1031. *Hydroxylation. Part II.*[1] *Electrophilic Hydroxylations with Trifluoroperoxyacetic Acid.*

By A. J. Davidson and R. O. C. Norman.

Quantitative results for the hydroxylation of three monosubstituted benzenes by trifluoroperoxyacetic acid in methylene chloride have been obtained and the electrophilic nature of the reagent established. The reagent has been used to convert chalcone into the 3-hydroxyflavylium cation, 4-phenylbut-1-ene into 1,2,3,4-tetrahydro-2-naphthol, and 4-*m*-anisylbut-1-ene into 6-methoxy-1,2,3,4-tetrahydro-2-naphthol. In the last two reactions cyclisation is concerted with the attack of the hydroxylating agent at the olefinic double bond, so that the results taken together demonstrate the feasibility of a process of electrophilic hydroxylation with concurrent ring-closure, as suggested by Ruzicka in his hypothetical scheme for the biogenesis of lanosterol from squalene.

The biosynthesis of the steroids involves the oxidative cyclisation of squalene to lanosterol,[2] but the details of this step remain to be clarified. Ruzicka suggested that it is initiated by addition of cationic oxygen, formally OH^+, to one of the terminal double bonds of squalene and that a series of four ring-closures, two 1,2-shifts of methyl groups, and the elimination of a proton then lead to lanosterol.[3] It is necessary only to assume that the naturally occurring all-*trans*-squalene is folded on the enzyme in a chair–boat–chair–boat conformation, that the transformations follow the rules of *anti*-planar 1,2-addition, 1,2-rearrangement, and 1,2-elimination, and that all the steps are concerted, so that no intermediates are formed by neutralisation of the cationic charge.[4] Moreover, suitable variations of the initial conformations and of the processes initiated by addition of a hydroxyl cation could give rise to the three main sub-groups of the pentacyclic triterpenes as well as to the tetracyclic triterpenes.[5]

Consistently with this hypothesis, the individual steps in the conversion of squalene into lanosterol are probably synchronous [6,7] and two 1,2-shifts of methyl groups and not one 1,3-shift are involved.[8] Further, although most "double-bond reagents" react with squalene *in vitro* more or less indiscriminately at all the double bonds, *N*-bromosuccinimide in a hydroxylic solvent preferentially oxidises the two terminal double bonds,[9] and squalene gives a mixture of isomeric tetracyclosqualenes when ring-closure is initiated by protonation of the terminal double bonds.[10] Evidence against the occurrence of various alternative ionic mechanisms has been presented,[7] but cyclisation may be initiated by a radical (*e.g.*, ·OH) and subsequent steps may take place after the loss of an electron from the cyclised radical.[11] However, although it is not yet possible to discount this possibility, an *in vitro* study has shown that the hydroxyl radical, produced by the irradiation of hydrogen peroxide, does not cyclise squalene, but gives glycols, apparently by random attack at the double bonds.[11]

Ruzicka's hypothesis is therefore strongly supported, but since there was no well established reaction *in vitro* in which ring-closure occurs synchronously with the addition of electrophilic hydroxyl to a double bond, we sought one; a preliminary account has been presented.[12]

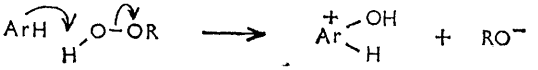
[1] Part I, Lindsay Smith and Norman, *J.*, 1963, 2897.
[2] Clayton and Bloch, *J. Biol. Chem.*, 1956, **218**, 305, 319; 1957, **224**, 175.
[3] Ruzicka, *Experientia*, 1953, **9**, 357.
[4] Ruzicka, *Proc. Chem. Soc.*, 1959, 341.
[5] Eschenmoser, Ruzicka, Jeger, and Arigoni, *Helv. Chim. Acta*, 1955, **38**, 1890.
[6] Tchen and Bloch, *J. Amer. Chem. Soc.*, 1956, **78**, 1516.
[7] Tchen and Bloch, *J. Biol. Chem.*, 1957, **226**, 931.
[8] Maudgal, Tchen, and Bloch, *J. Amer. Chem. Soc.*, 1958, **80**, 2589.
[9] van Tamelen and Curphey, *Tetrahedron Letters*, 1962, 121.
[10] Harvey, Heilbron, and Kamm, *J.*, 1926, 3136.
[11] Breslow, Barrett, and Mohacsi, *Tetrahedron Letters*, 1962, 1207.
[12] Brown, Davidson, and Norman, *Chem. and Ind.*, 1962, 1237.

Electrophilic Hydroxylating Species.—Several previous studies of electrophilic hydroxylation have centred around the reactions of benzenoid compounds with peroxides and peroxy-acids. Theory suggested that the hydroxyl cation should be present in acidified solutions of hydrogen peroxide owing to heterolysis of the conjugate acid of the peroxide [13]

$$H_2O_2 + H^+ \rightleftharpoons H_2\overset{+}{O}{-}OH \longrightarrow H_2O + OH^+$$

and in support of this, mesitylene gives mesitol when treated with hydrogen peroxide in the presence of acetic and sulphuric acids.[14] The electrophilic nature of aromatic oxidations by peroxides received support since polycyclic aromatic hydrocarbons are oxidised by perbenzoic acid at their nucleophilic centres rather than at those which are most reactive to " double-bond " reagents,[15] and the orders of reactivity of two series of aromatic ethers towards both perbenzoic acid and hydrogen peroxide in acetic acid containing a catalytic amount of sulphuric acid are those expected for an electrophilic reagent.[16,17] Trifluoroperoxyacetic acid is reported to be more effective than other per-acids in such aromatic oxidations.[18]

Two aspects of these oxidations remain in doubt. First, tracer experiments imply that neither peracetic nor performic acid forms OH^+ to a detectable extent, even in acid solution,[19] and it is therefore probable that the oxidations are initiated by nucleophilic displacement by the aromatic compound on an oxygen atom of the peroxy-compound (or its conjugate acid):



The greater reactivity of trifluoroperoxyacetic acid than other per-acids would then follow from the stability of the trifluoroacetate anion (the anion of a strong acid) as a leaving group. This factor does not, however, affect the issue of whether the hydroxylations should be classified as electrophilic.

The second, more fundamental problem is whether the peroxy-bond undergoes heterolysis or homolysis in the reactions mentioned above. The former has been assumed because the orders of reactivity and positions of attack are both those characteristic of electrophiles, but the hydroxyl *radical* is now known to possess electrophilic characteristics.[20,21] For example, anisole is about six times as reactive as benzene towards ·OH,[20] and gives the *o*- and *p*-hydroxy-derivatives in a ratio of ~6 : 1, no *meta*-substituted product being detectable.[20,22] Hence the order of reactivities of the aromatic ethers quoted above, and the fact that anisole gives only the *o*- and *p*-hydroxy-derivatives with trifluoroperoxyacetic acid,[23] do not in themselves enable the distinction to be made in these oxidations between the reagent's being an *electrophile* (*i.e.*, OH^+ or covalently bound hydroxyl from which OH is abstracted without its bonding-pair) and an *electrophilic radical* (*i.e.*, ·OH). This question is particularly pertinent since the peroxy-bond is susceptible to homolytic cleavage.

We decided, therefore, first to establish the electrophilic nature of a reagent capable of hydroxylating aromatic systems before examining the applicability of this reagent to the induction, in a suitable system, of ring-closure synchronously with hydroxylation. Trifluoroperoxyacetic acid was chosen because it is the most effective of the per-acids in oxidising aromatic compounds.[18]

[13] Evans and Uri, *Trans. Faraday Soc.*, 1949, **45**, 224.
[14] Derbyshire and Waters, *Nature*, 1950, **165**, 401.
[15] Roitt and Waters, *J.*, 1949, 3060.
[16] Friess, Soloway, Morse, and Ingersoll, *J. Amer. Chem. Soc.*, 1952, **74**, 1305.
[17] Davidge, Davies, Kenyon, and Mason, *J.*, 1958, 4569.
[18] Chambers, Goggin, and Musgrave, *J.*, 1959, 1804.
[19] Bunton, Lewis, and Llewellyn, *J.*, 1956, 1226.
[20] Norman and Radda, *Proc. Chem. Soc.*, 1962, 138.
[21] Dixon, Norman, and Buley, *J.*, 1964, 3625.
[22] Hamilton and Friedman, *J. Amer. Chem. Soc.*, 1963, **85**, 1008.
[23] McClure and Williams, *J. Org. Chem.*, 1962, **27**, 627.

Hydroxylation of Benzenoid Compounds with Trifluoroperoxyacetic Acid.—Since there are quantitative data [1,20] for the relative reactivities and isomer distributions in the free-radical hydroxylation of mono-substituted benzenes, the characteristics of trifluoroperoxyacetic acid as a hydroxylating reagent were examined by obtaining analogous data for it to compare hydroxylation by the two species.

One problem peculiar to the study of electrophilic substitutions in which the entering reagent is itself an activating group is that the initial product readily undergoes further substitution and measurements of relative reactivities and isomer distributions are not significant unless allowance can be made for this. For instance, the reaction of anisole with trifluoroperoxyacetic acid gave *o*- and *p*-hydroxy-derivatives in 27 and 7% yield, respectively, and this high *ortho* : *para*-ratio was attributed to the subsequent preferential oxidation of the latter product since, when equimolar proportions of the two products were treated with 0·5 mol. of the per-acid, twice as much of the *para* as the *ortho* compound was consumed in a given time.[23] To correct for this, we determined isomer distributions as a function of the mole ratio per-acid : anisole, and extrapolated a plot of the percentage of each isomer against this mole ratio to zero mole ratio. Results and the limiting isomer distributions so obtained are in Table 1.

TABLE 1.

Isomer distributions in the hydroxylation of monosubstituted benzenes, and their dependence on the concentration of per-acid.

Subst.	Mole ratio of per-acid to aromatic compound	Isomer distribution (%) *o*	*m*	*p*	Yield (%) of mono-hydroxylated products *
OMe	1·000	100·0	—	—	
	0·500	68·8	—	31·2	23
	0·333	68·2	—	31·8	25
	0·143	71·4	—	28·6	44
	0·036	73·2	—	26·8	53
	0 (extrapolation)	73·7	—	26·3	
Me	0·500	69·2	2·6	28·2	3
	0·072	75·6	2·3	22·1	
	0·036	75·8	2·2	22·0	17
	0·018	76·7	2·3	21·0	
	0·009	77·9	2·3	19·8	19
	0 (extrapolation)	78·2	2·3	19·5	
F	0·143	38·5	—	61·5	3
	0·072	35·6	—	64·4	5
	0·046	21·6	—	78·4	
	0·037	19·2	—	80·8	
	0·008	17·3	—	82·7	
	0 (extrapolation)	17·2	—	82·8	

* Based on added per-acid.

The isomer distributions for reactions of both anisole and toluene do not change very much until the mole ratio of per-acid to aromatic compound exceeds about 0·5, so errors due to extrapolation cannot be large. For fluorobenzene, the isomer distribution changes more drastically and the result obtained by the extrapolation is correspondingly less accurate. This difference no doubt arises from the very much lower reactivity of fluorobenzene than anisole and toluene and the consequent greater importance of further oxidation. Trends in the results indicate that *o*-cresol is more reactive than *p*-cresol to further oxidation and *p*-fluorophenol is more reactive than *o*-fluorophenol; also, whereas guaiacol is more reactive than *p*-methoxyphenol at low per-acid concentrations, this is reversed at higher ones, suggesting that the oxidations of these two phenols are reactions of different orders with respect to the per-acid, as could apply if the predominant reaction for guaiacol were *ortho*-hydroxylation (cf. ref. 24) with elimination of methanol,[16] and for *p*-methoxyphenol, hydroxylation *ortho* to the phenolic group [24] followed by further oxidation to the quinone.

[24] McClure, *J. Org. Chem.*, 1963, **28**, 69.

Toluene yielded small quantities of benzyl alcohol and benzaldehyde but no phenol. The formation of benzyl alcohol suggests the abstraction of hydride ion from the methyl group by the per-acid, and this is consistent with the evidence that benzylic carbonium ions are formed when 1,2,3,4-tetramethylbenzene is treated with trifluoroperoxyacetic acid in the presence of boron trifluoride.[25] Neither anisole nor guaiacol gave methylenedioxybenzene, but anisole gave phenol in very low yield.

The reactivities of anisole, toluene, and fluorobenzene relative to benzene were determined by a competitive method in which equimolar mixtures of pairs of aromatic compounds were treated with the per-acid and the phenolic products were analysed. Since a four-fold decrease in per-acid concentration produced changes in the ratios of *p*-cresol to phenol and guaiacol to *o*-cresol which were barely outside the limits of experimental accuracy, linear extrapolations were used to give the ratios at zero per-acid concentration (Table 2). Combination of these values with the limiting isomer distributions gives values for the reactivities relative to benzene: anisole, 530 ± 50; toluene, 11·7 ± 2·0.

The relative yields of *p*-fluorophenol and phenol varied widely with change in the per-acid concentration, and since the low yield of fluorophenols placed a lower limit on the per-acid concentration at which accurate values for the product ratios could be measured, the uncertainty in the extrapolated value is in this case large. The reactivity of fluorobenzene relative to benzene was therefore also determined by treating an equimolar mixture of the two with 0·7 mol. of the per-acid and measuring the proportional decrease in the concentrations of the starting materials.[26] The value obtained, 0·27, is in reasonable agreement with that (0·2) from the extrapolatory method.

The results are in Table 3, compared with those for hydroxylation by the hydroxyl radical.[1,20] Combination of the data for relative reactivities and isomer distributions in

TABLE 2.

Relative reactivities, and their dependence on the concentration of per-acid.

Aromatic compounds	Mole ratio of per-acid to total aromatic substrate	Mole ratio of products
		p-Cresol : phenol
Benzene, toluene	0·036	2·96
	0·009	2·45
	0 (extrapolation)	2·28
		Guaiacol : *o*-cresol
Toluene, anisole	0·036	37·2
	0·009	41·2
	0 (extrapolation)	42·5
		p-Fluorophenol : phenol
Benzene, fluorobenzene	0·107	1·2
	0·036	0·8
	0·018	0·4
	0 (extrapolation)	0·2

TABLE 3.

Comparison of results obtained with trifluoroperoxyacetic acid with those for homolytic hydroxylation.

	Trifluoroperoxyacetic acid				Hydroxyl radical			
	Isomer distribution (%)			Reactivity relative	Isomer distribution (%)			Reactivity relative
Aromatic compound	*o*	*m*	*p*	to benzene	*o*	*m*	*p*	to benzene
Anisole	73·7	0	26·3	530	84	0	16	6·35
Toluene	78·2	2·3	19·5	11·7	71	5	24	
Fluorobenzene ...	17·2	0	82·8	0·27	37	18	45	

[25] Buehler and Hart, *J. Amer. Chem. Soc.*, 1963, **85**, 2177.
[26] Ingold, Lapworth, Rothstein, and Ward, *J.*, 1931, 1959.

hydroxylation by trifluoroperoxyacetic acid leads to the partial rate factors set out in Table 4. These have an estimated uncertainty of ±20%, except for the value for f_m^{Me}: this is very sensitive to small errors in measurement of the low percentage of *m*-cresol, and the value of slightly less than unity cannot be taken to indicate that the *meta*-position in toluene is deactivated. (In most electrophilic substitutions f_m^{Me} lies between 1·3 and 6.)

TABLE 4.

Partial rate factors for hydroxylation by trifluoroperoxyacetic acid.

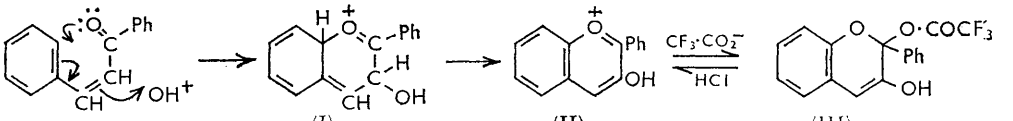
Aromatic compounds	Partial rate factors f_o	f_m	f_p
Anisole	1,170	—	830
Toluene	27·5	0·8	13·7
Fluorobenzene	0·14	—	1·35

Table 3 shows that the characteristics of trifluoroperoxyacetic acid as a hydroxylating agent are different from those of the hydroxyl radical. In particular, fluorobenzene gives an appreciable proportion of the *meta*-derivative with the hydroxyl radical while this could not be detected with the per-acid, and the spread in relative reactivities is far greater for the per-acid than for the radical. The data for reactions of the per-acid are typical of those in well established electrophilic substitutions,[27] and the spread in partial rate factors is comparable with those in protodesilylation and protodegermylation, from which we conclude that the per-acid reacts as an electrophile of relatively low selectivity.[27]

It is interesting that anisole gives so high an *ortho* : *para* ratio, for usually the methoxy-group, like others of $-I$, $+M$ type, is predominantly *para*-orienting,[28] as is the fluoro-substituent in this reaction. It is possible that *ortho*-substitution is here facilitated by hydrogen-bonding between substituent and reagent. On the other hand, the high *ortho* : *para* ratio of the cresols is not abnormal, for the methyl group gives similarly high ratios with many other electrophiles of low selectivity.[28]

Oxidation of Chalcone to the 3-Hydroxyflavylium Cation.—*trans*-Chalcone was oxidised in methylene chloride by the slow addition of 2 mols. of trifluoroperoxyacetic acid. Reaction was exothermic and when it had ceased a test for excess of peroxide was negative. After removal of the solvent and trifluoroacetic acid, the residue, which contained less than 10% of the original chalcone, was dissolved in a mixture of acetic and hydrochloric acids, boiled briefly, and then saturated with hydrogen chloride so as to convert the expected oxidation product, presumably in the form of the trifluoroacetate (III), into 3-hydroxyflavylium chloride (II). One component of the resulting mixture was identical with the authentic material as regards its visible absorption, its chromatographic properties in each of three eluting solvents, and its electrophoretic properties in a mixture of acetic and hydrochloric acids.

The annexed scheme is suggested to account for this conversion. Although *trans*-chalcone was used, the *cis*-isomer is present in equilibrium with it in acid solution.[29] The



(I) (II) (III)

reagent is written as OH^+ for simplicity, but hydroxylation may occur by nucleophilic displacement on the per-acid by the olefinic bond in chalcone.

3-Hydroxyflavylium stannichloride, obtained in 0·5% yield by treating the initial

[27] Stock and Brown in "Advances in Physical Organic Chemistry," ed. V. Gold, Academic Press, London, 1963, Vol. 1, p. 35.
[28] Norman and Radda, *J.*, 1961, 3610.
[29] Noyce and Jorgenson, *J. Amer. Chem. Soc.*, 1961, **83**, 2525.

oxidation product with excess of ammonium stannichloride, was characterised by satisfactory analytical data and by the identity of its visible spectrum with that of the authentic material, but attempts to isolate the 3-hydroxyflavylium cation as the chloride, ferrichloride, or perchlorate were unsuccessful. The low yield is probably the result partly of the occurrence of side-reactions at the other nucleophilic centres of chalcone and partly of the instability of the product, particularly towards oxidation (benzoic acid was identified as a by-product). The stability of the flavylium cation is markedly increased by the introduction of methoxyl groups at the 2′-, 4′-, 5-, and 7-position, but when chalcones substituted with methoxyl groups at the appropriate positions were oxidised by trifluoroperoxyacetic acid, ring-closure occurred to give flavylium salts without hydroxylation at the 3-position. These reactions have been discussed.[12]

Oxidative Cyclisation of 4-Arylbut-1-enes.—The oxidation of 4-phenylbut-1-ene (IV; R = H) by trifluoroperoxyacetic acid in methylene chloride, followed by neutralisation, gave mainly the 2-trifluoroacetate and the 1,2-ditrifluoroacetate esters of 4-phenylbutane-1,2-diol, which are the normal products of the reaction of this per-acid with an olefinic double bond.[30] Gas chromatography showed that a number of other products were present in low yield, two of which had retention times identical with those of 1,2,3,4-tetrahydro-2-naphthol (VI; R = H) and its trifluoroacetate ester, respectively, the relative peak areas indicating that the latter was present in the larger quantity. The tetralol, if formed in the oxidation, would be expected to give its trifluoroacetate in the reaction conditions, for this ester was formed from the alcohol by addition of trifluoroacetic acid at room temperature. A portion of the oxidation product which was not neutralised gave no peak corresponding to 1,2,3,4-tetrahydro-2-naphthol and a relatively larger one corresponding to its trifluoroacetate, while treatment of the oxidation product with methanolic hydrogen chloride under conditions in which trifluoroacetate esters are hydrolysed [30] led to an increase in the peak corresponding to 1,2,3,4-tetrahydro-2-naphthol and the disappearance of that corresponding to its trifluoroacetate. 4-Phenylbutane-1,2-diol was isolated as the main product after hydrolysis, while the peaks corresponding to its mono- and di-trifluoroacetate esters were no longer present. 1-Indanylmethanol and 1-methyleneindane, other possible products of oxidative cyclisation, and tetralin, a possible product of acid-catalysed cyclisation, were not detected either before or after hydrolysis.

Although it was not possible to isolate the tetralol either by distillation or by gas chromatography, because of the presence of other products of similar volatility and retention times, the above observations leave little doubt that oxidative cyclisation had occurred. The yield of the tetralol after hydrolysis, estimated by gas chromatography, was 7%.

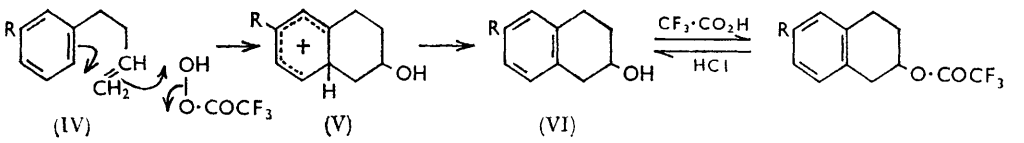
The reaction of 4-*m*-anisylbut-1-ene (IV; R = OMe) with trifluoroperoxyacetic acid in methylene chloride was more vigorous than that of (IV; R = H) and the solution refluxed under the heat of the reaction. Gas chromatography showed that many products were present of which one had the same retention time as 6-methoxy-1,2,3,4-tetrahydro-2-naphthol (VI; R = OMe). The trifluoroacetate of this compound had a retention time very slightly different from that of a second component of the mixture, and its presence may therefore have been masked. This second component was non-alcoholic since it was unaffected by treatment with trifluoroacetic acid, nor was it a trifluoroacetate ester since it was unaffected by methanolic hydrogen chloride. Two other major products had retention times equal to those of products obtained by treating the epoxide of the anisylbutene with trifluoroacetic acid, and since these two peaks were eliminated when the mixture was hydrolysed with methanolic hydrogen chloride, they were probably due to the mono- and di-trifluoroacetate esters of 4-*m*-anisylbutane-1,2-diol. This hydrolysis resulted also in an increase of the peak thought to be due to (VI; R = OMe), and it was now possible to isolate this material by collection from the column: it proved to be identical with authentic 6-methoxy-1,2,3,4-tetrahydro-2-naphthol. A small, unidentified peak in the original

[30] Emmons, Pagano, and Freeman, *J. Amer. Chem. Soc.*, 1954, **76**, 3472.

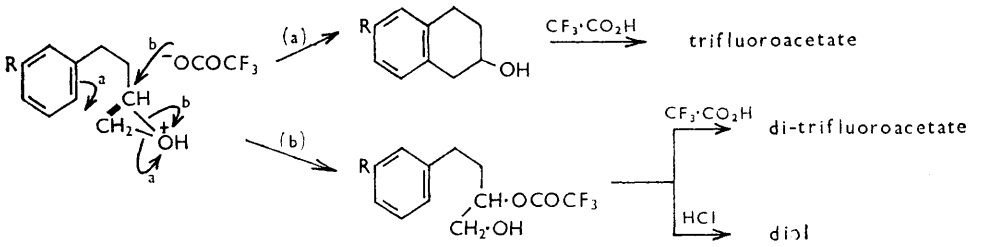
oxidation mixture also increased in area on hydrolysis, and this may be the 8-methoxy-isomer of (VI; R = OMe), but its yield as estimated from its peak area was less than 2% of that of (VI; R = OMe). Finally, a new peak which appeared on hydrolysis was found to be due to 4-*m*-anisylbutane-1,2-diol.

The reactions of the two arylbutenes with the per-acid evidently follow similar courses, but the extent of ring-closure differs appreciably in the two cases. Thus, after hydrolysis of the oxidation mixture, the yield of methoxytetralol was 25% whereas that of the unsubstituted tetralol was 7%; further, the relative quantities of cyclised product and glycol were 10 : 90 for the parent compound (IV; R = H) and 80 : 20 for the methoxy-derivative (IV; R = Me).

The results are consistent with the following scheme for ring-closure, which is discussed further below. Analogous reactions in which cyclisation is initiated by electrophilic attack on an olefin have been reported: *e.g.*, 1-phenylpentan-3-ol is converted into 1-methyltetralin by sulphuric acid, and reaction is thought to occur through the olefin.[31]



Evidence for the Concerted Nature of the Oxidative Cyclisations.—An alternative to the reaction scheme suggested above for the formation of the tetralols is that epoxidation of the olefin occurs first and is followed by acid-catalysed reactions leading both to the cyclised products and to the diols and their derivatives:



When 4-phenylbut-1-ene epoxide was treated with excess of trifluoroacetic acid, the 2-trifluoroacetate and 1,2-ditrifluoroacetate esters of 4-phenylbutane-1,2-diol were formed but there was no evidence for the formation of either 1,2,3,4-tetrahydro-2-naphthol or its trifluoroacetate ester. Hydrolysis of the mixture of products gave 4-phenylbutane-1,2-diol together with about 1% of a compound whose retention time was the same as that of 1,2,3,4-tetrahydro-2-naphthol. Since hydrolysis of the per-acid oxidation product gave this compound and the diol in a ratio of 10 : 90, it is clear that the epoxide route can account for only a very small fraction of tetralol formed by trifluoroperoxyacetic acid oxidation of 4-phenylbut-1-ene. The trace of the tetralol which does arise from the epoxide probably results from acid-catalysed cyclisation of the ditrifluoroacetate, for 4-phenylbutan-1-ol does not cyclise in acidic conditions [32] and therefore it may be presumed that 4-phenylbutane-1,2-diol would not.

Similar treatment of 4-*m*-anisylbut-1-ene epoxide gave the methoxytetralol and the diol in the ratio 18 : 82 after hydrolysis, but again there was no evidence for ring-closure occurring prior to hydrolysis. It is therefore apparent that the cyclised product mainly arises in the per-acid oxidations by a route which does not involve the epoxide.

[31] Roblin, Davidson, and Bogert, *J. Amer. Chem. Soc.*, 1935, **57**, 151.
[32] Heck and Winstein, *J. Amer. Chem. Soc.*, 1957, **79**, 3105.

By allowing for the proportions of the tetralols resulting from hydrolysis of the trifluoroacetates, it may be deduced that the introduction of *m*-OMe increases the ratio of the rates of ring-closure to epoxidation by a factor of ~30. The data for the effects of aromatic substituents on the rates of epoxidation of stilbenes and olefins with a phenyl substituent as far removed from the double bond as in the aryl-1-butenes [33] indicate that *m*-OMe would decrease the rate of epoxidation by less than a factor of 2, so that this substituent increases the rate of ring-closure compared with that for the unsubstituted compound at least 15-fold. [This may be compared with the factor of ~6 by which the introduction of a *m*-OMe group can be calculated to increase the rate of ring closure (to form tetralin derivatives) when 4-phenyl-1-butyl *p*-bromobenzenesulphonate is solvolysed in formic acid.[32,34]] The rate-determining step in the reactions leading to ring-closure of the anisylbutene must therefore involve the aromatic nucleus in such a way that *m*-OMe is able to enhance the rate relative to that for the unsubstituted compound. This step cannot be the addition of a hydroxyl cation to the olefinic bond unless aryl-participation occurs, for the aromatic ring is some distance from this functional centre and in any case a *m*-OMe substituent would have a retarding and not an enhancing effect. Two possible explanations remain: either (i) there is a rapid and reversible addition of a hydroxyl cation to C_2, followed by a relatively slow ring-closure (which would be faster for the *m*-methoxy-substituted compound since it would occur *para* to the activating OMe group), or (ii) aryl-participation occurs to assist hydroxylation so that oxidation and ring-closure are concerted. Such participation, at least for the methoxy-compound, would necessarily be of the Ar_2-6 type [34] [*i.e.*, as shown in (IV) to (VI)] rather than of Ar_1-5 type followed by ring-enlargement,[32] since a *m*-OMe substituent, while assisting the former by its stabilising effect on (V), should retard the latter.

It is possible to distinguish between these alternatives. If aryl-participation were not involved, cationic addition to the olefinic bond should occur more readily at the terminal carbon atom, to give a secondary carbonium ion, leading to at least a proportion of five-membered cyclised products, by analogy with the findings that both 2-methyl-4-phenylbut-2-ene [35] and 3,3-dimethyl-3-phenylpropan-1-ol [31] cyclise in presence of acid to give 1,1-dimethylindane, the latter reacting *via* the olefin, 3,3-dimethyl-3-phenylprop-1-ene.[31] Yet one characteristic of our reactions is that ring-closure occurs apparently specifically to give the six-membered tetralol system and not the five-membered indanol system. It is probable, then, that (ii) correctly describes the reaction, and this is consistent with the fact that six-membered rather than five-membered cyclisation occurs, for studies of Ar_2-5- and Ar_2-6-assisted reactions indicate that ring-closure occurs more readily to give six-membered rings.[34]

One further aspect of the suggested mechanism for cyclisation requires comment. The acid-catalysed opening of the epoxides of the arylbutenes should lead chiefly to the secondary carbonium ion, $Ar{\cdot}CH_2{\cdot}CH_2{\cdot}\overset{+}{C}H{\cdot}CH_2OH$, and the formation of the 2-trifluoroacetate ester of the diol in each case is in accord with this. This ion could also in principle bring about cyclisation to indanols, yet none were detected. Again, the ability of the protonated epoxide to open heterolytically, coupled with the presence of an aryl substituent in a suitable position for nucleophilic neighbouring-group participation, suggests that cyclisation to tetralols should ensue, as it does when cyclisation is initiated by the addition of cationic hydroxyl, yet no such products could be detected. A difference in the behaviour of the carbonium ions formed from an epoxide and from electrophilic addition to the related olefin has been discussed,[36] and a similar interpretation may apply in the protonation of the arylbutene epoxides: that is, as the oxygen moves away from the developing carbonium

[33] Yukawa and Tsuno, *Bull. Chem. Soc. Japan*, 1959, **32**, 971; Swern, *J. Amer. Chem. Soc.*, 1947, **69**, 1692.
[34] Heck and Winstein, *J. Amer. Chem. Soc.*, 1957, **79**, 3114.
[35] Bogert and Davidson, *J. Amer. Chem. Soc.*, 1934, **56**, 185.
[36] Ley and Vernon, *J.*, 1957, 3256.

ion centre it shields it to the extent that this centre is a weaker electrophile than that which develops as electrophilic oxygen adds to one end of the double bond, and, while it is reactive enough to undergo a neutralisation reaction with trifluoroacetate ion, it is not sufficiently electrophilic to react, intramolecularly, with the comparatively weak nucleophiles, benzene and anisole.

Experimental

Trifluoroperoxyacetic Acid.—The per-acid was prepared from trifluoroacetic anhydride since when it is prepared from trifluoroacetic acid its solutions are less stable and generally give lower yields of hydroxylated products with aromatic compounds.[18] Commercial "high-test" hydrogen peroxide, estimated as 83% (w/w) (1·68 ml., 1·0 mol.), was suspended in methylene dichloride (20 ml.) at 0° and trifluoroacetic anhydride (14·5 g., 1·2 mol.) was added. The solution was kept at 0°, with occasional shaking, for about 15 min. by which time it had become homogeneous and was estimated to contain about 0·05 moles of per-acid.

Aromatic Hydroxylations.—(a) *Analysis.* Gas chromatography was used for the quantitative analysis of reaction mixtures. The following columns were employed, in each of which nitrogen was the carrier. Inlet pressures were between 30 and 50 cm. with atmospheric pressure at the outlet, and a hydrogen-inject flame-ionisation detector coupled to a Sunvic recorder gave a linear response.

Column No.	Dimensions	Coating material and inert support	Temp.
1	200 cm. × 4·5 mm.	Diethylene glycol adipate polyester (25% w/w) and phosphoric acid (3% w/w) on Embacel	143°
2	200 cm. × 2·0 mm.	Tri-2,4-xylyl phosphate (5% w/w) on Embacel	90
3	200 cm. × 2·0 mm.	Polyethylene glycol monostearate "400" (10% w/w) on Celite	50

The relative amounts of materials in the reaction mixtures were determined by combining the peak areas, measured by constructing triangles made up by the tangents to the Gaussian curves and the intercepts on the base line, with the relative responses of the detector to these compounds. The results quoted are averages of at least three analyses in each case, and the reproducibility of percentage compositions was greater than ±2%. Synthetic mixtures of the materials were submitted to the extraction procedure used after each reaction and it was shown that there was no preferential loss of any component.

(b) *Isomer distributions.* The procedure used for determining the relative quantities of monohydroxylated derivatives of anisole, toluene, and fluorobenzene is described with reference to anisole. Trifluoroperoxyacetic acid (0·5 mol.) in methylene dichloride (20 ml.) at 0° was added dropwise during 1 hr. to a vigorously stirred solution of anisole (10·8 g., 1·0 mol.) in methylene dichloride (20 ml.). The temperature was maintained below 10° and, when the addition was complete, stirring was continued for 10 min. Methylene dichloride (100 ml.) was added and the solution was extracted with 10% aqueous sodium hydrogen carbonate (3 × 50 ml.) until the extracts were alkaline. The aqueous extracts were combined, acidified if necessary, and themselves extracted with methylene dichloride (2 × 50 ml.). The original solution and the methylene dichloride extracts were combined and extracted with 2N-sodium hydroxide (4 × 25, 2 × 50 ml.), and these extracts, after acidification with concentrated hydrochloric acid, were extracted with ether (4 × 25, 2 × 50 ml.). The ethereal solution was dried ($MgSO_4$), ether was distilled off, the solution was warmed to 60°/30 cm. to remove the last traces of acid, and the residue was dissolved in ether (10 ml.) for gas chromatography. Other experiments were carried out with different mole ratios of per-acid to anisole (Table 1).

Toluene and fluorobenzene were oxidised similarly, save that for fluorobenzene the per-acid was added more slowly, during 1½ hr., and the temperature of the mixture was kept as close to 20° as possible.

Guaiacol was oxidised similarly with 0·5 mol. of per-acid. The bicarbonate-insoluble material was washed and dried ($MgSO_4$), and the residue after distillation of the methylene dichloride was dissolved in ether and examined by gas chromatography (column 2) for the presence of methylenedioxybenzene. A similar test was carried out on the alkali-insoluble product of the oxidation of anisole. In neither case was methylenedioxybenzene detected.

The alkali-soluble product from anisole was shown to contain phenol, and the alkali-insoluble product from toluene was shown to contain benzaldehyde and benzyl alcohol.

The three hydroxyanisoles were fully resolved by column 1 and the cresols and fluorophenols by column 2. The response ratio of guaiacol to *p*-hydroxyanisole was 1·55, while the relative peak areas for the cresols and fluorophenols were proportional to within ±2% to the relative quantities of these materials. Because of the large difference in retention times of guaiacol and *p*-hydroxyanisole (11 and 47 min., respectively) and the large ratio of their relative quantities resulting from oxidation, it was found that it was more accurate to analyse these isomers separately. Each was determined relative to bibenzyl as a standard, guaiacol being estimated after dilution of the solution in which *p*-hydroxyanisole was determined.

The relative yields of monohydroxylated product, based on the per-acid added, were determined by the addition of external standards, bibenzyl being used for the hydroxyanisoles and diphenylmethane for the cresols and fluorophenols.

(c) *Competitive hydroxylations.* The procedure used for determining the relative reactivities of anisole and toluene is typical. Trifluoroperoxyacetic acid (0·072 mol.) in methylene dichloride (20 ml.) at 0° was added dropwise during 1 hr. to a vigorously stirred mixture of anisole (37·8 g., 1·0 mol.) and toluene (32·2 g., 1·0 mol.). The remainder of the procedure was the same as that described for the hydroxylation of anisole. Experiments were also carried out with different mole ratios of per-acid and aromatic compound.

The relative extents of monohydroxylation of anisole and toluene were measured by comparison of the amounts of guaiacol and *o*-cresol formed. Since this ratio was large (~40), *o*-cresol was determined (column 2) in a concentrated solution relative to a known weight of added diphenylmethane, chosen to give approximately equal areas, and the solution was then diluted and guaiacol was determined relative to a known weight of added durene. Combination of the resulting relative peak areas with the measured response ratios of equal weights of *o*-cresol and diphenylmethane (0·73) and of guaiacol and durene (0·46) then gave the relative extents of formation of the two phenols.

The relative reactivities of toluene to benzene and of benzene to fluorobenzene were obtained directly from the relative peak areas of *p*-cresol and phenol and of *p*-fluorophenol and phenol, respectively, together with the measured response ratios (0·87 and 0·62, respectively).

The reactivity of fluorobenzene relative to that of benzene was also determined as follows. A mixture of benzene (3·90 g., 1·0 mol.) and fluorobenzene (4·80 g., 1·0 mol.) was diluted to 20 ml. with dry methylene dichloride. One half of this solution was oxidised with trifluoroperoxyacetic acid (0·7 mol.) in methylene dichloride (20 ml.), the acid being added during 15 min. while the solution was stirred and the temperature was maintained at about 20°. Stirring was continued for 20 min. and the solution was then extracted with 2N-sodium hydroxide (2 × 25 ml.). The aqueous solution was extracted with ether (4 × 25 ml.) and the ethereal extract together with the original methylene dichloride solution was dried ($MgSO_4$). Most of the ether and methylene dichloride was distilled off very slowly through a spiral column with a maximum still-head temperature of 42°, the column was then washed down with ether, and the resulting solution was made up to 200 ml. by the addition of more ether. The second half of the original mixture of benzene and fluorobenzene was treated in the same way except that trifluoroacetic acid was substituted for trifluoroperoxyacetic acid. The proportional decreases in the concentrations of benzene and fluorobenzene on oxidation were found by gas chromatography of the resulting solutions (column 3), toluene being used as external standard (response ratios: benzene to toluene, 1·08; fluorobenzene to toluene, 0·86).

Oxidation of Chalcone.—(a) *Analytical methods.* The paper-chromatographic solvents used were: (i) Forestal (HOAc–HCl–H_2O) (30 : 3 : 10); (ii) "BWA" (the lighter liquid phase obtained from n-butanol, water, and acetic acid) (4 : 5 : 1); (iii) 2N-hydrochloric acid–acetic acid (7 : 3). For ordinary chromatograms Whatman No. 1 paper was employed, with descending technique, at a constant temperature of 24°. For strip-chromatograms Whatman No. 4 paper was used and was cut while wet. The paper was extracted as quickly as possible with a suitable solvent and the ultraviolet and visible spectra of the extracts were recorded by comparison with an extract obtained in the same way from blank paper. The spray developer used to identify the hydroxyflavylium salts was made from an aqueous solution of diazotised sulphanilic acid, freshly prepared from a solution of sulphanilic acid (1%) in 1N-hydrochloric acid (4 ml.), 5% aqueous sodium nitrite (2 ml.), and 20% aqueous potassium carbonate (4 ml.). For electrophoresis, a Locarte High-voltage Paper Electrophoresis instrument was used with Whatman No. 1 paper. The 3-hydroxyflavylium cation moved only in Forestal (~5 cm. in 3 hr.) of the solvents examined.

(b) *Preparation of 3-hydroxyflavylium salts.* ω-Acetoxyacetophenone [37] (10·0 g., 1·0 mol.) and salicylaldehyde (6·0 g., 1·0 mol.) were dissolved in dry ether (100 ml.) and hydrogen chloride was bubbled through the solution for 1 hr. at 0°,[38] and then for a further 3 hr. after removal of the ice-bath. The solution was then kept in the dark at 0° for 14 days during which time impure 3-hydroxyflavylium chloride gradually precipitated as bright red crystals which were removed daily. Both recrystallisation from 15% hydrochloric acid and precipitation from isopentyl alcohol by the addition of light petroleum were ineffective as methods of purification.

The crude chloride (5·0 g.) was dissolved in the minimum of hot glacial acetic acid and the solution was treated with a large excess of concentrated hydrochloric acid saturated with anhydrous ferric chloride. A brown oil was precipitated which was caused to crystallise, after the solution had stood for 2 days, by scratching the flask. This crude material was reprecipitated from hot glacial acetic acid by the addition of anhydrous ferric chloride in concentrated hydrochloric acid, giving *3-hydroxflavylium ferrichloride* (7·8 g.; 95%) as red crystals, m. p. 227—233° (decomp.) (Found: C, 42·9; H, 2·6; Cl, 28·5; Fe, 12·7. $C_{15}H_{11}Cl_4FeO_2$ requires C, 42·8; H, 2·6; Cl, 33·8; Fe, 13·3%). Maximum absorption in methylene chloride occurred at 444, 300, 252, and 230 mμ ($\log_{10}\varepsilon$ 4·42, 4·06, 4·29, and 4·30) and maximum absorption in HOAc–HCl (10 : 1) was at 435 mμ.

The crude chloride (2·0 g.) was dissolved in the minimum of hot glacial acetic acid and an excess of 60% perchloric acid was added. Slow cooling of the solution precipitated *3-hydroxyflavylium perchlorate* as purple-red crystals which, reprecipitated from hot glacial acetic acid by the addition of 60% perchloric acid, gave a purer product (2·2 g., 88%), m. p. 230—235° (Found: C, 54·2; H, 3·2; Cl, 10·0. $C_{15}H_{11}ClO_6$ requires C, 55·8; H, 3·4; Cl, 11·0%).

The crude chloride (5·0 g.) in boiling acetic acid–hydrochloric acid (10 : 1) was treated with excess of concentrated aqueous ammonium stannichloride. The solution, cooled slowly during 5 days, deposited *3-hydroxyflavylium stannichloride* as red crystals which, after being washed with methylene chloride and a small quantity of 2N-hydrochloric acid, had m. p. 215—217° (6·2 g.; 82%) (Found: C, 46·6; H, 3·0; Cl, 25·6. $C_{30}H_{22}Cl_6O_4Sn$ requires C, 46·3; H, 2·8; Cl, 27·4%). A test with ammonium phosphomolybdate showed that the material contained tin. The stannichloride had maximum absorption at 435 mμ ($\log_{10}\varepsilon$ 4·69) in HOAc–HCl (10 : 1).

(c) *The reaction of chalcone with trifluoroperoxyacetic acid.* Trifluoroperoxyacetic acid (2 mol.) in methylene dichloride (50 ml.) at 0° was added during 30 min. to a solution of *trans*-chalcone (15 g., 1 mol.) in methylene dichloride (25 ml.) at room temperature in the dark. The solution began to reflux gently under the heat of the reaction and, when addition was complete, refluxing was continued on a water-bath for 30 min. A test for peroxide was then negative. Methylene dichloride and trifluoroacetic acid were distilled off under reduced pressure and at a maximum temperature of 50°, leaving a dark red semi-solid. Part of this (1 g.) was treated with Brady's reagent (5 ml.) to give chalcone 2,4-dinitrophenylhydrazone (0·18 g., 10%) identical (m. p. and mixed m. p.) with the authentic material. A second part was suspended in ether and hydrogen chloride was bubbled through for 1 hr. at 0°, but no crystalline product was obtained.

The remainder of the residue was immediately dissolved in 50 ml. of glacial acetic acid–concentrated hydrochloric acid (10 : 1) and the solution was boiled briefly, cooled, and saturated with hydrogen chloride. A small portion of this solution was examined spectroscopically and chromatographically: it had the same properties as a solution of the crude 3-hydroxyflavylium chloride as regards its visible absorption, R_F values in each of our three solvents, and electrophoretic behaviour in Forestal. Most of this solution was then concentrated to about 20 ml. under reduced pressure and filtered. The filtrate was boiled and an excess of a concentrated aqueous solution of ammonium stannichloride was added. The solution was allowed to cool slowly in the dark and after 5 days the solvent was decanted from a solid brown precipitate. The precipitate was repeatedly washed by decantation with methylene chloride until the washings were colourless, leaving a residue which consisted partly of a white powder and partly of a red crystalline material which adhered to the walls of the flask. The crystals were removed manually and were washed again with methylene dichloride and a small quantity of 2N-hydrochloric acid. The resulting material, m. p. 210—215°, had the same ultraviolet and visible absorption spectrum (in HOAc–HCl, 10 : 1) as the authentic 3-hydroxyflavylium stannichloride (Found: C, 46·7; H, 3·1. Calc. for $C_{30}H_{22}Cl_6O_4Sn$: C, 46·3; H, 2·8%).

[37] Rather and Reid, *J. Amer. Chem. Soc.*, 1919, **41**, 75.
[38] Reichel and Burkart, *Annalen*, 1938, **536**, 164.

Oxidation of 4-Arylbut-1-enes.—(a) *Analytical and identification methods.* The gas-chromatographic column (200 cm. × 2 mm.) was packed with Apiezon "L" grease (10% w/w) coated on Embacel and was operated at 126° and 147° for the analysis of products from 4-phenylbut-1-ene and 4-*m*-anisylbut-1-ene, respectively. Materials were collected from the column by passing the eluant gas through a cold-trap at −70° and then through an electrostatic precipitator at 15,000 v, while a by-pass allowed 1% of the eluant to pass through to a hydrogen-inject flame ionisation detector.

Relative quantities of materials in the oxidation mixtures were determined by using external standards (2,3-dimethylnaphthalene and phenyl-*o*-tolylmethanol for the phenylbutene and anisylbutene systems, respectively) and measuring the response ratios for each product relative to the appropriate standard.

(b) *Materials.* 4-Phenylbut-1-ene, prepared from allyl bromide and benzylmagnesium chloride by adaption of a method used for the preparation of 3-phenylprop-1-ene,[39] distilled as a colourless oil, b. p. 76—79°/22 mm., n_D^{20} 1·5075 (lit.,[40] 1·5059) (Found: C, 89·8; H, 9·6. Calc. for $C_{10}H_{12}$: C, 90·9; H, 9·1%). The olefin was converted with perbenzoic acid [41] into its epoxide which was obtained by distillation as a colourless oil, b. p. 108—110°/12 mm., n_D^{20} 1·5165 (lit.,[42] 1·5129).

4-*m*-Anisylbut-1-ene was prepared from *m*-methoxybenzyl bromide and allyl bromide by the method used for 4-phenylbut-1-ene. The product after distillation contained about 10% of *m*-methoxybenzyl bromide, estimated by both microanalysis and gas chromatography, and this was removed as follows. Part of the reaction product (5 g.) was added to broken sodium wire (0·5 g.) and the mixture was heated. When the initial reaction had subsided, the rest of the product (35 g.) was added and the mixture was gently heated for 30 min. and then left for 2 hr. Excess of ethanol was added, and after 30 min. water was added and the organic products were extracted into ether. The ethereal layer was dried, the solvent was removed, and fractional distillation yielded 4-m-*anisylbut-1-ene* (30 g.; 53%) as a colourless oil, b. p. 54—55°/0·35 mm., n_D^{20} 1·5190 (Found: C, 80·8; H, 8·9. $C_{11}H_{14}O$ requires C, 81·5; H, 8·6%). The olefin was converted with perbenzoic acid into its *epoxide*, b. p. 102—103°/0·4 mm., n_D^{20} 1·5260 (Found: C, 74·1; H, 7·7. $C_{11}H_{14}O_2$ requires C, 74·2; H, 7·9%).

An impure commercial sample of 1,2,3,4-tetrahydro-2-naphthol could not be purified by distillation, but recrystallisation of the sodium salt of its hydrogen phthalate [43] followed by hydrolysis with methanolic sodium hydroxide gave chromatographically pure material after distillation, b. p. 159—161°/26 mm., n_D^{20} 1·5570 (lit.,[44] 1·5583).

1-Indanylmethanol, from indene-1-magnesium bromide and paraformaldehyde followed by reduction over Adams catalyst,[45] was an oil, b. p. 76·5—78·5°/0·45 mm., n_D^{20} 1·5565 (Found: C, 80·5; H, 8·4. Calc. for $C_{10}H_{12}O$: C, 81·1; H, 8·1%). Dehydration [46] gave indane-1-methylene, b. p. 38—39°/0·85 mm., n_D^{20} 1·5730.

6-Methoxy-1,2,3,4-tetrahydro-2-naphthol, from 2,6-dihydroxynaphthalene,[47] was obtained as white crystals, m. p. 52—54° (lit.,[47] 53—55°).

The trifluoroacetate esters of 1,2,3,4-tetrahydro-2-naphthol, 1-indanylmethanol, and 6-methoxy-1,2,3,4-tetrahydro-2-naphthol were prepared by treating the alcohol (1 g.) with trifluoroacetic acid (1·5 g.) and allowing the mixture to stand at room temperature, with occasional shaking, for 2 days. Excess of 10% aqueous sodium hydrogen carbonate was added and the organic material was extracted into methylene dichloride. The extracts were washed and dried and the solvent was removed giving compounds which were gas chromatographically pure and were identified as trifluoroacetate esters by their characteristic infrared absorption (carbonyl stretch at 5·6 μ). Hydrolysis with 6% methanolic hydrogen chloride under reflux for 2 hr. regenerated the alcohols, as expected for trifluoroacetate esters.[30]

(c) *Oxidation with trifluoroperoxyacetic acid.* Trifluoroperoxyacetic acid (1·0 mol.) in

[39] Hershberg, *Helv. Chim. Acta*, 1934, **17**, 351.
[40] Heilbron and Bunbury, "Dictionary of Organic Compounds," Eyre and Spottiswoode, London, 1953.
[41] Levy and Sfiras, *Bull. Soc. chim. France*, 1931, **49**, 1823.
[42] von Braun, *Chem. Ber.*, 1923, **56**, 2178.
[43] Kenyon and Pickard, *J.*, 1914, 2677.
[44] Linstead and Michaelis, *J.*, 1940, 1134.
[45] Courtot, *Ann. Chim.* (*France*), 1915, **4**, 58; 1916, **5**, 52.
[46] Courtot, *Ann. Chim.* (*France*), 1915, **4**, 157.
[47] Clarke and Martini, *J. Amer. Chem. Soc.*, 1959, **81**, 5716.

methylene dichloride (25 ml.) at 0° was added to a well stirred solution of 4-phenylbut-1-ene (15 g., 1·5 mol.) in methylene dichloride (60 ml.) at 20° during 1 hr. The solution was then maintained at 30° for 2 hr. and divided into two. One part was extracted with 10% aqueous sodium bicarbonate (2 × 25 ml.), the aqueous extracts were extracted with methylene dichloride (25 ml.), and the combined organic fractions were washed and dried ($MgSO_4$). Methylene dichloride and 4-phenylbut-1-ene were removed by distillation and a portion of the residue was analysed by gas chromatography. Fractional distillation under reduced pressure of the major portion of the residue did not separate the chromatographically identified products.

After 3 weeks, the second portion of the original oxidation product, which had been kept at 0°, was treated as above and the residue (4 g.) was refluxed with 6% methanolic hydrogen chloride (40 ml.) for 2 hr. Methanol was removed under reduced pressure, the residue was taken up in ether, and the ethereal solution was dried ($MgSO_4$). Part was analysed by gas chromatography and the remainder was fractionally distilled (0·75 mm.), but no separation of the products was effected.

The oxidation of 4-*m*-anisylbut-1-ene, the extraction of the products, and the hydrolytic treatment of one portion were carried out as for 4-phenylbut-1-ene. Following hydrolysis, 6-methoxy-1,2,3,4-tetrahydro-2-naphthol was collected from the chromatographic column from six separate injections and its identity was confirmed by comparison of its infrared spectrum with that of the authentic material.

(d) *Reactions of the epoxides with trifluoroacetic acid.* A solution of 4-phenylbutane-1,2-epoxide (5 g.) and trifluoroacetic acid (12 g.) in methylene dichloride (20 ml.) was refluxed for 2 hr. After extraction with 10% aqueous sodium hydrogen carbonate the organic layer was dried ($MgSO_4$). and the methylene dichloride was removed. A portion of the residue was dissolved in ether and analysed, and the remainder was refluxed with 6% methanolic hydrogen chloride for 2 hr. The methanol was removed under reduced pressure, and part of the residue was analysed and the remainder fractionally distilled to give 4-phenylbutane-1,2-diol, b. p. 135—137°/1·6 mm., n_D^{20} 1·5365 (lit.,[42] 1·5370).

4-*m*-Anisylbutane-1,2-epoxide was treated similarly. The hydrolysis product on fractional distillation gave 4-m-*anisylbutane*-1,2-*diol* as a colourless, viscous oil, b. p. 160—162°/0·45 mm., n_D^{20} 1·5471 (Found: C, 67·2; H, 8·0. $C_{11}H_{16}O_3$ requires C, 67·4; H, 8·1%).

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