >60%, giving an 'r' value of -0.83. Moreover, benzamide hydrolysis in sulphuric acid failed to give linear 'r' plots.

Inherent in the 'r' hydration treatment are two basic assumptions. One is that the substrate must either follow a defined acidity function in its protonation behaviour, or that the protonation of the substrate be considered linear in H_o, with a slope of 'm' in its $\log [SH^+]/[S]$ vs. $-H_o$ plot. The other and more serious assumption is that the activity coefficient ratio of the hydrated species, SH^+ and $S^{\ddagger}$, must vanish,

i.e. $$\log \frac{f_{SH^+}{}_h}{f_{\ddagger}{}_h} \simeq 0$$

It is impossible to know for sure whether this condition is ever met, since only formal activity coefficients, not

those of the hydrated species, are experimentally accessible. It is likely that this ratio will vary less than would be the case for the formally-defined species, but as was observed for methyl benzoate, the ratio of the formal activity coefficients becomes very large at high acid strengths. Also, this and other hydration parameter treatments essentially correlate the rate of the second, rate-determining, step with the water activity of the medium rather than some function of its acidity.

For these reasons it became clear that an approach correlating the effect of changing acidity on the rate of an acid-catalysed reaction in mineral acids should use parameters that can be obtained directly from experimental observation. Such a function is the variation in transition state activity coefficient behaviour as the acidity of the medium changes. The equation for the 'r' hydration treatment is given as

$$\log k_\psi + H_s = r\log a_{H_2O} \text{ (+ constant)}$$

or

$$\log k_\psi - \log \frac{h_o^m}{h_o^m + K'_{SH^+}{}^m} = r\log a_{H_2O} + \log k_o$$

whereas that for the transition state activity coefficient is given by

$$\log \frac{f_{\ddagger}^*}{k_o} = -\log k_\psi - \log K_{SH^+} + \log f_S + \log a^*_{H^+}$$

for which all the terms on the right-hand side are potentially measurable by experiment. There is an assumption made here that the role of water is not expressed explicitly, but that its involvement is incorporated into the activity coefficient variation of the transition state. However this seems reasonable in view of the fact that the presence or absence of water in the transition state species will affect the activity coefficient of that species. Moreover, the value of k_ψ must be modified to k_ψ (1+I) in those acid regions in which protonation becomes important. Nevertheless this only involves determining the protonation behaviour of each substrate individually rather than require the compound to ionise according to a known acidity function, H_S.

Overall, then, the main advantage of this activity coefficient approach is that it relies only on quantities which can be measured and, as a result, yields a parameter which can be readily understood and explained physically. Moreover, the activity coefficients of the transition state obtained can be, and have been, compared to those obtained for other cationic species. This enables conclusions to be drawn regarding

the charge distribution and solvent stabilisation of the activated complex in the transition state region.

One other advantage is that, unlike the unusual values derived from the 'r' plots in certain cases, and the widely varying behaviour of the rate profiles themselves, the calculation of log $f_{\ddagger}^{*}$ values gives results, in the dilute acid region at least, that are very similar to one another for a given class of compounds. In the A-1 region, where different cations are produced from a given series of, e.g. esters, the order of log $f_{\ddagger}^{*}$ values obtained is consistent with that expected on the basis of the relative stability of the cations produced - viz., the more stable the positively-charged species, the lower its value of $f_{\ddagger}^{*}$. This approach, unlike any other, also clearly demonstrates the reason why there is a mechanistic change in the hydrolysis reaction with increasing acidity. The tetrahedral intermediate produced in the A_{Ac}-2 reaction becomes increasingly unstable as the medium acidity is increased. A certain value of the acidity is then reached whereupon the acylium ion produced by the A_{Ac}-1 mechanism of benzoate esters becomes more stabilised relative to the tetrahedral intermediate. When this happens, the ester proceeds to hydrolyse via this new pathway.

In addition, the results obtained by the log $f_{\ddagger}^{*}$ treatment are generally in very good agreement re

mechanism changes with other evidence, e.g. the 'r' plots. Where a discrepancy has been observed, e.g. with p-methoxybenzyl acetate, it is the transition state activity coefficient approach that appears to give the more reliable interpretation.

For those systems on which this approach has been tested, it would appear that it is superior in its simplicity and usefulness to any previously-devised method. It remains to be seen how widespread its use will be.

IV. SUMMARY AND CONCLUSIONS

The rates of hydrolysis of a series of four benzoate esters were obtained over as wide an acidity range as possible and from 25-70°C. The esters were methyl benzoate, methyl para- and ortho-toluate and methyl 2,6-dimethyl benzoate. The rate profiles indicate that the first two esters exhibit the usual rate maximum for A_{Ac}-2 hydrolysis in 55-60% H_2SO_4, followed by a decrease in rate, and subsequently an increase in the very concentrated 80-90% H_2SO_4 range. Methyl ortho-toluate shows a monotonic rate increase over the acidity range in which its hydrolysis could be measured, and at any of a series of temperatures. However, the use of activation parameter plots indicated a very shallow maximum in the profile at ∿50% at 25°. Other evidence showed that, although these rates were not easily measured at that temperature, this ester too is hydrolysing by an A_{Ac}-2 mechanism until ∿70% H_2SO_4, after which the A_{Ac}-1 reaction takes over. Methyl 2,6-dimethyl benzoate hydrolyses via A_{Ac}-1 at >60% H_2SO_4, but neither the rate profiles, which show a monotonic increase at every temperature over the whole acid range studied, nor other approaches to analyse the kinetic results, give definitive conclusions concerning the mechanism(s) in more dilute acids.

Substituent effect studies on methyl benzoate hydrolysis in 40.0% and 90.5% H_2SO_4 at 50°C and 60°C give the following ρ values.

w/w%	T(°C)	ρ
40.0	50	+0.17
90.5	50	-5.40
40.0	60	+0.10
90.5	60	-3.73

These values are in good agreement with those of ∿+0.1 for benzoate hydrolyse in aqueous/organic systems (A_{Ac}-2 hydrolysis) and of -3.2 to -3.8 for benzoate hydrolysis proceeding via the A_{Ac}-1 mechanism. A value of -3.22 for the ρ of hydrolysis of 4-substituted-2,6-dimethyl benzoates in 62.6% H_2SO_4 was reported from the literature, supporting the assignment of the A_{Ac}-1 mechanism for the methyl 2,6-dimethyl benzoate in >60% H_2SO_4. Evidence was also presented showing that methyl esters have not been observed to hydrolyse unimolecularly with alkyl-oxygen fission (A_{Al}-1), resulting in only two possible mechanisms for the esters included in this study - A_{Ac}-2 and A_{Ac}-1.

Activation parameters were calculated for the various esters in as many of the acids as was possible to obtain them. These results were then interpolated to obtain values at common w/w% H_2SO_4 solutions. The data are given in Table 25. These activation parameters indicate, from the $\Delta S^{\ddagger}$ values especially, a change in

TABLE 25: ACTIVATION PARAMETERS AT CONSTANT w/w% H_2SO_4 FOR BENZOATE HYDROLYSIS IN H_2SO_4

w/w% H_2SO_4	MB		MPT		MOT		2,6-MDMB	
	$\Delta H^{\ddagger}$[a]	$\Delta S^{\ddagger}$[b]	$\Delta H^{\ddagger}$[a]	$\Delta S^{\ddagger}$[b]	$\Delta H^{\ddagger}$[a]	$\Delta S^{\ddagger}$[b]	$\Delta H^{\ddagger}$[a]	$\Delta S^{\ddagger}$[b]
20.0			24.74	-4.14	20.19	-18.3	28.07	-2.78
30.0			21.53	-12.5	21.78	-12.4	26.56	-5.92
40.0	20.18	-15.2	18.61	-20.0	19.55	-18.7	24.60	-9.80
50.0	20.30	-13.3	17.26	-23.1	20.47	-15.0	23.19	-11.1
60.0	20.09	-13.3	19.73	-15.1	25.55	+1.66	25.97	+2.74
65.0	19.92	-14.0	21.76	-8.95	26.85	+6.75	31.09	+22.7
70.0	20.27	-13.2	24.70	+0.01	27.58	+11.0	38.18	+50.3
75.0	21.90	-8.85	26.77	+7.22	29.24	+19.8	(52.70)	(+103)
80.0	25.66	+3.07	27.82	+13.0				
85.0	27.95	+12.3	29.85	+22.5				

[a] units = kcal/mole

[b] units = e.u.

mechanism for all four esters from A-2 in dilute acid to A-1 in concentrated acid. The acidities at which these changes are occurring are:

Methyl benzoate ∿80%.

Methyl para-toluate ∿70%.

Methyl ortho-toluate ∿60%.

Methyl 2,6-dimethyl benzoate ∿60%.

The rate data for the four esters, together with data from the literature for methyl mesitoate (at 90°C) were analysed by both the 'r' hydration treatment and the transition state activity coefficient approach. For both of these, a knowledge of the protonation behaviour of each ester was necessary and this was determined at 10°C for all four substrates, as well as at 25°C for methyl benzoate. The slopes of the ionisation plots and the pK_{SH}^+ values obtained, after converting the values to 25°C, were:

ESTER	m	pK_{SH}^+
MB	0.905	-7.38
MPT	0.787	-5.99
MOT	0.962	-7.64
2,6-MDMB	0.800	-6.47

The results from the 'r' hydration treatment are summarised in Table 26 and shown in Fig. 27. The calculated transition state activity coefficients are given in Table 27 and shown in Fig. 28.

TABLE 26: SUMMARY OF RESULTS FROM 'r' PLOT CORRELATIONS FOR HYDROLYSIS OF METHYL BENZOATE ESTERS IN SULPHURIC ACID AT 25°C

ESTER	RANGE w/w% H_2SO_4	'r'	log k_o	CORR. COEFFT.	MECHANISM	X-OVER[a]
Methyl Benzoate	40.0 - 77.61	2.299	2.096	0.9996	A_{Ac}-2	80.2%
	84.0 - 90.0	-0.435	-4.179	-0.984	A_{Ac}-1	
Methyl para-Toluate	45.0 - 70.0	2.539	1.298	0.9985	A_{Ac}-2	73.7%
	80.0 - 88.59	-0.474	-3.641	-0.9990	A_{Ac}-1	
Methyl ortho-Toluate	32.0 - 60.0	3.459	2.219	0.9999	A_{Ac}-2	66.9%
	76.0 - 87.67	-0.678	-2.489	-0.986	A_{Ac}-1	
Methyl 2,6-dimethyl Benzoate	38.0 - 60.0	-0.256	-1.216	-0.9924	A_{Ac}-2?	59.3%
	58.0 - 77.61	-0.833	-1.654	-0.9989	A_{Ac}-1	
Methyl Mesitoate	23.7 - 62.6	-2.59[b]	-0.411[b,c]	-0.9990	A_{Ac}-1	

[a] X-over is that value of log a_{H_2O}, and therefore the value of w/w% H_2SO_4, at which the two r plots intersect.

[b] At T = 90°C.

[c] Intercept = 4 + log k_o + $pK'_{SH^+}{}^m$; if $pK'_{SH^+}{}^m$ is assumed to ≃ -6.5 (similar to that for 2,6-MDMB), then log k_o ≃ 2.089.

FIGURE 27

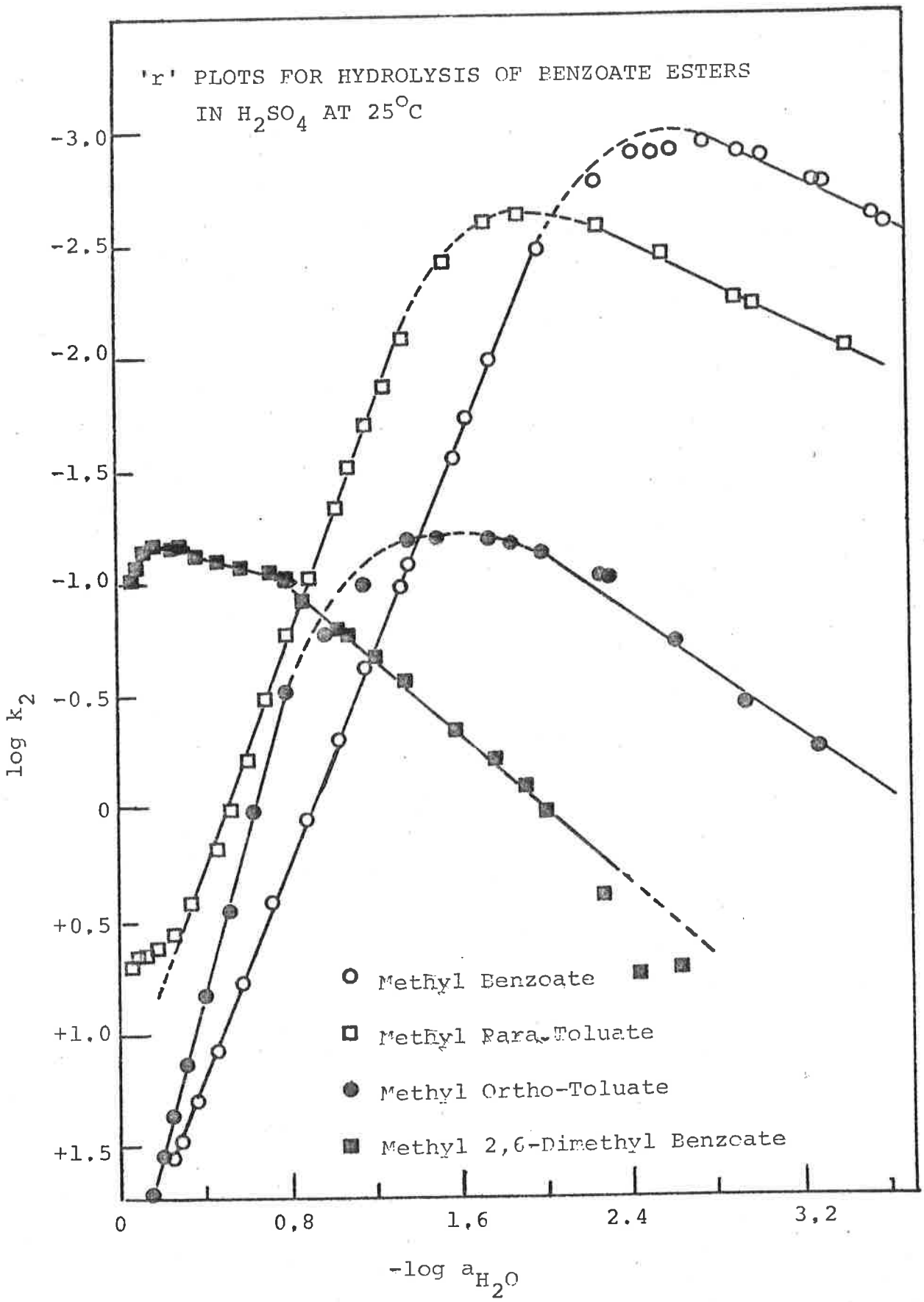
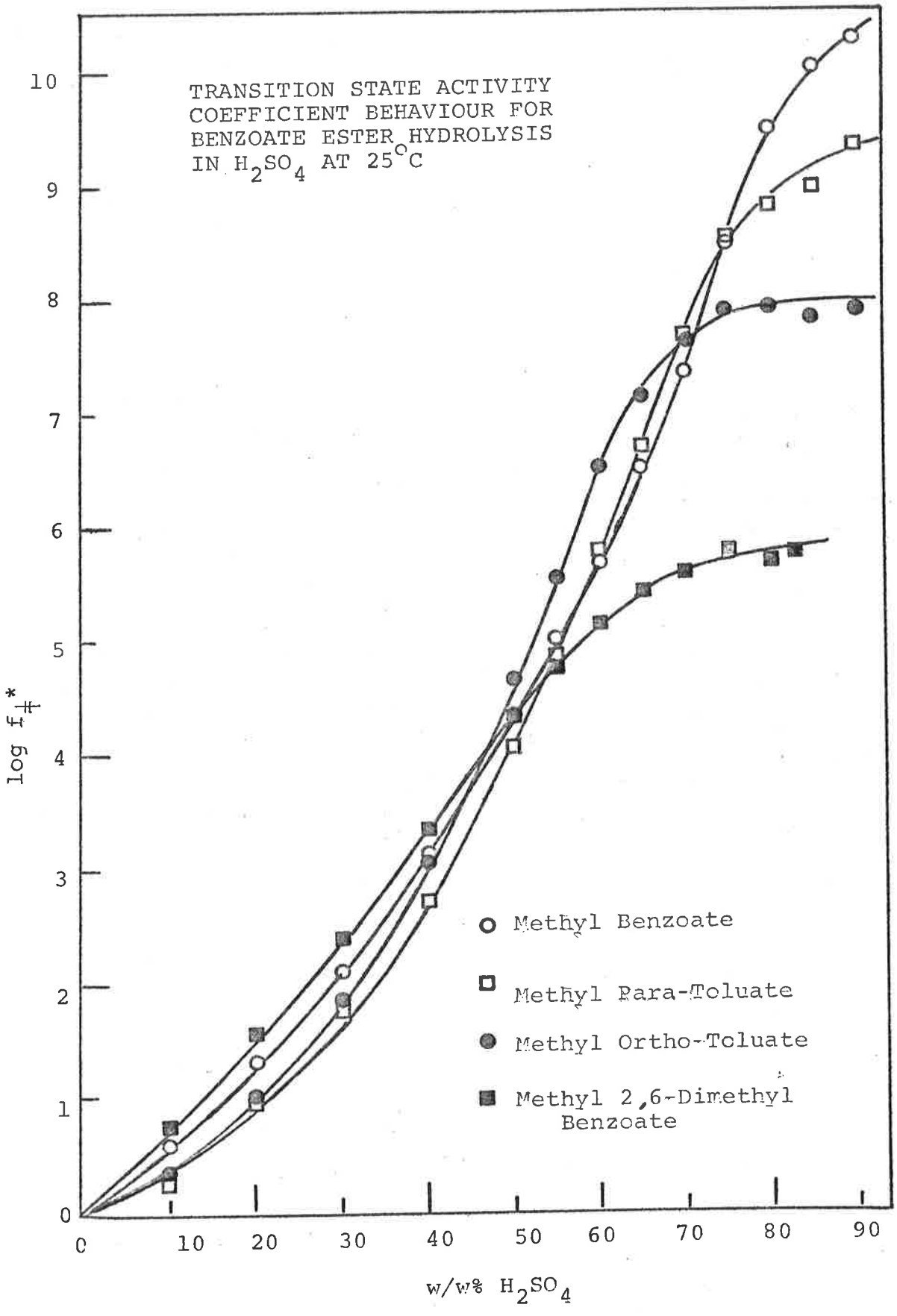

'r' PLOTS FOR HYDROLYSIS OF BENZOATE ESTERS IN H_2SO_4 AT 25°C
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0
+0.5
+1.0
+1.5
log k_2
0
0.8
1.6
2.4
3.2
-log a_{H_2O}
Methyl Benzoate
Methyl Para-Toluate
Methyl Ortho-Toluate
Methyl 2,6-Dimethyl Benzoate

TABLE 27: log $f_{\ddagger}^{*}$ VALUES FOR BENZOATE ESTER HYDROLYSIS IN H_2SO_4 AT 25°C

w/w% H_2SO_4	MB	MPT	MOT	2,6-MDMB	MM[a]
0	0.0	0.0	0.0	0.0	0.0
10	0.58	0.25	0.36	0.76	0.80
20	1.31	0.97	1.03	1.58	1.61
30	2.15	1.76	1.87	2.42	2.35
40	3.13	2.73	3.07	3.36	2.95
50	4.35	4.08	4.68	4.35	3.37
55	5.04	4.88	5.57	4.77	3.52
60	5.69	5.79	6.52	5.16	3.65
65	6.51	6.70	7.15	5.44	3.77
70	7.35	7.66	7.61	5.60	3.89
75	8.47	8.51	7.89	5.77	
80	9.46	8.78	7.93	5.70	
82.68				5.77	
85	10.02	8.96	7.83		
90	10.26	9.32	7.90		

[a]Values at 90°C

FIGURE 28


TRANSITION STATE ACTIVITY COEFFICIENT BEHAVIOUR FOR BENZOATE ESTER HYDROLYSIS IN H_2SO_4 AT 25°C
log $f_{\ddagger}^*$
w/w% H_2SO_4
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
Methyl Benzoate
Methyl Para-Toluate
Methyl Ortho-Toluate
Methyl 2,6-Dimethyl Benzoate

These results are all in good agreement with one another. They indicate mechanism changes from A_{Ac}-2 to A_{Ac}-1 for all the esters studied, giving the same acidity region of change by the different techniques to within 5% H_2SO_4. The only mechanism about which there is some uncertainty is that of methyl 2,6-dimethyl benzoate in the dilute acid region. The results from these rate data can be explained equally well by either a competing A-2 $\leftrightarrow$ A-1 mechanism or an A_{Al}-2 mechanism. The latter has not yet been observed in ester hydrolysis, although the steric crowding of this ester group could conceivably favour such a mechanism. Definitive conclusions regarding this mechanism must await O^{18}-exchange studies. The current evidence tends to support a competing mechanism hypothesis.

One of the principal aims of the present study was to determine the effect of "neutral" sterically-hindering groups on the rates of ester hydrolysis in sulphuric acid media. All the evidence presented shows that in the dilute acid region, in which the A_{Ac}-2 mechanism is operative, the order of hydrolytic rate is: MB $\sim$ MPT > MOT > 2,6-MDMB. In the more concentrated acid region, where hydrolysis is proceeding by A_{Ac}-1, the order is reversed: 2,6-MDMB >> MOT >> MPT > MB. This is in agreement with our understanding of both the electronic effects of the methyl groups, the difficulty

of hydrolysis afforded by their steric effects in the A-2 region, and the ease of hydrolysis in the A-1 region with a relief of steric strain.

APPENDIX A. FORMULAE FOR DETERMINING w/w% H_2SO_4

(1) FROM MEASURED WEIGHTS OF REAGENT

(a) For acids less concentrated than 95 w/w%:

$$x_1 = \frac{1000\ w_2}{w_1}\ ;\quad x_2 = (1000 - x_1)$$

where: x_1 = weight (gm) of 95% stock solution required

x_2 = weight (gm) of water

w_1 = w/w% of stock H_2SO_4 solution (≃95%)

w_2 = w/w% desired for the final solution.

This prepares $(x_1 + x_2) = 1000$ gm of acid solution at w_2 (w/w%).

(b) For acids more concentrated than 95 w/w%:

$$x = \frac{500\ (w_2 - w_1)}{107 - w_2}$$

where: x = weight (gm) of 30% oleum required

w_1 = w/w% of stock H_2SO_4 solution

w_2 = w/w% of the H_2SO_4 solution desired.

This prepares (500 + x) gms of acid solution at w_2 (w/w%).

(2) FROM DENSITY MEASUREMENTS

The densities of water and the aqueous acid solutions were measured on the Anton Paar Precision Density Meter. An inner chamber, thermostatted at 25°C, was filled with the particular solution being measured, and this chamber was vibrated by activating a switch. The instrument operates on the principle that the density of a solution is related, through the following formula, to its periodicity of vibration:

$$d_2 = A (T_2^2 - T_1^2) + d_1$$

where: d_1 = absolute density of water at 25°C = 0.997044

d_2 = density of the acid solution being measured

A = constant for the machine, determined on a regular basis by measuring the T-values for two or more solutions whose densities at 25°C are accurately known, and which usually = $\sim 3.6 \times 10^{-13}$

T_1 = period of vibration for pure water

T_2 = period of vibration for the acid solution being measured.

The w/w% of the sulphuric acid solution was then determined by a linear interpolation from the data in the International Critical Tables, Vol. III, p. 56 (1928), which lists values for the density of H_2SO_4 solutions at integral values of concentration for a number of temperatures.

APPENDIX B. DERIVATION FORMULAE FOR CALCULATING f_S

(i) $f_S = D^O/D$ = medium effect activity coefficient in a particular acid,

(ii) $D^O = C_S(w)/C_S{}^W(org.)$ = distribution ratio for partitioning of the solute ester between the organic layer and the pure water layer.

where: $C_S(w)$ = solute concentration in the pure water layer

$= A_S(w)/\varepsilon_S(w)$, assuming a 1.00-cm. cell

$C_S{}^W(org.)$ = solute concentration in the organic layer that was partitioned with pure water

$= A_S{}^W(org.)/\varepsilon_S{}^W(org.) \times F$

F = dilution factor = 1 /1/10 x 0.1 = 100

A = measured absorbance

ε = extinction coefficient of the solute in the particular layer being measured.

(iii) $D = C_S(a)/C_S{}^a(org.)$ = distribution ratio for partitioning of the solute between the organic layer and the aqueous acid layer,

where: $C_S(a)$ = solute concentration in the aqueous acid = $A_S(a)/\varepsilon_S(a)$

$C_S{}^a(org.)$ = solute concentration in the organic layer = $A_S{}^a(org.)/\varepsilon_S{}^a(org.)$ x F.

(iv) $f_S = D^o/D = C_S(w)/C_S{}^w(org.) \times C_S{}^a(org.)/C_S(a)$

Substituting and re-arranging:

$$f_S = \frac{A_S(w)}{\varepsilon_S(w)} \times \frac{\varepsilon_S{}^w(org.)}{A_S{}^w(org.)} \times \frac{\varepsilon_S(a)}{A_S(a)} \times \frac{A_S{}^a(org.)}{\varepsilon_S{}^a(org.)}$$

Furthermore, $\varepsilon_S{}^w(org.) = \varepsilon_S{}^a(org.)$ since the extinction coefficient of the solute in the organic phase is constant, regardless of the aqueous solution with which the organic solution was partitioned.

Hence,

$$f_S = \frac{A_S(w)}{A_S(a)} \times \frac{A_S{}^a(org.)}{A_S{}^w(org.)} \times \frac{\varepsilon_S(a)}{\varepsilon_S(w)}$$

APPENDIX C

Physical Properties of the Ester Substrates

Ester	B.p. or M.p.(°C)	I.r. (μ - CCl_4)	N.m.r. (δ- CCl_4)
Methyl Benzoate	100-103°/23 mm (lit.[a] 199°/760 mm)	5.78,6.86,6.95,7.59,7.83	7.4-8.0 (m, 5H) 3.88 (s, 3H)
Methyl Para-Toluate	m.p. 32-3° (lit.[a] 33°)	5.79,6.97,7.84	7.87 (d,2H,J=8Hz) 7.15 (d,2H,J=8Hz) 3.85 (s,3H); 2.37(s,3H)
Methyl Ortho-Toluate	104-107°/20 mm (lit.[a] 97°/15 mm)	5.81,6.85,7.22,7.71,7.95	7.83 (m,1H) 7.20 (m,3H) 3.82 (s,3H); 2.57 (s,3H)
Methyl 2,6-Dimethyl Benzoate	120-122°/25 mm (lit.[b] 109°/19 mm)	5.76,6.83,6.97,7.92	7.0 (m,3H) 3.87 (s,3H) 2.32 (s,6H)
Methyl Para-Anisoate	m.p. 50-51° (lit.[a] 49°)		7.87 (d,2H,J=8Hz) 6.79 (d,2H,J=8Hz) 3.87 (s,3H); 3.86 (s,3H)
Methyl Para-Chloro Benzoate	m.p. 42-3° (lit.[a]44°)		7.93 (d,2H,J=8Hz) 7.35 (d,2H,J=8Hz) 3.87 (s,3H)
Methyl Para-Nitro Benzoate	m.p. 94-96° (lit.[a] 96°)		8.27 (s,4H) 4.00 (s,3H)

[a] Handbook of Chemistry and Physics, 51st Ed., 1971

[b] Reference 114.

FIGURE C-1

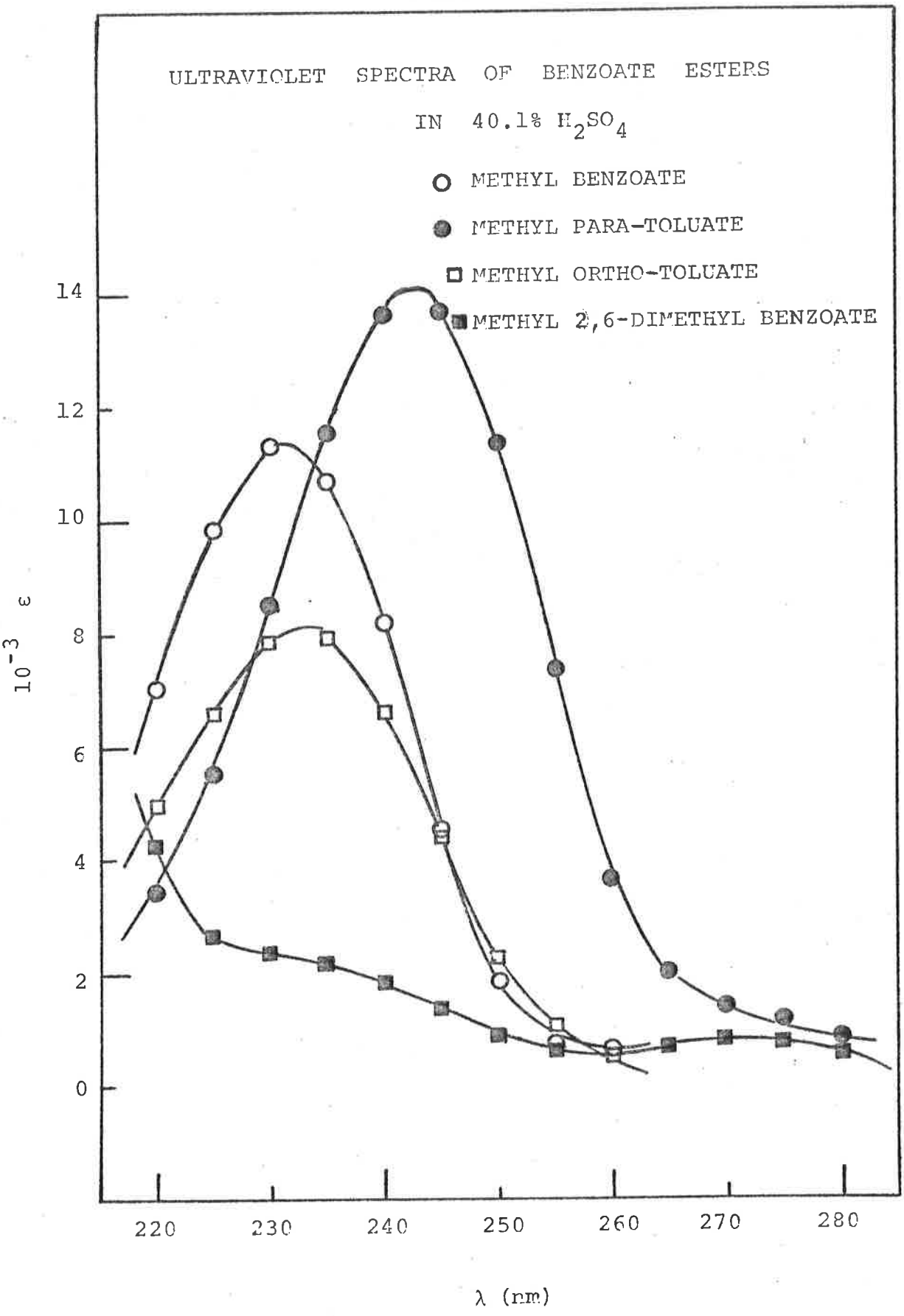

ULTRAVIOLET SPECTRA OF BENZOATE ESTERS
IN 40.1% H_2SO_4
METHYL BENZOATE
METHYL PARA-TOLUATE
METHYL ORTHO-TOLUATE
METHYL 2,6-DIMETHYL BENZOATE
10^{-3} ε
14
12
10
8
6
4
2
0
220
230
240
250
260
270
280
λ (nm)

FIGURE C-2

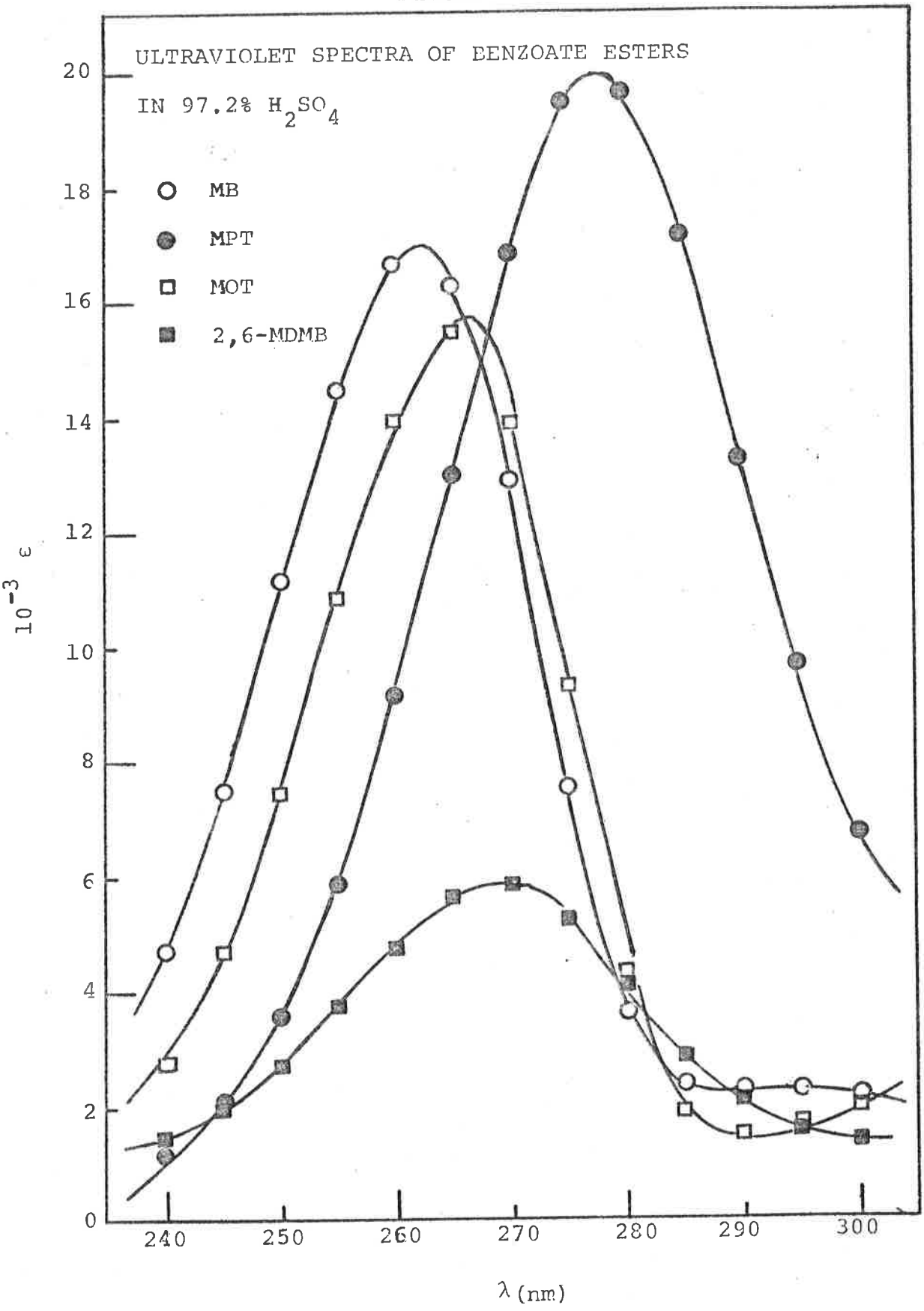

ULTRAVIOLET SPECTRA OF BENZOATE ESTERS
IN 97.2% H_2SO_4
MB
MPT
MOT
2,6-MDMB
10^{-3} ε
λ (nm)
0
2
4
6
8
10
12
14
16
18
20
240
250
260
270
280
290
300

FIGURE C-3

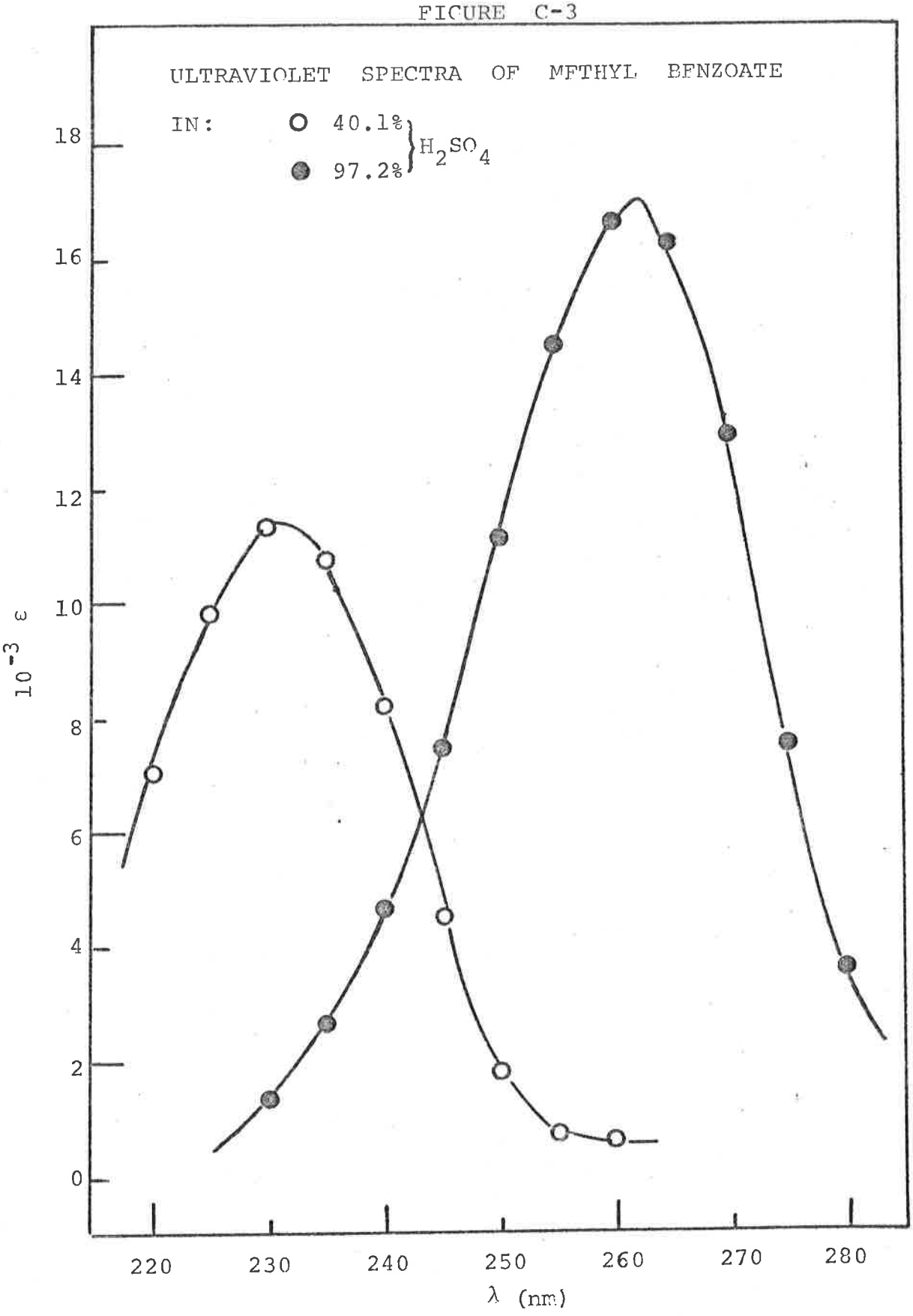

ULTRAVIOLET SPECTRA OF METHYL BENZOATE
IN: 40.1% 97.2% H2SO4
18
16
14
12
10
8
6
4
2
0
10-3 ε
220
230
240
250
260
270
280
λ (nm)

FIGURE C-4

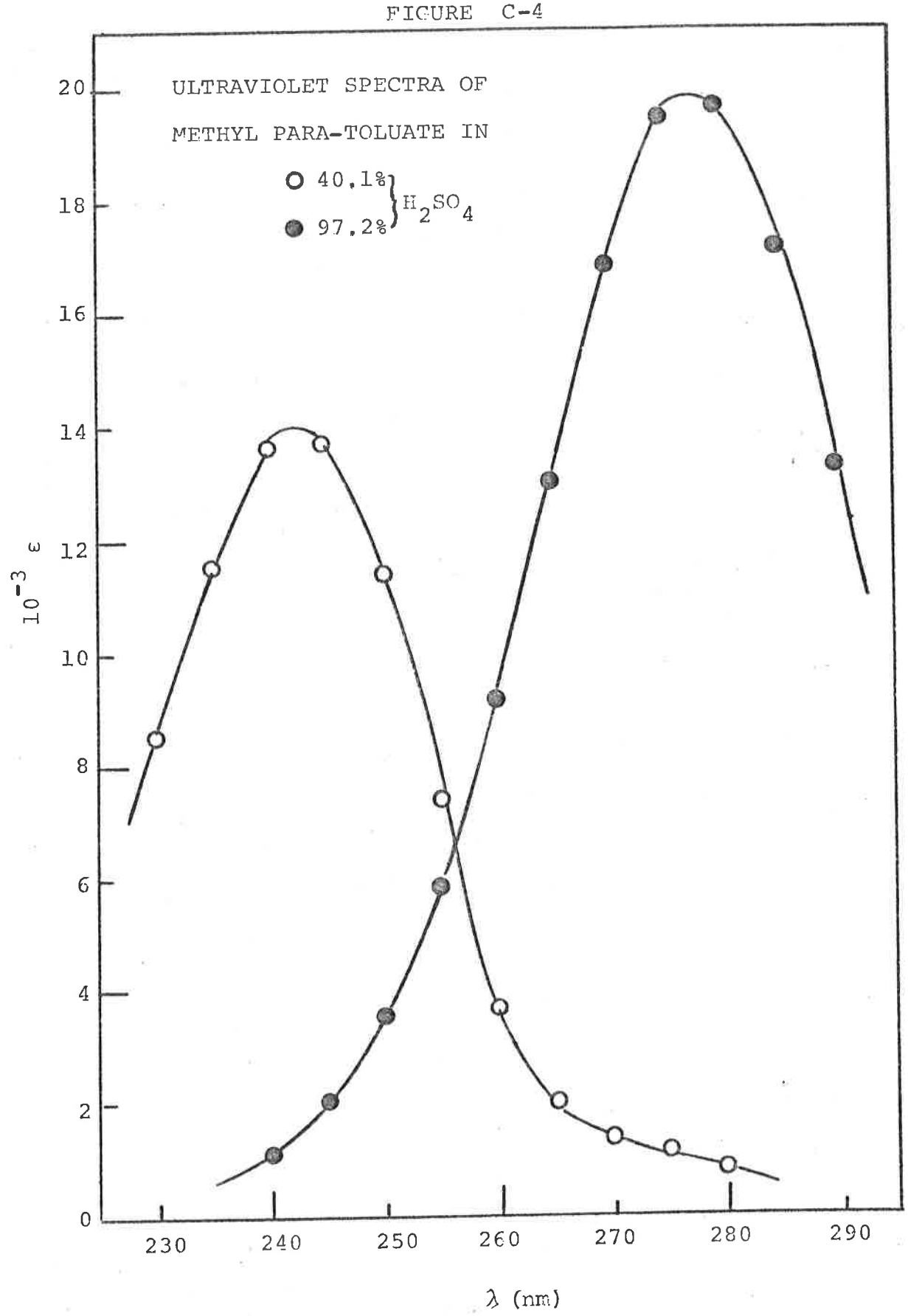

ULTRAVIOLET SPECTRA OF
METHYL PARA-TOLUATE IN
40.1%
97.2%
H2SO4
20
18
16
14
12
10
8
6
4
2
0
10-3 ε
230
240
250
260
270
280
290
λ (nm)

FIGURE C-5

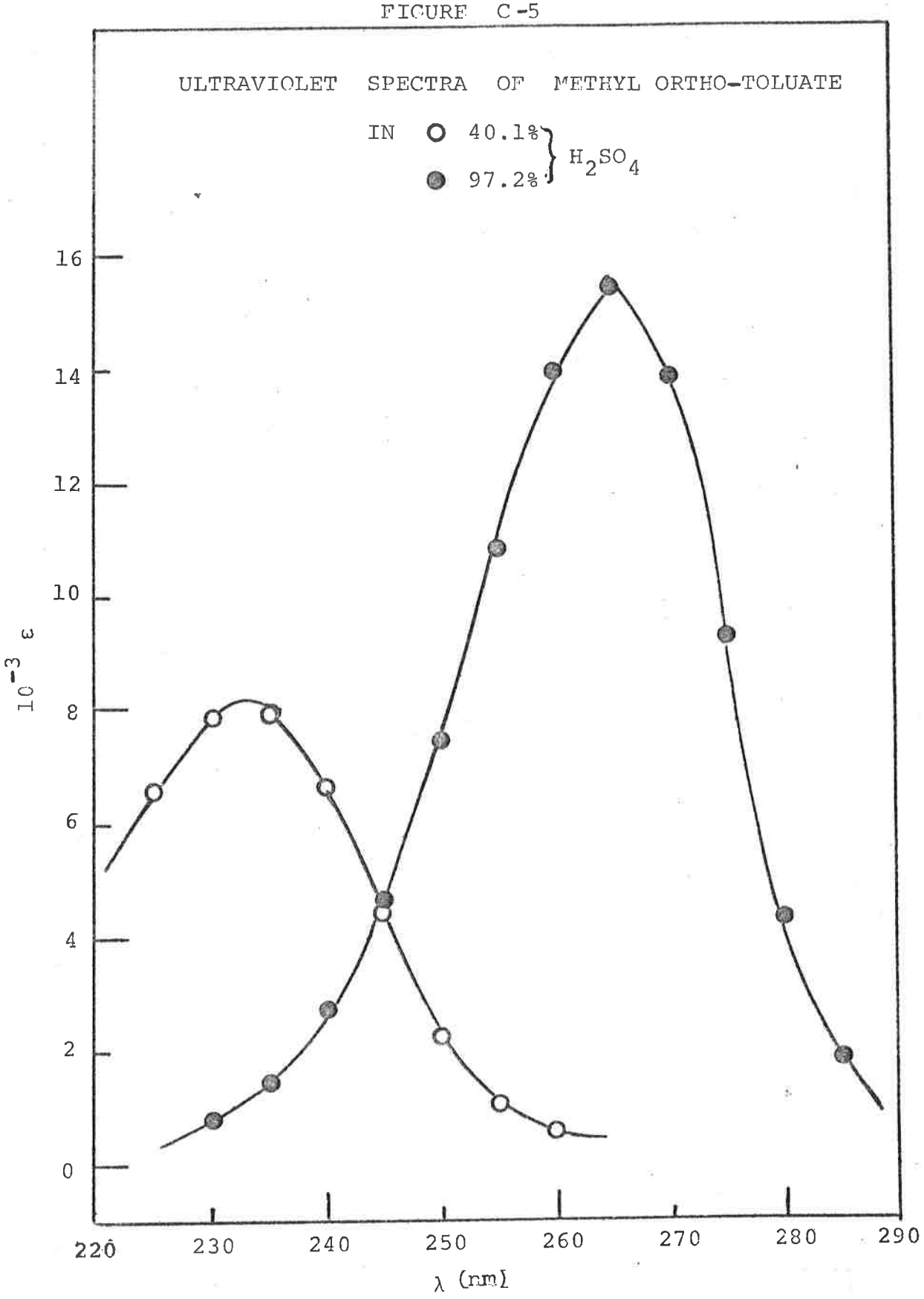
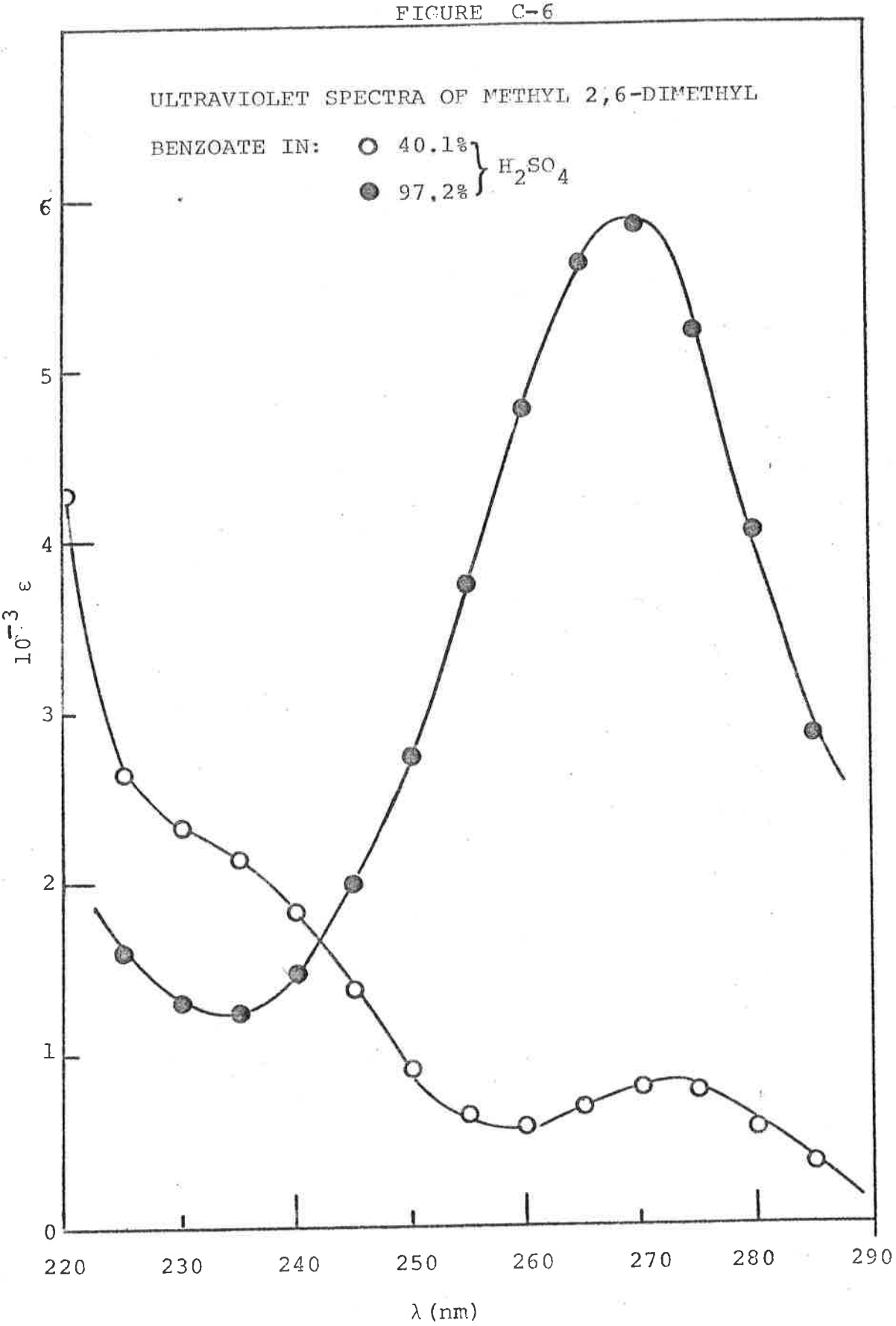

ULTRAVIOLET SPECTRA OF METHYL ORTHO-TOLUATE
IN 40.1% } H2SO4
97.2% }
16
14
12
10
8
6
4
2
0
10-3 ε
220
230
240
250
260
270
280
290
λ (nm)

FIGURE C-6


ULTRAVIOLET SPECTRA OF METHYL 2,6-DIMETHYL
BENZOATE IN: 40.1% 97.2% H2SO4
6
5
4
3
2
1
0
10^-3 ε
220
230
240
250
260
270
280
290
λ (nm)

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