Mechanism of Cyclization of Aryl Radicals containing Unsaturated *ortho*-Substituents

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Aryl radicals generated by interaction of tributylstannane with aryl iodides containing unsaturated *ortho*-substituents cyclize regiospecifically to afford products containing the newly formed-radical centre exocyclic to the newly-formed ring. The relative rates of cyclization of a number of related radicals have been determined. The results are consistent with the hypothesis that the transition state for homolytic addition to an olefin bond is formed by primary interaction of the semi-occupied orbital with one lobe of the π^* orbital.

In a previous paper [1] we described the use of e.s.r. spectroscopy as an exploratory tool for the investigation of intramolecular addition processes in aryl radicals containing suitably constituted, unsaturated *ortho*-substituents. Those experiments were intended to test the validity of the hypothesis [2,3] that the direction of cyclization of hex-5-enyl radical [4-6] and similar species [2,3,7-9] is determined by the ease of approach of the radical centre towards the olefinic bond along axes extending vertically from the terminal atoms and lying within the plane of the π orbital. Inspection of models suggested that the aryl radicals (2a and b) should undergo 1,6-intramolecular addition, unlike their aliphatic analogues, in which 1,5-cyclization predominates.[3-9] However, the e.s.r. data indicated that the

[1] A. L. J. Beckwith and W. B. Gara, *J.C.S. Perkin II*, 1975, 593.

[2] A. L. J. Beckwith, G. E. Gream, and D. L. Struble, *Austral. J. Chem.*, 1972, **25**, 1081.

[3] A. L. J. Beckwith, I. Blair, and G. Phillipou, *J. Amer. Chem. Soc.*, 1974, **96**, 1613.

[4] C. Walling, J. H. Cooley, A. A. Ponaras, and E. J. Racah, *J. Amer. Chem. Soc.*, 1966, **88**, 5362.

[5] A. L. J. Beckwith and G. Moad, *J.C.S. Chem. Comm.*, 1974, 472.

[6] C. L. Jenkins and J. K. Kochi, *J. Amer. Chem. Soc.*, 1972, **94**, 843, and references cited therein.

[7] C. Walling and A. Cioffari, *J. Amer. Chem. Soc.*, 1972, **94**, 6059.

[8] A. L. J. Beckwith, I. A. Blair, and G. Phillipou, *Tetrahedron Letters*, 1974, 2251.

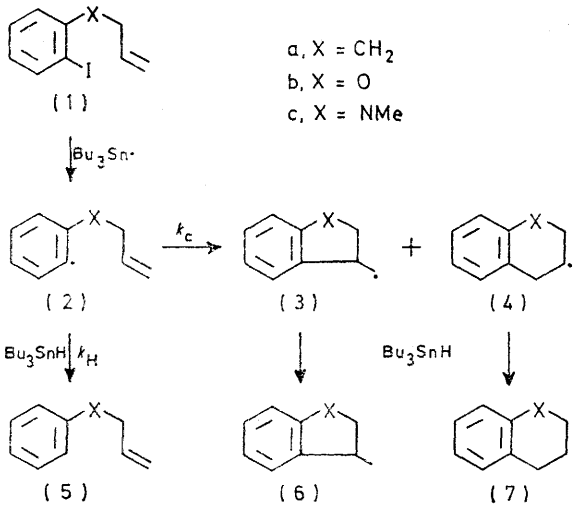
[9] For recent reviews of radical cyclization see (*a*) M. Julia, *Pure Appl. Chem.*, 1967, **15**, 167, *Accounts Chem. Res.*, 1971, **4**, 386; (*b*) A. L. J. Beckwith, 'Essays in Free-radical Chemistry, Chemical Society Special Publication No. 24, London, 1970, p. 239; (*c*) J. W. Wilt in 'Free Radicals,' ed. J. K. Kochi, Wiley–Interscience, New York, 1973, vol. 1, ch. 8.

radical (2b) exclusively underwent 1,5-addition to afford the primary radical (3b). The homologous radical (9b) also cyclized in that direction which affords the product (10b) containing the smaller possible ring.

The isolation of products from the one-electron reduction of suitable arenediazonium salts supported the conclusions based on e.s.r. spectral evidence, but the yields were insufficient to provide the basis of a quantitative investigation.[1] Consequently, we undertook a study of the reactions of suitable aryl iodides with tributylstannane in the hope that it would afford accurate data on the relative rates and direction of cyclization of aryl radicals containing unsaturated *ortho*-substituents, and that further mechanistic details of the cyclization process would thereby be revealed.*

METHODS

Although the intermediacy of alkyl radicals in the reduction of alkyl halides with tributylstannane has been adequately demonstrated,[10] there has been no unequivocal proof that the reduction of aryl halides also involves a free-radical chain mechanism. Accordingly, preliminary experiments were conducted with *o*-allyloxyiodobenzene (1b). When this iodo-compound was heated in benzene with tributylstannane and azobisisobutyronitrile as initiator, a clean reaction ensued and 3-methyl-2,3-dihydrobenzofuran (6b) was obtained in quantitative yield. In view of the results of the e.s.r. experiments [1] the only reasonable explanation for this outcome is that the radical (2b) is generated from the iodo-compound (1b), and undergoes cyclization to afford the radical (3b), from which the final product (6b) is formed by a hydrogen atom transfer process

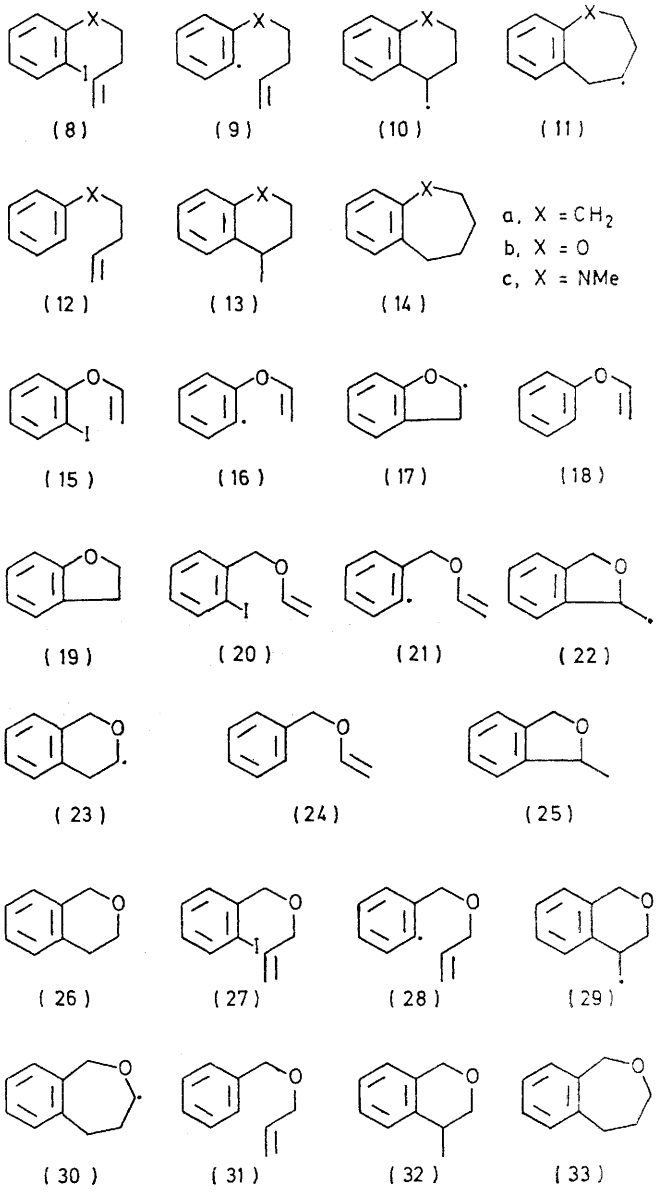


SCHEME

with stannane. The conclusion that aryl iodides interact with tributylstannane by a mechanism involving free aryl radicals is also supported by the kinetic behaviour of the other compounds studied (see below), and it appears, therefore, that the hypothesis that the reaction involves a four-centre concerted process [11] is incorrect.

The aryl iodides (1a—c), (8b), (8c), (15), (20), and (27) were employed. Samples of each were heated with tributylstannane and a trace of azobisisobutyronitrile in benzene solution in sealed, evacuated tubes at 130 ± 3°. Experiments were conducted in duplicate with initial concentrations of stannane of *ca.* 0·08, 0·16, 0·32, and 0·64M, and the reaction mixtures were analysed by g.l.c. using authentic samples of the expected products as standards.

The kinetic treatment was based on the expected mechanism, illustrated in the Scheme. Since cyclization of the intermediate radical (2) competes with its reaction with tributylstannane, the final yields of open chain (5) and cyclized products (6) and (7) should be approximately



related to the mean stannane concentration, $[Bu_3SnH]_m$, according to expression (1). Consequently a plot of (yield,

$$\frac{\text{(yield, \%, open-chain product)}}{\text{(total yield, \%, cyclized products)}} = \frac{k_H[Bu_3SnH]_m}{k_c} \quad (1)$$

* For a preliminary account of this work see A. L. J. Beckwith and W. B. Gara, *J. Amer. Chem. Soc.*, 1969, **91**, 5691.

[10] H. G. Kuivila, *Accounts Chem. Res.*, 1968, **1**, 299.

[11] D. H. Lorenz, P. Shapiro, A. Stern, and E. I. Becker, *J. Org. Chem.*, 1963, **28**, 2332.

%, open-chain products)/(total yield, %, cyclized products) against $[Bu_3SnH]_m$ should afford a linear graph passing through the origin, the gradient of which enables k_c/k_H to be evaluated.

A more accurate method for the estimation of k_c/k_H involves the solution by computer methods of the integrated rate expression (2), in which [C] is the total final concentration of cyclized products, and $[S]_0$ and $[S]_f$ are the initial

$$[C] = k_c/k_H\{\ln([S]_0 + k_c/k_H) - \ln([S]_f + k_c/k_H)\} \quad (2)$$

and final values respectively of $[Bu_3SnH]$. In practice the results obtained by graphical and computational methods were in good agreement.

Unequivocal syntheses of most of the compounds required as starting materials, or for reference, were accomplished by well-established methods. However, treatment of phenol with 4-bromobut-1-ene and potassium carbonate in acetone by the usual procedure gave only a small yield of the expected ether (12b), and the outcome was similarly disappointing when dimethyl sulphoxide or dimethylformamide were used as solvents, or when silver phenoxide was heated with the bromo-compound in benzene. Eventually the ether (12b) was obtained by alkylation of sodium phenoxide with 4-bromobut-1-ene in boiling water, and the iodo-ether (8b) was similarly prepared in good yield.

the appropriate values of k_c/k_H obtained by solution of the rate expression (2). Also included in the Table are the ranges of values of k_c/k_H similarly calculated from the results of experiments conducted at lower stannane concentrations; these are considered to be less reliable because of the relatively lower yields of open-chain compounds formed. In some cases the variation in k_c/k_H is due to the probable intervention of intramolecular hydrogen atom transfer reactions (see below). Values of k_c/k_H obtained by equation (2) from yields of products corrected for the fraction formed by hydrogen atom transfer are given in the column headed k_c/k_H (corrected). The final column contains values of k_c/k_H determined by the graphical method based on equation (1).

We shall consider first the data pertaining to those compounds [(1a—c) and (20)] which give radicals potentially capable of undergoing either 1,5- or 1,6-cyclization. In fact each reaction was highly regiospecific; in every case the yield of six-membered product was <1% of the total yield of cyclic products. Although the hypothesis [1] that the direction of intramolecular addition in alkenyl and similar radicals is related to the

Reduction of aryl iodides with tributylstannane at 130°

Compound	$[Bu_3SnH]_0$	Products; % Yields [a] Open chain	Cyclized [d]	$k_c k_H^{-1}$ [b]/mol l^{-1} (Calculated)	$k_c k_H^{-1}$ [b,c]/mol l^{-1} (Corrected)	$k_c k_H^{-1}$/mol l^{-1} (Graphical)
(1a)	0·563	(5a); 50	(6a); 50	0·52 (0·43—0·52)		0·50
(1b)	0·688	(5b); 1	(6b); 99	>60		
(1c)	0·592	(5c); 13	(6c); 78	3·1 (0·9—3·1)	4·0 (2·1—4·0)	4·0
(20)	0·612	(24); 76	(25); 24	0·18 (0·18—0·22)		0·19
(15)	0·830	(18); 94	(19); <1	<0·01		
(8b)	0·596	(12b); 38	(13b); 62	0·9 (0·3—0·9)	1·1 (0·9—1·15)	1·1
(8c)	0·600	(12c); 42	(13c); 45	0·6 (0·1—0·6)	1·3 (1·0—1·3)	1·3
(27)	0·599	(31); 71	(32); 14	0·12 (0·05—0·12)	0·14 (0·13—0·17)	0·15

[a] Mean absolute yields from duplicate experiments. [b] Figures in parentheses give the range of values obtained from the results of four sets of duplicate experiments (see Experimental section). [c] Values obtained by application of equation (2) to data corrected for the formation of open-chain products by hydrogen-atom transfer processes (see text). [d] In some experiments, traces (<1%) of other cyclized products were detected.

Attempts to form the iodo-amines (1c) and (8c) by two consecutive monoalkylation steps on *o*-iodoaniline gave intractable mixtures of products. Nor was attempted methylation of *N*-*o*-iodophenyltoluene-*p*-sulphonamide with dimethyl sulphate successful. However, reduction of *N*-*o*-iodophenylformamide with diborane [12] efficiently afforded *o*-iodo-*N*-methylaniline, alkylation of which with allyl bromide and with 4-bromobut-1-ene gave the amines (1c) and (8c) respectively.

The iodo-ether (27) was conveniently prepared by the interaction of sodium allyloxide with *o*-iodobenzyl bromide, whilst the addition of di-iodoacetylene to the Grignard reagent prepared from 4-(*o*-chlorophenyl)but-1-ene afforded the iodo-compound (1a).[13] Dehydrobromination of 2-bromoethyl *o*-iodophenyl ether by treatment with ethyldicyclohexylamine [14] gave the vinyl ether (15).

DISCUSSION

The yields of products formed by reduction of each iodo-compound with tributylstannane of initial concentration 0·5—0·8M are given in the Table together with

distance of closest unstrained approach between the radical centre and the terminal atoms of the double bond is clearly incorrect, there appears to be a relationship between the relative rates of cyclization of radicals (2a—c) and (21) and the distances between the appropriate reactive centres. Accurate dimensions for species such as these have not been determined, nor is it possible readily to estimate the effect of conjugative interactions of the heteroatoms with neighbouring π systems on bond angles and distances. However, examination of Dreiding models indicates the probable order of 1,5-distance in the unstrained radicals to be (2b) < (2c) < (2a) ≈ (21), whereas the order of reactivity is (2b) > (2c) > (2a) > (21). Possibly the comparatively low rate of cyclization of the radical (21) is due to polar effects, or to the loss of resonance energy associated with disruption of the vinyl ether function. The relative rate of cyclization of the allyloxyl radical (2b) is exceptionally high. The substitution of oxygen for carbon in an equivalent position in alkenyl radicals also enhances the

[12] H. C. Brown and P. Heim, *J. Amer. Chem. Soc.*, 1964, **86**, 3566.

[13] V. Franzen, *Chem. Ber.*, 1954, **87**, 1148.

[14] S. Hünig and M. Kiessel, *Chem. Ber.*, 1958, **91**, 380.

rate of cyclization,[3] but the effect is less than that observed here. Possibly conjugative interaction of the oxygen lone pairs with the aromatic ring increases the populations of conformers of the radical (2b) favourably disposed for cyclization.

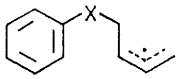
Cyclization of those radicals [(9b), (9c), and (28)] potentially capable of forming either six- or seven-membered rings occurs exclusively by 1,6-intramolecular addition, but the range of values of k_c/k_H is much less than that exhibited by the lower homologues. The greater flexibility of the longer side chains allows close unstrained approach between the 1- and 6-positions in each of the radicals (9b), (9c), and (28).

Since representative values of k_H, the rate constant for hydrogen atom transfer from tributylstannane to aryl radicals, are unavailable it is not possible to determine values of k_c. However, on the basis of the reasonable assumption [15] that $k_H \geqslant 10^6$ l mol^{-1} s^{-1}, the minimum values of k_c lie in the range $1{\cdot}5 \times 10^5$—6×10^7 s^{-1}. The rates of cyclization of radicals (2a—c) and (21) containing four-membered side chains appear to be of the same order of magnitude as those for the hex-5-enyl radical and similar species.[3-8] Presumably, the higher reactivity expected of an aryl radical as compared with alkyl radicals is counterbalanced by the greater strain engendered in the formation of five-membered rings fused to aromatic systems.

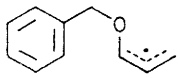
However, 1,6-cyclization occurs much more rapidly in the radicals (9b), (9c), and (28) than in the hept-6-enyl radical.[5] Angle strain in the product radicals (10b), (10c), and (29) is negligible, there are fewer non-bonded interactions than in the cycloheptyl radical, and the presence of the aromatic ring decreases the loss of rotational degrees of freedom which accompanies cyclization.

Intramolecular hydrogen atom transfer reactions are most likely to be observed when their occurrence through a six-membered transition state affords resonance-stabilized species, *e.g.* the formation of (34)—(36) from (9b), (9c), and (28) respectively. Plots of relative yields of products against $[Bu_3SnH]_m$ for reactions of each of the compounds (8b), (8c), and (27) gave straight lines as expected according to expression (1). However, the lines did not pass through the origin, but gave positive values of the function (yield of open-chain product)/(yield of cyclized product) at $[Bu_3SnH]_m = 0$. This indicates the formation of open-chain products by pathways which do not involve direct interaction of the parent aryl radicals with stannane. Such pathways are provided by the formation of the allylic radicals (34)—(36), and their subsequent conversion, by reaction with stannane, into open-chain products. The double bond isomers of olefins (12b), (12c), and (31), which should also be formed from (34)—(36), respectively, would not have been separately detected by the analytical methods employed.

The intercepts at $[Bu_3SnH]_m = 0$ for the appropriate graphs of data from reactions of the iodo-compounds (8b), (8c), and (27) are 0·11, 0·53, and 0·90 respectively from which it can be calculated that the appropriate



(34) X = O
(35) X = NMe



(36)

values of k_t/k_H, where k_t is the rate constant for intramolecular hydrogen atom transfer, are 0·13, 0·7, and 0·13 mol l^{-1}. On the basis of the assumption that $k_H \geqslant 10^6$ l mol^{-1} s^{-1} minimum values of k_t lie in the range $1{\cdot}3 \times 10^5$—$7{\cdot}0 \times 10^5$ s^{-1}. The fact that they are considerably greater than k_t/k_H for the hept-6-enyl radical can be attributed to the high aromatic C–H bond energy [16] and to the relative absence of non-bonded interactions in the transition states. Previous e.s.r. measurements allowed k_t/k_H to be estimated as $>10^2$ s^{-1} for aryl radicals with saturated side chains.[1]

When allowance was made for the amounts of uncyclized products arising *via* the allylic radicals (34)—(36), the values of k_c/k_H (corrected) calculated by means of equation (2) showed a small range and were in good agreement with those obtained directly from the gradients of the appropriate straight line graphs.

A plot of the appropriate data for the radical (2c) also gives a positive intercept of 0·04 on the stannane axis. The reason for this is not clear. Possibly it reflects experimental inaccuracy arising from the fact that k_c/k_H is large and hence, under our experimental conditions, the yields of open-chain products were small. On the other hand it may indicate the occurrence of intramolecular hydrogen atom transfer from the *N*-methyl group and/or the allylic position to the aryl radical centre. An example of 1,4-hydrogen atom transfer in a substituted aryl radical has been recently reported.[17] However, the relative rate ($k_c/k_H = 0{\cdot}13$ mol l^{-1}) is greater than might have been expected. When k_c/k_H was recalculated for radical (2c) on the assumption that intramolecular hydrogen atom transfer had occurred the range of values obtained was 2·1—4·0M.

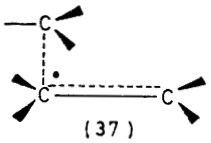
The most significant feature of these reactions is their regiospecificity; the primary radicals actually formed are thermodynamically less stable than the alternative secondary radicals. The specificity of the process [(21) ⟶ (22)] is especially noteworthy for in this case the alternative mode of cyclization would afford species (23) stabilized by conjugation of the free electron with the lone pairs on the adjacent oxygen atom. The observed regiospecificity cannot be attributed entirely to entropy factors for although the formation of the smaller possible ring will involve a lesser loss of rotational freedom,[18] and have a smaller activation volume, simple calculations show that the maximum reasonable difference between the values of $\Delta S^{\ddagger}$ for 1,5- and 1,6-addition

[15] D. J. Carlsson and K. U. Ingold, *J. Amer. Chem. Soc.*, 1968, **90**, 7047.
[16] A. S. Rodgers, D. M. Golden, and S. W. Benson, *J. Amer. Chem. Soc*, 1967, **89**, 4578.
[17] L. R. C. Barclay, D. Griller, and K. U. Ingold, *J. Amer. Chem. Soc.*, 1974, **96**, 3011.
[18] B. Capon, *Quart. Rev.*, 1964, **18**, 45.

reactions cannot be sufficiently large to account fully for their difference in rates. We conclude, therefore, that the regiospecificity exhibited in the reactions of the radicals studied here, like the selectivity of intramolecular addition in alkenyl radicals,[5] is due partly and probably predominantly to differences in the values of $\Delta H^{\ddagger}$ for the two modes of cyclization.

The results obtained accord with the view that the preferred transition state for alkyl radical addition to a double bond comprises a triangular array of centres (37) arising from an initial interaction of the half-filled p orbital (or σ orbital in the case of an aryl radical) with one lobe of the antibonding π^* orbital.[2,3,9b,19]

The distinguishing feature of all the cyclizations studied is that they specifically afford products in which the newly formed radical centre is exocyclic to the new ring. In the case of the one radical (16) for which the only feasible cyclization process is that which leads to a product (17) containing an endocyclic radical centre no intramolecular addition occurs, despite the fact that the radical (17) should be stabilized by $p\pi$ interaction.



(37)

We believe that the key structural feature distinguishing the cyclized radicals actually formed from the alternative products is the degree of coplanarity that can be attained between the newly formed bond and the semi-occupied orbital at the new radical centre. In primary radicals such as (3a), free rotation about the exocyclic C–C bond allows complete coplanarity to be achieved, but this is not possible in radicals containing an endocyclic centre, *e.g.* (4a). We conclude, therefore, that the reactions described here exhibit a high degree of regiospecificity because the proposed transition state, which requires the orbitals containing the three electrons involved in the redistribution process to lie in the one plane, is readily accommodated on pathways leading to exocyclic radicals but not on those leading to endocyclic radicals.

Comparison of the reactions of the radicals (8b), (8c), and (28) with cyclization of hept-6-enyl radical [5] affords support for this view. The last reaction proceeds to a considerable degree (*ca.* 15%) by 1,7-intermolecular addition; the flexibility of the cycloheptyl system allows the required planar transition state to be accommodated in structures leading to the endocyclic radical. The similar formation of the radicals (11b), (11c), and (29) is not possible because of the decrease in flexibility arising from the presence of the fused aromatic ring.

Finally, it is noteworthy that the mechanism proposed for intramolecular radical addition reactions is completely consistent with all the available data for the reverse process, namely the β-scission of cycloalkyl and cycloalkylcarbinyl radicals.[9b,c,20,21] Cyclopropylcarbinyl and cyclobutylcarbinyl radicals readily undergo ring opening. In rigid systems the reaction is stereospecific and affords the product arising from scission of that bond which lies closest to the plane of the semi-occupied orbital.[20,21] Conversely β-scission of cyclopropyl, cyclobutyl, and cyclopentyl radicals is relatively very slow and has large values of $\Delta H^{\ddagger}$.[22] In each of these approximately planar species, the bond undergoing fission is almost orthogonal to the plane of the half-filled orbital.

EXPERIMENTAL

Instruments and Apparatus.—Details of instruments and apparatus, and of physical methods employed, have been previously described.[1] The columns used for g.l.c. were as follows: (a) 10% Carbowax 20M on 100—120 Aeropak 30, 20 ft × 1/8 in stainless steel; (b) 3% PDEAS on 100—120 Aeropak 30, 14 ft × 1/8 in glass; (c) 10% SE 52 on 100—120 Aeropak 30, 6 ft × 1/8 in stainless steel.

Materials and Reference Compounds.—Allyl phenyl ether (5b),[23] 4-phenylbut-1-ene (5a),[24] 1-methylindane (6a),[25] 3-methyl-2,3-dihydrobenzofuran (6b),[2] chroman (7b),[26] *N*-methyl-1,2,3,4-tetrahydroquinoline (7c),[27] 2,3,4,5-tetrahydro-1-benzoxepin (14b),[28] benzyl vinyl ether (24),[29] 1-methylphthalan (25),[30] isochroman (26),[31] allyl benzyl ether (31), [32] 4-methylisochroman (32),[33] and 1,3,4,5-tetrahydro-2-benzoxepin (33) [34] were prepared by methods similar to or identical with those previously described. In each case the physical constants agreed with those given in the literature, the spectral data were consistent with the structure, and the purity of the sample was established by g.l.c.

Tributylstannane, prepared by reduction of tributyltin chloride with lithium aluminium hydride,[35] was distilled under reduced pressure, and stored in sealed evacuated ampoules at 0° in the dark. All solvents were purified by established procedures.

4-o-*Iodophenylbut*-1-*ene* (1a).—A mixture of magnesium turnings (0·65 g), 4-*o*-chlorophenylbut-1-ene [36] (4·18 g), and tetrahydrofuran (10 ml) was heated under reflux with stirring under nitrogen. When formation of the Grignard reagent was complete the mixture was cooled to 0°, and a

[19] H. Fujimoto, S. Yamabe, T. Minato, and K. Fukui, *J. Amer. Chem. Soc.*, 1972, **94**, 9205.
[20] A. L. J. Beckwith and G. Phillipou, *Chem. Comm.*, 1971, 658.
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[31] P. Maitte, *Ann. Chim. (France)*, 1954, **9**, 431.
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[33] P. Maitte, *Compt. rend.*, 1954, **239**, 1508.
[34] A. Rieche and H. Gross, *Chem. Ber.*, 1962, **95**, 91.
[35] H. G. Kuivila and O. F. Beumel, *J. Amer. Chem. Soc.*, *1961*, **83**, 1246.
[36] R. W. Bott, C. Eaborn, and K. Leyshon, *J. Chem. Soc.*, 1964, 1548.

solution of di-iodoacetylene [37] (3·47 g) in ether was added with stirring. After the addition, stirring was continued for 15 min, and the mixture was then poured into dilute sulphuric acid. Extraction of the mixture with ether, and distillation of the extract under reduced pressure afforded 4-o-*iodophenylbut*-1-*ene* (4·1 g, 63%), b.p. 130—132° at 19 mmHg (Found: C, 46·5; H, 4·3. $C_{10}H_{11}I$ requires C, 46·5; H, 4·3%), *m/e* 258 (M^+), δ 2·1—2·6 (2H, m, allylic CH_2), 2·6—2·9 (2H, m, $ArCH_2$), 4·7—5·2 (2H, m, $C=CH_2$), 5·5—6·2 (1H, m, CH=C), and 6·6—7·9 (4H, m, ArH). The compound showed only one peak on g.l.c. [column (b), 130°].

Allyl o-*Iodophenyl Ether* (1b).—Treatment of *o*-iodophenol with allyl bromide and potassium carbonate in acetone in the usual way [23] afforded the required *ether* (48%), b.p. 141—144° at 18 mmHg (Found: C, 41·5; H, 3·4; I, 48·5. C_9H_9IO requires C, 41·6; H, 3·5; I, 48·8%), *m/e* 260 (M^+), δ 4·4—4·6 (2H, m, OCH_2), 5·1—5·4 (2H, m, $C=CH_2$), 5·5—6·2 (1H, m, CH=C), and 6·2—7·9 (4H, m, ArH). The compound gave one peak on g.l.c. [column (a), 135°].

o-(N-*Allyl*-N-*methylamino*)*iodobenzene* (1c).—Treatment of *o*-iodoaniline with formic acid in benzene in the usual way [38] gave *N*-*o*-iodophenylformamide [39] (67%), m.p. 113°, a sample (31 g) of which was dissolved in tetrahydrofuran and kept at 0° whilst a stream of diborane (generated from 19 g of sodium borohydride) in nitrogen was bubbled in. When the addition was complete (5·5 h) the mixture was refluxed under nitrogen for 2 h, then set aside overnight at room temperature. After addition of 6N-hydrochloric acid (40 ml) to the cooled mixture it was slowly heated to 60° to complete the evolution of hydrogen. The mixture was then concentrated under reduced pressure, and the residue was made alkaline by the addition of aqueous sodium hydroxide. Extraction of the mixture with methylene chloride gave a red oil which was chromatographed on silica gel, using hexane–ether mixtures, to afford o-(N-*methylamino*)*iodobenzene* (25·5 g), b.p. 108—110° at 4·5 mmHg (Found: C, 36·4; H, 3·4; N, 6·1. C_7H_8IN requires C, 36·1; H, 3·5; N, 6·0%), *m/e* 233 (M^+), δ 2·85 (3H, s, NCH_3), 4·1br (1H, s, NH), and 6·4, 7·1, and 7·5 (4H, 3m ArH), $\nu_{max.}$ (film) 3420, 2815, 1310, and 735 cm^{-1}.

A mixture of the foregoing amine (2·33 g), allyl bromide (1·8 g), sodium carbonate (0·87 g), ethanol (4 ml), and water (1 ml) was refluxed for 48 h. The mixture was then concentrated under reduced pressure, diluted with water, and extracted with ether. Chromatography of the extract on silica gel using hexane–ether mixtures followed by distillation afforded o-(N-*allyl*-N-*methylamino*)*iodobenzene* (1·75 g, 64%), b.p. 83° at 2 mmHg (Found: C, 44·2; H, 4·4. $C_{10}H_{12}IN$ requires C, 44·0; H, 4·4%), *m/e* 273 (M^+), δ 2·65 (3H, s, NCH_3), 3·4—3·6 (2H, m, NCH_2), 4·9—5·4 (2H, m, $C=CH_2$), 5·6—6·2 (1H, m, CH=C), and 6·2—7·9 (4H, m, ArH), $\nu_{max.}$ (film) 3090, 3020, 2800, 1645, 1350, 995, 910, and 755 cm^{-1}. The compound gave one peak on g.l.c. [column (b), 130°].

4-o-*Iodophenoxybut*-1-*ene* (8b).—A mixture of *o*-iodophenol (4·36 g), sodium hydroxide (0·80 g), 4-bromobut-1-ene (2·80 g), and water (20 ml) was heated under reflux for 5 h, then cooled, diluted with water, and extracted with ether. The ether layer was washed successively with sodium hydroxide solution, water, and brine, dried, and concentrated under reduced pressure. The crude product was chromatographed on alumina, and distilled, to afford 4-o-*iodophenoxybut*-1-*ene* (3·11 g, 57%), b.p. 146—148° at 13 mmHg (Found: C, 43·9; H, 4·0; I, 46·4. $C_{10}H_{10}IO$ requires C, 43·8; H, 4·0; I, 46·3%), *m/e* 274 (M^+), δ 2·4—2·8 (2H, m, allylic CH_2), 3·97 (2H, t, *J* 7 Hz, OCH_2), 4·9—5·4 (2H, m, $C=CH_2$), 5·6—6·4 (1H, m, CH=C), and 6·6—7·8 (4H, m, ArH), $\nu_{max.}$ (film) 3060, 3020, 1645, 1245, 980, 915, and 745 cm^{-1}. The compound gave one peak on g.l.c. [column (b), 130°].

o-(N-*But*-3-*enyl*-N-*methylamino*)*iodobenzene* (8c).—A mixture of *o*-(*N*-methylamino)iodobenzene (4·61 g), 4-bromobut-1-ene (7·2 g), sodium carbonate (2·6 g), ethanol (8 ml), and water (2 ml) was refluxed for 14 days. G.l.c. of a sample of the mixture then showed the presence of starting amine. Further portions of 4-bromobut-1-ene (2·4 g), sodium carbonate (0·85 g), ethanol (4 ml), and water (1 ml) were added, and the mixture was heated under reflux for another 7 days. Work-up in the usual manner then afforded o-(N-*but*-3-*enyl*-N-*methylamino*)*iodobenzene* (4·05 g, 72%), b.p. 113° at 2·5 mmHg (Found: C, 45·7; H, 5·0. $C_{11}H_{14}IN$ requires C, 46·0; H, 4·9%), *m/e* 287 (M^+), δ 2·0—2·5 (2H, m, allylic CH_2), 2·70 (3H, s, NCH_3), 2·8—3·2 (2H, m, NCH_2), 4·8—5·2 (2H, m, $C=CH_2$), 5·5—6·2 (1H, m, CH=C), and 6·6—7·9 (4H, m, ArH), $\nu_{max.}$ (film) 3080, 3010, 2800, 1645, 1370, 980, and 910 cm^{-1}. The compound gave one peak on g.l.c. [column (b), 130°].

o-*Iodophenyl Vinyl Ether* (15).—A mixture of 2-*o*-iodophenoxyethyl bromide [40] (2·7 g) and ethyldicyclohexylamine (2·55 g) was heated at 170—180° for 5 h, then cooled, and diluted with acetone. After separation of amine hydrobromide by filtration, the filtrate was mixed with brine and extracted with ether. The ether layer was washed successively with dilute hydrochloric acid, water, aqueous sodium hydroxide, and brine, dried, and concentrated under reduced pressure. Chromatography of the residue on alumina, followed by preparative g.l.c., and short path distillation gave *o*-iodophenyl vinyl ether (0·07 g), *m/e* 246 (M^+), δ 4·40 (1H), 4·65 (1H), and 6·45 (1H) (ABX, J_{AB} 1·5, J_{AX} 6·0, J_{BX} 13·0 Hz, $OCH=CH_2$), and 6·6—7·8 (4H, m, ArH). The compound gave one peak on g.l.c. [column (c), 125°].

o-*Iodobenzyl Vinyl Ether* (20).—A mixture of *o*-iodobenzyl alcohol [41] (4·68 g), mercury(II) acetate (0·2 g), and ethyl vinyl ether was heated under reflux. After 11 h a further portion (0·2 g) of mercury(II) acetate was added, and heating of the mixture was continued for a further 10 h. The mixture was then cooled, washed with 10% aqueous potassium carbonate, dried, and concentrated under reduced pressure. Pentane (25 ml) was added to the residue, and the mixture was filtered to remove *o*-iodobenzyl alcohol (0·8 g). Evaporation of the filtrate afforded an oil which was purified by chromatography on alumina and distillation to give the required *ether* (3·35 g, 78%), b.p. 82—83° at 0·8 mmHg (Found: C, 41·5; H, 3·4; I, 48·4. C_9H_9IO requires C, 41·6; H, 3·5; I, 48·8%), *m/e* 260 (M^+), δ 4·10 (1H), 4·30 (1H), and 6·55 (1H) (ABX, J_{AB} 2·0, J_{AX} 14·0, J_{BX} 7·0 Hz, $OCH=CH_2$), 4·7 (2H, s, $ArCH_2$), and 6·8—7·9 (4H, m, ArH), $\nu_{max.}$ 3120, 3070, 1640, 1200, 990, 890, and 745 cm^{-1}. The compound gave one peak on g.l.c. [column (b), 120°].

Allyl o-*iodobenzyl ether* (27).—Treatment of *o*-iodobenzyl bromide [41] with sodium allyloxide in the usual way [32] gave

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the required *ether* (71%), b.p. 116—118° at 3·6 mmHg (Found: C, 43·9; H, 4·2; I, 46·5. $C_{10}H_{11}IO$ requires C, 43·8; H, 4·1; I, 46·3%), *m/e* 274 (M^+), δ 3·9—4·2 (2H, m, allylic CH_2), 4·40 (2H, s, $ArCH_2$), 5·0—5·5 (2H, m, $C{=}CH_2$), 5·6—6·3 (1H, m, CH=C), and 6·7—7·8 (4H, m, ArH), $\nu_{max.}$ 3070, 3020, 1085, 985, 920, and 745 cm^{-1}. The compound gave one peak on g.l.c. [column (b), 120°].

N-*Allyl*-N-*methylaminobenzene* (5c).—A mixture of *N*-methylaniline (16·0 g), allyl bromide (27·2 g), anhydrous sodium carbonate (9·55 g), ethanol (60 ml), and water (15 ml) was refluxed with stirring for 15 h, then cooled and worked up in the usual way to give the required amine [42] (11·84 g, 54%), b.p. 118—120° at 25 mmHg, δ 2·83 (3H, s, NCH_3), 3·7—3·9 (2H, m, NCH_2), 4·8—5·3 (2H, m, $C{=}CH_2$), 5·5—6·2 (1H, m, CH=C), and 6·5—7·3 (5H, m, ArH), $\nu_{max.}$ 3070, 3030, 2810, 1645, 1350, 985, 910, 740, and 685 cm^{-1}.

1,3-*Dimethylindoline* (6c).—Catalytic hydrogenation of 1,3-dimethylindole [43] in ethanol and aqueous fluoroboric acid [44] afforded 1,3-dimethylindoline (97%), b.p. 110° at 21 mmHg (picrate m.p. 110—111°),[45] δ 1·25 (3H, d, *J* 6 Hz, CCH_3), 2·65 (3H, s, NCH_3), 2·8—3·6 (3H, m, $CHCH_2$), and 6·0—7·1 (4H, m, ArH).

4-*Phenoxybut*-1-*ene* (12b).—Treatment of 4-bromobut-1-ene with sodium phenoxide in water according to the method used for the iodo ether (8b) gave the required ether [46] (42%), b.p. 130—131° at 72 mmHg, δ 2·2—2·7 (2H, m, allylic CH_2), 3·87 (2H, t, *J* 6·5 Hz, OCH_2), 4·8—5·3 (2H, m, $C{=}CH_2$), 5·5—6·3 (1H, m, CH=C), and 6·6—7·4 (5H, m, ArH), $\nu_{max.}$ (film) 3070, 3040, 1640, 1235, 985, 910, 750, and 685 cm^{-1}.

N-*But*-3-*enyl*-N-*methylaminobenzene* (12c).—A mixture of *N*-methylaniline (8·0 g), 4-bromobut-1-ene (13·5 g), sodium carbonate (4·8 g), ethanol (32 ml), and water (8 ml) was heated under reflux with stirring for 15 h. Work-up by the method used for the compound (1c) gave N-*but*-3-*enyl*-N-*methylaminobenzene* (9·5 g, 59%), b.p. 114° at 12 mmHg (Found: C, 81·7; H, 9·4. $C_{11}H_{15}N$ requires C, 81·9; H, 9·4%), *m/e* 161 (M^+), δ 2·0—2·5 (2H, m, allylic CH_2), 2·90 (3H, s, NCH_3), 3·2—3·5 (2H, m, NCH_2), 4·8—5·3 (2H, m, $C{=}CH_2$), 5·4—6·1 (1H, m, CH=C), and 6·4—7·3 (5H, m, ArH), $\nu_{max.}$ (film) 3070, 3030, 2810, 1635, 1340, 980, 905, 740, and 690 cm^{-1}.

4-*Methylchroman* (13b).—Hydrogenation of 4-methylchroman-4-ol [47] in ethanol over platinum oxide afforded 4-methylchroman [47] (70%), b.p. 102—104° at 13 mmHg, δ 1·25 (3H, d, *J* 7 Hz, CH_3), 1·4—2·3 (2H, m, CH_2), 2·5—3·1 (1H, m, CH), 4·05 (2H, t, *J* 5 Hz, OCH_2), and 6·5—7·1 (4H, m, ArH).

1,4-*Dimethyl*-1,2,3,4-*tetrahydroquinoline* (13c).—Heating of 4-methylquinoline with formic acid and triethylamine[48] gave 1-*formyl*-4-*methyl*-1,2,3,4-*tetrahydroquinoline* (70%), b.p. 168° at 12 mmHg (Found: C, 75·2; H, 7·5; N, 7·9. $C_{11}H_{13}NO$ requires C, 75·4; H, 7·5; N, 8·0%), *m/e* 175 (M^+), $\nu_{max.}$ (film) 1665 and 750 cm^{-1}, δ 1·30 (2H, d, *J* 6 Hz, CH_3), 1·4—2·4 (2H, m, CH_2), 2·5—3·2 (1H, m, CH), 3·4—4·0 (2H, m, NCH_2), 6·8—7·5 (4H, m, ArH), and 8·55 (1H, s, CHO).

The foregoing formyl compound (10·3 g) in ether (180 ml) was added dropwise with stirring to a suspension of lithium aluminium hydride (3·8 g) in ether (360 ml) under nitrogen, and the mixture was then refluxed for 15 h. After being cooled the mixture was cautiously treated with water (16 ml) and 15% aqueous sodium hydroxide (4 ml). The mixture was then filtered, and the filtrate was concentrated under reduced pressure. Chromatography of the residue on silica gel, followed by distillation gave 1,4-dimethyl-1,2,3,4-tetrahydroquinoline [49] (8·35 g, 88%), b.p. 122° at 12 mmHg, δ 1·25 (3H, d, *J* 7 Hz, CCH_3), 1·4—2·7 (3H, m, $CHCH_2$), 2·80 (3H, s, NCH_3), 2·9—3·3 (2H, m, NCH_2), and 6·3—7·1 (4H, m, ArH).

1-*Methyl*-2,3,4,5-*tetrahydro*-1H-1-*benzazepine* (14c).—Reduction of homodihydrocarbostyril [50] with lithium aluminium hydride by the usual procedure [51] gave 2,3,4,5-tetrahydro-1*H*-1-benzazepine,[52] a sample (7·3 g) of which was refluxed for 15 h with methyl iodide (9·5 g) and sodium carbonate (3·18 g) in ethanol (32 ml) and water (8 ml). Work-up in the usual way gave the required tertiary amine [53] (5·60 g, 75%), b.p. 114° at 12 mmHg, δ 1·2—2·0 (4H, m, CH_2CH_2), 2·6—3·0 (4H, m, NCH_2 and benzylic CH_2), 2·85 (3H, s, NCH_3), and 6·5—7·2 (4H, m, ArH).

Phenyl Vinyl Ether (18).—2-Phenoxyethyl toluene-*p*-sulphonate (8·76 g) was added in small portions with stirring to potassium t-butoxide (3·7 g) in dimethylformamide (50 ml) at 0° under nitrogen. After completion of the addition the mixture was kept at 0° for 2 h, then at 20° for 8 h. The mixture was then filtered, diluted with water (200 ml), and extracted with pentane. After being washed with aqueous sodium hydroxide and with water, the pentane solution was dried and concentrated. Distillation of the residue gave phenyl vinyl ether (1·38 g, 38%), b.p. 76—77° at 50 mmHg, δ 4·30 (1H), 4·60 (1H), and 6·55 (1H) (ABX, J_{AB} 1·5, J_{AX} 6·0, J_{BX} 13·5 Hz, $OCH{=}CH_2$), and 6·7—7·4 (5H, m, ArH).

2,3-*Dihydrobenzofuran* (19).—Reduction of benzofuran with sodium in ethanol, following the procedure described [1] for 3-methylbenzofuran, gave 2,3-dihydrobenzofuran [54] (89%), b.p. 78° at 12 mmHg, δ 3·00 (2H, t, *J* 8·5 Hz, $ArCH_2$), 4·35 (2H, t, *J* 8·5 Hz, OCH_2), and 6·4—7·2 (4H, m, ArH).

Reaction of Aryl Iodides with Tributylstannane.—A standard solution (5·0 ml) of the iodo-compound was prepared by dissolving a weighed sample (*ca.* 2·5 mmol) in benzene in a standard flask. The mixture was weighed, and azobisisobutyronitrile (4·5 mg) was added to it. A standard solution (10·0 ml) of tributylstannane (*ca.* 8 mmol) in benzene was similarly prepared. Weighed portions (0·50 ml) of the solution of iodo-compound were placed in 10 thick-walled ampoules. Then weighed portions of stannane solution were added as follows: to each of tubes nos. 1 and 2, 0·30 ml; to each of tubes nos. 3 and 4, 0·60 ml; to each of tubes nos. 5 and 6, 1·20 ml; to each of tubes nos. 7 and 8, 2·40 ml. Tubes nos. 9 and 10 were kept as blanks. Each mixture was made up to 2·90 ml with benzene, then

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frozen in an ethanol–dry ice bath whilst the tubes were evacuated (0·05 mmHg) and sealed. The tubes were then heated at 130 ± 3° for 24 h in the dark, cooled, and opened. After addition of weighed portions (1·0 ml) of a solution of internal standard in carbon tetrachloride to each tube the contents were analyed by g.l.c. The columns used for the analysis of the reaction mixtures from the various iodo-compounds were as follows: 4-*o*-iodophenylbut-1-ene (1a), column (a), 110°; allyl *o*-iodophenyl ether (1b), column (a), 130°; *o*-(*N*-allyl-*N*-methylamino)iodobenzene (1c), column (b), 130°; 4-*o*-iodophenoxybut-1-ene (8b), column (b), 100—130°; *o*-(*N*-but-3-enyl-*N*-methylamino)iodobenzene (8c), column (b), 100—120°; *o*-iodophenyl vinyl ether (*15*), column (a), 120°; *o*-iodobenzyl vinyl ether (20), column (b), 100—130°; allyl *o*-iodobenzyl ether (27), column (b), 100—130°. The results obtained are summarized in the Table.

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