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Mechanism of the Solvolysis of Allylic Diphenyl Phosphates in Phenol

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The alkylation of phenol by solvolysis of allylic diphenyl phosphates in phenol is shown to be a carbonium ion process, and to be autocatalysed by diphenyl hydrogen phosphate. The products obtained in these solvolyses have been compared with those obtained from the alkylation of phenol by diphenyl hydrogen phosphate and olefins, under comparable conditions. These studies have shown that alkylation on carbon is favoured with more stable carbonium ions, such as tertiary or 3,3-dimethylallyl, while alkylation on oxygen is favoured with secondary carbonium ions. The acid-catalysed rearrangement, to 2-methylcoumaran, of the initial alkylated products of the solvolysis of allyl diphenyl phosphate has been shown to be largely intramolecular.

THE alkylation of phenols by allylic diphenyl phosphates is a general reaction giving good yields of alkylated products, and the synthetic applications of the reaction have recently been described.^{1,2} The mechanisms of such alkylations have not been studied, and this paper is concerned with the mechanism and kinetics of the alkylation of phenol by solvolysis of allylic diphenyl phosphates in phenol.

In general, the alkylation of phenolic compounds is achieved by reaction of the appropriate phenoxide ions, either in homogeneous or heterogeneous solution, with

¹ J. A. Miller and H. C. S. Wood, Chem. Comm., 1965, 39, 40. ² J. A. Miller and H. C. S. Wood, J. Chem. Soc. (C), 1968,

81, 2705.
 ⁴ N. Kornblum and R. Seltzer, J. Amer. Chem. Soc., 1961, 83,

alkylating agents such as alkyl halides, and the factors controlling the mechanisms of these reactions are well understood.3-5 The alkylation of free phenols by Friedel-Crafts processes involving olefins and Lewis acids is also well documented,⁶ but examples of alkylation of free phenols by solvolysis of alkylating agents, such as alkyl halides and esters, are less common.⁷ There are, moreover, only a few examples of mechanistic studies of solvolysis reactions in the literature.^{8,9}

⁵ N. Kornblum, P. J. Berrigan, and W. J. LeNoble, J. Amer.

Chem. Soc., 1963, **85**, 1141. ⁶ S. H. Patinkin and B. S. Friedman, in 'Friedel-Crafts and Related Reactions,' vol. 2, Part 1, ed. G. A. Olah, Interscience science Publishers, New York, 1964, p. 77.

- ⁷ F. A. Drahowzal, ref. 6, p. 641.
 ⁸ G. W. Kenner and J. Mather, J. Chem. Soc., 1956, 3524.
 ⁹ H. Hart, J. L. Corbin, C. R. Wagner, and Ching-Yeng Wu, J. Amer. Chem. Soc., 1963, 85, 3269.

 <sup>1837.
 &</sup>lt;sup>3</sup> N. Kornblum and A. P. Lurie, J. Amer. Chem. Soc., 1959,

As reported,² the solvolysis of allyl diphenyl phosphate (I) in phenol results in the formation of allyl phenyl ether (II), o-allylphenol (III), and p-allylphenol (IV), each in comparable amounts, as well as of diphenyl hydrogen phosphate (V). It was also shown² that the diphenyl hydrogen phosphate (V) was responsible for the isomerisation of each of the initial alkylated products to 2-methylcoumaran (VI), which was stable under the reaction conditions. This requirement for diphenyl hydrogen phosphate (V) was taken as evidence that the conversion of allyl phenyl ether (II) into 2-methylcoumaran (VI) was not a Claisen-type process,¹⁰ but more likely an example of a type of acid-catalysed aromatic rearrangement, which has been known for some time.¹¹ The mechanisms of both the alkylation and rearrangement will be discussed in this paper.

Alkylation of Phenol by Allylic Phosphates.—The alkylation of phenol by an allylic phosphate could, in principle, be the result of either an $S_N 1$ or an $S_N 2$ process, or of one with a mechanism intermediate between these two extremes. Since the alkylations discussed here are all solvolyses, direct kinetic measurements do not permit a distinction between these possibilities, and indirect methods have to be used.



When the solvolysis of allyl diphenyl phosphate (I) in phenol at 88° was followed by titration of the liberated diphenvl hydrogen phosphate (V), autocatalysis was observed. A similar observation was made by Kenner and Mather⁸ in their study of the solvolysis of benzyl diphenyl phosphate (VII) in phenol. Table 1 shows the extent of the autocatalysis, which is not detectable during the early stages of the reaction, and also shows that the rate, at different initial concentrations of phosphate, is highly dependent upon the amount of phenol solvent used, *i.e.*, upon the dielectric constant of the medium.

The kinetics of the solvolysis of allyl diphenyl phos-

phate (I) in the presence of added hydrogen phosphate (V) were then studied, and the rate found to be proportional to the product of the concentration of allyl diphenyl phosphate and of the total concentration of diphenyl hydrogen phosphate (Table 2). At 88° the rate constant was found to be 8.4×10^{-5} mole⁻¹ l. sec.⁻¹. The autocatalysis is thus due to diphenyl hydrogen phosphate, which is presumably acidic enough to protonate the neutral allyl diphenyl phosphate.

The data in Table 2 can also be used to show that first-order kinetics are not followed when the solvolysis is carried out in the presence of acid. This eliminates the possibility that the autocatalysis is due to a solvent effect, such as that observed with the results shown in Table 1.

Further experiments, in which the rates of formation of the initial alkylated products (as estimated by g.l.c. during the first few minutes of reaction) resulting from solvolysis of the neutral ester were compared with those produced by solvolysis of the protonated ester, showed that the products were identical in each system, and that they were formed at the same relative rates. It thus seems likely that the species bringing about alkylation of phenol is the allyl carbonium ion, independent of the presence or absence of diphenyl hydrogen phosphate.

Alkylation of Phenol by Olefins.-The alkylation of phenols by treatment with olefins in the presence of acid has long been used as a preparative route to alkylphenols, and is generally recognised to be the result of carbonium-ion formation and subsequent attack on the phenol.⁶ It was decided to use diphenyl hydrogen phosphate (V) as the catalyst in the condensation of a variety of olefins with phenol, in order to establish the nature of the products formed under conditions analogous to those used in the solvolyses described above.

When a tertiary ion can be formed by protonation of an olefin in phenol, a mixture of o- and p-alkylphenols results, in which the ortho-isomer predominates. This was found with the olefins 2-methylbut-1-ene (VIII) and 2-methylhex-2-ene (XI), which yielded only phenols when heated in phenol in the presence of diphenyl hydrogen phosphate. The phenolic products were readily separated by column chromatography, and identified by i.r., n.m.r., and mass spectrometry.

Olefins which can only form secondary (or primary) carbonium ions on protonation were found to alkylate phenol on the oxygen, producing ethers. These ethers were the main products when cyclohexene or hex-1-ene were used as olefins, although alkylation was much slower and in poorer yield than in the experiments yielding phenols as alkylated products.

The acid-catalysed addition of isoprene to phenol has recently been studied 12 in considerable detail, by use of a system at 20° in which 71% phosphoric acid was the catalyst. The main products of this reaction

¹⁰ S. J. Rhoads, in 'Molecular Rearrangements,' Part 1, ed. P. de Mayo, Interscience Publishers, New York, 1963, p. 655. ¹¹ M. J. S. Dewar, ref. 10, p. 295.

¹² A. R. Bader and W. C. Bean, J. Amer. Chem. Soc., 1958, 80, 3073.

were 2,2-dimethylchroman (XVII), o-3',3'-dimethylallylphenol (XVIII), and p-3',3'-dimethylallylphenol (XIX). The alkylation of phenol at 20° by 3,3-dimethylallyl diphenyl phosphate (XX) has been shown ² to give 2,2-dimethylchroman (XVII) and p-3',3'-dimethylallylphenol (XIX). The similarity in products from these two reactions indicated that it might be worth while to



treat phenol at 20° with isoprene in the presence of diphenyl hydrogen phosphate. In such an experiment, isoprene was found to give the same products as the solvolysis of 3,3-dimethylallyldiphenyl phosphate (XX), in the same relative amounts at all stages of the reaction. This is further indication that, in the solvolysis reactions of allylic phosphates, the alkylating species is a carbonium ion, since it has also been shown that olefins and diphenyl hydrogen phosphate (V) do not produce alkyl diphenyl phosphates when heated together.

Previous studies ² have demonstrated that o-3',3'-dimethylallylphenol (XVIII) is spontaneously cyclised to (XVII) under the conditions of solvolysis, and that, when heated to 100°, p-3',3'-dimethylallylphenol also rearranges to (XVII). Alkylation of phenol by isoprene, or by 3,3-dimethylallyl diphenyl phosphate (XX), thus leads to initial carbon alkylation only.

These observations on the alkylation of phenol by olefin-diphenyl hydrogen phosphate (V) mixtures form a coherent pattern when compared with the results obtained from alkylation by allyl phosphates, provided that the *initial* products are considered. It appears that relatively stable carbonium ions, such as 3,3-dimethylallyl or tertiary alkyl, alkylate only on carbon, whereas less stable secondary ions alkylate on oxygen. Alkylation by the allyl carbonium ion shows it to be intermediate between secondary and tertiary ions.

The results of other workers who have studied carbonium-ion alkylation of phenol are compatible with the above picture. For example, Hart and his coworkers have shown that the solvolysis of 5-chloro-2-methylpent-2-ene (XXI) in phenol at 150° gives rise to approximately equal amounts of products (XXII— XXIV), arising from initial alkylation at oxygen, and at *ortho-* and *para-* carbon respectively. The same authors also demonstrated that the homoallylic carbonium ion (XXV) was the alkylating species in this system, which is therefore comparable with alkylation by allyl diphenyl phosphate (I).

The work of Kenner and Mather ⁸ has established that solvolysis of benzyl diphenyl phosphate (VII) in phenol leads to a mixture of o- and p-benzylphenols, as well as a little benzyl phenyl ether. Although the nature of the alkylating species was not rigorously established in this case, these results do not conflict with the overall picture outlined above.

The mechanism of alkylation of phenol by allyl diphenyl phosphates is dependent upon the solvent, and the above conclusions cannot be extended to other systems without experimental investigation. When the alkylation is carried out in benzene, for example, the



main product is allyl phenyl ether (II), and a minor product is o-allyl phenol (III).

Isomerisation of Initial Alkylated Products.—The mechanism of the acid-catalysed rearrangement of the initial alkylated products to cyclic ethers has not been established. In order to investigate this matter, allyl phenyl ether (II) was heated at 120° in *p*-cresol for 72 hr. in the presence of diphenyl hydrogen phosphate (V). The loss of allyl phenyl ether was followed by g.l.c., and the formation of phenol, 2-methylcoumaran (VI), and 2,5-dimethylcoumaran (XXVI) similarly observed. At the end of 72 hr., the allyl phenyl ether had all been isomerised, and 2-methylcoumaran (VI) formed 72% of the cyclic ether mixture.

This shows that the rearrangement of allyl phenyl ether to 2-methylcoumaran, under conditions of the solvolysis of allyl diphenyl phosphate (I), is likely to be largely intramolecular. This rearrangement may, however, be wholly intramolecular, since such 'crossover' experiments have been known ¹¹ to be inconclusive if they indicate some degree of intermolecularity in what appears to be a predominantly intramolecular process.

EXPERIMENTAL

Infra-red spectra were run as liquid films on a Perkin-Elmer 137 spectrophotometer. N.m.r. spectra were run on a Perkin-Elmer R-10 spectrometer, operating at 60 Mc./sec., with solutions in carbon tetrachloride with tetramethylsilane as internal standard. Analytical g.l.c. was carried out on a Beckmann GC-2A instrument, and a column of 20% silicone oil on 'Embacel.' Alumina chromatography was on Martindale and Samoore alumina. The phosphate esters were prepared by the general method described previously.²

Kinetic Measurements.—The rates of solvolysis were determined by titrating weighed samples of the reaction mixture, removed from the reaction at regular intervals and dissolved in carbon tetrachloride, against standard sodium carbonate solution with methyl orange indicator.

When the results in Tables 1 and 2 were plotted as $\log [b(c + x)/c(b - x)]$ against time (where b = initial molarity of allyl diphenyl phosphate, c = initial molarity of diphenyl hydrogen phosphate, and x = molarity of diphenyl hydrogen phosphate produced by solvolysis) a straight line was obtained. These results therefore show

TABLE 1

Percentage of reaction as a function of time in the autocatalysed solvolysis of allyl diphenyl phosphate $(2\cdot 9 \text{ g.})$ in phenol at 88°

Phenol (g.)	1 hr.	2 hr.	3 hr.	4 hr.	5 hr.	6 hr.
2.35	$1 \cdot 0$	$2 \cdot 0$	2.7	$3 \cdot 6$	5.6	8.0
3.76	$6 \cdot 3$	15.3	28.3	46.8	64.0	80.6
8.46	12.6	30.0	47.3	$65 \cdot 2$	79.0	88.6

TABLE 2

Solvolysis of allyl diphenyl phosphate (2.9 g.) in phenol (3.76 g.) in the presence of diphenyl hydrogen phosphate (1.25 g.) at 88°

Time (hr.) Reaction (%)	$0.25 \\ 4.80$	$0.5 \\ 10.60$	$0.75 \\ 15.53$	$1.0 \\ 20.10$	$1.25 \\ 25.45$	$1.75 \\ 37.45$
Time (hr.) Reaction (%)	2.0 43.70	$2.25 \\ 49.50$	$2.5 \\ 55.15$	$3.25 \\ 68.20$	4·0 79·40	

that the solvolysis has rate = k[b - x][c + x], and the value of k thus obtained was 8.38×10^{-5} l. mole⁻¹ sec.⁻¹.

Products of Alkylation by Allyl Diphenyl Phosphate.—(a) Solvolysis in phenol. Allyl diphenyl phosphate (2.9 g.) was dissolved in phenol (3.76 g.) and the mixture heated at 88° in a sealed flask. Every 5 min. a small sample was removed, washed with N-sodium hydrogen carbonate solution, and the relative amounts of allyl phenyl ether, 2-methylcoumaran, and o- and p-allylphenols determined by g.l.c. It was found that, in a similar experiment in which diphenyl hydrogen phosphate (1.25 g.) was added before heating commenced, the same products were produced at exactly the same relative rates.

(b) Alkylation in benzene. Phenol (0.47 g., 0.005 mole)and allyl diphenyl phosphate (1.45 g., 0.005 mole) were dissolved in AnalaR benzene (5 ml.) and the mixture refluxed for 30 hr. G.l.c. showed that allyl phenyl ether (15%) and *o*-allylphenol (3%) were the only alkylated products.

Products of Alkylation by Olefins.—The general procedure was to heat the olefin-phenol mixtures, dissolve the crude mixtures in ether, and then separate the products by extraction with N-sodium hydrogen carbonate, 2N-sodium hydroxide, and water in succession. (a) Phenol (3.76 g., 0.05 mole), 2-methylhex-2-ene (0.93 g., 0.01 mole), and diphenyl hydrogen phosphate (0.5 g., 0.002 mole) were heated at 100° for 4 hr. The phenolic products were chromatographed on alumina with benzene solvent, which eluted a colourless oil, identified as o-1',1'-dimethylpentylphenol (XII) [Found: M (mass spectrometry), 192. Calc. for C₁₃H₂₀O: M, 192], 0.72 g. (38%), v_{max}. 3440, 2920, 2820, 1248, 1186, and 752 cm.⁻¹, τ 2.9—3.8 (multiplet, 4H, aryl), 5.10 (singlet, 1H, OH), and 8.2—9.3 (multiplets, 15H, side-chain).

With benzene-ether (5:1) solvent the initial eluate was a colourless oil, pure by g.l.c., and identified as p-1',1'-dimethylpentylphenol (XIII) [Found: M (mass spectrometry), 192. Calc. for $C_{13}H_{20}O$: M, 192], 0.19 g. (10%), v_{max} . 3300, 2920, 2820, 1520, 1240, 1185, and 834 cm.⁻¹, τ 2.9—3.6 (A₂B₂ quartet, 4H, aryl), 3.90 (broad singlet, 1H, OH), and 8.1—9.3 (multiplets, 15H, side-chain). Subsequent elution with the same solvent yielded mainly phenol, and a little p-1',1'-dimethylpentylphenol (XIII).

(b) Phenol (3.76 g., 0.04 mole), 2-methylbut-1-ene (0.70 g., 0.07 mole), and diphenyl hydrogen phosphate (0.1 g., 0.004 mole) were heated together under reflux for 20 hr. Extraction and chromatography (as above) yielded two oils, identified as o-1',1'-dimethylpropylphenol (IX), 0.83 g.

(52%), v_{max} 3520, 1385, 1362, 1328, 1183, and 749 cm.⁻¹, τ 2.65—3.65 (multiplet, 4H, aryl), 5.4 (singlet, 1H, OH), and 7.9—9.25 (multiplet, 11H, side-chain), and p-1',1'-dimethylpropylphenol (X), 0.13 g. (8%), v_{max} 3333, 1383, 1362, and 830 cm.⁻¹, τ 2.7—3.4 (A₂B₂ quartet, 4H, aryl), 3.6 (singlet, 1H, OH), and 8.2—9.3 (multiplets, 11H, side-chain).

(c) Phenol (0.94 g., 0.01 mole), cyclohexene (0.84 g., 0.01 mole), and diphenyl hydrogen phosphate (2.50 g., 0.01 mole), were heated together at 37° for 60 hr. The alkaline extract yielded only phenol. The neutral fraction consisted of cyclohexyl phenyl ether (XIV), which was purified by distillation, 0.088 g. (5%), ν_{max} 2924, 2840, 1236, 749, and 691 cm.⁻¹.

(d) Phenol (0.94 g., 0.01 mole) and cyclohexene, when heated as above, but in the absence of diphenyl hydrogen phosphate, did not react.

(e) Phenol (3.76 g., 0.04 mole), hex-1-ene (0.84 g., 0.01 mole), and diphenyl hydrogen phosphate (0.5 g., 0.002 mole) were heated at 100° for 24 hr. The neutral extract yielded a colourless oil, pure by g.l.c., and identified as 1-methylpentyl phenyl ether (XV) [Found: M (mass spectrometry), 178. Calc. for C₁₂H₁₈O: M, 178], 0.24 g. (13%), ν_{max} . 2920, 2830, 1610, 1500, 1248, 755, and 694 cm.⁻¹, τ 2.9—3.5 (multiplet, 5H, aryl), 5.9 (multiplet, 1H, -O-CH-), and 8.4—9.3 (multiplets, 12H, side-chain).

The phenolic extract contained phenol and a small amount of another component, separated by chromatography on alumina with benzene. This was a colourless oil, identified tentatively as o-1'-methylpentylphenol (XVI), 0.038 g. (2%), $v_{\rm max}$ 3400, 2920, 2820, 1240, 1180, and 756 cm.⁻¹.

(f) Diphenyl hydrogen phosphate (0.5 g., 0.062 mole) and 2-methylhex-2-ene (0.98 g., 0.01 mole) were heated at 100° for 4 hr. in chloroform (4 ml.). Extraction showed that the diphenyl phosphate had not reacted, and that no alkyl diphenyl phosphate had been formed.

(g) Phenol (3.76 g., 0.04 mole), isoprene (0.68 g., 0.01 mole), and diphenyl hydrogen phosphate (1.0 g., 0.004 mole) were stirred at 20° in a sealed flask for 4 hr. Every 30 min. a small sample was removed, washed with N-sodium hydrogen carbonate, and examined by g.l.c. The major products were 2,2-dimethylchroman (XVII) and p-3',3'-dimethylallylphenol (XIX), and two other products were also formed in trace amounts. At each stage of the reaction, the relative amounts of these products were the same as those observed previously ² in an analogous solvolysis of 3,3-dimethylallyl diphenyl phosphate (XX) in phenol. When the crude mixture of the initial products was heated at 100° for 6 hr., each of the products was isomerised to 2,2-dimethylchorman (XVII).

2,5-Dimethylcoumaran (XXVI).—p-Cresol (4.3 g., 0.04 mole) and allyl diphenyl phosphate (2.90 g., 0.01 mole) were heated at 120° for 6 hr. in a sealed flask. The mixture was poured into 5N-sodium hydroxide (50 ml.) and washed with ether. The ether extract was washed with water and dried, before evaporation of the solvent to leave a colourless oil (1.12 g.). This oil was then fractionally distilled to give 2,5-dimethylcoumaran (XXVI) [Found: M (mass spectrometry), 148. Calc. for $C_{10}H_{12}O$: M, 148], 0.52 g. (35%), b.p. 97—98°/15 mm.,¹³ v_{max}. 1500, 1255, 1240, 1220, 1040, 840, and 812 cm.⁻¹, $\tau 2.4$ —2.7 (multiplet, 3H, aryl), 5.2—

5.8 (multiplet, 1H, -O-CH-), 6.8-7.7 (multiplet, 2H,

¹³ C. D. Hurd and W. A. Hoffman, J. Org. Chem., 1940, 5, 212.

–CH₂–), 7.90 (singlet, 3H, CH₃Ar), and 8.72 (doublet, 3H, CH₃–CH-O-).

Isomerisation of Allyl Phenyl Ether in p-Cresol.—Allyl phenyl ether (0.268 g., 0.002 mole) and diphenyl hydrogen phosphate (0.5 g., 0.002 mole) were heated at 120° for 72 hr. in p-cresol (1.08 g., 0.01 mole). Analytical g.l.c. showed that all the ether had been isomerised, and that phenol had been produced, together with 2-methylcoumaran (VI) and 2,5-dimethylcoumaran (XXVI) (ratio 72:28 by g.l.c.). When the crude mixture was extracted with 2N-sodium hydroxide the residual neutral fraction contained only the two coumarans.

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