Chemical Kinetics of the Reaction of 2,4-Dinitrohalobenzenes with Ammonia

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The rates of the reaction of 2,4-dinitrohalobenzenes with NH_3 were determined in the solvent methanol. The order of reaction rates is F > Cl ~ Br > I. Addition of salts caused either no change or a decrease in the reaction rate constant of the fluoro compound though the same salts caused reaction rate constant increases with the other halides.

Examination of the literature revealed a dearth of aromatic nucleophilic substitutions in which ammonia was the nucleophile. Brady and Cropper,[3] Blanksma and Schreinemachers,[4] Vorozhtsov and V. Kobelev,[5a,b] and Bunnett and Reinheimer,[6] have reported kinetic results with ammonia as nucleophile in alcohol, water and methanol solutions. In connection with our interest in salt effects in aromatic nucleophilic substitution reactions,[7] the reaction of ammonia with 2,4-dinitrohalobenzenes constitutes the case of a neutral reagent and a neutral substrate. Study of the kinetic effect of added neutral salts in this reaction was expected to provide important information.

Experimental

Materials.—The 2,4-dinitrochlorobenzene, 2,4-dinitrobromobenzene and 2,4-dinitroiodobenzene, abbreviated as 2,4-DNCB, 2,4-DNBB and 2,4-DNIB, were recrystallized from ether until the m.p. remained constant. The observed m.p. were 51–52° for 2,4-DNCB, 71.5–72° for 2,4-DNBB and 87.5–88.5° for 2,4-DNIB.[8] The 2,4-dinitrofluorobenzene (2,4-DNFB) was vacuum distilled through a Todd column; b.p. 140–141° (5 mm.). The refractive index was 1.5696 and compared favorably with the literature value of 1.5695–1.5698.[9] The purification of methanol and source of salts were given in the previous paper.[7]

Procedure for 2,4-DNCB, 2,4-DNBB and 2,4-DNIB.—The 2,4-DNCB was weighed in a previously weighed 50-ml. volumetric flask. The salts were weighed separately and transferred into the volumetric flask. The solids were dissolved in 25–35 ml. of methanol, and then was added 10 ml. of a standard solution of NH_3 in methanol, of concentration such that the concentration of ammonia would be twice that of 2,4-DNXB. After dilution to volume and thorough mixing, the solution was pipeted into the sample tubes which were then sealed and placed in a constant temperature bath. The tubes were removed and plunged into ice-water to stop the reaction, and then were opened by crushing the neck under the surface of a boric acid solution. The tube was rinsed three times, and then the NH_3 concentration was immediately determined by a potentiometric titration. The rate constants were determined graphically by plotting $1/[NH_3]$ vs. time.

Procedure for 2,4-DNFB.—The rapid reaction of 2,4-DNFB with ammonia was run in a flask, and samples were removed by a calibrated rapid delivery pipet. The reaction was stopped by pipeting the mixture into boric acid solution. The titrations were run in a batch at the end of the run. There was no detectable loss of ammonia because of the slight delay in titration. All runs were followed from 25–75% reaction. The initial concentration of NH_3 was about 0.19 M and that of 2,4-DNFB was 0.11 M. The rate constant was obtained by plotting

$$\frac{1}{2[2,4\text{-DNFB}]_0 - [NH_3]_0} \log \frac{[2,4\text{-DNFB}]}{[NH_3]} \text{ vs. time.}$$

The reaction product was precipitated from the 2,4-DNFB reaction by adding the reaction mixture to a large amount of water. The product melted at 180–181.5°, literature[10] 182°.

Results and Discussion

A summary of the data is given in Table I. The rate constants follow the general order that the

TABLE I

REACTION RATE CONSTANTS FOR THE REACTION OF 2,4-DINITROHALOBENZENES WITH AMMONIA

2,4-DNXB	Temp., °C.	Salt added[a]	Rate constant $k_2 \times 10^4$, 1./mole sec.	$\Delta k_2 \times 10^4$, 1./mole sec.	Δk_2, %
F	24.90	None	39.0; 39.4; 40.1 38.4; 38.5		
	24.90	LiI·3HOH[b]	32.0; 31.8	−7.2	−18
	24.90	NaI[b]	39.0; 39.2	0	0
	24.90	KI[b]	40.2; 39.0	0.6	1.5
	24.90	LiCl[b]	37.0; 38.5	−1.4	− 3.5
	24.90	LiClO₄·3HOH[b]	30.0; 30.8	−8.7	−22
	0.10	None	5.38; 5.43; 5.56		
	24.90	None	37.0;[e] 37.2[e]		
	24.90	LiClO₄·3HOH[b]	29.5;[e]	−7.6	−20
	24.90	LiCl[b]	36.0; 36.7[e]	−0.8	− 2.2
	24.90	LiNO[b]₃	35 0; 34.7[e]	−2.3	− 6.2
Cl	125.4	None	23.8; 22.7; 20.9		
	97.1	None	4.53; 4.28; 4.91		
	97.1	NaI[c]	5.19; 5 36	0.70	15.6
	97.1	KI[c]	5.31; 5.34	0.75	16.4
	97.1	LiI·3HOH[c]	5.10; 5.65	0.60	13.1
	97.1	NaI	6.05; 6.22	1.56	34.0
	97.1	KI	6.30; 6.05	1.60	35 0
	97.1	LiI·3HOH[d]	5.52; 5.43; 5.70	0.98	21.4
	97.1	LiCl	6.05	1.47	32.0
	79.63	None	1.57; 1.56		
Br	125.25	None	21.6; 22.0; 22.4		
	97.10	None	4.09; 4.47		
	97.10	LiI·3HOH	5.00; 5.08	0.75	17
	97.10	NaI	5.89; 5.83	1.57	36
	97.10	KI	5.94; 5 92	1.64	39.2
	79.65	None	1.55; 1.49; 1.50		
I	125.25	None	7.63; 7.55; 7.83		
	97.10	None	1.76; 1.60 1.58; 1.57		
	97.10	LiI·3HOH	2.08; 2.09	0.50	31.0
	97.10	NaI	2.32; 2.44	0.80	50.5
	97.10	KI	2.40; 2.41	0.83	52.5
	79.63	None	0.532		

[a] Concentration of all salts is 0.30 mole/l. unless specified otherwise. [b] Salt concentration is 0.372 M for all 2,4-DNFB runs. [c] Salt concentration is 0.10 M. [d] Salt concentration is 0.215 M. New sample of 2,4-DNFB.

(1) From the independent study theses submitted to the College of Wooster in partial fulfillment of the degree of Bachelor of Arts, of Philip E. Rohrbaugh, 1959, and R. Craig Taylor, 1960.

(2) Support by the Undergraduate Research Participation Program of the National Science Foundation during the summer of 1959 is gratefully acknowledged.

(3) G. L. Brady and F. R. Cropper, J. Chem. Soc., 507 (1950).

(4) J. J. Blanksma and H. H. Schreinemachers, Rec. trav. chim., 52, 428 (1933).

(5) (a) N. N. Vorozhtsov, Jr., and V. A. Kobelov, J. Gen. Chem. (USSR), 9, 1043 (1939); (b) 8, 1330 (1938).

(6) J. D. Reinheimer and J. F. Bunnett, J. Am. Chem. Soc., 81, 315 (1959).

(7) J. D. Reinheimer, W. F. Kieffer, S. W. Frey, J. C. Cochran and E. W. Barr, ibid., 80, 164 (1958).

(8) This sample was supplied by J. F. Bunnett.

(9) G. C. Finger and C. W. Kruse, J. Am. Chem. Soc., 78, 6036 (1956).

(10) Beilstein, "Handbuch der Organische Chemie," 4th ed., Julius Springer, Berlin, 1923, Vol. XII, p. 748.

TABLE II

ACTIVATION PARAMETERS FOR NUCLEOPHILIC REACTIONS OF SUBSTITUTED NITROBENZENES AT 50°

Substituted nitrobenzene	Piperidine		NH₃		OCH₃		C₆H₅S		Aniline		Others	
	ΔS^*	ΔE	ΔS^*	ΔE	ΔS^*	ΔE	ΔS^*	ΔE	ΔS^*	ΔE	ΔS^*	ΔE
p-F	−43.0	13.2[d]	−31.4	20.4[c]	− 7.1	21.2[a]	−11.6	19.8[c]			− 8.4	19.0[e]
p-Cl	−36.2	17.1[d]			− 9.0	24.0[a]					−18.8	20.1[e]
p-Br	−36.2	16.8[d]			− 8.6	24.6[a]					−18.5	20.3[e]
p-I	−36.2	18.0[d]			− 8.3	25.0[a]						
o-F	−35.1	14.8[d]			−12.0	19.7[b]					− 6.5	20.1[e]
o-Cl	−31.2	18.1[d]			−12.0	23.6[b]					−14.8	22.2[e]
o-Br	−29.0	18.3[d]			− 7.7	25.5[b]						
o-I	−27.2	19.2[d]			− 6.5	26.5[b]						
3-NO₂-4-F			−28.2	12.1	−14.2	12.3[j]			−49.0	6.4[k]	−10.5	17.6[h]
3-NO₂-4-Cl	−30.2	11.6[f]	−31.1	16.6	− 9.9	17.4[h]	−20.0	10.3[g]	−43.0	10.8[k]	−15.1	20.7[h]
3-NO₂-4-Br	−29.5	11.8[f]	−31.2	16.7	−10.8	17.1[h]	−20.6	9.8[c]				
3-NO₂-4-I	−31.7	12.0[f]	−31.3	17.0	− 6.9	19.0[h]	−17.6	10.7[g]				
3-CH₃-4-F	−46.0	12.6[c]	−36.8	19.3[c]	− 8.4	21.5[j]	−17.7	18.3				
3-CH₃-4-Cl					−10.2	24.5[i]						
3-Br-4-F	−39.6	15.2[c]	−29.1	18.5[c]	−12.3	17.3[c]	−16.3	11.0[c]				

[a] G. P. Briner, J. Miller, M. Liveris and Miss P. G. Lutz, *J. Chem. Soc.*, 1265 (1954); solvent was methanol. [b] B. Bolto, J. Miller and V. A. Williams, *ibid.*, 2926 (1955); solvent was methanol. [c] J. D. Reinheimer and J. F. Bunnett, *J. Am. Chem. Soc.*, 81, 315 (1959); solvent was methanol. [d] N. B. Chapman, R. E. Parker and P. W. Soanes, *J. Chem. Soc.*, 2109 (1954); solvent was ethanol. [e] C. W. L. Bevan, *ibid.*, 2340 (1951); solvent was ethanol and nucleophile was ethoxide ion. [f] J. F. Bunnett, E. W. Garbisch, Jr., and K. M. Pruitt, *J. Am. Chem. Soc.*, 79, 385 (1957); solvent methanol. [g] J. F. Bunnett and W. D. Merritt, Jr., *ibid.*, 79, 5967 (1957). [h] A. L. Beckwith, J. Miller and G. D. Levy, *J. Chem. Soc.*, 3552 (1952); solvent was methanol and nucleophile was p-nitrophenoxide ion. [i] R. L. Heppolette, J. Miller and V. A. Williams, *ibid.*, 2929 (1955); solvent was methanol. [j] C. W. L. Bevan and G. C. Bye, *ibid.*, 3091 (1954); solvent was methanol. [k] N. B. Chapman and R. E. Parker, *ibid.*, 3301 (1951); solvent was 99.8% ethanol. The entropy and activation energies for the reagents m-toluidine, m-chloroaniline, m-bromoaniline, p-chloroaniline and p-bromoaniline are very similar to those of aniline. For reaction with 2,4-DNFB, ΔS^* is −48 to −49 e.u. for all the substituted anilines. For 2,4-DNCB, ΔS^* is −41-42 e.u. for all the substituted anilines except the bromoanilines, where ΔS^* is −35 e.u.

fluoro compound reacted much more rapidly than the other halo compounds. The chloro and bromo reacted at practically the same rate, which was considerably faster than for the iodo compound. This is the expected order for activated aromatic nucleophilic substitutions if the nucleophile is fairly active.

The effect of salts was investigated. The concentration of added salt was varied from 0.10 to 0.30 M in the reaction of 2,4-DNCB and ammonia. The larger concentration was used in the remaining runs, for the salt effects were large enough to be well beyond experimental error. In the case of the fluoro compounds, a new sample was purified after the unexpected salt effects on the fluoro compound were observed. The kinetic check on its purity was not made until after several runs with LiCl, LiNO₃ and LiClO₄·3HOH were completed. The discrepancy in rate constants, 39.1 × 10⁻⁴ l./mole. sec. for the old sample and 37.1 × 10⁻⁴ for the new, is given in Table I. The first value is regarded as more reliable, but the salt effects, which are obtained by difference, are believed to be acceptable data.

The salt effects for the chloro, bromo and iodo compounds may be summarized: (1) All alkali iodides increase the rate of the reaction. (2) Potassium and sodium iodides cause a greater increase in rate than do lithium iodides. (3) The rate increase for the iodo compound is greater than that for the bromo or chloro compound. These results are similar to those of Ross and Finkelstein,[11] who observed a positive neutral salt effect in the reactions of 2,4-DNCB with piperidine or with n-butylamine in ethanol.

(11) S. D. Ross and M. Finkelstein, *J. Am. Chem. Soc.*, 79, 6547 (1957).

The effect of salts on the rate of reaction of the fluoro compound stands in sharp contrast to the other halides. The potassium and sodium iodides have little effect on the reaction rate, but lithium iodide causes a decrease of 20%. Other lithium salts show a qualitatively similar effect with the exception of LiCl, which causes only a slight decrease in reaction rate constant.

Several observations on the entropy of activation may be made on the data collected in Table II. In a reaction in which a Cl, Br or I is replaced by piperidine, ammonia, methoxide, thiophenoxide or ethoxide, the entropy of reaction is very nearly the same for a given reagent. The greatest variation is shown by methoxide in the o-nitrohalobenzenes and the least variation by NH₃ on 2,4-DNXB or piperidine on p-nitrohalobenzenes. In reactions in which fluorine is replaced, the data are less regular. The entropy of activation is more negative for the reagent piperidine and the substituted aromatic amines. There is practically no difference with the reagent −OCH₃, but two other reagents, namely OEt⁻ and p-nitrophenoxide ion, have a less negative entropy of activation. The observed entropy of activation for this reasearch seems to fit reasonably well with that of other aromatic nucleophilic substitutions.

The observed rate changes with added salts seem to be the result of two effects. The first is the general increase in rate in a more polar solvent if the transition state is more polar than the reagents. This effect calls for an increase in rate for all the compounds and for all the salts. This would seem to be the dominant effect in the replacement of Cl, Br and I from 2,4-DNXB by ammonia. On the other hand, the replacement of F is not affected in the expected manner.

A possible explanation for this decrease involved the *intimate* association of M^+ with oxygens of the nitro group, as in diagram A.

(A)
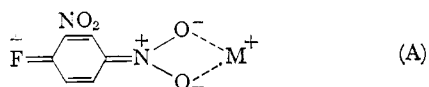
If this form is less readily attacked by the nucleophile, the over-all rate for the fluoro compound should be decreased. Since fluorine has the greatest tendency to resonate with the benzene ring,[12] est tendency to resonate with the benzene ring,[12]

(12) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953. p. 75.

this rate-decreasing association would be greatest with 2,4-DNFB. The salt which would be expected to form the most stable association or complex (A) would be that with the smallest ionic radius, Li^+. Some support concerning (A) is given by Taft's observation that the contribution
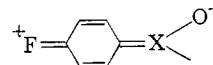
of the resonance form is increased in more polar solvents.[13]

(13) R. W. Taft, Jr., R. C. Olick, Irwin C. Lewis, Irwin Fox and Stenton Ehrenson, *J. Am. Chem. Soc.*, **82**, 756 (1960).

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Specific Solvent Effects in the Alkylation of Enolate Anions. IV. Kinetic Order of Solvent Participation

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The rates of alkylation at 25° of diethyl sodio-*n*-butylmalonate with *n*-butyl bromide in mixtures of benzene with increasing amounts of each of the additives tetrahydrofuran (THF), ethylene glycol dimethyl ether (monoglyme), dimethylformamide (DMF) and dimethyl sulfoxide (DMSO) have been measured. Participation orders for DMF and monoglyme are constant over the approximate concentration range 5 to 95%. For DMF the participation order is roughly three-halves and for monoglyme it is one. Participation orders for THF and DMSO are not constant but increase with concentration to maximum values of 1.4 and 1.7, respectively, after starting at orders of less than one at low concentrations. The relative rates (at 25°) of this reaction in five pure solvents are as follows: benzene = 1, THF = 14, monoglyme = 80, DMF = 970 and DMSO = 1420. The two diethers 1,4-dioxane and 1,3-dioxolane have been examined for catalytic action and participation order. In both respects they resemble the ineffective tetrahydrofuran more than the moderately effective monoglyme. In line with expectation, the cyclic N,N'-dimethylethyleneurea exhibits catalytic action quite superior to that of its acyclic analog tetramethylurea and slightly above that of N-methyl-2-pyrrolidone, the most active of the saturated amides previously found. Implications of these results relating to the mode of specific cation solvation, and to a previously proposed mechanism of rate acceleration, are discussed.

The rate of the reaction of alkyl halides with sodium enolates of malonic esters in benzene solution is variously influenced by the addition of small quantities (5-10%) of different polar substances.[1] Addition of esters, ketones, nitriles, simple ethers, sulfones, amines and nitro compounds causes only slight increases in the rate. In contrast, the presence of small amounts of many N,N-disubstituted amides and certain coördinate covalent P-, S- and N-oxides exerts a striking accelerating effect on the reaction. For example, a 5% concentration of dimethylformamide (DMF) serves to bring about roughly a 20-fold increase in reaction rate over that in benzene alone.

Preliminary study[1] of the rate acceleration as a function of additive concentration in the alkylation of diethyl sodio-*n*-butylmalonate with *n*-butyl bromide revealed at least four types of participation. The ineffective additives (*i.e.*, acetone, pyridine and tetrahydrofuran) possessed fractional participation orders. Two borderline cases (ethanol and monoglyme) displayed roughly a first-order relationship between concentration and rate acceleration. Five N,N-disubstituted amides showed an approximate three-halves order, and N-methyl-2-pyridone furnished the only example encountered of a second-order concentration dependency. All of these measurements were

(1) H. E. Zaugg, B. W. Horrom and S. Borgwardt, *J. Am. Chem. Soc.*, **82**, 2895 (1960).

conducted over a limited range of concentration (0.162 to 1.296 *M*, maximum).

It was the main purpose of the present work to extend this study to higher additive concentrations. To this end, tetrahydrofuran (THF), ethylene glycol dimethyl ether (monoglyme) and DMF, examples of the fractional order, first-order and three-halves-order types, respectively, were examined for their effect on the rate of this alkylation reaction at gradually increasing concentrations. Indeed, the concentration range was extended to the point where the additives constituted the only solvent species present in the reaction mixture (no benzene diluent). In addition, dimethyl sulfoxide (DMSO), an effective additive of the coördinate covalent class whose participation order had not been determined previously, was examined in the same way.

Three new compounds also were tested for their accelerating efficiency at low additive concentration. Two of them, 1,4-dioxane and 1,3-dioxolane, were included for comparison with the moderately effective diether, monoglyme. The third, N,N'-dimethylethyleneurea, was examined in order to test the validity of a prediction previously derived[2] as a consequence of the hypothesis that the presence of a high π-moment in the additive molecule is a primary requirement for outstanding catalytic efficiency.

(2) H. E. Zaugg, *ibid.*, **82**, 2903 (1960).