

### Substituent Effects on the Condensation of Nitrosobenzene with *para*- and *meta*-Substituted Anilines in Acetic Acid–Sodium Acetate Buffered Aqueous Ethanol Solutions

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The reaction of nitrosobenzene with *meta*- and *para*-substituted anilines has been studied in 94% (v/v) ethanol buffered with acetic acid and sodium acetate solutions. A linear Yukawa–Tsuno correlation was obtained ( $\rho -2.14$ ; correlation coefficient 0.990;  $r 0.741$ ).  $\Delta\Delta G_p$  Values for *p*-nitroaniline and ethyl *p*-aminobenzoate were obtained. It is suggested that two mechanisms can explain the data gathered. The kinetic behaviour of the reaction as a function of acetic acid and sodium acetate concentration in the buffer solution was also studied.

In spite of their importance in chemical and biochemical processes, reaction mechanisms involving the nitroso-group have not received much attention.<sup>1-3</sup>

Ueno and Akiyoshi<sup>4</sup> studied the kinetics of the reaction of aniline with substituted nitrosobenzenes in glacial acetic acid. They suggested a reaction mechanism in which the attack of aniline on the nitrosobenzene

is the rate-determining step because the order of the reaction rates was determined by the reactivity of the substituted nitrosobenzenes according to the influence of the substituent present.

Ogata and Takagi<sup>5</sup> studied the influence of acid catalysis on the condensation of substituted anilines and

<sup>1</sup> B. G. Gowenlock and W. Lüttke, *Quart. Rev.*, 1958, **12**, 321.

<sup>2</sup> J. Venulet and R. L. Van Ethen, in 'The Chemistry of the Nitro and Nitroso Groups,' ed. H. Feuer, Interscience, New York, 1970, Part 2, p. 203.

<sup>3</sup> B. E. C. Banks, in 'The Chemistry of the Amino Group,' ed. S. Patai, Interscience, New York, 1968, p. 499.

<sup>4</sup> K. Ueno and S. Akiyoshi, *J. Amer. Chem. Soc.*, 1954, **76**, 3670.

<sup>5</sup> Y. Ogata and Y. Takagi, *J. Amer. Chem. Soc.*, 1958, **80**, 3591.

nitrosobenzenes in buffered 94% (v/v) ethanol solutions (acetic acid-sodium acetate). They observed that the parameters of the substituents satisfied the Hammett equation (a  $\sigma$  value of 1.27 was used for *p*-nitroaniline, as suggested by Hammett for reactions of anilines and phenols<sup>6</sup>). These authors obtained  $\rho$  values of -2.14 for substituted anilines and 1.22 for substituted nitrosobenzenes respectively. On the basis of their results, which show that the reaction is more affected by polar effects of substituents in aniline than in nitrosobenzene, they suggested a reaction mechanism in which the attack of the protonated nitrosobenzene on the aniline in acid medium is the rate-determining step.

In this paper the kinetics of the condensation of 19 *para*- and *meta*-substituted anilines with nitrosobenzene in similar conditions to those described by Ogata and Takagi<sup>5</sup> are reported; in this way we have extended the exploration of substituent effects, including *m*-CO<sub>2</sub>H and *p*-CO<sub>2</sub>H which are specially interesting cases. The extrathermodynamic equations that best correlate with the substituent parameters and their relationship with the probable reaction mechanism and corresponding transition states are analysed.

#### EXPERIMENTAL

**Reactants.**—The anilines (pure grades) were purified by vacuum distillation over Zn powder or by recrystallization from ethanol-water before use. M.p.s and b.p.s agreed with those in the literature. Fresh nitrosobenzene was obtained each week by reduction of nitrobenzene<sup>7</sup> and purified by recrystallization from ethanol-water, m.p. 68 °C; it was kept at -5 °C over silica gel (Carlo Erba).

Commercial 96° G.L. ethanol was distilled twice and the azeotropic mixture obtained [97.6% (v/v) ethanol, *d* 0.8020 at 20 °C] was diluted to 94% (v/v) ethanol (*d* 0.8167 at 20 °C) with twice distilled water. Carlo Erba RS (spectrophotometric grade) methanol was employed. Other reactants were purified following the usual techniques.

**Kinetic Measurements.**—The techniques used in the present work have been already described by Ogata and Takagi.<sup>5</sup> When the reaction temperature was above 72.5 °C the closed tube technique was applied. Absorbance readings were made on the Hitachi-Perkin-Elmer model 124 u.v.-visible spectrophotometer. In most cases the data agreed within 2%; for *m*- and *p*-CF<sub>3</sub>-anilines agreement was within 5%. pH measurements were made with a Radiometer PHM4 pH meter. Nitrosobenzene undergoes a very slow decomposition in the same solvent employed for the reaction with a rate constant of 10<sup>-8</sup> s<sup>-1</sup> at 72.5 °C but this did not significantly affect the kinetic measurements.

We have considered the possibility of the equilibrium (1) which could affect the kinetic determinations. The most

unfavourable case, *p*-toluidine, was analysed using the  $pK_a$  for ethanol-water and  $\Delta H^0$  values from the literature.<sup>8-11</sup>



We found that to assume the *p*-toluidine was in its free basic form introduced negligible error.

U.v. spectrophotometry and conductimetry were carried out under the same conditions of our kinetic experiments, at 25, 50, and 72 °C to establish that the spectrum of *p*-toluidine does not show appreciable variations when the buffer acetic acid-acetate was added. Moreover, the conductivity of the buffered solution did not change appreciably when *p*-toluidine was added.

#### RESULTS AND DISCUSSION

Table 1 gathers the results obtained working in buffered 94% (v/v) ethanol solutions (sodium acetate 0.25M; acetic acid 0.88M). Our results were comparable with those obtained by Ogata and Takagi.<sup>5</sup>

The correlation between the apparent second-order constants for 17 anilines (*m*- and *p*-aminobenzoic acids were excluded because they show special behaviour that will be examined later) and the  $\sigma^*$  parameters defined by Van Bekkum *et al.*<sup>12</sup> gave a somewhat poor correlation coefficient of 0.946 with  $\rho$  -2.81, rather far from the  $\rho_m$  obtained for H, *m*-F, *m*-Cl, *m*-Br, *m*-I, and *m*-NO<sub>2</sub>-anilines when primary  $\sigma^*$  values are used (see Table 2).

When the  $\sigma^-$  values, taken from Tseng Kuang-Chih,<sup>13</sup> were introduced into the Yukawa-Tsuno equation,<sup>14,15</sup>  $\log(k/k_H) = \rho[\sigma^- + r(\sigma^- - \sigma^*)]$ , the correlation was substantially improved, giving  $\rho$  -2.14 with a correlation coefficient of 0.990, showing that the considerations made by these authors are applicable to the reaction studied. This  $\rho$  value of -2.14 is close to the  $\rho_m$  value obtained through the Hammett equation, using primary  $\sigma^*$  values.<sup>8</sup>

Similar behaviour has been observed in the alkaline hydrolysis of substituted phenyl-acetates and -benzoates<sup>16,17</sup> and also in the aromatic nucleophilic substitution with phenols and substituted anilines.<sup>18</sup>

If it is assumed, as an approximation that the coefficient  $r$  of the Yukawa-Tsuno equation is 1, the correlation still holds, but the value obtained (-1.93) is 10% lower than  $\rho_m$  value.

The value 0.7408 for the coefficient  $r$  of the Yukawa-Tsuno equation shows a clear difference of resonance interaction between the substituent and the reaction centre in the initial state in relation to the transition

<sup>12</sup> H. Van Bekkum, P. E. Verkade, and B. M. Wepster, *Rec. Trav. chim.*, 1959, **78**, 815.

<sup>13</sup> Tseng Kuang-chih, *Acta Chim. Sinica*, 1966, **32**, 107.

<sup>14</sup> Y. Tsuno, T. Iyata, and Y. Yukawa, *Bull. Chem. Soc. Japan*, 1959, **32**, 960.

<sup>15</sup> Y. Yukawa, Y. Tsuno, and M. Sawada, *Bull. Chem. Soc. Japan*, 1966, **39**, 2274.

<sup>16</sup> J. J. Ryan and A. A. Humfray, *J. Chem. Soc. (B)*, 1966, 842.

<sup>17</sup> A. A. Humfray and J. J. Ryan, *J. Chem. Soc. (B)*, 1967, 468.

<sup>18</sup> J. J. Ryan and A. A. Humfray, *J. Chem. Soc. (B)*, 1967, 1300.

<sup>6</sup> L. P. Hammett, 'Physical Organic Chemistry,' McGraw-Hill, New York, 1940, p. 188.

<sup>7</sup> A. I. Vogel, 'Practical Organic Chemistry,' Longmans, London, 1956, 3rd edn., p. 630.

<sup>8</sup> B. Gutbezahl and E. Grunwald, *J. Amer. Chem. Soc.*, 1953, **75**, 559.

<sup>9</sup> E. Grunwald and B. J. Berkowitz, *J. Amer. Chem. Soc.*, 1951, **73**, 4939.

<sup>10</sup> H. S. Harned and R. W. Ehlers, *J. Amer. Chem. Soc.*, 1933, **55**, 652.

<sup>11</sup> T. W. Zawidzki, A. M. Papée, W. J. Canady, and K. J. Laidler, *Trans. Faraday Soc.*, 1959, **55**, 1738.

state. In other words, the delocalization of the unpaired electrons of the amino-group in the aniline is very much reduced in the transition state with respect to the initial state.

In the special cases of *p*-nitroaniline and ethyl *p*-aminobenzoate, compounds with strong electron-withdrawing groups, the following equation was used, as suggested by Van Bekkum *et al.*:<sup>12</sup>  $\Delta\Delta G_p = 2.3RT(\sigma_{\text{exp}} - \sigma^n)$ .

In this equation  $\Delta\Delta G_p$  measures the difference of mesomeric *para*-interactions, in terms of free energy differences, between the transition and initial states.

ionization of methyl *p*-hydroxybenzoate in 49 and 95% ethanol<sup>8</sup> (0.82 and 0.79 kcal mol<sup>-1</sup> respectively) which is as large as the previous case.

The  $\Delta\Delta G_p$  values obtained suggest that in the transition state there is a notable decrease of the conjugative resonance between the substituents and the reaction centre with respect to the initial state.

The kinetic data corresponding to the substituted nitrosobenzenes gathered by previous workers<sup>4,5</sup> and our own results, agree with the hypothesis that the rate-determining step is the attack of the protonated nitrosobenzene, or of a complex involving a hydrogen bond

TABLE 1

Reaction rates and enthalpies, entropies, and free energies at 72.5° for the reaction of *m*- and *p*-R-anilines with nitrosobenzene in 94% ethanol-6% water (v/v) buffered with 0.25M-sodium acetate-0.88M-acetic acid

Substituent	$\sigma$ Values		$10^4 k_2 / \text{l mol}^{-1} \text{s}^{-1}$								$\Delta H^\ddagger / \text{kcal mol}^{-1}$	$\Delta S^\ddagger / \text{cal mol}^{-1} \text{K}^{-1}$	$\Delta G^\ddagger / \text{kcal mol}^{-1}$	
	R	$\sigma^-$	$\sigma^n$	40°	50°	56°	60°	72.5°	85°	100°				120°
H		0.000	0.000	13.4			20.4	25.8				3.65	-60.1	24.4
<i>p</i> -F		-0.056	0.056	13.6	17.9		23.0	30.9				4.75	-56.6	24.4
<i>p</i> -Cl		0.192	0.238	3.17			6.05	8.74				6.08	-55.3	25.2
<i>p</i> -Br		0.237	0.265	1.57			4.52	8.19				10.3	-43.3	25.3
<i>p</i> -I		0.267	0.299		2.11		3.81	7.54				11.9	-38.7	25.3
<i>p</i> -Me		-0.215	-0.129	34.9 <sup>a</sup>		50.0 <sup>a</sup>		73.4 <sup>a</sup>			192	4.56	-55.4	23.7
<i>p</i> -CF <sub>3</sub>		0.648	0.532					2.02	4.23	9.43		13.7	-36.2	26.2
<i>p</i> -CO <sub>2</sub> H		0.778	0.406	0.366 <sup>a</sup>		0.840 <sup>a</sup>		1.82 <sup>a</sup>				9.94	-47.2	26.3
<i>p</i> -CO <sub>2</sub> Et		0.752	0.450 <sup>b</sup>					1.44	2.65	5.20		11.3	-43.8	26.4
<i>p</i> -SH			0.150 <sup>b</sup>				8.39	12.0	14.7			4.66	-58.8	24.0
<i>p</i> -NO <sub>2</sub>		1.297	0.778					0.06 <sup>a</sup>						
<i>m</i> -F		0.337	0.337		1.60		2.46	4.05				8.49	-49.8	25.7
<i>m</i> -Cl		0.363	0.373		1.42		2.23	3.78				8.99	-48.5	25.8
<i>m</i> -Br		0.341	0.391		1.59		2.33	3.64				7.52	-52.8	25.8
<i>m</i> -I		0.330	0.352		2.95		3.42	4.05				2.44	-67.3	25.7
<i>m</i> -CF <sub>3</sub>		0.430	0.467					3.69	7.56	15.6		12.9	-37.3	25.8
<i>m</i> -CO <sub>2</sub> H		0.511	0.370 <sup>b</sup>				7.40	11.0	16.0			6.61	-53.3	25.0
<i>m</i> -CO <sub>2</sub> Et			0.370 <sup>b</sup>					7.37	12.0	21.1		9.01	-47.1	25.3
<i>m</i> -NO <sub>2</sub>		0.756	0.710			0.330 <sup>a</sup>		0.74 <sup>a</sup>			23.3	16.9	-28.4	26.7

<sup>a</sup> Values obtained from ref. 5. <sup>b</sup> Values obtained from ref. 23.

The value 1.5 kcal mol<sup>-1</sup> was obtained for *p*-nitroaniline, which compares with the dissociation of the *p*-nitroanilinium ion in water (1.68 kcal mol<sup>-1</sup>) and in 100% ethanol (2.35 kcal mol<sup>-1</sup>),<sup>12</sup> though in this latter case  $\Delta\Delta G_p$  will be less accurate because the  $\rho$  value (4.496) is well outside the range  $1 \leq \rho \leq 2$ .<sup>19</sup>

TABLE 2

Equation <sup>a</sup>	$\rho$	$r$	Correlation coefficient	Standard deviation $S_{y/x}$
$\log(k/k_H) = \rho\sigma^n$	-2.81		0.946	0.232
$\log(k/k_H) = \rho_m\sigma_m^n$ <sup>b</sup>	-2.17		0.998	0.032
$\log(k/k_H) = \rho[\sigma^n + r(\sigma^- - \sigma^n)]$	-2.14	0.741	0.990	0.110
$\log(k/k_H) = \rho\sigma^-$	-1.93	1.000	0.988	0.134

<sup>a</sup> *p*-CO<sub>2</sub>H and *m*-CO<sub>2</sub>H substituents were not considered in any of the equations. <sup>b</sup> Only H, *m*-F, *m*-Cl, *m*-Br, *m*-I, and *m*-NO<sub>2</sub> substituents with their primary  $\sigma^n$  values were considered.

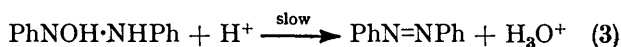
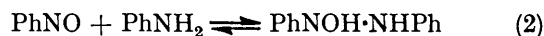
In the case of ethyl *p*-aminobenzoate, the value of  $\Delta\Delta G_p$  was 0.66 kcal mol<sup>-1</sup>, obtained using  $\sigma^n$  for *p*-CO<sub>2</sub>Me, since a  $\sigma^n$  constant for *p*-CO<sub>2</sub>Et has not been tabulated. This  $\Delta\Delta G_p$  value compares with  $\Delta\Delta G_p$  values of the

<sup>19</sup> P. Wells, *Chem. Rev.*, 1963, **63**, 171.

<sup>20</sup> E. F. Pratt and M. J. Kamlet, *J. Org. Chem.*, 1961, **26**, 4029.

between a molecule of acid catalyst and the nitrosobenzene oxygen, on the aniline, as the reaction rate is increased by electron-donating groups and decreased by electron-accepting groups in the aniline and *vice versa* in the nitrosobenzene.

However, the similar behaviour of the substituents in this reaction with respect to condensation between benzaldehyde and aniline,<sup>20</sup> and the similar correlation with the Yukawa-Tsuno equation of this reaction and the Schiff's base formation between benzaldehyde and *t*- or *n*-butylamine in dioxan<sup>21</sup> show that it is not possible to exclude a mechanism which involves a rapid and reversible interaction between the nitrosobenzene and the aniline to give the complex which then reacts with the acid in the rate-determining step [equations (2) and (3)].<sup>22</sup>



<sup>21</sup> T. I. Crowell, C. E. Bell, and D. H. O'Brien, *J. Amer. Chem. Soc.*, 1964, **86**, 4973.

<sup>22</sup> E. H. Cordes and W. P. Jencks, *J. Amer. Chem. Soc.*, 1962, **84**, 832.

The low  $\rho$  value (1.22) obtained by Ogata and Takagi<sup>5</sup> for the reaction of substituted nitrosobenzenes with aniline is also consistent with this mechanism, since the effect of any substituent in the equilibrium [equation (2)] is opposed to its effect in the dehydration [equation (3)]. Hence the reaction becomes rather insensitive to polar effects of the substituents.

The value of the parameter  $r$  of the Yukawa-Tsuno equation and those of  $\Delta\Delta G_p$  suggest that in the transition state the reaction centre cannot substantially conjugate with *para*-substituents of aniline. Thus if the rate-determining step is the aniline attack on protonated nitrosobenzene, the formation of the N-N bond must have proceeded to a marked extent; while if the rate-determining step is the dehydration, the breaking of the N-H bond must be starting in the transition state.

When the experimental ratio  $\log(k_p/k_H)/\log(k_m/k_H)$  is compared with the ratio  $\sigma_p/\sigma_m$ <sup>23</sup> *i.e.* when the relative effect of a substituent in the *para*-position with respect to the *meta*-position in any reaction is compared with the same relative effect in substituted benzoic acids (Table 3), the substituents NO<sub>2</sub>, CO<sub>2</sub>H, and CO<sub>2</sub>Et show

TABLE 3

Substituent	$\sigma_p/\sigma_m$	$\frac{\log(k_p/k_H)}{\log(k_m/k_H)}$
F	0.184	-0.099
Cl	0.608	0.562
Br	0.594	0.580
I	0.512	0.671
NO <sub>2</sub>	1.096	1.706
CO <sub>2</sub> H	1.216	3.097
CO <sub>2</sub> Et	1.216	2.305
CF <sub>3</sub>	1.256	1.321

greater reactivity in the *meta*-position than in the *para*-position owing to their conjugative effects through the aromatic ring with the amino-group. The *m*-CO<sub>2</sub>H is twice as reactive as the *p*-CO<sub>2</sub>H group. The *m*-CO<sub>2</sub>H- and *p*-CO<sub>2</sub>H-anilines were not considered in the correlations between apparent second-order rate constants and various  $\sigma$  parameters (Table 2), because they show larger and lower reaction rates respectively than those predicted from their  $\sigma$  values. This effect can be attributed to participation of *m*-CO<sub>2</sub><sup>-</sup>, and in the second case to the mesomeric effect of the carbonyl group that is in the opposite direction to the inductive effect of the *p*-CO<sub>2</sub><sup>-</sup> group.

This view is supported by the observed variation of the apparent second-order rate constant ( $k_2$ ) for *p*-Me-, *m*-NO<sub>2</sub>-, *p*-CO<sub>2</sub>H-, and *m*-CO<sub>2</sub>H-anilines as well as for aniline<sup>5</sup> as a function of the concentration of AcO<sup>-</sup> and AcOH (Table 4). When the AcO<sup>-</sup> concentration is kept constant,  $k_2$  varies linearly with the AcOH concentration in all cases. When the AcOH concentration is kept constant,  $k_2$  shows a linear relationship with 1/(AcO<sup>-</sup>) for aniline,<sup>5</sup> *p*-Me-, and *m*-NO<sub>2</sub>-anilines. On the other hand, *p*- and *m*-aminobenzoic acids show special behaviour (Figure), which can be attributed to the ioniz-

<sup>23</sup> D. H. McDaniel and H. C. Brown, *J. Org. Chem.*, 1958, **23**, 420.

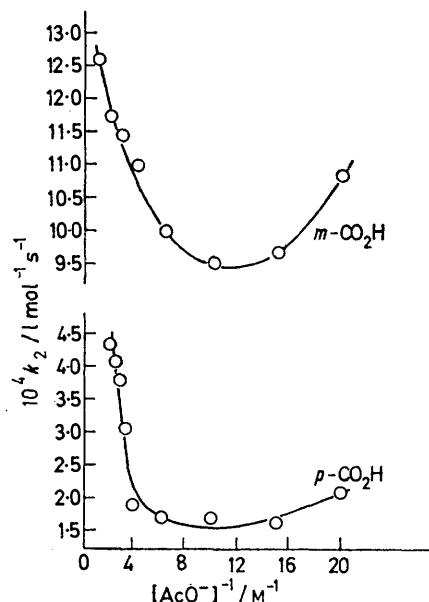
ation of the CO<sub>2</sub>H group, since the other anilines studied showed the theoretically predicted behaviour.

TABLE 4

Observed variation of the apparent second-order rate constant ( $k_2$ ) at 72.5 °C, in buffered solutions with different acetic acid-sodium acetate ratios for the condensation of nitrosobenzene with *p*-CO<sub>2</sub>H-, *m*-CO<sub>2</sub>H-, *p*-Me-, and *m*-NO<sub>2</sub>-anilines

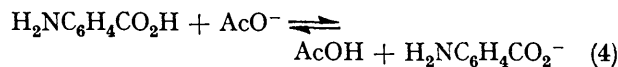
[AcOH]/ M	[AcO <sup>-</sup> ]/ M	Appar- ent pH	10 <sup>4</sup> $k_2$ /l mol <sup>-1</sup> s <sup>-1</sup>			
			<i>p</i> -CO <sub>2</sub> H	<i>m</i> -CO <sub>2</sub> H	<i>p</i> -Me <sup>a</sup>	<i>m</i> -NO <sub>2</sub>
0.88	0.05	5.44	2.07	10.8	118	
0.88	0.067	5.68	1.62	9.70		
0.88	0.10	5.83	1.68	9.50	86.1	1.51
0.88	0.16	5.96	1.69	10.0	73.9	1.06
0.88	0.25	6.07	1.88	11.0	65.9	0.74
0.88	0.30		3.05			
0.88	0.35	6.20	3.79	11.4		
0.88	0.40		4.08			
0.88	0.50	6.34	4.34	11.7	57.8	
0.88	0.90	6.55		12.6		
0.22	0.25	6.74			20.5	
0.44	0.25	6.52	1.66	7.49	35.1	
1.10	0.25	5.94	2.03	11.8	77.3	1.33
1.32	0.25	5.79		14.1	93.5	1.77
1.54	0.25	5.66	2.23	15.2		2.29
1.75	0.25		2.36			

<sup>a</sup> Experimental values at 69.6 °C.



Specific rate constants at 72.5 °C,  $k_2$ /l mol<sup>-1</sup> s<sup>-1</sup>, for the reaction of *m*- and *p*-aminobenzoic acids with nitrosobenzene as a function of 1/[AcO<sup>-</sup>]

At pH values near 5.8 the apparent second-order rate constant is a minimum, but at lower pH values,  $k_2$  increases slowly probably due to proton catalysis. At higher pH values (larger AcO<sup>-</sup> concentration), the rate increases sharply. This can be explained if the equilibrium (4) is considered. The equilibrium (5) is not



likely to be significant in this case, because in 94% (v/v) ethanol<sup>24</sup> *m*-aminobenzoic acid would not exist as a zwitterion in high proportion. Moreover the behaviour of *p*-aminobenzoic acid<sup>20</sup> is similar to a non-charged molecule and in the present study shows a kinetic behaviour very similar to *m*-aminobenzoic acid.

The similar  $pK_a$  values of the *p*- and *m*-aminobenzoic and acetic acids in water<sup>25</sup> and the similar change of  $pK_a$  values of benzoic and acetic acids in ethanol-water,<sup>9</sup> indicate that in the conditions of this work the  $pK_a$  values of the aminobenzoic acids and acetic acid should be similar. Thus, equation (4) should hold.

Shifts of the absorption bands of *p*-aminobenzoic acid from 250 [ $\epsilon$  16,300 ( $0.5 \times 10^{-4}M$ -AcO<sup>-</sup>)] to 287 nm [ $\epsilon$  15,600 ( $7.0 \times 10^{-4}M$ -AcO<sup>-</sup>)] and of *m*-aminobenzoic acid from 221 [ $\epsilon$  19,200 ( $0.5 \times 10^{-4}M$ -AcO<sup>-</sup>)] to 218 nm [ $\epsilon$  18,300 ( $7.0 \times 10^{-4}M$ -AcO<sup>-</sup>)] were observed. These u.v. absorption band shifts with the ionization of aminobenzoic acids were also observed by Doub and Vandenbelt.<sup>26,27</sup>

When changing the concentration of acetate from 0.067 to 0.50M (acetic acid 0.88M) the CO<sub>2</sub>H group in the *p*-aminobenzoic acid was partially ionized. This change promoted a three-fold increase in the reaction rate (Table 4).

In the light of this remarkable susceptibility and to the relatively large distance between the substituent and the nitrogen atom from which the water molecule leaves, it is very doubtful that dehydration could be the rate-determining step. On the other hand, it seems more logical to regard nucleophilic attack on the nitroso-benzene as the rate-determining step owing to the influence of the substituent on the amino-group.

Fluoro-anilines show greater reactivity when the fluorine atom is in the *para*- than in the *meta*-position. This can be attributed to the electron repulsion between the *p* electrons of the fluorine atom and the  $\pi$  electrons of the aromatic ring.

*Activation Parameters.*—A linear relationship is ob-

<sup>24</sup> E. J. Cohn, T. L. McMeekin, J. T. Edsall, and M. H. Blanchard, *J. Amer. Chem. Soc.*, 1934, **56**, 784.

<sup>25</sup> M. M. Davis and H. B. Hetzer, *J. Res. Nat. Bur. Stand.*, 1958, **60**, 569.

<sup>26</sup> L. Doub and J. M. Vandenbelt, *J. Amer. Chem. Soc.*, 1947, **69**, 2714.

<sup>27</sup> L. Doub and J. M. Vandenbelt, *J. Amer. Chem. Soc.*, 1949, **71**, 2414.

tained when  $\Delta H^\ddagger$  is plotted against  $\Delta S^\ddagger$  with a correlation coefficient 0.976 and a  $\beta$  value of 392 K. Using Exner's method<sup>28</sup> a better correlation 0.990 is obtained. Therefore, the activation parameters compensate each other as shown by the constancy of  $\Delta G^\ddagger$  for most compounds (see Table 1).

Experiments carried out at 120 °C show that the reaction of *p*-Me-aniline is approximately eight times more rapid than the *m*-NO<sub>2</sub>-aniline which means that the isokinetic relationship is not satisfied at the temperature corresponding to the correlation mentioned above.

Plots of  $\Delta H^\ddagger$  and  $\Delta S^\ddagger$  vs.  $\sigma^n$  (correlation coefficients 0.793 and 0.696 respectively) or vs.  $\sigma^n + r(\sigma^- - \sigma^n)$  (correlation coefficients 0.778 and 0.670 respectively) show a very poor correspondence, unlike the determinations of Ogata and Takagi<sup>5</sup> for fewer substituents.

This case is similar to other reactions, for instance, aryl isocyanates with methanol,<sup>29</sup> in which according to Ritchie and Sager<sup>30</sup> the Hammett correlation is the result of deviations from the isokinetic plot, or the isokinetic plot is a result of deviations from the Hammett plot.

Leffler and Grunwald<sup>31</sup> suggested that it could be due to the effect of two or more interactions between the substituent and the reaction centre, but this apparently cannot be applied to the present case because the substituents for which only one effect is important give points that scatter.

The reaction is not isoentropic, and considering that all the substituents studied are in the *meta*- and *para*-positions, important steric interactions are unlikely to occur, and the only reasonable explanation is that the entropy changes are the result of the changes in solvation between the reactants and the transition state.

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<sup>28</sup> O. Exner, *Coll. Czech. Chem. Comm.*, 1964, **29**, 1094.

<sup>29</sup> C. N. R. Rao and R. Venkataraghavan, *Tetrahedron*, 1962, **18**, 531.

<sup>30</sup> C. D. Ritchie and W. F. Sager, *Progr. Phys. Org. Chem.*, 1964, **2**, 323.

<sup>31</sup> J. E. Leffler and E. Grunwald, 'Rates and Equilibria in Organic Reactions,' Wiley, New York, 1963, p. 342.