of Table IV and using the average of 47% for phenylation and 53% for dimerization, we arrived at the estimates of biphenyl formed in the two processes b and c shown in Table IV.

TABLE V

| Source of R | Phenylation C₆H₅R, % | Dimerization R–R, % |
|---|---|---|
| C₆D₆[a] | 44 | 56 |
| C₆H₅F[b] | 47 | 53 |
| C₆H₅Cl[c] | 47 | 53 |

[a] Reference 1a.  [b] Reference 1b.  [c] Unpublished results.

Relative reactivities to phenyl radical from nitrobenzene at 600°, derived from the benzene–pyridine and benzene–thiophene product distributions, follow: benzene, 1; pyridine, 2.3; thiophene, 5. Calculated from the data in the fourth column of Table IV, the corresponding values are 1, 2.1, and 4.6. The agreement between the two sets of figures is quite good, especially as the concentration of nitrobenzene in the reaction with the mixture of all three reagents differs somewhat from that in the other reactions.

We are presently surveying the relative reactivities of a variety of aromatic and heteroaromatic compounds to phenyl and substituted phenyl radicals derived from nitrobenzene and substituted nitrobenzenes at 600°. As shown in the fourth column of Table IV, the total yield of phenylation and dimerization products increased appreciably when a mixture of all three reagents was allowed to react with nitrobenzene. In our present studies we find even more pronounced yield increases in the reactions of nitrobenzene with certain mixtures of more than one reagent, and we are exploring the cause.

# Kinetics of Reactions of Piperidine with Substituted Phenyl Ethers of 2,4-Dinitrophenol in 60% Dioxane–40% Water. Base Catalysis as a Function of the Group Displaced[1]

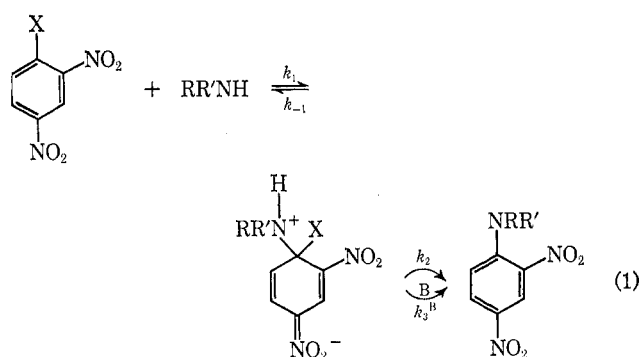J. F. BUNNETT AND C. F. BERNASCONI[2]

*Metcalf Chemical Laboratories, Brown University, Providence, Rhode Island*

The rates of reactions of piperidine with several 2,4-dinitrophenyl aryl ethers have been measured as functions of hydroxide ion and piperidine concentrations. The reactions of 2,4-dinitrophenyl 4-methoxyphenyl ether and of 2,4-dinitrophenyl 3,4,5-trimethylphenyl ether are strongly catalyzed by hydroxide ion, and plots of second-order rate coefficient $(k_A)$ vs. base concentration are curvilinear, as observed for similar reactions in other studies. These reactions are also catalyzed by piperidine, the plot of $k_A$ vs. piperidine concentration being linear. The reaction of 2,4-dinitrophenyl 4-nitrophenyl ether is weakly catalyzed by hydroxide ion, but no catalysis by piperidine has been detected. The effect of sodium hydroxide on the reaction of bis(2,4-dinitrophenyl) ether is very small and not considered to represent base catalysis. The partial rate coefficients $k_1$ and ratios $k_2/k_{-1}$, $k_3^P/k_{-1}$, and $k_3^{OH}/k_{-1}$ were calculated. The $k_1$ values give a reasonable Hammett plot with $\rho = 1.15$. Incidentally, our measurements furnished rate coefficients $(k_{OH})$ for the reaction of NaOH with the various substrates.

The occurrence or absence of base catalysis in reactions of primary and secondary amines with 1-substituted 2,4-dinitrobenzenes, as well as the efficiency of base catalysis (*i.e.*, whether a large or a small acceleration is brought about by a given catalyst) depend among other things on the leaving group ability or "nucleofugicity"[3] of the 1 substituent. Because this catalysis is associated with the second step of the intermediate complex mechanism (eq 1), rate accelerations by bases may be observed when $k_{-1} > (k_2 + \Sigma k_3^B[B])$, but not when $k_{-1} \ll (k_2 + \Sigma k_3^B \cdot [B])$. The first condition is generally fulfilled with poor (strongly or moderately basic) leaving groups X, the second with good (weakly basic) leaving groups. Incidentally, the occurrence or absence of base catalysis in a reaction series involving the same amine allows a crude classification of nucleofugicity in nucleophilic aromatic substitutions, if it is assumed that $k_{-1}$ is substantially independent of the leaving group. However, the ratios $k_2/k_{-1}$, which frequently can be determined experimentally, permit a more subtle ordering of such tendencies.



$$(1)$$

These statements concerning the relationship between the incidence or extent of base catalysis and the relative magnitudes of $k_{-1}$ and $(k_2 + \Sigma k_3^B[B])$ follow from qualitative consideration of the system of eq 1. Alternatively, these relationships emerge

(1) (a) Supported in part by a grant from the Petroleum Research Fund administered by the American Chemical Society. Grateful acknowledgment is made to the donors of this fund. (b) Based in part on the Dissertation of C. F. B., Eidgenössiche Technische Hochschule, Zürich, Switzerland, 1965.

(2) Address correspondence to either author at the University of California, Santa Cruz, Calif. 95060.

(3) J. Mathieu, A. Allais, and J. Valls, *Angew. Chem.*, **72**, 71 (1960).

from algebraic manipulation of eq 2, which is derived for this system on the basis of the steady-state approxi-

$$k_A = \frac{k_1(k_2 + \Sigma k_3{}^B[B])}{k_{-1} + k_2 + \Sigma k_3{}^B[B]} \qquad (2)$$

mation. In this equation, $k_A$ is the overall rate coefficient, in second-order units.

In order to determine the ratio $k_2/k_{-1}$ in an aqueous system, one must measure the dependence of the second-order rate coefficient on both the hydroxide ion and the amine concentration. In a previous study[4] and in complementary work by one of us,[5] $k_2/k_{-1}$ and $k_3{}^B/k_{-1}$ were evaluated or estimated for five different 1-substituted 2,4-dinitrobenzenes in 10% dioxane-90% water.

We wish now to report data for reactions of piperidine with substituted aryl ethers of 2,4-dinitrophenol in 60% dioxane-40% water.

## Experimental Section

**Materials.**—1,4-Dioxane and piperidine were purified as described earlier.[4] 2,4-Dinitrophenyl 4-nitrophenyl ether (mp 115-116°) and bis(2,4-dinitrophenyl) ether (mp 197.5-199°) had been prepared by Garst[6a] and were generously made available to us. 2,4-Dinitrophenyl 4-methoxyphenyl ether was prepared by refluxing for 2 hr a mixture prepared from 0.1 mol of 4-methoxyphenol and 0.1 mol of NaOH in 50 ml of water with 0.1 mol of 2,4-dinitrochlorobenzene in 50 ml of ethanol. The mixture was diluted with the twofold volume of water and filtered, and the precipitated product was washed and recrystallized five times from methanol; it had mp 110°.[6b] 2,4-Dinitrophenyl 3,4,5-trimethylphenyl ether was prepared by the same procedure from 3,4,5-trimethylphenol; it was recrystallized three times from ethanol and had mp 142°. The solvent was 60% dioxane-40% water (v/v).

**Rate Measurements.**—The same photometric procedure as described earlier[4] was used. In all cases, good pseudo-first-order kinetic plots were obtained. Rate coefficients are symbolized and were computed as follows: $k_\psi$, pseudo-first-order coefficient for the sum of the two reactions (piperidinolysis and hydrolysis) consuming the substrate, reckoned as $-2.30$ times the slope of the first-order plots; $k_A^*$, pseudo-first-order coefficient for formation of 2,4-dinitrophenylpiperidine, $k_A^* =$ (fractional yield of 2,4-dinitrophenylpiperidine) $\times k_\psi$; $k_A$, second-order coefficient for formation of 2,4-dinitrophenylpiperidine, $k_A = k_A^*/[C_5H_{10}\text{-}NH]$; $k_{OH}^*$, pseudo-first-order coefficient for formation of 2,4-dinitrophenol, $k_{OH}^* = k_\psi - k_A^*$; $k_{OH}$, second-order coefficient for formation of 2,4-dinitrophenol, $k_{OH} = k_{OH}^*/[NaOH]$.

Reference is also made to the following conceptual rate coefficients: $k_1$, $k_{-1}$, and $k_2$, coefficients for individual steps of the mechanism presented in eq 1; $k_3{}^B$, coefficient for transformation of the intermediate to product, as catalyzed by base B (see eq 1); $k_3{}^P$ for the case of base piperidine; $k_3{}^{OH}$ for the case of base hydroxide ion.

**Correction of Concentrations for the Piperidine–Piperidinium Ion Equilibrium.**—Contrary to the situation in 10% dioxane-90% water,[4] where the equilibrium reaction of piperidine with water was appreciable and had to be corrected for, this interaction is negligible in the present medium.[7] Thus, all concentrations of piperidine and hydroxide ion indicated are stoichiometric concentrations.
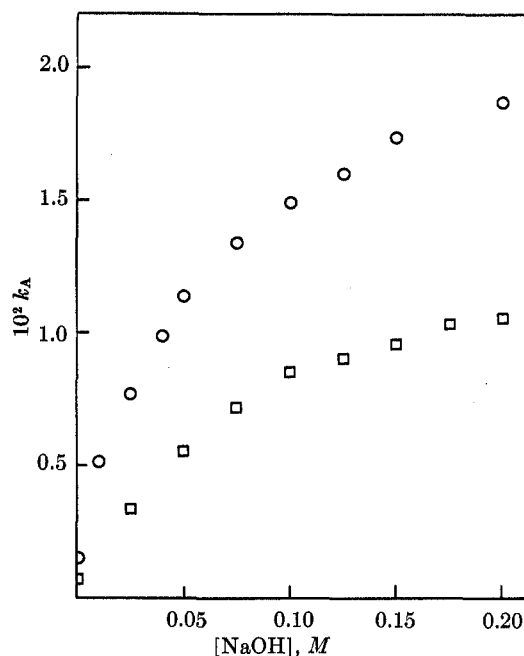


Figure 1.—Reactions of 2,4-dinitrophenyl 4-methoxyphenyl ether (O) and of 2,4-dinitrophenyl 3,4,5-trimethylphenyl ether (□) with piperidine, catalyzed by NaOH; data from Table I, parts C and D.

## Results

Our kinetic determinations are presented in Tables I and II. Table I summarizes data concerning catalysis by the hydroxide ion of the piperidinodearyloxylation reactions and also data on reactions of the various aryl ethers with the hydroxide ion; Table II presents data on piperidine catalysis of the piperidinodearyloxylations. All kinetic determinations were done at a constant ionic strength; NaCl was used as compensating electrolyte. The various symbols in the tables are defined in the Experimental Section; we shall focus attention on $k_A$ and $k_{OH}$, the second-order coefficients for formation of 2,4-dinitrophenylpiperidine and 2,4-dinitrophenol, respectively.

**2,4-Dinitrophenyl 4-Methoxyphenyl Ether and 2,4-Dinitrophenyl 3,4,5-Trimethylphenyl Ether.**—The reactions of both these substrates with piperidine are rather strongly catalyzed by hydroxide ions, as is evident from Table I, parts C and D. In the case of the 4-methoxyphenyl ether, the rate in the presence of 0.2 $M$ NaOH is 12.5 times the rate in the absence of any NaOH; for the 3,4,5-trimethylphenyl ether, this factor is over 15. Furthermore, the character of the plots of $k_A$ vs. the hydroxide ion concentration (Figure 1) is similar to the one found in the reaction of piperidine with 2,4-dinitrophenyl phenyl ether[10] in the same solvent or for reactions of the same or other amines with related substrates in more aqueous media.[4,5,11,12]

From parts B and C in Table II, it is evident that both reactions are also catalyzed by piperidine, though less strongly than by the hydroxide ion. Plots of $k_A$ vs. piperidine concentration are virtually linear (Figure 2). Moreover, for reactions with 2,4-dinitrophenyl 4-methoxyphenyl ether and 3,4,5-trimethylphenyl ether, plots of log ($k_A - k_A{}^0$) vs. log [C_5H_{10}-

(4) J. F. Bunnett and C. F. Bernasconi, *J. Amer. Chem. Soc.*, **87**, 5209 (1965).

(5) C. F. Bernasconi, *J. Org. Chem.*, **32**, 2947 (1967).

(6) (a) R. H. Garst, Ph.D. Thesis, Brown University, 1964; *Dissertation Abstr.*, **25**, 4404 (1965); (b) R. W. Bost and F. Nicholson, *J. Amer. Chem. Soc.*, **57**, 2368 (1935).

(7) The p$K$ of ammonium ions does not change appreciably from its value in pure water to its value in 60% dioxane-40% water,[8] but the self-ionization constant of the solvent does.[9] The net effect is a reduction of the basicity constant of the amine by an estimated 3 pK units.

(8) R. A. Robinson and R. H. Stokes, "Electrolyte Solutions," Butterworth and Co. Ltd., London, 1959, p 542.

(9) H. S. Harned and L. D. Fallon, *J. Amer. Chem. Soc.*, **61**, 2374 (1939).

(10) J. F. Bunnett and R. H. Garst, *ibid.*, **87**, 3879 (1965).

(11) C. F. Bernasconi and P. Schmid, *J. Org. Chem.*, **32**, 2953 (1967).

(12) A. J. Kirby and W. P. Jencks, *J. Amer. Chem. Soc.*, **87**, 3217 (1965).

TABLE I

REACTIONS OF PIPERIDINE AND SODIUM HYDROXIDE WITH ETHERS OF 2,4-DINITROPHENOL
IN 60% DIOXANE–40% WATER AT 29.4°[a]

| [NaOH], M | $10^4 k_\psi$, sec$^{-1}$ | Yield, % | $10^4 k_A*$, sec$^{-1}$ | $10^2 k_A$, M$^{-1}$ sec$^{-1}$ | $10^5 k_{OH}*$, sec$^{-1}$ | $10^4 k_{OH}$, M$^{-1}$ sec$^{-1}$ |
|---|---|---|---|---|---|---|
| A. Reactions of Bis(2,4-dinitrophenyl) Ether; [C₅H₁₀NH] = 2.50 × 10⁻³ M[b] | | | | | | |
| 0 | 27.3 | 99 | 27.0 | 108 | | |
| 0 | 52.0[c] | 100[c] | 52.0[c] | 104 | | |
| 0.02 | 36.6 | 84.7 | 31.0 | 124 | 56.0 | 280 |
| 0.05 | 41.6 | 74.9 | 31.2 | 125 | 104 | 208 |
| 0.10 | 54.9 | 62.4 | 34.2 | 137 | 207 | 207 |
| 0.10 | 90.3[c] | 75.3[c] | 68.1[c] | 136 | 222 | 222 |
| 0.20 | 81.5 | 47.5 | 38.5 | 154 | 430 | 215 |
| B. Reactions of 2,4-Dinitrophenyl 4-Nitrophenyl Ether; [C₅H₁₀NH] = 5.00 × 10⁻³ M[d] | | | | | | |
| 0 | 5.10 | 100 | 5.10 | 10.2 | | |
| 0.005 | 6.36 | 90.2 | 5.75 | 11.5 | | |
| 0.01 | 7.00 | 87.9 | 6.15 | 12.3 | 8.5 | 85 |
| 0.02 | 7.87 | 85.9 | 6.75 | 13.5 | 11.2 | 56 |
| 0.05 | 11.5 | 71.2 | 8.15 | 16.3 | 33.2 | 66 |
| 0.10 | 15.0 | 61.4 | 9.20 | 18.4 | 57.8 | 58 |
| 0.20 | 22.0 | 48.5 | 10.6 | 21.2 | 114 | 57 |
| C. Reactions of 2,4-Dinitrophenyl 4-Methoxyphenyl Ether; [C₅H₁₀NH] = 5.00 × 10⁻² M[e] | | | | | | |
| 0 | 0.745 | 100 | 0.745 | 0.149 | | |
| 0.01 | 2.63 | 98.2 | 2.58 | 0.517 | | |
| 0.025 | 3.97 | 97.6 | 3.86 | 0.712 | | |
| 0.04 | 5.14 | 96.3 | 4.94 | 0.988 | 1.99 | 5.0 |
| 0.05 | 6.00 | 95.2 | 5.72 | 1.14 | 2.84 | 5.7 |
| 0.075 | 7.21 | 93.0 | 6.71 | 1.34 | 5.00 | 6.7 |
| 0.10 | 8.17 | 91.2 | 7.45 | 1.49 | 7.16 | 7.2 |
| 0.125 | 8.95 | 89.3 | 8.00 | 1.60 | 9.50 | 7.6 |
| 0.15 | 9.98 | 87.2 | 8.70 | 1.74 | 12.8 | 8.5 |
| 0.20 | 11.15 | 84.0 | 9.38 | 1.87 | 17.8 | 8.9 |
| D. Reactions of 2,4-Dinitrophenyl 3,4,5-Trimethylphenyl Ether; [C₅H₁₀NH] = 5.00 × 10⁻² M[f] | | | | | | |
| 0 | 0.347 | 100 | 0.347 | 0.069 | | |
| 0.025 | 1.76 | 94.5 | 1.66 | 0.333 | 0.965 | 3.9 |
| 0.05 | 2.90 | 95.4 | 2.77 | 0.553 | 1.33 | 2.7 |
| 0.075 | 3.80 | 94.4 | 3.58 | 0.717 | 2.17 | 3.0 |
| 0.10 | 4.48 | 95.1 | 4.26 | 0.854 | 2.17 | 2.2 |
| 0.125 | 4.81 | 93.4 | 4.50 | 0.900 | 3.08 | 2.5 |
| 0.150 | 5.19 | 91.6 | 4.76 | 0.953 | 4.34 | 2.9 |
| 0.175 | 5.68 | 90.6 | 5.15 | 1.03 | 5.33 | 3.0 |
| 0.20 | 5.79 | 91.2 | 5.26 | 1.05 | 5.33 | 2.7 |
| E. Reactions of 2,4-Dinitrophenyl 3,4,5-Trimethylphenyl Ether; [C₅H₁₀NH] = 5.00 × 10⁻² M,[f] with (C₂H₅)₄NOH instead of NaOH | | | | | | |
| 0.05[g] | 3.23 | 93.2 | 3.04 | 0.607 | 1.93 | 3.86 |
| 0.10[g] | 5.19 | 90.2 | 4.68 | 0.937 | 5.16 | 5.16 |
| 0.15[g] | 7.01 | 84.4 | 5.91 | 1.18 | 11.0 | 7.34 |
| 0.20[g] | 8.64 | 76.9 | 6.64 | 1.33 | 20.0 | 10.0 |

[a] Total electrolyte concentration maintained at 0.2 M by addition of sodium chloride as required. [b] [Substrate]₀ = 9.75 × 10⁻⁵ M. [c] [C₅H₁₀NH] = 5.0 × 10⁻³ M. [d] [Substrate]₀ = 2.5 × 10⁻⁴ M. [e] [Substrate]₀ = 2.40 × 10⁻⁴ M. [f] [Substrate]₀ = 2.54 × 10⁻⁴ M. [g] Concentrations refer to (C₂H₅)₄NOH.

NH] (not shown) are linear with slopes of 0.95 and 0.96, respectively; $k_A^0$ represents the extrapolated $k_A$ value at [C₅H₁₀NH] = 0. Thus, as previously demonstrated for the reaction of piperidine with 2,4-dinitrophenyl phenyl ether in 60% dioxane,[10] these reactions are general base catalyzed by piperidine. Catalysis by hydroxide ion from the basic dissociation of piperidine is minimal.

For the reaction of the 4-methoxyphenyl ether with hydroxide ion, $k_{OH}$ shows a steady trend to higher values with increasing NaOH concentration. There is, however, a considerable uncertainty in $k_{OH}$ when the yields of 2,4-dinitrophenylpiperidine are high, because $k_{OH}$ then represents a small difference between two large numbers. In fact, if only runs with yields of less than 90% are considered, the variation is small and probably within experimental error. The average

value of $k_{OH}$ among the last three is 8.3 × 10⁻⁴ M⁻¹ sec⁻¹.

In the case of the 3,4,5-trimethylphenyl ether, the variation in the $k_{OH}$ values is random; the average among the runs where the yield was less than 95% is 2.70 × 10⁻⁴ M⁻¹ sec⁻¹.

**2,4-Dinitrophenyl 4-Nitrophenyl Ether.**—Table I, part B, shows that NaOH has a catalytic effect on the piperidinodearyloxylation, though a much less pronounced one than with the 4-methoxy- or 3,4,5-trimethylphenyl ether; 0.2 M NaOH accelerates the reaction about twofold. The plot of $k_A$ vs. the hydroxide ion concentration (Figure 3) again shows curvilinear response.

Values of $k_A$ as a function of piperidine concentration are recorded in Table II, part A. Over an extended
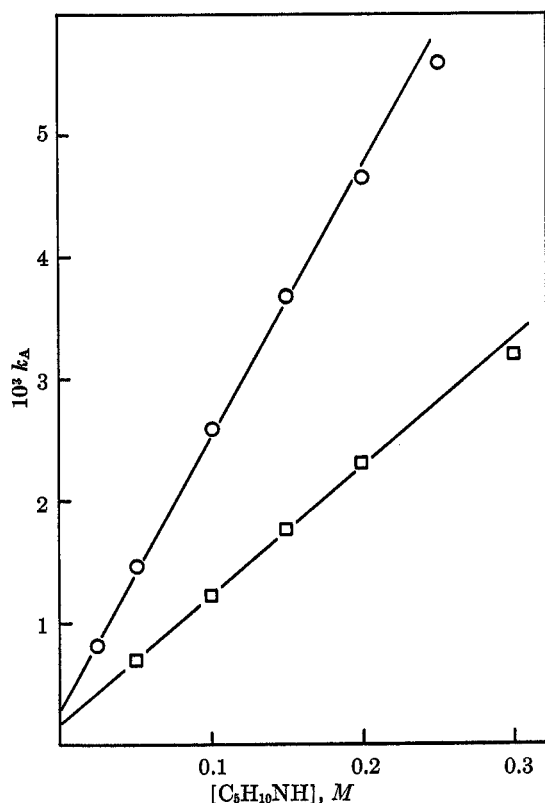
Figure 2.—Reactions of 2,4-dinitrophenyl 4-methoxyphenyl ether (O) and of 2,4-dinitrophenyl 3,4,5-trimethylphenyl ether (□) with piperidine, catalyzed by piperidine; data from Table II, parts A and B.



Figure 3.—Reaction of 2,4-dinitrophenyl 4-nitrophenyl ether with piperidine, catalyzed by NaOH; data from Table I, part B.

### TABLE II

REACTIONS OF PIPERIDINE WITH ETHERS OF
2,4-DINITROPHENOL IN 60% DIOXANE–40% WATER AT 29.4°[a]

| [$C_5H_{10}NH$], $M$ | $10^4 k_A*$, sec$^{-1}$ | $10^3 k_A$, $M^{-1}$ sec$^{-1}$ |
|---|---|---|
| **A.** Reaction of 2,4-Dinitrophenyl 4-Nitrophenyl Ether[b] | | |
| 0.001 | 1.04 | 104 |
| 0.005 | 5.10 | 102 |
| 0.01 | 10.8 | 108 |
| 0.02 | 21.4 | 107 |
| 0.05 | 54.5 | 109 |
| 0.10 | 101 | 101 |
| 0.20 | 192[c] | 96[c] |
| **B.** Reaction of 2,4-Dinitrophenyl 4-Methoxyphenyl Ether[d] | | |
| 0.025 | 0.204 | 0.815 |
| 0.05 | 0.730 | 1.46 |
| 0.10 | 2.60 | 2.60 |
| 0.15 | 5.52 | 3.69 |
| 0.20 | 9.33 | 4.66 |
| 0.25 | 14.01 | 5.60 |
| **C.** Reaction of 2,4-Dinitrophenyl 3,4,5-Trimethylphenyl Ether[e] | | |
| 0.05 | 0.347 | 0.69 |
| 0.10 | 1.23 | 1.23 |
| 0.15 | 2.66 | 1.77 |
| 0.20 | 4.62 | 2.31 |
| 0.30 | 9.60 | 3.20 |

[a] Total electrolyte concentration maintained at 0.2 $M$ by addition of sodium chloride as required. [b] [Substrate]$_0$ = 2.46 × $10^{-4}$ $M$. [c] Value is somewhat uncertain because rate was very fast for method of determination. [d] [Substrate]$_0$ = 2.41 × $10^{-4}$ $M$. [e] [Substrate]$_0$ = 2.54 × $10^{-4}$ $M$.

range of concentrations, no acceleration by piperidine is indicated.

The average value of $k_{OH}$ among the runs with yield of less than 90% is 5.9 × $10^{-3}$ $M^{-1}$ sec$^{-1}$.
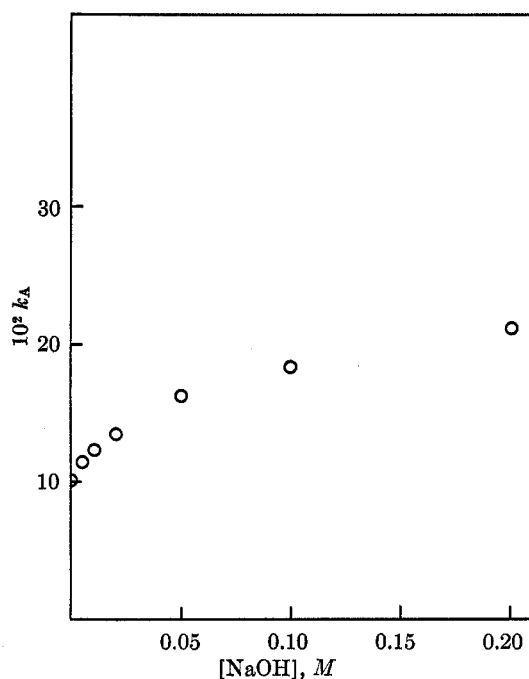
**Bis(2,4-Dinitrophenyl) Ether.**—As seen in Table I, part A, there is a small acceleration brought about by NaOH, which amounts to about 40% at 0.2 $M$ NaOH compared with runs in the absence of base. The effect of varying the piperidine concentration was investigated only in two runs at low concentrations (Table I, part A); no piperidine catalysis is indicated by those runs; and none would be expected even at higher piperidine concentrations, in analogy to the 2,4-dinitrophenyl 4-nitrophenyl ether reaction.

The average of $k_{OH}$ among the four runs with lowest yields is 2.13 × $10^{-2}$ $M^{-1}$ sec$^{-1}$.

**Tetraethylammonium Hydroxide Catalysis.**—For the reaction of piperidine with 2,4-dinitrophenyl 3,4,5-trimethylphenyl ether, the influence of $(C_2H_5)_4NOH$ as a basic catalyst was also studied. From data in Table I, parts D and E, it appears that $(C_2H_5)_4NOH$ is a slightly better catalyst than NaOH, presumably because ion pairing is less pronounced than with NaOH.[13]

The $k_{OH}$ values are also higher with $(C_2H_5)_4NOH$; furthermore, they show a considerable increase with increasing base concentration. This increase may be due to a specific salt effect; NaCl was probably a poor choice as compensating electrolyte for these runs.

### Discussion

Using standard procedures described elsewhere,[4,5,10] $k_1$ and the ratios $k_2/k_1$, $k_3^P/k_{-1}$, $k_3^{OH}/k_{-1}$, and $k_3^{OH}/k_2$ were calculated where this was feasible. They are summarized in Table III, which includes data for 2,4-dinitrophenyl phenyl ether determined by Bunnett and Garst[10] as well as data in 10% dioxane–90% water determined earlier;[4,5] also included are $k_{OH}$ values for reactions of the aryl ethers with hydroxide ion.

(13) G. R. Nash and C. B. Monk, *Trans. Faraday Soc.*, **54**, 1650 (1958).

TABLE III

REACTIONS OF 2,4-DINITROPHENYL ARYL ETHERS WITH PIPERIDINE AND SODIUM HYDROXIDE

| Compd | Leaving group | (pK[b]) | $k_1$, $M^{-1}$ sec$^{-1}$ | $k_2/k_{-1}$ | Dissection of rate coefficients[a] | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $k_3^P/k_{-1}$, $M^{-1}$ | $k_3^{OH}/k_{-1}$, $M^{-1}$ | $k_3^{OH}/k_2$, $M^{-1}$ | $10^4 k_{OH}$, $M^{-1}$ sec$^{-1}$ |
| 1 | 2,4-Dinitrophenoxy | (4.09) | 1.62[c] (0.80)[c] | | | | | 213 (58) |
| 2 | 4-Nitrophenoxy | (7.16) | 0.265 (0.15) | 0.60[d] | | 18.9[d] | 31.5[d] | 59.3 (14.4) |
| 3 | Phenoxy[e] | (9.99) | 0.035 (0.031) | 0.0121 (0.069) | 0.73 (7.86) | 12.2 (121) | 984 (1750) | 7.15 (4.6) |
| 4 | 4-Methoxyphenoxy | (10.20) | 0.0246 | 0.0112 | 0.81 | 15.8 | 1170 | 8.34 |
| 5 | 3,4,5-Trimethylphenoxy | (ca. 10.40)[f] | 0.0143 | 0.0114 | 0.73 | 13.5 | 1056 | 2.70 |

[a] Rate coefficients in parentheses refer to reactions in 10% dioxane–90% water, taken from ref 3 and 4; all the others are for 60% dioxane–40% water. [b] pK of respective phenols, from G. Kortüm, W. Vogel, and K. Andrussow, "Dissociation Constants of Organic Acids in Aqueous Solution," Butterworth and Co. Ltd., London, 1961. [c] Not statistically corrected. [d] Values uncertain; see Discussion Estimates for these coefficients in 10% dioxane–90% water are $k_2/k_{-1} \cong 2$, $k_3^{OH}/k_{-1} \cong 50$, and $k_3^{OH}/k_2 \cong 25$; they are believed to be even less reliable than in 60% dioxane–40% water. [e] From data of ref 3 and 7. [f] Estimated from data for phenol, 4-methylphenol, and 3,5-dimethylphenol.
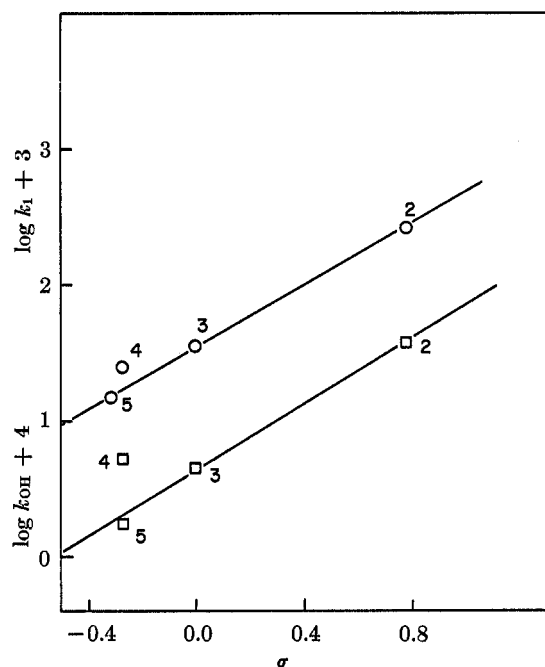


Figure 4.—Hammett plots of $k_1$ of the piperidinodearyloxylation (O) and of $k_{OH}$ (□) for hydroxydearyloxylation of the various 2,4-dinitrophenyl aryl ethers. The numbers are the same as in Table III. $\rho$ for $k_1$ is 1.15; $\rho$ for $k_{OH}$ is 1.35.

Owing to the smallness of the hydroxide ion catalysis in the case of bis(2,4-dinitrophenyl) ether, the data were judged appropriate only for calculation of $k_1$. The reaction of 2,4-dinitrophenyl 4-nitrophenyl ether constitutes a borderline case; values for $k_3^{OH}/k_{-1}$, $k_2/k_{-1}$, and $k_3^{OH}/k_2$ are included in the table, but it is realized that they may be rather uncertain. The data for the 4-methoxyphenyl and the 3,4,5-trimethylphenyl ether, on the other hand, were very suitable for these calculations; the ratios $k_3^{OH}/k_{-1}$, $k_3^P/k_{-1}$, $k_2/k_{-1}$, and $k_3^{OH}/k_2$ are considered reliable for these two reactions, as are those for the simple phenyl ether.

$k_1$ and $k_{OH}$.—The $k_1$ value for the nucleophilic attack of piperidine on the 2,4-dinitrophenyl aryl ethers increases when the group displaced becomes more electron-withdrawing. Figure 4 shows that the Hammett[14] $\sigma\rho$ relationship is reasonably well fulfilled, though the 4-methoxyphenyl ether does not quite fit in with the others.[15] The line as drawn in Figure 4 yields $\rho = 1.15$. This is about one-quarter of the magnitude

of $\rho$ values concerning variation of substituents in the aromatic ring undergoing nucleophilic attack,[16] and certainly fulfills qualitative expectations on the basis of the mechanism.

When the site of substituent change is even further removed from the reaction center, as for substituted arylsulfonyl esters of 2,4-dinitrophenol, $\rho$ becomes still smaller, as seen in the reaction with aniline in 60% dioxane–40% water ($\rho = 0.34$).[17]

Similar remarks pertain to $k_{OH}$, which is considered[4] to represent the rate of nucleophilic attack by the hydroxide ion. The line in Figure 4 gives $\rho = 1.35$, which is somewhat higher than $\rho = 0.97$ reported by Russian workers[18] for the same reaction in 50% dioxane–50% water; the very similar reaction of methoxide ion with 2,4-dinitrophenyl aryl ethers in methanol is reported to have $\rho = 1.45$.[19]

$k_2/k_{-1}$ Ratios.—The ratio of $k_2/k_{-1}$ is about equal for the three less reactive ethers 3, 4, and 5, and considerably higher for the 4-nitrophenyl ether 2. If $k_{-1}$, which pertains to the expulsion of piperidine from the intermediate, is assumed to be only slightly dependent on the leaving group, then $k_2/k_{-1}$ is an approximate measure for the leaving group capability or nucleofugicity of the various aryl oxides. For a series of leaving groups of the same type, as exemplified by our substituted aryl ethers, one expects a correlation between pK and nucleofugicity.[20] Inasmuch as the pK values for the three phenols 3, 4, and 5 are only slightly different from each other, it is reasonable that the $k_2/k_{-1}$ ratios are about the same for these three substrates. 4-Nitrophenol is ~3 pK units more acidic and consequently $k_2/k_{-1}$ is much larger. For the 2,4-dinitrophenoxy leaving group, the pK is again about 3 units lower; consequently, $k_2$ should greatly exceed $k_{-1}$, and thus $k_1$ should be solely rate determining. We are reluctant to interpret the slight acceleration of this reaction by NaOH as base catalysis.[21]

$k_3^{OH}/k_{-1}$, $k_3^P/k_{-1}$, and $k_3^{OH}/k_2$.—As shown in Table III, each of these ratios has nearly the same value for the three less reactive ethers 3, 4, and 5 but a very dif-

(14) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940.

(15) For the 3,4,5-trimethylphenyl group, $\sigma = 2\sigma_m + \sigma_p$ has been assumed.

(16) See, e.g., E. Berliner and L. C. Monack, *J. Amer. Chem. Soc.*, **74**, 1574 (1952); W. Greizerstein, R. A. Bonelli, and J. A. Brieux, *ibid.*, **84**, 1026 (1962).

(17) R. V. Visgert, S. M. Kononenko, and I. M. Ozdrovskaya, *Zh. Org. Khim.*, **1**, 264 (1964).

(18) A. V. Ivanov, A. J. Kaminski, S. S. Gitis, and Z. A. Kosina, *Reaktsii Sposobnost Organ. Soedin.*, **4**, 301 (1967).

(19) Y. Ogata and M. Okano, *J. Amer. Chem. Soc.*, **71**, 3212 (1949).

(20) See, e.g., E. R. Thornton, "Solvolysis Mechanisms," The Ronald Press Co., New York, N. Y., 1964, p 163; S. L. Johnson, *Advan. Phys. Org. Chem.*, **5**, 294 (1967).

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

ferent value for the 4-nitrophenyl ether; in fact, $k_3^P/k_{-1}$ is too small to be detected in the latter case and may well be zero. This pattern again suggests that these ratios mainly depend on the p$K$ of the respective phenols. The absence of piperidine catalysis in the reaction of the 4-nitrophenyl ether suggests that this reaction is only lyate ion catalyzed; absence of a general base catalysis term was observed previously with the same reaction in 10% dioxane–90% water[22] and in the reaction of 2,4-dinitrophenyl phenyl sulfide with piperidine in the same solvent.[5] The possible significance of these observations, along with other aspects of base catalysis in nucleophilic aromatic substitution reactions, will be dealt with elsewhere.[23]

**Solvent Dependence.**—For the reaction of piperidine with **1**, **2**, and **3**, a complete set of data in the two solvents 60% dioxane–40% water and 10% dioxane–90% water is now available; the numbers in parentheses in Table III refer to the latter solvent. The $k_1$ value for the unsubstituted phenyl ether is about the same in both solvents and at most a factor of 2 larger in the less aqueous medium for **1** and **2**. In view of the presumed dipolar character of the transition state, one might have anticipated a reduction in $k_1$ for the less aqueous solvent, rather than an increase. Ground-state solvation of the nucleophile probably accounts for the lower reactivity in the more aqueous solvent.

The solvent effect on $k_{OH}$ is consistent with the classical theory,[24] but might also be attributed to electrophilic solvation of hydroxide ion in the ground state.

The solvent dependence of $k_2/k_{-1}$ has been discussed previously.[4] Our conclusion was that, inasmuch as $k_{-1}$ refers to a conversion of a zwitterion into neutral molecules, it should increase when solvent polarity decreases,[24] and thus, $k_2/k_{-1}$ is expected to decrease unless a compensating effect of larger magnitude operates on $k_2$. This expectation is borne out by the results on the reaction of the 2,4-dinitrophenyl phenyl ether. An *a priori* prediction of the solvent effect on $k_2$, $k_3^P$, and $k_3^{OH}$ is rather difficult because of the complexity of these steps;[4,5,23] changes in the basicity of the catalyst and of the leaving group upon changing the solvent are considered to be as important as mere charge considerations. At this point, we do not feel that the drawing of conclusions from solvent dependence of $k_3^P/k_{-1}$ and $k_3^{OH}/k_{-1}$ is warranted.

(22) C. F. Bernasconi, unpublished observations.

(23) C. F. Bernasconi, manuscript in preparation.

(24) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, p 345.

**The Mechanism of Base Catalysis.**—In an earlier paper,[10] it was pointed out that steady-state kinetic data, such as obtained in the present study, are compatible with several mechanisms for the base-catalyzed step. One possibility, which we have favored in recent discussions,[4,10] is that the zwitterionic intermediate of eq 1 is in mobile acid–base equilibrium with its conjugate base, and that leaving-group expulsion from the latter is general acid catalyzed by the conjugate acid (BH) of the catalyzing base (B), as shown in eq 3. It is easily shown that the rate expression
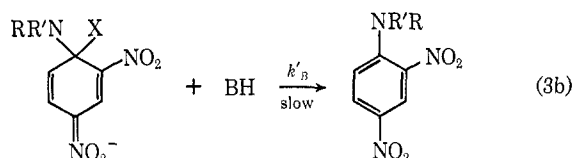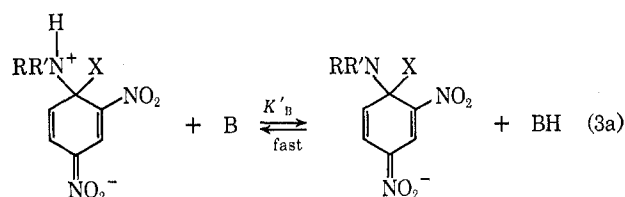


appropriate for this mechanism is that of eq 4. This

$$k_A = \frac{k_1(k_2 + \Sigma k_B'K_B[B])}{k_{-1} + k_2 + \Sigma k_B'K_B'[B])} \qquad (4)$$

is the same as eq 2, except that each $k_3^B$ in eq 2 is replaced by $k'_B K'_B$ in eq 4.

Recent experiments[25,26] concerning two rather different systems indicate that equilibria of the type of eq 3a lie predominantly on the right when the base is hydroxide ion or an aliphatic amine. Conceivable alternative interpretations of the base catalysis (other than that of eq 3) are difficult or impossible to reconcile with these recent observations. The mechanism of eq 3 is therefore strongly indicated.

For purposes of uniformity of notation with earlier studies, we have, however, continued to use the symbolism of eq 2 in treating the present data.

**Registry No.**—Piperidine, 110-89-4; bis(2,4-dinitrophenyl) ether, 2217-56-3; 2,4-dinitrophenyl 4-nitrophenyl ether, 2363-36-2; 2,4-dinitrophenyl 4-methoxyphenyl ether, 2363-27-1; 2,4-dinitrophenyl 3,4,5-trimethylphenyl ether, 22158-21-0.

(25) C. F. Bernasconi, *J. Amer. Chem. Soc.*, in press.

(26) J. F. Bunnett and J. Orvik, unpublished observations.