Curved Brønsted Plot in Pyridinolysis of 2,4-Dinitrophenyl Methyl Carbonate. Comparison of Leaving Group Abilities between Pyridines and Phenolates

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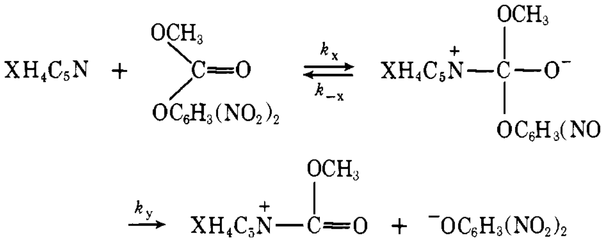
Abstract: The leaving abilities of pyridines and phenolates from a tetrahedral intermediate formed in the reactions of 2,4-dinitrophenyl methyl carbonate with 3- and 4-substituted pyridines are quantitatively compared through a curved Brønsted plot obtained from these nucleophilic reactions. Curvature is explained through a tetrahedral intermediate and a change in rate-determining step from its breakdown to its formation as the basicity of the nucleophile increases; a semiempirical equation reported based on these assumptions gives account of the experimental results. Curvature, centered at p$K_a \sim 7.8$, shows that 2,4-dinitrophenolate (p$K_a \sim 4$) has the same leaving ability as a pyridine of p$K_a \sim 7.8$, i.e., pyridines seem to be ca. 10^4 times better leaving groups from a tetrahedral intermediate than phenolates of the same basicity.

Leaving abilities of nitrogen and oxygen bases from tetrahedral intermediates can be evaluated from curved Brønsted plots obtained in nucleophilic reactions, but quantification has been difficult owing to scatter of points in the plots arising from dissimilar nucleophiles employed.[1] 3- and 4-substituted pyridines offer the advantage of a homogeneous series with a wide range of pK_a values, which has proved useful in quantitative interpretation of curved Brønsted plots.[2,3]

The present paper reports a quantitative evaluation of the relative leaving abilities between pyridines and 2,4-dinitrophenolate from the tetrahedral intermediate formed in the nucleophilic reactions of 2,4-dinitrophenyl methyl carbonate with a series of 3- and 4-substituted pyridines (eq 1).



$$XH_4C_5N + (CH_3O)(O_2N)_2H_3C_6O\text{C}{=}O \underset{k_{-x}}{\overset{k_x}{\rightleftarrows}} XH_4C_5\overset{+}{N}{-}C(OCH_3)(OC_6H_3(NO_2)_2){-}O^- \xrightarrow{k_y} XH_4C_5\overset{+}{N}{-}C(OCH_3){=}O + {}^-OC_6H_3(NO_2)_2 \qquad (1)$$

Experimental Section

2,4-Dinitrophenyl methyl carbonate was prepared according to Pianka,[4] mp 87 °C (lit.[4] 87-88 °C), and identified by NMR spectroscopy. Nicotinamide, p.a., Merck, was used directly. The rest of the pyridines and reagents were purified as previously described.[3]

Reactions were followed measuring the increase in 2,4-dinitrophenolate or the corresponding phenol absorbance by means of a Pye-Unicam SP 1800 spectrophotometer. Two to four pH values and several concentrations of total base were used (see Table I). Temperature was kept at 25 ± 0.1 °C and the ionic strength adjusted to 0.2 M with $NaClO_4$. Good pseudo-first-order rate constants (k_{obsd}) were obtained by the "infinity" method (at least 20-fold excess of total base over substrate was used). Reactions were followed for at least 3 half-lives and infinity absorbance values taken after 8-10 half-lives.

2,4-Dinitrophenolate was identified as a stable product of the reactions by comparison of its UV spectra with those of authentic samples. The existence of a methoxycarbonylpyridinium intermediate was inferred from the observation of a decrease in absorbance of the spectra obtained by repetitive scanning between 270 and 400 nm, after completion of the reactions of 2,4-dinitrophenyl methyl carbonate with 4-dimethylamino- and 4-methylpyridines under conditions such that the formation of the intermediate was faster than its hydrolysis. The rate constants for hydrolysis of these substituted intermediates have been previously measured.[3] The 2,4-dinitrophenolate formed in the above reactions was blanked out before scanning of the samples, since it absorbs strongly between 330 and 400 nm.

Results and Discussion

Second-order rate constants for nucleophilic attack (k_n) are shown in Table I, and were obtained from eq 2, where k_{obsd} is the pseudo-first-order rate constant observed, k_w is the rate constant for "spontaneous" hydrolysis (2×10^{-5} s^{-1}), and N represents the nucleophile.

$$k_{obsd} = k_w + k_n[N] \qquad (2)$$

Figure 1 shows the Brønsted plot obtained for the reactions. The curve can be explained as follows: Application of the steady state assumption to the tetrahedral intermediate (eq 1) yields $k_n = k_{-x}/[1 + (k_{-x}/k_y)]$, which becomes either $k_n = k_x k_y/k_{-x}$ or $k_n = k_x$ for the weakly basic ($k_{-x} \gg k_y$) or the strongly basic ($k_{-x} \ll k_y$) nucleophiles, respectively. Therefore, the curved Brønsted plot can be explained through the formation of an unstable intermediate in the reaction path and a change in the rate-determining step from its breakdown (k_y step) to its formation (k_x step) as the basicity of the nucleophile increases.[3]

The solid line in Figure 1 was calculated through a semiempirical equation (eq 3) previously reported[3] where β_1 and β_2 are the experimental Brønsted slopes for the more basic and less basic nucleophiles, respectively, and $k_n°$ and p$K_a°$ refer to the (hypothetical) substituted pyridine for which $k_{-x} = k_y$.

$$\log (k_n/k_n°) = \beta_2(\mathrm{p}K_a - \mathrm{p}K_a°) - \log \tfrac{1}{2}[1 + 10^{(\beta_2-\beta_1)(\mathrm{p}K_a-\mathrm{p}K_a°)}] \qquad (3)$$

For the present reactions, $\beta_1 = 0.2$, $\beta_2 = 0.9$, p$K_a° = 7.8$, and $\log k_n° = 1.7$, where p$K_a°$ is the pK_a value for the intercept of the two straight lines and $\log k_n° = \log (k_n'/2)$, where $\log k_n'$ is the value of $\log k_n$ for the above intercept.

Although more experimental points are needed in the region of the curvature and the value of β_1 is not precise, eq 3 seems to give satisfactory account of the experimental points.

The curvature of the Brønsted plot is centered at p$K_a \sim 7.8$, which, according to the assumption above, means that at this pK_a value the rate of breakdown of the tetrahedral intermediate to products equals that to reactants, i.e., 2,4-dinitrophenolate (pK_a of corresponding phenol ~ 4) has the same leaving ability as a substituted pyridine of p$K_a \sim 7.8$.

If the leaving ability of a phenolate from a tetrahedral intermediate were only a function of its basicity for the given

Table I. Experimental Conditions and k_n Values Obtained for the Reactions of 2,4-Dinitrophenyl Methyl Carbonate with Substituted Pyridines in Aqueous Solution at 25 °C, Ionic Strength 0.2 M

Substituent	pK_a[a]	Concn of total pyridine, M	pH[b] range	No. of runs	k_n,[c] $M^{-1} s^{-1}$
4-CN	1.98	0.10-0.25	1.1-2.6	12	$(6.9 \pm 0.6) \times 10^{-4}$
3-Cl	2.98	0.10-0.25	2.1-2.8	12	$(5.6 \pm 0.6) \times 10^{-3}$
3-CONH$_2$	3.46	0.10-0.30	3.7-5.1	14	$(1.2 \pm 0.06) \times 10^{-2}$
Unsubst	5.30	0.03-0.08	4.4-6.3	18	0.7 ± 0.04
3-CH$_3$	5.81	0.01-0.12	4.6-6.8	27	1.6 ± 0.1
4-CH$_3$	6.15	0.01-0.12	4.7-7.0	23	3.9 ± 0.3
4-NH$_2$	9.15	0.005-0.020	6.7-7.4	12	200 ± 13
4-N(CH$_3$)$_2$	9.55	0.005-0.015	6.6-7.3	12	260 ± 17

[a] Measured as previously described.[3] [b] pH maintained with each substituted pyridine as its own buffer except for 4-amino- and 4-dimethylaminopyridines, where phosphate buffer was used. [c] Value of the slope and its standard error obtained from eq 2 by least-squares analysis.

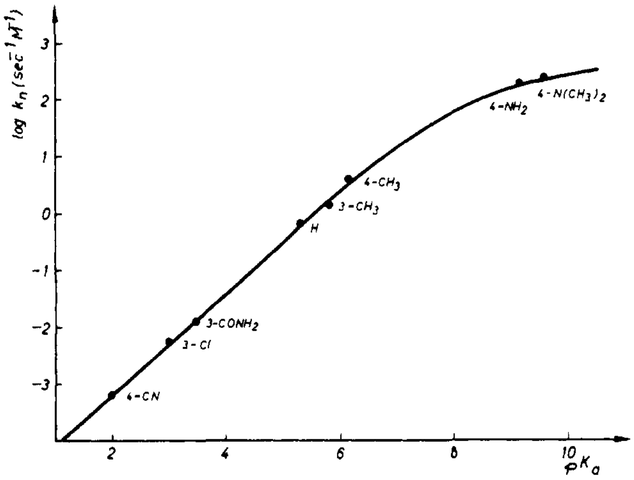


Figure 1. Brønsted plot for the reactions of 2,4-dinitrophenyl methyl carbonate with 3- and 4-substituted pyridines (substituents lettered in the figure), in aqueous solution at 25 °C, ionic strength 0.2 M. Full line calculated as in the text.

series of pyridines, then according to our results pyridines should be ca. 10^4 times better leaving groups than phenolates of the same basicity.

Bond and Moodie[5] did not find a curved Brønsted plot for the reactions of *p*-nitrophenyl methyl carbonate with a series of amines and pyridines, and this is in qualitative accord with our finding since that curvature should be centered at p$K_a \sim$ 11 (*p*-nitrophenol has p$K_a \sim 7$), which lies beyond the pK_a range they covered.

The nucleophilic reactions of methyl phenyl carbonate with a series of 3- and 4-substituted pyridines give a straight Bronsted plot[6] and this is expected since, according to our hypothesis, the curvature should be centered at p$K_a \sim 14$ (pK_a of phenol ~ 10).

As far as we know, this is the first time that the relative group ability of any phenolate and pyridines from a tetrahedral intermediate has been quantitatively measured.

Gravitz and Jencks[7] found amines ca. 10^5 times better leaving groups than alkoxide ions of the same basicity, although, according to the authors, this figure is not exact in view of uncertainties in the pK_a estimates of the amine adducts studied.

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