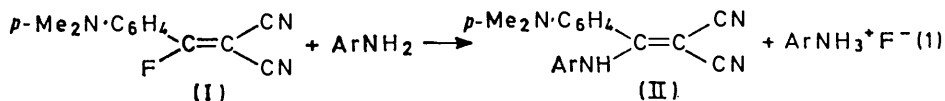


Nucleophilic Attacks on Carbon–Carbon Double Bonds. Part XV.¹ Further Evidence for Base-catalysis in the Reaction of 1,1-Dicyano-2-*p*-dimethylaminophenyl-2-fluoroethylene with Substituted Anilines in Acetonitrile

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The third-order reaction of 1,1-dicyano-2-*p*-dimethylaminophenyl-2-fluoroethylene (I) with *p*-toluidine in acetonitrile is catalysed by pyridines. These compete with *p*-toluidine in proton expulsion from the zwitterionic intermediate $\text{Ar}^2(\text{Ar}^1\text{N}^+\text{H}_2)\text{CF}-\text{C}(\text{CN})_2$. Two parallel Brønsted lines with $\alpha = 0.29$ are obtained: the higher for 3- and 4-substituted and the lower for 2-substituted pyridines. The reaction of *o*-phenylenediamine with (I) is nearly of the second order in the amine; 97% of the catalysis is by external amine and 3% by the *o*-amino-group of the intermediate. In their reaction with (I), *o*-, *m*-, and *p*-phenylenediamine are on the same Brønsted ($\alpha = 1.67$) and Hammett ($\rho = -3.88$) lines for the other substituents. It is concluded that the second amine operates as a base and not as an electrophilic catalyst for the fluorine expulsion. The isotope effects with *N*-deuteriated anilines are small and they are discussed in relation to the symmetry of the transition state.

THE substitution of the fluorine of 1,1-dicyano-2-*p*-dimethylaminophenyl-2-fluoroethylene (I) by *meta*- and *para*-substituted anilines in acetonitrile to form the dicyanoeneamine (II) [equation (1)] is a second-order process in the amine.² Scheme 1 demonstrates the



various mechanistic combinations for the substitution of the leaving group X; k_2 and k_{2A} are unassisted and an electrophilically (amine)-assisted steps for the expulsion of X^- , while k_3 and k_{3A} are unassisted and base (amine)-assisted proton-expulsion steps, respectively. Since one amine molecule participates in the initial nucleophilic attack to form the zwitterion (III) two routes may account for the involvement of the second amine molecule: (a) an amine-catalysed expulsion of the ammonium proton (k_{3A}) may precede a rapid C–F bond cleavage or (b) a rate-determining electrophilically assisted C–F bond cleavage by the amine (k_{2A}) may precede a rapid N–H bond cleavage. Both routes were suggested in the

analogous nucleophilic aromatic substitution of activated aryl fluorides by amines.³

A cognate variant of route (a) is one in which a fast reversible proton transfer from the zwitterion (III) to the amine is followed by a slow ammonium ion-catalysed

(or general acid-catalysed) detachment of the fluoride ion (Scheme 2).¹ For this, k_{3A} of Scheme 1 is replaced by $k_{3A}k_4/k_{-3A}$. This Scheme was discussed in connection to the reaction of (I) with anilines in alcoholic solvents,¹ and an analogous scheme was favoured in discussions⁴ and has been recently demonstrated⁵ for nucleophilic aromatic substitution.

Previous work in acetonitrile² suggested that for the chlorine analogue of (I) the substitution is mainly non-catalysed, while for (I) route (a) operates exclusively in attack by *meta*- and *para*-substituted anilines and route (a) and the non-catalysed route ($k_1 \rightarrow k_2$) compete when using *ortho*-substituted anilines. The present work was planned to give more conclusive evidence for

¹ Part XIV, Z. Rappoport and R. Ta-Shma, *J. Chem. Soc. (B)*, 1971, 1461.

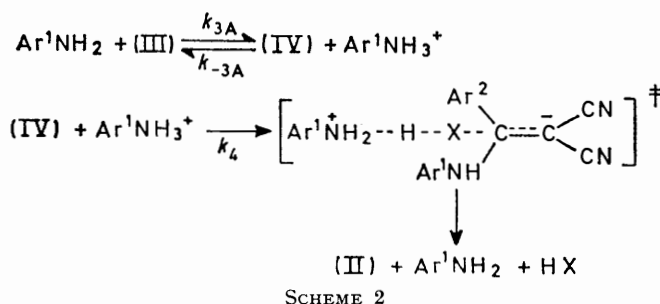
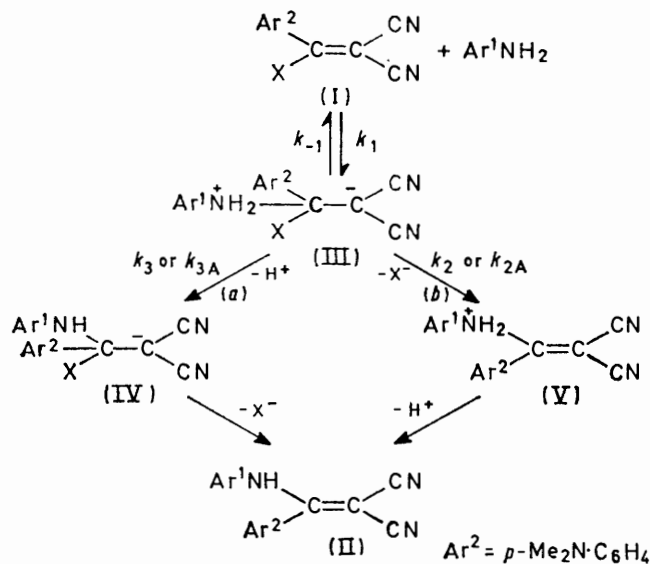
² Z. Rappoport and R. Ta-Shma, *J. Chem. Soc. (B)*, 1971, 871.

³ E.g., J. F. Bunnett and J. J. Randall, *J. Amer. Chem. Soc.*, 1958, **80**, 6020; F. Pietra and A. Fava, *Tetrahedron Letters*, 1963, 1535; F. Pietra, *Quart. Rev.*, 1969, **23**, 504.

⁴ J. F. Bunnett and R. H. Garst, *J. Amer. Chem. Soc.*, 1965, **87**, 3879; J. F. Bunnett and C. Bernasconi, *J. Amer. Chem. Soc.*, 1970, **92**, 2417.

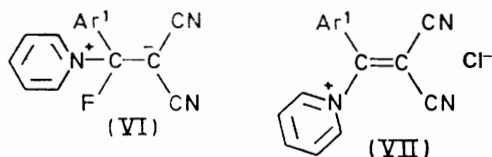
⁵ J. A. Orvik and J. F. Bunnett, *J. Amer. Chem. Soc.*, 1970, **92**, 2417.

route (a) in the reactions of (I), by studying the catalytic effects of various amines, by using an amine where internal competition between routes (a) and (b) is possible, and by measuring hydrogen isotope effects.

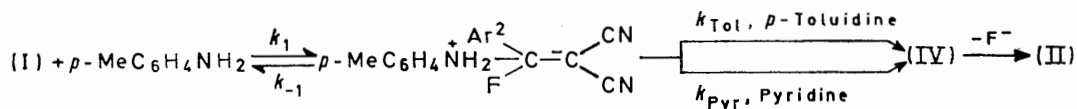


RESULTS AND DISCUSSION

Catalysis of the Reaction of (I) with *p*-Toluidine by Substituted Pyridines.—In order to differentiate between



routes (a) and (b) we studied the catalysis by substituted pyridines. These bases are capable of catalysing route (a) but should be ineffective in route (b). Pyridines



may attack the ethylene (I) to form the zwitterion (VI) but only with the chloro-analogue of (I) was further re-

* A. D. Josey, C. C. Dickinson, K. C. Dewhirst, and B. C. McKusick, *J. Org. Chem.*, 1967, **32**, 194.

action [leading to the cation (VII)] observed.⁶ The stability of solutions of (I) with and without added pyridines was found to be the same, and their u.v. absorption decreased only by 6% during 20 h.

Scheme 3 applies for a competition in the proton-expulsion step between a substituted pyridine (Pyr) and *p*-toluidine (Tol) from the intermediate formed from *p*-toluidine. The observed second-order coefficient $k_2' = \{d[(II)]/dt\}/[(I)] [Tol]$ is given by equation (2) and for a rate-limiting decomposition of the intermediate zwitterion, *i.e.*, $k_{-1} \gg k_{Tol}[Tol] + k_{Pyr}[Pyr]$, the observed third-order coefficient $k_3' = k_2'/[Tol]$ is given by equation (3). A plot of k_3' against the concentration of the

$$k_2' = \frac{k_1 k_{Tol}[Tol] + k_1 k_{Pyr}[Pyr]}{k_{-1} + k_{Tol}[Tol] + k_{Pyr}[Pyr]} \quad (2)$$

$$k_3' = k_1 k_{Tol}/k_{-1} + k_1 k_{Pyr}[Pyr]/k_{-1}[Tol] \quad (3)$$

added pyridine should be linear at a constant *p*-toluidine concentration with a slope of $k_1 k_{Pyr}/k_{-1}[Tol]$ and an

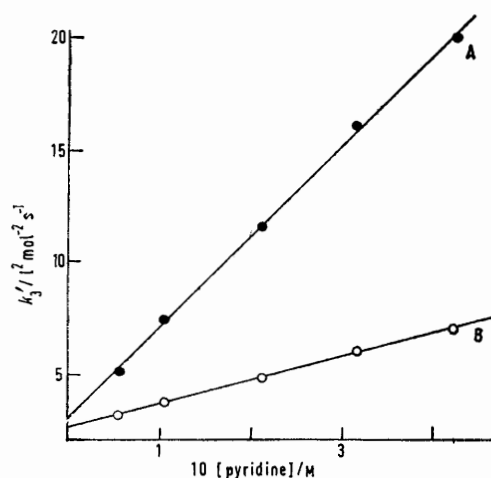


FIGURE 1 Dependence of k_3' for the reaction of (I) with *p*-toluidine on the concentration of added pyridine; A, [*p*-toluidine] = 0.0214M; B, [*p*-toluidine] = 0.0856M

intercept of $k_1 k_{Tol}/k_{-1}$. From the ratio of the slope to the intercept ($k_{Pyr}/k_{Tol}[Tol]$) the catalytic reactivity ratios of the pyridine to that of *p*-toluidine, namely k_{Pyr}/k_{Tol} is obtained.

A linear relationship of k_3' to [Pyr] was found earlier² for a single concentration of *p*-toluidine and several concentrations of pyridine with $k_{Pyr}/k_{Tol} = 3.15$.

The reaction of *p*-toluidine with the cyanoethylene (I) was followed spectrophotometrically up to 70–90%

reaction in the presence of ten substituted pyridines of different basic strengths. The catalysis is appreciable with several of the amines and the plots of k_3' (Table 1) against the [substituted pyridine] were linear up to the

highest concentrations used. For example, the reaction with 0.02M-*p*-toluidine is accelerated 10-fold on addition of 0.04M-4-methylpyridine. With most of the pyridines a single concentration of *p*-toluidine was used, but in the cases of pyridine and 3- and 4-methylpyridines the concentration of the *p*-toluidine was also changed and

toluidine) and $\Delta\Delta S^\ddagger = \Delta S^\ddagger(\text{pyridine}) - \Delta S^\ddagger(\textit{p}\text{-toluidine})$ are in Table 2. The intercepts from most of the catalysed reactions, at each temperature, are reasonably similar, and since they are due to the reaction with *p*-toluidine alone they are equal to the previously determined k_3' value for *p*-toluidine.² The intercept and the

TABLE 1
Catalysis by pyridines (Pyr) in the reaction of *p*-toluidine (Tol) with 1,1-dicyano-2-*p*-dimethylaminophenyl-2-fluoroethylene in acetonitrile^a

Pyridine	At 30 °C												At 45 °C						
	$10^3[\text{Tol}]/\text{M}$	$10^3[\text{Pyr}]/\text{M}$	$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$																
Pyridine	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14
$10^3[\text{Tol}]/\text{M}$	0	0.53	1.06	2.12	3.18	4.25	0	0.53	1.06	2.12	3.18	4.25	0	0.26	0.52	1.03	1.55		
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	2.95 ^b	5.15	7.40	11.6	16.1	20.1	2.69	3.17	3.72	4.85	6.01	7.06	4.10 ^b	7.30	10.9	17.6	23.4		
3-Methylpyridine	2.14	2.14	2.14	2.14	2.14	2.14	4.28	4.28	4.28	4.28	4.28	4.28	3.00	3.00	3.00	3.00	3.00		
$10^3[\text{Tol}]/\text{M}$	0	0.50	1.02	2.04	3.06	4.08	0	0.50	1.02	2.04	3.06	4.08	0	0.38	0.76	1.51	3.02		
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	2.80 ^b	5.40	8.20	14.0	18.9	23.8	2.68	4.05	5.37	7.95	10.5	13.1	3.40 ^b	5.70	7.50	11.7	20.4		
4-Methylpyridine	2.14	2.14	2.14	2.14	2.14	2.14	4.28	4.28	4.28	4.28	4.28	4.28	1.80	1.80	1.80	1.80	1.80		
$10^3[\text{Tol}]/\text{M}$	0	0.51	1.02	2.04	3.06	4.08	0	0.50	1.02	2.04	3.06	4.08	0	0.27	0.53	1.05	2.10		
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	2.90 ^b	6.20	9.40	16.0	22.6	28.5	2.75	4.00	6.30	8.90	12.6	14.8	3.80 ^b	6.90	9.60	16.1	28.9		
2-Methylpyridine	4.00	4.00	4.00	4.00	4.00	4.00							3.00	3.00	3.00	3.00	3.00		
$10^3[\text{Tol}]/\text{M}$	0	0.50	1.00	2.00	3.00	4.00							0	0.50	1.00	2.00	4.00		
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	3.16 ^b	4.24	5.10	7.12	8.65	10.4							3.84 ^b	5.12	6.92	9.62	15.3		
2,6-Dimethylpyridine	4.00	4.00	4.00	4.00	4.00	4.00							3.00	3.00	3.00	3.00	3.00		
$10^3[\text{Tol}]/\text{M}$	0	0.49	0.97	1.95	2.92	3.90							0	0.38	0.76	1.51	2.27		
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	2.89 ^b	3.12	3.28	3.47	4.06	4.30							3.73 ^b	4.04	4.26	5.16	5.73		
Quinoline	3.50	3.50	3.50	3.50	3.50	3.50							3.50	3.50	3.50	3.50	3.50		
$10^3[\text{Tol}]/\text{M}$	0	0.93	1.86	2.79	3.72								0	0.98	1.97	2.97	3.99		
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	2.84 ^b	3.97	5.07	6.45	7.48								3.58 ^b	4.59	5.46	6.36	11.2		
3-Bromopyridine	4.00	4.00	4.00	4.00	4.00	4.00													
$10^3[\text{Tol}]/\text{M}$	0	0.50	1.00	2.00	3.00	4.00													
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	3.12 ^b	3.33	3.63	4.25	4.88	5.51													
3-Cyanopyridine	3.00	3.00	3.00	3.00	3.00	3.00													
$10^3[\text{Tol}]/\text{M}$	0	0.38	0.75	1.50	2.25	3.00													
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	2.49 ^b	2.49	2.49	2.75	2.86	2.97													
2-Chloropyridine	4.08	4.08	4.08	4.08	4.08	4.08													
$10^3[\text{Tol}]/\text{M}$	0	0.50	1.00	2.00	3.00	4.00													
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	2.93 ^b	2.93	2.93	3.08	3.08	3.11													
2-Fluoropyridine	3.30	3.50	3.50	3.50	3.50	3.50							3.00	3.00	3.00	3.00	3.00		
$10^3[\text{Tol}]/\text{M}$	0	0.45	0.90	1.80	2.70	3.60							0	0.38	0.77	1.54	2.31		
$10k_3'/\text{l}^2\text{mol}^{-2}\text{s}^{-1}$	2.89 ^b	2.90	2.88	2.85	2.85	2.85							3.91 ^b	3.89	3.91	3.93	3.89		

^a $[(I-F)] = 1.7-3.6 \times 10^{-4}\text{M}$. Extrapolated value.

TABLE 2
Kinetic data for substituted-pyridine catalysed reactions of the cyanoethylene (I) with *p*-toluidine

Substituted pyridine	pK_a^a	At 30 °C				At 40 °C				$\Delta\Delta H^\ddagger$ ^d	ΔH^\ddagger ^e	$\Delta\Delta S^\ddagger$ ^f	ΔS^\ddagger
		$10^3[\text{Tol}]/\text{M}$	$10(\text{Intercept})^b$	Slope ^c	k_{Pyr}	$10^3[\text{Tol}]/\text{M}$	$10(\text{Intercept})^b$	Slope ^c	k_{Pyr}				
H	5.25	2.14	3.0	39.6	2.82	1.07	3.8	134	3.76	2.5	3.8	10.5	-42
		4.28 ^g	2.8 ^g	20.6 ^g	3.15 ^g								
		8.56	2.7	10.3	3.34								
2-Me	5.94	4.0	3.2 ^h	18.1	2.24	3.0	3.8	28.7	2.29	0.13	1.4	2.0	-50
3-Me	5.63	2.14	2.7	48.0	3.80	3.0	3.4	55	4.85	2.6	3.9	11.3	-41
		4.28	2.7	25.5	4.05								
4-Me	6.03	2.14	2.8	64.4	4.84	1.8	3.7	116.5	5.66	2.0	3.3	9.7	-42
		4.28	2.7	30.0	4.83								
2,6-MeO	6.60	4.00	2.9	3.67	0.52	3.0	3.7	8.28	0.67	3.1	4.4	8.9	-43
3-Br	2.84	4.00	3.0	6.25	0.83								
3-CN	1.39	3.00	2.5	1.56	0.19								
2-Cl	0.49	4.10	2.9	0.5	0.07								
2-F	-0.44	3.50	2.9	ca. 0	ca. 0								
Quinoline	4.81	3.50	2.8	12.8	1.6	3.5	3.6	18.1	1.81	1.5	2.8	5.9	-46

^a pK_a of the conjugate acid of the pyridine in water. Taken from ref. 7. ^b Intercept = k_1k_{Tol}/k_{-1} . ^c Slope = $k_1k_{\text{Pyr}}/k_{-1}[\text{Tol}]$. ^d $\Delta\Delta H^\ddagger = \Delta H^\ddagger(\text{Pyr}) - \Delta H^\ddagger(\text{Tol})$. ^e Activation parameters for the k_{Pyr} step. ^f $\Delta\Delta S^\ddagger = \Delta S^\ddagger(\text{Pyr}) - \Delta S^\ddagger(\text{Tol})$. ^g From ref. 2. ^h In a less reliable set of experiments: $10(\text{intercept}) = 2.8$.

equation (3) was obeyed (Figure 1). The single value for pyridine from previous work² fits those of Table 1. The values of the slopes and the intercepts of equation (3), the catalytic ratios $k_{\text{Pyr}}/k_{\text{Tol}}$, and the derived activation parameters $\Delta\Delta H^\ddagger = \Delta H^\ddagger(\text{pyridine}) - \Delta H^\ddagger(\textit{p}\text{-toluidine})$

and the $\Delta\Delta S^\ddagger = \Delta S^\ddagger(\text{pyridine}) - \Delta S^\ddagger(\textit{p}\text{-toluidine})$ values of 2-methylpyridine deviate from the values for the other amines. For all the pyridines the $\Delta\Delta H^\ddagger$ and the $\Delta\Delta S^\ddagger$ values are 0.1—3.1 kcal mol⁻¹, and 2—11.3 cal mol⁻¹ K⁻¹ respectively. Since $\Delta H^\ddagger(\textit{p}\text{-toluidine}) = 1.3$ kcal mol⁻¹ and $\Delta S^\ddagger(\textit{p}\text{-toluidine})$

$= -51.8 \text{ cal mol}^{-1} \text{ K}^{-1}$, the ΔH^\ddagger values for the k_{Pyr} step are very low and the ΔS^\ddagger values are highly negative (Table 2).

Attempts to follow the reactions with 3- and 4-amino-pyridines showed that a fast non-catalytic reaction, probably attack by the primary amino-group, is superimposed on the catalytic reaction. For example, k_1' for the reaction of the cyanoethylene (I) with 0.03–0.04M-3-aminopyridine at 25 °C is *ca.* $6 \times 10^{-4} \text{ s}^{-1}$. These reactions were not studied further.

The catalytic ratios follow the basicity of the amine, and the weakest base (2-fluoropyridine) had no catalytic effect. A Brønsted plot of $\log(k_{\text{Pyr}}/k_{\text{Tot}})$ against the $\text{p}K_a$'s of the conjugate acids of the pyridines (in water) (Figure 2) shows dispersion. The 3- and 4-substituted

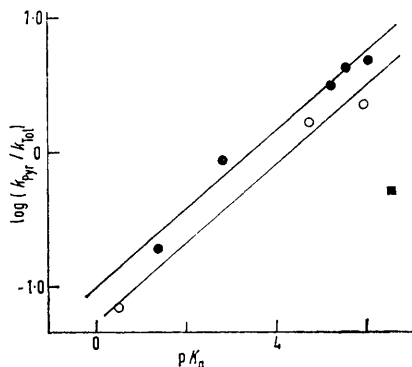


FIGURE 2 Dependence of the catalytic ratio $\log(k_{\text{Pyr}}/k_{\text{Tot}})$ on the $\text{p}K_a$ of the pyridinium ion in the reaction of (I) with *p*-toluidine; ●, 3- and 4-substituted pyridines; ○, 2-substituted pyridines; ■, 2,6-lutidine

pyridines give a line with a slope of $\alpha = 0.29 \pm 0.02$ (correlation coefficient $r = 0.99$) and the 2-substituted pyridines (including quinoline) give a parallel line with $\alpha = 0.29 \pm 0.03$ ($r = 0.99$) but 0.3 log unit lower. This is due to steric effects as shown by the much lower reactivity (and the high deviation from the Brønsted lines) of 2,6-dimethylpyridine, the strongest but the most hindered base studied. *p*-Toluidine itself deviates from the Brønsted plot of the pyridines; it is less reactive than quinoline which is a weaker base by 0.25 pK unit.

The higher catalytic reactivities of the pyridines than *p*-toluidine are controlled by the more positive entropies for the pyridines, which more than compensate for the higher activation energies. The energy of the transition state for the expulsion of the proton by *p*-toluidine may be lowered by hydrogen bonding with the carb-anionic centre or with the cyano-groups. The formation of a more 'ordered' transition state will result in a more negative ΔS^\ddagger .

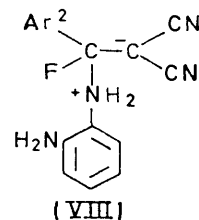
The success of equation (3) and the Brønsted relationship in correlating the data argues strongly that route (a) of Scheme 1 is the one followed in the presence of added pyridines. However, this does not exclude the electro-

⁷ Z. Rappoport, 'Handbook of Tables for Organic Compounds Identification,' The Chemical Rubber Co., Ohio, 3rd edn., 1967.

philic-assisted route for substituted anilines in the absence of added base. Evidence for route (a) in these cases too is discussed below.

Reaction of the Ethylene (I) with Phenylenediamines; Brønsted and Hammett Relationships in the Reaction of (I) with Anilines.—Routes (a) and (b) can also be differentiated by studying a suitable diamine where one amino-group is the nucleophile and the other the catalytic entity. For base catalysis, of second order, of an order between one and two, or of first order in the amine would be observed, respectively, when the free amino-group in the intermediate zwitterion would be much less basic, have a similar basicity, or be much more basic than the unchanged diamine molecule. For electrophilic catalysis the reaction order in the amine would be again unity, between one and two, or two, if the free amino-group is better, a similar, or a much worse electrophile, respectively, than the unchanged diamine.

Molecular models show that in the zwitterion (VIII) formed in the initial nucleophilic attack of *o*-phenylenediamine (PDA) on (I), the *o*-amino-group is perfectly situated for any of basic (with five-membered transition state), electrophilic (with seven-membered transition state), or bifunctional catalysis. For comparison, all three phenylenediamines and *o*-toluidine were studied. The inductive and the field effect of the ammonium



group would make the *o*-amino-group in (VIII) much less basic than the amino-groups of *o*-phenylenediamine.

Comparison of the two $\text{p}K_a$'s of the conjugate acid of *o*-phenylenediamine (0.6 and 4.74)⁷ gives an approximate estimate of the ratio of the $\text{p}K_a$ of the *o*-amino-group in (VIII) to that of free *o*-phenylenediamine. For the same reasons, the *o*-amino-group in (VIII) is a better electron-donor than those of *o*-phenylenediamine. If route (b) is important we expect a first-order dependency on the amine, and high reactivity since an internal electrophilic assistance will be favoured by the entropy term.

Table 3 shows that the reaction order in *o*-phenylenediamine is much closer to second than to first. A 3.6-fold increase in the amine concentration increases k_2' 2.5-fold while k_3' decreases by 33%. The slope and the intercept of the linear plot of k_2' against [amine] are $0.136 \text{ l}^2 \text{ mol}^{-2} \text{ s}^{-1}$ and $0.0037 \text{ l mol}^{-1} \text{ s}^{-1}$, respectively. This result eliminates electrophilic catalysis for the expulsion of the fluoride by the other anilines studied, since the contribution of route (b) is small (see below) even for *o*-phenylenediamine which is much more prone to this catalysis than the other amines.

The small decrease in the k_3' values can be due to a small contribution of internal base catalysis, but steric effects or reduction of the dielectric constant ϵ of the solvent ($\epsilon = 37.5$ for acetonitrile)^{8a} by the anilines are

TABLE 3

Reactions of amines with (I) in acetonitrile at 30.7 °C ^a						
<i>o</i> -Phenylenediamine						
$10^2[\text{Amine}]/M$	0	3.0	4.5	6.0	8.4	10.8
$10^2k_2'/l \text{ mol}^{-1} \text{ s}^{-1}$	0.38 ^b	0.72	1.04	1.13	1.62	1.78
$k_3'/l^2 \text{ mol}^{-2} \text{ s}^{-1}$	0.27 ^b	0.24	0.23	0.19	0.18	0.17
<i>m</i> -Phenylenediamine						
$10^2[\text{Amine}]/M$	0	1.0	2.0	4.0	5.0	
$10^2k_2'/l^2 \text{ mol}^{-2} \text{ s}^{-1}$	6.6 ^b	6.9	7.0	7.5	7.6	
<i>p</i> -Phenylenediamine						
$10^2[\text{Amine}]/M$	0	0.29	0.34	0.39		
$k_3'/l^2 \text{ mol}^{-2} \text{ s}^{-1}$	71.5 ^b	77	77	79		
<i>o</i> -Toluidine						
$10^2[\text{Amine}]/M$	0	15.1	22.6	37.6	52.6	67.7
$10^2k_2'/l \text{ mol}^{-1} \text{ s}^{-1}$	2.0 ^b	7.71	11.9	18.2	24.8	30.3
$10^2k_3'/l^2 \text{ mol}^{-2} \text{ s}^{-1}$	5.3 ^b	5.1	5.2	4.8	4.7	4.5

^a $[(I-F)] = 1.4-2.9 \times 10^{-5}M$. ^b Extrapolated value.

also possible. The latter effect is eliminated since it was not observed with aniline ($\epsilon = 6.89$ at 20 °C)^{8b} or *p*-toluidine ($\epsilon = 4.98$ at 54 °C)^{8b} which were studied at similar concentrations.² The constancy or the slight

It seems therefore that the deviations are indeed due to steric effects. Owing to the presence of two identical amino-groups in *o*-phenylenediamine, its reactivity does

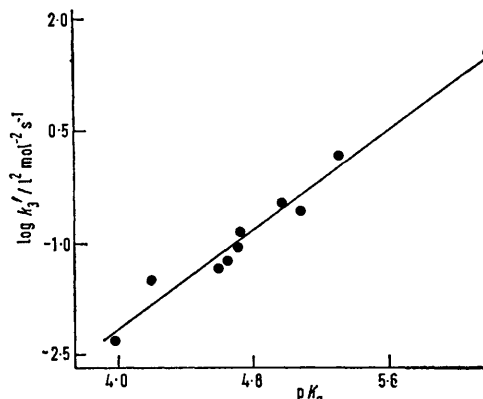
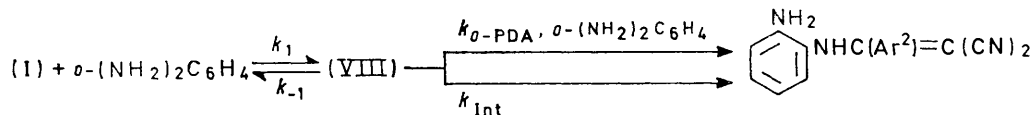


FIGURE 3 Brønsted plot for $\log k_3'$ in the reaction of anilines with (I) in acetonitrile at 30 °C against the pK_a 's of the anilinium ions in water

not decrease for steric reasons but increases because of the availability of the two potentially reacting groups.

The small decrease in k_3' with the increase in the amine concentration seems therefore to be caused by an internal



SCHEME 4

increase in k_3' for *m*- and *p*-phenylenediamine (Table 3) exclude any special effect of the amino-substituent. Internal base catalysis in these amines is also absent.

The decrease of k_3' with the increase in the amine concentrations was observed previously in the reactions of (I) with 2,6-diethyl- and 2,4,6-trimethyl-anilines and was attributed to a simultaneous decrease in k_1 and k_{3A} and increase in k_{-1} and k_2 , caused by steric reasons.² *o*-Toluidine which is sterically similar to *o*-phenylenediamine shows the same behaviour. A plot of $\log k_2'$ against [amine] is linear, with a slope of $0.0427 l^2 \text{ mol}^{-2} \text{ s}^{-1}$ and an intercept of $1.87 \times 10^{-3} l \text{ mol}^{-1} \text{ s}^{-1}$. By applying the steady-state treatment to Scheme 1 it was shown² that the ratio of the slope to the intercept is k_{3A}/k_2 . The ratio for *o*-toluidine (22.8) is higher than the values for the reactions of 2-chloro-1,1-dicyano-2-*p*-dimethylaminophenylethylene with anilines and shows that the uncatalysed route contributes *ca.* 5% to the overall process. However, all the *o*-alkylanilines are much less reactive than expected from their basicity, while *o*-phenylenediamine shows 'normal' reactivity. A Brønsted plot for the *meta*- and *para*-substituted anilines studied here and previously² and for *o*-phenylenediamine (with the pK_a 's in water) is linear with $\alpha = 1.67 \pm 0.09$ ($r = 0.989$) (Figure 3), but the three *o*-alkylanilines deviate from the line. The k_3' values of the diamines were corrected for this plot by the statistical factor of 2.⁹

base catalysis. For competition of internal (k_{Int}) and external ($k_{o\text{-PDA}}$) base in the proton expulsion from the intermediate (VIII) derived from *o*-phenylenediamine (*o*-PDA) (Scheme 4) a plot of k_2' against [*o*-PDA] would give an intercept : slope ratio which is equal to $k_{\text{Int}}/k_{o\text{-PDA}}$ when $k_{-1} \gg k_{\text{Int}} + k_{o\text{-PDA}}[o\text{-PDA}]$ [equation (4)]. When the observed ratio of 0.03 is corrected for the presence

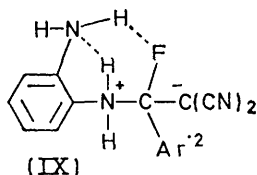
$$k_2' = k_1 k_{\text{Int}}/k_{-1} + (k_1 k_{o\text{-PDA}}/k_{-1})[o\text{-PDA}] \quad (4)$$

of two amino-groups in *o*-phenylenediamine a ratio of 0.06 is obtained for these two catalytic 'amine entities' for which we estimated above a ΔpK_a of *ca.* 4.1 units. This value is very close to the reactivity ratio for another pair of amines with $\Delta pK_a = 4.6$: *k_p*-Chloropyridine/*k_p*-Toluidine is 0.07 according to Table 2. Since the behaviour of the latter pair is 'normal', the internal catalysis by the *o*-amino-group of (VIII) is also 'normal' and is not accelerated in comparison with other amines of similar basicity. The contribution of the intramolecular catalysis is 3% of the overall process. This value also suggests that a bifunctional catalysis in the cyclic transition state (IX) contributes little, if at all, to the overall process.

⁸ (a) A. J. Parker, *Adv. Phys. Org. Chem.*, 1965, **5**, 173; (b) R. C. Weast, 'Handbook of Chemistry and Physics,' The Chemical Rubber Co., Cleveland, 51st edn., 1970-1971, p. E62.

⁹ S. W. Benson, *J. Amer. Chem. Soc.*, 1958, **80**, 5151.

According to Scheme 1 (with the usual assumptions) $k_3' = k_1 k_{3A} / k_{-1}$. From the linear relationship of k_3' to pK_a it is highly likely that plots of both $\log k_{3A}$ and of $\log (k_1/k_{-1})$ against pK_a are linear. The pK_a values of our



anilines and the pyridines of Table 1 are in the same region and the slope of the plot of $\log k_{3A}$ against pK_a for the anilines was therefore estimated as 0.29, the value found for the pyridines from Figure 1. This gives a slope of *ca.* 1.4 for a plot of $\log (k_1/k_{-1})$ against pK_a . Since k_1/k_{-1} is the equilibrium constant for the initial nucleophilic attack step, $\log (k_1/k_{-1})$ [the carbon basicity of the anilines towards the double bond ($pK_{C=O}$)] is higher than their hydrogen basicity. This basicity difference seems inherent and not a result of the use of the pK_a values in water. The very limited data on pK_a 's of anilines in acetonitrile¹⁰ suggest that the slope of a plot of $pK_a(\text{MeCN})$ against $pK_a(\text{H}_2\text{O})$ for the anilines would be lower than 1.4. Precedents for a higher basicity towards a C=O bond than towards hydrogen are known for alkoxides,¹¹ and since there are certain analogies between oxygen and the dicyanomethylene [$\text{C}(\text{CN})_2$] group,¹² such behaviour is not surprising in our system.

The study of *m*- and *p*-phenylenediamine enlarges the range of substituents used for the Hammett correlation for the reaction of the cyanoethylene (I) with anilines. As discussed earlier,² we are investigating a multiple variation within the reaction series: both the proton donor (the anilinium ion) and the proton acceptor (the aniline) are simultaneously changed. It can be shown that if the reactions of the same anilinium ion with different anilines, and the reactions of the same aniline with different anilinium ions, both obey the Hammett relationship with ρ_A and ρ_B respectively, a linear Hammett plot with $\rho = \rho_A - \rho_B$ would be obtained on a multiple variation. Our observed ρ value would be therefore composite: $\rho = \rho_1 - \rho_{-1} + \rho_A - \rho_B$. A plot of $\log k_3'$ against σ for nine substituents is satisfactory:¹³ $\rho = -3.88 \pm 0.27$ ($r = 0.983$). The k_3' values of the diamines were divided by 4 for this plot since the amines are involved in both the (k_1/k_{-1}) and in the k_{3A} terms which constitute k_3' , and both require statistical correction. While the ρ value is high and negative, it is not possible at present to dissect it to the contributions of the different ρ constituents.

¹⁰ J. F. Coetzee, *Progr. Phys. Org. Chem.*, 1967, **4**, 45.

¹¹ J. Hine and R. D. Weimar, jun., *J. Amer. Chem. Soc.*, 1965, **87**, 3387.

¹² W. J. Middleton and V. A. Engelhardt, *J. Amer. Chem. Soc.*, 1958, **80**, 2788; W. J. Middleton, E. L. Little, D. D. Coffman, and V. A. Engelhardt, *J. Amer. Chem. Soc.*, 1958, **80**, 2795; K. Wallenfels, *Chimia*, 1966, **20**, 303; Z. Rappoport, *Israel J. Chem.*, 1970, **8**, 749.

Deuterium Isotope Effects.—From the above evidence for base catalysis the deuterium isotope effect is expected to give qualitative information on the transition state for the abstraction of the proton. *N*-Deuterated *p*-chloro- and *p*-methylaniline were prepared by mixing the amines with deuterium oxide in acetonitrile. By n.m.r. the *N*-deuteration is 75–92%, while mass spectra showed the presence of the ArNH_2 , ArNHD , and ArND_2 species. The reactions of the labelled and the unlabelled compounds were followed simultaneously, and the degree of deuteration was taken into account when the concentration of the former was computed. The data for two different samples of deuterated *p*-toluidine and one *p*-chloroaniline are in Table 4. After correction for the

TABLE 4

Deuterium isotope effects in the reaction of (I) with amines; values of $10^3 k_3' / 1^2 \text{ mol}^{-2} \text{ s}^{-1}$

$10^2 [p\text{-Toluidine}] / \text{M}$	4.2	5.6	8.4	
$^1\text{H}_1^b$	2.74	2.68	2.51	2.64 ± 0.09^f
$^2\text{H}_1^c$	1.97	2.01	1.92	1.97 ± 0.05
$^2\text{H}_2^d$	2.28	2.36	2.30	2.31 ± 0.03^f
$10^2 [p\text{-Chloroaniline}] / \text{M}$	12	18	24	
$^1\text{H}_1^b$	5.19	5.17	5.20	5.19 ± 0.01^f
$^2\text{H}_1^e$	6.31	6.30	6.20	6.27 ± 0.05^f

^a $[(\text{I})] = 2.2\text{--}3.1 \times 10^{-5} \text{M}$. ^b Unlabelled compound. ^c Sample contains 86% *N*-deuteration. ^d Sample contains 75% *N*-deuteration. ^e Sample contains 92% *N*-deuteration. ^f Average value.

isotopic impurity (assuming that $k_{\text{H}}/k_{\text{D}}$ is linear with the D-content) $k_{\text{H}}/k_{\text{D}}$ values based on average k_3' values are 1.42 and 1.20 for *p*-toluidine containing 86% and 75% deuterium, respectively, and 0.82 for *p*-chloroaniline.

The two values found for *p*-toluidine reflect the high error associated with the presence of several isotopic species in the donor and the acceptor of the proton. The difference between the isotope effects for the two amines seems to us beyond the experimental error. The differences probably reflect inherent differences in the primary and secondary isotope effects in both the initial equilibrium step and in the proton abstraction step.

If to a first approximation the secondary isotope effect on the equilibrium (k_1/k_{-1}) step is small, the isotope effects are mainly those for the k_{3A} step. Even when the error in $k_{\text{H}}/k_{\text{D}}$ is taken into account, the isotope effects are much smaller than the maximum value expected for a proton transfer (k_{3A}) between two nitrogen atoms which are not very different in their basicity.¹⁴ Accordingly, the surprising conclusion is that the transition state for the proton transfer is very 'unsymmetrical'.^{14,15} Similar small isotope effects were observed, but not satisfactorily explained,¹⁶ in the analogous

¹³ H. H. Jaffe, *Chem. Rev.* 1953, **53**, 191.

¹⁴ R. P. Bell, 'The Proton in Chemistry,' Cornell Univ. Press, Ithaca, New York, 1959, ch. 11; R. P. Bell and D. M. Goodall, *Proc. Roy. Soc.*, 1966, **A**, **294**, 273; J. E. Dixon and T. C. Bruice, *J. Amer. Chem. Soc.*, 1970, **92**, 905.

¹⁵ F. H. Westheimer, *Chem. Rev.*, 1961, **61**, 265; E. R. Thornton, *J. Org. Chem.*, 1962, **27**, 1943.

¹⁶ F. Pietra, D. Vitali, and S. Frediani, *J. Chem. Soc. (B)*, 1968, 1595.

nucleophilic aromatic substitution by aromatic amines of systems with sluggish leaving groups. While more data are required, we note that if the proton abstraction step follows Scheme 2, the transition state of the k_4 step is far from being symmetrical, and if the isotope effect on the k_{3A}/k_{-3A} equilibrium is small, this may account for an isotope effect not far from unity.

EXPERIMENTAL

Solvent.—Commercial acetonitrile (Baker Analysed) was dried for 1 day (P_2O_5), refluxed for 3 h, and distilled twice through a fractionating column and the middle fraction, b.p. 78.5 °C, was kept under argon and used.

of 2-chloro-1,1-dicyano-2-*p*-dimethylaminophenylethylene⁶ in acetonitrile. After several hours the alkylammonium chlorides were filtered off, water was added, and the products obtained were recrystallised. Their analyses and physical properties are in Table 5.

Kinetic Procedure.—Solutions of the cyanoethylene (I) show 6% decrease in their optical density after 20 h. Material for each run was therefore prepared separately, and owing to the low solubility of (I) its initial concentration was determined from the optical density of the solutions at zero reaction time (which was extrapolated from the kinetic runs). Amine was added at the reaction temperature and the reaction was followed spectrophotometrically at 420 nm [the λ_{max} of (I)] in a thermostat-controlled chamber of a

TABLE 5
Enamines (*p*-(Me₂NC₆H₄)ArNH·C=C(CN)₂)^a

Ar	M.p. (°C) ^b	$\lambda_{max.}/nm$ (ϵ) ^c	Found (%)			Formula	Required (%)		
			C	H	N		C	H	N
<i>o</i> -H ₂ NC ₆ H ₄	198	351 (20,000)	71.03	5.54	23.25	C ₁₈ H ₁₇ N ₅	71.3	5.6	23.1
<i>m</i> -H ₂ NC ₆ H ₄	252—253	353 (21,800)	70.90	5.62	22.65	C ₁₈ H ₁₇ N ₅	71.3	5.6	23.1
<i>p</i> -H ₂ NC ₆ H ₄	251—252	348 (24,800)	71.30	5.73	22.82	C ₁₈ H ₁₇ N ₅	71.3	5.6	23.1

^a Crystallised from acetonitrile–water. ^b Uncorrected. ^c In acetonitrile.

Materials.— 1,1-Dicyano-2-*p*-dimethylaminophenyl-2-fluoroethylene was prepared by a modification² of the method of Josey *et al.*⁶ The pyridines, phenylenediamines, and *o*-toluidine were all commercial products. The pyridines were refluxed for 2 h over KOH, and distilled. They were not contaminated with their isomers within the limit of detection by n.m.r. The other amines were distilled twice or thrice and the middle colourless fraction was used. The b.p.s of all the amines agree with literature values.⁷ The *N*-deuterioamines were prepared by adding 5 molar equivalents of deuterium oxide to one equivalent of the amine in acetonitrile, shaking, distilling the solvents after 24 h, and repeating the process 3–4 times. The percentage of deuterium was calculated by using a combination of n.m.r. and mass spectra. The enamines were prepared by adding 2 molar equivalents of the amine to one equivalent

Beckman DU-spectrophotometer. The infinities were measured after 10 half-lives when the spectra of the solutions corresponded to those of the pure enamines.

The pseudo-first-order plots which were observed with excess of amines were linear (giving k_1') except for a few runs with the phenylenediamines. The discrepancies in these cases are due to the oxidation of the diamines and the formation of coloured species at the reaction times required for the infinity measurements. In these cases improvement was achieved by using the calculated instead of the observed infinities. The k_2' and k_3' values were calculated by dividing k_1' by [amine] and [amine]², respectively.

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