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HALOGEN MIGRATION AND ELIMINATION IN THE CLAISEN REARRANGEMENT OF ALLYL 2,6-DIHALOPHENYL ETHERS¹

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ABSTRACT

A study has been made of some factors affecting the migration or elimination of halogen in the Claisen rearrangement of allyl 2,6-dihalophenyl ethers. In the thermal rearrangement of allyl 2,6-dichlorophenyl ether, carried out in a number

In the thermal rearrangement of allyl 2,6-dichlorophenyl ether, carried out in a number of solvents of different dielectric constant, halogen migration proceeds somewhat better in highly polar solvents. However, a competitive reduction to the monohalogenated allylphenol occurs in the presence of oxidizable solvents and/or products. The reaction is also complicated by the catalytic effects of certain solvents and the phenolic products, which give results similar to those obtained with Lewis acids. Stannous chloride acts as a Lewis acid and catalyzes the rearrangement of allyl 2,6-dichlorophenyl ether with simultaneous halogen rearrangement. As well, a competitive removal of the halogen takes place. Results from the rearrangement of allyl 2,6-dibromophenyl ether with zinc chloride and of allyl 2,6-dichlorophenyl ether with zinc bromide, as well as those from the stannous chloride reactions indicate that the halogen *migration* takes place not only by an allylic shift but also via a competitive halogen *substitution* probably occurring by an $S_N 2'$ pathway possibly assisted by a zinc halide bridge mechanism and/or an ionic species such as $ZnX_2Y\Theta$.

INTRODUCTION

In a recent publication (1) it was shown that the thermal Claisen rearrangement of allyl 2,6-dichlorophenyl ether gave not only the previously reported products, 4-allyl-2,6-dichlorophenol and 2-allyl-6-chlorophenol (2), but also a small yield (2%) of the halogen migration product, 2-allyl-4,6-dichlorophenol. The proportion of the halogen migration product increased to 7% and 11% respectively if the thermal rearrangement was conducted in nitrobenzene and in nitrobenzene containing lithium chloride. Addition of the Lewis acid, anhydrous zinc chloride, to a nitrobenzene solution of allyl 2,6-dichlorophenyl ether not only accelerated the rate of rearrangement but also increased the proportion of 2-allyl-4,6-dichlorophenol to as much as 91% of the product (1). It was suggested that the migration of the halogen occurred during the dienone intermediate stage partly by an allylic rearrangement assisted by increased polarity of solvent and/or the presence of the Lewis acid, and partly by a zinc halide bridge mechanism (Fig. 1, routes a and b). The work reported in the present paper was designed to give additional information concerning the mechanism of rearrangement of the halogen atom.

RESULTS AND DISCUSSION

Thermal Rearrangement of Allyl 2,6-Dichlorophenyl Ether in Various Solvents

To determine the effect of polarity of solvent on the extent of halogen migration, the

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thermal rearrangement of allyl 2,6-dichlorophenyl ether was carried out in a number of solvents^{*} whose polarity, as indicated by their dielectric constant, differed widely. The results are shown in Table I. Although the dielectric constant of a substance generally decreases with increase in temperature, it is reasonable to assume that the *relative* dielectric constants, and hence relative polarity, of a number of solvents would be roughly the same at 170–190° (the temperature of our reaction) as they are at 20° (the temperature at which the dielectric constants are usually measured). Some support for this view is obtained by comparison of the dielectric constant values of several organic liquids at various temperatures (3).

A. Occurrence of Ether Cleavage

In phenol, 10% of the total product of the rearrangement was the ether cleavage material 2,6-dichlorophenol, and 5% of the product was a substance identified as 2-methyl-7-chlorocoumaran, obviously obtained by the cyclization of 2-allyl-6-chlorophenol. Both of these products are characteristic of the zinc chloride catalyzed rearrangement (1) and indicate that phenol not only catalyzes the Claisen rearrangement as has been shown by Goering and Jacobson (5) but also acts in a manner somewhat like that of a Lewis acid by causing ether cleavage as well as coumaran formation. In both N,N-diethylformamide and N-methylformamide the cleavage product also occurred (to the extent of 8% and 6% respectively) but unaccompanied by coumaran formation. A great deal of decomposition took place in these two solvents. The cause of the formation of the cleavage product is not known.

B. Occurrence of Reductive Removal of Halogen

The reduction product, 2-allyl-6-chlorophenol, was found in larger amount in those solvents most easily oxidized. Thus, in decalin, a non-polar solvent wherein considerable decomposition took place during the reaction, 64% of the product was 2-allyl-6-chlorophenol. It is possible that the phenolic products could act as reducing agents under the reaction conditions to yield the monochlorophenol, as is likely in the case of experiment No. 4 where no solvent was used, or in benzonitrile (experiment 6) or in nitrobenzene solutions (experiments 8 and 9). However, for the decalin solution, the fact that the reduction product, 2-allyl-6-chlorophenol, appeared even at a very early stage of the reaction when relatively little phenolic product was present, and that it was present in such a large proportion at the end of the reaction, indicates that the solvent decalin did participate as a reducing agent. Due to the extensive decomposition it was impossible to isolate oxidation products of decalin, such as tetralin etc. to support this view. In N-methylformamide and N,N-diethylformamide, much decomposition took place and the proportion of the solvent and/or its decomposition products.

C. Occurrence of Halogen Migration

In non-acidic solvents of low polarity (diphenyl ether, *o*-dichlorobenzene, allyl 2,6dichlorophenyl ether) little or no halogen migration occurred (0-2%). The exception to this was decalin wherein 6% of the product was 2-allyl-4,6-dichlorophenol. Since very little of this compound appeared *before* 50% of the original ether had disappeared, it is likely that the phenolic products, associating minimally with the non-polar solvent decalin, and therefore to a greater extent with the remaining unreacted ether, aided the rearrangement of the halogen via a protonation or hydrogen bonding of the acidic proton in the

*The number of solvents was necessarily limited to those of suitable physical characteristics and chemical inertness.

Solvent	Dielectric		Composition of re	eaction mixture, %‡		
reaction conditions*	of solvent†	2,6-Dichloro- phenol	2-Allyl-6- chlorophenol	2-Allyl-4,6- dichlorophenol	4-Allyl-2,6- dichlorophenol	Character of the reaction
Decalin, 180–185° 8 hr	2	Nil	648	68	30	Considerable decomposition
Diphenvl ether.	•	1.1	0-3	03		Very little
180–185°, 6 hr	3.6	Nil	. 3	Nil	97	decomposition
o-Dichlorobenzene,		1				Clean, no
178°, 9 hr	7.5	Nil	Trace	Nil	~ 100	decomposition
No solvent,						A small amount
193–200°, 90 min	?	Nil	7	2	91	of decomposition
Phenol,	·	1	- 11			Moderate amount
175–180°, 2 hr	9.9	10	9	11	65	of decomposition
Benzonitrile,						Very little
180–185°, 4.5 hr	25.2	Nil	2^+	3	95	decomposition
N,N-Diethylformamide,	2	0			10	Much
177° , 4.5 hr	r e	8	23	38	31	decomposition
Nitrobenzene,	0.0	NT*1	14	-	70	Moderate amount
$180-185^{-}, 4 \text{ hr}$	30	1811	14	1	79	Moderate emount
Nitropenzene $+$ LiCi,	2	NI	15	11	74	of decomposition
N Mathriformamida	Ŧ	1411	10	11	74	Very much
180° 27 br	100	6	50	25	10	decomposition
	Solvent and reaction conditions* Decalin, 180-185°, 8 hr Diphenyl ether, 180-185°, 6 hr o-Dichlorobenzene, 178°, 9 hr No solvent, 193-200°, 90 min Phenol, 175-180°, 2 hr Benzonitrile, 180-185°, 4 hr Nitrobenzene, 180-185°, 4 hr Nitrobenzene + LiCl, 180-185°, 3 hr N-Methylformamide	$\begin{array}{cccc} Solvent & Dielectric \\ and & constant \\ reaction & of \\ conditions^* & solvent^{\dagger} \\ \hline \\ Decalin, & & \\ 180-185^\circ, 8 hr & ? \\ Diphenyl ether, & & \\ 180-185^\circ, 6 hr & 3.6 \\ o-Dichlorobenzene, & & \\ 178^\circ, 9 hr & 7.5 \\ No solvent, & & \\ 193-200^\circ, 90 min & ? \\ Phenol, & & \\ 175-180^\circ, 2 hr & 9.9 \\ Benzonitrile, & & \\ 180-185^\circ, 4.5 hr & 25.2 \\ N,N-Diethylformamide, & & \\ 177^\circ, 4.5 hr & ? \\ Nitrobenzene, & & \\ 180-185^\circ, 3 hr & ? \\ Nitrobenzene + LiCl, & \\ 180-185^\circ, 3 hr & ? \\ N-Methylformamide & & \\ \end{array}$	Solvent andDielectric constant of $2,6$ -Dichloro- phenolConditions*solvent† $2,6$ -Dichloro- phenolDecalin, 180-185°, 8 hr?NilDiphenyl ether, 180-185°, 6 hr3.6Nil o -Dichlorobenzene, 178°, 9 hr7.5Nil $no solvent,$ 193-200°, 90 min?NilPhenol, 175-180°, 2 hr9.910Benzonitrile, 180-185°, 4.5 hr25.2NilNN-Diethylformamide, 180-185°, 3 hr?NilNitrobenzene, 180-185°, 3 hr?NilNitrobenzene + 180-185°, 3 hr?Nil	Solvent andDielectric constant ofComposition of re- 2.6-Dichloro- phenolComposition of re- 2-Allyl-6- chlorophenolDecalin, 180-185°, 8 hr?Nil64§Diphenyl ether, 180-185°, 6 hr3.6Nil3o-Dichlorobenzene, 178°, 9 hr7.5NilTrace178°, 9 hr7.5Nil7193-200°, 90 min Benzonitrile, 175-180°, 2 hr9.9109 Benzonitrile, 180-185°, 4.5 hr25.2Nil2NN-Diethylformamide, 180-185°, 3 hr?Nil14Nitrobenzene, 180-185°, 3 hr?Nil15N-Methylformamide101510	Solvent and reaction conditions*Dielectric constant ofComposition of reaction mixture, $\%$ ‡and reaction conditions*of2,6-Dichloro- phenol2-Allyl-6- chlorophenol2-Allyl-4,6- dichlorophenolDecalin, 180-185°, 8 hr?Nil64§6§Diphenyl ether, 180-185°, 6 hr3.6Nil3Nilo-Dichlorobenzene, 178°, 9 hr7.5NilTraceNilno solvent, 193-200°, 90 min?Nil72Phenol, 175-180°, 2 hr9.9109 11Benzonitrile, 180-185°, 4.5 hr25.2Nil23NN-Diethylformamide, 180-185°, 3 hr?Nil147Nitrobenzene, 180-185°, 3 hr?Nil1511N-Methylformamide00111511	Solvent and reaction conditions*Dielectric constant of solvent†Composition of reaction mixture, $\%$ ‡Decalin, reaction conditions*2,6-Dichloro- phenol2-Allyl-6- chlorophenol2-Allyl-4,6- dichlorophenol4-Allyl-2,6- dichlorophenolDecalin, 180–185°, 8 hr?Nil64§6§30Diphenyl ether, 180–185°, 6 hr3.6Nil3Nil97o-Dichlorobenzene, 178°, 9 hr7.5NilTraceNil~100No solvent, 193–200°, 90 min?Nil7291Phenol, 175–180°, 2 hr9.9109 1165Benzonitrile, 180–185°, 4.5 hr25.2Nil2395NN-Diethylformamide, 180–185°, 4 hr?8233831Nitrobenzene, 180–185°, 4 hr?Nil14779Nitrobenzene, 180–185°, 3 hr?Nil1474

TABLE I Solvent effect on the halogen migration in the thermal rearrangement of allyl 2,6-dichlorophenyl ether

er expected, e.g. N,N-diethyl-btained from A. A. Maryotte and N,N-dimethylformamide formanide is expected to have a dielectric constant not too much dimerent from that of dimension manifest (37.6). values of the dielectric constants of pure liquids, Natl. Bur. Std., Circ. 514, 1951; reference 3; and reference 4, p. 43. Those for N-methylformamide and N,N-dimethylformamide vere obtained from G. R. Leader and J. F. Gormley, J. Am. Chem. Soc., 73, 5731 (1951). TSeparate tests showed that in all cases the products were stable under the reaction conditions. §Analysis of samples of the reaction mixture showed that 2-allyl-6-chlorophenol was formed very early in the reaction (10% after 0.5 hour) and that only very little (1%) of 2-allyl-4.6-dichlorophenol was formed before 50% of the original ether had disappeared. ||Experiment 5 also gave 5% of a substance which was found to be 2-methyl-7-chlorocoumaran, no doubt derived from the cyclization of some of the 2-allyl-6-chlorophenol in the presence of the acidic phenol solvent. No coumaran was found in any of the other cases.

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phenol with the allylic halogen in the intermediate dienone stage, thus promoting the ionization of the allylic halogen. Similarly, rearrangement of halogen in the solvent phenol no doubt is assisted not only by the polarity of the solvent but probably more so by the same effect mentioned above, resulting in the products characteristically produced in the presence of Lewis acids.

In the more highly polar but non-acidic solvents, those of dielectric constant greater than 30 (nitrobenzene, nitrobenzene + LiCl, N,N-diethylformamide, and N-methylformamide) there is a larger extent of halogen migration (7% to 38%). However, the amount of halogen migration does not parallel the polarity of the solvent as expressed by dielectric constant (D.C.) values since N-methylformamide (D.C. = 190) yields 25%of the product as 2-allyl-4,6-dichlorophenol while N,N-diethylformamide (D.C. = 38) vields 38% of the product as halogen-migrated material. However, this can be rationalized if one considers that at the dienone stage there are two competing reactions, one in which the halogen undergoes allylic rearrangement and the other in which the allyl group migrates to the C_4 position. At this stage the halogen migration from C_2 to C_4 is assisted by the greater polarity of solvent while allyl migration from C_2 to C_4 is influenced only minimally if at all by increased solvent polarity (5). Thus the ratio of chlorine migration to allyl rearrangement should give an indication of the effect of polarity of solvent on the extent of halogen migration. In N-methylformamide the ratio is 25/10 while in N,N-diethylformamide it is 38/31. The larger ratio in N-methylformamide parallels its larger dielectric constant. The reductive removal of halogen, greater in the case of Nmethylformamide than for N,N-diethylformamide, also must occur at the dienone stage and thus competes with halogen migration. It is likely that if this reductive removal of halogen were not present, the difference in the ratios of halogen to allyl migration in the solvents N-methylformamide and N,N-diethylformamide would be even greater.

Benzonitrile (D.C. = 25.2) is considered to be a polar solvent, yet very little of either the halogen migration product, 2-allyl-4,6-dichlorophenol (3%), or the reduction product, 2-allyl-6-chlorophenol (2%), was formed.

D. Summary re Factors which Affect Halogen Migration and Reductive Removal of Halogen From the experiments shown in Table I it is seen that a highly polar solvent (expt. 7–10) does assist in the halogen migration as well as in the reductive removal of one of the halogen atoms, with the latter reaction depending upon the presence of an oxidizable substance. However, acidic solvents of lower polarity (and this includes phenolic products of the reaction to some extent) can accomplish the same thing. From the results with benzonitrile it appears that a moderate polarity of the solvent does not promote rearrangement significantly, but requires some additional factor. There is thus no linear comparison between rearrangement of halogen and polarity of solvent due to the complicating effects of solvent and product acidity as well as the effects of the decomposition products.

The Rearrangement of Allyl 2,6-Dichlorophenyl Ether in the Presence of Stannous Chloride

Carlin *et al.* (6) had found that several 2,6-dichlorophenylhydrazones, heated to 260° with a large excess of anhydrous stannous chloride, gave only the corresponding 7-chloroindoles, and these only in small yield (3–17%). Apparently no 5,7-dichloroindole, the result of halogen migration, was obtained. In view of the observation that the presence of oxidizable substances did cause a competitive reductive removal of one halogen atom during the Claisen rearrangement, it was of interest to discover whether stannous chloride

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would yield only the monohalo product, 2-allyl-6-chlorophenol, analogous to the finding by Carlin concerning the Fischer indole synthesis (6). The results of the rearrangement of allyl 2,6-dichlorophenyl ether in the presence of stannous chloride are shown in Table II.

A. Stannous Chloride as a Lewis Acid

There is no doubt that the presence of stannous chloride accelerates the Claisen rearrangement since, for example, in 8 hours 30% of the original ether was left when stannous chloride was used, whereas without stannous chloride under otherwise identical conditions 60% of the ether remained after 8 hours' time (Table II columns 1 and 2, compare sections A and B). Furthermore, both the ether cleavage product, 2,6-dichlorophenol, and the coumaran were formed in the presence but not in the absence of stannous chloride. These products are characteristic of Lewis acid catalyzed rearrangements of the allyl phenyl ethers and do not appear in the purely thermal rearrangement. Thus stannous chloride does behave as a Lewis acid.*

B. Halogen Rearrangement and Reductive Removal

Both the reduction product, 2-allyl-6-chlorophenol, and the halogen migration product, 2-allyl-4,6-dichlorophenol, are formed, the former in somewhat larger amount in the first 6 hours of reaction but in a relatively lesser amount by the end of the reaction.[†]

The possibility that a large excess of stannous chloride might increase the amount of reduction product was examined. The solubility of stannous chloride in *o*-dichlorobenzene is quite limited, hence relatively dilute solutions of reagents were employed in this experiment. A mixture of 1.25 g (0.006 mole) of allyl 2,6-dichlorophenyl ether and 2.5 g (0.012 mole) of stannous chloride‡ in 125 ml of *o*-dichlorobenzene, when heated to 150–155° for 24 hours, gave only two products, the 2-allyl-6-chlorophenol (reduction product), 37%, and 2-allyl-4,6-dichlorophenol (rearrangement product), 63%. Thus, an increase in the proportion of stannous halide enhanced the proportion of halogen rearrangement. This is in contrast to the findings of Carlin, Wallace, and Fisher (6), who added their hydrazones to an excess of fused (260°) stannous chloride. Such vigorous conditions might account for their failure to find any dihalogenated indole.

The Rearrangement of Allyl 2,6-Dichlorophenyl Ether in the Presence of Anhydrous Zinc Bromide and of Allyl 2,6-Dibromophenyl Ether in the Presence of Anhydrous Zinc Chloride

It was suggested (1) that the halogen migration in the zinc chloride catalyzed Claisen rearrangement of allyl 2,6-dichlorophenyl ether might occur via a zinc chloride§ bridge as shown below (Fig. 1, route *a*). Alternatively, the Lewis acid could promote ionization and create an ion pair which could then rearrange more readily (route *b*) in a manner similar to that which takes place in the thermal rearrangement of the halogen. Route *b* might also be modified to give a species such as $ClZnX_2^{\ominus}$ which could then cause substitution at C₄ by X^{\ominus} as well as enhance migration of Cl^{\ominus}. In addition to these routes,

*It is possible that the accumulating stannic chloride is responsible at least in part for the acceleration of reaction. However, it cannot be completely so, since if stannous chloride were not a Lewis acid, some 4-allyl-2,6-dichlorophenol (the product from thermal rearrangement) would have been formed at least in the early stages of the reaction. No 4-allyl-2,6-dichlorophenol was detected.

†It is possible that the accumulating stannic chloride from the reduction process could be responsible for the increasing proportion of migration product as compared with the reduction product as the reaction progressed. ‡Nearly all of this quantity of stannous chloride went into solution.

§The state of the zinc halides under the conditions of our reactions is not certain. In an organic solvent which only partially dissolves the zinc halides, there might exist a mixture of monomeric, dimeric, and higher aggregate species possibly existing in part, for example, as $ZnX^{\oplus}ZnX_3^{\ominus}$. Because of the lack of more precise information, the designation ZnX_2 is used for simplicity.

	Composition of reaction mixture, $\%^*$							
Reaction time, hr	Allyl 2,6-dichloro- phenyl ether	2,6-Dichloro- phenol	2-Allyl-6- chlorophenol	2-Methyl-7- chlorocoumaran	2-Allyl-4,6- dichlorophenol	2-Methyl-5,7- dichlorocoumaran	4-Allyl-2,6- dichlorophenol	
	A. With S	nCl ₂ at 150–155° (r	atio of SnCl ₂ to ethe	$r^{\dagger} = 1:1$ (0.05 mole	of halide and ether	in 50 ml of solvent)		
1	90	Nil	6	Nil	4	Nil	Nil	
2	79	Trace	12	**	9	"	"	
4	59	2	$\overline{23}$	"	16	,,	**	
ā	48	$\overline{2}$	28	,,	22	,,	"	
ŝ	30	2	20	,,	22	,,	,,	
10	10	3	. 39	,,	20	,,	,,	
24	Nil	7	35	8	55 46	А	,,	
21	1111	•		, O	10	Ĩ		
		B. Withou	t SnCl ₂ , at 150-155°	0.05 mole of ether i	n 50 ml of solvent)			
6	74	Nil	Nil	Nil	Nil	Nil	26	
Ř	0	"	**	,,	**	,,	40	
24	23	**	**	**	,,	,,	77	
	-0						••	
	C. With SnCl ₂ at	150-155° (ratio of S	nCl_{2} to ether = 2:1	(0.012 mole of SnCl	at and 0.006 mole of	f ether in 125 ml of sc	lvent)	
24	Nil	Nil	37	Trace	63	Trace	Nil	

TABLE II Rearrangement of allyl 2,6-dichlorophenyl ether in o-dichlorobenzene

*Separate tests showed that in all cases the products were stable under the reaction conditions, except that in the presence of stannous chloride the 2-allylphenols were converted partly to their respective 2-methylcoumarans. †A considerable portion of the stannous chloride remained undissolved. ‡Nearly all the stannous chloride dissolved.

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FIG. 1. Mechanistic routes for halogen migration.

H

Zn-X

halogen rearrangement might be accomplished by an $S_N 2'$ mechanism (reference 4, pp. 127-131) involving attack by the metal halide, with or without assistance of the Lewis acid, on the allylic system (route c).

In an effort to determine whether all or some of these schemes contribute in the rearrangement of the 2,6-dihalophenyl ethers in the presence of a Lewis acid, the rearrangement of allyl 2,6-dichlorophenyl ether was carried out in the presence of anhydrous zinc bromide. As well, allyl 2,6-dibromophenyl ether was rearranged in the presence of anhydrous zinc chloride. A high proportion of 2-allyl-4-bromo-6-chlorophenol in the first case and of 2-allyl-4-chloro-6-bromophenol in the second would favor the zinc halide bridge concept (Fig. 1, route a) and/or the $S_N 2'$ mechanism (Fig. 1, route c). The results of these experiments are shown in Tables III and IV.

A number of observations can be made from the information in Tables III and IV.

(i) No Rearrangement of the Allyl Group to the Para Position

In neither case was there any indication of the formation of 2,6-dihalo-p-allylphenol, the product found in large amount in the purely thermal rearrangement (Table I). Apparently the presence of the Lewis acid was sufficient to cause, at the dienone intermediate stage, reaction exclusively with the halogen atom.

(ii) Little or No Reductive Removal of Halogen

The zinc bromide catalyzed reaction of the dichloro ether (Table III) showed no evidence of reductive removal of a chlorine atom. On the other hand, approximately 3% of the product of the zinc chloride catalyzed reaction of the dibromo ether (Table IV. columns 3 and 4) was the monobromo reduction product. Thus, the carbon-bromine bond is more susceptible to the competitive reductive cleavage than is the carbon-chlorine bond.

III	
ABLE	
Ţ	

Zinc bromide catalyzed rearrangement of allyl 2,6-dichlorophenyl ether in nitrobenzene solution (concentration of ether: 0.15 mole of ether in 1 mole of nitrobenzene) (molar ratio of zinc bromide^{*} to ether = 2:1)

I		Co	mposition of th	e reaction mix	ture, %†		
Reaction time and temperature‡	2,6-Dichloro- phenol	2-Allyl-4,6- dichloro- phenol	2-Met dicl cou	hyl-5,7- hloro- maran	2-Allyl-4- bromo-6- chlorophenol	2-Methyl-5- bromo-7-chloro- coumaran	Ratio of bromine substitution to chlorine migration§
100-110° 200 hr	16	30	-	4	45	20	-
130-135°)	2	-	4	2	כ	1.0
28 hr	28	21	- 	12	24	15	1.2
30 hr	40	4	. ~	20	6	24	1.2
26 hr	47	Trace		23	Trace	30	
$140-145^{\circ}$			-)	0
18 hr	47	Trace		24	Trace	29	1.2
18 hr	51	Nil		23	IIN	$\overline{26}$	1.1
150-155°							
12 hr	52	IIN		23	Nil	25	1.1
12 hr	55	lin		21	Nil	24	1.1
*Not all of the z †Separate tests s	inc bromide dissolved.	ere stable under the	reaction conditions	except that the	2-allylphenols were part	v or completely converted to	their resnective commarans

Time of reaction was sufficient for complete disappearance of the original ether. §The ratios are obtained by comparisons of the sums of the 4,6-dihalophenol and 5,7-dihalocoumaran in each case, i.e. the sums of columns 3 and 4 vs. 5 and 6. A drop of water was deliberately added to the reaction mixture.

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	(concentration	on or ether. 0.1			(molar r	atio of zilic chio	ride" to ether = $2:1$) <u> </u>
		-	Composit	ion of the reacti	ion mixture, %†			
Reaction time and temperature‡	2,6-Dibromo- phenol	2-Allyl- 6-bromo- phenol	2-Methyl- 7-bromo- coumaran	2-Allyl-4,6- dibromo- phenol	2-Methyl-5,7- dibromo- coumaran	2-Allyl-4- chloro-6- bromophenol	2-Methyl-5- chloro-7-bromo- coumaran	Ratio of chlorine substitution to bromine migration§
130–135° 30 hr 140–145°	8	3	Nil	55	2	30	2	0.56
26 hr $150-155^{\circ}$	16	2	1	38	6	31	6	0.84
22 hr	26	1	2	25	10	24	12	1.03

TABLE IV

Zinc chloride catalyzed rearrangement of allyl 2,6-dibromophenyl ether in nitrobenzene solution (concentration of ether: 0.15 mole of ether in 1 mole of nitrobenzene) (molar ratio of zinc chloride* to ether 0 1)

*Not all of the zinc chloride dissolved. †Separate tests showed that the products were stable under the reaction conditions except that the 2-allylphenols were partly converted to their respective coumarans. Sufficient time for complete disappearance of the original ether. \$The ratios are obtained by comparing the sums of the 4,6-dihalophenol and 5,7-dihalocoumaran in each case, i.e. the sums of columns 5 and 6 vs. 7 and 8.

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(iii) Ether Cleavage, Dependent upon Temperature and the Presence of Water

Cleavage of the ether to the 2,6-dihalophenol in both instances increased with increase in temperature of the reaction, but was more pronounced when zinc bromide was the catalyst. It is noteworthy that, in contrast to the results obtained with zinc chloride as catalyst, those for the zinc bromide catalyzed reactions were difficult to reproduce in duplicate reactions. Commercial anhydrous zinc bromide* itself was particularly bad in this regard, hence it was heated to its melting point (as was done for zinc chloride) to drive off traces of water. If one prepared zinc bromide in this way and then allowed it to cool in a desiccator containing P_2O_5 and dry nitrogen, and as well stored the desiccator in a dry box (P_2O_5) flushed with dry nitrogen and then carried out all weighings, transfers, and mixing manipulations in this dry box, considerable improvement in reproducibility was found, although the results even then were not entirely satisfactory. Traces of water could be the cause of this difficulty in variability of results. Zinc bromide from our observations was found to be considerably more hygroscopic than was zinc chloride. Furthermore, the addition of one drop of water to the reaction mixture containing zinc bromide catalyst (Table III, 26 hour run at 130-135°) increased the amount of ether cleavage. It is already known that addition of a small amount of water to anhydrous boron trifluoride does enhance the catalytic power of this Lewis acid, probably by production of a proton according to the reaction $BF_3 + H_2O \rightleftharpoons BF_3(OH)^{\ominus} + H^{\oplus}$ (7–10).

The greater effectiveness of zinc bromide as compared with zinc chloride in causing cleavage of the ether and also in promoting cyclization of the *o*-allyl-4,6-dihalophenols to the coumarans (a distinctly acid-catalyzed reaction) might be due to a somewhat stronger Lewis acid character of zinc bromide. Analogously, aluminum bromide is considered to be a more effective catalyst in the Friedel and Crafts reaction than is aluminum chloride (11). Also, it has been shown that the electrophilicities of the boron halides towards pyridine or nitrobenzene are in the order $BF_3 < BCl_3 < BBr_3$ (12). To our knowledge no such comparison has yet been reported concerning the aluminum halides (or zinc halides) although such work has been under consideration (12). If one can extrapolate these results to the zinc halides, support is thus obtained for the view that zinc bromide is a stronger Lewis acid than is zinc chloride. The greater solubility of zinc bromide in nitrobenzene as observed in our work indicates greater coordinating power with the solvent. On the other hand, the greater solubility of the bromide in nitrobenzene, as well as that of aluminum bromide in benzene in the Friedel and Crafts reaction (11), could well explain the greater catalytic effect observed. The limited amount of information available precludes any definite conclusion as yet concerning the cause of the greater activity of the zinc bromide.

(iv) Allylic Halogen Migration in Competition with Halogen Substitution by Halide Ion The ratio of halogen substitution to halogen migration increased with temperature for the zinc chloride catalyzed rearrangement of allyl 2,6-dibromophenyl ether but decreased slightly for the zinc bromide catalyzed rearrangement of allyl 2,6-dichlorophenyl ether. Under the same conditions, more bromine (from ZnBr₂) replaced chlorine than chlorine (from ZnCl₂) replaced bromine in the dihalo ethers, but the difference was nearly eliminated at the higher temperature (150–155°). It is clearly seen that predominant substitution, which must occur if the zinc halide bridge concept and/or S_N2' mechanism is 100% operative, does not take place. Hence halogen "migration" can occur only partially, if at all, by one or both of these processes. Alternatively, simple allylic rearrangement of the

*Reagent grade material obtained from Matheson, Coleman and Bell, Norwood, Ohio, U.S.A.

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halogen atom at the dienone stage, with the assistance of the zinc halide, and involving a rather tight ion pair (route b) is also not completely operative since halogen substitution is quite substantial.

Conclusions as to Possible Mechanistic Routes in Halogen Migration and/or Substitution in the Zinc Halide Catalyzed Rearrangement of Allyl 2,6-Dihalophenyl Ethers

Unquestionably, the Lewis acids exert a marked control over these reactions. The absence of *para*-allyl rearrangement must mean that the zinc halide must first be associated with the allylic halogen of the dienone intermediate stage in every case. Subsequently, only halogen substitution and halogen migration, and in some cases reductive halogen elimination, take place.

The results shown in Tables III and IV might be interpreted in terms of the modified route b involving the species $ZnClBr_2^{\ominus}$ and $ZnBrCl_2^{\ominus}$ respectively. Thus, in the rearrangement of allyl 2,6-dichlorophenyl ether in the presence of $ZnBr_2$, the carbonium ion could abstract from $ZnClBr_2^{\Theta}$ either a chloride ion to form the dichloro "migration" product or a bromide ion to give the chlorobromo "substitution" product. One would expect that more bromide than chloride ion would be extracted on the basis of both the greater nucleophilicity and greater amount of bromine atoms in the species $ZnClBr_2\Theta$, hence giving rise to a high ratio of bromine substitution to chlorine migration. The ratio actually found is only about 1.2 to 1.3 at 130–135°. On the other hand, for the $ZnCl_2$ catalyzed rearrangement of the dibromoether, where the involvement of the species $ZnBrCl_2^{\ominus}$ is suggested, the ratio of bromine "migration" to chlorine "substitution" at C4 is 1.8 (i.e. 1/0.56) at the same temperature. One would expect the reverse on the basis of relative amount and nucleophilicity of the halogen. Furthermore, the decrease of these ratios to nearly 1.0 in both cases as the temperature of reaction rose from 130° to $150-155^{\circ}$ cannot readily be explained solely by this reaction path. Hence the modified route b can contribute only partly to the reaction.

The formation of a greater amount of the product, 2-allyl-4,6-dichlorophenol, as compared with the reduction product, 2-allyl-6-chlorophenol rather than the reverse when the proportion of stannous chloride to the dichloroether was increased (Table II) can be taken as support for the participation of a second molecule of stannous chloride in an $S_N 2'$ reaction (route c) in competition with reduction. However, from the results of the zinc bromide and zinc chloride catalyzed reactions (Tables III and IV) it is clear that substantial amounts of migration product occurred and therefore a scheme such as c can contribute only partly to the reaction.

The results of the zinc bromide catalyzed rearrangement of allyl 2,6-dichlorophenyl ether (Table III) in which the ratio of halogen substitution product to halogen migration product decreases from 1.5 at 100–110° to 1.1 at 150–155° can be rationalized as a competition between the slower allylic migration of chlorine and the reaction by an $S_N 2'$ pathway (route c) and/or zinc halide bridge (route a). Higher temperatures facilitate the breaking of the carbon-chlorine bond and hence route b becomes more important, decreasing the ratio of bromine to chlorine attachment at C₄.

The more readily ionizable carbon-bromine bond in the dibromoether (Table IV, catalysis by $ZnCl_2$) would permit greater contribution of allylic halogen migration (route b) even at the lower temperature of 130°. Higher temperatures could cause the formation of the species $ZnBrCl_2^{\ominus}$ and modified mechanism b could become predominant, thus decreasing the amount of bromine relative to chlorine attachment at C₄.

It is clear that the zinc halide catalyzed reactions of the allyl 2,6-dihalophenyl ethers

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are quite complex and that the results obtained so far cannot be explained solely on the basis of any one of the suggested routes. It is likely that contributions from several or all might be involved in the halogen migration and substitution reactions.

EXPERIMENTAL

Analyses by Gas Chromatography

A Burrell Model K-2 Kromo-Tog, equipped with an integrator and with helium as the carrier gas, was used for all analyses. A 2 m column, packed with 20% Apiezon L on Gas Chrom P (60-80 mesh), afforded good separation of components of the mixtures into clearly resolved peaks. Analyses of carefully weighed authentic mixtures of the reaction products showed that the paper areas of the peaks could be used as a direct measure of the molar compositions of the reaction mixtures. Products were identified by comparison of their retention times with those of authentic samples and/or by means of infrared spectroscopy as well as n.m.r. analyses (Varian H-60).

2,6-Dibromophenol

Decarboxylation of 3,5-dibromo-4-hydroxybenzoic acid (148 g, 0.5 mole) (13) according to the procedure used by Tarbell and co-workers for the corresponding dichloro compound (14) afforded 112 g (89%) of 2,6-dibromophenol, m.p. 55-56° (from hexane). Lit. m.p. 56-57° (15).

Preparation of Ring-Halogenated Allyl Phenyl Ethers

The method previously described (1) for the preparation of allyl 2,6-dichlorophenyl ether was employed to obtain a number of ethers necessary for the present work. The required phenols were all commercially available. A summary of the properties and yields of the ethers is given in Table V.

TABLE V

Allyl phenyl ethers	Allyl	phenyl	ethers
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D'	V:-14	Boiling poin	t, °C (mm)	
substituents		Found	Reported	Ref.
2-Chloro 2-Bromo- 2,4-Dichloro- 2,4-Dibromo- 2,6-Dibromo- 2-Bromo-4-chloro 2-Chloro-4-bromo-	89 85 86 95 90 88 92	$\begin{array}{cccc} 100{-}102 & (11) \\ 66{-}67 & (0.8) \\ 73{-}73{}.5 & (0.55) \\ 90 & (0.4) \\ 73 & (0.4) \\ 82 & (0.5) \\ 84{-}85 & (0.7) \end{array}$	108–110 (15) 130–134 (20) 144–145 (20) 127–134 (0.5)* 112–113 (2) New compound [†] New compound [‡]	2 16 17 - 16 18

*The reported boiling point is in disagreement with that observed, and appears to be too high. †Anal. Calc. for CsHsBrClO: C, 43.67; H, 3.26; Br, 32.29; Cl, 14.32. Found: C, 43.93; H, 3.26; Br, 32.61; Cl, 14.17. np³⁵ 1.5737. ‡Anal. Calc. for CsHsBrClO: C, 43.67; H, 3.26; Br, 32.29; Cl, 14.32. Found: C, 43.68; H, 3.19; Br, 32.14; Cl, 14.51. np²⁵ 1.5752.

Preparation of Ring-Halogenated 2-Allylphenols

Several 2-allylphenols were obtained from the correspondingly substituted allyl phenyl ethers by rearrangement according to the following general procedure.

A solution of the allyl phenyl ether (0.2 mole) in 80 ml of diphenyl ether was heated with stirring, under an atmosphere of nitrogen, to 205-210° and kept at this temperature for 3 hours. When the solution had cooled. it was diluted with 400 ml of commercial pentane and extracted thrice with Claisen's alkali (19). The combined alkaline extracts were washed several times with pentane, thoroughly cooled in an ice-water bath. acidified with concentrated hydrochloric acid and then twice extracted with pentane. The combined extracts were washed with saturated salt solution and dried with anhydrous sodium sulphate. Removal of the solvent gave an oil which was distilled under vacuum through a short Vigreux column, thus giving the desired phenol. The results are tabulated in Table VI.

Preparation of Halogenated 2-Methylcoumarans

The general procedure reported in the literature (18) was employed to obtain the halogenated 2-methylcoumarans from the corresponding halogen-substituted 2-allylphenols. The results are shown in Table VII.

Thermal Rearrangement of Allyl 2,6-Dichlorophenyl Ether in Various Solvents. General Procedure

Dried and redistilled solvent (50 ml) was stirred and heated, under an atomsphere of purified dry nitrogen, to the desired temperature and then allyl 2,6-dichlorophenyl ether (10 g, 0.05 mole) slowly added over a period of approximately 30 minutes. The resulting solution was then heated for the required time, cooled,

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Ring halogenated 2-allylphenols

D!	¥7:-1.J	Boiling po	oint, °C (mm)	
substituents	<i>x</i> leid, %	Found	Reported	Ref.
6-Chloro 6-Bromo- 4,6-Dichloro- 4,6-Dibromo- 4-Chloro-6-bromo- 4-Bromo-6-chloro-	90 77 87 60 75 76	$71-72 (2) \\59-60 (0.7) \\77 (0.9) \\88 (0.4) \\80-81 (0.6) \\80 (0.4)$	215–220 (750) 87–88 (2) 264 (759) 118–122.5 (1.0) New compound* New compound†	$2 \\ 16 \\ 20 \\ 16$

*Anal. Calc. for C₉H₈BrClO: C, 43.67; H, 3.26; Br, 32.29; Cl, 14.32. Found: C, 43.82; H, 3.36; Br, 32.20; Cl, 14.07. n_{D}^{25} 1.5838. *Anal. Calc. for C₉H₈BrClO: C, 43.67; H, 3.26; Br, 32.29; Cl, 14.32. Found: C, 43.60; H, 3.31; Br, 32.08; Cl, 14.43. n_{D}^{25} 1.5855.

TABLE VII Halogenated 2-methylcoumarans

	371-1-1	Boiling 1	point, °C (mm)	
Substituents		Found	Reported	Ref.
7-Chloro- 7-Bromo- 5,7-Dibromo- 5-Chloro-7-bromo- 5-Bromo-7-chloro- 5,7-Dichloro-	56 57 68 73 73 48	$\begin{array}{c} 74 \ (1.8) \\ 71 \ (0.75) \\ 90 \ (0.3) \\ 95 \ (0.9) \\ 99 \ (0.8) \\ 81 \ (0.7) \end{array}$	New compound* New compound† 129–134 (1.0) New compound‡ New compound§ New compound	18

*Anal. Calc. for CaHaClO: C, 64.10; H, 5.38; Cl, 21.03. Found: C, 64.17; H, 5.21; Cl, 21.24. nD^{ss} 1.5496. †Anal. Calc. for CaHaBrO: C, 50.73; H, 4.26; Br, 37.51. Found: C, 50.97; H, 4.21; Br, 37.26. nD^{ss} 1.5735. †Anal. Calc. for CaHaBrO: C, 43.67; H, 3.26; Br, 32.29; Cl, 14.32. Found: C, 43.71; H, 3.22; Br, 32.17; Cl, 14.53. nD^{ss} 1.5863. ÅAnal. Calc. for CaHaBrClO: C, 43.67; H, 3.26; Br, 32.29; Cl, 14.32. Found: C, 43.47; H, 3.39; Br, 32.51; Cl. 14.42. nD^{ss} 1.5863. Anal. Calc. for CaHaBrClO: C, 53.23; H, 3.97; Cl, 34.92. Found: C, 52.91; H, 4.08; Cl, 35.20. nD^{ss} 1.5640.

and then analyzed directly for products by vapor phase chromatography (v.p.c.) by injecting aliquots of the reaction solution into the Kromo-Tog. The results are recorded in Table I.

Zinc Halide Catalyzed Rearrangement of Allyl 2,6-Dihalophenyl Ethers. General Procedure

A quantity (0.1 mole) of anhydrous zinc halide (prepared by heating the salt to the molten state, cooling it in a desiccator in a dry box flushed with nitrogen, and then grinding it under anhydrous conditions in the dry box) was stirred into 50 ml of dry ether. The mixture was then gently heated to permit evaporation of the ether while dried, redistilled nitrobenzene (41 g) was slowly added. The resulting mixture was heated to the desired rearrangement temperature. Much of the zinc halide remained undissolved as a suspension. After slow addition of the allyl 2,6-dihalophenyl ether (0.05 mole), the resulting mixture was stirred and heated under an atmosphere of purified, dry nitrogen for the specified time. The reaction mixture was then cooled and poured into a mixture of ether and water (1:1). When the resulting solution was filtered, the ether layer was separated, washed twice with saturated salt solution, and then dried (Na_2SO_4) . Removal of the ether gave a mixture of reaction products which was analyzed directly by v.p.c. The results are recorded in Tables III and IV.

Rearrangement of Allyl 2,6-Dichlorophenyl Ether in the Presence of Stannous Chloride

(a) Anhydrous powdered stannous chloride (9.5 g, 0.05 mole) (21) was stirred into 50 ml of dried, redistilled o-dichlorobenzene. After the mixture had been heated to 150-155° under an atmosphere of purified, dry nitrogen, allyl 2,6-dichlorophenyl ether (10 g, 0.05 mole) was slowly added. The reactants were then heated at 150-155° for 24 hours. The cooled material was treated as described above for the zinc halide catalyzed rearrangements and product analysis carried out directly by v.p.c. The results are recorded in Table II.

(b) Procedure (a) was repeated, employing 1.25 g (0.006 mole) of allyl 2,6-dichlorophenyl ether and 2.5 g (0.012 mole) of stannous chloride in 125 ml of dried, redistilled o-dichlorobenzene. After treatment of the cooled reaction mixture as described above, 50 ml of o-dichlorobenzene was removed by careful fractional distillation under vacuum. The distillate was shown by v.p.c. to be pure solvent, containing no phenolic products. The residual solution was analyzed by v.p.c. and the results recorded in Table II, section C.

Stability Tests on Products under Reaction Conditions

In all cases synthetic mixtures of the products of the reactions were shown, by the use of an internal

standard (n-tetradecane) in the v.p.c. analysis, to be stable within the limits of experimental error. However, in the case of the metal halide catalyzed reactions the 2-allylphenols were converted in part or completely to the corresponding stable 2-methylcoumarans and to no other product.

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