

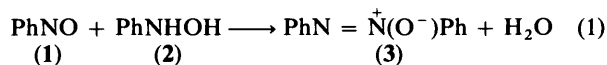
## Azoxybenzene Formation from Nitrosobenzene and Phenylhydroxylamine. A Unified View of the Catalysis and Mechanisms of the Reactions

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Azoxybenzene formation from nitrosobenzene and *N*-phenylhydroxylamine has been studied in the pH range 1–11 with different buffers in 10% methanol at 25 °C and ionic strength 0.5 (KCl). The reaction exhibits general-acid ( $\alpha = 0.29$ ), general-base ( $\beta = 0.15$ ), and specific-base catalysis by hydroxide ion. The plot of  $\log k_2$  ( $k_2$  = second-order rate constant) vs. pH, the specific-base catalysis by hydroxide ion, and the substituent effects demonstrate that in the pH range studied only one step, *i.e.* the dehydration of a *N,N'*-dihydroxy intermediate, rapidly formed from the reagents, is rate-determining. The mechanism suggested in this work is also supported by the general acid- and base-catalysis and by the effect of the solvent polarity on the rate of the reaction. Other mechanisms and intermediates are considered, and shown to be inadequate in explaining all the experimental results.

The condensation of nitrosobenzene (1) with *N*-phenylhydroxylamine (2) to form azoxybenzene (3) [equation (1)] has been studied in a variety of systems. In water and in aqueous methanol solutions, in acidic or neutral conditions, an ionic



mechanism has been suggested by Ogata *et al.*,<sup>1</sup> with the attack of phenylhydroxylamine on protonated or free nitrosobenzene as the rate-determining step. Russell and Geels<sup>2</sup> considered that in an ethanol solution containing sodium hydroxide, phenylhydroxylamine reacts first with hydroxide ion and then with (1) to give a nitrosobenzene radical anion, which in turn produces (3) through an anionic intermediate. In ethanolic Britton-Robinson buffer it has been shown, by Darchen and Moinet,<sup>3</sup> that the reaction exhibits catalysis by hydronium and hydroxide ions and a pH-independent mechanism. The results were explained by assuming a rate-determining step of dehydration of an *N*-hydroxy-*N'*-oxide intermediate; this latter is formed by a rapid equilibrium between two phenyl nitroxide radicals produced by a redox reaction between (1) and (2). Mulvey and Waters,<sup>4</sup> following Bowman *et al.*,<sup>5</sup> have suggested that a mixture of (1) and (2), in 30% *t*-butyl alcohol, results in the formation of aryl nitroxide radicals and then in (3). In contrast with the Darchen and Moinet intermediate, other authors have postulated the formation of a *N,N'*-dihydroxy intermediate.<sup>6,7</sup>

The fact that there is much controversy<sup>1–7</sup> about the mechanism of azoxybenzene formation, and the lack of detail on the general-acid and base catalysis, have provided the impetus for this work. The results reported in this paper clearly demonstrate the presence of general-acid and specific-base catalysis for the hydronium- and hydroxide-ion-catalysed reaction. Additionally, a single rate-determining step in the pH range 1–11, namely the dehydration of a *N,N'*-dihydroxy intermediate, is demonstrated.

### Results and Discussion

The pH-dependence of the observed pseudo-first-order rate constant ( $k_{\text{obs}}$ ) for the formation of (3), extrapolated to zero buffer concentration, is shown in Figure 1. The pH-rate profile indicates acid-catalysed condensation reaction at low pH, base-catalysed formation of (3) at high pH, and a pH-independent pathway in the pH range 4–9.

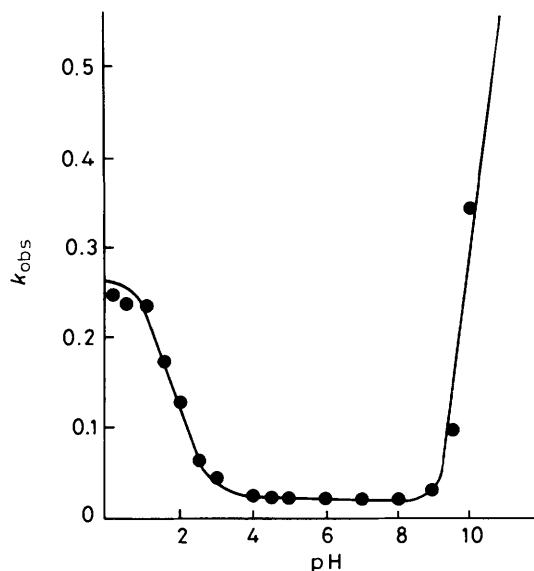


Figure 1. pH-dependence of the observed pseudo-first-order rate constant for azoxybenzene formation from nitrosobenzene ( $2 \times 10^{-3}$  mol dm<sup>-3</sup>) and phenylhydroxylamine ( $10^{-4}$  mol dm<sup>-3</sup>) in 10% methanol at 25 °C and ionic strength 0.5 mol dm<sup>-3</sup>. Solid line calculated from equation (2) and Table 1.

Equation (2) is consistent with the experimental results,

$$k_{\text{obs}} = k_{\text{H}}[\text{PhNO}][\text{H}^+]K_{\text{a}}/\{K_{\text{a}} + [\text{H}^+]\} + k_0[\text{PhNO}] + k_{\text{OH}}[\text{PhNO}][\text{OH}^-] \quad (2)$$

including terms for acid ( $k_{\text{H}}$ ) and base ( $k_{\text{OH}}$ ) catalysis and a pH-independent pathway ( $k_0$ ). In fact, the line in Figure 1 was calculated using equation (2) with the rate constants given in Table 1 and the acid dissociation constant of phenylhydroxylammonium ion ( $K_{\text{a}} = 0.0141$  mol dm<sup>-3</sup>). The plateau observed below pH 2 can be explained by extensive protonation of (2). In acidic conditions equation (2) can be simplified to equation (3)

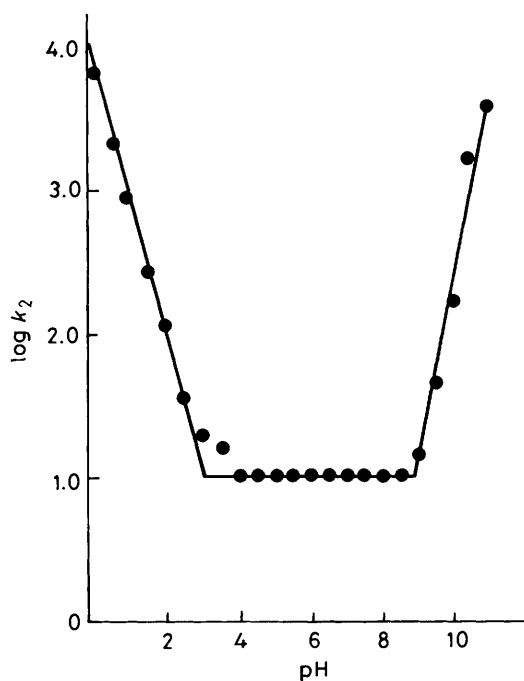
$$k_{\text{obs}} = k_{\text{H}}[\text{PhNO}][\text{H}^+]K_{\text{a}}/\{K_{\text{a}} + [\text{H}^+]\} \quad (3)$$

which in turn, when  $[\text{H}^+] \gg K_{\text{a}}$ , reduces to equation (4).

$$k_{\text{obs}} = k_{\text{H}}[\text{PhNO}]K_{\text{a}} \quad (4)$$

Accordingly a plateau should be observed at low pH values.

The  $\text{p}K_{\text{a}}$  of (2) determined from the plot of Figure 1 (*i.e.* 1.90) is different from that given in the literature ( $\text{p}K_{\text{a}} = 3.2$ ).<sup>8</sup> However, a spectroscopic  $\text{p}K_{\text{a}}$  determination of (2) under our



**Figure 2.** pH-dependence of the logarithms of second-order rate constants for azoxybenzene formation from nitrosobenzene ( $2 \times 10^{-3}$  mol dm<sup>-3</sup>) and phenylhydroxylamine ( $10^{-4}$  mol dm<sup>-3</sup>) in 10% methanol at 25 °C and ionic strength 0.5 mol dm<sup>-3</sup>. All rate constants have been extrapolated to zero buffer concentration.

**Table 1.** Rate constants for the formation of azoxybenzene from nitrosobenzene and phenylhydroxylamine.<sup>a</sup>

Rate constants	Values/dm <sup>6</sup> mol <sup>-2</sup> min <sup>-1</sup>
$k_{\text{H}}$	$9.2 \times 10^3$
$k_{\text{O}}$	10.5
$k_{\text{OH}}$	$2.75 \times 10^6$

<sup>a</sup> 10% aqueous methanol, 25 °C, ionic strength 0.5 (KCl).

experimental conditions gives a value of 1.85 which is consistent with the value calculated from the kinetic data. The difference between the  $\text{p}K_{\text{a}}$  reported in the literature and our value is too large to be caused by different experimental conditions; it seems that the literature value is in error. The dependence of the second-order rate constant ( $k_2$ ) on pH is shown in Figure 2.

The third-order rate constants determined in the presence of the buffers were plotted against the molar fraction of free acid for several different concentrations and a least-square fit was made (plots not shown). The right-hand intercept gives the catalytic constant for the acidic component of the buffer ( $k_{\text{AH}}$ , Table 2) whereas the left-hand intercept (where the fraction of free acid equals zero) gives the catalytic constant for the basic component of the buffer ( $k_{\text{B}}$ ), a maximum error of 5% for  $k_{\text{B}}$  and  $k_{\text{AH}}$  value being considered acceptable. Changing the ionic strength from 0 to 1.2 (KCl) does not affect the second-order rate constant, which indicates that the buffer effect is due to catalysis and not to ionic strength changes.

**Specific- and General-base Catalysis.**—The Brønsted plot for the formation of azoxybenzene, catalysed by different bases, is shown in Figure 3 ( $\beta = 0.15$ ,  $r = 0.999$ ). The linear correlation indicates that the extent of proton transfer at the transition state is insensitive to base strength, in the  $\text{p}K_{\text{a}}$  range studied. For the hydroxide-ion-catalysed reaction a large positive deviation is observed, which is  $7.6 \times 10^3$  times larger than that predicted from the Brønsted plot. From the observation that the hydroxide-ion catalysis is two orders of magnitude larger than expected, on the basis of the Brønsted line for carboxylate-catalysed decomposition of formaldehyde hydrate, Jencks *et al.*<sup>9</sup> suggested that the hydroxide-ion reaction is mechanistically different from the base-catalysed reaction.

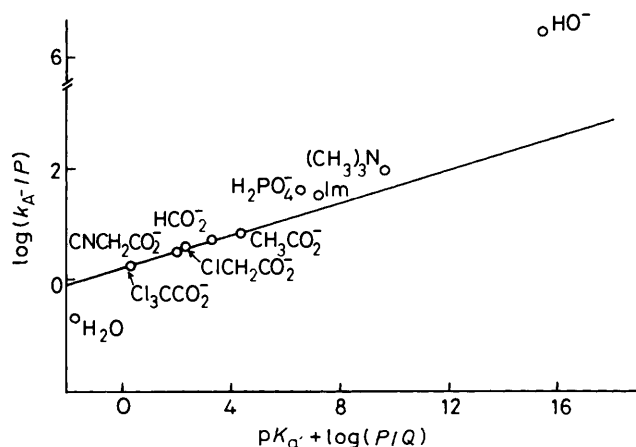
Following Jencks' reasoning, the large positive deviation of the experimental value for hydroxide-ion catalysed azoxybenzene formation reaction, with respect to the predicted value from the Brønsted line, is strong evidence for specific-base catalysis by hydroxide ion (other evidence will be discussed later).

To determine the nature of the general-base catalysis, experiences were performed at pH = 7.5 with different concentrations of acetate and formate. Both bases showed catalysis, *i.e.* evidence that the mechanism is of true general-base catalysis, since at this pH value the concentration of the acid form is negligible, and the observed catalysis corresponds to that effected by the bases. The co-existence of stepwise and concerted mechanism of base catalysis is one of the most significant findings of this work.

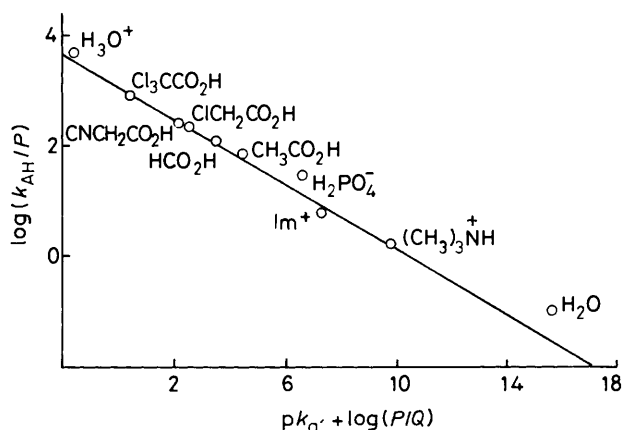
**Table 2.** Rate constants for general-acid and -base catalysed azoxybenzene formation from nitrosobenzene and phenylhydroxylamine.<sup>a</sup>

Catalyst	$\text{p}K_{\text{a}}^b$	Buffer range (total)/mol dm <sup>3</sup>	$k_{\text{AH}}/\text{dm}^6 \text{ mol}^{-2} \text{ min}^{-1}$	$k_{\text{B}}/\text{dm}^6 \text{ mol}^{-2} \text{ min}^{-1}$
H <sub>2</sub> O	15.70 <sup>c</sup>	—	0.21	$2.75 \times 10^6$
(CH <sub>3</sub> ) <sub>3</sub> NH <sup>+</sup>	9.76	0.1–0.5	1.60	$1.04 \times 10^2$
Imidazolium	7.02	0.08–0.4	$1.20 \times 10$	$3.50 \times 10$
H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	6.78	0.08–0.35	$5.60 \times 10$	$1.40 \times 10^2$
CH <sub>3</sub> CO <sub>2</sub> H	4.67	0.1–0.5	$7.00 \times 10$	$1.50 \times 10$
HCO <sub>2</sub> H	3.69	0.1–0.5	$1.20 \times 10^2$	$1.10 \times 10$
ClCH <sub>2</sub> CO <sub>2</sub> H	2.76	0.1–0.5	$2.20 \times 10^2$	8.10
CNCH <sub>2</sub> COH	2.36	0.1–0.5	$2.60 \times 10^2$	6.90
Cl <sub>3</sub> CCO <sub>2</sub> H	0.65	0.1–0.5	$7.8 \times 10^2$	3.70
H <sub>3</sub> O <sup>+</sup>	-1.70 <sup>d</sup>	0.1–0.5	$1.44 \times 10^4$	0.21

<sup>a</sup> 10% aqueous methanol, 25 °C, ionic strength 0.5 (KCl). <sup>b</sup> Determined by potentiometric titration or from the observed pH values of buffers at 25 °C, 10% aqueous methanol, ionic strength 0.5 (KCl), unless otherwise quoted. <sup>c</sup> Value considering the molecular weight of water. <sup>d</sup> L. P. Hammett 'Physical Organic Chemistry,' 2nd edn., McGraw-Hill, New York, 1970, p. 23, considering the molecular weight of water.



**Figure 3.** Brønsted plot for general-base catalysed formation of azoxybenzene from nitrosobenzene and phenylhydroxylamine in 10% methanol at 25 °C and ionic strength 0.5 mol dm<sup>-3</sup>.



**Figure 4.** Brønsted plot for general-acid catalysed formation of azoxybenzene from nitrosobenzene and phenylhydroxylamine in 10% methanol at 25 °C and ionic strength 0.5 mol dm<sup>-3</sup>.

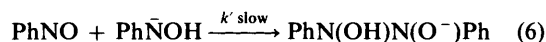
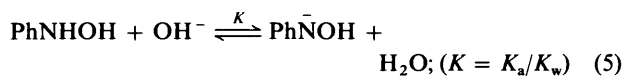
**General-acid Catalysis.**—The catalytic rate constants for different acids follow the Brønsted relationship (Figure 4) and give a value of  $\alpha = 0.29$  ( $r = 0.997$ , statistical corrections were applied according to the method of Bell and Evans<sup>10</sup>). The  $pK_a$  range of the acids used was approximately 12 units and in this range the Brønsted coefficient shows no change with increasing acidity of the acids. This fact corresponds to a coefficient  $p_x = \delta\alpha/\delta(pK_a) \geq 0$  and is expected for a concerted mechanism with proton participation in the formation or rupture of bonds from heavy atoms in the transition state. Experiments performed at pH = 3.17 with different concentrations of acetic acid showed a value of the catalytic constant which agrees acceptably well with that obtained from the plot of second-order rate constant *vs.* molar fraction of free acid. This result indicates that the mechanism is of true general-acid catalysis and not specific-acid/general-base catalysis.

**Rate-determining Step of the Reaction.**—Different reactive species and intermediates have been suggested for the reaction of phenylhydroxylamine and nitrosobenzene.<sup>1–7</sup> No intermediate was shown experimentally.

The reaction of nitrosobenzene with aromatic amines exhibits a similar mechanism to that of carbonyl compounds with nitrogen nucleophiles<sup>11</sup> and so it is possible to assume that the azoxybenzene formation proceeds analogously to the reaction

of nitron formation from *p*-chlorobenzaldehyde and *N*-methylhydroxylamine.<sup>12</sup> Thus, the reaction will proceed *via* a two-step process, namely initial attack of the nucleophile on the nitroso compound to give an addition *N,N'*-dihydroxy intermediate and a second step where the intermediate undergoes an elimination to give the product.

If the nucleophilic attack of some species of phenylhydroxylamine on nitrosobenzene is rate-determining, the specific-base catalysis could be explained by equations (5)–(7). This



mechanism is similar to that proposed by Brown and Kipp<sup>13</sup> for the reaction between nitrosobenzene and aniline. It corresponds to an initial deprotonation of phenylhydroxylamine followed by attack of the anion on nitrosobenzene as the rate-determining step. For this mechanism the rate law is given by equation (8),

$$v = k_{\text{exp}} [\text{PhNO}][\text{PhNHOH}][\text{OH}^-] \quad (8)$$

where  $k_{\text{exp}} = k'K_a/K_w$  and accordingly  $k' = k_{\text{exp}}K_w/K_a$  ( $K_a$  = acid dissociation constant of phenylhydroxylamine). The  $pK_a$  value for the dissociation of phenylhydroxylamine ( $\text{PhNHOH} \rightleftharpoons \text{Ph}\bar{\text{N}}\text{OH} + \text{H}^+$ ) was calculated using the  $\Delta pK_a$  method [equation (9)], with values of 35,<sup>14</sup> 9.25,<sup>15</sup> and 1.85<sup>16</sup> for the  $pK_a$  of  $\text{NH}_3$ ,  $\text{NH}_4^+$  and  $\text{Ph}\overset{+}{\text{N}}\text{H}_2\text{OH}$ , respectively.

$$pK_a(\text{PhNHOH}) = pK_a(\text{NH}_3) - 1.3[pK_a(\text{NH}_4^+) - pK_a(\text{Ph}\overset{+}{\text{N}}\text{H}_2\text{OH})] = 25 \quad (9)$$

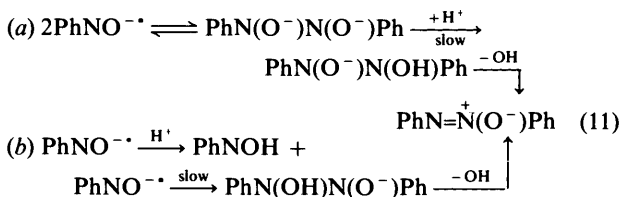
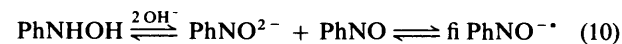
The value of 1.3 corresponds to a sensitivity correction.<sup>17</sup> Using a value of  $2.75 \times 10^6 \text{ dm}^6 \text{ mol}^{-2} \text{ min}^{-1}$  for  $k_{\text{exp}}$  (Table 1) and the calculated  $pK_a$  of 25 for the deprotonation of phenylhydroxylamine, a value of  $2.7 \times 10^{17} \text{ dm}^6 \text{ mol}^{-2} \text{ min}^{-1}$  can be calculated for  $k'$ . This  $k'$  value is larger than the diffusion-controlled limit<sup>18</sup> indicating that deprotonated phenylhydroxylamine is not an intermediate along the reaction pathway.

The attack of free phenylhydroxylamine on nitrosobenzene as the rate-determining step must also be ruled out since it cannot explain the reactivity order (*p*-chlorophenylhydroxylamine > phenylhydroxylamine > *p*-methylhydroxylamine) reported by Knight and Saville,<sup>19</sup> and the similar reactivities, at neutral pH, for 4-cyano-, 3-cyano-, 3-nitro-, and phenylhydroxylamine determined by Darchen and Moinet.<sup>3</sup> Furthermore, in this kind of reaction,<sup>11</sup> the change of the first step (the attack of the nucleophile) to the second step (the dehydration of the intermediate), would, as the rate-determining step, give a negative deviation in the profile of  $\log k_2$  *vs.* pH.<sup>11,20–22</sup> Since this negative deviation is not observed (Figure 1), unlike the reaction between *p*-chlorobenzaldehyde and phenylhydroxylamine, it is evidence that the former reaction only exhibits the dehydration as the rate-determining step over all the pH range studied. Besides, the shape of the curve of  $\log k_2$  *vs.* pH corresponds to that obtained in the reaction between carbonyl compounds and amines when the acid-, water-, and base-catalysed dehydration of the addition intermediate is the rate-determining step.<sup>21,22</sup> In our work the base-catalysed dehydration exhibits both a concerted (general-base catalysed) and a stepwise (specific-base catalysed) mechanism.

**Mechanism of the Reaction.**—The mechanisms proposed by Ogata *et al.*<sup>1</sup> must be ruled out, according to the previous

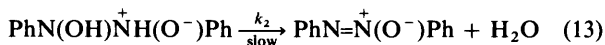
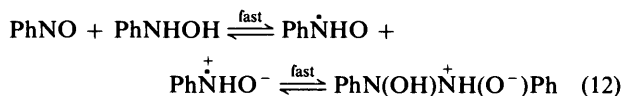
discussion, because they consider the attack of the nucleophile as the rate-determining step. Thus, three different mechanisms must be analysed to see if they are consistent with all the facts now available.

The most widely accepted mechanism,<sup>6,12</sup> in basic conditions, was proposed by Russell and Geels<sup>2</sup> and is described by equations (10) and (11)



Equations (10) and (11) must be ruled out since (a) the experimental evidence is consistent neither with a step where only a process of proton transfer is rate-determining as in equation (11a), nor with the nucleophilic attack as the rate-determining step, as in equation (11b), (b) equations (10) and (11) describe the formation of the ion  $\text{PhNO}^{2-}$ , but as  $\text{PhNOH}^{\cdot-}$  is highly unstable [as demonstrated in equations (5)–(7)] this further ionized species must be even more unstable and hence very improbable, (c) more importantly, equations (11a) and (11b) are not consistent with the true general-base catalysis observed.

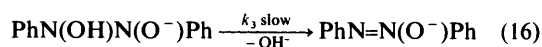
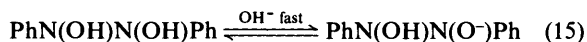
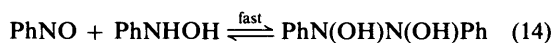
In equations (12) and (13), originally proposed by Darchen and Moinet,<sup>3</sup> the rate-determining step is the dehydration of a *N*-hydroxy-*N'*-oxide intermediate. This intermediate would be formed rapidly and reversibly from two free radicals produced from a redox reaction between nitrosobenzene and phenylhydroxylamine [equation (12)].



The *N*-hydroxy *N'*-oxide intermediate supports the general-acid and -base, and specific-base catalysis observed. However, the mechanism proposed implies that the oxygen of the azoxybenzene must originate from the phenylhydroxylamine. Neiman *et al.*<sup>23</sup> have shown that the reaction between nitrosobenzene and <sup>18</sup>O-labelled phenylhydroxylamine, carried out under different conditions (aqueous alcoholic alkali or aprotic media such as benzene), gave azoxybenzene with 50% of the original <sup>18</sup>O, independent of the conditions. From this fact it is possible to conclude that the oxygen of the azoxybenzene originates in equal proportion from nitrosobenzene and phenylhydroxylamine and accordingly equations (12) and (13) should be ruled out.

Our results give new firm evidence that the reaction proceeds through the formation of a *N,N'*-dihydroxy intermediate. It is possible to see immediately that this symmetrical intermediate satisfies the results of Neiman *et al.*<sup>23</sup> because the two hydroxy groups have the same statistical possibility as leaving groups.

The formation of a *N,N'*-dihydroxy intermediate supports the existence of specific-base catalysis by hydroxide ion [equations (14)–(16)].

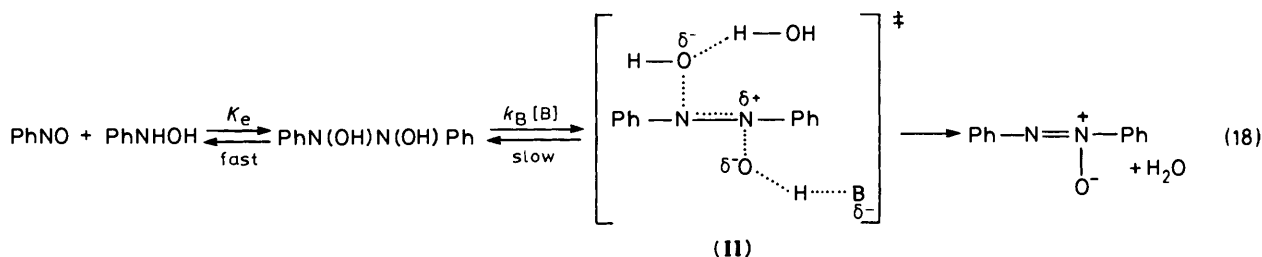
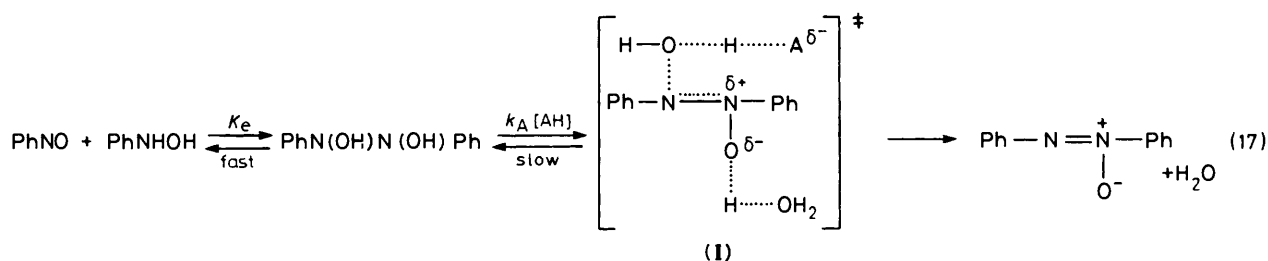


For a compound to act as a true general catalyst, its  $\text{p}K_a$  value must lie between those of the initial and the final substrate site<sup>24</sup> where the proton transfer occurs. The  $\text{p}K_a$  for the first ionization of the hydroxy groups of the *N,N'*-dihydroxy intermediate can be calculated from the  $\text{p}K_a$  of *N*-phenylbenzohydroxamic acid (i.e. 9.15)<sup>25</sup> considering the change caused by the substitution of the  $-\text{COPh}$  group for the  $-\text{N(OH)Ph}$  group. Using the  $\Delta\text{p}K$  method, the acid strengthening effect of  $-\text{COPh}$  group on  $C_a$  is obtained<sup>26</sup> from the  $\sigma^*$  value of 2.26, and is calculated as  $-1.45$ . As this group is directly bonded to the functional group, the effect, assuming normal behaviour, will be  $-1.45/0.4 = -3.61$ . The  $-\text{NH(OH)Ph}$  group can be considered as formed by the  $-\text{NHOH}$  and  $-\text{Ph}$  groups, and the acid strengthening effects of these is calculated from their  $\sigma^*$  values (0.30 and 0.75 respectively)<sup>26</sup> as  $-0.62$  and  $-0.53$ , giving  $\Delta\text{p}K = -1.15$ . Thus the  $\text{p}K_a$  of the dihydroxy intermediate is  $9.15 + 3.61 - 1.15 = 11.61$ . Using the same method and considering the *N*-phenylbenzohydroxamic acid as a derivative of the phenylhydroxylamine, the  $\text{p}K_a$  of this last compound, as an oxygen acid, is  $9.15 + 3.61 = 12.76$ . This value agrees acceptably well with that calculated from the  $\text{p}K_a$  of  $\text{CF}_3\text{CH}_2\text{HNOH}$  (11.3),<sup>15</sup> confirming the accuracy of calculations. Even with an error of 1  $\text{p}K_a$  unit in the values obtained for this method it is clear that the  $\text{p}K_a$  of the dihydroxy intermediate is smaller than the  $\text{p}K_a$  of the hydroxide ion and greater than the  $\text{p}K_a$  of trimethylamine. Thus, catalysis by hydroxide ion must be mechanistically specific. The value of the  $\text{p}K_a$  for the first ionization of the hydroxy groups also supports the true general-base catalysis of the other bases.

Darchen and Moinet<sup>3</sup> have demonstrated that the values of  $k_H$  for 4-cyano- and 4-nitro-phenylhydroxylamine are smaller than the value for phenylhydroxylamine, and that the values of  $k_{OH}$  for the same compounds are greater than the value for phenylhydroxylamine. Equations (14)–(16) are consistent with this fact because the difference of  $k_H$  values can be explained by the unfavourable substituent effect on the equilibrium (14) and the difference of  $k_{OH}$  values by the favourable substituent effect on equilibrium (15) which compensates for the unfavourable effect on equilibrium (14).

The co-existence of stepwise and concerted mechanisms of base catalysis was observed for the attack of hydrogen peroxide on *p*-chlorobenzaldehyde,<sup>27</sup> and is now reported for the dehydration step of azoxybenzene formation. The concerted mechanism demonstrates that, in the dehydration step, the removal of the proton from the hydroxy group by the base catalyst is an important factor of stabilization of the transition state. Analogously, general-base catalysis in the nitron formation, from *p*-chlorobenzaldehyde and *N*-methylhydroxylamine, cannot be ruled out solely on the lack of an hydrogen atom bonded to the nitrogen of the intermediate.<sup>22</sup> The general-base catalysis may well assist the departure of the proton of the hydroxy group, as in the present study.

The observed true general-acid catalysis is also supported by the intermediate proposed. The  $\text{p}K_a$  of the protonated *N,N'*-dihydroxy intermediate was estimated as approximately  $-6.76$  on the following considerations: the  $\text{p}K_a$  of the hydronium ion of  $-1.74$  should be decreased by 3.87 units by the effect of the  $\text{PhNH}-$  group bonded to it  $\{1.3[\text{p}K_a(\text{H}_2\text{O}) - \text{p}K_a(\text{PhNHOH})] = 1.3^{14} (15.74^{15} - 12.76)\}$  (the factor of sensitivity correction of nitrogen compounds is used, which should not introduce significant error) and by 1.15  $\text{p}K$  units by the  $-\text{N(OH)Ph}$  group (as was considered previously). The acidity of the protonated *N,N'*-dihydroxy intermediate is, as expected, greater than that of a protonated azoxybenzene ( $\text{p}K_a = -5.15$ )<sup>28</sup> which has the positive charge on the nitrogen. The proton transfer from the protonated intermediate to water



**Table 3.** Effects of ethanol-water mixtures on the second-order rate constants of formation of azoxybenzene from nitrosobenzene and phenylhydroxylamine.<sup>a</sup>

vol EtOH (%)	$k_2/\text{dm}^3 \text{ mol}^{-1} \text{ min}^{-1}$
100 <sup>b</sup>	5.60
80	9.90
70	11.55
60	13.50
50	14.30
40	14.10
30	13.70
20	12.05
10	10.40
0 <sup>b</sup>	9.50

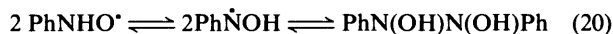
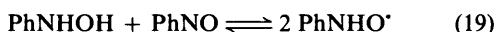
<sup>a</sup> 25 °C, ionic strength 0.5 (KCl). <sup>b</sup> Values obtained by extrapolation.

should be very favourable thermodynamically with no significant Gibbs energy barrier. The instability of the intermediate enforces the mechanistically observed general-acid catalysis.

The general-acid and -base catalysed mechanisms are described, similarly to Becker and Sternson,<sup>6</sup> in equations (17) and (18), structures (I) and (II) representing the transition states. The departures of the proton and of the hydroxide ion, in equations (17) and (18), respectively, are assisted most probably by one or more water molecules.

The catalytic rate constant for  $\text{H}_2\text{PO}_4^-$  is approximately two and three times greater than those expected from the Brønsted plots for general-acid and -base catalysis, respectively. Enhanced catalytic reactivity (tenfold) of  $\text{H}_2\text{PO}_4^-$  has been observed in a number of cases.<sup>29-31</sup> Some form of bifunctional catalysis<sup>29,30</sup> or electronic interaction<sup>32</sup> in the transition state is usually invoked to explain this fact. In this case  $\text{H}_2\text{PO}_4^-$  will probably act as a weak bifunctional catalyst as otherwise proton transfer would have to occur in the  $N,N'$ -dihydroxy intermediate. This would occur through a nine-membered ring, which would be a very unfavourable arrangement.<sup>33</sup>

**Intermediate Formation.**—The rapid formation of the  $N,N'$ -dihydroxy intermediate can be explained *via* the formation of free radicals as proposed by Mulvey and Waters<sup>4</sup> and Ingold *et al*<sup>5</sup> [equation (19)], and by the mechanism suggested by Knight and Seville<sup>19</sup> [equation (20)], or by an ionic mechanism similar



to that proposed for nitron formation.<sup>12</sup> In our experiment two types of radical scavenger were added to the reaction between nitrosobenzene and phenylhydroxylamine, (i) ferrous sulfate which reacts with radical intermediates by donating electrons and (ii) hydroquinone and BHT [2,6-di(*t*-butyl)-4-methylphenol] which react with radical intermediates by donating hydrogen atoms. The results demonstrate that the scavengers did not interfere with the azoxybenzene formation. Although this result is not conclusive proof that the formation of the  $N,N'$ -dihydroxy intermediate does not proceed *via* free radicals, the absence of any compelling evidence for a radical mechanism and the analogy with the nitron formation from *p*-chlorobenzaldehyde and *N*-methylhydroxylamine<sup>12</sup> lead us to assume that  $N,N'$ -dihydroxy intermediate formation occurs by an ionic mechanism. This assumption does not interfere at all with our conclusions, since (as described below) a single step, namely the dehydration of the  $N,N'$ -dihydroxy intermediate, is rate-determining in the pH range studied.

**Solvent Effect.**—In neutral aqueous solutions, when the proportion of ethanol is increased from 10% to 70% by volume, the second-order rate constants initially increase slightly and then decrease rapidly. Extrapolation of the experimental values to 100% water gives a rate constant of  $0.6 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$  that is greater than that in 100% ethanol<sup>19</sup> ( $0.1 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$ ). Extrapolation of our values to pure ethanol gives a rate constant of  $0.09 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$ , in agreement with the above value. The observed initial increase in the rate constant of azoxybenzene formation with reduction of solvent polarity could be explained by a favourable effect on the equilibrium formation of the  $N,N'$ -dihydroxy intermediate and the subsequent decrease at lower polarity (Table 3) could be due to an unfavourable effect on the dehydration step which involves small charge formation. The mechanisms with the suggested *N*-hydroxy-*N'*-oxide or dianion intermediates should give a larger decrease of the rate constant with the reduction of solvent polarity.

## Conclusions

The most significant new conclusions to be drawn from this work are the following:

(a) The reaction between nitrosobenzene and phenylhydro-

xylamine to form azoxybenzene exhibits general-acid, general-base ( $\alpha = 0.29$  and  $\beta = 0.15$ , respectively), and specific-base catalysis by hydroxide ion. General-base (concerted) and specific-base (stepwise) mechanisms are coexistent.

(b) The specific-base catalysis by hydroxide ion, the substituent effect, and the plot of  $\log k_2$  vs. pH for the azoxybenzene formation demonstrate that the dehydration of a *N,N'*-dihydroxy intermediate, which is rapidly formed from the reagents, is rate-determining over the pH range (1–11) studied.

(c) The *N,N'*-dihydroxy-intermediate supports the general-acid and -base catalysis, the specific-base catalysis and the effect of solvent polarity on the rate of the reaction.

## Experimental

**Materials.**—Nitrosobenzene was synthesized and was purified by sublimation.<sup>34</sup> Phenylhydroxylamine was prepared according to Smismann and Corbett<sup>35</sup> and was purified by recrystallization from benzene–light petroleum.

**Kinetic Procedure.**—The solvent in most of the kinetic measurements was a 90% water–10% methanol (v/v) mixture with ionic strength 0.5 (KCl). The reactions were followed spectrophotometrically at 25 °C, by monitoring the formation of azoxybenzene at  $\lambda = 360$  nm. The initial concentrations were  $2 \times 10^{-3}$  mol dm<sup>-3</sup> and  $10^{-4}$  mol dm<sup>-3</sup> for nitrosobenzene and phenylhydroxylamine, respectively. The solutions were prepared immediately before use and degassed with nitrogen. Reactions were followed for three half-lives under the indicated pseudo-first-order conditions. First-order rate constants were calculated from the standard rate equation. Second-order rate constants were calculated by dividing the first-order rate constant  $k_{\text{obs}}$  by the concentration of nitrosobenzene, multiplied by  $f_c$  ( $f_c = K_a/(K_a + [\text{H}^+])$ ), where  $K_a$  is the acid dissociation constant of phenylhydroxylamine ( $k_2 = k_{\text{H}}[\text{H}^+]$  in equation (3)).

**Experiments with Scavengers.**—The experiments with scavengers were carried out in silica cells, with a silicon stopper, containing nitrosobenzene and the trapping agent in 10 to 100-fold molar excess over the phenylhydroxylamine. The cell was degassed with nitrogen and then the phenylhydroxylamine was added. Controls were performed without the trapping agent.

**pK<sub>a</sub> Determination.**—The pK<sub>a</sub> of phenylhydroxylamine in 90% water–10% methanol (v/v) solution with ionic strength 0.5 (KCl) was determined following the spectrophotometric method of Albert and Sergeant.<sup>36</sup> The pH meter was standardized following Bates' method.<sup>37</sup>

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