

Received: September 29, 1977

HOMOLYTIC REACTIONS OF POLYFLUOROAROMATIC COMPOUNDS. Part XII.
ARYLDEHYDROGENATION AND ARYLDEFLUORINATION IN POLYFLUOROBENZENES

ROGER BOLTON, JOHN P.B. SANDALL, and GARETH H. WILLIAMS

Chemistry Department, Bedford College, London NW1 4NS (Great Britain)

SUMMARY

The thermal decomposition of benzoyl peroxide in a range of polyfluorobenzenes at 200° gives biaryls arising from both the displacement of fluorine and hydrogen. Phenyl-defluorination predominated only in the attack of 1,2,3,4-tetrafluorobenzene and of pentafluorobenzene, but was evident even in the attack of *o*-difluorobenzene. The relative rates of displacement, as shown by the isomer distributions, were generally well reflected by the application of partial rate factors found in the phenylation of fluorobenzene; however, phenyldefluorination was not so easily amenable to this treatment, a possible consequence of complex formation between radical precursor and substrate.

INTRODUCTION

The decomposition of benzoyl peroxide in benzene and in mono-substituted benzenes provides biaryls by the displacement of hydrogen [1] although fluorine displacement predominates when the reaction is carried out in hexafluorobenzene [2] or in

pentafluorobenzene [3]. The mechanism of fluorine displacement has been proposed [4] to involve hydrogen bonding between aryl acids formed concomitantly and the expelled fluorine atom. Other instances of similar halogen displacement are rare. The small yield of decafluorobiphenyl formed in the thermal decomposition of bis(pentafluoro)benzoyl peroxide in hexafluorobenzene suggests that quite subtle factors are involved in determining biaryl yields [5] in these aryldefluorination processes, and the unexpected formation of phenyl pentafluorobenzoate in the thermolysis of this peroxide in chlorobenzene or bromobenzene [6] shows that displacement of chlorine or bromine from aryl systems may also occur.

In principle, aryldefluorination should also occur with aryldehydrogenation in the attack of fluorobenzene, although we have not observed it in either phenylation [7] or pentafluorophenylation [8]. In the phenylation of pentafluorobenzene, however, [3] both types of reaction were evident. We now report a study of the phenylation of a number of derivatives of fluorobenzene to determine the generality of aryldefluorination in more simply substituted benzene systems.

DISCUSSION

Table 1 shows the relative yields of biaryls from the thermolysis of benzoyl peroxide in the various substrates. These biaryls usually comprised the major products (50-90%) of the decomposition, as well as the largest amount of the steam-volatile material; their high yields make it unlikely that selective volatilisation has altered the isomer distributions.

In the attack of hexafluorobenzene by phenyl radicals from benzoyl peroxide, the yield of 2,3,4,5,6-pentafluorobiphenyl could be raised from 35-40% [4] by pyrolysis of the higher-boiling residue formed at the same time [2, 9]. This

Table 1

Molar yields of polyfluorobiphenyls from the thermolysis of benzoyl peroxide (0.2-0.4M; 80°; 5-10 half-lives) in polyfluorobenzenes

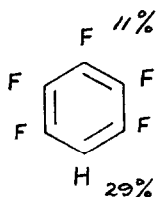
Polyfluorobenzene	Biaryl (yield in parenthesis)*	Isomer ratio (**)	
		(exp.)	(calc.)
Fluorobenzene	2-Fluorobiphenyl (47.7)	50	50
	3-Fluorobiphenyl (34.4)	36	36
	4-Fluorobiphenyl (13.3)	14	14
<u>o</u> -Difluorobenzene	2-Fluorobiphenyl (9.1)	13	13
	2,3-Difluorobiphenyl (42.5)	60	56
	3,4-Difluorobiphenyl (19.1)	27	31
<u>m</u> -Difluorobenzene	3-Fluorobiphenyl (4.7)	7	8
	2,4-Difluorobiphenyl (25.7)	38	39
	2,6-Difluorobiphenyl (23.3)	35	35
	3,5-Difluorobiphenyl (16.6)	20	24
<u>p</u> -Difluorobenzene	2,5-Difluorobiphenyl (58.0)	100	94
1,2,4-Trifluorobenzene	2,4-Difluorobiphenyl (3.7)	6	5
	2,5-Difluorobiphenyl (3.7)	7	6
	3,4-Difluorobiphenyl (<3)	<5	4
	2,3,5-Trifluorobiphenyl (16.1)	27	27
	2,4,5-Trifluorobiphenyl (12.1)	20	21
	2,3,6-Trifluorobiphenyl (20.5)	34	37
	3,5-Difluorobiphenyl (<2)	<8	13
1,3,5-Trifluorobenzene	2,4,6-Trifluorobiphenyl (22)	92	87
	2,3,4-Trifluorobiphenyl (4.9)	14	14
1,2,3,4-Tetrafluorobenzene	2,3,6-Trifluorobiphenyl (13.9)	54	61
	2,3,4,5-Tetrafluorobiphenyl (8.3)	32	25
	2,3,5-Trifluorobiphenyl (4.2)	12	16
1,2,3,5-Tetrafluorobenzene	2,4,6-Trifluorobiphenyl (10.8)	32	9
	3,4,5-Trifluorobiphenyl (<0.7)	<2	5
	2,3,4,6-Tetrafluorobiphenyl (18.2)	54	72
1,2,4,5-Tetrafluorobenzene	2,4,5-Trifluorobiphenyl (15.0)	26	21
	2,3,5,6-Tetrafluorobiphenyl (44.2)	74	79

(*) (Moles of biaryl per mole of peroxide decomposed) x 100

(**) Using partial rate factors derived from arylation of fluorobenzene; see text for details

pyrolysis occurred, to some extent, during g.l.c. [10] but was minimised by isolating the biaryls by steam distillation [11]. The present yields of biaryl are similarly expected to be only marginally affected by such secondary decompositions, and may be held to reflect the relative extents of primary phenylation in each case.

In the trifluorobenzenes, phenyldehydrogenation is preferred over phenyldefluorination although there are equal numbers of hydrogen and fluorine atoms which may be displaced. Only in the more fully fluorinated substrates is phenyldefluorination favoured as a source of biaryls, and this apparently arises from the statistical factor. In pentafluorobenzene, where the 3- and 6-positions are approximately equally affected by the other fluorine substituents (presupposing the effect of para-fluorine to be small, in keeping with homolytic and heterolytic mechanisms [12, 13]), hydrogen displacement proceeds with three times the ease of phenyldefluorination [3], as judged by the yields of the relevant biaryls.



However, phenyldefluorination occurs even in the attack of o- and m-difluorobenzenes, although in small amount. The 2-fluorobiphenyl found in the former process is uncontaminated by the 3-isomer; nor are any other monofluorobiphenyls found along with 3-fluorobiphenyl in the attack of m-difluorobenzene. In the latter case, however, the certain identification of the 3-fluorobiphenyl is not assured, since other absorptions occurred in the same area of the n.m.r. spectrum. Phenyldefluorination in such systems must therefore involve primary attack at the

carbon atoms bearing fluorine, and does not arise from an addition-elimination sequence in which the aryl radical initially attacks a proton-bearing aromatic site:

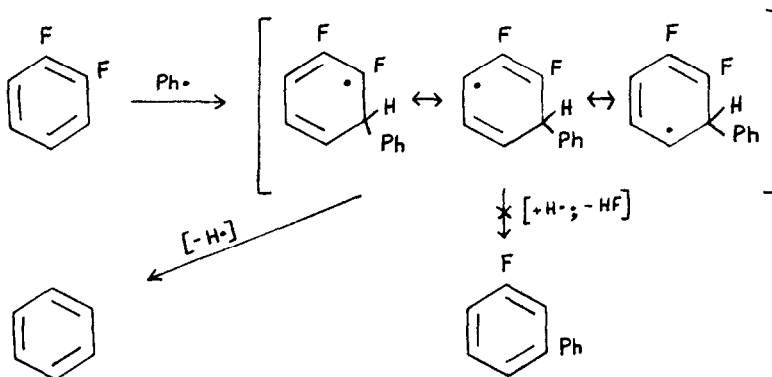


Fig. 1 Sequences of phenyldefluorination of o-difluorobenzene

Hydrogen uptake (Fig. 1) is precluded in systems which are hydrogen-rich by the ease with which the radical may undergo dimerisation or oxidation. Aryldefluorination of polyfluorobenzenes becomes significant partly because of the reduced incidence of the competing oxidation reactions, on statistical grounds, and perhaps because of the reversibility of dimerisation of the appropriate intermediate radicals [9, 10]. This process, although not observed in hydrogen-rich systems, is well known in the phenylation of hexafluorobenzene where the formation of pentafluorobiphenyl can become thermodynamically preferred, and this process is presumably a general reaction of the radical intermediates in homolytic aromatic substitution involving fluorine displacement.

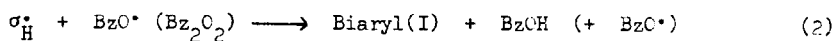
Orientation - The orientation of attack of fluorobenzene by phenyl radicals (Table 1), combined with the observed [1] relative rates of phenylation of fluorobenzene and of benzene give partial rate factors (f_{o-F} , 1.62; f_{m-F} , 1.17; f_{p-F} , 0.91)

which can be used successfully to predict the relative rates of attack of polyfluorobenzenes at hydrogen-bearing sites. We have already warned [3, 14] of the contribution which may arise from the formation of complexes between competing substrates and radicals or their precursors. The effects of this, clearly seen in pentafluorophenylation [14] and in the arylation of derivatives of pentafluorobenzene [3], are to add another contribution to the selection process and to cause the additivity principle to fail. When the substrates (benzene, fluorobenzene) and the reagent (benzoyl peroxide) have similar electron densities, such a complication is unlikely to be serious; also the results have been applied only within a single molecule, where we have noted [14] that selection appears to be free.

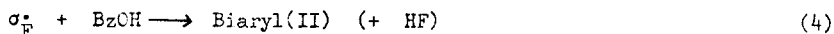
These same partial rate factors may be used to reflect the (small) extent of aryldefluorination occurring in attack of the di- and tri-fluorobenzenes. In this case, an empirical factor of 0.27 must be incorporated. The numerical value is that needed to correlate the experimental figures with the partial rate factors, and has no particular physical significance except to point to the greater difficulty of aryldefluorination with respect to aryldehydrogenation. The more fully fluorinated substrates show a greater divergence between calculated and experimental figures, although a reversal of order only occurs in one case.

The partial rate factors for aryldefluorination which may be deduced by comparing the rates and orientation of attack of hexa- and penta-fluorobenzenes [3] are rather different (f_{o-F} , 2.47; f_{m-F} , 0.82; f_{p-F} , 1.69) from these. They give some measure of the relative rates of aryldefluorination of the tetrafluorobenzenes, but then become rapidly and increasingly less correct in their predictions as they are applied to less fully fluorinated systems. For this reason we have not shown their predictions in Table 1, for the parent partial rate factors, having been derived from studies of attack of penta- and hexa-fluorobenzenes, must be subject to all the errors which we have found [3, 14] in such systems.

The relative rates of aryldefluorination and aryldehydrogenation within the same molecule are conditioned by two terms. One reflects the inherent reactivity of the aromatic site to aryl radical attack; the second involves the relative yields of each biaryl from their appropriate radical intermediate. The relative rates of formation of these biaryls, which determines their yields, are dependent upon not only the individual rate constants associated with aromatisation (k_H and k_F below) and the relative concentrations of the two radical intermediates (σ_H^\bullet and σ_F^\bullet) but also the concentrations of the appropriate aromatising reagents



$$d[\text{Biaryl(I)}]/dt = k_H \cdot [\sigma_H^\bullet][Bz_2O_2] \text{ and/or } k_H' \cdot [\sigma_H^\bullet][BzO^\bullet] \quad (3)$$



$$d[\text{Biaryl(II)}]/dt = k_F \cdot [\sigma_F^\bullet][BzOH] \quad (5)$$

In the attack of a polyfluorobenzene such as tetrafluorobenzene the amount of hydrogen displacement must necessarily be influenced by the relative paucity of available sites. The yield of benzoic acid which is formed in this way is therefore considerably less than that found in the phenylation of fluorobenzene. As it is this benzoic acid, however, which is held [4] to be the essential reagent in the defluorination of intermediates such as σ_F^\bullet in (4), a fall in the concentration of this species must cause a corresponding diminution in the extent to which defluorination can compete with dimerisation as a fate of this intermediate radical. The discrepancies which we have observed throughout the series may arise from this simple fact, and have no deep mechanistic significance. In contrast, the failure of the additivity principle [3] in these systems cannot arise from such a simple source, and suggests a more complicated selection process than that previously envisaged.

EXPERIMENTAL

Fluorobenzene, o-, m-, and p-difluorobenzene, 1,2,4- and 1,3,5-trifluorobenzene, 1,2,3,5- and 1,2,4,5-tetrafluorobenzene were all supplied by Bristol Organics Ltd.; 1,2,3,4-tetrafluorobenzene was a product of Fluorochem Ltd.. Each substrate was analysed by g.l.c. and by ^{19}F -nmr spectroscopy, and was substantially pure (>99%). Benzoyl peroxide was purified by crystallisation from chloroform-methanol mixtures; m.p. 105-106°.

The decompositions were carried out using weighed amounts of benzoyl peroxide in 5ml. or 10ml. quantities of the fluorocarbon, together with a known weight of a marker by which the yields of the various biaryls could be assessed. Compounds were selected on the bases (a) that they had similar volatilities to the expected products (b) that they showed no tendency to overlap with these products either under g.l.c. conditions or in the ^{19}F -nmr spectrum. Three compounds were used as markers; 4-fluorobiphenyl, 3-fluoro-1,2,4,5-tetrachlorobenzene, and 1,4-dibromotetrafluorobenzene. The yields of these biaryls are therefore certain. The identification of the biaryls was made on a number of bases: (a) that the number and relative intensities of the absorptions in the ^{19}F -nmr spectrum are consistent with the assignment (b) that the chemical shifts and coupling constants agree with those predicted (c) that, where the same compound was found in two different systems (e.g. 2,4,6-trifluorobiphenyl, formed in reactions in both 1,3,5-trifluorobenzene and 1,2,3,5-tetrafluorobenzene), the detailed ^{19}F -nmr spectra agreed in each case. Finally, a number of the biaryls were available by unambiguous synthesis.

The crude reaction mixtures, obtained after 50-100 hours in an oil thermostat at 80°, were cooled and evaporated under reduced pressure at room temperature. The steam-volatile materials from exhaustive steam-distillation were then combined and examined, as a solution in fluorochloroform, by g.l.c. (Pye 104) and ^{19}F -nmr using a Perkin-Elmer R12B instrument operating at 56.4 MHz.

Table 2

¹⁹F-NMR shifts used in analysis of fluorinated biphenyls^(a)

Substituents	δ (ppm, upfield of CFC1 ₃)
2-Fluoro-	118.2
3-Fluoro-	113.3
4-Fluoro-	116.1
2,3-Difluoro-	F ₂ , 144.2 (142.7); F ₃ , 138.6 (137.8)
2,4-Difluoro-	F ₂ , 113.5 (113.9); F ₄ , 112.2 (112.3)
2,5-Difluoro-	F ₂ , 124.2 (124.4); F ₅ , 120.1 (120.2)
2,6-Difluoro-	F ₂ , 114.8 (114.3)
3,4-Difluoro-	F ₃ , 138.1 (138.0); F ₄ , 139.9 (140.7)
3,5-Difluoro-	F ₃ (109.4)
2,3,4-Trifluoro-	F ₂ , 139.3 (139.3); F ₃ , 160.7 (162.2); F ₄ , 136.5 (137.0)
2,3,5-Trifluoro-	F ₂ , 149.0 (149.2); F ₃ , 133.5 (134.3); F ₅ , 116.2 (115.5)
2,3,6-Trifluoro-	F ₂ , 138.1 (138.2); F ₃ , 142.8 (142.7); F ₆ , 120.1 (120.4)
2,4,5-Trifluoro-	F ₂ , 120.1 (119.9); F ₄ , 135.7 (135.9); F ₅ , 143.5 (143.5)
2,4,6-Trifluoro-	F ₂ , 111.5 (111.5); F ₄ , 109.8 (110.1)
3,4,5-Trifluoro-	F ₃ (134.3); F ₄ (165.9)
2,3,4,5-Tetrafluoro-	F ₂ , 143.8 (144.3); F ₃ , 156.2 (156.0); F ₄ , 158.5 (158.0) F ₅ , 140.5 (140.4)
2,3,4,6-Tetrafluoro-	F ₂ , 135.8 (136.3); F ₃ , 165.5 (166.0); F ₄ , 134.1 (134.2); F ₆ , 118.5 (118.3)
2,3,5,6-Tetrafluoro-	F ₂ , 144.5 (144.3); F ₃ , 140.0 (139.9)

(a) Figures in parenthesis refer either to values found for samples of authentic material, or to values derived from assuming additivity of substituent effects ($\Delta\delta_{o-F}$, 24.5; $\Delta\delta_{m-F}$, -3.9; $\Delta\delta_{p-F}$, 6.1 ppm, from the difluorobenzenes) upon the figures for the monofluorobiphenyls

REFERENCES

- 1 G.H. Williams, Essays in Free Radical Chemistry, Chem.Soc.Special Publication No. 24, p. 25
- 2 P.A. Claret, J. Coulson and G.H. Williams, Chem.and Ind., (1965) 228.
- 3 R. Bolton, J.P.B. Sandall, and G.H. Williams, J.Fluorine Chem., (1974) 4, 355

- 4 R. Bolton and J.P.B. Sandall, Chem. Commun. (1973) 286; R. Bolton, J.P.B. Sandall, and G.H. Williams, J. Fluorine Chem. (1974) 4, 347.
- 5 J. Burdon, J.G. Campbell and J.C. Tatlow, J. Chem. Soc. (C) (1969) 822.
- 6 P.H. Oldham, G.H. Williams, and B.A. Wilson, J. Chem. Soc. (B) (1970) 1346.
- 7 P. Lewis and G.H. Williams, J. Chem. Soc., (B) (1969) 120.
- 8 R. Bolton, J.P.B. Sandall, and G.H. Williams, J. Fluorine Chem. (1973/4) 3, 35.
- 9 P. Claret, J. Coulson, and G.H. Williams, J. Chem. Soc., (C) (1968) 341; P.H. Oldham and G.H. Williams, J. Chem. Soc. (C) (1970) 1260.
- 10 L.V. Vlasova, L.S. Kobrina, and G.G. Yakobson, Izv. Sib. Otdel. Akad. Nauk. SSSR (1974) 3, 97.
- 11 R. Bolton, W.K. Adrian Moss, J.P.B. Sandall, and G.H. Williams, J. Fluorine Chem. (1976) 2, 597.
- 12 D.H. Hey, Advances in Free Radical Chemistry (1969) 2, 47.
- 13 J. Miller, Aromatic Nucleophilic Substitution, Elsevier (1968)
R.O.C. Norman and R. Taylor, Electrophilic Substitution in Benzenoid Systems, Elsevier (1965).
- 14 R. Bolton, J.P.B. Sandall, and G.H. Williams, J. Chem. Research (1977) S, 24; M, 0373.