extracted twice with 100-ml portions of ether. The aqueous layer was treated with 10 g of NaCl dissolved in 100 ml of water and the resulting white crystals were collected by filtration and washed with water and acetone to give 5.12 g (53%) of pure phenyl-*p*-tolyliodonium chloride, mp 197–199 °C.

Phenyl-*o*-tolyliodonium Chloride. To a well-stirred, cold suspension of 9.63 g (28.6 mmol) of iodo-*o*-tolyl diacetate and 10.0 ml (113 mmol) of benzene in 100 ml of acetic anhydride was added dropwise 10 ml of concentrated H_2SO_4. Stirring was continued for 1 h and the mixture was allowed to stand overnight at room temperature. The reaction mixture was then added dropwise to 200 ml of ice water contained in an ice bath and the resulting solution was extracted twice with 100-ml portions of ether. The aqueous phase was treated with 10 g of NaCl dissolved in 50 ml of water, and the white precipitate which formed was filtered, washed, and dried to give 2.89 g (30%) of phenyl-*o*-tolyliodonium chloride, mp 177–178 °C.

Other Arylphenyliodonium Chlorides. The other arylphenyliodonium chlorides listed in Table I were prepared in the same manner as described for phenyl-*p*-tolyliodonium chloride.

Phenyl-*p*-tolyliodonium Iodide. A saturated solution of 10.2 g (27.2 mmol) of phenyl-*p*-tolyliodonium bromide in ethanol was treated with excess KI to give a precipitate of 3.90 g (34%) of phenyl-*p*-tolyliodonium iodide.

Other Arylphenyliodonium Iodides. The other arylphenyliodonium iodides listed in Table I were prepared by metathesis of the appropriate bromide salt in the same manner as for phenyl-*p*-tolyliodonium iodide.

Preparation of Labeled Iodonium Iodides. A ~20% aqueous KI solution was spiked with iodide-131. This solution was used to prepare the labeled iodonium iodides by metathesis of the appropriate iodonium bromides in ethanol.

Proof of Structure. Infrared spectra were in accord with the structure of the aromatic systems of the respective iodonium halides. In a series of halides for a given salt, the spectra were similar.

Pyrolysis products were identified using GC retention times. All of the iodonium salts, when pyrolyzed, gave the products expected from their thermal decomposition, and in no case was any significant amount of unexpected product found.

Product Compositions, Chlorides and Bromides. All of the iodonium chlorides and bromides listed in Table I were pyrolyzed for 5 min at 235 ± 3 °C in 6-mm Pyrex tubes about 30 cm long sealed at one end. Only about 2 cm of the sealed end of the tube was immersed in the oil bath, the remainder of the tube acting as an air condenser. Six runs were made for each individual salt, except in the case of phenyl-*p*-anisyliodonium bromide, where 12 runs were made.

All of the gas chromatograms obtained had sufficient resolution and peak shape to permit calculation of the amounts of aryl halides contained in the pyrolysates. Areas of the peaks were obtained by multiplying the peak height by the peak width at half height, and were corrected for differences in detector sensitivity. The results of these analyses are given in Table II.

Pyrolysis of Iodonium Iodides Labeled with Iodide-131. The pyrolysis products were collected by preparative GC, weighed (approximately 0.1 g), and counted in an end window G-M counter. Because of limited amounts of materials only one sample of each labeled salt was used. The data, presented in Table II, are probably good to ±2%.

Registry No.—Iodobenzene, 591-50-4; *o*-iodotoluene, 615-37-2; peracetic acid, 79-21-0; acetic acid, 64-19-7; acetic anhydride, 108-24-7.

References and Notes

(1) This work is based on the M.S. Thesis of K.M.L., Idaho State University, Pocatello, Idaho, 1975.
(2) Whittenberger Fellow, Idaho State University, 1974–1975.
(3) F. M. Beringer, M. Drexler, E. M. Gindler, and C. C. Lumpkin, *J. Am. Chem. Soc.*, **75**, 2705 (1953).
(4) F. M. Beringer, R. A. Falk, M. Karniol, I. Lillien, G. Masullo, M. Mausner, and E. Sommer, *J. Am. Chem. Soc.*, **81**, 342 (1959).
(5) Y. Yamada and M. Okawara, *Bull. Chem. Soc. Jpn.*, **45**, 1860 (1972).
(6) Y. Yamada and M. Okawara, *Bull. Chem. Soc. Jpn.*, **45**, 2515 (1972).
(7) Y. Yamada, K. Kashima, and M. Okawara, *Bull. Chem. Soc. Jpn.*, **47**, 3179 (1974).
(8) H. J. Lucas, E. R. Kennedy, and C. A. Wilmot, *J. Am. Chem. Soc.*, **58**, 157 (1937).
(9) R. B. Sandin, M. Kulka, and R. McCready, *J. Am. Chem. Soc.*, **59**, 2014 (1937).
(10) F. M. Beringer and M. Mausner, *J. Am. Chem. Soc.*, **80**, 4535 (1958).
(11) G. H. Wiegand and W. E. McEwen, *J. Org. Chem.*, **33**, 2671 (1968).
(12) M. C. Caserio, D. L. Glusker, and J. D. Roberts, *J. Am. Chem. Soc.*, **81**, 336 (1959).
(13) M. C. Caserio, D. L. Glusker, and J. D. Roberts, "Theoretical Organic Chemistry", papers presented to the Kekulé Symposium, Section of Organic Chemistry, London, Sept 1958, p 103.
(14) T. L. Khotsyanova, *Kristallografiya*, **21**, 51 (1957); *Chem. Abstr.*, **52**, 1704*b* (1958).
(15) D. F. Banks, *Chem. Rev.*, **66**, 260 (1966).
(16) V. S. Petrosyan, *Dokl. Akad. Nauk SSSR*, **175**, 613 (1967); *Chem. Abstr.*, **68**, 7940u (1968).
(17) J. W. Knapczyk and W. E. McEwen, *J. Am. Chem. Soc.*, **91**, 145 (1969).
(18) S. L. Nickol and J. A. Kampmeier, *J. Am. Chem. Soc.*, **95**, 1908 (1973).
(19) F. M. Beringer and I. Lillien, *J. Am. Chem. Soc.*, **82**, 5135 (1960).
(20) H. J. Lucas and E. R. Kennedy, "Organic Syntheses", Collect. Vol. III, Wiley, New York, N.Y., 1955, p 482.
(21) H. J. Lucas, E. R. Kennedy, and M. W. Formo, "Organic Syntheses", Collect. Vol. III, Wiley, New York, N.Y., 1955, p 483.
(22) J. G. Sharefkin and H. Saltzman, *Org. Synth.*, **43**, 62 (1963).
(23) J. E. Leffler and L. J. Story, *J. Am. Chem. Soc.*, **89**, 2333 (1967).
(24) R. B. Sandin, M. Kulka, and R. McCready, *J. Am. Chem. Soc.*, **58**, 157 (1936).
(25) M. O. Forster and J. H. Schaeppi, *J. Chem. Soc.*, **101**, 382 (1912).
(26) F. M. Beringer, E. M. Gindler, M. Rapoport, and R. J. Taylor, *J. Am. Chem. Soc.*, **81**, 351 (1959).

Kinetics and Mechanism of Benzylation of Anilines

Francesco Paolo Ballistreri, Emanuele Maccarone,* and Antonino Mamo

Istituto di Chimica Industriale dell'Università di Catania, 95125 Catania, Italy

Received May 7, 1976

Second-order rate constants for the reactions of benzyl halides (Cl, Br, I) and some para-substituted benzyl chlorides (OCH_3, CH_3, Cl, NO_2) with substituted anilines (*p*-OCH_3, *p*-CH_3, H, *p*-Cl, *m*-Cl) were measured in ethanol solution. The reactivity order found for benzyl halides (I > Br > Cl) is in accord with the leaving group polarizability. The reaction rate is increased by electron-donating substituents and decreased by electron-withdrawing ones, both in the nucleophile and in the substrate. Hammett plots are linear on varying the substituents in the aniline, but show remarkable curvature on varying those in the benzyl chloride. The reaction can be adequately described as an S_N2 bimolecular process. The reaction rate depends on the electronic availability on the nitrogen atom (bond making) and on the mesomeric interaction between the substrate substituent and the reaction center, which favors the halogen displacement (bond breaking). Electron-donating (electron-withdrawing) groups make the transition state looser (tighter). The C–halogen bond breaking is more advanced with respect to the C–N bond formation.

Solvolytic and nucleophilic reactions of benzyl halides can proceed through an unimolecular, bimolecular, or mixed substitution mechanism, depending on the solvent polarity and on the substrate and nucleophile structures.[1] Benzylation of tertiary amines (Menschutkin reaction) was widely studied and it has long been regarded as one of the best examples of

Table I. Second-Order Rate Constants and Activation Parameters for the Reactions of Benzyl Halides with Aniline in Ethanol[a]

	$k_2 \times 10^3$, l. mol^{-1} s^{-1}			$\Delta H^{\ddagger}$, kcal mol^{-1}	$\Delta S^{\ddagger}$, cal mol^{-1} K^{-1}
Halide	40 °C	50 °C	60 °C		
Cl	0.0655	0.142	0.267	14.0	−33.0
Br	3.06	6.13	10.0	11.6	−33.2
I	8.55	17.4	24.4	10.6	−34.2

[a] The estimated precision is ±6% for k_2, ±0.6 kcal mol^{-1} for $\Delta H^{\ddagger}$, and ±3 cal mol^{-1} K^{-1} for $\Delta S^{\ddagger}$ values.

solvent effects on reaction rates,[2-5] but the reaction with primary or secondary amines has not been examined to the same extent.

Peacock[6] and Baker[7] measured respectively the reaction rates of benzyl chloride with some substituted anilines and those of some substituted benzyl halides with aniline, in different experimental conditions. Radhakrishnamurti and Panigrahi[8] correlated the reaction rates of benzyl chloride and bromide with substituted anilines by linear free energy relationships. Recently, Saksena and Bose[9] studied the activation parameters of the benzylation of various mono- and disubstituted anilines in ethanol and in nitrobenzene solutions.

Notwithstanding these results, the lack of a systematic investigation of the substituent effect (both in the nucleophile and in the substrate) and of the leaving group role is evident. The variety of the experimental conditions, in fact, does not allow homogeneous comparisons of kinetic data. Moreover, the reaction mechanism is not yet clarified, Radhakrishnamurti and Panigrahi proposing a transition state symmetrical in the timing of bond making and bond breaking,[8] while Haberfield and co-workers, for the analogous reaction of benzyl halides with pyridine, suggest a transition state shifted toward products.[4]

Following studies on the reactivity of some chloromethyl derivatives with aniline,[10,11] in this paper we report a kinetic study on the substituent and the leaving group effects in the reactions of benzyl halides with anilines in ethanol, to provide a homogeneous set of data and to obtain further informations on the reaction mechanism.

Results and Discussion

Benzyl halides and anilines yield quantitatively *N*-benzylanilines, according to eq 1.

$$p\text{-YC}_6\text{H}_4\text{CH}_2\text{X} + 2\text{ZC}_6\text{H}_4\text{NH}_2 \rightarrow p\text{-YC}_6\text{H}_4\text{CH}_2\text{NHC}_6\text{H}_4\text{Z} + \text{ZC}_6\text{H}_4\text{NH}_2 \cdot \text{HX} \quad (1)$$

X = Cl, Br, I; Y = H; Z = *p*-OCH_3, *p*-CH_3, H, *p*-Cl, *m*-Cl

X = Cl; Y = OCH_3, CH_3, Cl, NO_2; Z = *p*-OCH_3, *p*-CH_3, H, *p*-Cl, *m*-Cl

The kinetics were done in 99.5% ethanol by titration of the acid produced in the reaction 1 (see Experimental Section). The reactions, carried out in a large excess of aniline with respect to substrate concentration,[12] follow a pseudo-first-order kinetics to at least 75% completion. k_{obsd} values are linearly correlated with the nucleophile concentration, indicating that the reaction is second order overall, first order with respect to each reactant, according to eq 2.

$$k_{\text{obsd}} = k_2[\text{C}_6\text{H}_5\text{NH}_2] \quad (2)$$

Second-order rate constants were calculated from the slope of the plot of k_{obsd} vs. aniline concentration, obtained from four to six kinetic runs. The intercept of these plots is practically zero, indicating that the solvolysis reaction is negligible, also for extremely reactive substrates (e.g., *p*-methoxybenzyl chloride, benzyl bromide and iodide).

Table I reports k_2 values and activation parameters for the reactions of benzyl halides with aniline.

The relative rates 2.9/1.0/0.023, respectively, for benzyl iodide/bromide/chloride (with aniline at 50 °C) are almost coincident with the average values reported for other nucleophilic reactions in protic solvents.[13] The activation parameters indicate that the greater reactivity observed for benzyl iodide and bromide with respect to benzyl chloride is ascribed to the more favorable change in enthalpy, the entropy change being constant within experimental errors.

The $k_{\text{I}}/k_{\text{Cl}}$ ratio increases with increasing the basicity of nucleophile (Table II), varying from 64 for the reactions with *m*-chloroaniline to 147 for those with *p*-anisidine. A hypothesis based on the hard and soft acids and bases (HSAB) principle[14] might be useful to interpret this trend.

In fact the $k_{\text{I}}/k_{\text{Cl}}$ ratio for the reactions of methyl iodide and chloride with hard nucleophiles (CH_3O^-, amines) in protic solvents is about 40 and increases when the substrates react with softer nucleophiles ($k_{\text{I}}/k_{\text{Cl}} = 150$ with N_3^-; $k_{\text{I}}/k_{\text{Cl}} = 600$ with SCN^-). The symbiotic effect then makes the iodide anion a better leaving group with respect to the chloride.[15]

In our case, the saturated carbon atom bearing a softer leaving group, namely in the benzyl iodide, should be better attacked by a softer nucleophile. *p*-Anisidine, owing to its easily polarizable valence electrons, is a softer base with respect to other anilines;[16] hence the enhancement of the $k_{\text{I}}/k_{\text{Cl}}$ ratio.

Table II reports second-order rate constants at 50 °C for the reactions of para-substituted benzyl chlorides, benzyl

Table II. Second-Order Rate Constants ($k_2 \times 10^4$, l. mol^{-1} s^{-1}) for the Reactions of *p*-$YC_6H_4CH_2X$ + $ZC_6H_4NH_2$ in Ethanol at 50 °C[a]

			Z					
X	Y	Registry no.	*p*-OCH_3[b]	*p*-CH_3[c]	H[d]	*p*-Cl[e]	*m*-Cl[f]	ρ Hammett
Cl	OCH_3	824-94-2	48.5	45.1	26.2	24.4	21.5	−0.59
Cl	CH_3	104-82-5	6.10	5.85	3.82	2.46	2.35	−0.73
Cl	H	100-44-7	3.00	2.19	1.42	1.12	0.761	−0.87
Cl	Cl	104-83-6	3.85	2.49	1.56	0.863	0.582	−1.24
Cl	NO_2	100-14-1	2.11	1.27	0.749	0.361	0.190	−1.55
Br	H	100-39-0	163	93.7	61.3	28.9	19.3	−1.40
I	H	620-05-3	442	279	174	80.0	48.6	−1.46
$k_{\text{I}}/k_{\text{Cl}}$			147	127	123	71	64	

[a] The estimated precision of k_2 values is ±6%. [b] Registry number, 104-94-9. [c] Registry number, 106-49-0. [d] Registry number, 62-53-3. [e] Registry number, 106-47-8. [f] Registry number, 108-42-9.

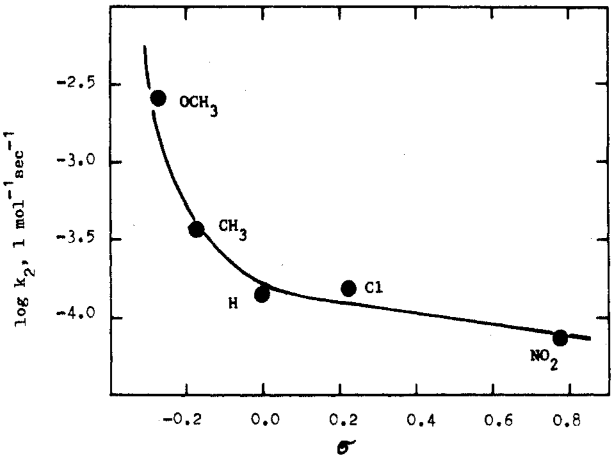


Figure 1. Hammett plot for the reactions of para-substituted benzyl chlorides with aniline in ethanol at 50 °C.

bromide and iodide with substituted anilines. The variation of nucleophilicity with para substituents in the aniline is as expected.[7,8,17] A linear correlation is obtained between log k_2 and Hammett σ.

The ρ values (Table II) depend on the substrate reactivity: the more (less) reactive is the substituted benzyl chloride, the lower (higher) is the reaction sensitivity to substituent effects in the aniline, in agreement with the Hammond postulate and the selectivity principle.[18]

Nevertheless, for the reactions of benzyl halides with anilines, reactivity and selectivity both increase in the order Cl < Br < I. Moreover, for the reactions of *p*-nitrobenzyl chloride and benzyl iodide, where ρ values are almost identical, the reactivity ratio is about 250.

These results confirm that the simultaneous application of the Hammett equation and of the Hammond postulate is not always correct.[19] However, for the benzyl chlorides series, where the reactivity varies within a small range ($k_{OCH_3}/k_{NO_2} = 35$, with aniline at 50 °C), ρ values might be compared assuming that the transition state structures do not vary meaningfully. The relative reactivities for the benzyl halides, instead ($k_I/k_{Cl} = 123$, with aniline at 50 °C), already interpreted with the HSAB principle, probably reflect transition states which do not lie in the same position along the reaction coordinate, the comparison of ρ values being not consistent.

The Hammett plots relative to the substituents in the benzyl chlorides show remarkable curvature (Figure 1), analogously to other nucleophilic reactions of substituted benzyl chlorides.[3,20,21] Smooth upward curvature is observed also using σ^+ values, indicating that even Brown's treatment cannot describe adequately the strong effect of mesomeric release from electron-donating substituents to the saturated carbon atom bearing most of the positive charge. The higher reactivity determined by these groups can be ascribed to resonance stabilization of the reaction center, which favors the C–Cl bond breaking.

This trend would be indicative of mechanistic changeover from S_N2 to S_N1 limit on going from electron-withdrawing substituents to those electron donating,[22] but the reaction was always found to depend on the aniline concentration, also for the reactive *p*-methoxybenzyl chloride, which seems to proceed by a mechanism which is essentially S_N2, but not far from the S_N1 limit, analogously to the solvolysis reactions.[21]

Electron-donating substituents in the benzyl chloride favor bond breaking, while electron-withdrawing ones favor bond making. Assuming *virtually* separate ρ values for bond making and bond breaking:

$$\rho_{\text{break}} < 0 \text{ and } \rho_{\text{mak}} > 0$$

In the S_N2 transition state bond making and bond breaking are synchronous, and Hammett slope value, which is variable but always negative (Figure 1), indicates the prevailing contribution of the bond breaking on the transition state, which is looser or tighter depending on the substituent effects.

In particular, electron-donating substituents accelerate the chloride ion displacement from the saturated carbon atom more than they decrease nucleophilic attack on it (slope more negative), and electron-withdrawing ones balance the difficulty in the leaving group displacement by favoring the nucleophile attack (slope less negative).

Experimental Section

Starting Materials. Benzyl chloride and its *p*-methyl, *p*-chloro, and *p*-nitro derivatives, benzyl bromide, and the anilines, commercially available samples, were distilled or crystallized before use.

p-Methoxybenzyl chloride[23] was obtained by treatment of *p*-methoxybenzyl alcohol with dry hydrogen chloride, 70% yield, bp 78 °C (1.5 mm).

Benzyl iodide[24] was prepared by reaction of sodium iodide with benzyl bromide, 65% yield, bp 45–46 °C (0.2 mm), mp 28–30 °C.

Ethanol containing 0.5% water (Carlo Erba) was used throughout.

Kinetic Procedure. Rate measurements were done conductometrically by continuous titration of the acid produced with 0.1 M sodium hydroxide, following the procedure already described.[25] The concentration of benzyl halides was about 0.002 mol l.$^{-1}$; aniline concentration ranges were 0.1–0.4 or 0.25–1.0 mol l.$^{-1}$, depending on the substrate reactivity.

Pseudo-first-order rate constants (k_{obsd}, s^{-1}) were obtained from the slope of the conventional plots of log $(a - x)$ vs. time, using the least-squares method.

Reaction Products. Ethanol solutions of benzyl halides (0.05 mol) and anilines (0.1 mol) were refluxed for 2–6 h, depending on the reaction rates. Ethanol was evaporated, and then the residue treated with anhydrous ether; the solution, separated from the anilinium chloride precipitate, was evaporated. The residue was crystallized or distilled under vacuum, yield about 90%.

N-Para-Substituted Benzyl Anilines, *p*-$YC_6H_4CH_2NHC_6H_4Z$ [Y, Z, mp or bp (mm)]: OCH_3, *p*-OCH_3, 97–99;[26] OCH_3, *p*-CH_3, 68;[27] OCH_3, H, 54;[28] OCH_3, *p*-Cl, 69–71;[29] OCH_3, *m*-Cl, 158 (0.1);[29] CH_3, *p*-OCH_3, 68;[29] CH_3, *p*-CH_3, 60;[30] CH_3, H, 47;[30] CH_3, *p*-Cl, 71;[29] CH_3, *m*-Cl, 141–142 (0.3);[29] H, *p*-OCH_3, 50;[28] H, *p*-CH_3, 162–163 (3);[31] H, H, 36–37;[28] H, *p*-Cl, 47–48;[28] H, *m*-Cl, 172–173 (3);[32] Cl, *p*-OCH_3, 69–70;[33] Cl, *p*-CH_3, 47–48;[30] Cl, H, 137–139 (0.3);[34] Cl, *p*-Cl, 70–71;[28] Cl, *m*-Cl, 98;[35] NO_2, *p*-OCH_3, 91;[36] NO_2, *p*-CH_3, 68;[37] NO_2, H, 70;[35] NO_2, *p*-Cl, 97–98;[29] NO_2, *m*-Cl, 62–63.[29]

Acknowledgments. We thank the Consiglio Nazionale delle Ricerche (Rome) for the financial support.

Registry No.—*p*-Methoxybenzyl alcohol, 105-13-5.

References and Notes

(1) C. K. Ingold, "Structure and Mechanism in Organic Chemistry", 2d ed, Cornell University Press, Ithaca, N.Y., 1969, p 421.
(2) N. Menschutkin, *Z. Phys. Chem. (Leipzig)*, **5**, 589 (1890); **6**, 41 (1890).
(3) C. G. Swain and W. P. Langsdorf, *J. Am. Chem. Soc.*, **73**, 2813 (1951), and references cited therein.
(4) P. Haberfield, A. Nudelman, A. Bloom, R. Room, and M. Ginsberg, *J. Org. Chem.*, **36**, 1792 (1971).
(5) M. H. Abraham, *J. Chem. Soc. B*, 299 (1971).
(6) D. H. Peacock, *J. Chem. Soc.*, **125**, 1975 (1924).
(7) J. W. Baker, *J. Chem. Soc.*, 2631 (1932).
(8) P. S. Radhakrishnamurti and G. P. Panigrahi, *Isr. J. Chem.*, **6**, 137 (1968); *J. Indian Chem. Soc.*, **45**, 323 (1968); **46**, 318 (1969); *Bull. Chem. Soc. Jpn.*, **43**, 81 (1970).
(9) J. P. Saksena and A. N. Bose, *Indian J. Chem.*, **13**, 421 (1975).
(10) A. Arcoria, E. Maccarone, G. Musumarra, and G. A. Tomaselli, *Tetrahedron*, **31**, 2523 (1975).
(11) Work in progress.
(12) The reaction, carried out at comparable reagent concentration, gives also *N,N*-dibenzylanilines: ref 6.
(13) A. Streitwieser, Jr., "Solvolytic Displacement Reactions", McGraw-Hill, New York, N.Y., 1962, p 30.
(14) R. G. Pearson, *J. Am. Chem. Soc.*, **85**, 3533 (1963). For a comprehensive review of this subject see Tse-lok Ho, *Chem. Rev.*, **75**, 1 (1975).
(15) R. G. Pearson in "Advances in Linear Free Energy Relationships", N. B. Chapman and J. Shorter, Ed., Plenum Press, New York, N.Y., 1972, p 304.
(16) Aniline is considered a "borderline" base (ref 14).
(17) T. Matsui and N. Tokura, *Bull. Chem. Soc. Jpn.*, **43**, 1751 (1970).

(18) G. S. Hammond, *J. Am. Chem. Soc.*, **77**, 334 (1955); L. Melander, "The Transition State", *Chem. Soc., Spec. Publ.*, **No. 16**, 119 (1962).
(19) C. D. Johnson, "The Hammett Equation", University Press, Cambridge, 1973, p 152; *Chem. Rev.*, **75**, 755 (1975); D. Farcasiu, *J. Chem. Educ.*, **52**, 76 (1975).
(20) S. Sugden and J. B. Willis, *J. Chem. Soc.*, 1360 (1951); W. T. Miller and J. Bernstein, *J. Am. Chem. Soc.*, **70**, 3600 (1948); R. Fuchs and A. Nisbet, *ibid.*, **81**, 2371 (1959); J. W. Hill and A. Fry, *ibid.*, **84**, 2763 (1962); Y. Tsuno, Y. Kusuyama, M. Sawada, T. Fujii, and Y. Yukawa, *Bull. Chem. Soc. Jpn.*, **48**, 3337 (1975).
(21) E. Tommila, *Acta Chem. Scand.*, **20**, 923 (1966); E. Tommila and I. P. Pitkanen, *ibid.*, **20**, 937 (1966); E. Tommila and M. Savolianen, *ibid.*, **20**, 946 (1966).
(22) Reference 19, p 49.
(23) S. Cannizzaro and C. Bertagnini, *Justus Liebigs Ann. Chem.*, **98**, 19 (1856); M. M. Tiffeneau, *Bull. Soc. Chim. Fr.*, **9**, 825 (1911).
(24) F. C. Withmore and E. Thurman, *J. Am. Chem. Soc.*, **51**, 1497 (1929).
(25) A. Arcoria, E. Maccarone, G. Musumarra, and G. A. Tomaselli, *J. Org. Chem.*, **38**, 2457 (1973); E. Maccarone, G. Musumarra, and G. A. Tomaselli, *ibid.*, **39**, 3286 (1974). The quantity of water added with titrating solution (max 1.5% of methanol solution volume) does not affect the electrode response. We have verified that the kinetic procedure, by continuous titration of the acid produced, provides rate constant values coincident with those reported by other authors who use different analytical methods (ref 6–8).
(26) J. W. Cusik, U.S. Patent 2 772 289; *Chem. Abstr.*, **52**, 1288 (1958).
(27) O. J. Steinhart, *Justus Liebigs Ann. Chem.*, **241**, 339 (1887).
(28) J. H. Billman and J. B. McDowell, *J. Org. Chem.*, **26**, 1437 (1961).
(29) This work. Satisfactory combustion analytical data for C, H, N (±0.2%) were found. Moreover, the NMR spectrum confirms the structure.
(30) E. D. Law, *J. Chem. Soc.*, **101**, 158 (1912).
(31) C. Courtot and P. Petitcolas, *Bull. Soc. Chim. Fr.*, **39**, 455 (1926).
(32) V. I. Stavroskaja, *Zh. Obshch. Khim.*, **24**, 1038 (1954).
(33) K. Fitzi, R. Goeschke, and R. Pfister, Swiss Patent 454 858; *Chem. Abstr.*, **69**, 106548 (1968).
(34) E. Knoblok, F. Macha, O. Exner, and M. Protiva, *Chem. Listy*, **48**, 226 (1954).
(35) J. H. Billman and C. A. Diesing, *J. Org. Chem.*, **22**, 1068 (1957).
(36) V. A. Izmailsky and V. E. Limanov, *Izv. Akad. Nauk SSSR*, 1500 (1959).
(37) E. Lellman and N. Mayer, *Ber.*, **25**, 3581 (1892).

A Molecular Orbital Approach to the SRN1 Mechanism of Aromatic Substitution[1]

Roberto A. Rossi,* Rita H. de Rossi, and Antonio F. López

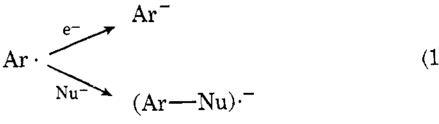
Departamento de Química Organica, Facultad de Ciencias Químicas, Universidad Nacional de Córdoba, Est. 32, 5000 Córdoba, Argentina

Received February 23, 1976

The perturbation molecular orbital approach applied to the reaction of an aromatic radical with an anionic nucleophile gives a good starting point to rationalize the SRN1 mechanism of aromatic substitution. It is shown that there is an attractive molecular orbital interaction between an aromatic radical and a carbanion nucleophile; the strongest interaction occurs at the nucleophile position with highest coefficient in the highest occupied molecular orbital (HOMO). Experimental results suggest that when the nucleophile has two or more equivalent positions (equal coefficients in the HOMO) the coupling occurs at the one which leads to the more stable radical anion as predicted by comparing the energy of the lowest unoccupied molecular orbital (LUMO) of the radical anion intermediate. When the nucleophile is of the type $^-CH_2Z$, where Z is an unsaturated moiety, the extra electron in the radical anion intermediate is probably mainly located in the lowest LUMO either in Ar or Z. The body of experimental data to date is in good agreement with the predictions made using this approach.

Chemical reactivity is usually discussed in terms of transition state theory, but in recent years the principles of orbital symmetry,[2] the perturbation molecular orbital, and frontier molecular approaches[3] have been particularly successful in delineating in a simple way those reactions which can occur and in predicting which reaction path is more favorable.

It is a known fact that aryl radicals (Ar·) react with some nucleophiles (Nu$^-$) at rates which can compete efficiently with the rate of the reaction with solvated electrons (eq 1) as indicated by the product ratio analysis.[4–6]



(1)

As far as we know, there are no kinetic or thermodynamic data available for reactions of Ar· with Nu$^-$, although it is known that such reactions are quite fast.

It has been shown by the frontier molecular orbital approach that the strongest interaction between two reacting centers occurs through the frontier orbitals of similar energy,[3] so the single occupied molecular orbital (SOMO) of Ar· will interact with the highest occupied molecular orbital (HOMO) of the Nu$^-$. This interaction will give one two-electrons bonding orbital and only one electron in the antibonding orbital. Assuming that the energy of the SOMO of Ar· and the HOMO of the Nu$^-$ are equal, the change in the π energy as calculated by the first-order perturbation is given by eq 2.[3a]

$$\Delta E\pi = c_{\mathrm{Ar}\cdot}{}^{\mathrm{SOMO}} c_{\mathrm{r,Nu}^-}{}^{\mathrm{HOMO}} \beta \tag{2}$$

Since $c_{\mathrm{Ar}\cdot}{}^{\mathrm{SOMO}} = 1$, eq 2 simplifies to eq 3.

$$\Delta E\pi = c_{\mathrm{r,Nu}^-}{}^{\mathrm{HOMO}} \beta \tag{3}$$

If the SOMO of Ar· and the HOMO of Nu$^-$ are not degenerate, the first-order change in π energy is zero. In this case the change in π energy is given by the second-order perturbation for the interaction of atom r of the Nu$^-$ with s of the electrophile which can be calculated by eq 4.[3a]

$$\Delta E\pi = 2\sum_{j}^{\mathrm{occ}} \sum_{k}^{\mathrm{unocc}} \frac{c_{rj}{}^2 c_{sk}{}^2 \beta_{rs}{}^2}{E_j - E_k} \tag{4}$$

In our particular case where the electrophile is Ar· we have only one orbital with energy close to α and $c_s = 1$; then for the interaction eq 4 simplifies to eq 5.

$$\Delta E\pi = \sum_{j}^{\mathrm{all}} \frac{c_{rj}{}^2 \beta_{rs}{}^2}{E_j} \tag{5}$$

It follows from eq 5 that the coefficient c_{rj} will determine the position of the coupling. Provided that the predominant term in eq 5 is the one involving the coefficients of the HOMO, this coefficient will determine the most reactive position of the Nu$^-$.

In the coupling of an Ar· with a carbanionic nucleophile of $^-CH_2Z$ type, Ar and Z will not be conjugated in the product, since the two moieties are separated by an sp^3 carbon. Therefore the extra electron must be located in the lowest