Substituent Effects in the Radical-induced Deiodination of Substituted Iodobenzenes by Methoxide Ion†

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The title reaction effects replacement of iodine by hydrogen. It occurs by a radical chain mechanism involving a crucial step of electron transfer to the aryl iodide. By two different but largely consistent competition strategies, we have determined relative reactivities of pairs of substituted iodobenzenes, and have reckoned from the data a reactivity index for each aryl iodide relative to 1.00 for *m*-chloro(iodo)benzene. The plot of log (reactivity index) *versus* Hammett σ is approximately linear, with slope +2.2. The spread in reactivity between the fastest- and slowest-reacting aryl iodides is about 1300-fold; *ergo*, reactivity is, for the most part, not encounter-controlled.

Aryl iodides are readily deiodinated by reaction with methanolic sodium methoxide if there is a source of radicals in the system.[1,2] There is evidence to support the assignment of a radical chain mechanism, involving an electron-transfer step. Our present interest is to determine substituent effects on the rate of deiodination.

For this purpose, instead of comparing rate constants, we have determined relative reactivities of pairs of aryl iodides reacting concurrently under identical conditions. We have employed two competition strategies. In the one, *mingled* competition, two aryl iodides that afford different deiodination products were combined and allowed to react in a solution of sodium methoxide in methanol containing a suitable (thermally activated) radical initiator. In the other, *separated* competition, separate solutions of two or more different aryl iodides, each with the same concentrations of sodium methoxide and of the same thermally activated initiator in methanol from the same batch, were sealed in identical ampoules; the ampoules containing reaction solutions of the different aryl iodides were heated identically for equal times.

In either competition method, reaction is interrupted before completion; from the extents of reaction of the competing aryl iodides their relative reactivities are calculated. One uses the integrated form of a simple differential equation.[3]

Letting RI symbolize one aryl iodide and ArI the other, we can write overall equations for the two competing reactions as in eqns. (1a) and (1b).

$$\mathrm{RI} + \mathrm{CH_3O^-} \longrightarrow \mathrm{RH} + \mathrm{CH_2O} + \mathrm{I^-} \qquad (1a)$$

$$\mathrm{ArI} + \mathrm{CH_3O^-} \longrightarrow \mathrm{ArH} + \mathrm{CH_2O} + \mathrm{I^-} \qquad (1b)$$

The mingled competition method involves the assumption that both RI and ArI react according to the same kinetic order with some reagent or reactive intermediate. For this familiar competition method to be valid, a number of conditions need to be satisfied, among them that the various reactants and products are all stable under the reaction conditions, except for their participation in the reaction under study. In particular, they should not react with each other.

One can reasonably doubt whether these conditions are fully satisfied for the deiodinations of present interest. These reactions occur via aryl radical intermediates.[1,2] In mingled competition, the radical from one aryl iodide [*e.g.*, Ar• from reaction (1b)] may attack the other aryl iodide (RI) and abstract its iodine, as in eqn. (2), to form ArI and radical R•.

$$\mathrm{Ar^{\bullet}} + \mathrm{RI} \rightleftharpoons \mathrm{ArI} + \mathrm{R^{\bullet}} \qquad (2)$$

Such iodine-atom abstraction is well recognized.[4,5] The consequence is an apparent increase in the reactivity of RI with respect to ArI, unless iodine-atom capture by R• from ArI compensates for the disturbance.

Such interaction is impossible if the two competing aryl iodides are in separate vessels, as in our separated competition experiments. On the other hand, there is the possibility that one vessel might contain adventitious impurities that either provide extra initiation or act as inhibitors for these radical reactions, so that the reaction in that vessel goes faster or slower than in a similar vessel that happens not to contain those impurities.

Thus there are conceivable complications with both of the competition strategies. They are however complications of different nature, unlikely to be coupled in their incidence. It turns out that our estimates of relative reactivity by the two methods are consistent with each other. We are thereby assured that neither method is grossly in error.

Experimental

Equipment and Materials.—Methanol was purified and methanolic sodium methoxide was prepared as previously described.[2] Samples of aryl iodides were either purchased commercially or were available in the laboratory; they were repurified by distillation or crystallization and their purity was verified by gas chromatography. Azoisobutyronitrile (AIBN), m.p. 100–101 °C, was from Eastman Kodak Co. Equipment was as previously described.[2]

Mingled Competition Experiments.—Mixtures of two aryl iodides, each about 0.05 mol dm^{-3}, and AIBN (about 0.025 mol dm^{-3}) were dissolved in *ca.* 0.8 mol dm^{-3} sodium methoxide,

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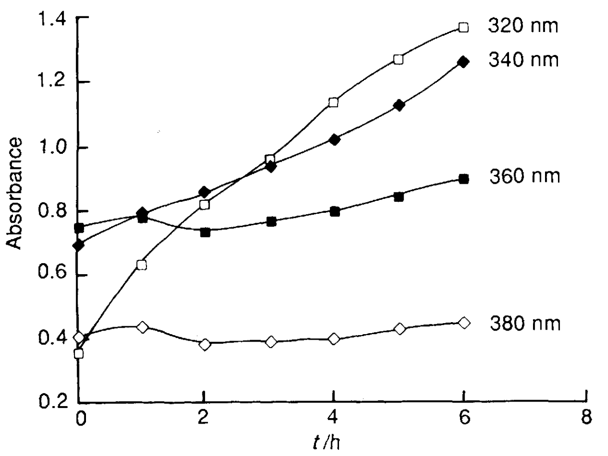

Fig. 1 Absorbance changes as azoisobutyronitrile (AIBN; 0.05 mol dm^{-3}) is heated at reflux in methanol in the presence of CH_3ONa (0.8 mol dm^{-3}).

and reaction was conducted in sealed tubes in a thermostat at 70.2 °C for time enough so that each aryl iodide had reacted at least 10% yet remained at least 10% unchanged. The procedure was similar to that for kinetic runs previously described.[2] For each experiment, a solution (25 or 50 cm^3) of the two aryl iodides, the internal standard (usually bromobenzene or *m*-dichlorobenzene) and of AIBN in methanolic sodium methoxide was prepared. Aliquots (5 cm^3) of this solution were dispensed into aluminium-foil-wrapped ampoules, and each ampule was sealed with a torch. The ampoules (usually 3 or 5) were placed in the thermostat bath at 70.2 °C all at once. Single ampoules were removed at different, recorded times, in order to assure that the reaction should be interrupted at one or more times that would afford data appropriate to calculate relative reactivities.

After removal from the thermostat, each ampoule was immersed in ice–water for several minutes, opened, and its contents poured into distilled water and extracted twice with pentane or diethyl ether. The extracts were dried over anhydrous $CaCl_2$, stored in a small volumetric flask and multiple portions were analysed by gas chromatography (GC). In general, a 1.8 m column packed with 10% UC-W98 on 80–100 mesh WAW DMCS was used. It was, however, necessary to use a 2.4 m column packed with 0.1% SP-1000 on Carbopack C in order to distinguish isomeric dibromo- and diiodo-benzenes. Peak areas were measured with a Spectra-Physics calculating integrator, and were corrected with use of molar response factors separately determined.

The reaction products were identified by comparison of their retention times with those of authentic samples, and by their mass spectra. Besides the expected products and unconsumed reactants, the chromatograms showed an additional peak that was taken from its MS (*m*/*z* 69, 54, 41), probably the cyanoisopropyl cation, to represent isobutyronitrile or tetramethylsuccinonitrile. Another peak that was often observed, although in very small amount, had *m*/*z* 153, 85, 68, 58, 44, 41; it perhaps represents the mono-amide, mono-nitrile of tetramethylsuccinic acid.

A few entries in Table 1 concern di- or tri-iodobenzenes, or substituted derivatives thereof, with non-equivalent iodine atoms. With reference to deiodination product proportions, total deiodination reactivity was apportioned among the replaceable iodine atoms. In such cases, dual entries appear in Table 1 (21, 22; 26, 27; 47, 48), each reporting the disposition of substituents with respect to the iodine atom replaced.

In a few experiments, as noted in Table 1, a cosolvent was added to the reaction mixture to overcome solubility problems with some aryl iodides.

Relative reactivities were reckoned by means of the well-known[3] eqn. (3), where $[RI]_t$ is taken to be $[RI]_0 - [RH]_t$,

$$k_{RI}/k_{ArI} = \log([RI]_0/[RI]_t)/\log([ArI]_0/[ArI]_t) \quad (3)$$

$[RH]_t$ is the concentration of that deiodination product at the time of interruption of the reaction, and $[ArI]_t$ is similarly calculated. Each experiment involved at least 3, but more often 5–10, and sometimes more than 10 GC analyses. The relative reactivities listed in Table 1 are mean values. For two thirds of those experiments, the standard deviations were 6–15% of the mean values, and for one fifth of them standard deviations exceeded 15%.

Benzophenone or fluorenone was present during some experiments, at concentrations in the range 0.001–0.08 mol dm^{-3}. The same analytical procedure was used as when no ketone was present.

Separated Competition Experiments.—Experiments were conducted in sealed ampoules. Each competition involved concurrently one reaction of a comparison aryl iodide, which was *m*-chloroiodobenzene or a 'relay' [*p*-chloro(iodo)benzene or *o*-bromo(iodo)benzene], and one, two or three reactions of other substituted iodobenzenes. There were normally three ampoules of reacting solution for each aryl iodide. The reacting solutions comprised the aryl iodide (0.04 or 0.05 mol dm^{-3}), AIBN (0.020 or 0.025 mol dm^{-3}), and sodium methoxide (0.8 mol dm^{-3}) in purified methanol. All the sealed ampoules of a competition were immersed at once in the thermostat bath at 70.0 ± 0.4 °C, and later they were removed all at once. The contents of each ampoule were separately poured into water, extracted twice with diethyl ether, and the aqueous layer was acidified with nitric acid to pH *ca.* 1; each aqueous layer was titrated potentiometrically with standard silver nitrate solution to determine the iodide-ion content. Mean iodide-ion contents for the ampoules of any aryl iodide were used to calculate, by means of eqn. (3), the relative reactivity of any substrate against the comparison aryl iodide for that run.

The standard deviation of percentage iodide ion formed between the three ampoules of any run that contained the same aryl iodide was from 0.4 to 6.5% of the percentage of iodide ion; the mean relative standard deviation was 2.5 ± 1.5%.

Results

Decomposition of AIBN in Methanolic Sodium Methoxide.—In our experiments, azoisobutyronitrile (AIBN) was used as the initiator. At our usual reaction temperature of 70 °C, the thermal decomposition of AIBN is relatively slow. Its half-life in toluene[6] is 4.8 h * and in propylene carbonate[7] 4.6 h. When we attempted to carry out a photometric determination of the rate constant for the decomposition of AIBN in 0.8 mol dm^{-3} sodium methoxide in methanol at 69.9 ± 0.3 °C, we found that the absorbance did not decrease uniformly at 360 nm, as it did in toluene,* but increased somewhat after an initial dip. At 320 nm, the absorbance increased steadily but we were not able to fit the absorbance values to any simple rate law. We present in Fig. 1 plots of absorbance at 320, 340, 360 and 380 nm *versus* time up to 6 h; absorbance change continued beyond 6 h, to 48 h values of 3.464, 2.961, 2.481 and 1.573, respectively.

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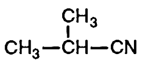
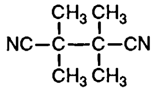
* We repeated determination of the rate constant for thermolysis of AIBN in toluene at 70 °C, after Talât-Erben and Bywater,[6] and obtained rate constant 4.17×10^{-5} s^{-1}, whereas they reported 4.0×10^{-5} s^{-1}.



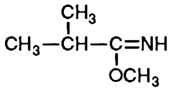
$\mathrm{CH_3{-}CH(CH_3){-}CN}$

1



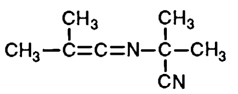
$\mathrm{NC{-}C(CH_3)_2{-}C(CH_3)_2{-}CN}$

2



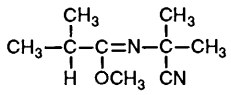
$\mathrm{CH_3{-}CH(CH_3){-}C(OCH_3){=}NH}$

3



$\mathrm{CH_3{-}C(CH_3){=}C{=}N{-}C(CH_3)_2{-}CN}$

4



$\mathrm{CH_3{-}CH(CH_3){-}C(OCH_3){=}N{-}C(CH_3)_2{-}CN}$

5

In order to ascertain what products were formed, we heated AIBN in 0.8 mol dm^{-3} MeONa–MeOH at reflux for 48 h, and then by common extraction procedures obtained a fraction of the products formed in diethyl ether solution. The IR, proton NMR and GC–MS spectra of the extract indicated the presence of isobutyronitrile (**1**), tetramethylsuccinonitrile (**2**) and perhaps of one or more methyl imidate esters such as **3** or **5**.

In their study of the thermolysis of AIBN in toluene at 80 °C, Talât-Erben and Bywater[6] observed an increase in absorbance at 320 nm to a maximum at about 100 min, and then a decrease to low final values. They provided evidence that the high absorbance at 100 min was due to the formation of the keteneimine **4**, a substance that has been isolated and characterized.[8] No doubt **4** was formed in our experiment, and it may have been mainly responsible for the initial rise in 320 nm absorbance evident in Fig. 1, but our experience differs from that of Talât-Erben and Bywater in that we saw the 320 nm absorbance rise continually until $t = 48$ h. It is unlikely[9] that the 48 h absorbance was due to **3**. We do not know the cause of the persisting high absorbance at 320 nm. If it was due to a species formed from **1** or **2**, its formation was of little significance to our *separated* competitions. Whatever its genesis, it could have had no effect on relative reactivity as estimated by *mingled* competition.

Insofar as **4** remains unconverted in the system, it can act as a radical initiator. Hammond *et al.*[8] determined the rate of decomposition of **4** in benzene at 70 °C to be 3.92×10^{-5} s^{-1}; it is thus about as reactive as AIBN* as an initiator.

Mingled Competition Experiments.—Our main relative reactivity determinations are summarized in Table 1. Our arbitrarily chosen standard for comparison was *m*-chloroiodobenzene, and many of our determinations involved that aryl iodide as a competitor. Some involved a 'relay' standard for comparison, the reactivity of which *versus* *m*-chloro(iodo)benzene was known. The relay used was *o*- or *p*-chloro(iodo)benzene, *o*- or *m*-bromo(iodo)benzene, 2,6-dichloro(iodo)benzene or *p*-iodoanisole.

Separated Competition Experiments.—In these experiments, separate ampoules containing otherwise identical reaction solutions of different aryl iodides were subjected to an identical thermal regimen. Data for 22 iodobenzene derivatives studied by this technique appear in Table 2.

In Tables 1 and 2, the measured reactivity of any aryl iodide against *m*-chloroiodobenzene is listed in the right-hand column. If a 'relay' comparison standard was used, reactivity *versus* the relay is listed in an identified column and the calculated reactivity *versus* *m*-chloro(iodo)benzene as 1.00 (the reactivity index) is listed in the right-hand column. In the calculation of the reactivity index, the relative reactivity *versus* the relay was multiplied by the relative reactivity of that standard with respect to *m*-chloro(iodo)benzene.

Some aryl iodides (the diiodobenzenes and 1,3,5-triiodobenzene) have two or three iodine atoms in equivalent situations. The reactivity indices listed for them are whole-molecule values. In reckoning log (reactivity index) for correlation purposes (*vide infra*), we made the appropriate statistical correction.

Benzophenone or fluorenone was present in a few experiments, not included in Table 1. Reaction was somewhat slower in the presence then in the absence of one of these ketones, but they had relatively little effect on reactivity ratios. Benzophenone (*ca.* 0.0015 mol dm^{-3}) did not significantly alter the relative reactivity of *o*-chloro- or *o*-fluoro-(iodo)benzene with respect to *m*-bromo(iodo)benzene. The relative reactivity of *o*-iodobenzotrifluoride with respect to *o*-bromo(iodo)benzene was not significantly affected, in five experiments, by benzophenone at concentrations from 8.8×10^{-4} to 6.9×10^{-2} mol dm^{-3}, nor by 0.055 mol dm^{-3} fluorenone. Benzophenone, at concentrations 0.0011 to 0.078 mol dm^{-3}, in three experiments did increase the apparent reactivity of 2,6-dichloro(iodo)benzene *versus* *m*-chloro(iodo)benzene from 21 to 35. Whether the apparent increase was significant can, however, be doubted, inasmuch as standard deviations in measurement of those reactivity ratios, each stemming from variation in product analyses on replicate samples from an experiment, were mostly 10–20% of the magnitudes of the ratios. The same competition was not significantly affected by 0.002 mol dm^{-3} fluorenone.

Discussion

Earlier studies[1,2] have provided evidence that these deiodination reactions occur by the radical chain mechanism of Scheme 1. We shall discuss our results with respect to it.

$$\text{radical source} \longrightarrow \text{radicals } (R^{\bullet}) \qquad (M1)$$

$$R^{\bullet} + CH_3OH \longrightarrow RH + HOCH_2^{\bullet} \qquad (M2)$$

$$R^{\bullet} + CH_3O^{-} \longrightarrow RH + CH_2O^{\bullet -} \qquad (M3)$$

$$HOCH_2^{\bullet} + CH_3O^{-} \rightleftharpoons CH_3OH + CH_2O^{\bullet -} \qquad (M4)$$

$$CH_2O^{\bullet -} + ArI \longrightarrow CH_2O + ArI^{\bullet -} \qquad (M5)$$

$$ArI^{\bullet -} \longrightarrow Ar^{\bullet} + I^{-} \qquad (M6)$$

$$Ar^{\bullet} + CH_3OH \longrightarrow ArH + HOCH_2^{\bullet} \qquad (M7)$$

$$Ar^{\bullet} + CH_3O^{-} \longrightarrow ArH + CH_2O^{\bullet -} \qquad (M8)$$

$$2\ HOCH_2^{\bullet} \longrightarrow \text{termination products} \qquad (M9)$$

$$HOCH_2^{\bullet} + CH_2O^{\bullet -} \longrightarrow \text{termination products} \qquad (M10)$$

$$2\ CH_2O^{\bullet -} \longrightarrow \text{termination products} \qquad (M11)$$

Scheme 1

Even cursory inspection of the data of Table 1 or 2 reveals that deiodination reactivity is enhanced by electron-attracting substituents and that it is considerable for *ortho*-substituted iodobenzenes.

Comparison of Competition Strategies.—Have the 'mingled' and 'separated' methods provided consistent estimates of relative reactivity? The answer is that consistency is either excellent or fairly good, depending on which data are examined,

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* See footnote on page 10.

Table 1 Relative reactivities of substituted iodobenzenes with methanolic sodium methoxide, in mingled competition

Entry no.	Substituent(s)	Reactivity vs. relay	Relay	Reactivity[a] *vs.* *m*-ClC$_6$H$_4$I	Notes
1	***m*-Cl**			**1.000**	
2	***o*-Cl**	1.98	*m*-BrC$_6$H$_4$I	***2.2***	
3	***p*-Cl**	0.518	*m*-BrC$_6$H$_4$I	***0.57***	
4	***m*-Br**			**1.1**	
5	***o*-Br**			**3.0**	
6	*p*-Br			0.31	
7	*m*-I			2.7	*b*
8	*m*-I	2.1	*m*-BrC$_6$H$_4$I	*2.4*	*b*
9	*o*-I			7.1	*b*
10	*o*-I	2.4	*o*-BrC$_6$H$_4$I	*7.0*	*b*
11	*p*-I			0.53	*b, c*
12	*m*-F			0.64	
13	*o*-F			1.55	
14	*o*-F	1.0	*m*-BrC$_6$H$_4$I	*1.1*	
15	*p*-F			0.24	
16	2,4-Cl$_2$			8.2	
17	**2,6-Cl$_2$**			**21**	*d*
18	**2,6-Cl$_2$**			**21**	*d*
19	3,5-Cl$_2$			10	
20	2,4-Br$_2$			13	
21	2,4-I$_2$	0.6	2,6-Cl$_2$C$_6$H$_4$I	*13*	*e*
22	2,5-I$_2$	1.4	2,6-Cl$_2$C$_6$H$_4$I	*29*	*e*
23	3,5-I$_2$	0.8	2,6-Cl$_2$C$_6$H$_4$I	*17*	*b*
24	2-Br,4-Cl	3.2	*o*-BrC$_6$H$_4$I	*9.6*	
25	3-Br,4-Cl	0.93	*o*-BrC$_6$H$_4$I	*2.8*	
26	2-I,4-Br	4.6	*o*-ClC$_6$H$_4$I	*10.0*	*f*
27	2-I,5-Br	8.1	*o*-ClC$_6$H$_4$I	*17.8*	*f*
28	2,4,6-Cl$_3$	1.2	2,6-Cl$_2$C$_6$H$_4$I	*24*	
29	2-Br,4 6-Cl$_2$	1.0	2,6-Cl$_2$C$_6$H$_4$I	*21*	
30	2,4,6-Br$_3$	1.4	2,6-Cl$_2$C$_6$H$_4$I	*29*	
31	*m*-CF$_3$	0.32	*o*-BrC$_6$H$_4$I	*1.0*	
32	*o*-CF$_3$	1.9	*o*-BrC$_6$H$_4$I	*5.7*	*d*
33	*o*-CF$_3$	2.2	*o*-BrC$_6$H$_4$I	*6.6*	*d*
34	*p*-CF$_3$	0.7	*m*-BrC$_6$H$_4$I	*0.8*	
35	2-Cl,5-CF$_3$	2.8	*o*-BrC$_6$H$_4$I	*8.4*	
36	H	0.2	*p*-ClC$_6$H$_4$I	*0.11*	
37	*m*-OCH$_3$	0.33	*p*-ClC$_6$H$_4$I	*0.19*	
38	*o*-OCH$_3$	0.25	*p*-ClC$_6$H$_4$I	*0.14*	
39	***p*-OCH$_3$**	0.104	*p*-ClC$_6$H$_4$I	***0.059***	
40	*m*-CH$_3$			0.078	
41	*o*-CH$_3$			0.08	
42	*p*-CH$_3$			0.06	
43	2,6-(CH$_3$)$_2$	1.4	*p*-CH$_3$OC$_6$H$_4$I	*0.08*	
44	2,4,6-(CH$_3$)$_3$	0.8	*p*-CH$_3$OC$_6$H$_4$I	*0.05*	
45	3-Cl,4-CH$_3$	1.6	*p*-ClC$_6$H$_4$I	*0.94*	
46	2-Br,4-CH$_3$	8.0	*p*-ClC$_6$H$_4$I	*4.6*	
47	2-I,4-CH$_3$	1.3	*o*-ClC$_6$H$_4$I	*2.8*	*g*
48	2-I,5-CH$_3$	2.2	*o*-ClC$_6$H$_4$I	*4.9*	*g*
49	*p*-O$^-$Na$^+$	0.3	*p*-CH$_3$OC$_6$H$_4$I	*0.018*	
50	*m*-NH$_2$	0.57	*p*-CH$_3$OC$_6$H$_4$I	*0.033*	
51	*o*-NH$_2$	0.59	*p*-CH$_3$OC$_6$H$_4$I	*0.035*	
52	*p*-NH$_2$	0.45	*p*-CH$_3$OC$_6$H$_4$I	*0.026*	*h*
53	*p*-(CH$_3$)$_2$N	0.38	*p*-CH$_3$OC$_6$H$_4$I	*0.022*	
54	*p*-C$_6$H$_5$NH	0.9	*p*-CH$_3$OC$_6$H$_4$I	*0.052*	
55	*p*-CN	0.7	*o*-BrC$_6$H$_4$I	*2.1*	
56	*p*-PhCO			3.9	*i*

[a] Reactivities in **bold** type are for substances used as relays for other determinations. Reactivities in *italics* have been determined *via* relays. Experimental uncertainties in listed reactivities are about ± 10%. [b] Not statistically corrected. [c] Solvent was 80% methanol–20% acetone. [d] Replicate determinations. [e] The whole-molecule reactivity of 1,2,4-C$_6$H$_3$I$_3$ was apportioned between I-1 and I-2 according to product yields as determined in unpublished experiments. [f] The whole-molecule reactivity of 4-bromo-1,2-diiodobenzene was apportioned between I-1 and I-2 according to product yields as determined in unpublished experiments. [g] The whole-molecule reactivity of 3,4-diiodotoluene was apportioned between I-3 and I-4 according to product yields as determined in unpublished experiments. [h] Reaction was extremely slow; see the Experimental section. [i] Formation of chlorobenzene was slower than usual.

and how. Consider first the reactivity indices for 2,6- and 3,5-dichloro(iodo)benzenes, which are 21 for the former in Table 1 *versus* 21.7 in Table 2, and 10 for the latter in Table 1 *versus* 9.1 in Table 2. Agreement is within experimental error. But then consider the reactivity indices for the methyl(iodo)benzenes, in Tables 1 (mingled) and 2 (separated), respectively: for *o*-CH$_3$, 0.08 *versus* 0.044; for *m*-CH$_3$, 0.078 *versus* 0.049; for *p*-CH$_3$, 0.06 *versus* 0.038. The reactivity index for the deactivating methyl group, in whatever orientation, is estimated by mingled competition to be nearly double what it is by separated competition.

These comparisons suggest that the ratio of reactivity estimates by the two methods is related to the activating effect of the substituent(s). So it is; a plot (not shown) of logarithms

Table 2 Relative reactivities of substituted iodobenzenes with methanolic sodium methoxide, in separated competition

Entry no.	Substituent(s)	Reactivity *vs.* relay	Relay	Reactivity[a] *vs.* *m*-ClC_6H_4I	Notes
1	***m*-Cl**			**1.000**	
2	*o*-Cl			2.3	
3	***p*-Cl**			**0.35**	*c*
4	***p*-Cl**			**0.35**	*c*
5	*m*-Br			1.2	
6	***o*-Br**			**3.64**	*c*
7	***o*-Br**			**3.79**	*c*
8	*p*-Br	1.13	*p*-ClC_6H_4I	*0.396*	
9	*m*-I			2.7	*b*
10	*o*-I	1.88	*o*-BrC_6H_4I	*7.0*	*b*
11	*p*-I			0.72	*b*
12	2,6-Cl_2	5.83	*o*-BrC_6H_4I	*21.7*	
13	3,5-Cl_2	2.44	*o*-BrC_6H_4I	*9.1*	
14	*m*-F			0.56	
15	*o*-F			1.50	
16	*p*-F			0.182	
17	H	0.185	*p*-ClC_6H_4I	*0.065*	
18	*m*-OCH_3	0.290	*p*-ClC_6H_4I	*0.102*	
19	*o*-OCH_3	0.26	*p*-ClC_6H_4I	*0.091*	
20	*p*-OCH_3	0.100	*p*-ClC_6H_4I	*0.035*	
21	*m*-CH_3	0.14	*p*-ClC_6H_4I	*0.049*	
22	*o*-CH_3	0.13	*p*-ClC_6H_4I	*0.044*	
23	*p*-CH_3	0.109	*p*-ClC_6H_4I	*0.038*	
24	*p*-$CH_3)_2N$	0.028	*p*-ClC_6H_4I	*0.0098*	

[a] Reactivities in **bold** type are for substances used as relays for other determinations. Reactivities in *italics* have been determined *via* relays. Experimental uncertainties in listed reactivities are about ± 5%. [b] Not statistically corrected. [c] Replicate determinations.

of mingled/separated reactivity index ratios *versus* Hammett σ for 23 substituents studied by both methods is scattered but has an unmistakeable downward trend. The linear regression slope is -0.26, with $r = 0.73$.

That is interesting but not cause for alarm insofar as a general assessment of substituent effects on reactivity is concerned. Plots (not shown) of log (reactivity index) *versus* σ, for the 22 substituents, have slopes (ρ values) of 1.8 from the 'mingled' series and 2.1 from the 'separated' series. Either way, deiodination is shown to be substantially accelerated by electron-attracting substituents.

Why is there a mild divergence of reactivity estimates by the two methods? One factor that may be involved is iodine-atom abstraction by one aryl radical from the other aryl iodide present during mingled competition [eqn. (2)]. Two further questions need attention. Does such iodine-atom abstraction actually occur in competition with hydrogen-atom abstraction from the abundant, reactive hydrogen donors[10] methoxide ion and methanol? Even if iodine-atom abstraction does occur, does it make any difference?

The first question has been answered by the work of Reed,[11] who recovered radioactive 4-iodobiphenyl from interrupted deiodination, by CH_3ONa–CH_3OH, in competition with a modest excess of iodobenzene containing ^{125}I tracer. Of 64% of 4-iodobiphenyl recovered, 2.3% of it was revealed by its radioactivity to have resulted from iodine capture from iodobenzene. Thus iodine-atom abstraction does occur in that environment, to a small extent.

In our mingled competition experiments, if two aryl radicals from competing aryl iodides were liberated to the same extent and participated at equal rates in crossover iodine atom abstraction, the two types of crossover abstraction would offset each other, so as to negate any effect on the ultimate product proportions. On the other hand, if one aryl iodide lost iodine (from electronation and ensuing fragmentation) faster than the other, radicals derived from it would be generated in greater number, and iodine capture according to eqn. (2) would depopulate the less reactive aryl iodide and repopulate the more reactive, causing the less reactive to seem more rapidly deiodinated by methoxide–methanol than is really the case, and the more reactive aryl iodide to seem less reactive. The observed differences in reactivity estimates for methyl(iodo)benzenes, between the two methods, are in the direction called for by this discussion.

The picture just sketched involved a simplifying assumption that forward and reverse reactions according to eqn. (2) have equal rate constants. In general, that is not likely to be the case. Although we know of no study of the effects of substituents in an aryl radical on the rate of iodine atom abstraction from a single aryl iodide,[12] it is known from studies by Danen[13,14] and Tanner[15] and their co-workers that iodine-atom abstraction by phenyl radical from substituted iodobenzenes is accelerated by electron-attracting groups (with ρ about $+0.5$).[16] This factor would operate somewhat to counter the distortion discussed in the preceding paragraph.

While mingled competition has the problems outlined, separated competition conceivably has some problems too. Besides the possible effects of adventitious impurities that might be present in some ampoules but not in others, as mentioned above, there is the fact that as reactions occur at different rates in two competing ampoules, conditions within them change unequally. The deiodination reaction [eqns. (1)] consumes methoxide ion, and methoxide-ion concentration affects reaction rate.[2] For reactions at 0.8 mol dm^{-3} sodium methoxide, this factor would tend slightly to reduce the apparent reactivity of the more reactive competitor.

Rate Correlations.—Inasmuch as we have data for many more substituents by mingled than by separated competition, we focus attention on the 'mingled' data in attempting correlation by the Hammett $\rho\sigma$ approach. Since several *ortho*-substituted iodobenzenes are involved, it is necessary to decide what σ values to choose for the *ortho* substituents. Our choice is the values derived by Tribble and Traynham[17] from NMR chemical shifts of the hydroxy proton in dimethyl sulfoxide solutions of *ortho*-substituted phenols. We regard their σ

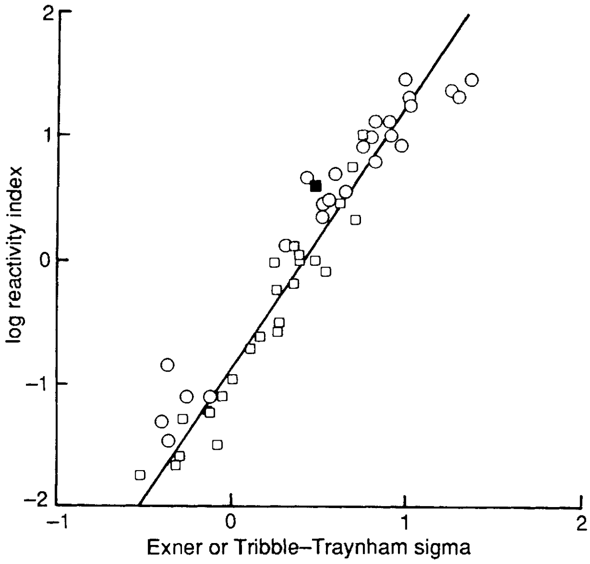

Fig. 2 Hammett-type correlation of reactivity of substituted iodobenzenes with σ-parameters. Most data for *meta* and *para* substituents are represented by points in squares, and the linear regression line through the points (of slope +2.15, *r* 0.966) is based on them. ○, Data for *ortho* substituents; ■, for *p*-benzoyl.

values as legitimate and useful, but our choice should not be taken to represent a rejection of other *ortho* σ values that have been proposed.[18–20]

Presented as Fig. 2 is a Hammett plot of our log (reactivity index) from mingled competition *versus* σ, the σ values for *meta*- and *para*-substituents being those of Exner.[21] The points for substrates that carry one or more *ortho*-substituents are symbolized differently from the others. The line drawn through the data stems from linear regression treatment of the data for those iodobenzene derivatives without *ortho* substituents (nor with the *p*-benzoyl group). Its slope (ρ) is +2.2, and one can see by cursory inspection that most of the data points, including those for *ortho*-substituted iodobenzenes, cluster close to the line.

A point that does not lie close to the line drawn is that for the *p*-benzoyl group, represented by a special symbol in Fig. 2. *p*-Iodobenzophenone reacts somewhat faster than would be expected from its σ value. We have some thoughts about this matter.[†,22–24]

It is noteworthy that although *ortho*-substituted iodobenzenes conform fairly well to that line, the points for *ortho*-substituents with $\Sigma\sigma$ below +0.7 all lie above it. Those *ortho*-substituted iodobenzenes have reactivity higher than would be expected from their σ values. That suggests some mild steric acceleration. We hesitate to conclude that steric acceleration has been demonstrated, for the small observed deviations may be due to shortcomings of the *ortho* σ values employed, but we can at least say that steric hindrance is not evident.

The three *ortho* points toward the left side of Fig. 2, with $\Sigma\sigma < -0.25$, are for substituents *o*-methoxy, 2,6-dimethyl and 2,4,6-trimethyl. Their higher than expected reaction rates seem contrary to our usual understanding of steric and polar effects on a reaction with a positive ρ value.

The spread of reactivity-index values in Table 1 is about 1300-fold, from *p*-dimethylamino- to 2,4,6-tribromo(iodo)-benzene. Such a wide spread in reactivities informs us that reactivity is not encounter-controlled. We do, however, see a suggestion that the encounter-controlled rate limit may be approached; it is the pattern of the points at the far right of Fig. 2, for $\Sigma\sigma > +1$, which have among themselves a slope approximately zero. Those are the most reactive of the substrates we have examined. Incidentally, those concern substrates that are all 2,4,6-trihalo(iodo)benzenes, in which the halogens are bromine and/or chlorine.

Reaction Mechanism.—We believe this deiodoination reaction to occur by the radical chain mechanism of Scheme 1, but we think it possible that steps (M5) and (M6) are merged into a single step.

The rate law[2] informs us that step (M5) [or merged (M5) and (M6)] is the crucial one that determines the involvement of an aryl iodide molecule in the reaction. Thus our rate data pertain, essentially, to reactivity in step (M5) or (M5)–(M6). If the suggested steric acceleration by *ortho*-substituents is real, interpretation of it in terms of an effect on step (M5) would be difficult. On the other hand, *ortho*-substituents of large bulk would plausibly accelerate step (M6), helping to push an iodide ion out of $\text{ArI}^{\bullet -}$. Thus our data offer some support for a merger of steps (M5) and (M6).

The Hammett ρ value of +2.2 would conventionally be interpreted as indicating the development, in the transition state, of negative charge in a side-chain.[‡] Alright, but what is the side-chain? On the basis of other work,[25] we believe that in the rate-limiting step [(M5) or merged (M5)–(M6)] the electron being transferred from $CH_2O^{\bullet -}$ enters the σ^* MO of the carbon–iodine bond, rather than an aromatic π^* MO. The C–I σ^* location for the 'extra' electron in the transition state is fully compatible with the observed Hammett ρ of +2.2.

Benzophenone and Fluorenone Effects.—We observed the presence of one of these ketones in a mingled competition reaction mixture obviously to reduce the reaction rate. In a kinetic study,[2] 1.14×10^{-3} mol dm^{-3} benzophenone caused about 40% reduction of rate (in systems 0.05 mol dm^{-3} in *m*-chloro(iodo)benzene, 0.8 mol dm^{-3} in CH_3ONa, and 0.025 mol dm^{-3} in azoisobutyronitrile).

On the other hand, our data show that benzophenone or fluorenone had no detectable effect on the relative reactivities of competing aryl iodides in five comparisons that can be drawn from our data, and a marginal effect scarcely beyond experimental error in a sixth.

The lack of effects on relative reactivity suggests that electron transfer from the radical anions (ketyls) of these ketones to the aryl iodides does not account for much if any deiodination.[26] The decelerating effect of these ketones can be attributed to a combination of two factors: (*a*) 'theft' of an electron from the

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[†] Inasmuch as the benzophenone system has a high affinity for electrons (the gas-phase attachment of an electron to *p*-chlorobenzophenone has $\Delta G - 20.4$ kcal/mol,[22] and the considerable stability of the benzophenone radical anion has been conducive to extensive electron spin resonance studies),[23] it seems likely that an electron furnished to *p*-iodobenzophenone in step (M5) enters the π^* LUMO, whereas for most aryl iodides the transferred electron probably enters the σ^* MO of the C–I bond. Also, it is probable that the usual σ^* radical anion fragments into $\text{Ar}^{\bullet}$ and I^- immediately after, if not during, its formation, but the fragmentation of the π^* radical anion of *p*-iodobenzophenone may be slow enough[24] to enable electron loss to compete with fragmentation. If these doubts are well-founded, the near-conformity of the *p*-iodobenzophenone point in Fig. 2 to the line may be fortuitous.

[‡] There is an unlikely possibility that the reaction series conforms to an isokinetic relationship, with an isokinetic temperature within the range of usual experimentation; we do not know whether it does because we did not determine the variation of reactivity with temperature. If it does, the *qualitative* effect of substituents on reaction rate will be opposite the other side of the isokinetic temperature, that is, the reaction will be retarded by electron-attracting substituents. For a brief discussion of the isokinetic relationship, see ref. 3, p. 295.

formaldehyde radical anion produced in step (M3) or (M4), Scheme 1, thereby thwarting electronation of the aryl iodide in step (M5) [or merged (M5)–(M6)]; and (*b*) termination of chain-propagating radicals by the ketyls, possibly by electronation to the corresponding anions.

Summary Comment.—The substituent effects on deiodination reactivity that we have observed are consistent with the mechanistic model of Scheme 1, and the hypothesis that in the rate-limiting step an electron is supplied into the C–I σ* MO of the iodine atom that is replaced in the reaction.

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