

## Kinetics of the Reactions between Phenylureas and Nitrous Acid. Part 2.† Nitrosation of 2,4,6-Trimethyl- and 4-Bromo-phenylurea

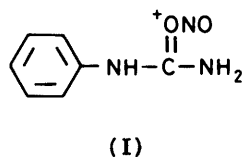
Albino Castro, Manuel González, Francisco Meijide,\* and Manuel Mosquera

Departamento de Química Física, Facultad de Química, Universidad de Santiago de Compostela, Santiago de Compostela, Spain

The kinetics of the reactions between nitrous acid and the 2,4,6-trimethyl and 4-bromo derivatives of phenylurea have been studied at 25 °C in aqueous perchloric acid solution ( $[H^+]$  0.5–2.0 mol dm<sup>-3</sup> and  $\mu$  2.0 mol dm<sup>-3</sup>). The mechanism suggested for the trimethyl derivative is completely analogous to that proposed for phenylurea itself: an initial fast equilibrium step in which the electrophile NO<sup>+</sup> attacks the urea oxygen atom is followed by two parallel reaction paths, both of which begin with the rate-controlling loss of a proton by the protonated *O*-nitroso compound to produce both of its two possible conjugate bases. One of these bases undergoes internal rearrangement to the *N*-nitroso compound, and the other, after a series of fast steps, yields the corresponding benzenediazonium ion. This is the only final product, since the formation of the *N*-nitroso compound is reversible. In the case of 4-bromophenylurea the loss of proton by the protonated *O*-nitroso compound no longer determines the reaction rate of the second of the above reaction paths. The observed kinetics and the suggested reaction mechanism for various ureas allow a value of the order of 0.15 mol<sup>-1</sup> dm<sup>3</sup> to be calculated for the equilibrium constant between NO<sup>+</sup> and substrate on the one hand and the corresponding protonated *O*-nitroso compound on the other. This value implies that for 2,4,6-trimethylphenylurea and phenylurea proton loss is not diffusion-controlled, which is in keeping with the general base catalysis found previously for phenylurea.

Recent work on the reactions of nitrous acid with amides or ureas<sup>1,2</sup> suggests that the *N*-nitroso compound is formed *via* an initial *O*-nitrosation step. A similar mechanism involving the transfer of the NO group from S to N appears to hold in the case of thioureas.<sup>3,4</sup>

In the case of phenylurea (PhU) we have found<sup>2</sup> that the rapid formation of the *O*-nitroso compound (I) is followed by



two parallel reaction paths, both of which begin with the rate-controlling loss of a proton by (I) to produce one of its two possible conjugate bases. One of these bases undergoes internal rearrangement to *N*-nitroso-*N*-phenylurea; the other, after a series of fast steps, yields the benzenediazonium ion, perhaps with the intervention of the primary and unstable *N'*-nitroso-*N*-phenylurea, the other conjugate base of (I). Since the intervention of the nitrosating agent in this latter path cannot be deduced kinetically in the case of PhU, we have studied the nitrosation of two ring-substituted derivatives [2,4,6-trimethyl-(TMPhU) and 4-bromo-phenylurea (BrPhU)] in order to obtain further information. At the same time, we confirmed the initial *O*-nitrosation step and analysed the effect of substituents on the various rate constants.

### Experimental

TMPhU and BrPhU were synthesized by reaction between Merck p.s. potassium cyanate and the corresponding Merck p.s. anilines and recrystallized from ethanol–water.<sup>5</sup> The remainder of the experimental procedure has been described elsewhere,<sup>2</sup>

except that the reaction with TMPhU was followed at 285 nm and the reaction with BrPhU at 292 nm, both of which wavelengths correspond to the absorption maximum of the corresponding product. A large excess of nitrous acid was employed in all experiments so as to guarantee accurate application of the integration method. In all cases it was verified that no more than 5% decomposition had occurred.

### Results and Discussion

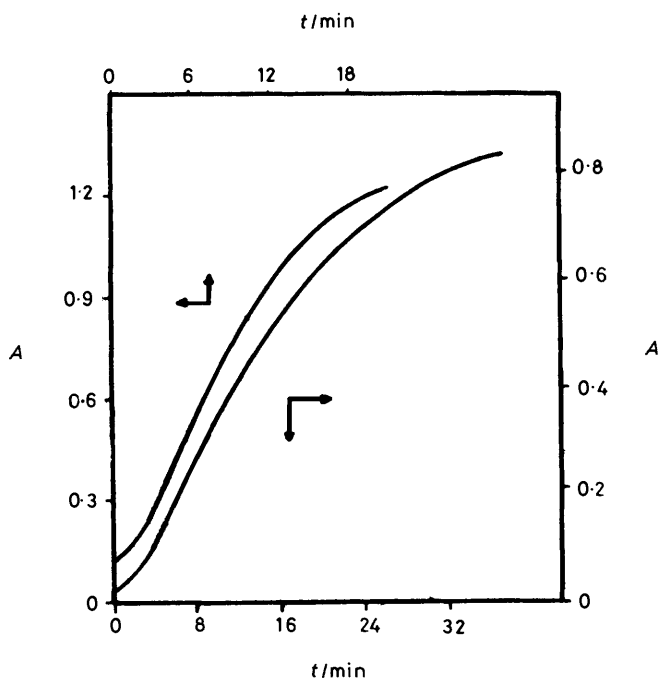
The kinetics observed when studying the nitrosation of TMPhU and BrPhU exhibit a considerable induction period (Figure 1) as in the case of PhU.<sup>2</sup> This suggests that the mechanisms of these reactions are analogous to that of the nitrosation of PhU. Further support for a mechanism of this kind is provided by the established fact<sup>2</sup> that at the acidities used the final products correspond to substituted benzenediazonium ions (in the present work it was verified that the subsequent decomposition of these products is too slow to interfere in the kinetic measurements).

For both substrates investigated, the experimental absorbance–time data fitted a biexponential equation (1) where  $A_t$

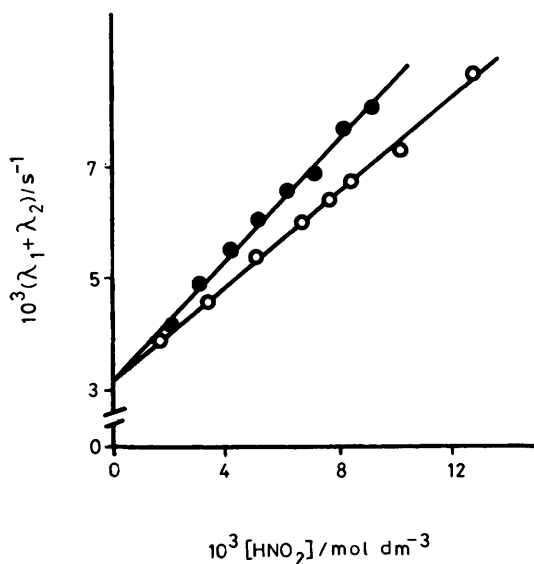
$$A_t = A_\infty + C_1 \exp(-\lambda_1 t) - C_2 \exp(-\lambda_2 t) \quad (1)$$

and  $A_\infty$  are the absorbances of the reaction mixture at times  $t$  and  $\infty$  respectively. The parameters of equation (1) were computed by non-linear optimization on a Univac 1108 computer. In series of experiments in which the concentration of HNO<sub>2</sub> was varied at constant acidity it was found (Figures 2 and 3) that for TMPhU the parameters  $\lambda_1$  and  $\lambda_2$  of equation (1) satisfy the relations (2) and (3) where the value of  $a$  is

† Part 1, ref. 2



**Figure 1.** Absorbance-time graphs for the reactions between nitrous acid and TMPPhU (upper curve) and BrPhU (lower curve). TMPPhU, wavelength 285 nm, [SUBS]  $8.63 \times 10^{-5}$ ,  $[\text{HNO}_2]$   $8.4 \times 10^{-3}$ ,  $[\text{H}^+]$  0.745;  $\mu$  2.0 mol dm $^{-3}$ ,  $T$  25 °C; BrPhU, wavelength 292 nm, [SUBS]  $6.15 \times 10^{-5}$ ,  $[\text{HNO}_2]$   $2.09 \times 10^{-3}$ ,  $[\text{H}^+]$  2.00;  $\mu$  2.0 mol dm $^{-3}$ ,  $T$  25 °C

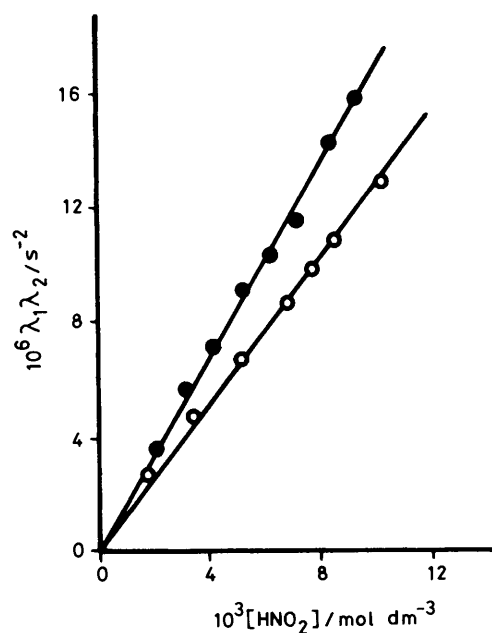


**Figure 2.** Influence of the concentration of nitrous acid on  $\lambda_1 + \lambda_2$  for TMPPhU.  $[\text{H}^+]$  1.80 (●) and 0.745 (○),  $\mu$  2.0 mol dm $^{-3}$ ,  $T$  25 °C

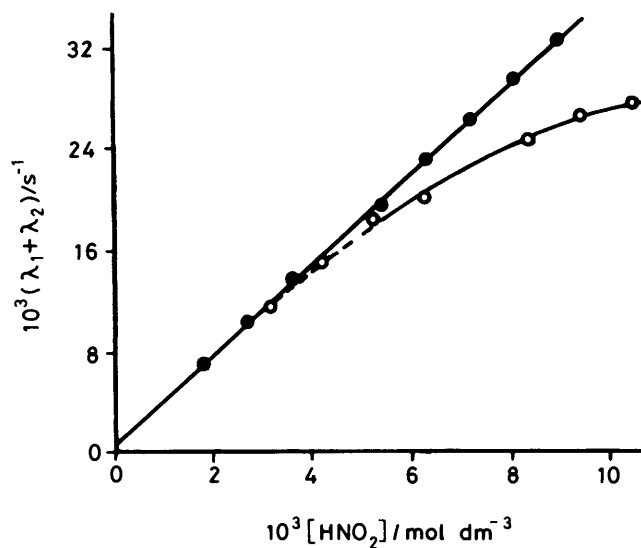
$$\lambda_1 + \lambda_2 = a + b[\text{HNO}_2] \quad (2)$$

$$\lambda_1 \cdot \lambda_2 = c[\text{HNO}_2] \quad (3)$$

independent of the concentration of acid at the acidities considered ( $[\text{HClO}_4]$  0.50–1.80 mol dm $^{-3}$ ). In similar experiments carried out with BrPhU equation (2) held for the lowest acidities employed ( $[\text{HClO}_4]$  1.0–1.5 mol dm $^{-3}$ ) but not at higher



**Figure 3.** Influence of the concentration of nitrous acid on  $\lambda_1 \cdot \lambda_2$  for TMPPhU.  $[\text{H}^+]$  1.80 (●) and 0.745 (○),  $\mu$  2.0 mol dm $^{-3}$ ,  $T$  25 °C



**Figure 4.** Influence of the concentration of nitrous acid on  $\lambda_1 + \lambda_2$  for BrPhU.  $[\text{H}^+]$  1.00 (●) and 2.00 (○),  $\mu$  2.0 mol dm $^{-3}$ ,  $T$  25 °C

acidities (Figure 4), though  $a$ , the ordinate at the origin, apparently remained independent of the acidity of the medium. The behaviour of BrPhU likewise differed from that of TMPPhU as regards the dependence of  $\lambda_1 \cdot \lambda_2$  on the concentration of nitrous acid, which Figure 5 shows to be of the form (4).

$$\frac{[\text{HNO}_2]^2}{\lambda_1 \cdot \lambda_2} = d + e[\text{HNO}_2] \quad (4)$$

Scheme 1 shows the proposed mechanism for the nitrosation of PhU, TMPPhU, and BrPhU (rate and equilibrium constants are numbered as in ref. 2). The first step is the equilibrium for substrate protonation, which must be taken into account at the acidities employed;<sup>6</sup> the second is the equilibrium of formation of the nitrosating agent; and the remaining steps comprise the

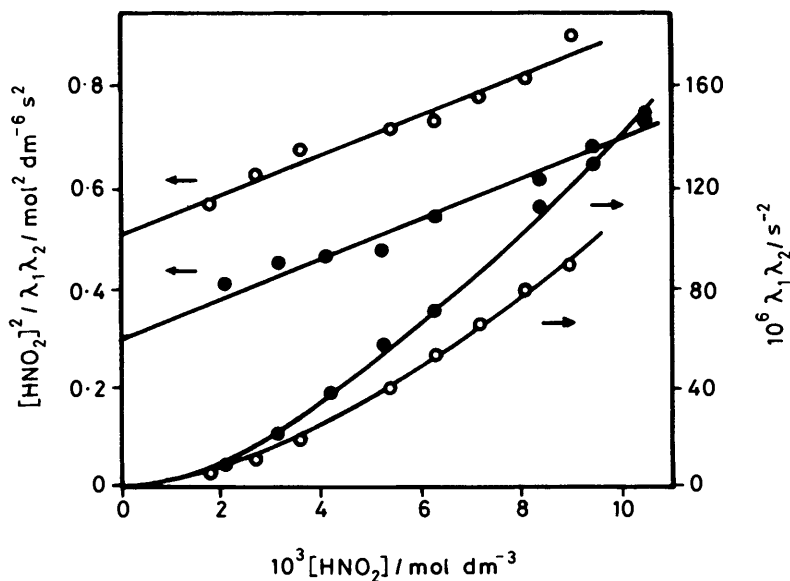
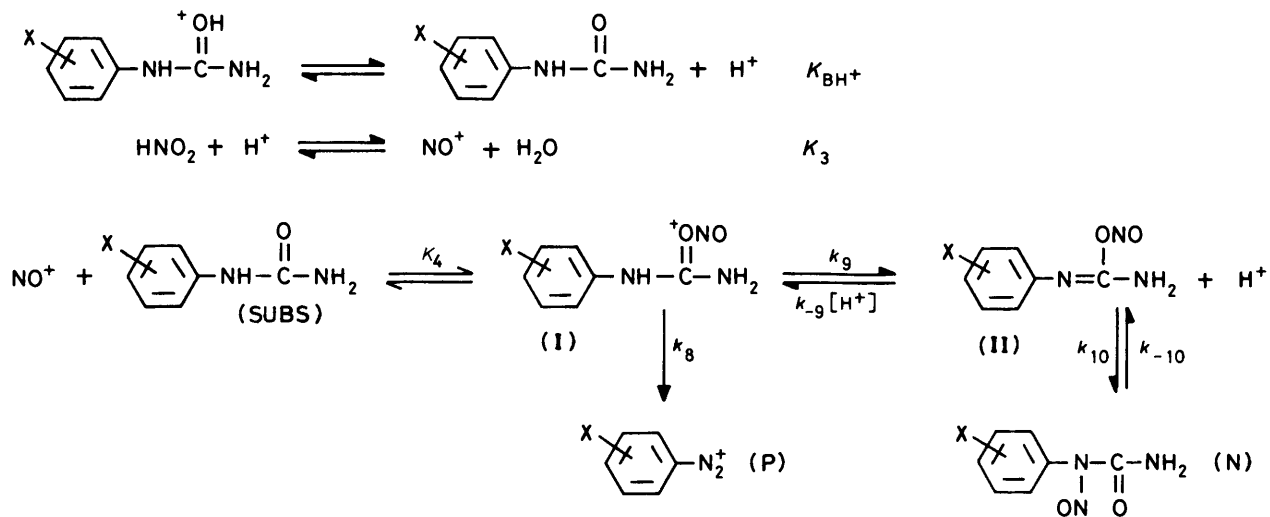


Figure 5. Influence of the concentration of nitrous acid on  $\lambda_1 \cdot \lambda_2$  for BrPhU in accordance with equation (4).  $[H^+] 1.00$  (○) and  $2.00$  (●),  $\mu 2.0 \text{ mol dm}^{-3}$ ,  $T 25^\circ\text{C}$



Scheme 1. X = H, 2,4,6-(CH<sub>3</sub>)<sub>3</sub>, or 4-Br

formation of the initial *O*-nitroso compound and its subsequent conversion into products.<sup>2</sup>

Assuming that the only species of Scheme 1 in appreciable concentration are (SUBS), (N), and (P) and that the intermediate (II) obeys the steady-state approximation, the result of solving the differential equations controlling the concentration of those species yields the absorbance-time dependence (5) where the relations (6)–(8) hold. [SUBS]<sub>0</sub> is the total

$$\begin{aligned}
 A_t = A_\infty + \frac{[\text{SUBS}]_0}{\lambda_1 - \lambda_2} & \left\{ \left[ (\epsilon_P - \epsilon_{\text{SUBS}}) \left( \frac{k'_{-9}k_{-10}}{k'_{-9} + k_{10}} - \lambda_1 \right) \right. \right. \\
 + (\epsilon_P - \epsilon_N) \frac{k_9k_{10}}{k'_{-9} + k_{10}} & \left. \left. \right] \exp(-\lambda_1 t) - \left[ (\epsilon_P - \epsilon_{\text{SUBS}}) \cdot \right. \right. \\
 \left. \left. \left( \frac{k'_{-9}k_{10}}{k'_{-9} + k_{10}} - \lambda_2 \right) \right. \right. & \left. \left. + K'_4 \frac{k_9k_{10}}{k'_{-9} + k_{10}} (\epsilon_P - \epsilon_N) \right] \exp(-\lambda_2 t) \right\} \quad (5)
 \end{aligned}$$

$$k'_{-9} = k_{-9} \cdot h_a \quad (6)$$

$$K'_4 = K_3 K_4 [\text{HNO}_2] h_0 K_{\text{BH}^+} / (K_{\text{BH}^+} + h_a) \quad (7)$$

$$\begin{aligned}
 \lambda_1, \lambda_2 = & \left( \frac{k'_{-9}k_{-10}}{k'_{-9} + k_{10}} + K'_4 \left\{ k_8 + \frac{k_9k_{10}}{k'_{-9} + k_{10}} \right\} \right) \pm \\
 & \left\{ \left[ \frac{k'_{-9}k_{-10}}{k'_{-9} + k_{10}} + K'_4 \left( k_8 + \frac{k_9k_{10}}{k'_{-9} + k_{10}} \right) \right] \right. \\
 & \left. - 4K'_4 k_8 \frac{k'_{-9}k_{-10}}{k'_{-9} + k_{10}} \right\}^{1/2} \quad (8)
 \end{aligned}$$

concentration of substrate. As before,<sup>7</sup> the acidity function  $h_0$  [here adapted for  $\mu 2.0 \text{ mol dm}^{-3}$  (ref. 8)] has been used to describe the concentration of protons in the equilibrium of formation of the nitrosating agent. The acidity function  $h_a$ ,<sup>9</sup> which is typical of the acid-base behaviour of amides and is known to be suitable for describing that of phenylurea,<sup>2</sup> has

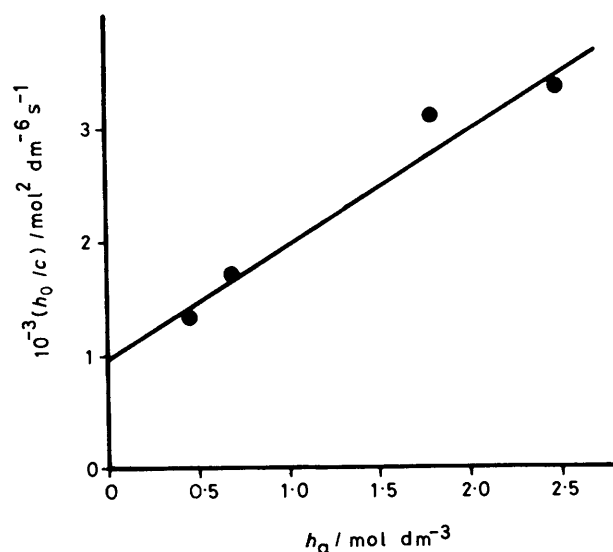


Figure 6. Influence of the acidity of the medium on the parameter  $c$  of equation (3) for TMPPhU, in accordance with equation (12).  $\mu$  2.0 mol  $\text{dm}^{-3}$ ,  $T$  25 °C

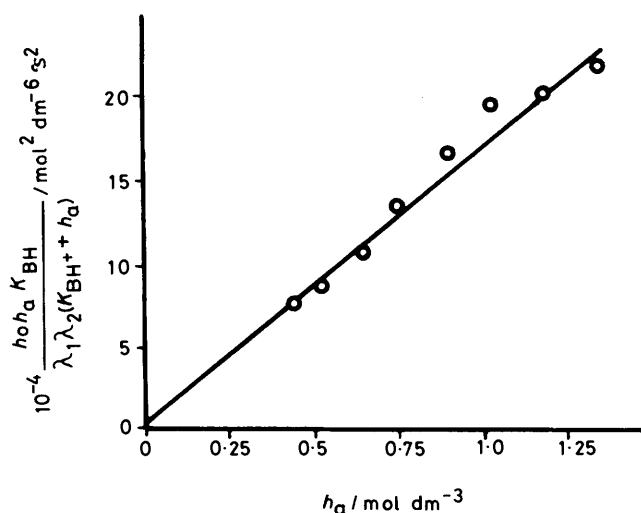


Figure 7. Influence of the acidity of the medium on  $\lambda_1 \cdot \lambda_2$  for TMPPhU in accordance with equation (17).  $[\text{HNO}_2]$   $6.11 \times 10^{-3}$ ,  $\mu$  2.0 mol  $\text{dm}^{-3}$ ,  $T$  25 °C

been used for the protonation equilibrium of the substrates and (by analogy) for the  $k_{-9}$  step, the protonation of the nitroso compound. Equation (5) is of the same form as relationship (1).

Relationships (9) and (10) can be derived from (8) where the

$$\lambda_1 + \lambda_2 = \frac{k'_{-9}k_{-10}}{k'_{-9} + k_{10}} + K'_4 \frac{k_9k_{10} + k_8(k'_{-9} + k_{10})}{k'_{-9} + k_{10}} \quad (9)$$

$$\lambda_1 \cdot \lambda_2 = K'_4 \cdot k_8 \cdot \frac{k'_{-9}k_{-10}}{k'_{-9} + k_{10}} \quad (10)$$

factor  $k'_{-9}k_{-10}/(k'_{-9} + k_{10})$  corresponds to the denitrosation of the *N*-nitroso compound (N): at low acidities the rate-controlling step of this process is the protonation of (II), while at

Table 1. Constants and constants ratios for phenylureas–nitrous acid systems (Scheme 1);  $T$  25 °C;  $\mu$  2.0 mol  $\text{dm}^{-3}$

	$10^3 k_{-10}/\text{s}^{-1}$	$K_3 K_4 k_8 / \text{mol}^{-2} \text{dm}^6 \text{s}^{-1}$	$k_{-9}/k_{10} / \text{mol}^{-1} \text{dm}^3$
TMPhU	$3.2 \pm 0.1$	$0.30 \pm 0.07$	$\approx 30$
BrPhU	$0.7 \pm 0.2$	$17 \pm 7$	$43 \pm 12$
PhU <sup>a</sup>	$12.0 \pm 1.0$	$0.23 \pm 0.03$	$2.4 \pm 1.1$

<sup>a</sup> Ref. 2.

high acidities the rate of denitrosation is controlled by  $k_{-10}$ , the rate of internal rearrangement of (N).

We discuss separately the results for TMPhU and BrPhU because of the different dependence of  $\lambda_1 \cdot \lambda_2$  and  $\lambda_1 + \lambda_2$  on  $[\text{HNO}_2]$ .

(a) *Trimethylphenylurea*.—The experimental results for the dependence of  $\lambda_1 + \lambda_2$  and  $\lambda_1 \cdot \lambda_2$  on  $[\text{HNO}_2]$  (Figures 2 and 3) are perfectly explained by equations (9) and (10), and Scheme 1 may accordingly be proposed for this substrate without any change. The fact that the value of  $a$  in equation (2) is independent of acidity is compatible with (9) if relationship (11)

$$k'_{-9} \gg k_{10} \quad (11)$$

holds in which case  $a = k_{-10}$  (see Table 1). This also implies that the rate of denitrosation of species (N) is controlled by its internal rearrangement (*i.e.* the acidities employed are high for the purposes of the previous paragraph).

The inequality (11) implies that if equations (3) and (10) are compared, then (12) holds. Figure 6 shows that this equation is

$$\frac{h_0}{c} = \frac{1}{K_3 K_4 k_8 k_{-10}} \left( 1 + \frac{h_a}{K_{\text{BH}^+}} \right) \quad (12)$$

perfectly compatible with the experimental results, and yields equations (13) and (14). Similarly, comparison of equations (2)

$$K_3 k_4 k_8 = (3.1 \pm 0.7) \times 10^{-1} \text{mol}^{-2} \text{dm}^6 \text{s}^{-1} \quad (13)$$

$$K_{\text{BH}^+} = (1.0 \pm 0.2) \text{mol} \text{dm}^{-3} \quad (14)$$

and (9) in the light of (11) yields (15) which with equation (14)

$$\frac{b(K_{\text{BH}^+} + h_a)}{h_0 \cdot K_{\text{BH}^+}} = K_3 K_4 \left( k_8 + \frac{k_9 k_{10}}{k_{-9}} \cdot \frac{1}{h_a} \right) \quad (15)$$

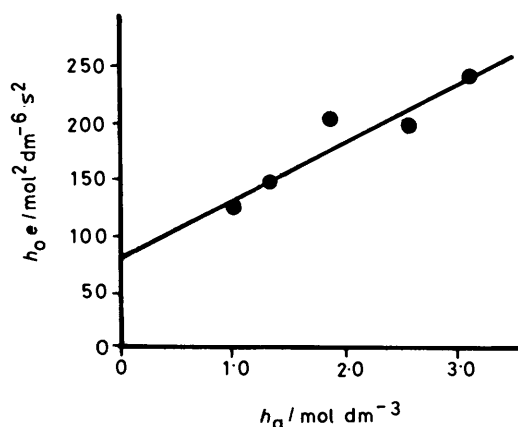
$$K_3 K_4 k_9 k_{10} / k_{-9} = (0.025 \pm 0.005) \text{mol}^{-1} \text{dm}^3 \text{s}^{-1} \quad (16)$$

affords (16) together with a value of  $K_3 K_4 k_8$  quite close to that of equation (13) (Table 1 shows the mean value obtained by these two paths in various series of experiments).

In order to compare the behaviour of different substrates as regards the relative importance of the two paths from (I) to the products in Scheme 1, it is desirable to possess values of the ratio  $k_9/k_8$ , which if the ratio  $k_{-9}/k_{10}$  were known could be calculated from equation (16) and the value of  $K_3 K_4 k_8$  given in Table 1. To determine  $k_{-9}/k_{10}$  we therefore carried out a series of experiments in which  $[\text{HNO}_2]$  remained constant while the acidity was reduced as far as experimentally feasible in an attempt to obtain conditions in which  $k_{-10}$  no longer controlled the rate of denitrosation of (N). Comparison of equation (3) and (10) without the use of (11) leads to equation (17), and Figure 7

**Table 2.** Values of  $K_3K_4k_9$  and Brønsted behaviour for the nitrosation of various compounds at  $T$  25 °C

Compound	$K_3K_4k_9/\text{mol}^{-2}\text{dm}^6\text{s}^{-1}$	Brønsted plot	Reference
<i>N</i> -Methylacetamide	0.0055	Linear, $\beta = 0.49$	1
Ethyl <i>N</i> -ethylcarbamate	0.29	Linear, $\beta = 0.49$	1
TMPPhU	0.75		This work
PhU	0.8	See text	2
<i>N</i> -Methylurea	27	Linear, $\beta = 0.24$	13
Ethylenethiourea	209		4
<i>NN'</i> -Dimethylurea	280	Curve	1
<i>NN'</i> -Dimethylthiourea	645		4
2-Imidazolidone	660		1

**Figure 8.** Influence of the acidity of the medium on the parameter  $e$  of equation (4) for BrPhU, in accordance with equation (21).  $\mu$  2.0 mol  $\text{dm}^{-3}$ ,  $T$  25 °C

$$\frac{h_0 K_{\text{BH}^+} + h_a}{\lambda_1 \lambda_2 (K_{\text{BH}^+} + h_a)} = \frac{1}{K_3 K_4 k_8 k_{-10} [\text{HNO}_2]} \left( \frac{k_{10}}{k_{-9}} + h_a \right) \quad (17)$$

shows the results of fitting the experimental data to this equation using equation (14) for  $K_{\text{BH}^+}$ . The value of  $K_3K_4k_8$  calculated from the slope of Figure 7 is compatible with those obtained previously, but the ordinate at the origin,  $(0.5 \pm 1.3) \times 10^4 \text{ mol}^2 \text{ dm}^{-6} \text{ s}^2$ , statistically negligible, suggests that in spite of our intentions, the inequality (11) held in these experiments too.

An indirect means of estimating  $k_{-9}/k_{10}$  for TMPPhU follows from results on the denitrosation of a series of *N*-nitrosophenylureas<sup>10</sup> which can be studied at acidities low enough for the rate-controlling step to be protonation of the *O*-nitroso compound (II). It was found that the reactivity of substrates with electron-withdrawing substituents was practically constant, whereas substrates with electron-donating substituents obeyed a Hammett-type relationship. From this relationship (18) can be estimated for TMPPhU so that  $k_{-9}/k_{10} \approx 30 \text{ mol}^{-1}$

$$k_{-9}k_{-10}/k_{10} \approx 9 \times 10^{-2} \text{ mol}^{-1} \text{ dm}^3 \text{ s}^{-1} \quad (18)$$

$\text{dm}^3$ , in agreement with supposition (11) which holds for all the acidity conditions in the present work. The last ratio implies the value of  $K_3k_4k_9$  listed in Table 2. Behaviour similar to that reported in ref. 10, though much more pronounced, has been observed in experiments on the denitrosation of 4-substituted *N*-alkylaryl-*N*-nitrosamines by Porai-Koshits *et al.*,<sup>11</sup> who attribute it to the basicity of the amino group of the activated substrates and the polarizability of the N–N bond of those with deactivating substituents.

(b) 4-*Bromophenylurea*.—The results in Figure 4 imply that for BrPhU, as for TMPPhU,  $k'_{-9} \gg k_{10}$ , so that the parameter  $a$  is again equal to  $k_{-10}$ . The value shown in Table 1 is the mean of those determined in a variety of experiments. The behaviour exhibited in Figure 4 at the higher acidities may be explained by supposing  $k_8$ , the only post- $K_4$  step in which nitrous acid is involved (see Introduction), to be given by an expression of the form (19), in which case equation (10) becomes

$$k_8 = \frac{f[\text{HNO}_2]}{g + [\text{HNO}_2]} \quad (19)$$

(20) where  $K''_4 = K'_4/[\text{HNO}_2]$ . Equation (20) is of the same

$$\lambda_1 \cdot \lambda_2 = K''_4 k_{-10} f [\text{HNO}_2]^2 / (g + [\text{HNO}_2]) \quad (20)$$

form as (4), and comparison of the two yields  $d = g/K''_4 k_{-10} f$  and  $e = 1/K''_4 k_{-10} f$ . Indeed, if  $f$  is independent of the acidity of the medium, then  $e$  is given by (21) and that a relation of

$$e = \frac{K_{\text{BH}^+} + h_a}{K_3 K_4 k_{-10} f h_0 K_{\text{BH}^+}} \quad (21)$$

this form does indeed hold is shown by Figure 8, which with equation (21) yields (22) and (23).

$$1/K_3 K_4 k_{-10} f = (8 \pm 3) \times 10^4 \text{ mol}^2 \text{ dm}^{-6} \text{ s}^2 \quad (22)$$

$$K_{\text{BH}^+} = 1.6 \pm 0.5 \text{ mol dm}^{-3} \quad (23)$$

Equation (19) implies that at high  $[\text{HNO}_2]$ , the loss of a proton by (I) to produce the conjugate base (III) (Scheme 2) is no longer the rate-controlling step of the process leading to the 4-bromobenzenediazonium ion. If it is assumed instead that (III) is in the steady state, then it follows that equations (24) and

$$f = k_8 \quad (24)$$

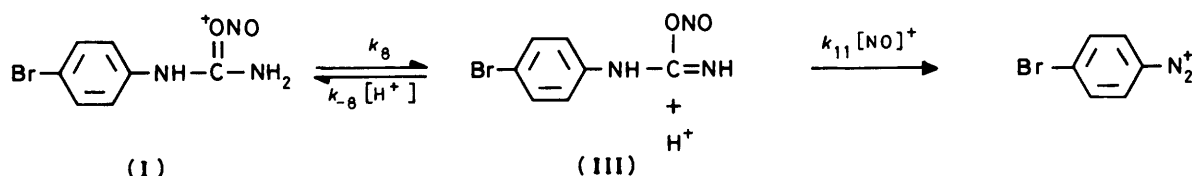
$$g = k'_{-8}/K_3 k_{11} h_0 \quad (25)$$

(25) hold where  $k'_{-8} = k_{-8} h_a$ . By equation (22), and with the value of  $k_{-10}$  listed in Table 1, the first of these relations in turn allows the calculation of  $K_3 K_4 k_8$  (see Table 1), and the second implies that  $g$  ( $\equiv d/e$ ) is proportional to  $h_a/h_0$ . The slope of the straight line obtained when the experimental data are drawn in this way affords  $k_{-8}/K_3 k_{11} = (2.45 \pm 0.14) \times 10^{-2} \text{ mol dm}^{-3}$ ; accepting<sup>12</sup> that  $k_3 = 3 \times 10^{-7} \text{ mol}^{-1} \text{ dm}^3$  then yields  $k_{11}/k_{-8} = (1.36 \pm 0.08) \times 10^8$ .

On the other hand, the value of  $3 \times 10^{-2} \text{ mol}^{-1} \text{ dm}^3 \text{ s}^{-1}$  for  $k_{-9}k_{-10}/k_{10}$  found when studying the denitrosation of *N*-nitroso-*N*-4-bromophenylurea<sup>10</sup> under conditions in which protonation controlled the reaction rate implies that  $k_{-9}/k_{10} = 43 \pm 12 \text{ mol}^{-1} \text{ dm}^3$ .

Values of  $K_3K_4k_9$  for several compounds (some of them studied previously) are shown in Table 2. It is clear that  $K_3K_4k_9$  depends on the nature of the substrate. This may be due to a variation either in  $K_4$  or in  $k_9$ , although a simultaneous variation of both constants cannot be ruled out. Since it is known that for 2-imidazolidone and *NN'*-dimethylurea  $k_9$  is a diffusion-controlled reaction,<sup>1</sup> values of  $K_3K_4$  of  $2.8 \times 10^{-8}$  and  $6.6 \times 10^{-8} \text{ mol}^{-2} \text{ dm}^6$ , respectively, can be calculated. Accepting again that  $K_3 = 3 \times 10^{-7} \text{ mol}^{-1} \text{ dm}^3$  a value of  $0.15 \text{ mol}^{-1} \text{ dm}^3$  is obtained for the equilibrium constant  $K_4$ .

On the basis of the structural similarity of the ureas in Table 2 and for the fact that  $K_4$  is practically the same for a large series of thioureas,<sup>14</sup> we can admit that value for  $K_4$  as representative



Scheme 2.

for ureas. Values of  $k_9$  of  $1.67 \times 10^7 \text{ s}^{-1}$  (TMPhU) and  $1.78 \times 10^7$  (PhU) can be now obtained, in agreement with the general base catalysis found<sup>2</sup> for PhU.

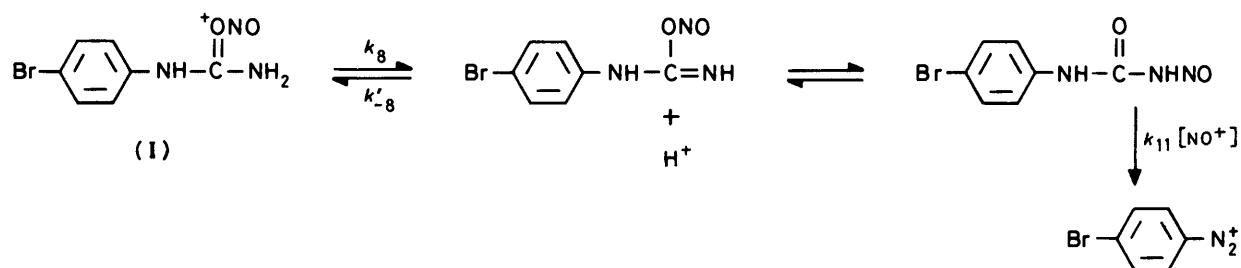
From Table 2 it could be expected that a linear Brønsted behaviour was also found for PhU. However, for this urea in parallel with  $k_9$  (leading to *N*-nitrosophenylurea) a second reaction,  $k_8$  (leading finally to benzenediazonium ion), also takes place. The latter also involves proton loss and is, therefore, subject to general base catalysis. Since it is not possible to choose experimental conditions to study the reactions separately [ $k_9/k_8 = 3.6 \pm 1.5$  (ref. 2)], a conclusive Brønsted relationship cannot be established. A similar conclusion is expected for TMPhU in view of the value of 2.5 for the ratio  $k_9/k_8$  calculated from Tables 1 and 2.

Although the values of  $K_4K_4k_9$  for some ureas and thioureas are very close to each other (Table 2), which imply similar experimental nitrosation rates, this is a consequence of two different facts which act in opposite directions: the value of  $K_3K_4$  for thioureas (*ca.*  $5\,000 \text{ mol}^{-2} \text{ dm}^6$ ) is much larger than for

TMPhU as intermediate between that of PhU and BrPhU (Table 1, columns 1 and 2).

Finally, values of  $k_9k_{10}/k_{-9}k_{-10}$  may be calculated from Table 1 and from the results of the denitrosation studies<sup>10</sup> on both TMPhU and PhU. These values lead to an overall  $\text{p}K_a$  (corresponding to both proton loss and subsequent internal rearrangement) of  $-8.25$  and  $-8.8$ , respectively, which seem to be reasonable for this kind of compound, especially when they are compared with those for alkylureas<sup>1</sup> (*ca.*  $-12$ , from  $\text{p}K_9$  *ca.*  $0$  and  $\text{p}K_{10}$  *ca.*  $-12$ ).

For BrPhU we have been able to obtain further information on the parallel reaction by calculating the ratio  $k_{11}/k_{-8}$ . Assuming now that the reaction between  $\text{NO}^+$  and the substrate (in the form of an intermediate) is diffusion-controlled (as for amines,<sup>15-17</sup> certain ureas,<sup>1</sup> and thioureas<sup>14</sup>) a maximum value of  $72 \text{ s}^{-1}$  is obtained for  $k_{-8}$ . This value together with that of  $k_8$  (from Table 1) lead to a minimum  $\text{p}K$  *ca.*  $6.7$  corresponding to the proton-loss step. In view of the results reported in the previous paragraph we think that this value is



Scheme 3.

ureas but the value of  $k_9$  for the former substrates [*ca.*  $0.2 \text{ s}^{-1}$  (ref. 4)] is much smaller than for the latter, cancelling each other. The first of these facts has been explained<sup>4</sup> by the suggestion that back-donation of sulphur  $3p$  electrons to a  $\pi^*$  orbital of the nitroso group leads to the increased stability of the thionitrosyl compounds. Perhaps, this may be supported by the very similar  $\text{p}K_a$  values of ureas and thioureas; in this equilibrium, back-donation is not possible. On the other hand, the much higher rates of proton loss,  $k_9$ , for ureas have been ascribed<sup>4</sup> to the considerably greater electronegativity of oxygen than of sulphur, reducing the electron density at the nitrogen acid and thus facilitating proton loss.

For the compounds studied in the present work, the assumption of a constant value for  $K_3K_4$  and the values of  $K_3K_4k_8$  listed in Table 1 show that  $k_8$  is considerably greater for BrPhU than for TMPhU and PhU. Since, furthermore, BrPhU has the smallest  $k_{-10}$  value, it would seem that formation of the  $\text{C}=\text{N}$  double bond is favoured by the nitrogen atom being terminal and hampered by its conjugation to the ring. This behaviour may be related to the finding<sup>1</sup> that the nitrosation reactivities of a series of ureas and amides (PhU may be included now) are correlated with the ability of the substituent on the  $-\text{C}(=\text{O})-\text{NH}_2$  group to donate charge by resonance, for by donating charge in this fashion the considerable resonance effect of Br at position 4 would destabilize the conjugated double bond. The less pronounced donor effect due to hyperconjugation of the three methyl groups would explain the behaviour of

also compatible with an overall  $\text{p}K_a$ , corresponding not only to the proton loss step but to the posterior rearrangement of the NO group as well (Scheme 3). Given this suggestion the second intervention of the nitrosating agent should be posterior to the rearrangement. Since subsequent steps are fast, a detailed mechanism for the formation of the benzenediazonium ion cannot be deduced kinetically.

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*Received 16th November 1987; Paper 7/2025*