Although autoxidation rates are of the order of ten times faster for cyclohexene relative to 1-octene, the data of Table III indicate that *tert*-butyl hydroperoxide decomposes some hundred times faster in 1-octene than in cyclohexene. It is suggested that this effect is due to the greater ease of hydrogen abstraction from cyclohexene,[14] the greater stability of the cyclohexenyl radical, and the statistical factor (four allylic hydrogen atoms in cyclohexene *vs.* two in 1-octene).

An effort to observe the disappearance of chromium(III) acetylacetonate *via* its ultraviolet absorption peak at 336 mμ[23] was thwarted by the appearance of an absorption of unknown origin at that wavelength. None of the known[5] products of cyclohexene autoxidation were observed to absorb in that region. Since this absorption of unknown origin occurs even in the absence of metal acetylacetonate, it is suggested that the peak arises from a complex between the peroxide and either cyclohexene or product(s). In the 1-octene system[2] the presence of Cr(VI) was detected both chemically and spectrophotometrically; only at higher initial chromium(III) acetylacetonate concentrations ($\sim 10^{-3}$ *M*) than runs reported in this communication was Cr(VI) detected in the cyclohexene system. This implies that the oxidation state of chromium remains essentially unchanged over the course of the reaction[24] probably *via* the usual oxidation–reduction scheme proposed[26] for metal–peroxide reactions (eq 3 and 4). In the presence of 1-octene a similar scheme was proposed[2] in which, however, Cr(III) does not survive but is oxidized eventually to Cr(VI). Since the Cr(III) disappearance rate is essentially zero in cyclohexene the chain lengths for these reactions must be extremely large based on initiation solely *via* reactions 3 and 4. However, unlike the 1-octene system, the data for cyclohexene autoxidation indicate that an initiation process involving only *tert*-butyl hydroperoxide is also important.

$$\text{Cr(III)} + \text{ROOH} \longrightarrow \text{Cr(IV)} + \text{RO}\cdot + \text{OH}^- \quad (3)$$

$$\text{Cr(IV)} + \text{ROOH} \longrightarrow \text{Cr(III)} + \text{RO}_2\cdot + \text{H}^+ \quad (4)$$

The products detected in cyclohexene autoxidations initiated by chromium(III) acetylacetonate–*tert*-butyl hydroperoxide were the same as those found using azobisisobutyronitrile initiator[5] (cyclohexenone, cyclohexenol, and cyclohexene epoxide) and analyzed under identical gas chromatograph conditions. Results with azobisisobutyronitrile gave good agreement with other product studies[5] made under somewhat different conditions. More ketone was found in the presence of chromium than in the presence of azobisisobutyronitrile; more epoxide was found *in vacuo* than under autoxidation conditions. Although chromium(III) acetylacetonate enhances epoxide formation, the presence of oxygen either causes further reaction of the epoxide or adversely affects complexes that favor epoxide formation.

Registry No.—Cyclohexene, 110-83-8; *tert*-butyl hydroperoxide, 75-91-2; chromium(III) acetylacetonate, 13681-82-8; 1-octene, 111-66-0.

Acknowledgment.—Equipment grants from the City University of New York are gratefully acknowledged.

(23) R. H. Holm and F. A. Cotton, *J. Amer. Chem. Soc.*, **80**, 5658 (1958).

(24) Although no effort was made to detect other chromium oxidation states (*e.g.*, +2, +4, and +5), these states are known to be unstable relative to the +3 and +6 states (*cf.* ref 25).

(25) J. Kleinberg, Wm. J. Argersinger, Jr., and E. Griswold, "Inorganic Chemistry," D. C. Heath, Boston, Mass., 1960, p 513 ff.

(26) R. Hiatt, K. C. Irwin, and C. W. Gould, *J. Org. Chem.*, **33**, 1430 1968).

Kinetics of Reactions of Amines with Tricarbonyl(fluorobenzene)chromium[1a]

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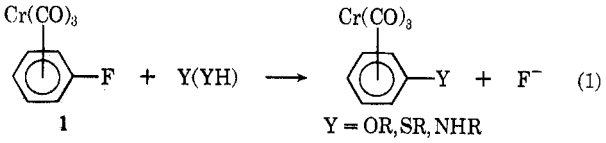
These aminodefluorination reactions occur at convenient rates in dipolar, aprotic solvents. Third-order terms predominate in their rate laws. These terms are first order in substrate, first order in the reacting nucleophilic amine, and first order in a catalytic amine which may or may not be the same as the "reacting" amine. The catalytic effect is taken to be base catalysis, and as an indication that expulsion of fluorine from the intermediate complex is the rate-limiting step, whereas in analogous reactions of *p*-fluoronitrobenzene the initial nucleophilic attack is rate limiting. The data are consistent with the hypothesis that the amine attacks exo to the chromium tricarbonyl moiety and that steric hindrance in the general acid catalyzed expulsion of fluorine from the conjugate base of the intermediate complex is a critical factor.

Chromium tricarbonyl complexes (CTC complexes) of aryl halides undergo nucleophilic replacement of halogen by moieties such as OR, SR, and NR_2 much more rapidly than does the parent halobenzene.[2]



A similar effect is found in the pK_a's of the CTC complexes of phenol, aniline, and benzoic acid; the acid dissociation constant is considerably increased by complexing. In its effects on pK_a's,[2a,3a] on rates of saponification of methyl benzoates,[3b] and on substitution rates with methoxide,[4] the chromium tricarbonyl moiety demonstrates approximately the same electron-attracting effect as the nitro group. However, the activating effects of the nitro group and of the chromium tricarbonyl moiety are not closely correlated. The activating effect of the latter is sometimes greater

(1) (a) This investigation was supported in part by Public Health Service Research Grant No. GM 14647 from the National Institute of General Medical Sciences; (b) NATO Fellow, 1967–1968, on leave from University of Göttingen, Germany.

(2) (a) B. Nichols and M. C. Whiting, *J. Chem. Soc.*, 551 (1959). (b) M. C. Whiting, U. S. Patent 3,225,071 (1965); *Chem. Abstr.*, **64**, 6694 (1966). (c) U. S. Patent 3,317,522 (1967); *Chem. Abstr.*, **67**, 64543 (1967).

(3) (a) E. O. Fischer, K. Öfele, H. Essler, W. Fröhlich, J. P. Mortensen, and W. Semmlinger, *Chem. Ber.*, **91**, 2763 (1958); (b) G. Klopman and F. Calderazzo, *Inorg. Chem.*, **6**, 977 (1967).

(4) D. A. Brown and J. R. Raju, *J. Chem. Soc. A*, 40 (1966).

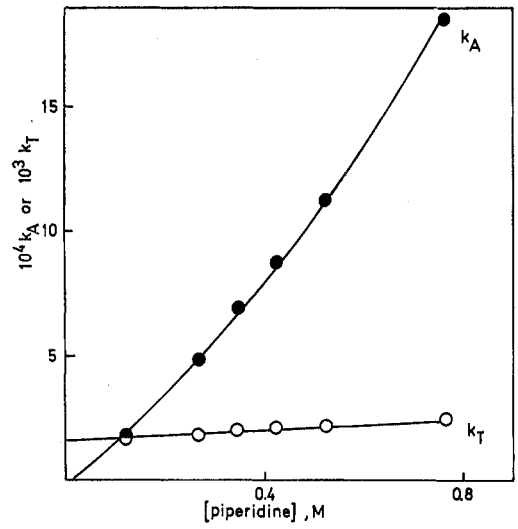


Figure 1.—Reaction of CTC–fluorobenzene with piperidine in acetonitrile at 25°. Second-order (k_A) and third-order (k_T) rate coefficients as functions of piperidine concentration.

than, sometimes less than, and sometimes nearly equal to that of the nitro group. This suggests that, besides its electronic effect, the chromium tricarbonyl moiety exerts a large steric effect.

It is known that nucleophiles may attack metal carbonyl complexes with conjugated systems such as cyclopentadiene or benzene in three ways: on carbonyl carbon, on the conjugated ligand, or on the metal atom (to effect replacement of ligands). Which pathway is followed depends on the metal atom and on the nucleophile.[5,6] In the cases of the complexes of Cr, Mo, and W with a benzene ring bearing a leaving group,[2,4] and with the tropylium cation,[7] and even in the case of the cationic manganese tricarbonyl–benzene complex,[8] nucleophiles attack almost exclusively on the aromatic moiety, but cleavage of the aromatic moiety from the metal by phosphine nucleophiles[6] and displacement of one carbonyl group by an amine in the presence of light[9] also have been observed.

Previous studies of aromatic nucleophilic substitution in CTC complexes are chiefly those of Whiting and coworkers[2] and of Brown and Raju.[4] These studies have demonstrated several similarities with familiar aromatic nucleophilic substitutions activated by nitro groups.[10] Substitutions occur without change of ring position; this testifies against an aryne mechanism. The order of halogen mobility is F ≫ Cl.

A further similarity is that reactions of CTC–fluorobenzene with amines are strongly catalyzed by amines. This is reported by Whiting in a published lecture[11] and in a patent,[2c] but we have been unable to find any fully documented report on these catalytic effects in the journal literature. Reactions of amines with 2,4-dinitrofluorobenzene are base catalyzed in some situations[12,13] but not in others.[14] Inasmuch as base catalysis of aromatic nucleophilic substitution reactions involving amine reagents is a matter of considerable interest in this laboratory,[15–17] we undertook to study the phenomenon in reactions of CTC–fluorobenzene.

Kinetic Results

Reactions of tricarbonyl(fluorobenzene)chromium (CTC–fluorobenzene) with amines in several solvents were followed photometrically. CTC–fluorobenzene has an absorption maximum at *ca.* 311 nm, and the CTC complexes of *N*-phenylpiperidine, *N*-phenylpyrrolidine, and *N*-*n*-butylaniline have maxima at *ca.* 316–320 nm. The most satisfactory difference in extinction coefficients is at 350 nm, the wavelength used in the kinetic studies. Reactions were run with the amine in large excess, so as to afford pseudo-first-order kinetics. The spectra of infinity solutions matched those of the expected aminodefluorination products, showing that side reactions did not occur to any appreciable extent. A few runs were also followed by titration of fluoride ion. The infinity titers showed the reactions to be essentially quantitative, and the rate coefficients were in agreement with those from photometric runs under the same conditions.

The pseudo-first-order rate coefficients (k_ψ) were divided by the amine concentration to afford second-order coefficients (k_A), and in some cases the k_A values were again divided by amine concentration to afford third-order coefficients (k_T).

Reactions of CTC–Fluorobenzene with Piperidine.—This reaction was studied in three solvents. In *acetonitrile*, the solvent favored by Whiting,[2b,c,10] the rate was determined at from two to six piperidine concentrations at each of three temperatures. Results at 25° are plotted in Figure 1, and data for all three temperatures are set forth in Table IV.[18] It is to be noted that the second-order rate coefficient (k_A) rose steeply with increasing amine concentration, and that even the third-order coefficient (k_T) increased to some extent. Extrapolation of k_A to zero amine concentration (Figure 1) gives an intercept which is zero or nearly zero; this shows that piperidino defluorination is essentially wholly catalyzed by piperidine. Whiting's report[10] of overall third-order kinetics is thus confirmed. The moderate rise in k_T with increase in amine concentration evidently represents the same kind of mild augmentation that has been observed in numerous other investigations.[14,19,20]

The variation of rate with temperature was remark-

(5) (a) D. A. White, *Organometal. Chem. Rev., A*, **3**, 497 (1968); (b) P. H. Treichel and R. L. Shubkin, *Inorg. Chem.*, **6**, 1328 (1967).

(6) (a) F. Zingales, A. Chiesa, and F. Basolo, *J. Amer. Chem. Soc.*, **88**, 2707 (1966); (b) A. Pidcock, J. D. Smith, and B. W. Taylor, *J. Chem. Soc. A*, 872, 877 (1967); (c) H. Werner, *Angew. Chem.*, **80**, 1026 (1968).

(7) P. L. Pauson, G. H. Smith, and J. H. Valentine, *J. Chem. Soc. C*, 1057 (1967).

(8) D. Jones, L. Pratt, and G. Wilkinson, *ibid.*, 4458 (1962); D. Jones and G. Wilkinson, *ibid.*, 2479 (1964).

(9) W. Strohmeier, *Angew. Chem., Int. Ed. Engl.*, **3**, 730 (1964).

(10) J. F. Bunnett and R. E. Zahler, *Chem. Rev.*, **49**, 273 (1961); J. F. Bunnett, *Quart. Rev., Chem. Soc.*, **12**, 1 (1958).

(11) M. C. Whiting, *Chem. Weekbl.*, **59**, 119 (1963).

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(13) C. F. Bernasconi and H. Zollinger, *Helv. Chim. Acta*, **49**, 103 (1966); **50**, 3 (1967).

(14) J. F. Bunnett and R. H. Garst, *J. Amer. Chem. Soc.*, **87**, 3875 (1965).

(15) J. F. Bunnett, T. Kato, and N. S. Nudelman, *J. Org. Chem.*, **34**, 785 (1969).

(16) J. F. Bunnett and D. H. Hermann, *Biochemistry*, **9**, 816 (1970).

(17) J. A. Orvik and J. F. Bunnett, *J. Amer. Chem. Soc.*, **92**, 2417 (1970).

(18) Tables IV–VIII, inclusive, appear only in the microfilm edition of this journal. These tables will appear following these pages in the microfilm edition of this volume of the journal. Single copies may be obtained from the Reprint Department, ACS Publications, 1155 Sixteenth St., N.W., Washington, D. C. 20036, by referring to author, title of article, volume, and page number. Remit check or money order for $3.00 for photocopy or $2.00 for microfiche.

(19) T. C. Bruice and S. J. Benkovic, *J. Amer. Chem. Soc.*, **86**, 418 (1964).

(20) C. F. Bernasconi and H. Zollinger, *Helv. Chim. Acta*, **49**, 2570 (1966).

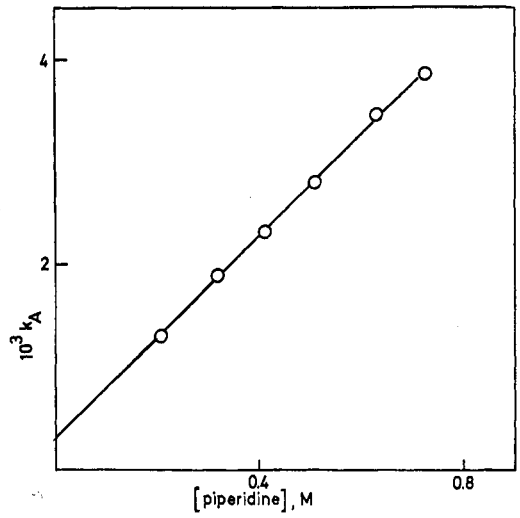


Figure 2.—Second-order rate coefficient for reaction of CTC–fluorobenzene with piperidine in DMF as function of piperidine concentration.

ably small. The extrapolated k_T at zero piperidine concentration increased only from 1.19×10^{-3} M^{-2} sec^{-1} at 10° to 1.87×10^{-3} M^{-2} sec^{-1} at 40°. This effect was previously noted by Whiting.[10] The Arrhenius plot is linear; $\Delta H^{\pm}$ is 2.1 kcal/mol and $\Delta S^{\pm}$ is −64 gibbs/mol. There is precedent for exceedingly large negative entropies of activation for third-order reactions of very low activation energy.[19] The fact that translational and rotational entropy of two molecules are lost in forming the transition state is largely responsible for the low activation entropy.

In dimethylformamide (DMF) solvent (Table V[18]), k_A again rose with increasing amine concentration. The plot of k_A *vs.* piperidine concentration (Figure 2) is linear. In this case the intercept is not zero. The plot conforms to eq 2 in which S is the substrate and

$$-d[S]/dt = k'[S][A] + k''[S][A]^2 \quad (2)$$

A the amine. Clearly the k'' term, representing catalysis by piperidine, is the dominant one, but a small fraction of the reaction occurs uncatalyzed or with catalysis only by solvent.

A plot of the third-order coefficient, k_T, *vs.* piperidine concentration, analogous to Figure 1, was tried. It was approximately linear and had negative slope of modest magnitude; *cf.* Table V.[18] This suggests the alternative view that the reaction is for the most part third order and that the third-order rate coefficient, k_T, is somewhat depressed by increasing piperidine concentration through a medium effect. Although analogies to such an interpretation appear in data presented below, representation with respect to eq 2 seems on the whole to be more legitimate.

The situation *in dimethyl sulfoxide* (DMSO) solvent (Table I) is similar to that in DMF. The correlation of k_A with piperidine concentration is cleanly linear while the plot of k_T against amine concentration has obvious curvature. Neither plot is shown, but correlation coefficients appear in Table II. Representation according to eq 2 is clearly indicated.

Reactions with piperidine in DMSO in the presence of varying concentrations of 1,4-diazobicyclo[2.2.2]octane (DABCO), *quinuclidine, or N-methylpiperidine* were also investigated. In each set of experiments, piperidine concentration was held essentially constant. *N*-Methylpiperidine depressed the reaction rate. There was a gentle, linear increase of k_A with increase in DABCO concentration, and a much sharper, linear augmentation with quinuclidine concentration. Plots for all three amines are presented in Figure 3, and full data appear in Table VI.[18]

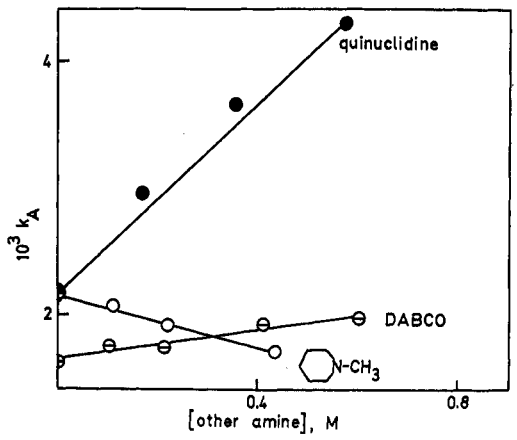


Figure 3.—Second-order rate coefficients for reactions of CTC–fluorobenzene with piperidine in DMSO, in the presence of diverse concentrations of other amines. Piperidine was 0.15 *M* in the DABCO runs and 0.20 *M* in the others.

TABLE I

REACTION OF CTC–FLUOROBENZENE WITH PIPERIDINE IN DMSO AT 25°

$[C_5H_{10}NH]$	$10^4 k_\psi$, sec^{-1}	$10^3 k_A$, M^{-1} sec^{-1}	$10^3 k_T$, M^{-2} sec^{-1}
0.103	1.30	1.26	12.2
0.108	1.31	1.22	11.3
0.108[a]	1.23	1.13	10.5
0.158	2.63	1.66	10.5
0.208	4.51	2.16	10.4
0.223	4.89	2.19	9.83
0.313	9.05	2.89	9.24
0.425	16.4	3.87	9.10
0.525	23.2	4.42	8.43
0.627	33.8	5.40	8.61

[a] Piperidine hydrochloride, 0.108 *M*, also present.

The behavior with *N*-methylpiperidine suggests a negative medium effect, while that with DABCO or quinuclidine might be interpreted either as a positive medium effect or as catalysis of the reaction of piperidine with CTC–fluorobenzene by the added amine as well as by piperidine, according to eq 3, in which B

$$-d[S]/dt = k'[S][A] + k''[S][A]^2 + k'''[S][A][B] \quad (3)$$

stands for DABCO or quinuclidine. In other situations in which such modest positive slopes as for that with DABCO in Figure 3 have appeared,[14,20,21] interpretation as a medium effect appears better justified than as catalysis. However, in the present case there is good evidence for catalysis by piperidine, and therefore interpretation of positive slopes as catalysis by other amines is admissible, though not compelled.

Reactions with piperidine in DMSO in the presence of varying concentrations of tert-butylamine were studied at three levels of piperidine concentration. Whiting[2c,10] has recommended *tert*-butylamine as a catalyst for

(21) (a) O. L. Brady and F. R. Cropper, *J. Chem. Soc.*, 507 (1950); (b) J. F. Bunnett and C. C. King, unpublished experiments.

TABLE II

SUMMARY OF CORRELATIONS OF k_A OR k_T *vs.* AMINE CONCENTRATION

Reagent amine	Other amine	Solvent	Temp, °C	Quantities correlated y^a	x^b	No. of points	Slope × 10^3	Intercept × 10^3	Slope/intercept ratio	r^c
$C_5H_{10}NH$		CH_3CN	10	k_T	$[C_5H_{10}NH]$	4	1.17	1.19		0.811
			25	k_T		6	0.95	1.58		0.847
			40	k_T		2	0.79	1.87		
$C_5H_{10}NH$		DMF	25	k_A	$[C_5H_{10}NH]$	6	5.03	0.26	19	0.9994
			25	k_T		6	−1.44	6.35		0.965
$C_5H_{10}NH$		DMSO	25	k_A	$[C_5H_{10}NH]$	9	7.85	0.44	18	0.999
				k_T		9	−5.9	11.7		0.881
$C_5H_{10}NH^d$	Quinuclidine	DMSO	25	k_A	[Quinuclidine]	4	3.68	2.25[f]		0.994
$C_5H_{10}NH^e$	DABCO	DMSO	25	k_A	[DABCO]	5	0.56	1.65[f]		0.967
$C_5H_{10}NH^d$	$C_5H_{10}NCH_3$	DMSO	25	k_A	$[C_5H_{10}NCH_3]$	4	−1.09	2.17[f]		0.997
C_4H_8NH		DMSO	25	k_A	$[C_4H_8NH]$	8	38.7	0.52	74	0.997
$C_5H_{10}NH^g$	*tert*-$BuNH_2$[h]	DMSO	25	k_A	[*tert*-$BuNH_2$]	4	8.3 (initial segment)			
						7	5.5 (final segment)			
$C_5H_{10}NH^e$	*tert*-$BuNH_2$[h]	DMSO	25	k_A	[*tert*-$BuNH_2$]	3	11.1 (initial segment)			
						4	6.3 (final segment)			
$C_5H_{10}NH^d$	*tert*-$BuNH_2$[h]	DMSO	25	k_A	[*tert*-$BuNH_2$]	3	12.6 (initial segment)			
						5	5.9 (final segment)			

[a] Dependent variable. [b] Independent variable. [c] Correlation coefficient. [d] 0.20 *M*. [e] 0.15 *M*. [f] This intercept includes substantial catalysis by piperidine. [g] 0.10 *M*. [h] *tert*-Butylamine.

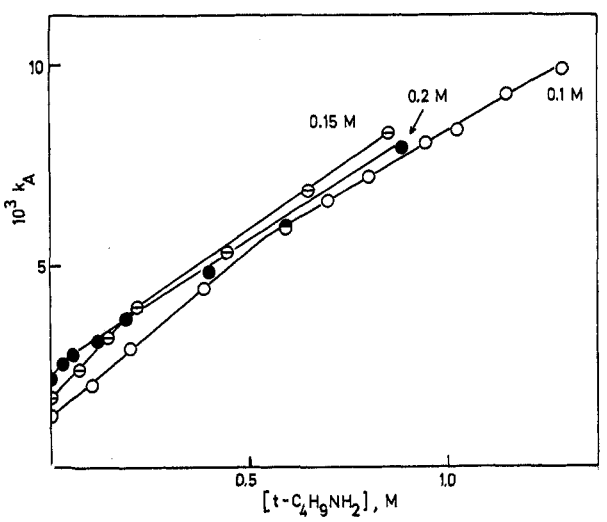


Figure 4.—Second-order rate coefficients for reaction of CTC–fluorobenzene with piperidine in DMSO in the presence of various concentrations of *tert*-butylamine. Three series of experiments are shown, each at a different piperidine concentration as indicated.

preparative purposes. Our data are plotted in Figure 4, and appear in full in Table VII.[18] At each level of piperidine concentration, the increase of k_A with *tert*-butylamine concentration is nonlinear but can be represented by two segments, each linear, the segment at lower *tert*-butylamine concentrations having the greater slope. The initial segment is shorter and steeper the higher the level of piperidine concentration, while the final slopes are nearly the same in all three plots; see Table II. The second-order rate coefficients (k_A), defined as $k_\psi/[C_5H_{10}NH]$, are dependent mainly on *tert*-butylamine concentration and only slightly on piperidine concentration.

Reactions of CTC–Fluorobenzene with Pyrrolidine in DMSO.—There are some remarkable differences between aromatic nucleophilic substitution reactions of piperidine and pyrrolidine. For example, reaction of 2,4-dinitrophenyl phenyl ether with piperidine in 10% dioxane–90% water is strongly (but curvilinearly) catalyzed by NaOH,[22] whereas the corresponding reaction with pyrrolidine is not catalyzed by NaOH.[16] It was therefore conceivable that differences would be found between their reactions with CTC fluorobenzene.

It was found that k_A increases linearly with pyrrolidine concentration. The plot (not shown) resembles Figure 2. The slope, intercept, etc., are listed in Table II, and full data are given in Table VIII.[18] The intercepts in the plots for pyrrolidine and piperidine in DMSO are nearly the same (*cf.* Table II), but the slope in the plot for pyrrolidine is about five times greater.

Reactions of CTC–Fluorobenzene with *n*-Butylamine in DMSO.—In several cases it has been observed that reactions of aromatic substrates with secondary amines are base catalyzed whereas reactions with closely related primary amines under the same conditions are not.[14,23]

In the present investigation a difference is also observed, as evident in Figure 5. The numerical data appear in Table III. k_A rises with *n*-butylamine concentration, but in curvilinear fashion. In cases somewhat related to this,[16,22-24] such curvature has been

TABLE III

REACTION OF CTC–FLUOROBENZENE WITH *n*-BUTYLAMINE IN DMSO AT 25°

[*n*-Butylamine], *M*	$10^4 k_\psi$, sec^{-1}	$10^3 k_A$, M^{-1} sec^{-1}
0.101	0.675	0.668
0.203	2.73	1.34
0.301	5.28	1.75
0.406	8.66	2.13
0.605	16.7	2.76
0.698	20.9	2.99
0.818	26.1	3.19
0.958	32.8	3.42
1.195	45.6	3.82

(22) J. F. Bunnett and C. F. Bernasconi, *J. Amer. Chem. Soc.*, **87**, 5209 (1965).
(23) C. F. Bernasconi, *J. Org. Chem.*, **32**, 2947 (1967).
(24) J. F. Bunnett and R. H. Garst, *J. Amer. Chem. Soc.*, **87**, 3879 (1965).

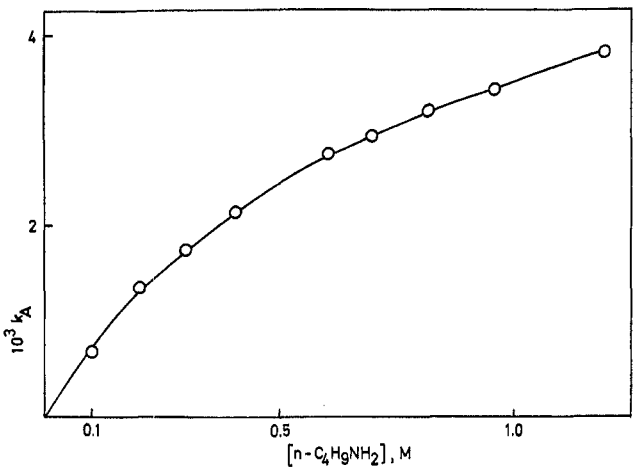


Figure 5.—Second-order rate coefficients for reaction of CTC–fluorobenzene with *n*-butylamine in DMSO at 25° as function of *n*-butylamine concentration.

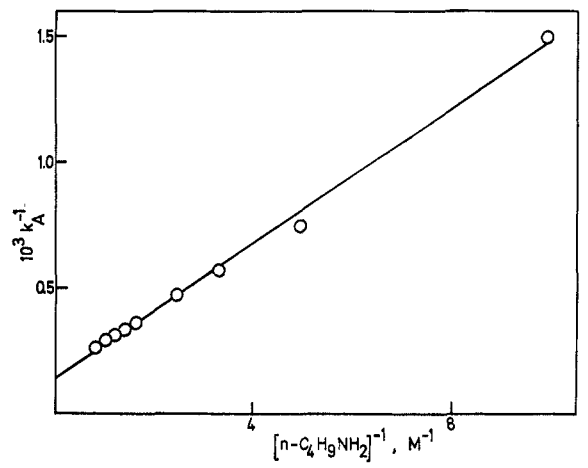
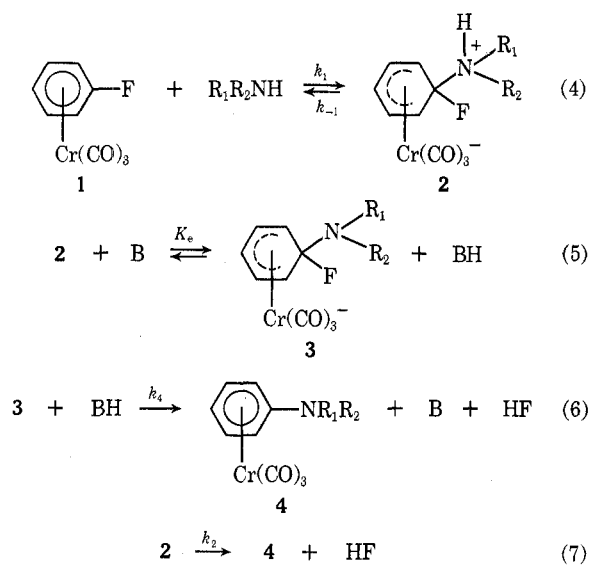


Figure 6.—Reaction of CTC–fluorobenzene with *n*-butylamine in DMSO at 25°. Inversion plot.

attributed to a change in rate-limiting step with change of amine concentration.

A mechanistic model which serves well for other aromatic nucleophilic substitution reactions involving amine reagents[17] is sketched in Scheme I for reactions

SCHEME I



of CTC–fluorobenzene. By the usual steady-state assumption, one may derive from this mechanism an expression for k_A

$$k_A = \frac{k_1k_2 + [k_1k_3B]}{k_{-1} + k_2 + k_3[B]} \quad (8)$$

in which k_3 represents the product, k_4K_e, regardless of whether equilibrium 5 lies mainly on the right or on the left.[22]

Equation 8 is qualitatively consistent with the curvature in Figure 5, if a molecule of *n*-butylamine is playing the role of base B. A more searching test involves inverting eq 8 to obtain

$$\frac{1}{k_A} = \frac{k_{-1}}{k_1k_2 + k_1k_3[B]} + \frac{1}{k_1} \quad (9)$$

If $k_3[B] \gg k_2$, which is likely except at low base concentrations

$$\frac{1}{k_A} = \frac{k_{-1}}{k_1k_3}\frac{1}{[B]} + \frac{1}{k_1} \quad (10)$$

An "inversion plot" according to eq 10, based on the data in Table III, is presented as Figure 6. It closely approximates linearity, and the negative deviations at lower amine concentrations (higher $1/[n\text{-}BuNH_2]$) are as expected if the assumption whereby eq 9 is transformed into eq 10 is not fully justified. (The conformity of the point at the far right to the linear regression line is perhaps fortuitous.) From the intercept in Figure 6, k_1 is evaluated as 7.25×10^{-3} M^{-1} sec^{-1}, and from dividing the slope by the intercept the ratio k_{-1}/k_3 is evaluated as 1.03 M.

To evaluate also the ratio k_2/k_{-1}, one rearranges eq 8 into

$$\frac{k_A}{k_1 - k_A} = \frac{k_2}{k_{-1}} + \frac{k_3[B]}{k_{-1}} \quad (11)$$

The plot (not shown) of the data of Table III (excepting that for 0.1 M *n*-$BuNH_2$) according to eq 11 is linear (r = 0.998). From the intercept, k_2/k_{-1} is evaluated as 0.04 and from the slope k_3/k_{-1} is 0.910 M^{-1}, or k_{-1}/k_3 is 1.09 M. The ratio k_3/k_2 is 24 M^{-1}.

According to the model of Scheme I, with attention especial to eq 8, linear dependence of k_A on base concentration is observed when $k_{-1} \gg (k_2 + k_3[B])$, independence is observed when $(k_2 + k_3[B]) \gg k_{-1}$, and curvilinear dependence in the sense of Figure 5 when k_{-1} and $(k_2 + k_3[B])$ are of similar magnitude. The frequently observed shift from linear or curvilinear dependence on base with secondary amines to independence with primary amines is understood as a consequence of an increase in the relative magnitude of $(k_2 + k_3[B])$ over k_{-1}. The present shift from linear dependence (Figures 2 and 3) to curvilinear dependence (Figure 5) may be attributed to the same cause.

Summary of Correlations.—In the foregoing presentation, we have described several linear correlations (or attempted correlations) between k_A or k_T and amine concentration. These are summarized in Table II.

Experiments with Other Leaving Groups.—Efforts were made to observe reactions of amines with analogs of CTC–fluorobenzene in which the (intended) leaving

group was chlorine, nitro, dimethylsulfonio, or trimethylammonio. These were unsuccessful, but some chemistry of qualitative interest was encountered.

It is reported that the dimethylsulfonio and trimethylammonio groups of, respectively, *p*-nitrophenyldimethylsulfonium ion and *p*-nitrophenyltrimethylammonium ion are exceptionally mobile in reactions with sodium methoxide in methanol.[25a] We obtained CTC–phenyldimethylsulfonium fluoroborate easily by methylation of CTC–thioanisole with trimethyloxonium fluoroborate. However, reactions of this sulfonium salt with piperidine in water, methanol, or acetonitrile and with sodium thiophenoxide in water or methanol afforded CTC–thioanisole in high yield, but no other CTC-complexed aromatic. CTC–thioanisole was also the chief product from reaction with sodium methoxide in methanol; the infrared and mass spectra of the crude product mixture suggested the presence also of about 2% of CTC–anisole. Thus nucleophilic displacement on methyl carbon, releasing CTC–thioanisole as leaving group, was the predominant reaction. Displacement on methyl carbon occurs on reaction of *p*-nitrophenyldimethylsulfonium ion with thiocyanate ion[25b] or piperidine (this work), but methoxide ion attacks to form *p*-nitroanisole.[25a]

In contrast to the behavior of CTC–thioanisole, CTC–dimethylaniline was not methylated by trimethyloxonium fluoroborate. Several attempts were made, but only unreacted CTC–dimethylaniline or decomposition products were obtained. Trimethyloxonium fluoroborate did, however, smoothly methylate both *p*-nitrophenyl methyl sulfide and *N*,*N*-dimethyl-*p*-nitroaniline. Thus the unreactivity of CTC–dimethylaniline with trimethyloxonium fluoroborate contrasts sharply with the facility of analogous reactions.

Reactions of CTC–chlorobenzene with 2 *M* piperidine in DMSO afforded little chloride ion, and only decomposition products. This was a surprise, because CTC–chlorobenzene reacts smoothly with $NaOCH_3$ in CH_3OH,[2a] and the reaction rate has been measured.[4]

The nitro group is exceptionally mobile in many aromatic nucleophilic substitution reactions. However, like Whiting,[2a] we were unable to prepare CTC–nitrobenzene. We attempted the preparation under nonoxidizing conditions, by allowing sodium nitrite to act upon CTC–fluorobenzene.[26]

Discussion

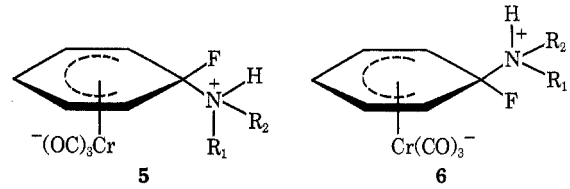
We shall give a large measure of attention to the form of the rate law, and especially to the pattern and extent of variation of the second-order rate coefficient, k_A, with the concentration of the reacting nucleophilic amine and/or the concentration of an accompanying "catalytic" amine. It is a fact that third-order terms predominate in the rate laws for these reactions, being first order in substrate, first order in the reacting amine, and first order in a "catalytic" amine which may be the reacting amine or another one. Although we have not specifically demonstrated that the observed catalytic effects represent base catalysis, as contrasted, say, to a general medium effect, we shall interpret them as base catalysis because (a) base catalysis is well established for closely related reactions of benzene derivatives,[17,22,24] and (b) the accelerations produced by most amines in the present work are quite large.

In this type of reaction, the incidence and form of base catalysis are instructive as to which step of the intermediate complex mechanism, as sketched in Scheme I for reaction of CTC–fluorobenzene with an amine, is rate-limiting.[24] By analogy to reactions of analogous benzene derivatives, the second stage of reaction, from intermediate **2** to product **4**, is catalyzed by base but the first step is not. Therefore, if the reaction is not catalyzed by base, the first step is rate limiting, that is $(k_2 + k_3[B]) \gg k_{-1}$. Base catalysis with linear dependence of k_A on base concentration indicates that expulsion of fluorine from complex **3** is rate limiting, that is that $k_{-1} \gg (k_2 + k_3[B])$. Base catalysis with curvilinear dependence of k_A on base concentration indicates that each stage is partially rate limiting, that is that k_{-1} and $(k_2 + k_3[B])$ are of similar magnitude, depending on the base concentration.

The salient outcome of the present study is that reactions of CTC–fluorobenzene with amines in dipolar, aprotic solvents are quite sensitive to catalysis by amines. In contrast, reactions of *p*-fluoronitrobenzene with amines in the same solvents are not base catalyzed.[27] We conclude that the second stage of the intermediate complex mechanism is largely or wholly rate limiting in these reactions of CTC–fluorobenzene, while the first is rate limiting for corresponding reactions of *p*-fluoronitrobenzene.

The reaction of CTC–fluorobenzene with piperidine is wholly base catalyzed in acetonitrile (Figure 1), and mainly base catalyzed in DMF (Figure 2) and in DMSO (Figure 3). In DMSO, the reaction with piperidine is catalyzed strongly by quinuclidine and weakly by DABCO (a weaker base), but is repressed by *N*-methylpiperidine (Figure 4). The same reaction is accelerated by *tert*-butylamine, but in a curious nonlinear fashion (Figure 4) which is not understood. The reaction of CTC–fluorobenzene with pyrrolidine in DMSO is strongly catalyzed by pyrrolidine, in linear fashion, but that with *n*-butylamine in DMSO shows a curvilinear dependence of k_A on amine concentration (Figure 5). With *n*-butylamine the first and second stages of the mechanism are both partially rate limiting, while in all other cases expulsion of fluoride ion from intermediate complex **2** or **3** is rate limiting.

Whiting[10] has pointed out that, conceptually, an amine might attack CTC–fluorobenzene either endo (syn) or exo (anti) with respect to the chromium tricarbonyl moiety to form, respectively, intermediate **5** or **6**. He judged the evidence to support endo at-



5 6

(25) (a) B. A. Bolto and J. Miller, *Aust. J. Chem.*, **9**, 79 (1956); (b) *J. Org. Chem.*, **20**, 558 (1955).

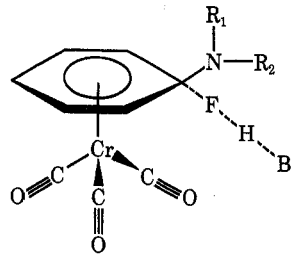
(26) *Cf.* T. J. Broxton, Thesis, University of Western Australia, 1967.

(27) H. Suhr, *Ber. Bunsenges. Phys. Chem.*, **67**, 893 (1963); *Justus Liebigs Ann. Chem.*, **687**, 175 (1965); *ibid.*, **689**,, 109 (1965).

tack, largely because piperidine is about 100,000-fold more reactive than diethylamine toward CTC–fluorobenzene but only about 100-fold more reactive with ordinary aromatic substrates such as 1-chloro-2,4-dinitrobenzene.

On the other hand, related complexes bearing a positive charge, such as the tropylium cation–CTC complex[6] and the cationic tricarbonyl(benzene)–manganese complex,[7] add nucleophiles on the less hindered exo side. Also, the reduction of CTC–1-indanone by $LiAlH_4$ or $NaBH_4$ occurs almost exclusively by exo attack of the reducing agent,[28a] and the Friedel–Crafts acylation of CTC–alkylbenzenes is believed to involve exo attack of the electrophile.[28b]

A number of observations in the present research and in the earlier work of Whiting[10] are compatible with the hypothesis that the amine attacks CTC–fluorobenzene on the exo side. The lack of catalytic activity by *N*-methylpiperidine (Figure 3) or by triethylamine[10] may be ascribed to steric hindrance when the *N*-methylpiperidium or triethylammonium ion, with its comparatively large steric requirements, attempts to approach the endo fluorine atom in order to provide electrophilic assistance to its severance from carbon.[29] By analogy with reactions of substrates such as 2,4-dinitro-1-naphthyl ethyl ether with amines,[17] the mechanism of general base catalysis of fluorine expulsion from intermediate complex **2** (Scheme I) is general acid catalysis of departure of the leaving group from the conjugate base intermediate complex (**3**). The transition state for fluorine expulsion, if the original nucleophilic attack is exo, may then be represented by structure **7**. If the amine moiety,



7

B, has large steric requirements, structure **7** will present obvious problems of fit.

In similar terms, the fact that diethylamine is enormously less reactive than piperidine in reaction with CTC–fluorobenzene may be understood. If the reacting amine is also the catalytic amine, its steric requirements will affect the rate of the fluorine expulsion step, as well as having some effect on the equilibrium concentration of intermediate complex **3** through steric interactions with the benzene moiety.

The very circumstance that reactions of CTC–fluorobenzene with amines of modest steric requirements, such as piperidine, pyrrolidine, and *n*-butylamine, in DMSO solvent are base-catalyzed whereas corresponding reactions of *p*-fluoronitrobenzene are not[27] also finds explanation in the hypothesis of exo attack and ultimate expulsion of fluorine *via* transition state **7**. With the nitro-activated substrate, leaving group expulsion from the intermediate complex is much faster than rejection of the amine moiety, but with CTC–fluorobenzene fluorine dismissal is the slower step. Steric problems evident in transition state **7**, even when the steric requirements of the amine are not great, are a plausible cause. If endo attack of amine were postulated, steric interactions between the amine and chromium tricarbonyl moieties would surely accelerate amine rejection, but they would also find relief in fluorine expulsion which would allow the amino group to move into coplanarity with the benzene ring carbons. If the latter factor predominated, no base catalysis would be observed.

The fact that *tert*-butylamine is an effective catalyst for reaction of CTC–fluorobenzene with piperidine, although not effective as a nucleophilic amine with this substrate, calls for comment. The bulkiness of *tert*-butylamine is about its α carbon, not about the nitrogen atom as in triethylamine. Although its bulkiness does adversely affect exo attack by *tert*-butylamine to form complexes of type **2** or **3** (its reactivity with ordinary aromatic substrates is also very low), the fact that in **7** the bulkiness is about an atom four atoms removed from aromatic carbon allows the *tert*-butyl group to be adjusted into conformations in which it does not experience formidable compressions against other moieties in the transition state.

The unreactivity of CTC–phenyldimethylsulfonium ion with methoxide ion, insofar as replacement at aromatic carbon is concerned, is also consistent with the hypothesis of exo attack by the nucleophile. In this case the intended leaving group is large, and in the intermediate complex it would be forced against the chromium tricarbonyl moiety. No such problem is involved in attack at aromatic carbon in *p*-nitrophenyldimethylsulfonium or *p*-nitrophenyltrimethylammonium ion.

Experimental Section

Preparations.—All tricarbonyl(arene)chromium complexes were prepared from the corresponding benzene derivative and chromium hexacarbonyl in an apparatus designed by Strohmeier,[30] which allows back-transport of the sublimed chromium hexacarbonyl to the reaction solution. The complexes were purified by recrystallization from *n*-heptane or better by high-vacuum sublimation.

CTC–fluorobenzene[2a] was obtained from fluorobenzene and chromium hexacarbonyl, mp 116–117° (lit.[2a] 122.5–124°). The melting point of the literature could not be obtained, even after extended purification by crystallization from *n*-heptane and sublimation. The complex was pure according to its mass spectrum; uv–visible in acetonitrile λ_{max} 310.5 nm (ϵ 9050); in DMF λ_{max} 310.5 (9360); in DMSO λ_{max} 311.5 (9020).

CTC–chlorobenzene[2a] was obtained from chlorobenzene and chromium hexacarbonyl, mp 98° (lit.[2a,31] 102–103°, 97–100°).

CTC–anisole was obtained from anisole and chromium hexacarbonyl, mp 86° (lit.[2a] 86–87°).

CTC–dimethylaniline was obtained from dimethylaniline and chromium hexacarbonyl, mp 146° (lit.[2a] 146–146.5°).

CTC–phenylpiperidine was obtained from phenylpiperidine and chromium hexacarbonyl, in 70% yield after sublimation, or from CTC–fluorobenzene and piperidine in acetonitrile[3] in 99% yield: mp 126–127° (lit.[2c] 125–126.5); uv–visible λ_{max} in acetonitrile 320 nm (ϵ 7800); in DMF 320 (8030); in DMSO 320 (7750).

CTC–phenylpyrrolidine was obtained from CTC–fluorobenzene and pyrrolidine in acetonitrile in 99% yield: mp 161–162° (lit.[2c] 161–162°); uv–visible λ_{max} in DMSO 317.5 nm (ϵ 7550).

(28) (a) W. R. Jackson and T. R. B. Mitchell, *J. Chem. Soc. B*, 1228 (1969); (b) W. R. Jackson and W. B. Jennings, *ibid.*, 1221 (1969).

(29) *Cf.* F. Covitz and F. H. Westheimer, *J. Amer. Chem. Soc.*, **85**, 1773 (1963).

(30) W. Strohmeier, *Chem. Ber.*, **94**, 2490 (1961).

(31) M. C. Whiting, British Patent 941,061 (1963); *Chem. Abstr.*, **60**, 3006 (1964).

CTC-*N*-*n*-butylaniline was obtained from CTC–fluorobenzene and *n*-butylamine in acetonitrile in 94% yield: mp 67°; uv-visible λ_{max} in DMSO 316 nm (ϵ 6650). *Anal.* Calcd for $C_{13}H_{15}CrNO_3$: C, 54.73; H, 5.30; N, 4.91. Found: C, 55.04; H, 5.01; N, 4.80.

CTC–thioanisole was obtained from thioanisole and chromium hexacarbonyl in 71% yield (after the first sublimation) or from CTC–fluorobenzene and sodium methyl mercaptide in DMSO after 24 hr at room temperature in 50% yield (after the first sublimation). The complex slightly decomposes during sublimation: mp 101°; ir (KBr) $\nu_{C=O}$ 1940, 1880, 1850 cm^{-1}. *Anal.* Calcd for $C_{10}H_8CrO_3S$: C, 46.15; H, 3.10; S, 12.32; mol wt ,260. Found:[32] C, 46.48; H, 3.23; S, 12.12; mol wt (mass spectrum, parent peak), 260.

CTC–Phenyldimethylsulfonium Fluoroborate.—A mixture of 4.2 g of CTC–thioanisole and 10 g of trimethyloxonium fluoroborate in 50 ml of dichloromethane was kept at room temperature for 15 hr. After evaporation of the solvent the residue was crystallized from ethanol (under N_2). The yield was 5.2 g (89%): on heating, it decomposed at 170–180°; ir (KBr) $\nu_{C=O}$ 1980, 1915, 1890, 1855 cm^{-1} (shoulder); nmr (CD_3SOCD_3) S, 6 H, τ 6.24 (CH_3); multiplet, 5 H, τ 3.24–4.10 (aromatic protons). *Anal.* Calcd for $C_{11}H_{11}BCrF_4O_3S$: C, 36.49; H, 3.06. Found:[32] C, 36.25; H, 3.00.

Reactions of CTC–Phenyldimethylsulfonium Fluoroborate. With Piperidine in Water.—From 10-hr reaction at room temperature, after which time the water phase was colorless, only CTC–thioanisole in a yield of 95% could be isolated. The result was the same when the reaction was carried out in acetonitrile as solvent. No CTC–phenylpiperidine was detectable (by ir) in either experiment.

With sodium methoxide in methanol, a mixture of CTC–thioanisole and CTC–anisole was obtained, but, according to ir and mass spectra, the yield of the latter was less than 5%. The yield of CTC–thioanisole was 97%.

Attempts to Prepare CTC–Phenyltrimethylammonium Fluoroborate.—Under the same conditions as for the preparation of the corresponding sulfonium salt, only starting material was detectable after a reaction time of 24 hr. Heating a solution of CTC–dimethylaniline with an excess of trimethyloxonium fluoroborate in ethylene chloride for 5 hr caused partial decomposition of the complex, but only starting material could be isolated. Carrying out the same experiment in tetrachloroethylene at its reflux temperature (140°) caused complete decomposition of the complex to form ill-defined products.

Attempts to Prepare CTC–Nitrobenzene.—CTC–Fluorobenzene (320 mg) in 5 ml of a saturated solution of sodium nitrite in DMSO was heated for 40 min at 80°. The dark brown reaction mixture was diluted with water and extracted with ether. After removal of the ether, the oily residue did not contain a trace of CTC–nitrobenzene, but only starting material according to ir and mass spectra. From the same reaction carried out in acetonitrile (2 hr under reflux), the only isolable substance was starting material. No CTC–nitrobenzene was detectable by mass spectrum in the reaction mixture after careful removal of the solvent by evaporation at room temperature.

***p*-Nitrophenyldimethylsulfonium Fluoroborate.**—A mixture of 2.3 g of *p*-nitrothioanisole[24] and trimethyloxonium fluoroborate (tenfold excess) in dichloromethane was kept at room temperature for 12 hr. The solvent was evaporated and the residue was crystallized twice from methanol; the product formed white plates, mp 118°, in 60% yield.

Reactions of *p*-Nitrophenyldimethylsulfonium Fluoroborate. With Piperidine in Water.—The sulfonium salt (305.5 mg) was kept for 10 hr at room temperature in a 15% solution of piperidine in water. The only isolable product, in 91% yield, was *p*-nitrothioanisole. The same reaction carried out in methanol in the presence of piperidine hydrochloride gave *p*-nitrothioanisole in 85% yield. With sodium methoxide in methanol, *p*-nitroanisole was formed in 86% yield.

Solvents.—DMSO (Crown Zellerbach) was purified by repeated fractional freezing until its ultraviolet spectrum was constant. DMF was purified by distillation from P_2O_5 at 45° in the dark. Acetonitrile was purified after O'Donnell, Ayres, and Mann.[33]

(32) Elemental analysis by Micro-Tech Laboratories, Skokie, Ill.

(33) J. F. O'Donnell, J. T. Ayres, and C. K. Mann, *Anal. Chem.*, **37**, 1161 (1965).

Kinetic Measurements.—Runs were conducted spectrophotometrically under conditions to afford pseudo-first-order kinetics. A few crystals of CTC–fluorobenzene were placed in a nitrogen-flushed 10-mm cuvette with neck. The cuvette was flushed again with nitrogen and closed under a nitrogen stream with a cap made from silicone rubber tubing which was stoppered at the top with a flat-ended piece of glass rod. (Other types of rubber tubing were slowly attacked by solvent vapor.) After injection of a solution, prepared under nitrogen, of all reaction ingredients except CTC–fluorobenzene through the wall of the silicone rubber tubing by means of a syringe, the cap was pushed down, so that the planar end of the glass rod was attached to the neck of the cuvette as tightly as possible, so as to minimize direct contact of the silicone rubber tubing with the reaction solution. Then the reaction solution was thoroughly mixed and placed in the thermostated cell compartment of a Gilford 2000 automated kinetics spectrophotometer. Absorbance was then determined as a function of time, and the data were treated according to standard methods.

Ultraviolet spectra were determined by a similar procedure, by injecting solutions of the complexes in appropriate solvents. The spectra obtained in this way were reproducible and stable for several hours, an indication that this technique effectively excluded oxygen. In DMSO and DMF all complexes slowly decomposed, but too slowly to interfere with the kinetic measurements. All reaction solutions were light sensitive and had to be kept in the dark, because the photolytic decomposition of the complexes is quite rapid.

That reactions with amines in DMSO were entirely aminodefluorination was shown in two ways. First, ultraviolet–visible spectra taken during the course of the reaction with piperidine showed two isosbestic points, at 285 and 322 nm. The final spectrum was identical with that of CTC–phenylpiperidine, and intermediate spectra could be mimicked by combination of the spectra of CTC–fluorobenzene and CTC–phenylpiperidine. Only at low concentrations of piperidine (0.1*M* and below) was there a slight deterioration of the isosbestic points after the first half-life, owing to the slow deterioration of these CTC complexes in DMSO, but the error caused in the infinity absorbance was not more than 3%. Similar observations were made in respect to reactions with pyrrolidine and *n*-butylamine.

The second type of evidence showing that the reactions occurred in the expected sense was from fluoride ion titration against lanthanum nitrate solutions with reference to a fluoride ion-selective electrode (Orion Model 94-09). Kinetic runs were performed, with CTC–fluorobenzene (0.01 *M*) and piperidine (0.158 *M*) in DMSO, under nitrogen, with samples being removed at recorded times by syringe. The samples were quenched with HCl in water to pH 3, extracted with ether to remove CTC complexes, diluted with isopropyl alcohol and water to constant volume of 50% isopropyl alcohol content by volume, adjusted to pH 4 by addition of a few drops of piperidine solution in DMSO, and titrated with $La(NO_3)_3$ solution. The end-point potential was found to depend on the volume of titrant added. It was therefore necessary to employ several $La(NO_3)_3$ solutions for each run in order to get meaningful results, and to perform numerous test titrations with solutions of known fluoride ion concentration. Two identical runs at 25° afforded k_ψ values of 2.74 and 2.59 × 10^{-4} sec^{-1}, and infinity fluoride ion yields of 90 and 91%. The photometric k_ψ under the same conditions (Table I) was 2.63 × 10^{-4} sec^{-1}.

The infinity solutions from runs in acetonitrile and DMF had ultraviolet–visible spectra which matched that of CTC–phenylpiperidine. Reactions in DMF showed well-defined isosbestic points at 220 and 283 nm (with piperidine 0.134 *M*). A preparative run in acetonitrile afforded CTC–phenylpiperidine in 99% yield.

Registry No.—**1**, 12082-05-2; piperidine, 110-89-4; pyrrolidine, 123-75-1; *n*-butylamine, 109-73-9; quinuclidine, 100-76-5; DABCO, 280-57-9; *N*-methylpiperidine, 626-67-5; *tert*-butylamine, 75-64-9; CTC–*N*-*n*-butylaniline, 32104-33-9; CTC–thioanisole, 32104-34-0; CTC–phenyldimethylsulfonium fluoroborate, 32104-35-1.