1-Ethyl-4-carbomethoxypyridinyl radical (Py·) was prepared as described previously.[1a,6] Solutions of the radical in acetonitrile were stored in break-seal tubes in the freezer. Solutions of the radical in other solvents were prepared by removal of the acetonitrile and addition of purified, degassed solvent.

Rate Measurements. The apparatus used for studies of the reaction of 4-substituted benzyl chlorides with Py· (at concentrations greater than 10^{-3} *M*) was similar to that previously used[1c] except that all-glass connections replaced the stopcock. For reactions with concentrations of radical below 10^{-3} *M*, the apparatus shown in Figure 1 was used. After cleaning and flaming, a weighed amount of 4-nitrobenzyl chloride in a glass ampoule was put into F, the end sealed off, and the halide sublimed into the U tube after evacuation through J. After sealing at C_1, then C_3, the halide was sublimed into A and C_2 sealed off.

The apparatus, with the free radical ampoule (as shown in Figure 1) was connected to the pump through H and baked under vacuum. The free radical solution was allowed to run into D and after sealing C_6 and then C_4, the reaction vessel was rinsed with free radical solution and then rinsed with the solvent distilled from the free radical. A dilute solution ($\sim 10^{-5}$ *M*) of free radical is obtained by distillation from D to B. After having the desired volume of the solution, D was sealed off at C_5. (In some cases, D was another break-seal ampoule to retain the unused portion of the free radical.) Preliminary optical spectra were taken to find the concentration ($\sim 10^{-5}$ *M*) and the purity of the free radical solution. The side-arm tube G was then used to bring the concentration of the free radical in the desired range.

Before reaction, free radical stability was checked for 30–120 min; if any absorption changes were noted, the sample was rejected. The break-seal of the tube A was broken and the solution shaken without mixing, then checked for 15–30 min to ensure the absence of leaks in A.

The reactants were then mixed and the decrease in optical density with time was followed by scanning the near-ultraviolet and ultraviolet spectrum of the free radical. Reactions were followed at 3950 or at 6300 Å, either with scans or at a single wavelength.

Another optical cell was attached to the compartment A for CH_3CN and DMF to facilitate the start of recording.

Rate measurements at elevated temperature were generally carried out in a sealed Pyrex square cell to prevent distillation of the solvent.

The concentrations of the halides were determined by glc or titration. The concentration of 4-nitrobenzyl chloride was determined from the weight of the amount introduced and from the total volume of the solution. Quantitative sublimation was checked spectroscopically. The concentration of benzyl bromide was determined spectroscopically from standards at 2750 Å or at λ_{max} 2267 Å (ϵ 8200).

The extinction coefficients of the free radical in the near-uv region in the solvents acetonitrile and DME were determined by titration against methyl viologen dichloride and measurement of the concentration of methyl viologen cation radical (λ_{max} 6050, ϵ_{max} 10,060).[1b]

Acknowledgment. Grateful acknowledgment is made for support from the National Institutes of Health, the Army Research Office (Durham), the Petroleum Research Fund (PRF-3695A1), Edgewood Arsenal, and the National Science Foundation.

Stable Free Radicals. VI. The Reaction between 1-Ethyl-4-carbomethoxypyridinyl Radical and 4-Nitrobenzyl Halides[1]

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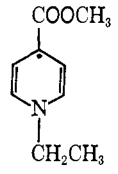
Abstract: Reaction rates for the stable free radical, 1-ethyl-4-carbomethoxypyridinyl (Py·) (**1**), with 4-nitrobenzyl fluoride, chloride, and bromide are extremely sensitive to solvent polarity (criterion: *Z* values). The constant for the chloride increases from 1.62 M^{-1} sec^{-1} in 2-MTHF (E_a = 6 kcal/mol) to 24,000 M^{-1} sec^{-1} in CH_3CN, results compatible only with an electron-transfer mechanism. Polarographic reduction potentials are reported for benzyl chloride (−2.20 V), benzyl bromide (−1.67 V), 4-nitrotoluene (−1.505 V), 4-nitrobenzyl fluoride (−1.40 V), 4-nitrobenzyl chloride (−1.16 V), and 4-nitrobenzyl bromide (−0.95 V) [reference $Ag^0/AgClO_4$ in CH_3CN]. Use of the rate and polarographic data along with some information on nitrobenzyl halide radical anion intermediates leads to a four-step mechanism for the reactions of Py· with 4-nitrobenzyl halides: (1) relatively fast electron transfer, (2) dissociation of the initial pyridinium 4-nitrobenzyl halide radical anion pair, (3) decomposition of the 4-nitrobenzyl halide radical anion to halide ion and 4-nitrobenzyl radical, and (4) rapid reaction of Py· and 4-nitrobenzyl radical. Our analysis suggests that the rate-limiting steps in CH_3CN are not the same for the three halides: bromide, step 1; chloride, step 2; and fluoride, step 3.

The stable pyridinyl radical, 1-ethyl-4-carbomethoxypyridinyl (**1**), reacts with 4-nitrobenzyl chloride far more rapidly than might have been anticipated on the basis of the rate constants found for a number of substituted benzyl chlorides.[4] The anomalous rate indicated that the mechanism of the reaction was different from the atom-transfer process found for the other benzyl chlorides. The nature of 4-nitrobenzyl



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[1] The previous article in this series is M. Mohammad and E. M. Kosower, *J. Amer. Chem. Soc.*, **93**, 2709 (1971).

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[4] A preliminary report has been published: E. M. Kosower and M. Mohammad, *J. Amer. Chem. Soc.*, **90**, 3271 (1968).

Table I. Rate Constants for the Reaction of 1-Ethyl-4-carbomethoxypyridinyl Radical with 4-Nitrobenzyl Fluoride at 25°

4-Nitrobenzyl fluoride concn, M^a	Radical concn, M^b	Solvent (Z value)^c	k_2, M^{-1} sec^{-1}
2.73×10^{-2}	7.1×10^{-3}	Ethanol (79.6)	4.8
6.30×10^{-3}	1.12×10^{-2}	2-Propanol (76.1)	0.31
7.5×10^{-4}	2.7×10^{-3}	2-Propanol (76.1)	0.3
1.1×10^{-3}	2.18×10^{-3}	CH_3CN (71.3)	1.5×10^{-2}
1.8×10^{-4}	3.5×10^{-4}	CH_3CN (71.3)	2.0×10^{-2}

[a] Concentration based on the amount weighed and the total volume (at 25°) of the reaction solution. [b] Concentration determined from the optical absorption at the maximum (~3950 or near 6300 Å) and the absorption coefficient as described in the text. [c] Z values for ethanol and 2-propanol taken from Kosower, ref 7.

Table II. Rate Constants for the Reaction of 1-Ethyl-4-carbomethoxypyridinyl Radical with 4-Nitrobenzyl Chloride and Bromide at 25°

4-Nitrobenzyl chloride (bromide) concn, M^a	Radical concn, M^b	Solvent^c (Z value)^d	k_2, M^{-1} sec^{-1}
5.4×10^{-6}	1.02×10^{-5}	CH_3CN (71.3)	2.4×10^{4}
7.50×10^{-6}	8.3×10^{-6}	DMF^e (68.4)	1.2×10^{4}
1.02×10^{-5}	2.08×10^{-5}	CH_3COCH_3 (65.5)	4.50×10^{2}
1.05×10^{-4}	2.50×10^{-4}	CH_2Cl_2 (64.7)	75
2.70×10^{-4}	2.14×10^{-5}	DME^f (59.1)	8.3
7.21×10^{-4}	2.14×10^{-5}	MTHF^g (55.3)	1.62
8.5×10^{-6} (Br)	1.48×10^{-5}	DME^f (59.1)	1.9×10^{4}
1.1×10^{-5} (Br)	2.28×10^{-5}	MTHF^g (55.3)	2.0×10^{3}

[a] See footnote *a*, Table I. [b] See footnote *b*, Table I. [c] All solvents were rigorously purified. [d] All values were based on new determinations with extrapolation to infinite dilution, as described in the present paper. [e] Dimethylformamide. [f] 1,2-Dimethoxyethane. [g] 2-Methyltetrahydrofuran.

chloride (strong electron-withdrawing substituent) as well as previous reports on the chemical behavior of 4-nitrobenzyl chloride[5] suggested electron-transfer as an elementary step in the reaction of the chloride with **1**.

We have therefore examined the effect of solvent on the rates of reaction of several 4-nitrobenzyl halides with **1**, and have measured the one-electron reduction potentials for a variety of benzyl halide derivatives.[6]

Rate constants for the reaction of **1** with 4-nitrobenzyl fluoride in ethanol, 2-propanol, and acetonitrile are listed in Table I. The fluoride reacts with **1** at a rate about 10^{-6} of that for the chloride in acetonitrile. Using the Z value as a criterion of solvent polarity,[7] the data in Table I show that the sensitivity of the rate of reaction of 4-nitrobenzyl fluoride with the pyridinyl radical **1** is high.

Rate constants for the reaction of **1** with 4-nitrobenzyl chloride are listed in Table II for solvents ranging in polarity from 2-methyltetrahydrofuran (Z 55.3) to acetonitrile (Z 71.3). Over this range, the rate constant changes by more than 10^4.

The reaction of the pyridinyl radical **1** with 4-nitrobenzyl bromide is about 10^3 faster than that of **1** with the chloride, and could be measured only in the low polarity solvents, 2-MTHF (Z 55.3) and 1,2-dimethoxyethane (Z 59.2). Nevertheless, the rate constant (Table II) rises by a factor of 9.5 over this range, providing strong evidence that the solvent sensitivity of the reaction of **1** with the bromide is comparable to the solvent sensitivities found for the reaction of **1** with chloride and fluoride.

The solvent sensitivities of the rate constants for the reaction of **1** with 4-nitrobenzyl fluoride, chloride, and bromide are summarized in Table III. The sensitivities are expressed in terms of the transition state free energy differences corresponding to a rate change on replacing one solvent with another divided by one-half the Z value difference for the same pair of solvents. The reason for this manner of presenting the results will be explained in the Discussion.

The effect of temperature on the reaction of **1** with 4-nitrobenzyl chloride was examined in 2-MTHF (Table IV). The plot of log k against $1/T$ is shown in Figure 1; an activation energy of 6.0 kcal/mol was found.

Table III. Pyridinyl Radical–4-Nitrobenzyl Halide Reactions. Solvent Effect on Transition State Free Energies^a

4-Nitrobenzyl halide	$\Delta\Delta F^*$	$0.5\Delta Z$	$\dfrac{\Delta\Delta F^*}{0.5\Delta Z}$
Fluoride	3.42	4.15	0.822
Chloride	4.72	6.05	0.781
Bromide	1.33^b	1.90	0.700^c

[a] Rate data may be found in Tables I and II. [b] Rapidity of the reaction between **1** and the bromide permitted only a small range of solvent polarity to be examined, and these solvents were the least polar. [c] Probably too low, see footnote *b*.

Table IV. The Effect of Temperature on the Rate Constant for the Reaction of 1-Ethyl-4-carbomethoxypyridinyl Radical with 4-Nitrobenzyl Chloride in 2-Methyltetrahydrofuran

4-Nitrobenzyl chloride concn, M	Radical concn, M	Temp, °C	k_2,^{a} M^{-1} sec^{-1}
1.63×10^{-4}	1.94×10^{-4}	15	1.05
2.1×10^{-5}	3.4×10^{-5}	15	1.25
7.2×10^{-4}	2.14×10^{-5}	25	1.62
4.0×10^{-5}	5.5×10^{-5}	40	2.50
1.8×10^{-5}	3.6×10^{-5}	40	2.85

[a] $E_a^* = 6$ kcal/mol, $\Delta H_{25}^* = 5.4$ kcal/mol, $\Delta S_{25}^* = -39.2$ eu (standard state 1 M).

The rates were measured in the apparatus already described;[1] a plot of optical density *vs.* time for the reaction of **1** with 4-nitrobenzyl chloride in 1,2-dimethoxyethane (DME) is illustrated in Figure 2.

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[5] N. Kornblum, R. E. Michel, and R. C. Kerber, *J. Amer. Chem. Soc.*, **88**, 5660 (1966).

[6] Previous attempts to measure such potentials have been summarized by J. G. Lawless, D. E. Bartak, and M. D. Hawley, *ibid.*, **91**, 7121 (1969).

[7] E. M. Kosower, "An Introduction to Physical Organic Chemistry," Sect. 2.8, Wiley, New York, N. Y., 1968.

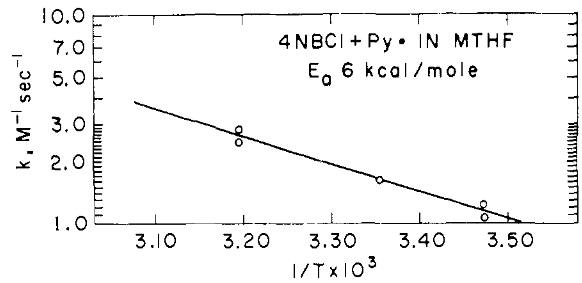

Figure 1. Logarithm of the rate constant of the reaction of 1-ethyl-4-carbomethoxypyridinyl (1) with 4-nitrobenzyl chloride in 2-methyltetrahydrofuran (MTHF) as a function of the reciprocal of the temperature. The activation energy derived from the plot is 6 kcal/mol.

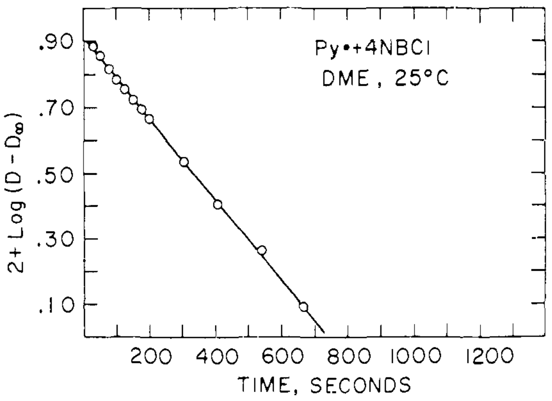

Figure 2. The logarithm of the optical density of 1-ethyl-4-carbomethoxypyridinyl (1) at 3940 Å as a function of time during the reaction of 1 with 4-nitrobenzyl chloride in 1,2-dimethoxyethane at 25°: $[\mathrm{Py}\cdot]_0 = 2.6 \times 10^{-5}$ *M*, $[\mathrm{4NBCl}] = 1.65 \times 10^{-4}$ *M*.

The second-order rate constants were calculated according to the rate equation (eq 1)

$$k = \frac{1}{t}\frac{1}{(2A_0 - B_0)} \ln \frac{B_0[(2A_0 - B_0) + B]}{2A_0B} \tag{1}$$

where $A = (\mathrm{RCl})$ and $B = (\mathrm{Py}\cdot)$.

The rate equation is based on a general scheme in which a radical reacts with a halide in a rate-limiting manner to give a product and another radical; the second radical reacts at a diffusion-controlled rate with another molecule of the pyridinyl radical to yield dihydropyridines (eq 2 and 3). The overall stoichi-

$$\mathrm{Py}\cdot + \mathrm{RX} \longrightarrow \mathrm{Py}^+\mathrm{X}^- + \mathrm{R}\cdot \tag{2}$$

$$\mathrm{R}\cdot + \mathrm{Py}\cdot \longrightarrow \mathrm{RPy} \tag{3}$$

ometry (two pyridinyl radicals per alkyl halide) has been confirmed by a careful measurement of the pyridinyl radical consumed for a known quantity of 4-nitrobenzyl chloride, and the expected quantity of 1-ethyl-4-carbomethoxypyridinium chloride is formed (eq 4).

$$2\mathrm{Py}\cdot + \mathrm{RX} \longrightarrow \mathrm{Py}^+\mathrm{X}^- + \mathrm{RPy} \tag{4}$$

Although air sensitivity precluded a detailed investigation of the other products of the pyridinyl radical–4-nitrobenzyl halide reactions, they appear to be dihydropyridines, like those found by Kosower and Waits in the reaction of 1-isopropyl-4-carbomethoxypyridinyl and bromochloromethane.[8]

Electrochemical Studies. In considering an electron-transfer process like that shown in eq 1, information concerning the partial reactions, pyridinyl radical → pyridinium ion (eq 5) and 4-nitrobenzyl chloride → corresponding radical anion (eq 6) is clearly of value.

$$\mathrm{Py}\cdot \longrightarrow \mathrm{Py}^+ + \mathrm{e}^- \tag{5}$$

$$\mathrm{e}^- + \mathrm{4NBCl} \longrightarrow \mathrm{4NBCl}\cdot^- \tag{6}$$

These one-electron processes can be summed up to produce the overall electron-transfer reaction. We may expect to establish several points with the aid of the electrochemical parameters for these reactions: (1) evaluation of the thermodynamics of the electron-transfer reaction, (2) comparison of the variation in rates of reaction with reduction potentials, (3) stability of the expected radical anions.

One-electron processes in organic solvents can be best studied by three-electrode polarographic and cyclic voltammetric techniques.[9] Lawless and coworkers[6] have applied these techniques to nitrobenzyl halides. We have independently made a number of measurements on compounds of interest to the present work, and our results are summarized in Table V.

Table V. Electrochemical Data for Benzyl Halides and Related Compounds

Compound	$E_{1/2}$[a]	$E_{3/4} - E_{1/2}$	$(\alpha)_n$[b]	Stability[c]
4-Nitrotoluene	−1.505	0.055	0.91	Stable
4-Nitrobenzyl fluoride	−1.40	≃0.065	0.90	Stable[g]
4-Nitrobenzyl chloride	−1.16	0.065	0.88	Unstable
4-Nitrobenzyl bromide	−0.95[d]			
Benzyl chloride	−2.20[e]	0.135		
Benzyl bromide	−1.67			
1-Ethyl-4-carbomethoxypyridinium ion	−1.095 −0.93[f]	0.060		Stable

[a] *Vs.* Ag/AgClO$_4$ in CH$_3$CN except as noted, in volts. [b] α is the transfer coefficient. [c] As indicated by the appearance of an appropriate reoxidation wave upon reversal at 33 mV/sec scan rate. Stable ≡ reoxidation wave height ≈ reduction wave. [d] An adsorption (?) wave is seen at −0.70 V. [e] Second wave at −2.74 V, with $E_{3/4} - E_{1/4}$ of 0.180 V. [f] *Vs.* sce. [g] The rate of decomposition of the 4-nitrobenzyl fluoride radical anion is about 0.014 sec^{-1} (M. Mohammad and E. M. Kosower, results to be published elsewhere).

It should be noted that our reference electrode is silver silver perchlorate in acetonitrile. A correction to the standard calomel electrode (sce) may be obtained by a comparison of $E_{1/2}$ for 1-ethyl-4-carbomethoxypyridinium iodide in our system with that previously reported *vs.* sce, with the difference amounting to +0.16–0.17 V.[10] A hanging mercury drop electrode was used for cyclic voltammetric studies so as to minimize surface effects.[11] At scans carried out at rates up to 36 V/sec, a reduction wave was observed for 4-nitrobenzyl chloride in the region expected on the basis of polarographic studies (near −1.15 V). An oxidation wave was observed at a position reasonable for that of the radical anion of 4-nitrobenzyl chloride (at −1.05

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(8) E. M. Kosower and H. P. Waits, Abstracts of the 150th Meeting of the American Chemical Society, Atlantic City, N. J., Sept 1965, p 109S, and manuscript in preparation.

(9) *Cf.* R. S. Nicholson and I. Shain, *Anal. Chem.*, **36**, 706 (1964), and W. M. Schwarz, Jr., Ph.D. Thesis, University of Wisconsin, 1961.

(10) W. M. Schwarz, E. M. Kosower, and I. Shain, *J. Amer. Chem. Soc.*, **83**, 3164 (1961). The apparatus and experimental procedure used in the present work were very similar to that used in ref 10.

(11) W. A. Underkofler and I. Shain, *Anal. Chem.*, **33**, 1966 (1961). See also K. J. Martin, Ph.D. Thesis, University of Wisconsin, 1960.

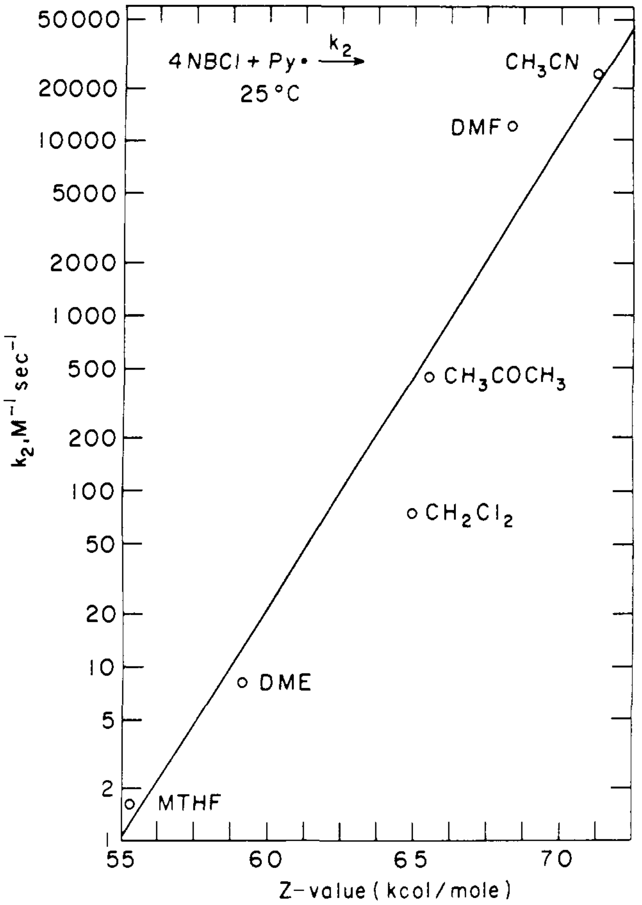

Figure 3. The logarithm of the rate constant for the reaction of 1-ethyl-4-carbomethoxypyridinyl (1) with 4-nitrobenzyl chloride in different solvents plotted against the Z value (position of the charge-transfer band for 1-ethyl-4-carbomethoxypyridinium iodide in kilocalories per mole) of these solvents.

V). The maximum current (for the fastest scan) was about one-half of the reduction wave, and a histogram (multiple cyclic scans at different scan rates stored on the CRT) indicated a relationship between the reduction and oxidation waves. The approximate half-life suggested by these experiments was 30 msec, corresponding to a rate constant for disappearance of $k = 20$ sec^{-1}. This value has been strikingly confirmed by single scan cyclic voltammograms in which the current due to the product of 4-nitrobenzyl chloride radical anion decomposition, 4,4′-dinitrodibenzyl ($E_{1/2} = -1.50$ V) falls in concentration as the scan rate is increased (estimated $k = 10$ sec^{-1}).[12a] Lawless[6] estimated a considerably higher rate constant from his calculated $E_{1/2}$, but the lower value is in agreement with the values suggested by others for the same radical anion.[12b-14]

Discussion

Solvent Effect. The fact that 4-nitrobenzyl chloride reacted with pyridinyl radical much more rapidly than expected on the basis of the rates of reaction of other substituted and unsubstituted benzyl chlorides implied that the mechanism of the reaction with the 4-nitro compound was different from that of the others. The most obvious possibility was that an electron-transfer step was either rate limiting or involved in an equilibrium preceding a rate-limiting step. Since the initial reactants were neutral species and an ion pair was produced on the reaction path, a substantial response to solvent change would be predicted for the rate constant for reaction 7.

$$Py + BNX \longrightarrow Py^+NBX\cdot^- \qquad (7)$$

initial state: modest change in energy on transfer from nonpolar to polar solvent

product or transition state or intermediate: substantial change in energy on transfer from nonpolar to polar solvent

How much change in the rate constant might be expected for a change in solvent? A quantitative evaluation is possible by the use of the solvent polarity parameters, the Z values.[7] The difference between Z values for two solvents can be divided equally into a stabilization energy for the ground state and a destabilization energy for the excited state.[15] Transfer energies for ion pairs from one solvent to another are simply the Z value difference divided by two. Although such transfer energies can only be approximate, they are directly obtained in an objective measurement and are defensible in terms of the microscopic basis for the Z value (the charge-transfer band for 1-ethyl-4-carbomethoxypyridinium iodide in kilocalories per mole).[7]

A plot of log k for the reaction of 4-nitrobenzyl chloride against Z reveals a remarkable parallelism over a wide range of solvent polarities (Figure 3). The high slope of the correlation is consistent only with the intervention of an ion pair as shown in eq 7. In fact, comparison of the changes in transition state energies ($\Delta\Delta F^*$) with $\Delta Z/2$ shows that the rate constant changes from 70% (4NBBr) to 80% (4NBF, NBCl) of the maximum expected from the Z value criterion. If the solvent sensitivity factor (listed in Table III) could be corrected for the interaction of the initial state with the solvent, the rate change would approach even more closely the maximum expected. *We can thus conclude, on the basis of the solvent effect, that the reaction of the pyridinyl radical with the 4-nitrobenzyl halides is an electron-transfer reaction.*

Mechanism. Although the magnitude of the solvent effect on the rate of reaction of pyridinyl radical and 4-nitrobenzyl halides proves that an electron-transfer step is present on the reaction pathway, it does not define the rate-limiting step of the reaction. We can consider at least two general mechanisms, both of which might be preceded by complex formation (eq 8).

$$Py\cdot + NBCl \rightleftharpoons Py\cdot, NBCl \qquad (8)$$

However, no charge-transfer band could be detected in the spectrum of a 2-MTHF solution of pyridinyl radical and 4-nitrobenzyl chloride (mixed at −30°, examined as a glass at 77°K).[16]

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(12) (a) M. Mohammad, J. Hajdu, and E. M. Kosower, *J. Amer. Chem. Soc.*, **93**, 1792 (1971); (b) W. A. Waters and L. Kolker, *Proc. Chem. Soc. London*, 55 (1963).

(13) G. L. Closs, University of Chicago, private communication.

(14) *Cf.* also G. A. Russell and W. C. Danen, *J. Amer. Chem. Soc.*, **90**, 347 (1968), who were unable to observe the 4-nitrobenzyl chloride radical anion under conditions successfully used for the examination of the 3-nitrobenzyl chloride radical anion.

(15) A more detailed discussion can be found in ref 7. An alternate approach suggesting the same general conclusion is based on the energy required to introduce a cavity suitable for a dipole, μ, *i.e.*, $\frac{1}{2}\mu R$, less the energy of interaction of that dipole with the reaction field R, *i.e.*, μR. *Cf.* C. J. F. Böttcher, "Theory of Electric Polarization," Elsevier, Amsterdam, 1952.

(16) Assuming that our experiments would not have detected 10% or less of complex, the equilibrium constant for complex formation cannot be more than 100 M^{-1}.[17-19]

Mechanism I

$$\mathrm{Py\cdot} + \mathrm{NBX} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \mathrm{Py^+, NBX^-} \tag{9}$$

$$\mathrm{Py^+, NBX^-} \xrightarrow{k_2} \mathrm{Py^+, Cl^-, NB\cdot} \tag{10}$$

$$\mathrm{Py\cdot} + \mathrm{NB\cdot} \longrightarrow \mathrm{PyNB} \tag{11}$$

The second mechanism differs from the first in that the initially formed ion pair dissociates to yield the pyridinium ion and 4-nitrobenzyl halide radical anion.

Mechanism II

$$\mathrm{Py\cdot} + \mathrm{NBX} \underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \mathrm{Py^+, NBX^-} \tag{12}$$

$$\mathrm{Py^+, NBX^-} \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} \mathrm{Py^+} + \mathrm{NBX^-} \tag{13}$$

$$\mathrm{NBX^-} \xrightarrow{k_3} \mathrm{NB\cdot} + \mathrm{X^-} \tag{14}$$

$$\mathrm{Py\cdot} + \mathrm{NB\cdot} \longrightarrow \mathrm{PyNB} \tag{15}$$

In order to consider these mechanisms, we must first estimate the equilibrium constants for initial electron-transfer reaction, K_1, (k_1/k_{-1}), from the reduction potentials measured for 1-ethyl-4-carbomethoxypyridinium ion and the 4-nitrobenzyl halides. In the case of 4-nitrobenzyl chloride, the half-reactions are illustrated in eq 16–18, and K_1 is estimated as about 0.1 M^{-1}. (A lower limit is 0.01 M^{-1}.)

$$\mathrm{Py\cdot} \longrightarrow \mathrm{Py^+} + \mathrm{e^-} \qquad E_{1/2} = +1.095\ \mathrm{V} \tag{16}$$

$$\mathrm{NBCl} + \mathrm{e^-} \longrightarrow \mathrm{NBCl^-} \qquad E_{1/2} = -1.16\ \mathrm{V} \tag{17}$$

$$\mathrm{Py\cdot} + \mathrm{NBCl} \rightleftharpoons \mathrm{Py^+, NBCl^-} \qquad E_{1/2} = -0.065\ \mathrm{V} \tag{18}$$

The kinetic expression for mechanism I leads to the relation shown in eq 19. If we assume that electron

$$k_{\mathrm{obsd}} = \frac{k_1}{k_{-1}}k_2 = K_1k_2 \tag{19}$$

transfer is rapid, k_2 must be at least 10^5 sec^{-1} to account for the observed rate constant of over 10^4 M^{-1} sec^{-1} in $\mathrm{CH_3CN}$. If electron transfer is slow (*i.e.*, order of magnitude of the observed rate constant), k_2 must be at least 10^5 sec^{-1}, given the expression in eq 20. Direct

$$k_{\mathrm{obsd}} = k_1\frac{k_2}{k_{-1} + k_2} \tag{20}$$

determination by two electrochemical techniques indicates that the magnitude of k_2 falls far short (10–20 sec^{-1} rather than 10^5 sec^{-1}) of that required for either version of mechanism I. (We assume that the occurrence of pyridinium ion as the reaction partner in the kinetic experiment in place of the tetra-*n*-butylammonium ion in the electrochemical experiment will not alter the validity of the comparison.) On these grounds, we may exclude mechanism I for the reaction of pyridinyl radical and 4-nitrobenzyl chloride.

A steady-state treatment of mechanism II yields the equation for the observed rate constant, under conditions in which (Py$^+$) is still small, shown in eq 21.

$$k_{\mathrm{obsd}} = k_1\left[1 - \frac{1}{1 + k_2/k_{-1}}\right] \tag{21}$$

The rate-limiting step for mechanism II, with reasonably fast electron transfer as the first step, is the dissociation of the intermediate ion pair. A set of values which would satisfy the experimental results is $k_1 = 10^6$ M^{-1} sec^{-1}, $k_{-1} = 10^7$ sec^{-1}, and $k_2 = 10^5$ sec^{-1}. We should expect that a reaction which produces a pair of ions from a pair of neutral species might proceed more slowly than a diffusion-controlled reaction because of the entropy of activation. (Preliminary measurements for the activation energy of the reaction of pyridinyl radical with 4-nitrobenzyl chloride in acetonitrile indicate that the entropy of activation is substantial although less than that in 2-MTHF.)[21] The value of k_{-1} is fixed by the values of K_1 and k_1. The value of k_2 is the dissociation rate for an ion pair, and, at first sight, is lower than one might have guessed from diffusion-controlled rates of association for ions (10^8–10^9 M^{-1} sec^{-1}) and equilibrium constants for association in acetonitrile (at infinite dilution K_{assoc} for 1-ethyl-4-carbomethoxypyridinium iodide in $\mathrm{CH_3CN}$ is *ca.* 30).[22] The ion pair with which we are concerned is of a special class, one of the partners being a π radical. The weak, delocalized π bonds formed by two such rings can add from 1.4 to 2.5 kcal/mol in association energy beyond that expected for electrostatic association and other weak interactions.[23] The pyridinium ion–radical anion pairs produced from 4-nitrobenzyl halides and pyridinyl radicals might thus dissociate to the radical anion and pyridinium ion at rates between 10^5 and 10^6 sec^{-1}.

We believe that return from Py$^+$ and NBCl$\cdot^-$, for which the rate constant k_{-2} may be close to diffusion controlled, does not contribute very much to the kinetics of the reaction. The rate of loss of NBCl$\cdot^-$ through unimolecular decomposition is high enough (10–20 sec^{-1}) so as not to change the bimolecular character of the reaction.

Slow electron transfer is not excluded by these arguments, but is made unlikely by the examination of the rate of reaction of pyridinyl radical with 1,3-dinitrobenzene. On the basis of reduction potential (−1.22 V), 1,3-dinitrobenzene should react at about 0.1 of the rate for 4-nitrobenzyl chloride, were electron-transfer rate limiting. Instead, the compound reacts at 0.00001 of the rate observed for 4NBCl.[24] We thus regard rate-limiting electron transfer as unlikely for 4NBCl.

Our discussion leads us to regard mechanism II with ion pair dissociation as rate limiting as the appropriate description for the reaction of pyridinyl radical and 4-nitrobenzyl chloride. Does the same mechanism apply to the fluoride and bromide?

Element Effect. Assuming that linear relationship between log k_{obsd} and Z applies to the reaction of 4-nitrobenzyl bromide as is found for the chloride and fluoride, we may estimate a rate constant of somewhat more than 10^7 M^{-1} sec^{-1} for the reaction of Py·

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(17) R. Foster, "Organic Charge-Transfer Complexes," Academic Press, New York, N. Y., 1969, p 470.

(18) R. S. Mulliken and W. B. Person, "Molecular Complexes," Interscience, New York, N. Y., 1969, p 498.

(19) *Cf.* the charge-transfer transition reported by D. O. Cowan and F. Kaufman, *J. Amer. Chem. Soc.*, **92**, 6198 (1970). The relationship of Hush[20] cited therein would have predicted a charge-transfer band at 12,000 Å in the case of pyridinyl radical and 4-nitrobenzyl chloride.

(20) N. S. Hush, *Progr. Inorg. Chem.*, **8**, 391 (1967).

(21) M. Mohammad and E. M. Kosower, unpublished results.

(22) E. M. Kosower, *J. Amer. Chem. Soc.*, **80**, 3253 (1958).

(23) M. Itoh and E. M. Kosower, *ibid.*, **90**, 1843 (1968). π bonds in "π-mers" are probably between 1.4 and 2.5 kcal/mol in energy per excess electron. See also E. M. Kosower and J. Hajdu, *ibid.*, **93**, 2534 (1971).

(24) M. Mohammad and E. M. Kosower, to be submitted. Application of the solvent effect criterion shows that the reaction of 1,3-dinitrobenzene with pyridinyl radical involves electron transfer.

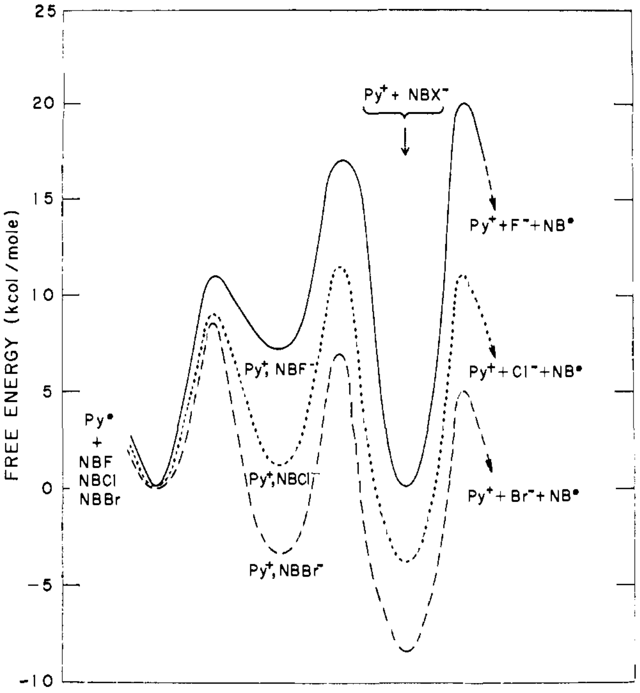

Figure 4. A free-energy *vs.* reaction coordinate diagram for the reaction of pyridinyl radical with 4-nitrobenzyl halides in acetonitrile. All initial states were fixed at the same value (see text for data).

and 4NBBr in CH_3CN. The ion pair formed in the reaction, however, is much more stable and K_1 should be about 500 M^{-1}. Taking the estimated value for k_{obsd} as that for k_1, the return from the ion pair characterized by k_{-1} will be slower than the rate of ion-pair dissociation, k_2. (We take the rates of ion-pair dissociations as the same for the fluoride, chloride, and bromide.) Thus, the rate-limiting step in the reaction of pyridinyl radical and 4-nitrobenzyl bromide is the first electron transfer, with the rates through all subsequent steps higher at any concentrations which might be used for rate measurements.

The rate of decomposition of the 4-nitrobenzyl fluoride radical anion, measured electrochemically, and the rate of reaction of pyridinyl radical and 4-nitrobenzyl fluoride in acetonitrile are the same order of magnitude (see footnote *g*, Table V). On this basis, it is most probable that the rate-limiting step for the reaction of Py· with the fluoride is the decomposition of the radical anion.

Our present information suggests that the mechanism of the reaction of pyridinyl radical with 4-nitrobenzyl fluoride, chloride, or bromide is the same, but that the rate-limiting step for each of the reactions is different. These cases are instructive with respect to the extent to which one must inquire into the details of electron-transfer reactions before even a rough understanding of the facts is possible. A diagram (free energy *vs.* reaction coordinate) is given in Figure 4 to illustrate the differing behavior of the three related halides. The remarkable difference in the reduction potentials of the three benzyl halides is best understood in terms of $\sigma^*-\pi^*$ conjugation, demonstrated so clearly for tetracyanoethylene complexes of formally saturated molecules by Traylor and coworkers.[25]

Conclusions

The approaches described in the present work, combining electrochemical techniques and consideration of thermodynamic equilibria and solvent effects, should be applicable to other investigations of organic electron-transfer reactions. One can anticipate an enormous range of reactivities and interesting new chemical behavior for organic compounds when the quantitative aspects of electron-transfer reactions are better understood.

Experimental Section

Materials. 4-Nitrobenzyl Chloride (4NBCl). See preceding article.[1]

4-Nitrobenzyl bromide (4NBBr) was twice-crystallized from pure ethanol, then vacuum sublimed, mp 98.5–99° (lit.[26] 98.5°).

4-Nitrotoluene (4-NT) (Eastman Kodak) was recrystallized from pure methanol, then vacuum sublimed, mp 51.8–52.5° (lit.[27] 51.7°).

4-Nitrobenzyl Fluoride (4-NBF). A sample supplied by Dr. C. Beguin and Professor J. J. Delpuech, University of Grenoble, France, was vacuum sublimed, mp 37.5–38.5° (lit.[28] 38.5°).

1-Ethyl-4-carbomethoxypyridinium perchlorate was prepared from the iodide according to Schwarz.[29]

1-Ethyl-4-carbomethoxypyridinium iodide had mp 111° (lit.[22] 111–112°).[22]

1-Ethyl-4-carbomethoxypyridinyl (Py·) was prepared and stored in acetonitrile solution as described previously.[9,30] Transfers to other solvents were readily carried out on the vacuum line by removal of the acetonitrile and introduction of the desired solvent by distillation.

Tetra-*n*-butylammonium perchlorate (Matheson Coleman and Bell, Polarographic grade) and **silver perchlorate** (anhydrous, G. Frederick Smith Co.) were used without further purification.

Lithium perchlorate (G. Frederick Smith Co.) was twice recrystallized from acetonitrile and dried under vacuum.

Solvents. Acetonitrile, 1,2-dimethoxyethane, and **acetone** were purified as previously described.[1] **Dichloromethane** (Spectrograde) was fractionated through a platinum spinning band column, degassed, and distilled onto degassed molecular sieve (Linde type 4A, heated under high vacuum at over 450° until pressure readings had reached the usual low values, 10^{-6} mm, 1–2 hr).

Dimethylformamide (Baker, reagent grade) (DMF) was distilled from potassium carbonate under high vacuum and fractionated in an all-glass apparatus; the middle fraction was collected, degassed (seven or eight freeze–thaw cycles), and redistilled, the middle fraction being collected for use. **2-Methyltetrahydrofuran** (2-MTHF) (Eastman Kodak, White Label) was passed through fresh neutral alumina and fractionated, collecting the material with bp 79.5–80.0°. After degassing, solvent was distilled onto degassed molecular sieve, then distilled onto anthracene and a sodium mirror. Solvent was distilled from the *green* solution onto potassium mirror or sodium–potassium alloy, from which it was distilled for further use. **Formamide** (Fisher reagent) was fractionated under reduced pressure, and the middle 50% was taken, redistilled, and thoroughly degassed. **2-Propanol** (Matheson Coleman and Bell, spectroquality) was degassed (five to six freeze–thaw cycles) and distilled onto degassed molecular sieve. **Ethanol** was dried over calcium sulfate (Drierite), thoroughly degassed, and distilled onto degassed molecular sieve.

Methods. Rate measurements were made as described in the preceding paper.[1] Z values were evaluated from the charge-transfer band of 1-ethyl-4-carbomethoxypyridinium iodide in the same solvents used for kinetic studies. Z values for ethanol and 2-propanol were taken from the literature.[7] The C–T maxima were measured over a wide range of concentrations and the Z values were taken from extrapolations to zero concentration. The data

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illustrated elsewhere[31] reveal a nonlinear relationship between Z value and salt concentration, especially in nonpolar solvents. Electrochemical studies were carried out with a Heath polarographic apparatus (Heath Co., Benton Harbor, Mich.). Fast scans were performed with a Hewlett-Packard function generator 3300A and Tektronix oscilloscopes (532 or 564). The polarographic cells used were like those described by Schwarz[29] or a simpler H type. The counterelectrode was platinum wire (22 gauge) sealed into soda glass. The working electrode was either a dropping mercury type (Sargent and Co., "2–5 sec" capillary) or a hanging mercury drop. All polarographic measurements were made with the same capillary and at the same head of mercury. Potentials are referred to (silver wire) $Ag/AgClO_4$ (0.01 *M*) in CH_3CN (0.1 *M* tetra-*n*-butylammonium perchlorate). (This reference system is easier to use than the saturated calomel electrode (sce).) Solutions were deoxygenated with nitrogen passed over BTS catalyst (Badische Anilin und Sodafabrik, Ludwigshafen-am-Rheim, Germany) at 120°, through a deep blue solution of methylviologen cation radical[32] in CH_3CN, and through CH_3CN over molecular sieve 4A and Drierite. The system was calibrated against a mercury cell (1.35 V) before and after each experiment. The scan rate was checked against a previously recorded 100-mV change.

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N-Alkoxypyridinium Salts from Amine Oxides and Epoxides. Preparation, Reactions, and Mechanism of Base-Induced Decomposition[1,2]

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Abstract: Aromatic amine oxides react readily with epoxides in nitromethane in the presence of strong, nonnucleophilic acids to yield *N*-alkoxypyridinium salts. Several adducts of 2,6-lutidine *N*-oxide with styrene oxide and 1,2-epoxycyclohexane have been obtained as analytically pure solids as the perchlorate (**3a**, **5a**, **5c**) and the fluoroborate salts (**3b**, **5b**). The perchlorate salt of 2,6-lutidine *N*-oxide with 1,2-epoxybutane has also been prepared. An adduct of 2,4-lutidine *N*-oxide, 1,2-epoxycyclohexane, and perchloric acid has been isolated as its acetylated derivative (**6**). These salts undergo base-induced decomposition to the amine and carbonyl compounds; in addition, the styrene oxide adducts are susceptible to nucleophilic substitution with displacement of the amine oxide moiety. Deuterium-labeling experiments indicate that base-induced decomposition of *N*-(2-acetoxycyclohexyloxy)-2,6-lutidinium perchlorate (**5c**) and of *N*-methoxy-2,6-lutidinium iodide (**9**) to 2,6-lutidine and the respective carbonyl compounds does not occur by direct abstraction of the α proton, to any detectable extent. Instead, the α proton is transferred to a ring methyl group by an intramolecular process involving N–O bond cleavage. Since it also is demonstrated that a ring methyl group proton is removed reversibly to give an ylide, it is likely that the α proton is transferred to the carbanionic center of that ylide.

Virtually no literature exists on the reactions of amine oxides with epoxides, though there is a plethora of reactions of epoxides with other nucleophiles.[5] The one reported study[6] demonstrated only that some oxygen transfer occurs and, under the vigorous reaction conditions used, mixtures of products were obtained in low yield with no isolation of intermediates. The present research was initiated (a) to determine the scope of the reaction of aromatic amine oxides with epoxides in the presence of strong, nonnucleophilic acids; (b) to elucidate pathways of decomposition of the intermediate *N*-alkoxypyridinium salts, with particular attention to the mechanism of base-induced decomposition, using deuterium labeling; and (c) to ascertain the products of thermal and base-induced decomposition of the intermediate alkoxypyridinium salts.

Aromatic amine oxides are highly dipolar species. The dipole moment of pyridine *N*-oxide (in benzene, 25°) is 4.24 D,[7] a value close to those of dimethyl sulfoxide (4.3),[8] nitromethane (3.99),[8] and dimethylformamide (3.82).[9] Because of the tight negative

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(4) To whom all correspondence should be addressed.

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