

# Catalysis in Strongly Acidic Media and the Wallach Rearrangement

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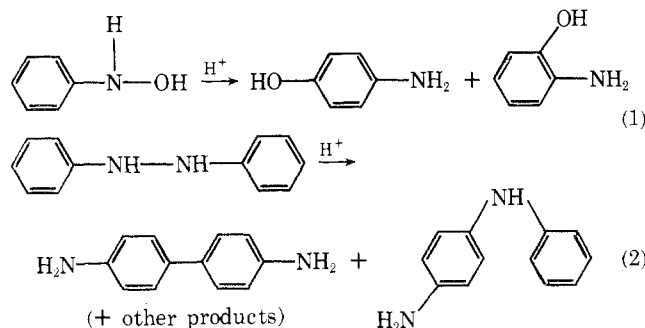
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The study of acid-catalyzed reactions is important since the proton transfer process is fundamental to many areas of chemistry.<sup>1-3</sup>

The experimental observation that in a number of reacting systems the initial proton transfer can trigger an array of reaction sequences is particularly challenging. In such cases the investigator is faced with unravelling both quantitative aspects of the initial proton transfer step and a fairly complex series of processes involving transient reaction intermediates (proven as well as hypothetical) and unknown transition states.

Acid-catalyzed molecular rearrangements have provided fertile territory in the development of concepts which have led to significant advances in our understanding of mechanisms; it is not surprising that they have received extensive study.

Of the numerous known acid-catalyzed rearrangements, of special interest are the Beckmann rearrangement of oximes,<sup>4</sup> the Schmidt rearrangement,<sup>5</sup> the nitramine rearrangement,<sup>6</sup> the Fisher-Hepp rearrangement,<sup>7</sup> the Bamberger rearrangement (eq 1),<sup>8</sup> and the benzidine rearrangement (eq 2).<sup>9</sup> A common link for these transformations is that they all involve, in a formal sense, electron-deficient nitrogen centers.

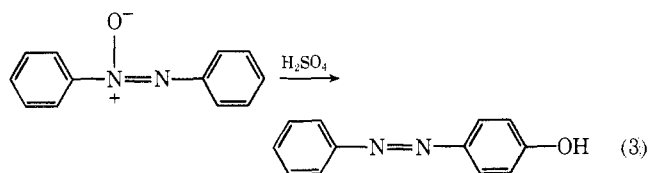


Although the main features of most of these rearrangements have likely been established, none is understood in its entirety. Also, novel experimental approaches periodically bring new perspective to our views of the mechanisms of the transformations. The benzidine rearrangement, however, is unmatched in defying our capability to resolve satisfactorily what appears at first sight to be a relatively simple process. C. K. Ingold,<sup>9a</sup> as one of its chief investigators, was

Erwin Buncel was born in Czechoslovakia and educated in England, receiving the Ph.D. at University College, University of London, in 1957. Postdoctoral work at the University of North Carolina and at McMaster University was followed by a period in industry with the American Cyanamid Company. In 1962 he joined Queen's University as Assistant Professor and is now Professor of Chemistry. Dr. Buncel's research interests cover a number of aspects of physical organic chemistry, especially catalysis in strongly acidic and strongly basic media, deuterium exchange, and kinetic isotope effects.

prompted to show a cloud halving the potential energy-reaction coordinates diagram, stating that "a cloud hangs over the high central region of the mechanistic route, wherein lies the transition state." It is noteworthy that the benzidine rearrangement is an intramolecular process. Also, unlike the majority of acid-catalyzed transformations, it is characterized by the requirement of *two* proton transfers in one of its mechanistic pathways.

It will be shown in this Account that the Wallach rearrangement of azoxyarenes (e.g., eq 3)<sup>10</sup> also in-



volves two proton transfers. However, whereas the benzidine rearrangement normally occurs quite readily in the dilute acid region (e.g., 0.05–1 M HClO<sub>4</sub>), the Wallach rearrangement requires the use of moderately concentrated acid (i.e., 60–100% H<sub>2</sub>SO<sub>4</sub>). The latter characteristic is of particular interest in the present context. The reaction medium in the Wallach rearrangement system can by no means be considered as ideally behaved, whereas the medium in the benzidine rearrangement does approximate such to a close degree.

A brief overview of the sulfuric acid system is needed in order that the kinetic studies of the Wallach rearrangement can be placed in proper perspective, particularly with respect to the possibility of ob-

(1) R. P. Bell, "The Proton in Chemistry," 2nd ed, Cornell University Press, Ithaca, N.Y., 1973.

(2) W. P. Jencks, "Catalysis in Chemistry and Enzymology," McGraw-Hill, New York, N.Y., 1969.

(3) M. L. Bender, "Mechanisms of Homogeneous Catalysis from Protons to Proteins," Wiley, New York, N.Y., 1971.

(4) B. J. Gregory, R. B. Moodie, and K. Schofield, *J. Chem. Soc. B*, 338 (1970).

(5) P. A. S. Smith in "Molecular Rearrangements," Part I, P. de Mayo, Ed., Interscience, New York, N.Y., 1963, Chapter 8.

(6) (a) D. V. Banthorpe and J. A. Thomas, *J. Chem. Soc.*, 7149, 7158 (1965); (b) W. N. White, D. Lazdins, and H. S. White, *J. Am. Chem. Soc.*, 86, 1517 (1964).

(7) T. D. B. Morgan and D. L. H. Williams, *J. Chem. Soc., Perkin Trans. 2*, 74 (1972).

(8) H. J. Shine, "Aromatic Rearrangements," Elsevier, Amsterdam, 1967, pp 182–190.

(9) (a) C. K. Ingold, *Chem. Soc., Spec. Publ.*, No. 16, 118 (1962); (b) M. J. S. Dewar and A. P. Marchand, *Annu. Rev. Phys. Chem.*, 16, 321 (1965); (c) H. J. Shine in "Mechanisms of Molecular Migrations," Vol. 2, B. S. Thyagarajan, Ed., Wiley, New York, N.Y., 1969, pp 191–247; (d) D. V. Banthorpe, *Top. Carbohyd. Chem.*, 1, 1 (1969); (e) R. A. Cox and E. Buncel in "The Chemistry of the Hydrazo, Azo and Azoxy Groups," S. Patai, Ed., Interscience, New York, N.Y., 1975, pp 775–859.

(10) E. Buncel in "Mechanisms of Molecular Migrations," Vol. 1, B. S. Thyagarajan, Ed., Wiley, New York, N.Y., 1968, pp 61–119.

servation of general acid catalysis. The detection of general acid catalysis<sup>1</sup> in moderately concentrated acid media is characterized by inherent difficulties that are not encountered with studies in weak acids (*vide infra*).

### General Acid Catalysis in the Sulfuric Acid System

The sulfuric acid system contains a complex milieu of species in equilibrium.<sup>11</sup> The nature and concentration of the species present are dependent on the acid region under consideration (Figure 1).<sup>11</sup> In the dilute acid region the important species (besides H<sub>2</sub>O) are H(H<sub>2</sub>O)<sub>n</sub><sup>+</sup>, HSO<sub>4</sub><sup>-</sup>, and, to lesser degree, SO<sub>4</sub><sup>2-</sup>. The actual hydronium ion, H<sub>3</sub>O<sup>+</sup>, reaches maximum concentration at ca. 85% H<sub>2</sub>SO<sub>4</sub>. In the region 85–100% H<sub>2</sub>SO<sub>4</sub>, the H<sub>3</sub>O<sup>+</sup>, HSO<sub>4</sub><sup>-</sup> and SO<sub>4</sub><sup>2-</sup> species (as well as H<sub>2</sub>O) rapidly decrease in concentration. Simultaneously, undissociated H<sub>2</sub>SO<sub>4</sub> increases in concentration and becomes the principal species present. In the 100% H<sub>2</sub>SO<sub>4</sub> region and through the dilute oleum region the acidic species present are H<sub>2</sub>SO<sub>4</sub>, H<sub>2</sub>S<sub>2</sub>O<sub>7</sub>, SO<sub>3</sub>, and H<sub>3</sub>SO<sub>4</sub><sup>+</sup>, while the basic species are HSO<sub>4</sub><sup>-</sup>, HS<sub>2</sub>O<sub>7</sub><sup>-</sup> (and H<sub>2</sub>SO<sub>4</sub>). A number of interesting relationships have been put forth relating various properties of the sulfuric acid system to species concentrations or activities, including acidity function correlations.<sup>11</sup>

It will be seen from Figure 1 that evaluation of kinetic data in the concentrated sulfuric acid region could, in principle, afford differentiation between specific catalysis by the hydronium ion and general Brønsted acid catalysis, the latter involving one or more of the species H<sub>2</sub>SO<sub>4</sub>, H<sub>3</sub>SO<sub>4</sub><sup>+</sup>, and H<sub>2</sub>S<sub>2</sub>O<sub>7</sub>. The availability of kinetic data for the Wallach rearrangement over a wide range of acidity has allowed evaluation of rate correlations involving species concentrations, activities, and acidity functions, and has led to some general proposals concerning catalysis in moderately concentrated acid media. These proposals are complementary to other criteria which have been advanced in recent years for catalysis in strongly acid media.<sup>12</sup>

### The Two-Proton Process in the Wallach Rearrangement of Azoxybenzene

Although the transformation of azoxybenzene to *p*-hydroxyazobenzene was first observed nearly 100 years ago,<sup>13</sup> mechanistic studies date back only about 15 years. Since that time, hypotheses concerning the

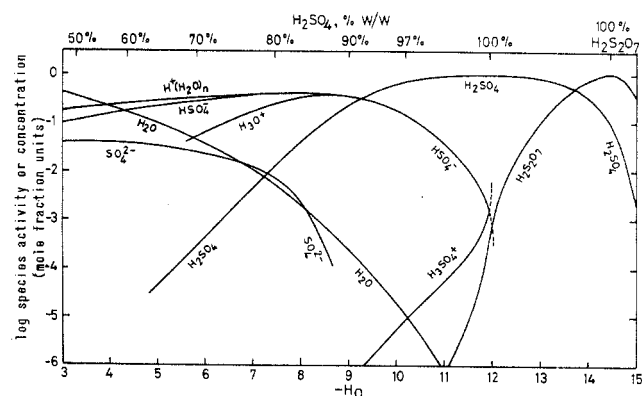
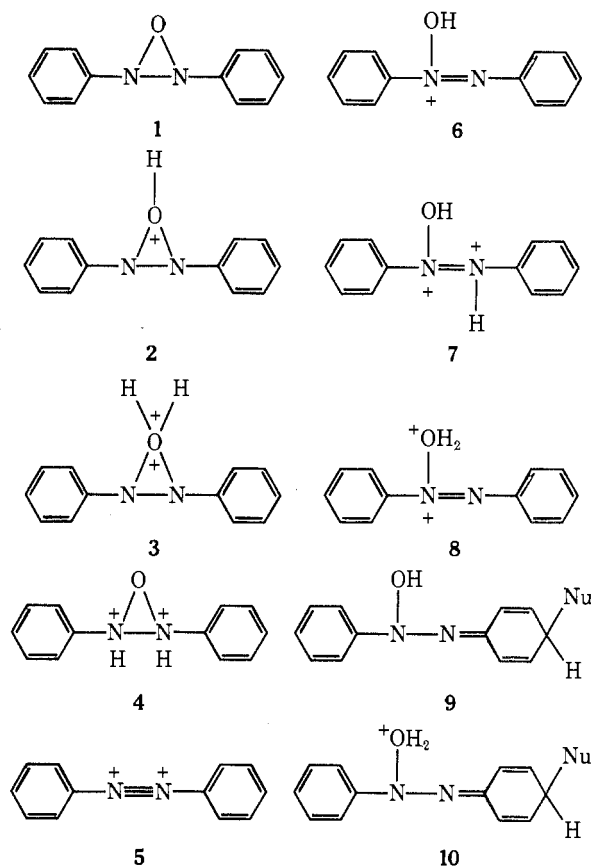


Figure 1. The species present in sulfuric acid. Concentrations of H<sup>+</sup>(H<sub>2</sub>O)<sub>n</sub>, HSO<sub>4</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup>, and H<sub>3</sub>SO<sub>4</sub><sup>+</sup>, and activities of H<sub>2</sub>O, H<sub>2</sub>SO<sub>4</sub>, H<sub>3</sub>O<sup>+</sup>, and H<sub>2</sub>S<sub>2</sub>O<sub>7</sub>, in log mole fraction units, plotted against  $-H_0$ , for the system H<sub>2</sub>O–H<sub>2</sub>SO<sub>4</sub>–H<sub>2</sub>S<sub>2</sub>O<sub>7</sub> at 25°.

mechanism of the transformation have proliferated. These hypotheses have advocated a number of unusual reaction intermediates, of which the main contenders are given by structures 1–10. Of these



species, several are in fact known to be formed in strongly acidic media from azoxybenzene. However, the mere fact of the existence of a given species does not necessarily prove that it actually occurs along the reaction pathway. Our subsequent discussion will consider this point in more detail.

Some of these structures are symmetrical in nature while others are not. The apparent involvement of a symmetrical intermediate was indicated by Shemyakin's observation<sup>14</sup> that azoxybenzene specifically labeled on one nitrogen yielded on rearrangement *p*-hydroxyazobenzene in which each nitrogen carried

(11) (a) L. P. Hammett, "Physical Organic Chemistry," 2nd ed, McGraw-Hill, New York, N.Y., 1970, Chapter 9; (b) C. H. Rochester, "Acidity Functions," Academic Press, New York, N.Y., 1970; (c) M. Liler, "Reaction Mechanisms in Sulfuric Acid," Academic Press, New York, N.Y., 1971; (d) N. C. Deno and R. W. Taft, *J. Am. Chem. Soc.*, **76**, 244 (1954); (e) P. A. H. Wyatt, *Trans. Faraday Soc.*, **56**, 490 (1960); (f) E. Högfeltdt, *Acta Chem. Scand.*, **14**, 1597, 1627 (1960); (g) E. B. Robertson and H. B. Dunford, *J. Am. Chem. Soc.*, **86**, 5080 (1964); (h) R. J. Gillespie and E. A. Robinson, in "Non-Aqueous Solvent Systems," T. C. Waddington, Ed., Academic Press, London 1965, Chapter 4; (i) C. W. F. Kort and H. Cerfontain, *Recl. Trav. Chim. Pays-Bas*, **87**, 24 (1968); **88**, 1298 (1969); (j) R. A. Cox, *J. Am. Chem. Soc.*, **96**, 1059 (1974).

(12) (a) F. A. Long and M. A. Paul, *Chem. Rev.*, **57**, 935 (1957); (b) J. F. Bunnett, *J. Am. Chem. Soc.*, **83**, 4956, 4968, 4973, 4978 (1961); (c) J. F. Bunnett and F. P. Olsen, *Can. J. Chem.*, **44**, 1917 (1966); (d) J. F. Bunnett, R. L. McDonald, and F. P. Olsen, *J. Am. Chem. Soc.*, **96**, 2855 (1974); (e) A. J. Kresge, R. A. More O'Ferrall, L. E. Hakka, and V. P. Vitullo, *Chem. Commun.*, 46 (1965); (f) K. Yates and J. C. Riordan, *Can. J. Chem.*, **43**, 2328 (1965).

(13) O. Wallach and L. Belli, *Chem. Ber.*, **13**, 525 (1880).

(14) M. M. Shemyakin, V. I. Maimind, and B. K. Vaichunaite, *Chem. Ind. (London)*, 755 (1958).

Table I  
Kinetic Data for Rearrangement of Azoxybenzene to  
4-Hydroxyazobenzene in Aqueous H<sub>2</sub>SO<sub>4</sub> at 25°

H <sub>2</sub> SO <sub>4</sub> , wt %	-H <sub>0</sub> <sup>a</sup>	$\frac{C_{SH^+}^b}{C_S + C_{SH^+}}$	$10^5 k_{\psi}^c$ , sec <sup>-1</sup>
75.30	6.65	0.967	0.016
80.15	7.42	0.994	0.208
85.61	8.35	0.999	2.17
90.37	9.05	1.000	7.23
95.19	9.82	1.000	20.9
97.78	10.35	1.000	43.8
99.00	10.82	1.000	76.8
99.59	11.18	1.000	227
99.90	11.64	1.000	860
99.97	11.84	1.000	2310
99.99	11.90	1.000	4160

<sup>a</sup> Data from ref 11b, h. <sup>b</sup> Calculated using a pK<sub>a</sub> for azoxybenzene of -5.15 (ref 19). <sup>c</sup> Pseudo first-order rate constants as determined spectrophotometrically.

half the <sup>15</sup>N label of the reactant. To account for this observation, Shemyakin proposed the intermediacy of the *N,N*-oxide species 1. Gore, on the other hand, pointed out<sup>15</sup> that the dicationic structure 5 equally fulfilled the <sup>15</sup>N equalization result.<sup>16</sup> In related work, studies with [1-<sup>14</sup>C]azoxybenzene<sup>17</sup> confirmed the isotopic scrambling result in H<sub>2</sub>SO<sub>4</sub>, while <sup>18</sup>O tracer studies have shown the rearrangement to be intermolecular,<sup>18</sup> i.e., the OH in the product is solvent derived.

A kinetic study of the Wallach rearrangement by Buncel and Lawton<sup>19</sup> provided the first evidence for the dicationic intermediate 5. Some of the kinetic data, determined as a function of sulfuric acid concentration, are set forth in Table I.<sup>20,21a</sup> (Data obtained at 75° for 65–90% H<sub>2</sub>SO<sub>4</sub> show similar response of rate to acidity.) Also given are the extents of monoprotection as derived from the measured pK<sub>a</sub>, which was evaluated spectrophotometrically.<sup>19</sup> Azoxybenzene was shown to approximate the behavior of a Hammett base, with near unit slope in the log C<sub>S</sub>/C<sub>SH<sup>+</sup></sub> vs. H<sub>0</sub> plot.<sup>22</sup>

The striking aspect of the data in Table I is that

(15) P. H. Gore, *Chem. Ind. (London)*, 191 (1959).

(16) Gore formulated the dication as a dinitrenium species, C<sub>6</sub>H<sub>5</sub>N<sup>+</sup>—N<sup>+</sup>C<sub>6</sub>H<sub>5</sub>, while the structure 5 with the triple bond was preferred by Buncel and Lawton due to the favorable energy factor associated with N≡N.

(17) L. C. Behr and E. C. Hendley, *J. Org. Chem.*, **31**, 2715 (1966).

(18) (a) S. Oae, T. Fukumoto, and M. Yamagami, *Bull. Chem. Soc. Jpn.*, **34**, 1873 (1961); (b) M. M. Shemyakin, T. E. Agadzhanian, V. I. Maimind, and R. V. Kudryavtsev, *Izv. Akad. Nauk SSSR, Ser. Khim.*, 1339 (1963).

(19) E. Buncel and B. T. Lawton, *Chem. Ind. (London)*, 1835 (1963); *Can. J. Chem.*, **43**, 862 (1965).

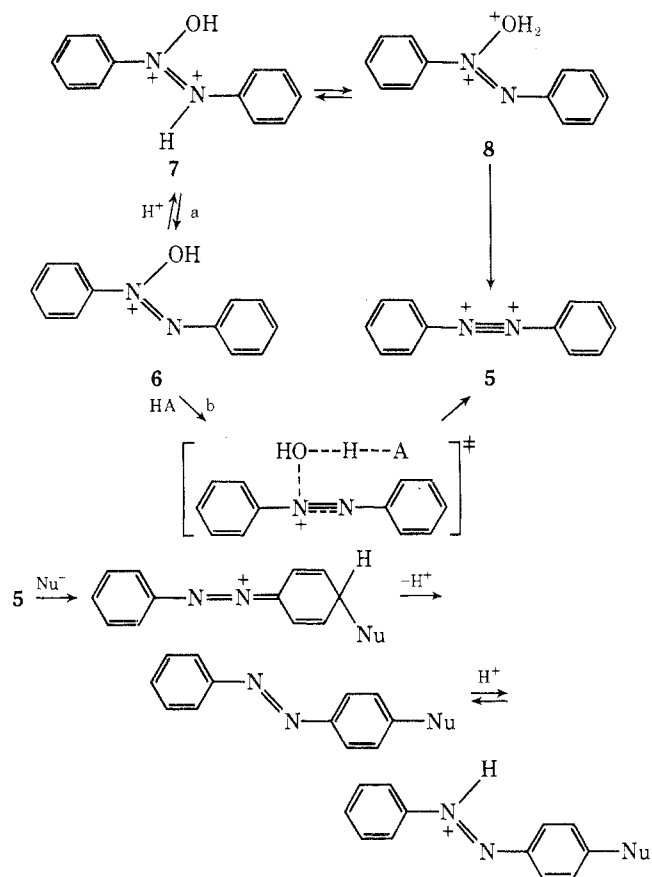
(20) In >95% H<sub>2</sub>SO<sub>4</sub>, sulfonation of *p*-hydroxyazobenzene becomes important and the rate measurements must separate the primary rearrangement from the consecutive sulfonation process.<sup>21</sup>

(21) (a) E. Buncel and W. M. J. Strachan, *Can. J. Chem.*, **48**, 377 (1970); (b) E. Buncel, W. M. J. Strachan, R. J. Gillespie, and R. Kapoor, *Chem. Commun.*, 765 (1969); (c) E. Buncel and W. M. J. Strachan, *Can. J. Chem.*, **47**, 4011 (1969); (d) W. M. J. Strachan, A. Dolenko, and E. Buncel, *ibid.*, **47**, 3631 (1969); (e) E. Buncel, W. M. S. Strachan, and H. Cerfontain, *ibid.*, **49**, 152 (1971).

(22) It is interesting that protonation of pyridine *N*-oxides<sup>23a</sup> follows closely the H<sub>A</sub> function,<sup>23b</sup> whereas protonation of azoxybenzene is reasonably well described by the (steeper) H<sub>0</sub> function. The reason presumably lies in the differing hydration requirements of the corresponding conjugate acids, relative to the neutral bases, possibly as a result of steric factors.<sup>23c–e</sup>

(23) (a) C. D. Johnson, A. R. Katritzky, and N. Shakir, *J. Chem. Soc. B*, 1235 (1967); (b) A. R. Katritzky, J. B. Stevens, and K. Yates, *Can. J. Chem.*, **42**, 1957 (1964); (c) E. M. Arnett, *Prog. Phys. Org. Chem.*, **1**, 223 (1963); (d) J. T. Edward, *Trans. Roy. Soc. Can.*, [4] **2**, Sect. III, 313 (1964); (e) G. Scorrano, *Acc. Chem. Res.*, **6**, 132 (1973).

Scheme I



the rate of rearrangement continues to increase beyond the stage of complete monoprotection of the substrate. The lack of leveling off in the 100% H<sub>2</sub>SO<sub>4</sub> region is also noteworthy. This behavior indicates requirement of a *second proton transfer*.<sup>24</sup>

Since protonation of the substrate in most of these media is extensive, any reasonable scheme will start with the conjugate acid of azoxybenzene (6) as the effective substrate; this is the case in Scheme I. Conceptually, the second proton transfer may be utilized in two ways. In path a an equilibrium proton transfer is followed by rate-determining loss of H<sub>2</sub>O to yield dication 5, while in path b rate-determining proton transfer occurs concertedly with N–O scission to yield the same dication. Product formation occurs via attack by H<sub>2</sub>O or HSO<sub>4</sub><sup>-</sup> at aromatic carbon followed by proton loss and rearomatization. It has been shown<sup>25</sup> that if the azoaryl hydrogen sulfate were formed under the reaction conditions (as is likely once the bisulfate ion concentration is comparable to or exceeds that of water (Figure 1)), it would be rapidly hydrolyzed to the azophenol.

As an initial approach toward treating involvement of the second proton, one can plot log *k*<sub>ψ</sub> – log (C<sub>SH<sup>+</sup></sub>/ (C<sub>S</sub> + C<sub>SH<sup>+</sup></sub>)) vs. H<sub>0</sub>, which takes into account the extent of monoprotection.<sup>26</sup> This graph shows strong curvature; initially the slope is ca. 1.4 but decreases to ca. 0.6 in the 90–95% H<sub>2</sub>SO<sub>4</sub> region, while in >95%

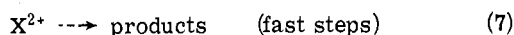
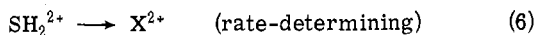
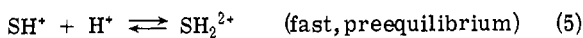
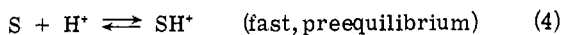
(24) D. Landini, G. Modena, F. Montanari, and G. Scorrano, *J. Am. Chem. Soc.*, **92**, 7168 (1970), observed a second proton transfer in the reduction and racemization of sulfoxides by halide ions in aqueous HClO<sub>4</sub> (H<sub>0</sub> range, -0.5 to -4.4).

(25) E. Buncel and W. M. J. Strachan, *Can. J. Chem.*, **47**, 911 (1969).

(26) (a) W. M. Schubert and H. K. Latourette, *J. Am. Chem. Soc.*, **74**, 1829 (1952); (b) W. M. Schubert and R. H. Quacchia, *ibid.*, **85**, 1278 (1963).

H<sub>2</sub>SO<sub>4</sub> the slope increases once more to a value of ca. 2.3. Evidently, a simple log rate-*H*<sub>0</sub> relationship does not hold.

For the mechanism depicted in Scheme I, path a, eq 4-9 apply. It is assumed in eq 8 that the extent of

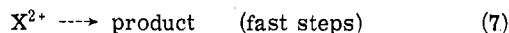
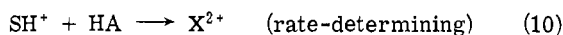
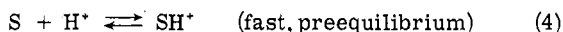


$$\text{rate} = -\frac{d(C_S + C_{SH^+})}{dt} = k_\psi(C_S + C_{SH^+}) = k_0 \frac{a_{SH_2^{2+}}}{f_\ddagger} \quad (8)$$

$$\log k_\psi - \log \frac{C_{SH^+}}{C_S + C_{SH^+}} = -H_+ + \log \frac{k_0}{K_{SH_2^{2+}}} + \log \frac{f_{BH_2^{2+}} f_{SH^+}}{f_{BH^+} f_\ddagger} \quad (9)$$

diprotonation is negligible ( $C_{SH_2^{2+}} \ll C_{SH^+}$ ).<sup>27</sup> In eq 9, *H*<sub>+</sub> is the acidity function supposedly applicable to the protonation of a standard positively charged base ( $BH^+ + H^+ \rightleftharpoons BH_2^{2+}$ ). Hence the log *k*<sub>ψ</sub> - log (*C*<sub>SH<sup>+</sup></sub>/*C*<sub>S</sub> + *C*<sub>SH<sup>+</sup></sub>) vs. *H*<sub>0</sub> plot referred to above would be expected to have unit slope, provided that the activity coefficient term can be neglected, *H*<sub>0</sub> and *H*<sub>+</sub> are parallel functions,<sup>28</sup> and the substrate behaves as a Hammett base. These assumptions are unlikely to hold rigorously, but neither do they appear to be totally unacceptable. At any rate, linearity in the plot might well be expected, though the slope could differ from unity; it is noted that acidity functions bear an approximately linear relationship to one another.<sup>29</sup> The distinctly curved plot suggests that the above mechanism is not in fact followed.

The alternative mechanism given in path b of Scheme I leads to the following kinetic scheme:



$$\text{rate} = \frac{-d(C_S + C_{SH^+})}{dt} = k_\psi(C_S + C_{SH^+}) = k_0' \frac{a_{SH^+} a_{HA}}{f_\ddagger} \quad (11)$$

$$\log k_\psi - \log \frac{C_{SH^+}}{C_S + C_{SH^+}} = \log a_{HA} + \log k_0' + \log \frac{f_{SH^+}}{f_\ddagger} \quad (12)$$

This mechanism requires a plot of log *k*<sub>ψ</sub> - log (*C*<sub>SH<sup>+</sup></sub>/*C*<sub>S</sub> + *C*<sub>SH<sup>+</sup></sub>) vs. log *a*<sub>HA</sub> to be linear, providing that *f*<sub>SH<sup>+</sup></sub>/*f*<sub>‡</sub> changes in a uniform manner (or remains constant) with increased acidity. Since all acidic species should be capable of partaking in the proton transfer process, according to their proton-donating abilities, a test of the equation must be made accord-

(27) If the second equilibrium protonation occurred to an appreciable extent, a downward curvature would be expected in the plot; the experimental data give no such indication.

(28) (a) P. J. Brignell, C. D. Johnson, A. R. Katritzky, N. Shakir, H. O. Tarhan, and G. R. Walker, *J. Chem. Soc. B*, 1233 (1967); (b) P. Vetesnik, J. Bielavsky, and M. Vecera, *Collect. Czech. Chem. Commun.*, **33**, 1687 (1968).

(29) (a) K. Yates, H. Wai, G. Welch, and R. A. McClelland, *J. Am. Chem. Soc.*, **95**, 418 (1973); (b) K. Yates and R. A. McClelland, *ibid.*, **89**, 2686 (1967); (c) K. Yates, *Acc. Chem. Res.*, **4**, 136 (1971).

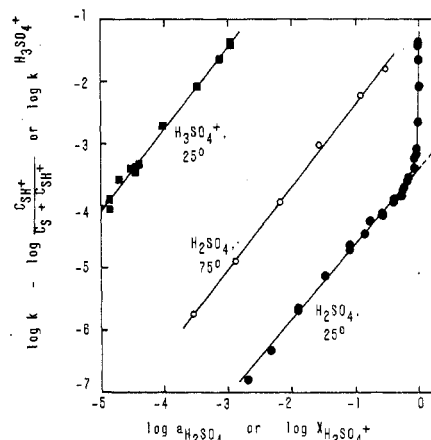


Figure 2. Graphs of log *k*<sub>ψ</sub> - log (*C*<sub>SH<sup>+</sup></sub>/*C*<sub>S</sub> + *C*<sub>SH<sup>+</sup></sub>) at 25° (●) and 75° (○) vs. log *a*<sub>H<sub>2</sub>SO<sub>4</sub></sub>, and of log *k*<sub>ψ</sub> *H*<sub>3</sub>SO<sub>4</sub><sup>+</sup> at 25° (■) vs. log *X*<sub>H<sub>3</sub>SO<sub>4</sub><sup>+</sup></sub>, for the rearrangement of azoxybenzene in H<sub>2</sub>SO<sub>4</sub>.<sup>30</sup>

ingly. This has been done in Figure 2 for the species H<sub>2</sub>SO<sub>4</sub> and H<sub>3</sub>SO<sub>4</sub><sup>+</sup>.<sup>30</sup> Above ~67% H<sub>2</sub>SO<sub>4</sub> the undissociated sulfuric acid molecule is a better proton donor toward 6 than H<sub>3</sub>O<sup>+</sup>, while above ~96% H<sub>2</sub>SO<sub>4</sub> the protonated sulfuric acid molecule is better still; cf. Figure 1. The quality of the correlations between log (rates) and log *a*<sub>HA</sub> given in Figure 2, which have near unit slopes, provides strong evidence that the Wallach rearrangement of azoxybenzene involves rate-determining proton transfer.

This test for general acid catalysis, employing eq 12, is dependent on the availability of kinetic data in the region of acid concentration in which the acid is not fully dissociated. At lower acid concentrations in which the solvated proton is the principal acidic species, we have

$$a_{HA} = a_{H^+} = h_+ \frac{f_{BH_2^{2+}}}{f_{BH^+}} \quad (13)$$

and eq 14 takes the place of eq 12. However, eq 14 is

$$\log k_\psi - \log \frac{C_{SH^+}}{C_S + C_{SH^+}} = -H_+ + \log k_0' + \log \frac{f_{BH_2^{2+}} f_{SH^+}}{f_{BH^+} f_\ddagger} \quad (14)$$

indistinguishable in practice from eq 9. Thus general acid catalysis merges with specific acid catalysis. The occurrence of general acid catalysis in moderately concentrated acid media has been proposed in only a few cases.<sup>31</sup>

The work of Olah<sup>32</sup> has provided some pertinent evidence on reaction intermediates. Monoprotonation of azoxybenzene has been confirmed by direct nmr observation in FSO<sub>3</sub>H-SO<sub>2</sub> solutions at -78° and structure 6 was fully characterized. Diprotonated azoxybenzene 7 was also observed, in SbF<sub>5</sub>-HF-SO<sub>2</sub> solution at -78°. When solutions containing 7 were

(30) Above ~96% H<sub>2</sub>SO<sub>4</sub>, the limit of the linear correlation in the log *k*<sub>ψ</sub> vs. log *a*<sub>H<sub>2</sub>SO<sub>4</sub></sub> plot, the rate constants are apportioned according to *k*<sub>ψ</sub> = *k*<sub>ψ</sub>H<sub>2</sub>SO<sub>4</sub> + *k*<sub>ψ</sub>H<sub>3</sub>SO<sub>4</sub><sup>+</sup>. Literature data<sup>11ij</sup> are used for *a*<sub>H<sub>2</sub>SO<sub>4</sub></sub> and *a*<sub>H<sub>3</sub>SO<sub>4</sub><sup>+</sup></sub>. Note (Figure 1) that in the 96-100% acid region the H<sub>2</sub>SO<sub>4</sub> species levels off while the H<sub>3</sub>SO<sub>4</sub><sup>+</sup> species increases in importance.

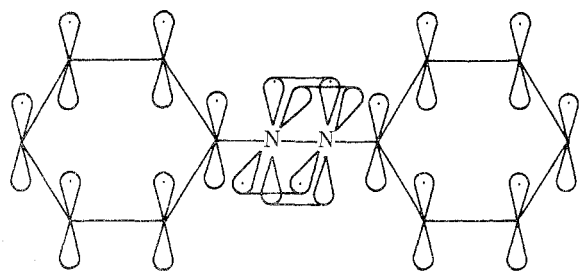
(31) (a) W. M. Schubert and P. C. Myhre, *J. Am. Chem. Soc.*, **80**, 1755 (1958); (b) J. F. Bunnett and E. Bunzel, *ibid.*, **83**, 1117 (1961); (c) M. M. Kreevov and R. A. Kretschmer, *ibid.*, **86**, 2435 (1964); (d) A. J. Kresge, S. G. Mylonakis, and L. E. Hakka, *ibid.*, **94**, 4197 (1972).

(32) G. A. Olah, K. Dunne, D. P. Kelly, and K. Y. Mo, *J. Am. Chem. Soc.*, **94**, 7438 (1972).

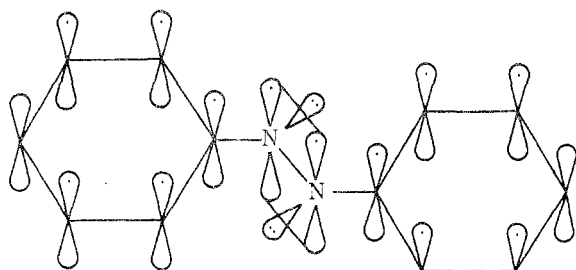
warmed to  $-50^\circ$  for 5 min and again cooled to  $-78^\circ$ , the nmr spectra had changed; the characteristic OH and NH signals of **7** had disappeared and a large  $\text{H}_3\text{O}^+$  peak had formed, together with aromatic proton signals characteristic of the dicationic species **5**. (The corresponding dicationic structure derived from 4,4'-dichloroazoxybenzene was also observed.) Quenching of solutions containing **5** in water gave 4-hydroxyazobenzene.<sup>32</sup>

Is species **5** an intermediate on the reaction pathway in the Wallach rearrangement? It will be noted with reference to Scheme I that Olah's work provides direct evidence for structures **5**, **6**, and **7** but not for **8**, a precursor of **5**. It would be reasonable to expect the equilibrium  $7 \rightleftharpoons 8$  to favor **7**, though this does not preclude formation of **8** enroute to **5**. The medium used in Olah's work, more strongly acidic than employed in the kinetic study, would tend to favor diprotonation. The use of fluorosulfuric acid as the medium in the Wallach rearrangement is known to give rise to the azoaryl fluorosulfate,<sup>33,34</sup> while chlorosulfuric acid yields the corresponding chlorosulfate.<sup>34,35</sup>

Molecular orbital calculations<sup>36</sup> on the delocalized dicationic species **5** point to a linear diphenylacetylene-like structure rather than a bent azobenzene-like structure. The orbital diagrams for the two systems (14  $\pi$  and 12  $\pi$  electrons respectively) are given by **5a** and **5b**. The dinitrenium type of structure  $\text{Ph}\ddot{\text{N}}^+\text{-}$



5a



5b

$\ddot{\text{N}}^+\text{Ph}$  is probably not representative of the electronic structure of the dication. Since the Bamberger rearrangement probably involves a nitrenium intermediate,<sup>8</sup> close analogy between the two rearrangements is not to be expected.

### Structural Effects and the Wallach Rearrangement Mechanism

Numerous studies of the effect of ring substituents

(33) T. E. Stevens, *J. Org. Chem.*, **33**, 2664 (1967).

(34) E. Buncel, R. A. Cox, and R. Bolduc, unpublished work.

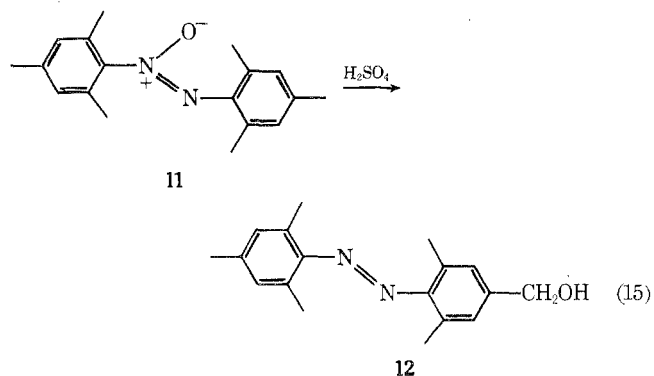
(35) V. O. Lukashovich and T. N. Kurdyumova, *Zh. Obshch. Khim.*, **18**, 1963 (1948).

(36) E. Buncel, A. Dolenko, I. G. Csizmadia, J. Pincock, and K. Yates, *Tetrahedron*, **24**, 6671 (1968).

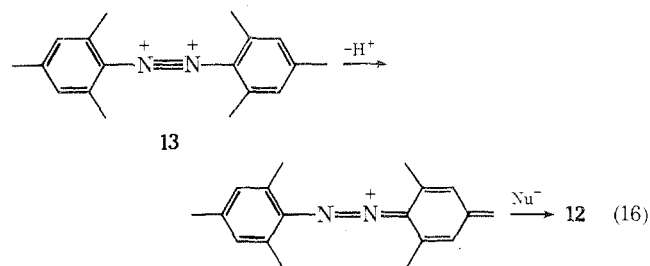
on the course of the Wallach rearrangement have been reported,<sup>10</sup> though intensive investigations are few in number. The kinetic studies by Jaffé and co-workers,<sup>37</sup> and Duffey and Hendley,<sup>38</sup> have already been discussed in detail<sup>10</sup> and only the conclusions will be cited here. Based on study of isomeric substituted azoxybenzenes (e.g., the  $\alpha$  and  $\beta$  *p*-bromoazoxybenzenes), Hahn et al.<sup>37</sup> postulate formation of the symmetrical diprotonated species **3** and/or **4** in a fast preequilibrium process, followed by rate-determining formation of dication **5**.

On the other hand Duffey and Hendley, as a result of study of an extended series of substituted azoxybenzenes, contend that a symmetrical intermediate is not formed. They propose, instead, that the conjugate acid of azoxybenzene (**6**) reacts with bisulfate ion in a preequilibrium process to yield the quinoid intermediate **9**, followed by a rate-determining proton transfer at the azoxy oxygen with its concerted removal. Alternatively, equilibrium protonation of **9**, yielding **10**, would be followed by loss of  $\text{H}_2\text{O}$ . The quinoid-type intermediates will be referred to again below.<sup>39</sup>

We reported recently the somewhat unusual course of rearrangement undergone by 2,2',4,4',6,6'-hexamethylazoxybenzene<sup>40</sup> (eq 15). It was hoped originally



that blocking of the ortho and para positions would lead to stabilization of the dicationic intermediate corresponding to **5**, which could still be formed as in Scheme I. However, once the nature of the actual product has been established, one can logically formulate a pathway to follow from the dication (eq 16).



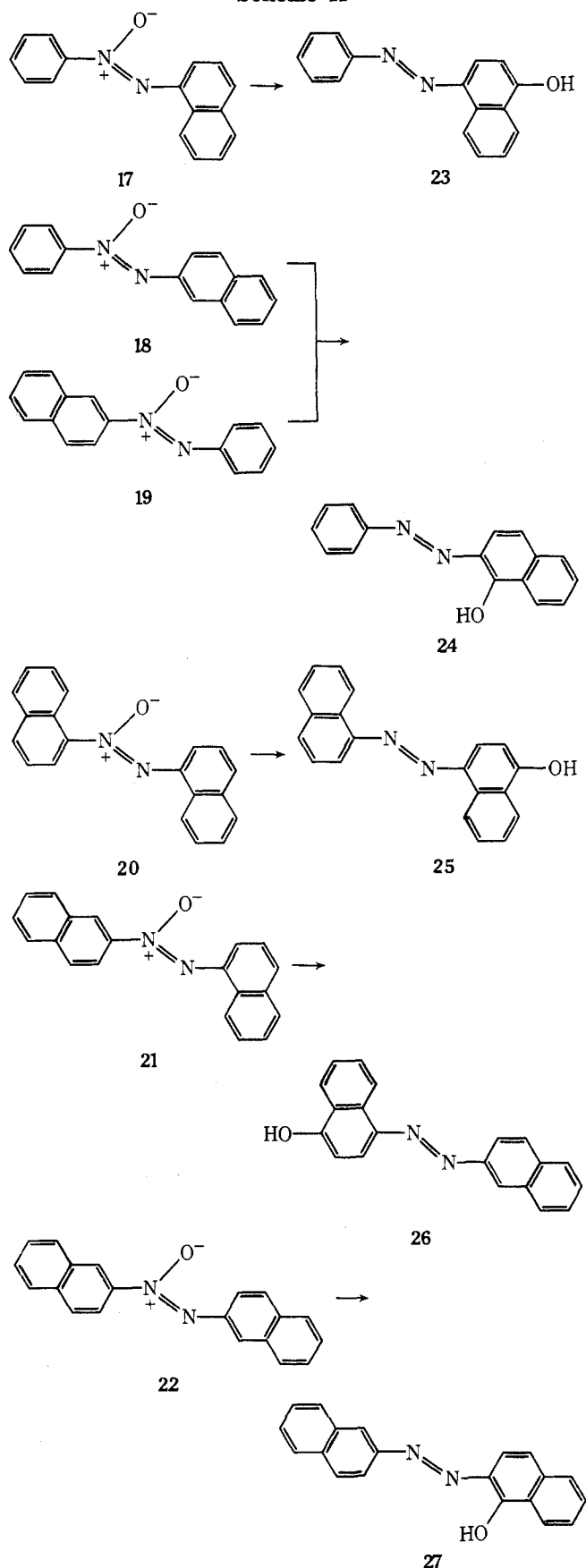
(37) C. S. Hahn, K. W. Lee, and H. H. Jaffé, *J. Am. Chem. Soc.*, **89**, 4975 (1967).

(38) D. Duffey and E. C. Hendley, *J. Org. Chem.*, **33**, 1918 (1968); *ibid.*, **35**, 3579 (1970).

(39) Pathways involving quinoid structures as the key intermediates are often referred to as the Duffey-Hendley (D-H) mechanistic type; those that include the *N,N*-oxide intermediates, as the Shemyakin-Oae-Jaffé (S-O-J) mechanisms; while those requiring the dicationic species (**5**) are termed as the Gore-Buncel-Lawton (G-B-L) mechanisms.

(40) (a) E. Buncel and R. A. Cox, *J. Chem. Soc., Chem. Commun.*, 1259 (1972); (b) R. A. Cox and E. Buncel, *Can. J. Chem.*, **51**, 3143 (1973); (c) R. A. Cox and E. Buncel, *J. Am. Chem. Soc.*, in press.

Scheme II



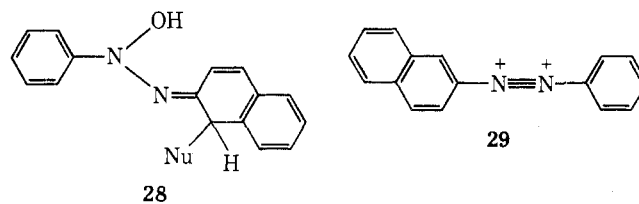
The nucleophile in eq 16 would most likely be  $\text{HSO}_4^-$  and the initially formed sulfate derivative should readily hydrolyze to yield the primary alcohol. Reaction 15 represents a rare instance<sup>41</sup> of the introduc-

tion of a functional group into a methyl group attached to an aryl residue through nucleophilic substitution.

An alternative to the dicationic intermediate pathway can be formulated, however. Thus the conjugate acid of 11 could lose a proton from the para methyl of the ring removed from the azoxy function to form a quinoid intermediate. A second equilibrium protonation of the  $-\text{NOH}$  function would be followed by nucleophilic attack on the methylene group with loss of  $\text{H}_2\text{O}$  and rearomatization.

A kinetic study of the reaction indicates that either of these mechanisms can operate depending on the medium acidity. Below 75%  $\text{H}_2\text{SO}_4$  the quinoid intermediate mechanism is followed, while above 80%  $\text{H}_2\text{SO}_4$  the dicationic intermediate pathway prevails, and in the intermediate region both reaction types occur.<sup>40c</sup> The occurrence of two mechanisms is further illustrated in the azoxynaphthalene series considered below.

In studies of the benzidine rearrangement<sup>9</sup> some interesting facets were revealed through evaluation of the effect of benzo annelation on product orientation and on the kinetic form of the acid catalysis. We have performed a similar study with the Wallach rearrangement,<sup>42</sup> and the results have likewise proven informative. The course of rearrangement for the naphthyl azoxy series is shown in Scheme II. Kinetic study of these reactions,<sup>42d</sup> coupled with measurement of  $\text{p}K_a$  values,<sup>42a</sup> has yielded data which indicate, once more, that two mechanisms obtain: dicationic (G-B-L) and quinoid (D-H) types of mechanism.<sup>39</sup> The D-H type of mechanism is applicable, at low acidities, to reactions in which the quinoid intermediates are relatively stable; for instance the aromaticity of one annelated benzo group is retained in 28, so that compound 18 follows this route. However, its isomer

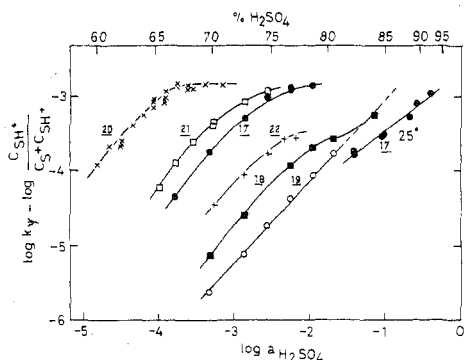


19 cannot give rise to structures like 28 since the naphthyl ring is not suitably located with respect to the protonated  $N$ -oxide function for nucleophilic attack. Although a quinoid type of structure involving attack at phenyl is possible, energetically this appears to be unfavorable. Hence, as with azoxybenzene, the dicationic mechanism is followed, forming 29, which is then attacked at the most favorable site.

Kinetic data for the azoxynaphthalene series are presented in Figure 3<sup>42d</sup> in the form of a plot of  $\log k_{\text{v}} - \log C_{\text{SH}^+}/(C_{\text{S}} + C_{\text{SH}^+})$  vs.  $\log a_{\text{H}_2\text{SO}_4}$ . It is recalled (cf. eq 12 and Figure 2) that a linear correlation should be characteristic of rate-limiting proton transfer and formation of dicationic intermediate. A linear plot is in fact obtained for compound 19, in accord

(41) P. B. Baker, V. R. Holland, and B. C. Saunders, *Tetrahedron*, **29**, 85 (1973).

(42) (a) A. Dolenko, K. Mahendran, and E. Buncl, *Can. J. Chem.*, **48**, 1736 (1970); (b) A. Dolenko and E. Buncl, *Can. J. Chem.*, **52**, 623 (1974); (c) E. Buncl and A. Dolenko, *Tetrahedron Lett.*, 113 (1971); (d) R. A. Cox, A. Dolenko, and E. Buncl, *J. Chem. Soc., Perkin Trans. 2*, in press; (e) E. Buncl, R. A. Cox, and A. Dolenko, *Tetrahedron Lett.*, 215 (1975).

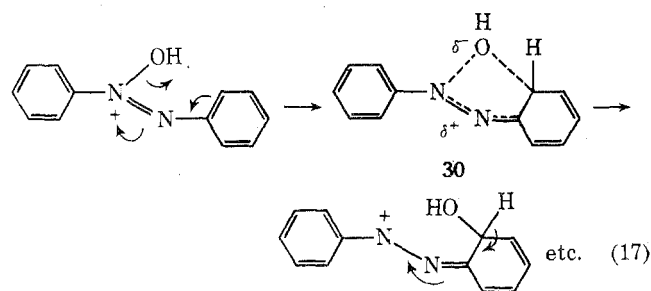


**Figure 3.** Graphs of  $\log k_p - \log (C_{SH+}/(C_S + C_{SH+}))$  vs.  $\log a_{H_2SO_4}$  for the Wallach rearrangements of 17 (●), 18 (■), 19 (○), 20 (×), 21 (□) and 22 (+), all at 44.4°, and of 17 at 25.0° (●) in sulfuric acid.

with the above structural argument. In addition, the kinetic point for 18 taken at the highest acidity appears to fall on the extrapolated curve due to 19. The 25° data for 17 also yield a linear plot, indicating that in the strong acid media, where  $a_{H_2SO_4}$  is relatively large (Figure 1), the G-B-L mechanism tends to be followed. In the weaker acid media, where  $HSO_4^-$  is the dominant species, the D-H mechanism obtains for those compounds where this is structurally favorable. It is interesting that in the moderately weak acid region the isomeric compounds 18 and 19 yield a common product by different pathways.<sup>42e</sup>

The relative reactivities in the phenyl-naphthyl azoxy series follow the order phenyl < 2-naphthyl < 1-naphthyl, leading to an inverse  $pK_a$ -reactivity relationship for the substrates concerned. This order is followed in reactions proceeding by both the dicationic and the quinoid intermediate mechanistic pathways. Thus a parallel exists between the Wallach and the benzidine rearrangements, since the latter is also subject to two reaction pathways, involving intermediates with one or two positive charges, and follows the same order of reactivity.<sup>9</sup> The benzidine rearrangement is characterized by the requirement of substantial charge delocalization in the transition state.

The course of rearrangement in the naphthyl azoxy series has another noteworthy aspect, namely, that ortho orientation prevails with 18, 19, and 22. Only few instances of acid-catalyzed ortho rearrangements of azoxyarenes have been recorded hitherto.<sup>10</sup> Isotopic tracer studies of acid-catalyzed ortho Wallach rearrangements (normally occurring when the para position is blocked) have shown that, generally, the hydroxyl is solvent derived.<sup>43,44</sup> However, in one case, that of *p,p'*-dimethylazoxybenzene, it was found that the reaction is in part intermolecular and in part intramolecular.<sup>44</sup> The probable pathway for the intramolecular component is given in eq 17, though Oae et al.<sup>43</sup> consider that 30 would be an intimate ion pair intermediate rather than a transition state. In a most interesting report, Jaffé et al.<sup>45</sup> have obtained evidence for a photochemical process involving the monoprotonated azoxybenzene substrate. The photochemical Wallach rearrangement of azoxyarenes<sup>46,47</sup>



gives rise exclusively to *o*-hydroxyazobenzene, in an intramolecular process.

### Concluding Remarks

It may be useful to summarize some of the essential conclusions which have been reached.

First, the rearrangement of azoxybenzene to *p*-hydroxyazobenzene in moderately concentrated sulfuric acid media (65–100%  $H_2SO_4$ ) is characterized, overall, by two proton transfer stages. Direct spectral observation of the degree of monoprotonation of azoxybenzene in these media, and of the rate of the rearrangement to product, has led unambiguously to this conclusion.<sup>19,21a</sup> Simple mono- and disubstituted azoxybenzenes likewise react by two-proton processes.<sup>37,38</sup> This conclusion is independent of assumptions concerning the nature of the acidity function governing substrate protonation.

Second, evidence is given in the form of linear kinetic plots for  $\log k_p$  vs.  $\log a_{H_2SO_4}$  (or  $X_{H_3SO_4^+}$ ) that the second proton transfer is rate determining, signifying general acid catalysis in moderately concentrated acid media by undissociated  $H_2SO_4$  (or  $H_3SO_4^+$ ) species. This conclusion depends on an assumption that the activity coefficient ratio  $f_{SH^+}/f_{\ddagger}$  does not vary in irregular manner with changing acidity.<sup>12c,29c</sup> Reaction rates are not correlated satisfactorily by  $H_0$  (or another) acidity function.

Third, a reaction pathway involving formation of a dicationic, delocalized, intermediate ( $Ar-N^+ \equiv N^+-Ar$ ) is proposed for those systems adhering to the linear  $\log k_p$  vs.  $\log a_{H_2SO_4}$  (or  $X_{H_3SO_4^+}$ ) plot. Such species are known to be formed in highly acidic systems,<sup>32</sup> though their intermediacy under typical Wallach rearrangement conditions remains hypothetical.

Fourth, quinonoid intermediates resulting from attack by  $HSO_4^-$  on the conjugate acid of the azoxyarene are believed to be formed, in the low acid region (60–80%  $H_2SO_4$ ), in the case of hexamethylazoxybenzene and those azoxynaphthalenes in which structural characteristics bestow stability onto the resulting quinonoid species.

Fifth, instances of ortho orientation in the acid-catalyzed Wallach rearrangement are encountered in the naphthyl azoxy series.

Nevertheless, some areas of investigation still require attention. It would be desirable to obtain kinetic data for a variety of acids, as it is known<sup>12,48</sup> that such comparative data can be of value in mechanistic interpretation. Kinetic isotope effect measurements,

(43) S. Oae, T. Fukumoto, and M. Yamagami, *Bull. Chem. Soc. Jpn.*, **36**, 601 (1963).

(44) M. M. Shemyakin, T. E. Agadzhanian, V. I. Maimind, and R. V. Kudryavtsev, *Dokl. Akad. Nauk SSSR, Ser. Khim.*, 1339 (1963).

(45) R. H. Squire and H. H. Jaffé, *J. Am. Chem. Soc.*, **95**, 8188 (1973).

(46) G. G. Spence, E. C. Taylor, and O. Buchardt, *Chem. Rev.*, **70**, 231 (1970).

(47) D. J. W. Goon, N. G. Murray, J.-P. Schoch, and N. J. Bunce, *Can. J. Chem.*, **51**, 3827 (1973).

(48) C. A. Bunton and L. Robinson, *J. Am. Chem. Soc.*, **91**, 6072 (1969).

substrate and solvent, should be informative (e.g., in naphthyl azoxy series in which there is evidence for two mechanisms). Systematic study is needed of the course of reaction, and acidity dependence, of unsymmetrically substituted azoxybenzene derivatives.<sup>49</sup> Finally, heteroaromatic substrates have not yet been studied, and little is known about the rear-

(49) B. T. Newbold in "The Chemistry of the Hydrazo, Azo, and Azoxy Groups," S. Patai, Ed., Wiley, New York, N.Y., 1975.

angement of aliphatic azoxy compounds. Thus one may look to future investigations of the Wallach rearrangement to provide some of the clues which have thus far not been revealed.

*My thanks go to my most able coworkers, R. A. Cox, A. Dolenko, B. T. Lawton, K. Mahendran, and W. M. J. Strachan, for their enthusiasm in pursuing the research, and to the National Research Council of Canada for providing financial support.*

## Nonclassical Condensed Thiophenes

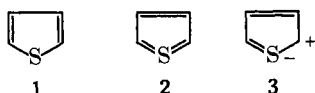
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Received April 29, 1974

The great chemical stability of thiophene (1) as compared with either pyrrole or furan has long been known to organic chemists.

In 1939, Schomaker and Pauling suggested that an expansion of the sulfur octet could be a special factor in stabilization of the thiophene molecule. In resonance terminology, this concept can be represented by including structures with tetravalent sulfur (2) as well as related dipolar structures (i.e., 3) in which the sulfur atom bears a negative charge.<sup>1</sup>



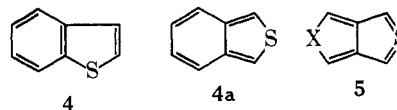
Longuet-Higgins later developed this concept in molecular orbital terms, showing that the mixing of sulfur  $3p_z$ ,  $3d_{xz}$  and  $3d_{yz}$  orbitals would provide three  $pd^2$  hybrid orbitals, two of which are nonorthogonal and capable of  $\pi$  overlap.<sup>2</sup> In this way, sulfur heteroatoms can be treated as structurally analogous to  $-\text{CH}=\text{CH}-$  units in conjugated systems. This formulation has been expressed in quantitative terms and used in Hückel-type calculations on thiophene and other sulfur heterocycles.<sup>3</sup>

Critics of this model contend that there is no reason to suppose on the basis of stability alone that d-orbital participation is significant.<sup>4a</sup> Mangini and Zauli, for example, have argued that sulfur  $pd^2$  orbitals would be of too high energy and cause too much angle strain to participate effectively.<sup>4b</sup>

Many molecular orbital calculations have been carried out on thiophene in recent years. The sophis-

ticated studies of Clark, and those of Dewar and Trinajstić, are particularly noteworthy. They have led to the general conclusion that sulfur d-orbital participation is insignificant in the thiophene molecule.<sup>5</sup>

Fusion of thiophene to a benzene nucleus gives rise to either of the well-known heterocycles benzo[*b*]thiophene (4) or benzo[*c*]thiophene (4a); both of these are examples of classical condensed thiophenes, and can be represented by the usual Kekulé structures. It is possible, however, to conceive of condensed thiophene heterocycles (i.e., general structure 5) for which no uncharged singlet structure can be



written other than one containing a tetravalent sulfur as part of a thiophene ring. Such systems represent novel structures in which one may consider the sulfur atom as being coaxed to the maximum, so to speak, into using  $pd$  hybrid orbitals, even if this type of participation is negligible in thiophene itself.

In this Account, we review the chemistry of compounds of this type, which we shall refer to as nonclassical condensed thiophenes, and which have been the object of chemical investigation only since 1967.<sup>6</sup>

(1) V. Schomaker and L. Pauling, *J. Am. Chem. Soc.*, **61**, 1769 (1939).

(2) H. C. Longuet-Higgins, *Trans. Faraday Soc.*, **45**, 173 (1949).

(3) A. Streitwieser, "Molecular Orbital Theory for Organic Chemists," Wiley, New York, N.Y., 1961.

(4) (a) M. J. S. Dewar, "The Molecular Orbital Theory of Organic Chemistry," McGraw-Hill, New York, N.Y., 1969; (b) A. Mangini and C. Zauli, *J. Chem. Soc.*, 2210 (1960).

(5) (a) D. T. Clark, *Tetrahedron*, **24**, 2663 (1968); (b) M. J. S. Dewar and N. Trinajstić, *J. Am. Chem. Soc.*, **92**, 1453 (1970).

(6) For an earlier review of this subject, see M. P. Cava, *Int. J. Sulfur Chem., Part C*, **7**, 55 (1972). For the synthesis of some nonclassical six-membered sulfur heterocycles, see (a) M. P. Cava, N. M. Pollack, and D. A. Repella, *J. Am. Chem. Soc.*, **89**, 3640 (1967); (b) R. H. Schlessinger and I. S. Ponticello, *ibid.*, **89**, 3641 (1967); (c) I. S. Ponticello and R. H. Schlessinger, *ibid.*, **90**, 4190 (1968); (d) J. M. Hoffman, Jr., and R. H. Schlessinger, *ibid.*, **91**, 3953 (1969).

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