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MECHANISMS OF FREE-RADICAL AROMATIC SUBSTITUTION

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SINCE Hey's and Waters' studies on free-radical aromatic substitution,[1] such diverse reactions as the Gomberg-Bachmann reaction and the decomposition of nitrosoacetanilides, arylazotriphenylmethanes and diaroyl peroxides in aromatic substrates have been widely assumed to proceed by the same general mechanism once the substituting aryl radicals are generated.[2] Work in DeTar's laboratory[3] and ours[4,5] has shown that an important contributing step in the free-radical arylation of benzene by diaroyl peroxides is disproportionation:

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[1] D.F. Hey, J. Chem. Soc. 1966 (1934); D.H. Hey and W.A. Waters, Chem. Rev. 21, 169 (1937).

[2] D.R. Augood and G.H. Williams, Chem. Rev. 57, 123 (1957); G.H. Williams, Homolytic Aromatic Substitution Chap. 4. Pergamon Press, New York (1960). See, however, H. Zollinger, Diazo and Azo Chemistry pp. 153-159, Interscience, New York (1961), for a contrary view.

[3] D.F. DeTar and R.A.J. Long, J. Amer. Chem. Soc. 80, 4742 (1958); D.F. DeTar, Abstracts, Seventeenth National Organic Chemistry Symposium American Chem. Soc., Bloomington, Indiana, 1961, p. 59.

[4] E.L. Eliel, S. Meyerson, Z. Welvart and S.H. Wilen, J. Amer. Chem. Soc. 82, 2936 (1960).

[5] M. Eberhardt and E.L. Eliel, J. Org. Chem. 27, 2289 (1962).

We have now found evidence that arylation with nitrosoacetanilides and arylazotriphenylmethanes does not involve dihydrobiaryls (II) as intermediates and therefore differs in essential fashion from arylation with diaroyl peroxides.

Three essential criteria for the mechanism of arylation with diaroyl peroxides are: (a) formation of dihydrobiaryls (II) in dilute[3] (0.02 M) and, though to a much lesser extent, in concentrated[5] (0.2 M) solutions of decomposing diaroyl peroxides in benzene; (b) an apparent isotope effect in the arylation of benzene-d̲ as computed from the deuterium content of the arylbenzene (I) formed[4] - due, at least in part, to isotopic discrimination in the disproportionation of hydrobiaryl radicals; (c) appearance of biaryl-$\underline{d}_2$ in the arylation of benzene-d̲, as a result of oxidation of dideuterated dihydrobiaryl (II) species. We have now applied these criteria to the arylation of benzene and benzene-d̲ with nitrosoacetanilides and with phenylazotriphenylmethane and its p̲-chloro analog.

No dihydrobiphenyl could be detected by gas chromatography in either concentrated (c̲a̲. 0.15 M) or dilute (c̲a̲. 0.015 M) solution after decomposition of nitrosoacetanilide or phenylazotriphenylmethane in benzene.[6] When dihydrobiphenyl was added to the dilute solutions, about 75 per cent of it survived the arylation reaction. In control experiments, dihydrobiphenyl was readily found in the decomposition of benzoyl peroxide in benzene in dilute (0.02 M) solution (c̲f̲. ref. 3) and even at concentrations as high as 0.2 M.[5]

Whereas the decomposition of diaroyl peroxides in benzene-d̲ involves appreciable apparent isotope effects,[4] these effects (I.E.) in the decomposition of nitrosoacetanilides and arylazotriphenylmethanes in benzene-d̲ are

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[6] One of us (O.S.) has independently confirmed this result in the laboratories of the University of Tokyo, Tokyo, Japan, by isotope dilution analysis.

very small, well within the range to be expected of secondary isotope effects:

Ar	C_6H_5	p-$CH_3OC_6H_4$	p-$CH_3C_6H_4$	p-ClC_6H_4
I.E.[4] for $(ArCOO)_2$	1.0-6.6	1.3	2.9	1.3-1.7
I.E. for $ArN(NO)COCH_3$	1.00	1.05-1.12	1.00	1.04-1.07
I.E. for $ArN{=}NCPh_3$	1.06	-	-	1.14

While appreciable amounts of dideuterated biaryls were found in the decomposition of aroyl peroxides in benzene-d (e.g. 0.39 mole per cent for p-chlorobenzoyl peroxide,[4] 0.53 mole per cent for p-toluyl peroxide), the amounts of dideuterated biaryl found in the decomposition of p-methoxy-N-nitrosoacetanilide (0.0-0.20 mole per cent), p-methyl-N-nitrosoacetanilide (0.23 mole per cent), p-chloro-N-nitrosoacetanilide (0.0-0.09 mole per cent) and p-chlorophenylazotriphenylmethane (0.0 per cent) were much less; in fact, in four of the eight cases studied, no d_2 material was found at all.[7]

Also, we have confirmed the report by Hey[8] that the yield of biaryl climbs sharply (e.g. from 66.5 to 91 per cent for biphenyl, from 50 to 91 per cent for p-methoxybiphenyl, from 44.5 to 80 per cent for p-chlorobiphenyl) when N-nitrosoacetanilides are decomposed in dilute (0.025 M) instead of in concentrated (0.25 M) solution. This increased yield is at the expense of hydrocarbon - ArH from $ArN(NO)COCH_3$ - and, mainly, of nitrogen-containing tars. A similar increase in yield (from 55 per cent at *ca.* 0.15 M to 85 per cent at 0.015 M) occurs with phenylazotriphenylmethane. Such increases in yield strongly suggest a first-order process competing with higher-order side reactions. In contrast, decomposition of diaroyl peroxides in benzene results in low yields of arylbenzene (<50 per cent) in

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[7] No explanation is apparent for the occurrence of small amounts of d_2 material in the other four cases.

[8] E.C. Butterworth and D.H. Hey, *J. Chem. Soc.* 116 (1938).

either concentrated or dilute solution. In dilute solution, dihydrobiphenyls and tetrahydroquaterphenyls are formed as by-products.[5]

Finally, a major by-product in the decomposition of nitrosoacetanilides in benzene is acetic acid (nearly 1 mole/mole of nitroso compound), and little or no methane and carbon dioxide are formed. This suggests that any acetate radicals formed must abstract hydrogen with extreme rapidity before they have a chance to undergo decarboxylation, known to occur with great ease.[9]

Huisgen and coworkers[10] have shown that the rate-determining step in the arylation with nitrosoacetanilides is rearrangement to trans-diazoacetates, Ar-N=N-$OCOCH_3$. The present results prove beyond any doubt that the further reaction of these diazoacetates with benzene does not involve free aryl (Ar•) radicals of the type encountered in the decomposition of diaroyl peroxides in benzene.[3,4] Huisgen and Horeld[11] have already spoken of this reaction as proceeding by a "cryptoradical mechanism". The reason for the difference in behavior between benzoyl peroxide on one hand and nitrosoacetanilide and phenylazotriphenylmethane[12] on the other in our view lies in the fact that homolysis of benzoyl peroxide gives rise to the relatively stable benzoate radicals which then diffuse away from each other before they gradually lose carbon dioxide to give the reactive phenyl radicals, whereas benzenediazoacetate and phenylazotriphenylmethane undergo a concerted decomposition producing immediately the very reactive phenyl radicals along with nitrogen and acetate or triphenylmethyl radicals.

Two possibilities suggest themselves for the attack of phenyl and

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[9] L. Jaffe, E.J. Prosen and M. Szwarc, J. Chem. Phys. 27, 416 (1957).

[10] R. Huisgen and L. Krause, Liebigs Ann. 574, 157, 171 (1951). See also D.F. DeTar, J. Amer. Chem. Soc. 73, 1446 (1951).

[11] R. Huisgen and G. Horeld, Liebigs Ann. 562, 137 (1949).

[12] R. Huisgen and H. Nakaten, Liebigs Ann. 586, 70 (1954) have rejected the "cryptoradical mechanism" for Ph-N=N-CPh_3 on the basis of the finding that the $Ph_3C\cdot$ radical could be intercepted by iodine or NO. This finding may, however, be explainable on the basis of a cage effect (see below).

acetate (or triphenylmethyl) on substrate benzene to give biphenyl and acetic acid (or triphenylmethane). One is a concerted attack which occurs before the bonds to nitrogen are completely broken. We do not favor such a picture for several reasons. One is that it does not properly account for the substitution pattern[1] characteristic of the "radical" substitution reaction. More seriously, it does not explain the intervention of iodine or NO observed for the phenylazotriphenylmethane reaction by Huisgen and Nakaten[12]. There is also a geometric difficulty in that the aryldiazoacetates generated by rearrangement of nitrosoacetanilides are in the relatively unfavorable *trans* configuration[10] and one would probably have to postulate a rapid *cis*-*trans* interconversion[13] to invoke a concerted attack.

A more likely picture, in our view, is that of a diffusion controlled ("cage-effect") reaction[14] in which phenyl radicals and acetate (or triphenylmethyl) radicals are generated simultaneously and in juxtaposition and then rapidly and simultaneously react (by addition and hydrogen abstraction, respectively) with the nearest corner of a solvent benzene molecule. This mechanism demands that the activation energy of the addition of a phenyl radical to benzene is close to zero, a postulate which is perhaps not unreasonable in view of the large exothermicity of this reaction. It also requires a very low activation energy for the subsequent reaction of the resulting arylcyclohexadienyl radical with acetate which must follow immediately, before the acetate radical has time to decompose. Iodine and NO in large concentration may compete for the caged radicals with the benzene molecules in the walls of the cage.

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[13] However this is possible as suggested by the results of R. Huisgen and H. Nakaten, *Liebigs Ann.* *586*, 84 (1954).

[14] C.S. Rondestvedt and H.S. Blanchard, *J. Org. Chem.* *21*, 229 (1956). These authors suggested a cage-effect also for the diaroyl peroxide reaction where it has now been shown *not* to operate (refs. 3,4). See also G.S. Hammond, J.T. Rudesill and F.J. Modic, *J. Amer. Chem. Soc.* *73*, 3929 (1951).