Acid-Catalyzed Aromatic Nucleophilic Substitution. II. The Reaction of 2-Halo-3-nitropyridines and 2-Halo-5-nitropyridines with Water in Sulfuric Acid

JOHN D. REINHEIMER, JAMES T. MCFARLAND,[1,2] RICHARD A. AMOS,[1] JOHN M. WOOD,[2] MARK ZAHNISER,[1] AND WAYNE BOWMAN[2]

Department of Chemistry, The College of Wooster, Wooster, Ohio 44691

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The reaction rate constants for the reaction of several 2-halo-5-nitropyridines and 2-halo-3-nitropyridines have been determined. The plot of k_ψ *vs.* molarity of sulfuric acid shows a maximum. φ values from the Bunnett–Olsen plot indicate that a slow proton transfer to water is involved. Some limitations for preparation of halopyridines by an acid-catalyzed halogen exchange are indicated.

A mechanism has been proposed for the hydrolysis of 2-halo-5-nitropyridines to 2-hydroxy-5-nitropyridine in acid solution.[3] This mechanism was based on four considerations: (1) the reaction is an aromatic nucleophilic substitution reaction; (2) the reaction is acid catalyzed; (3) there is a deuterium isotope effect; and (4) four molecules of water are involved in the transition state. The reaction rate constants in this earlier investigation were determined by wet chemical methods, so the rate constants could not be conveniently measured at very low substrate concentrations. Spectrophotometric methods, with the requirement of very low substrate concentrations, can be applied to this system at both high and low acid concentrations and hence at both high and low percentage protonation of the pyridine nitrogen.

The previous kinetic relationships between the activity of water, a_{HOH}, and the protonated substrate were deduced from a plot of (k_ψ/F) *vs.* $(a_{HOH})^n$, where k_ψ was the observed pseudo-first-order rate constant and F was the fraction of the pyridine protonated. A linear plot was obtained with $n = 4$ for the substrate 2-chloro-5-nitropyridine. Our interest in studying other closely related substrates was to find answers to some of the following questions. Is the power of 4 on a_{HOH} applicable to other 2-halo-5-nitropyridines? Will the 2-halo-3-nitropyridines show the same kinetic relationship with respect to a_{HOH}? Can the *o*-nitro group replace one or more of the waters of solvation? How good is the bromo- and iododechlorination reaction; can one prepare the corresponding bromo and iodo compounds in a pure state from 2-chloro-5-nitropyridine and 2-chloro-3-nitropyridine. To answer these questions, 2-halo-5-nitropyridines and 2-halo-3-nitropyridines were synthesized (or purified) and their reaction rates with aqueous sulfuric acid were investigated.

Results

pK_a Determination.—The pK_a's of the halonitropyridines were determined by the method of Davis and Geissman[4] or Katritzky[5] or Bunnett and Olsen.[6] The pK_a's were determined by adding concentrated sulfuric acid from a weight buret to a fixed amount of the halonitropyridine. Readings were taken, and the cuvette carefully rinsed to ensure that no sample was lost before the next addition of sulfuric acid. This procedure was followed for all the substrates except 2-bromo-5-nitropyridine. The Davis and Geissman procedures were carried out by different investigators at Wooster with variations on the technique of adding known volumes of concentrated sulfuric acid to an aliquot of the sample. This technique was not satisfactory for the Katritzky or Bunnett and Olsen method, for slight changes in the value of the absorbance caused disproportionate changes in the calculated pK_a. The results are displayed in Table I.

The order of pK_a is roughly that expected. The steric inhibition of resonance of *ortho* group in the 2-halo-3-nitropyridines would be expected to decrease the electron-withdrawing effectiveness of the 3-nitro group as compared to the 5-nitro group. The chloro-substituted compounds are the least basic in both the 3-nitro and the 5-nitro series; this is in the order of the electronic effects of the halogens.

There are some differences in these pK_a values. For 2-chloro-5-nitropyridine, the Bunnett–Olsen pK_a is somewhat lower than the other values. The ratio $(C_{BH^+}/C_B) = 1.0$ occurs between $H_0 = 2.96$ and $H_0 = -2.78$. The extrapolation of a plot of $[H_0 + \log (H^+)]$ *vs.* $H_0 + \log [(C_{BH^+})/(C_B)]$ with the same data does not yield a Kp_a of the above range. The more negative value of -2.85 seems to be more consistent with the remainder of the data.

The rate data are displayed in Table II. In Table III the variation of k_ψ with temperature and the Arrhenius activation energies are given.

The H_0 data were taken from the review of Long and Paul.[7] The more recent data of Noyce and Jorgensen[8] were not needed, since our experiments were in the range of lower acidities where the two functions have the same value. (H^+) was taken to be the molarity of the sulfuric acid. The fraction protonated was calculated as $F = h_0/(h_0 + K_{SH^+})$.

The first attempted correlation of the pseudo-first-order rate constants with pK_a and a_{HOH} was a plot of $\log (k_\psi/F)$ *vs.* $\log (a_{HOH})$. The slope of such a plot would give "*n*," the power on a_{HOH}. These plots showed evidence of curvature at both high and low per cent protonation. The central portion of such plots

(1) Participant in the Undergraduate Research Participation Program of the National Science Foundation, 1966, 1968.

(2) Taken in part from the Independent Study thesis of James McFarland, 1964, John Wood, 1968, and Wayne Bowman, 1962.

(3) J. D. Reinheimer, J. T. Gerig, R. Garst, and B. Schrier, *J. Amer. Chem. Soc.*, **84**, 2770 (1962).

(4) C. T. Davis and T. A. Geissman, *J. Amer. Chem. Soc.*, **76**, 3507 (1954).

(5) C. D. Johnson, A. R. Katritzky, B. J. Ridgewell, N. Shakir, and A. M. White, *Tetrahedron*, **21**, 1055 (1965).

(6) J. F. Bunnett and F. P. Olsen, *Can. J. Chem.*, **44**, 1899 (1966).

(7) F. A. Long and M. A. Paul, *Chem. Rev.*, **57**, 1 (1957).

(8) D. S. Noyce and M. J. Jorgenson, *J. Amer. Chem. Soc.*, **84**, 4312 (1962).

TABLE I

pK_a AND φ FOR SUBSTITUTED PYRIDINES AT 30°

Compound	pK_a			φ[b]	φ[b]
	H_0 method	Davis & Geissman	Bunnett & Olsen	Bunnett & Olsen	from[c] pK_a
2-Chloro-5-nitro	−2.85	−2.95[a]	−2.42	0.66 (25°)	0.76
2-Bromo-5-nitro	−2.40[a]	−2.50[a]	−2.60[a]	0.68	
2-Iodo-5-nitro	−1.43	−1.70	−1.40	0.64	0.62
2-Chloro-3-nitro	−2.44		−2.39	0.63	0.67
2-Bromo-3-nitro	−2.05	−2.25	−2.02	0.68	
				0.69 (25°)	

[a] Temperature was 25°. [b] Temperature was 80° unless noted otherwise. [c] Plot of log (k_ψ/F) *vs.* $[H_0 - \log (H^+)]$ where $F = h_0/(h_0 + K_{SH^+})$.

TABLE II

RATE CONSTANTS AT 80° FOR 2-HALO-*x*-NITROPYRIDINES

$M_{H_2SO_4}$	k_ψ, sec^{-1}
2-Iodo-5-nitropyridine	
0.892	5.31×10^{-5}
1.784	11.9×10^{-5}
2.689	17.6×10^{-5}
3.142	19.3×10^{-5}
3.594	19.0×10^{-5}
4.047	17.9×10^{-5}
4.500	16.2×10^{-5}
5.404	10.2×10^{-5}
6.311	6.0×10^{-5}
2-Bromo-3-nitropyridine at 80.8°	
1.50	10.5×10^{-5}
2.45	20.1×10^{-5}
3.38	29.3×10^{-5}
4.16	31.6×10^{-5}
5.10	30.4×10^{-5}
6.03	21.5×10^{-5}
6.91	14.0×10^{-5}
7.82	7.45×10^{-5}
2-Bromo-3-nitropyridine at 25°	
1.50	4.15×10^{-7}
2.45	8.10×10^{-7}
3.38	11.8×10^{-7}
4.16	12.5×10^{-7}
5.10	12.1×10^{-7}
6.03	8.6×10^{-7}
6.91	5.5×10^{-7}
7.82	3.0×10^{-7}
2-Chloro-3-nitropyridine at 80.2°	
1.44	6.55×10^{-5}
2.40	13.0×10^{-5}
3.36	21.6×10^{-5}
4.32	26.7×10^{-5}
5.28	27.5×10^{-5}
6.24	22.7×10^{-5}
7.20	13.8×10^{-5}
8.16	6.8×10^{-5}
2-Bromo-5-nitropyridine	
2.40	1.23×10^{-4}
3.36	1.90×10^{-4}
4.32	2.46×10^{-4}
5.28	2.66×10^{-4}
6.21	2.11×10^{-4}
6.24	2.12×10^{-4}
7.20	1.52×10^{-4}
8.16	0.751×10^{-4}
9.12	0.438×10^{-4}

TABLE III

RATE CONSTANT AT DIFFERENT TEMPERATURES FOR 2-HALO-*x*-NITROPYRIDINES

Molarity	Temp, °C	k_ψ, sec^{-1}	Activation energy, kcal
2-Iodo-5-nitropyridine			
1.78	102.3	7.56×10^{-4}	
	89.9	2.78×10^{-4}	
	80.1	1.19×10^{-4}	
	60.0	0.195×10^{-4}	21.3
3.59	102.3	11.8×10^{-4}	
	89.9	4.58×10^{-4}	
	80.1	1.90×10^{-4}	
	60.0	1.02×10^{-4}	21.9
5.40	102.3	6.23×10^{-4}	
	89.9	2.61×10^{-4}	
	80.1	1.02×10^{-4}	
	60.0	0.144×10^{-4}	23.1
2-Bromo-3-nitropyridine			
2.45	100.7	74.2×10^{-5}	
	80.8	20.1×10^{-5}	
	70.7	8.91×10^{-5}	20.1
6.91	100.7	64.8×10^{-5}	
	80.8	14.0×10^{-5}	
	70.7	5.19×10^{-5}	21.4
2-Chloro-3-nitropyridine			
3.36	100.2	10.1×10^{-4}	
	80.2	2.16×10^{-4}	
	59.6	0.368×10^{-4}	20.6
4.32	100.2	12.5×10^{-4}	
	80.2	2.67×10^{-4}	
	59.6	0.479×10^{-4}	20.5
5.28	100.2	12.2×10^{-4}	
	80.2	2.74×10^{-4}	
	59.6	0.481×10^{-4}	20.0
6.24	100.2	10.5×10^{-4}	
	80.2	2.27×10^{-4}	
	59.6	0.343×10^{-4}	21.1
2-Bromo-5-nitropyridine			
3.36	99.9	8.54×10^{-4}	
	80.0	1.90×10^{-4}	
	60.1	3.18×10^{-5}	19.4
4.32	99.9	1.13×10^{-3}	
	80.0	2.46×10^{-4}	
	60.1	4.00×10^{-5}	19.7
5.28	99.9	1.47×10^{-3}	
	80.1	2.67×10^{-4}	
	60.1	4.21×10^{-5}	20.7

approximated a straight line; these plots were regarded as unsatisfactory.

The next approach was to apply the empirical method of Bunnett and Olsen.[6] Their plot of $[\log k_\psi - \log (C_{BH^+}/C_{st})]$ *vs.* $[H_0 + \log (H^+)]$ does not use the pK_a. The concentration of the protonated species and stoichiometric concentration are obtained from the spectra in the acid solution. A similar plot, log (k_ψ/F) *vs.* $[H_0 + \log (H^+)]$, was also made for each substrate.

Bunnett and Olsen have argued that the use of $F = [h_0/(h_0 + K_{SH^+})]$ is not as accurate as the use of $F = (C_{BH^+}/C_{st})$. The latter F may be obtained from pro-

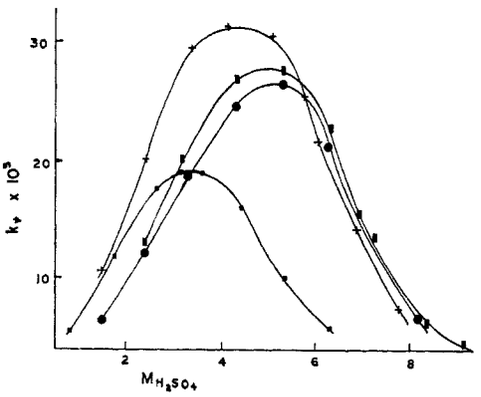


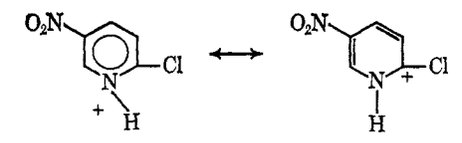
Figure 1.—k_ψ (sec^{-1}) *vs.* $M H_2SO_4$: ●, 2-bromo-5-nitropyridine; ■, 2-chloro-3-nitropyridine; ■, 2-iodo-5-nitropyridine; +, 2-bromo-3-nitropyridine.

tonation data directly without the intervention of a pK_a to determine K_{SH^+}. Further, if the substrate does not obey the acidity function that is applied, the pK_a that is determined may or may not give the proper F from $(h_0/(h_0 + K_{SH^+})]$. In the present case, both pyridine and pyridine N-oxides are Hammett bases.[9] Both types of plots were linear, and their slopes are in reasonable agreement. These results are displayed in Table I, columns 5 and 6.

Discussion

The acid-catalyzed bromodechlorination reaction is only a fair method for the preparation of the bromonitropyridines from chloronitropyridines. The reaction is acid catalyzed, for no reaction took place in the absence of acid and only partial exchange in the presence of acid.[10,11] However, iododechlorination is effective for the preparation of 2-iodo-5-nitropyridine from 2-chloro-5-nitropyridine. This was also an acid-catalyzed reaction; refluxing 2-chloro-5-nitropyridine with KI in methyl ethyl ketone gave no product. There is some indication that the halodechlorination reaction may be quite sensitive to the nature of the nucleophile. For example, $NaHF_2$ gave a 3% yield, but KHF_2 gave a 74% yield in the fluorodechlorination of 2-chloropyridine with no solvent.[12] It is possible that the use of CsI or some other alkali metal halide could give higher yields than we have been able to achieve.

The pseudo-first-order rate constants for the halonitropyridines *vs.* acid concentration are given in Figure 1. The shape of this curve may be qualitatively understood on the basis of two competing effects: protonation of the substrate and the activity of water. If the active species in solution is the protonated substrate, the rate should increase as the fraction protonated (F) increases. The activity of water, the nucleophile, decreases with increasing acid concentration. If $k_\psi = kF(a_{HOH})^n$, where k is the rate constant, a composite k_ψ results. At low acid concentrations, where a_{HOH} changes slightly with changing acid concentration, (F) is the major factor with its larger value (with increasing acid concentration) controlling the over-all rate. However, at higher acid concentrations, the decreasing a_{HOH} becomes more important and the over-all rate decreases with increasing acid concentration. During a particular experiment, both a_{HOH} and (F) remain constant.



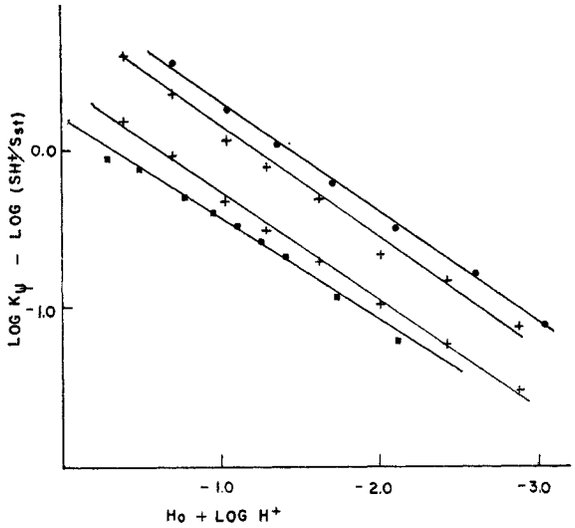


Figure 2.—[Log k_ψ − log (SH$^+$/S_{st})] *vs.* [H_0 + log (H$^+$)]: ●, 2-bromo-5-nitropyridine (80°); +, 2-bromo-3-nitropyridine (upper curve 80°, lower curve 25°); ■, 2-iodo-5-nitropyridine (80°).

It is interesting to note that the maximum is not the result of complete protonation of the substrate. The fraction protonated at the maximum value of k_ψ varies from 0.33 for 2-bromo-3-nitropyridine to 0.42 for 2-iodo-5-nitropyridine. These maxima occur between 3 and 5 M sulfuric acid.

There does not seem to be a good basis for the comparison of the rate constants of these reactions. The maximum values for k_ψ seem to be the most reasonable comparison. Chlorine and bromine are replaced at approximately equal rate, with iodine the slowest. This is the order expected for an activated aromatic nucleophilic substitution.[13]

Attempts to evaluate the role of water in the reaction were made with two plots. The method of Bunnett and Olsen gave reasonable straight lines with slopes which varied from 0.64 to 0.76. These slopes (φ) are in the range in which rate-determining proton transfer to water is indicated. It is of interest to note that the slope of the line depends upon the value of the pK_a which is used. Before the pK_a of 2-chloro-3-nitropyridine was determined, several rough estimates of −2.12, −2.25, and −2.50 were made and the kinetic data [log (H$^+$) + H_0 *vs.* log (k_ψ/F)] were plotted. The lines for each plot were equally good, with slopes (φ) of 0.58, 0.62, and 0.67, respectively. In another plot, the Bunnett–Olsen plot was made for the same substrate with k_ψ (80°) and also k_ψ (25°). The experimental data for 2-bromo-3-nitropyridine were measured at 80.8° and were extrapolated to 25.0° in order to use the H_0 and pK_a data that were obtained the the lower tem-

(9) C. D. Johnson, A. R. Katritzky, and B. J. Ridgewell, *J. Amer. Chem. Soc.*, **21**, 1057 (1965).

(10) A. H. Berrie, G. T. Newbold, and F. S. Spring, *J. Chem. Soc.*, 2042 (1952).

(11) Y. Yamamoto, *J. Pharm. Jap.*, **71**, 662 (1951).

(12) M. M. Boudakin, *J. Heterocycl. Chem.*, **4**, 381 (1967).

(13) J. F. Bunnett and R. E. Zahler, *Chem. Rev.*, **49**, 173 (1951).

perature. The plots were both linear, but $\varphi_{80.8} = 0.68$ and $\varphi_{25.0} = 0.69$. This difference is not regarded as highly significant. It has been suggested by Yates and Riordan[14] that kinetic data at temperatures other than 25° can be combined with acidity function data and a_{HOH} data at 25° without serious error for weakly basic substrates. Our observations do suggest that the combination of a poor estimate of pK_a and collection of data far removed from 25° may cause considerable differences in the slopes obtained (see Figure 2).

Some conclusions which may be drawn from this body of data are as follows.

(1) The hydrolysis reactions of 2-halo-5-nitropyridines and 2-halo-3-nitropyridines have the same mechanism.

(2) The mechanism involves a rate-determining proton transfer to water. The mechanism offered in ref 3 is supported, but the number of waters of hydration cannot be as definite as these authors have indicated.

(3) The role of the 3-nitro group in contrast to that of the 5-nitro group cannot be evaluated from this data. On the extreme hypothesis of hydration,[6] 4.5φ should give the hydration change for the reaction in terms of number of molecules of water.[8] Values of φ for 3-nitro compounds are 0.63 and 0.67; for 5-nitro they are 0.66, 0.67, and 0.64. There seems to be no difference in φ (where the same halogen is displaced) with change in position of the nitro group. A greater change in φ occurs when the iodine atom is displaced. This may suggest a steric factor is involved, but there are not sufficient data to draw a firm conclusion.

Experimental Section

Kinetic Methods. 2-Iodo-5-nitropyridine.—A stock solution of the reagent was prepared by dissolving 2-iodo-5-nitropyridine in concentrated sulfuric acid. A 9.85-ml sample was pipeted into a volumetric flask, and the desired concentration attained by suitable dilution in an ice bath (final dilution at room temperature). Nitrogen was used to deaerate the solution and to fill the sample tubes. Samples (10 ml) were sealed in Pyrex glass ampoules which were then placed in a constant-temperature bath. The reaction was stopped by plunging the tube into ice. The tubes were opened and the contents were rinsed into a 50-ml volumetric flask with 9 M H_2SO_4; the absorbance at 2840 Å was determined on a Beckman D.U. spectrophotometer. The rate constants were determined from eq 1.

$$2.303 \log [A_\infty/(A_\infty - A_t)] = k_\psi t \quad (1)$$

2-Bromo-3-nitropyridine and 2-Chloro-3-nitropyridine.—The procedures were the same as above, except that the use of nitrogen was not required. The samples were read without dilution on a Beckman D.U. spectrophotometer which had a Gilford phototube and electronics. The wavelength was 3480 Å.

2-Bromo-5-nitropyridine.—The procedures were the same as above, but certain complications ensued. The product and reagent absorbed at the same wavelengths, and their absorptivities were similar. Since the absorptivity changed slightly with acid concentration, it was necessary to prepare absorbance *vs.* wavelength curves for each product and reagent at each kinetic acid concentration. The wavelength that gave the greatest ($A_{reagent} - A_{product}$) was selected for analysis. This procedure allowed one to "read" the absorbance of the kinetic sample without dilution. The modified Beckman D.U. spectrophotometer was used. The wavelengths were approximately 2500–2600 Å in these experiments.

Precautions and Product Identification.—The sulfuric acid was standardized by titration against tris(hydroxymethyl)methylamine. The products were shown to follow Beer's law at several concentrations. The infinity samples were found to have the calculated absorbance within 2% in all cases; generally the agreement was to 1%. Qualitatively, the spectrum of the product was the same as that of the authentic sample—this comparison was made for the infinity samples of both 2-hydroxy-5-nitropyridine and 2-hydroxy-3-nitropyridine. The product was shown to be stable to the kinetic conditions by placing an authentic sample of the 2-hydroxy-3-nitropyridine in the kinetic medium at 102° for 24 hr. The absorbance of the sample did not change. All pipets and thermometers have been calibrated. All rate constants were determined by a least-squares regression analysis. The rate constants reported in Table II are the average of two or more experiments; those in Table III are singlet experiments.

Preparation of Substrates. Hydrolysis of 2-Chloro-3-nitropyridine.—2-Chloro-3-nitropyridine (1 g) was dissolved in 8 ml of 9 M sulfuric acid. The mixture was refluxed for 3 hr. Sodium hydroxide solution (6 M) was added to the cooled mixture until a precipitate formed; the still acidic solution was filtered. The product was isolated in 91% yield [0.89 g of 2-hydroxy-3-nitropyridine, mp 220–224° (lit.[10] mp 224°)]. In a second experiment, 20 g of 2-chloro-3-nitropyridine was added to 200 ml of glacial acetic acid and 200 ml of concentrated HCl and refluxed for 3 hr. The solvent was distilled away, and the product filtered. The product was recrystallized from methanol to give a product, mp 223–225°, in a yield of 16.0 g (89%). Thin layer chromatography on alumina with benzene showed no trace of the starting material in the product. Attempts to hydrolyze in basic solution gave a viscous oil which slowly crystallized and melted above 300°.

2-Iodo-5-nitropyridine was prepared by the method of Reinheimer, *et al.*[2] The final product was purified by column chromatography on alumina with benzene: purified yield 27%; mp 162.5–164.5°.

2-Bromo-5-nitropyridine.—Several attempts to prepare 2-bromo-5-nitropyridine by the reaction of LiBr with 2-chloro-5-nitropyridine in different solvents gave a product of mp 132–133°. Attempts to purify this material by column chromatography were unsuccessful. Finally, the method of Yamamoto[11] was used. 2-Hydroxy-5-nitropyridine (2.5 g), red phosphorus (0.8 g), and 0.83 ml of toluene were mixed and 3.82 ml of bromine was slowly added over a period of 2.5 hr while the temperature was maintained at 120–130°. The reaction mixture was cooled and poured on ice; the solid was filtered and dried. Purification on an alumina column with benzene as the eluting agent gave 1.0 g (29%) of 2-bromo-5-nitropyridine, mp 136.5–138°. In a second preparation, bromobenzene was substituted for toluene in the above preparation to avoid the formation of benzyl bromide. During chromatographic work-up, several bands appeared and the crude product melted over a considerable range, 122–133° (61% yield). With further purification on the alumina column and acetone as the eluting agent, the crude product separated into two bands; the desired product moved with the solvent front and the impurity remained at the origin. Two recrystallizations from acetone–ligroin gave 4.7 g (34% yield), mp 138–139.5° (lit.[5] mp 138°).

Anal. Calcd for $C_5H_3BrN_2O_2$: C, 29.58; H, 1.49; N, 13.80. Found: C, 29.57; H, 1.42; N, 13.81.

2-Bromo-3-nitropyridine was prepared by the procedure of Berrie, Newbold, and Spring.[10] The product was recrystallized six times, mp 122–124° (lit.[10] mp 124°). Thin layer chromatography gave no indication of impurities, and a bromide analysis indicated a purity of 98%.

Bromodechlorinations of 2-Chloro-5-nitropyridine.—2-Chloro-5-nitropyridine (13.16 g, 0.0083 mol) was dissolved in 480 ml of anhydrous methyl ethyl ketone. LiBr (36.15 g, 0.415 mol) and 4 ml of concentrated sulfuric acid were added and the mixture was refluxed for 1.5 hr. The reaction mixture was cooled, poured on ice, and the organic layer separated. After drying, concentration (by evaporation of the solvent under reduced pressure) to one-third the original volume, and cooling, 13.5 g (80% yield) of a crude product, mp 120–125°, was obtained. Three recrystallizations from benzene–ligroin gave a product of mp 132–133°. In a similar reaction, 0.02 mol of 2-chloro-5-nitropyridine and 0.10 mol of LiBr in 60 ml of glacial acetic acid gave 35% yield of white crystals, mp 130–132°. Recrystallization from benzene–ligroin gave a product melting at 131.5–132.5°.

Iododechlorination of 2-Chloro-5-nitropyridine.—The procedure of Klingsberg[15] was followed. 2-Chloro-5-nitropyridine

(14) K. Yates and J. C. Riordan, *Can. J. Chem.*, **43**, 2333 (1965).

(15) E. Klingsberg, *J. Amer. Chem. Soc.*, **72**, 1031 (1950).

(25 g) and KI (75 g) were refluxed in 350 ml of methyl ethyl ketone. The solvent was evaporated, the residue washed with water, and recrystallized from benzene to give starting material.

Attempted Bromodechlorination of 2-Chloro-3-nitropyridine.—The molar ratio was 0.08 mol of aryl chloride and 0.416 mol of LiBr. In three experiments, methyl ethyl ketone, glacial acetic acid, and dimethyl sulfoxide were used as the solvent. Starting material was recovered when no acid was added to methyl ethyl ketone. In each case, the reaction mixture was refluxed for several hours, then the product isolated by pouring the reaction mixture on ice. If the product did not precipitate immediately, the solvent was removed by evaporation to obtain the solid product. The melting point of the product was 118–120°, and did not change with recrystallization. Potentiometric titration of the halide by silver nitrate showed the presence of both bromide and chloride ions.

Registry No.—Sulfuric acid, 7664-93-9; 2-bromo-5-nitropyridine, 4487-59-6; 2-chloro-3-nitropyridine, 5470-18-8; 2-iodo-5-nitropyridine, 19755-52-3; 2-bromo-3-nitropyridine, 19755-53-4.

The Photochemistry of Unsaturated Nitrogen Containing Compounds. II. The Mechanism of Benzonitrile and Benzaldimine Formation during Irradiation of Benzalazine

ROGER W. BINKLEY

Department of Chemistry, The Cleveland State University, Cleveland, Ohio 44115

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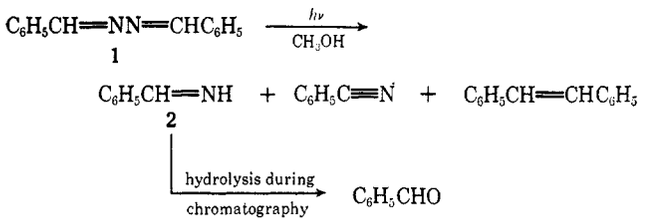
The photochemical reaction of benzalazine (1) to give benzonitrile and benzaldimine (2) was studied in the presence of various hydrogen donors in an effort to obtain information which would determine whether the mechanism for this photochemical transformation is inter- or intramolecular. These studies showed that with the addition of effective hydrogen donating agents such as benzhydrol and decyl mercaptan a definite decrease in product yield occurred; however, a limiting value in the decrease of this yield was reached beyond which further addition of trapping agents had no effect. These results are interpreted as indicative of both intra- and intermolecular reaction being operative in the photochemical conversion of benzalazine (1) to benzonitrile and benzaldimine (2). Mechanisms for these two processes are presented and discussed.

In the previous publication in this series[1] it was shown that benzalazine (1) reacted photochemically to produce benzonitrile, benzaldimine (2), and *trans*-stilbene. Benzaldimine (2) was discovered to be an

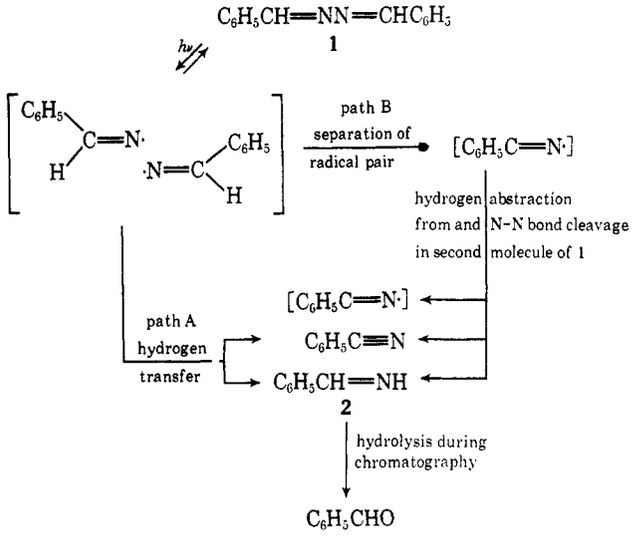


unstable photoproduct which hydrolyzed to benzaldehyde during chromatography. Two mechanisms were proposed at the time of the previous study in order to rationalize the apparently coupled benzonitrile–benzaldimine (2) formation (Scheme I); unfortunately, it was not feasible at that time with the evidence available to make a choice between these two mechanistic possibilities.

The fundamental difference between the two pathways under consideration (Scheme I) exists in the fact that path A postulates an intramolecular reaction mechanism with a hydrogen transfer which occurs within the solvent cage (a disproportionation within the solvent cage of the photochemically produced radical pair) while path B, in contrast, proposes an intermolecular reaction which requires the diffusion of the $C_6H_5CH{=}N$ radical through solution (*i.e.*, escape of the radical species from the solvent cage prior to further reaction) to react with a second molecule of benzalazine (1) in a hydrogen abstraction process. Accordingly, reaction *via* path A should be effectively insensitive to the presence of radical trapping agents in solution while a process such as that indicated by path B should show

SCHEME I

FORMATION OF BENZONITRILE AND BENZALDEHYDE FROM BENZALAZINE (1)



a change in reaction course in a solution where the $C_6H_5CH{=}N$ radical could be intercepted and could undergo reaction before reaching a benzalazine (1) molecule. As a basis for selection between these two possible pathways, a series of irradiations was undertaken in which alcohols with different hydrogen-donating abilities were used as reaction solvents; in addition, a number of reactions were also conducted in which decyl mercaptan was present in the reaction mixtures in various concentrations.

Results

The data given in Table I described the Vycor-filtered irradiations of benzalazine (1) with four dif-

(1) R. W. Binkley, *J. Org. Chem.*, **33**, 2311 (1968).