Polar Effects in Radical Reactions. 6. The Separation of Substituent Effects on Transition States from Substituent Effects on Bond Dissociation Energies. Abstraction of Iodine from Substituted Iodobenzenes by *p*-Nitrophenyl Radicals[1]

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The Hammett equation correlation is reported for the reaction of *p*-nitrophenyl radicals, generated by thermolysis of *p*-nitrophenylazotriphenylmethane at 60 °C, with a series of ten substituted iodobenzenes. Rates of iodine abstraction from the iodobenzenes were measured relative to chlorine abstraction from CCl_4. A plot of log (relative rate) *vs.* σ constants gives meta substituents only, $\rho = 0.0 \pm 0.2$, $s_y = 0.05$ (4 points); para substituents only, $\rho = 0.0 \pm 0.3$, $s_y = 0.01$ (6 points); meta and para substituents, $\rho = 0.1 \pm 0.2$, $s_y = 0.03$ (10 points). Although these zero ρ values could be interpreted as an absence of substituent effects on the rate of this reaction, such an explanation would not be consistent with other data. Instead, these zero ρ values are rationalized in terms of both the effects of substituents on the bond dissociation energy (BDE) of the Ar–I bond of the reactants and the effects of substituents on the stability of the transition state (SETS). For iodobenzenes, positive ρ's are produced by the effects of substituents on BDE, but the perturbation due to SETS for *p*-nitrophenyl radicals is toward negative ρ's. The necessity for considering both of these effects in other reaction systems also is discussed.

Polar effects on free-radical reactions have usually been explained as arising from the contribution of dipolar structures to the stabilities of the transition states of reactions of neutral free radicals.[3a,4a,5] In recent years it has become clear that an extremely useful technique for probing the contribution of these polar effects is the application of the Hammett equation to atom abstraction reactions such as hydrogen abstraction from substituted toluenes by a radical R· (eq 1),[6] in which Ar = C_6H_4X.

$$R\cdot + HCH_2Ar \rightarrow [\text{transition state}] \rightarrow RH + \cdot CH_2Ar \quad (1)$$
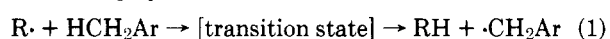
The transition state for eq 1 can be represented by the three resonance structures shown in eq 2.

$$[R\cdot + \dot{H} \cdot CH_2Ar \leftrightarrow R^+H^-:CH_2Ar \leftrightarrow R:^-\dot{H}\,^+CH_2Ar] \quad (2)$$
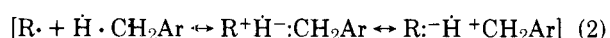
In most of the early discussions of polar effects, polar resonance structures were only explicitly written for the transition state.[7] This appears to have led most chemists in more recent years to rationalize Hammett equation correlations of radical reactions solely in terms of the effect of substituents on the stabilities of the structures shown in eq 2.[5-7]

An opposing viewpoint was suggested in 1972 by Zavitsas and Pinto.[8] These authors suggested that polar substituent effects on transition states were unimportant in understanding the relative reactivities of substituted toluenes toward various radicals. Instead, they claimed that these results could be explained by considering only the effects of substituents on eq 3—that is, on the bond dissociation energy (BDE) of the benzylic C–H bond—"without postulating charge separation in the transition state".[8]

$$XC_6H_4CH_2H \rightarrow XC_6H_4CH_2\cdot + H\cdot \quad (3)$$

In our view, it is no more likely that the relative reactivities in Hammett equation studies can be rationalized *only* in terms of substituents effects on BDE than it is that they can be explained *only* in terms of SETS. We suggest that Hammett correlations of both radical and nonradical reactions must be understood in terms of at least two different effects: one, the influence of substituents in the substrate on the BDE of the bond being broken; and, two, the substituent influence (usually by polar contributions) on the absolute free energy of the transition state. One effect depends only on the series of substrates being studied; the other depends on the nature of the reaction. In this paper, we apply this reasoning to understanding Hammett correlations of radical reactions.

Consider the reaction shown in eq 1. Substituents can influence the relative rates of this reaction by (1) affecting transition state stabilities, eq 2, or (2) by affecting BDE's, eq 3.

(1) For convenience, we have coined the acronym SETS (substituent effects on transition states) to indicate the first effect, i.e., electronic (everything except steric) effects of substituents on transition states. Many chemists have only considered SETS in rationalizing Hammett equation studies[9,10] of radical reactions, since it is assumed, because of the greater polarizability of the transition state than the ground state, that substituents have a greater influence on stabilities of transition states of atom abstraction reactions (eq 1) than on BDE (eq 3).[3a]

(2) The BDE of the bond being broken affects the rate of a reaction like eq 1 through its influence on the heat of reaction. The heat of this reaction, ΔH, is given by $D(XC_6H_4CH_2–H) - D(R–H)$, where the D's indicate the BDE's of the bonds being broken and being made.[3b,4b] Since $D(R–H)$ is unchanged as X is varied, the substituent effect on the BDE of the $XC_6H_4CH_2–H$ bond can be a source of the variation in relative rates of eq 1 with change in substituent.

We will discuss several examples from the literature in which consideration of either substituent effects on BDE or SETS *alone* leads to inconsistencies. The point which we wish to make is that these inconsistencies can be resolved by consideration of both SETS and BDE effects.[1d]

On the basis of NMR[11] and isotope effect[12] data, Zavitsas concluded that electron-donating substituents weaken and electron-withdrawing substituents strengthen benzylic C–H bonds in substituted toluenes.[8] Neglecting SETS, Zavitsas reasoned that this ordering of BDE meant that *only* negative ρ's for hydrogen abstraction from toluenes were possible. We have recently shown that SETS cannot be neglected; we obtain positive ρ values for the *tert*-butyl,[1e,13] isopropyl,[13] and undecyl[1d,14] radicals.

A striking example of the inconsistencies that result from consideration of SETS alone can be seen in possible rationalizations of Hammett studies involving thiols and thiyl radicals. Gleicher obtained a ρ of −0.3 for hydrogen abstraction from substituted benzenethiols (ArSH) by *p*-chloro-α-substituted cumyl radicals (X·) (eq 4).[15a]

$$X\cdot + ArSH \rightarrow XH + ArS\cdot \quad (4)$$

This negative ρ was interpreted in terms of the traditional SETS approach to give the description of the transition state shown in eq 5.

$$[X \cdot \; \overset{.}{H} \cdot SAr \leftrightarrow X^- \colon \overset{.}{H} \; ^+SAr] \qquad (5)$$
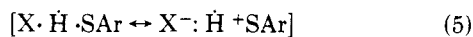
However, in reactions involving benzenethiyl radicals reacting with substituted ethylbenzenes[16] and with substituted α-methylstyrenes,[15b] negative ρ's were obtained and interpreted by the SETS concept as indicating a charge distribution in the transition state as shown in eq 6.

$$PhS \cdot XH \rightarrow [PhS \cdot \overset{.}{H} \cdot X \leftrightarrow PhS^- \colon \overset{.}{H} \; ^+X] \rightarrow PhSH + X \cdot \quad (6)$$
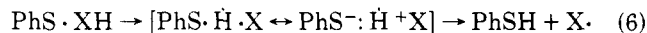
Certainly, we would expect the transition states for eq 4 and 6, one of which is the reverse of the other, to have a consistent placement of positive and negative charges. This expectation is not realized in the published descriptions because only SETS were considered; clearly, other effects of substituents on the relative ⁻ ɪtes of the reactions shown in eq 4–6 must also be taken into account.

Furthermore, it is evident a priori that both SETS and substituent effects on BDE must be considered in rationalizing the ρ values for eq 4 and 6: consideration of SETS alone would predict that one of these reactions should have a positive and one a negative ρ. Since they both are found to have negative ρ's, BDE effects must be more important than SETS in one of the these systems. It appears probable that electronic effects are more easily transmitted through a sulfur atom than a carbon;[17] thus, the effect of substituents on BDE should be relatively more important in eq 4 than in the reaction of thiyl radicals with ethylbenzenes. That is, electron-donating substituents substantially weaken the S–H bond in the ground state of thiols and thereby establish a negative ρ for eq 4 of such magnitude that even SETS of the type which would lead to a positive ρ, eq 5a
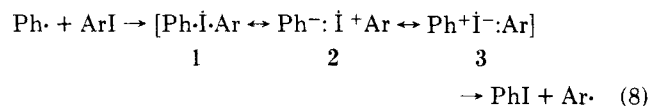
$$[X \cdot \; \overset{.}{H} \cdot SAr \leftrightarrow X^+ \; \overset{.}{H}^- \colon SAr] \qquad (5a)$$
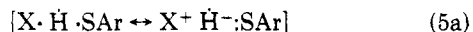
are not sufficient to produce a positive ρ for X· radicals such as α-substituted cumyl radicals that are only modestly nucleophilic. In order to observe a positive ρ for eq 4, a strongly nucleophilic radical would be required.[18]

The effect of electron-donating substituents on X–H compounds in eq 6 would be expected to be less than the effect of these substituents on thiols in eq 4.[17] However, electron-donating substituents do moderately weaken the C–H bond in the toluenes.[11,12] Also, the thiyl radical is probably more electrophilic than the benzyl radical.[16] Thus a negative ρ is observed for eq 6 because both BDE effects and SETS produce a negative ρ. A negative ρ is observed for eq 4 because the perturbation due to SETS, which would lead to a positive ρ, is overwhelmed by substituent effects on BDE, which lead to a negative ρ.

Another reaction which requires consideration of both SETS and substituent effects on BDE is shown in eq 7.

$$Ar' \cdot + Ar\text{-}I \rightarrow Ar'\text{-}I + Ar \cdot \qquad (7)$$
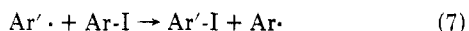
Danen[19] has reported a ρ of $+0.57$ for abstraction of iodine from substituted iodobenzenes when the aryl radical is phenyl (i.e., Ar'· = Ph·). The SETS concept, as usually applied, would view the transition state for this reaction as shown in eq 8. Since ρ is positive, the typical SETS arguments would be that **3** is more important than **2**.

$$\text{Ph} \cdot + \text{ArI} \rightarrow [\text{Ph} \cdot \overset{.}{I} \cdot \text{Ar} \leftrightarrow \text{Ph}^- \colon \overset{.}{I} \; ^+ \text{Ar} \leftrightarrow \text{Ph}^+ \overset{.}{I}^- \colon \text{Ar}]$$

$$\qquad \qquad \mathbf{1} \qquad \qquad \mathbf{2} \qquad \qquad \mathbf{3}$$

$$\rightarrow \text{PhI} + \text{Ar} \cdot \qquad (8)$$

Danen argued in this way and invoked SETS alone to explain the positive ρ value he observed for this reaction.[19] However, we believe that it is not reasonable to postulate that SETS

could produce a linear Hammett plot for a reaction in which the direction of the dipole must vary. Surely structure **2** must be more important than **3** when Ar–I is p-$MeOC_6H_4$–I, and **3** must be more important than **2** for Ar–I equal to p-$NO_2C_6H_4$–I. But if this were true, SETS alone would produce a V-shaped Hammett plot for eq 8.

Thus, the normal SETS view of the transition state for eq 8 predicts a result which is inconsistent with the linear Hammett equation plot which Danen observed. Instead, we propose[20] the description shown in eq 9.[21]

$$[\text{Ph} \cdot \; \overset{.}{I} \cdot \text{Ar} \quad \leftrightarrow \quad \overset{\frown}{\text{Ph}^{\delta^-} \quad I^- \quad ^{\delta^-}\text{Ar}}] \qquad (9)$$
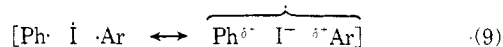
The advantages of this description are that it has a symmetrical charge distribution (as it must) when Ar' = Ph and it predicts a linear Hammett correlation. However, this dipolar form predicts a negative ρ value for eq 8; thus, for this reaction SETS alone predict the wrong sign for ρ. The observed positive ρ could be rationalized if the partial negative charges were placed on the Ph and Ar and the partial positive charge on the iodine in eq 9. However, the relative electron affinities of these species (Ph· = 1.2–1.6[22] or 2.3[23] eV and I· = 3.24,[22] 3.063,[24] or 3.41[25] eV) preclude this possibility.

In order to rationalize the positive ρ which is observed for eq 8, BDE effects must also be considered.[1d] We assume that in Ar–I compounds, electron-donating substituents strengthen the C–I bond[26] [perhaps by stabilizing the dipolar resonance structure ($Ar\text{-}I \leftrightarrow Ar^+ \; ^-I$) *more* than they stabilize the dipolar resonance structure of the transition state (eq 9)].[29] Therefore, the BDE may be more susceptible to the perturbing effects of substituents than the transition state, and a positive ρ is observed because the tendency to produce a negative ρ from effects of substituents on the transition state in eq 9 is more than counteracted by these effects on the BDE.

In this paper we will report the results of our study of iodine abstraction from substituted iodobenzenes by p-nitrophenyl radicals ($NO_2Ph\cdot$) and discuss these results in terms of SETS and substituent effects on BDE.

Experimental Section

Chemicals. The liquid iodobenzenes (m-Me-, p-F-, m-F-, m-CF_3-, and p-CF_3-iodobenzenes and iodobenzene itself) were washed with a 10% aqueous solution of sodium thiosulfate to remove any dissolved iodine, dried with anhydrous magnesium sulfate, and vacuum distilled. The solid iodobenzenes (p-MeO-, p-Ph-, and p-Br-iodobenzenes) were recrystallized from ethanol and dried under vacuum. All the iodobenzenes were stored under refrigeration in the dark. MCB Chromatoquality carbon tetrachloride was used as received. p-Nitrophenylazotriphenylmethane (NAT) was prepared by the method of Cohen, Cohen, and Wang.[30] In order to get reasonable yields of N-triphenylmethyl-N'-p-nitrophenylhydrazine the following modification of Cohen's procedure should be noted. The "mud" which formed during reflex of triphenylmethyl chloride and p-nitrophenylhydrazine in ether must be repeatedly washed with hot dichloromethane. These washings were combined with the ether layer and treated according to Cohen.
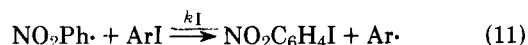
Procedures for Kinetic Runs. For a single kinetic run for one substituted iodobenzene (ArI), reaction solutions of three or four different ArI to CCl_4 ratios were prepared by adding ArI and NAT to CCl_4. The $[CCl_4]/[ArI]$ ratio varied from 5 to 30; the concentration of NAT in solutions when this ratio was less than 10 was 0.2 M; in the other solutions the concentration of NAT was 0.05 M. After placing the reaction mixtures in sample tubes, degassing by four freeze–pump–thaw cycles, and sealing the tubes, the solutions were heated in an oil bath at 60 °C for 16 h (10 initiator half-lifes[31]). The ratio of p-iodonitrobenzene ($NO_2C_6H_4I$) to p-chloronitrobenzene ($NO_2C_6H_4Cl$) in the reacted solution was determined by VPC from the ratio of their peak areas. All VPC analyses were performed on a Varian 1440 flame ionization gas chromatograph using a 10 ft × 2 mm glass column of 10% OV-1 on 100/120 Chromosorb W AW-DMCS. A Spectro-Physics System I computing integrator was used to measure the relevant peak areas.

Results

Kinetic Analysis. *p*-Nitrophenyl radicals, NO₂Ph·, were generated, in a system analogous to Danen's,[19] by thermolysis of *p*-nitrophenylazotriphenylmethane (NAT) at 60 °C for 16 h in a mixture of a substituted iodobenzene (ArI) and carbon tetrachloride (eq 10).

$$NAT \xrightarrow{60\ °C} NO_2Ph· + N_2 + Ph_3C· \qquad (10)$$
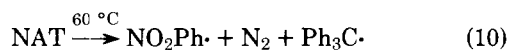
After escaping from the cage, the NO₂Ph· radicals may either abstract iodine from ArI (eq 11) to produce *p*-iodonitrobenzene (NO₂C₆H₄I) or abstract chlorine from CCl₄ (eq 12) to give *p*-iodonitrobenzene (NO₂C₆H₄Cl).

$$NO_2Ph· + ArI \xrightarrow{k_I} NO_2C_6H_4I + Ar· \qquad (11)$$

$$NO_2Ph· + CCl_4 \xrightarrow{k_{Cl}} NO_2C_6H_4Cl + ·CCl_3 \qquad (12)$$

Values of k_I relative to k_{Cl} were determined by measuring by VPC the yields of NO₂C₆H₄I and NO₂C₆H₄Cl produced from various [ArI]/[CCl₄] ratios (eq 13).

$$\frac{k_I}{k_{Cl}} = \frac{[NO_2C_6H_4I][CCl_4]}{[NO_2C_6H_4Cl][ArI]} \qquad (13)$$

There are four possible complications which could invalidate our kinetic analysis. (1) NO₂C₆H₄I or (2) NO₂C₆H₄Cl could be formed by reactions other than those shown in eq 11 and 12. (3) NO₂C₆H₄I or (4) NO₂C₆H₄Cl could be consumed in subsequent reactions. These complexities are discussed below.

(1) NO₂C₆H₄I could be produced by nitrophenylation of ArI at the position bearing the iodine atom followed by iodine abstraction from the substituted cyclohexadienyl radical by NO₂Ph· (eq 14).

$$\xrightarrow{NO_2Ph·} NO_2C_6H_4I + NO_2C_6H_4Ar \qquad (14)$$
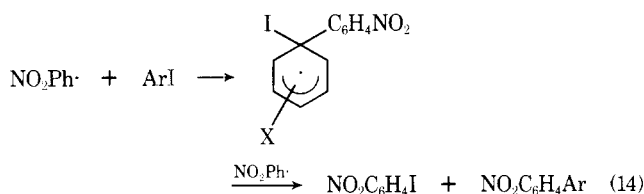
However, reaction 14 was shown to be insignificant in our system since no 4-nitrobiphenyl was found by VPC in a thermolyzed solution of 0.2 M NAT in 0.8 M iodobenzene and 9.3 M CCl₄.[32] Also, decomposition of 0.050 M NAT in 0.50 M *p*-bromoiodobenzene and 9.9 M CCl₄ gave 0.013 M NO₂C₆H₄Cl and 0.027 M NO₂C₆H₄I. This accounts for 80% of the NO₂Ph· that could possibly be formed, and the remaining 20% of the radicals may be accounted for as cage products or free-solution combination products such as NO₂C₆H₄–CPh₃.[33] Danen also reported that phenylation of ArI was insignificant in his system.[19] Therefore, we conclude that eq 11 is the only important source of NO₂C₆H₄I.

(2) Excluding CCl₄, the most likely chlorine donor in our reaction mixture is hexachloroethane, which is formed by the dimerization of trichloromethyl radicals. This chloro compound is not only less reactive than CCl₄,[34] but also is present at such low concentrations (always less than 0.02 M) that abstraction of chlorine from it must be at least 500 times slower than abstraction from CCl₄.

(3) Although NO₂C₆H₄I is an iodine donor, its concentration is so small (generally less than 0.03 M) that the primary fate of the Ar· formed in eq 11 is reaction with CCl₄ to form ArCl rather than re-forming ArI by the reverse of reaction 11. In the kinetic runs with the larger initial NAT concentration, the concentration of NO₂C₆H₄I may be as high as 0.15 M; however, the consistency of the k_I/k_{Cl} values as the concentrations

of the substrates and, therefore, the concentration of NO₂C₆H₄I, are varied indicates that NO₂C₆H₄I is not consumed in subsequent reactions (see Table I).

(4) Aryl chlorides must be very stable in our reaction system because they should be less reactive than the corresponding aryl bromides which are, in fact, quite stable. We find k_{Br}/k_{Cl} = 0.39 for NO₂Ph· reacting with bromobenzene (4.8 M) and CCl₄ (5.2 M). Therefore, NO₂C₆H₄Cl is stable under our reaction conditions.

We conclude that eq 13 is an accurate expression for the reactivity of ArI relative to CCl₄ toward *p*-nitrophenyl radicals in our kinetic system.

Reactivities of Substituted Iodobenzenes. A Hammett $\sigma\rho$ correlation of our data at 60 °C (Table I and Figure 1) gives meta substituents only, $\rho = 0.0 \pm 0.2$, $s_y = 0.05$, four points; para substituents only, $\rho = 0.0 \pm 0.3$, $s_y = 0.01$, six points; meta and para substituents, $\rho = 0.1 \pm 0.2$, $s_y = 0.03$, ten points.[35] Since the para-substituted iodobenzenes are, in general, *less reactive* than the meta derivatives, the fit of all the points to a single least-squares line is not good. Instead, there appear to be two nearly parallel lines in Figure 1, one for the meta-substituted compounds and one for the para. Danen also noted this difference in reactivity of meta- and para-substituted iodobenzenes in his study of iodine abstraction by phenyl radicals.[19] He suggested that para substituents may decrease the reactivity of ArI either by strengthening the carbon–iodine bond in the ground state or by stabilizing this bond in the "presumed phenylaryliodine intermediate" (Ar–İ–Ar') more than is accounted for by σ values. We prefer Danen's first proposal which rationalizes the difference as being entirely to BDE effects.[37] It seems unlikely that Ar–İ–Ar' is ever formed; eq 7 probably is a one-step reaction. In addition, if this intermediate were involved in eq 7, its formation would probably have a higher activation energy than its subsequent decomposition, and stabilization of Ar–İ–Ar' by para substituents would enhance the rate of iodine abstraction rather than decrease it.

Discussion

Since the ρ value for the reaction studied here, eq 11, is zero, it might appear tempting to simply propose that substituents have no effect at all on this reaction: that they influence neither transition state stabilities nor BDE's. However, this simple view is not tenable; rather, we propose that this zero ρ value results from a fortuitous balance of SETS and BDE effects.

It is easy to show that SETS cannot be negligible in eq 11. Since the *p*-nitrophenyl radical is more electrophiic than any other aryl radical (Ar·) produced in this study,[33a,38] there should be charge separation in the transition state of this reaction (eq 11). In fact, judging from the known electronic nature of aryl radicals,[33a,38] *more* charge separation would be expected in the *p*-nitrophenyl radical reaction (eq 11) than in the phenyl radical case (eq 8). However, the ρ value for the *p*-nitrophenyl radical is smaller than that for the phenyl radical contrary to the trend expected on the basis of SETS considerations alone.

It also is obvious that BDE effects must be important in eq 11. If substituent effects on BDE are not important for the *p*-nitrophenyl radical reactions, then they should not be significant in the phenyl radical reaction either, but they are.[39]

Therefore, we interpret the zero ρ value for this reaction of *p*-nitrophenyl radical (eq 11) as evidence of the interplay between SETS and substituent effects on BDE which is involved in this system; in contrast, the reaction of the phenyl radical (eq 8) has little contribution from SETS and the observed ρ appears to result from essentially pure BDE effects. Since the *p*-nitrophenyl radical is electrophilic and the phenyl

Table I. Relative Rate Constants (k_I/k_{Cl}) for Iodine Abstraction from Substituted Iodobenzenes (XArI) by the *p*-Nitrophenyl Radical at 60 °C[a]

Registry no.	X	[NAT][b]	$\dfrac{[CCl_4]}{[XArI]}$	$\dfrac{A_{p\text{-}NPI}{}^{c,d}}{A_{p\text{-}NPCl}}$	$\dfrac{k_I}{k_{Cl}}$	$\dfrac{k_I}{k_{Cl}}$[e]
696-62-8	*p*-MeO	0.05	10.0	3.12	35.5	
		0.05	14.29	2.36	38.3	36 ± 2
		0.05	20.0	1.54	35.0	
624-31-7	*p*-Me	0.2	4.95	9.69	54.6	
		0.05	10.4	4.62	54.7	54.6 ± 0.1
		0.05	20.8	2.31	54.6	
625-95-6	*m*-Me	0.2	6.7	6.58	50.1	
		0.05	13.4	4.01	61.0	60 ± 10
		0.05	26.8	2.43	74.1	
1591-31-7	*p*-Ph	0.05	5.0	6.84	38.9	
		0.05	10.0	3.52	40.1	
		0.05	14.29	2.53	41.2	40.0 ± 0.9
		0.05	20.0	1.76	40.0	
591-50-4	H	0.05	11.6	4.33	57.5	
		0.05	16.6	3.07	58.2	57.3 ± 0.9
		0.05	23.2	2.12	56.3	
352-34-1	*p*-F	0.05	11.9	3.75	50.6	
		0.05	17.0	2.43	46.9	48 ± 2
		0.05	23.8	1.73	46.8	
589-87-7	*p*-Br	0.2	5.0	8.76	49.8	
		0.05	10.0	4.31	49.1	
		0.05	14.29	2.76	44.9	47 ± 2
		0.05	20.0	1.98	45.1	
1121-86-4	*m*-F	0.2	5.9	8.98	60.6	
		0.05	11.8	4.78	64.4	
		0.05	16.9	3.24	62.4	64 ± 1
		0.05	23.6	2.41	65.1	
401-81-0	*m*-CF$_3$	0.05	15.1	3.64	62.6	
		0.05	21.6	2.42	59.6	61 ± 2
		0.05	30.2	1.78	61.3	
455-13-0	*p*-CF$_3$	0.05	15.1	2.82	48.5	
		0.05	21.6	2.02	49.7	48 ± 1
		0.05	30.2	1.37	47.2	

[a] Rate constants for iodine abstraction (k_I) were measured relative to rate constants for chlorine abstraction from CCl_4 (k_{Cl}). [b] Molar concentration of *p*-nitrophenylazotriphenylmethane. [c] Ratio of the areas of the *p*-iodonitrobenzene peak ($A_{p\text{-}NPI}$) to the area of the *p*-chloronitrobenzene peak ($A_{p\text{-}NPCl}$) obtained by VPC. [d] This ratio of areas is corrected by a response factor to give the ratio of concentrations used to calculate k_I/k_{Cl} by eq 13. [e] Average k_I/k_{Cl} ± one standard deviation.
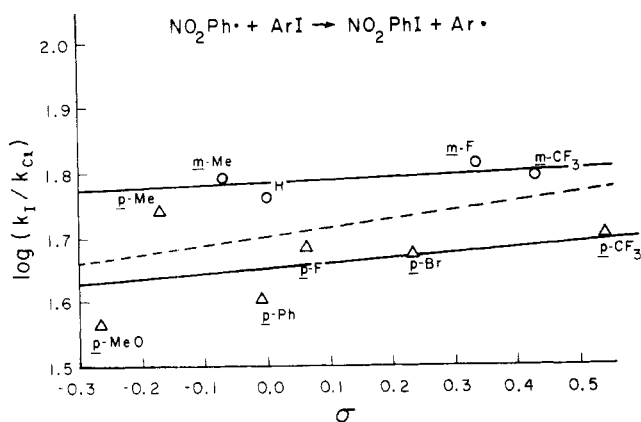

Figure 1. A Hammett equation plot of log (k_I/k_{Cl}) vs. σ for *p*-nitrophenyl radicals reacting at 60 °C with substituted iodobenzenes and CCl_4. Least squares treatment of these data gives ρ = 0.0 ± 0.2 for meta (O) substituents only (upper solid line); ρ = 0.0 ± 0.3 for para (△) substituents only (lower solid line); and ρ = 0.1 ± 0.2 for both meta and para substituents (dashed line).[35]

radial nearly electroneutral relative to the benzyl radical,[33a,38] it is expected that there would be more charge development in the transition state of eq 11 than of eq 8. Therefore, SETS are more important in reaction 11 than in 8.[40] In fact, SETS

become nearly as important as substituent effects on BDE, and a ρ of approximately zero results for reaction 11. (BDE effects should be about equal in both the phenyl and the *p*-nitrophenyl radical systems because the substrates, iodobenzenes, are the same, and the radicals are similar in reactivity.[33a,38])

The rationalization of the results of these two Hammett equation studies in terms of free energy *vs.* reaction coordinate diagrams is shown in Figures 2 and 3. In these plots, the curves with *positive slopes* represent the energy of the system Ph· (or $NO_2Ph·$) + ArI as the Ar–I bond is stretched and broken to form three noninteracting radicals, Ph· (or $NO_2Ph·$), I·, and Ar·. There is no bond formation along this curve. The curves with *negative slopes* show the free-energy changes which occur as the Ph–I (or NO_2Ph–I) bonds are being formed. These bond-making curves are parallel in Figures 2A and 2B since bond formation is assumed to occur without any interaction with the corresponding Ar· group, and the two bond-breaking curves differ only by the difference in BDE of the $CH_3C_6H_4$–I and BrC_6H_4–I bonds. If resonance contributions are not important, then the activation energies of the two reactions, indicated by arrows a and b in Figure 2, are the energy differences between the initial states and the intersection of the corresponding bond-breaking and bond-making curves. (See the caption for Figure 2 for details.)

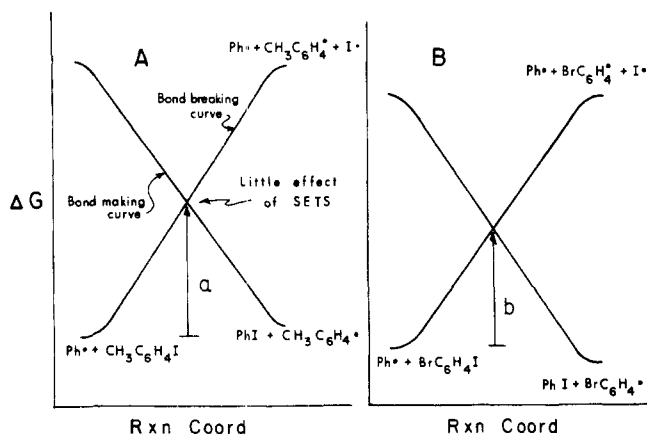Since electron-withdrawing substituents weaken the Ar–I

Figure 2. The free energy vs. reaction coordinate curves for iodine abstraction from substituted iodobenzenes by phenyl radicals are shown. The activation energy for abstraction from $CH_3C_6H_4I$, represented by arrow a, is greater than that for abstraction from BrC_6H_4I, arrow b, because electron-withdrawing substituents weaken the Ar–I bond and because there is little resonance contribution to the transition states of these reactions. A positive ρ is predicted.

Figure 3. The free energy vs reaction coordinate curves for iodine abstraction from substituted iodobenzenes by p-nitrophenyl radicals are shown. In this case, resonance contributions to the transition state stability as well as substituent effects on BDE, are important. Since electron-donating substituents stabilize and electron-withdrawing substituents destabilize the transition state $[NO_2Ph\cdot^{\delta\delta+}\ I\cdot^{\delta-}\ \cdot^{\delta\delta+}Ar]$, the intersections of the bond-breaking and bond-making curves are perturbed as indicated by the solid lines. These resonance effects cause the activation energy for abstraction from $CH_3C_6H_4I$, represented by arrow c, to become approximately equal to that for abstraction from BrC_6H_4I, arrow d. This argument predicts a ρ of about zero.

bond, and, if resonance contributions to the transition state are not important, the activation energy for abstraction of iodine from BrC_6H_4I will be less than that for abstraction from $CH_3C_6H_4I$. This is the case for the phenyl radicals as shown in Figure 2, and the predicted positive ρ is observed. However, resonance contributions (SETS), indicated by the solid lines rounding off the intersections of the curves in Figure 3, are important in the p-nitrophenyl radical case. Since SETS stabilize the transition state of the $CH_3C_6H_4I$ + $NO_2Ph\cdot$ reaction system and destabilize that of the BrC_6H_4I + $NO_2Ph\cdot$ system, the activation energies for iodine abstraction from ArI substituted with both electron-withdrawing and electron-donating groups are approximately equal. Therefore, a near-zero ρ is predicted as shown in Figure 3. (See the caption of Figure 3.)

Conclusion

We have stressed in this paper the necessity for considering both substituent effects on transition states (SETS) and substituent effects on bond dissociation energies (BDE) in rationalizing the results of Hammett equation studies. Unfortunately, although the theoretical correctness of this may be widely recognized, in practice it has become common to consider only the effects of substituents on transition states. It is true that in many cases SETS and BDE effects operate in the same direction, and, therefore, consideration of either one alone will "give the right answer", albeit for the wrong reason. However, we have here shown that it is both correct and necessary to consider both types of effects; in the case of the reactions considered here, we have been able to separate SETS and BDE effects and demonstrate the reality of both and the possibility of their mediating different signs of ρ for a given reaction.

Specifically, in the work discussed here, we have shown that BDE effects alone can lead to either negative ρ's (e.g., for hydrogen abstractions from toluenes[8] and benzenethiols[18]) or positive ρ's (e.g., for iodine abstraction from iodobenzenes). However, SETS perturbs the pattern of relative rates which is established by the effects of substituents on BDE. The direction and magnitude of this perturbation depends on the electronic nature of the radical and the substrate, the heat of reaction, and the reaction conditions (e.g., temperature and solvent). These polar transition state effects appear to be well understood. However, consequences of the BDE effects have rarely been considered in radical abstraction reactions. Failure
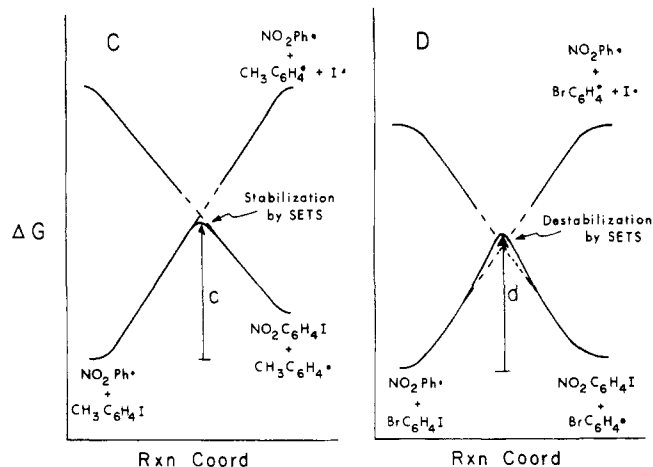
to consider *both* SETS and substituent effects on BDE in rationalizing the results of Hammett equation studies led, at worst, to the inconsistencies in interpretations such as we noted, and at best, to the right answers obtained by partially incorrect reasoning.

References and Notes

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(29) As Zavitsas points out,[8] substituents also influence the bond strength of benzylic C–H bonds in toluenes. However, substituent effects on BDE in the iodobenzenes are probably more important than in toluenes because of the direct linkage of the iodine to the aromatic ring.

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(40) If our suggested order of bond dissociation energies is correct, the reactions of the *p*-nitrophenyl radical are more endothermic than are those of phenyl. Therefore, SETS should be more important in the reactions of the *p*-nitrophenyl radical because of this factor as well.

Acylanthranils. 3. The Influence of Ring Substituents on Reactivity and Selectivity in the Reaction of Acylanthranils with Amines

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Sixteen acylanthranils were prepared and allowed to react with primary amines to give the corresponding benzamides, **4**, and/or quinazolones, **5**, which confirms the results of other investigators. The product distributions, however, are consistent with our recent suggestion that these products are formed competitively via alternative pathways A and B, as indicated in Scheme I, rather than sequentially **5** from **4** as believed originally. Although ring substituents on the acylanthranil affect markedly the overall *rate* of reaction, they do not necessarily affect *selectivity*. The latter is determined primarily by the electronic and steric factors associated with the substituent R at the 2 position only. As a general rule, the acetylanthranils, which are more reactive, favor pathway A, but the benzoylanthranils, which are less reactive, favor pathway B. Nevertheless the ratio k_A/k_B decreases with increase in bulk of the substituent R at the 2 position because of steric hindrance.

Our reinvestigation[1,2] of the reaction of acylanthranils, **1**, with primary amines, **2**, confirmed the reports of earlier investigators[3,4,5] that *o*-acylamidobenzamides, **4**, and/or the corresponding N-substituted quinazolones, **5**, are isolated as the major products if the reaction is made to occur at about 100 °C or above. We reported,[2] however, that on the one hand

N-substituted N'-(2-carboxyphenyl)acetamidines, **3**, are almost always produced exclusively as the primary products of the reaction of acetylanthranil, **1b** (R = CH₃), with anilines at room temperature, and that these intermediates are convertible to the corresponding quinazolones by cyclodehydration in solution even at room temperature. On the other