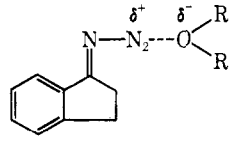
III). One possible explanation is that in ether-type solvents the diazonium ion is solvated (see **14**) and therefore relatively stabilized, raising the transition-state energy for rearrangement.



14

Experimental Section

The vinyl azides 1-azido-1-phenylpropene (**3a**), 2-azido-3-phenylpropene (**3b**), and 1-azidoindene (**7**) were prepared according to the procedure described by Hassner, *et al.*[7,14] The nmr spectra were taken on a Varian A60-A spectrometer.

An Example of Vinyl Azide Hydrolysis. Diethyl ether (23 ml) was cooled to 0° in an ice–water bath and 76% sulfuric acid (4 ml) was slowly added with stirring. The ice bath was removed and the solution was allowed to come to room temperature. 1-Azido-1-phenylpropene (**3a**) (1 g) in 2 ml of ether was rapidly added with stirring. The reaction mixture was vigorously stirred at room temperature for 1 hour, then quenched by pouring it onto 15 g of potassium carbonate cooled in an ice–water bath. The slurry was diluted with 100 ml of diethyl ether and ice–cold water was slowly added to neutralize the sulfuric acid. The aqueous fraction was separated, diluted with more water, and extracted 4 times with ether. The combined ether fractions were washed once with water, saturated NaCl, and dried over anhydrous $MgSO_4$. The solution was filtered and the solvent was removed *in vacuo*. The nmr spectrum of the crude reaction mixture was then taken in $CDCl_3$. The results of the vinyl azide hydrolysis are tabulated in Tables II and III.

An Example of the Schmidt Reaction with a Ketone. Diethyl ether (23 ml) was cooled to 0° in an ice–water bath and 76% sulfuric acid (4 ml) was slowly added. The ice bath was removed and the solution was allowed to come to room temperature. Propiophenone (1 g) in 2 ml of diethyl ether was rapidly added followed immediately by sodium azide (0.590 g). The mixture was vigorously stirred at room temperature for 1 hr, then poured onto 15 g of potassium carbonate at 0°. The work-up was the same as described in the vinyl azide hydrolysis.

Acknowledgment. Support of this work by Grant No. GP 8675 from the National Science Foundation is gratefully acknowledged.

(14) F. W. Fowler, A. Hassner, and L. A Levy, *J. Amer. Chem. Soc.*, **89**, 2077 (1967).

Rearrangements of Azidoquinones. V.[1] Stereoselective Acid-Catalyzed Rearrangements of Azidoquinones to γ-Cyanoalkylidine- (Cyanoarylidine-) $\Delta^{\alpha,\beta}$-butenolides

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Abstract: Thirteen azido-1,4-benzo- and -1,4-naphthoquinones (**1**) have been shown to rearrange in strong acid to γ-cyanoalkylidine- (or cyanoarylidine-) $\Delta^{\alpha,\beta}$-butenolides (**3**). This rearrangement proceeds by a highly stereoselective, if not stereospecific, process to give the butenolides in which the cyano group on the exocyclic double bond is *trans* to the lactone oxygen. Utilization of the rearrangement as a key step in the total synthesis of a naturally occurring tetronic acid, vulpinic acid (**13**), is described. The mechanism of the rearrangement is discussed in regard to the stereoselectivity of the rearrangement and spectral detection and kinetics of decomposition of the intermediate iminodiazonium ions (**2**).

Very little work has appeared in the literature concerning the chemistry of azidoquinones. This is somewhat surprising in view of their ease of formation, relative stability, and the fact that they are structurally related to vinyl and acyl azides, both of which have received extensive study.[3] A thorough investigation of azidoquinone chemistry has therefore been initiated, and reported here is a general, highly stereoselective acid-catalyzed ring contraction of azido-1,4-quinones (**1**) to the butenolide ring system (**3**).

A general azidoquinone synthesis was reported by Fieser and Hartwell[4] who prepared 2-azido-1,4-naphthoquinone by treating the corresponding 2-chloroquinone with azide ion in ethanolic solution. In the same paper, these investigators proposed that azidohydroquinones disproportionate to aminoquinones, a hypothesis which has recently been substantiated experimentally.[5] Mosby and Silva[6] have investigated the reactions of azidonaphthoquinones with phosphines and phosphites and have presented evidence for the intermediacy of a linear phosphazene in these reactions. Van Allen, Priest, Marshall, and Reynolds[7] have shown that the thermal decomposition of azidoquinones follows first-

(1) A preliminary account of this research has appeared: H. W. Moore and H. R. Shelden, *Tetrahedron Lett.*, 5431 (1968).

(2) (a) Based on the Ph.D. dissertation of Harold Raymond Shelden; (b) NDEA Fellow; (c) NSF Trainee.

(3) R. A. Abramovitch and B. A. Davis, *Chem. Rev.*, **64**, 149 (1964); L. Horner and A. Christmann, *Angew. Chem. Intern. Ed. Engl.*, **2**, 599 (1963); W. Lwowski, Ed., "Nitrenes," John Wiley and Sons, Inc., New York, N. Y., in press; J. H. Boyer in "Mechanisms of Molecular Migrations," Vol. 2, B. S. Thyagarajan, Ed., Interscience Publishers, New York, N. Y., 1969.

(4) L. F. Fieser and J. L. Hartwell, *J. Amer. Chem. Soc.*, **57**, 1482 (1935).

(5) H. W. Moore and H. R. Shelden, *J. Org. Chem.*, **33**, 4019 (1968).

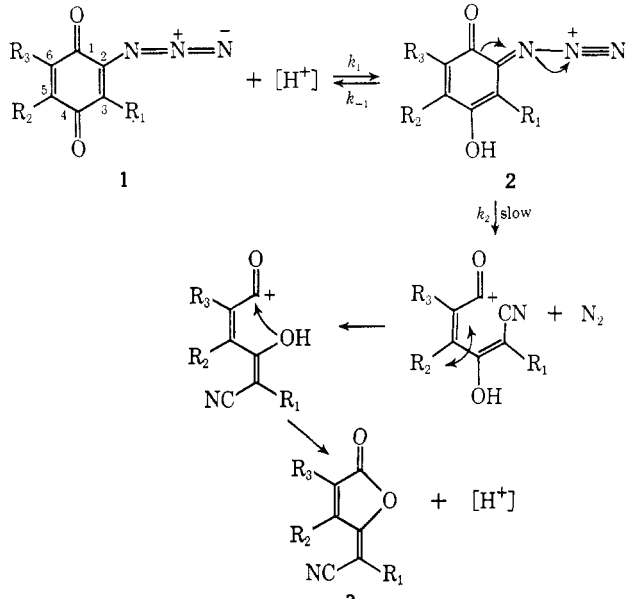
(6) W. L. Mosby and M. L. Silva, *J. Chem. Soc.*, 1003, 2727 (1965).

(7) J. A. Van Allen, W. J. Priest, A. S. Marshall, and G. A. Reynolds, *J. Org. Chem.*, **33**, 1100 (1968).

order kinetics and that 2,3-diazido-1,4-naphthoquinone thermally and photochemically rearranges to *ortho*-phthaloyl cyanide. This transformation is analogous to the pyrolytic conversions of 1,2-diazidobenzene to muconononitrile[8] and diazido-N-phenylmaleimide to the N-phenylimide of cyanoformic acid.[9] Finally, Rees[10] has observed an interesting transformation of thymoquinone to α-methyl-β-amino-γ-(1-cyano-2-methylpropylidine)-$\Delta^{\alpha,\beta}$-butenolide upon treatment of the quinone with sodium azide in trichloroacetic acid, a transformation which we have recently shown to involve an acid-catalyzed rearrangement of an azidoquinone intermediate.[5]

Synthetic Scope. The highly stereoselective acid-catalyzed rearrangements of azido-1,4-quinones to the ring-contracted γ-cyanoalkylidine-(cyanoarylidine-)

Scheme I

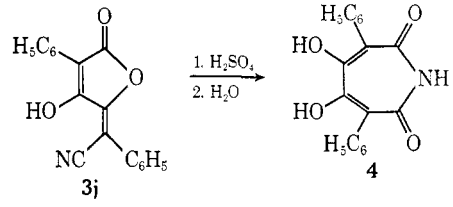


	R_1	R_2	R_3	Yield
a	H	$C(CH_3)_3$	H	95
b	H	C_6H_5	H	80
c	H	CH_3	H	65
d	CH_3	H	CH_3	70
e	CH_3	H	$CH(CH_3)_2$	87
f	CH_3	N_3	CH_3	77
g	H			59
h	CH_3			95
i	C_6H_5	H	C_6H_5	30
j	C_6H_5	OH	C_6H_5	65
k	CH_3	NH_2	$CH(CH_3)_2$	94
l	$CH(CH_3)_2$	NH_2	CH_3	95
m	H	NH_2	H	44

$\Delta^{\alpha,\beta}$-butenolides is of mechanistic significance in regard to certain reactions which have appeared in the literature[5,10,11] and also finds synthetic utility in the preparation of vulpinic acid (**13**), a naturally occurring tetronic acid found in a number of lichins.[12] The general structures (**1**) and (**3**) illustrate the overall chemical transformation as indicated by the mechanism presented in Scheme I.

The azidoquinones (**1a–j**) were prepared from the respective chloro- or bromo-substituted quinones by the direct nucleophilic displacement of halogen by azide ion in aqueous ethanolic solution.[4] In all cases the azidoquinones are formed in high yields (>85%) and usually precipitate in high purity from the reaction solution. The 2-azido-5-amino-1,4-benzoquinones (**1k–m**) were prepared by the thermal disproportionation of the corresponding diazidohydroquinones as previously described.[5,13] All of these compounds thermally decompose at or near their melting points (sometimes violently), but appear to be quite stable for prolonged periods of time at room temperature in the dark.

Rearrangements of the azidoquinones (**1a–i**) were accomplished by the *slow* addition of the azide to rapidly stirred, cold (0–5°) concentrated sulfuric acid. After nitrogen evolution ceased the butenolides (**3a–i**) were isolated in high yield and purity by pouring the reaction onto ice and collecting the products by filtration. Trichloroacetic acid at 65° can also cause rearrangement of the azidoquinones and in fact was found to be superior to sulfuric acid for the 2-azido-5-amino-1,4-benzoquinones (**1k–m**). Refluxing an ethanolic or chloroform solution of 2-azido-5-hydroxy-3,6-diphenyl-1,4-benzoquinone (**1j**) for a few minutes resulted in its rearrangement to the known[14] butenolide (**3j**) in 65% yield. No external source of acid was necessary for this transformation, the hydroxy group of **1j** apparently being of sufficient acidity to initiate the reaction. In fact, when the azidoquinone (**1j**) or the butenolide (**3j**) was treated with concentrated sulfuric acid a new product was formed in high yields, the structure of which is proposed to be the ring-expanded azepinedione (**4**). An analogous rearrangement has been reported by



Rees[15] for the butenolide (**31**). The structure of **4** is based only upon spectral (ir, nmr, mass spectral) and analytical data (see Experimental Section).

The structures of the butenolides (**3a–m**) are in complete agreement with their spectral data which are presented in Table I. They all show characteristic absorptions for nitrile, carbon–carbon double bonds, and γ-lactone carbonyl groups in their ir spectra. Their nmr spectra show the expected proton count, coupling constants, and chemical shifts and the mass spectra show molecular ions and fragmentation patterns in accord with their formulation.

Stereochemistry. The rearrangement of the azidoquinones (**1a–m**) to the butenolides (**3a–m**) proceeds in a highly stereoselective, if not stereospecific, manner. Only a single detectable isomer was formed as evidenced by spectral (ir and nmr) and/or gas chromatographic analysis of the crude products. The stereochemistry of selected examples of these ring-contracted products have been unambiguously demonstrated by both spec-

(8) J. H. Hall, *J. Amer. Chem. Soc.*, **87**, 1147 (1965); J. H. Hall and E. Patterson, *ibid.*, **89**, 5856 (1967).
(9) G. Smolinsky, *J. Org. Chem.*, **27**, 3557 (1962).
(10) A. H. Rees, *Chem. Ind.* (London), 931 (1964).
(11) H. W. Moore and H. R. Shelden, *J. Org. Chem.*, **32**, 3603 (1967).
(12) O. P. Mittal and T. R. Seshadri, *Curr. Sci.*, **26**, 4 (1957).
(13) H. W. Moore, H. R. Shelden, and D. Shellhamer, *J. Org. Chem.*, **34**, 1999 (1969).
(14) J. Volhard and F. Henke, *Ann.*, **282**, 61 (1894).
(15) A. H. Rees, *Chem. Ind.* (London), 1298 (1965).

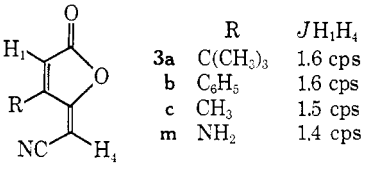
Table I. Spectral Properties of Butenolides

Compd	Mp, °C	Ir (cm^{-1})[a]	Nmr (ppm from TMS)[b]	Mass spectrum
3a	89–90	2230, 1820, 1780, 1640, 1580	6.33 d (1) J = 1.6 cps; 5.67 d (1) J = 1.6 cps; 1.48 s (9)	M^+, 177 (26%); 162 (28%); 134 (66%); 110 (23%); 95 (34%); 79 (33%); 67 (59%); 28 (100%)
3b	136–137	2230, 1810, 1650, 1590, 1570	7.45 s (5); 6.40 d (1) J = 1.6 cps; 5.50 d (1) J = 1.6 cps	M^+, 197 (95%); 169 (15%); 141 (57%); 114 (11%); 102 (100%)
3c	63–64	2210, 1785, 1630, 1600	5.35 m (1); 4.60 d (1) J = 1.5 cps; 2.50 d (3) J = 1.3 cps	M^+ 135 (30%); 108 (27%); 79 (24%); 68 (55%) 52 (62%); 40 (100%)
3d	78–80	2230, 1800	7.42 m (1); 2.13 s (3), 2.05 d (3)	M^+, 149 (99%); 120 (12%); 93 (20%); 81 100%; 66 (24%)
3e[c]	38–40	2210, 1780, 1645	7.30 d (1) J = 1.7 cps; 2.80 h (1) J = 7 cps; 2.12 s (3); 1.26 d (6) J = 7 cps	*c*
3f	115 dec	2230, 2140, 1780, 1670, 1630	2.16 s (3); 2.07 s (3)	M^+, 190 (45%); 82 (60%); 81 (100%); 53 (95%)
3g	170–172	2230, 1800, 1650	8.3–8.4 m (1); 7.9–8.1 m (3); 5.9 s (1)	M^+, 171 (100%); 143 (22%); 104 (53%); 76 (43%)
3h	144–145	2210, 1800, 1665, 1590	8.3–8.6 m (1); 7.6–8.1 m (3); 2.24 s (3)	M^+, 185 (100%); 130 (22%); 129 (27%); 104 (85%); 76 (54%)
3i	190–191	2240, 1780, 1610	7.91–8.22 m (5); 7.35–7.65 m (6)	M^+, 273 (100%); 245 (9%); 217 (12%); 143 (78%); 115 (69%); 102 (69%)
3j	189–191	3400, 2250, 1820, 1630, 1610	7.42–8.03 m (10)	M^+, 289 (100%); 261 (4%); 144 (85%); 118 (80%); 89 (80%)
3k[c]	139–140	3500, 3340, 2210, 1750	5.18 b (2); 2.60 h (1) J = 7 cps; 2.05 s (3); 1.27 d (6) J = 7 cps	*c*
3l[c]	175–177	3350, 3400, 2220, 1775, 1675, 1640	1.20 d (6) J = 7 cps; 1.78 s (3); 3.13 h (1) J = 7 cps; 5.25 b (2)	*c*
3m[d]	204 dec	3450, 3220, 2230, 1750, 1640	7.10–7.21 b (2); 6.00 d (1) J = 1.4 cps; 5.10 d (1) J = 1.4 cps	M^+, 136 (59%); 108 (3%); 69 (25%); 41 (100%)

[a] Nujol. [b] b = broad; d = doublet; s = singlet; h = heptet. [c] See ref 5. [d] See ref 13.

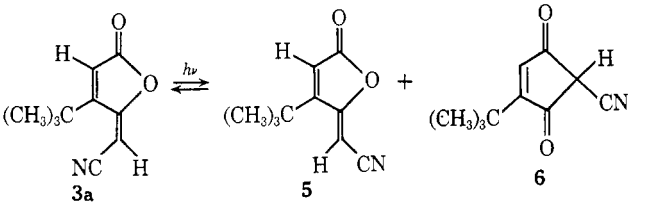
tral (nmr) and chemical methods. The butenolides (**3a–c, m**) lend themselves to direct stereochemical analysis by nmr spectroscopy which shows the vinyl protons in these four compounds to be in a 1,4-*trans–trans* relationship to one another on the butadiene moiety. This assignment is based on the long range coupling constants of the vinyl protons which are in strict agreement with the elegant work of Bothner-By, *et al.*,[16] concerning simpler butadiene derivatives. These investigators have shown that 1,4-vinyl protons in a *trans–trans* configuration show coupling constants ranging from 1.3 to 1.9 cps. All other long range couplings were found to be appreciably smaller. For example, the coupling constants for 1,4-vinyl protons in the *cis–trans* configuration (the other possible stereochemical configuration for the butenolides **3a–c, m**) were found to range between 0 and 0.9 cps. The nmr spectra of the butenolides (**3a–c, m**) show an AB pattern for the vinyl protons with coupling constants ranging from 1.4 to 1.6 cps, in agreement with the proposed structures (Scheme II). In order to confirm this stereochemical assignment,

Scheme II

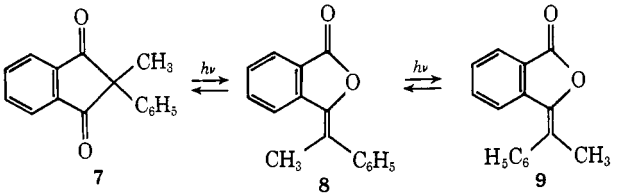


	R	$J_{H_1H_4}$
3a	$C(CH_3)_3$	1.6 cps
b	C_6H_5	1.6 cps
c	CH_3	1.5 cps
m	NH_2	1.4 cps

it was necessary to measure the coupling constant of 1,4-vinyl protons in a *cis–trans* relationship in the butenolide ring system. The desired compound (**5**) was obtained by photoisomerization of (**3a**) in hexane with 2537-Å light and the desired product (**5**) isolated by preparative gas chromatography. This photolysis resulted in an equilibrium mixture composed of approximately 1:1:2, respectively, of compounds **3a**, **5**, and **6**. The same mixture could also be obtained by subjecting **5** to these photolysis conditions. The nmr spectrum of **5** showed an AB pattern for the vinyl protons with a coupling constant of 0.6 cps, in agreement with the *cis–trans* configuration of the butadiene moiety.



The structural assignment of the cyclopentendione **6** is not unambiguous, being based only upon spectral data (Experimental Section). However, such a product is not unexpected in view of the observed photoisomerization of the analogous compounds **7**, **8**, and **9** reported by Rigandy and Derible.[17]



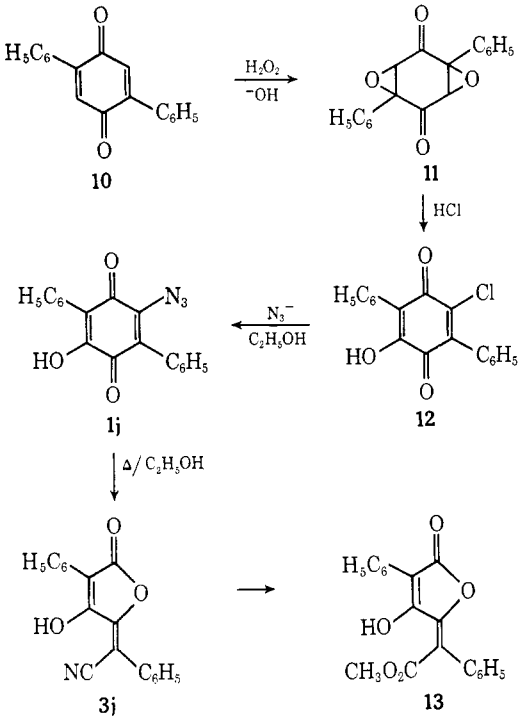
Chemical evidence for the stereochemistry of **3j** as well as an illustration of the synthetic utility of the azidoquinone rearrangement was obtained by the total synthesis of vulpinic acid (**13**) (Scheme III). Reaction

(16) A. A. Bothner-By and R. K. Harris, *J. Amer. Chem. Soc.*, **87**, 3451, 3445 (1965); A. A. Bothner-By and D. Jung, *ibid.*, **90**, 2342 (1968); A. A. Bothner-By and E. Moser, *ibid.*, **90**, 2347 (1968); A. A. Bothner-By and D. F. Koster, *ibid.*, **90**, 2351 (1968).

(17) J. Rigandy and P. Derible, *Bull. Soc. Chim. Fr.*, 3047, 3055 (1965).

of 2,5-diphenyl-1,4-benzoquinone (**10**) with basic 30% hydrogen peroxide in dioxane gave the diepoxide **11** in 75% isolated yield. The spectral data (Experimental Section) for this new compound are in complete agreement with structure **11**. A surprising transformation was observed when **11** was hydrolyzed with concentrated hydrogen chloride in dioxane–ethanol (8:2). Instead of

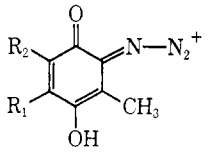
Scheme III



the expected chlorohydrin or 2,5-dihydroxy-3,6-diphenyl-1,4-benzoquinone the chlorohydroxyquinone (**12**) was obtained in 68% yield. The spectral properties of this compound are in agreement with structure **12** and its physical properties are the same as those previously reported by Cain.[18] Reaction of 2-chloro-5-hydroxy-3,6-diphenyl-1,4-benzoquinone (**12**) with ethanolic sodium azide gave the azidoquinone **1j** in 89% yield which was converted to the butenolide **3j** in 65% yield in refluxing chloroform or ethanol.[19] The butenolide **3j** was converted to the known[20] vulpinic acid (**13**) (95% yield) by methanolysis of the nitrile function with methanolic hydrogen chloride. Comparison of this compound with an authentic sample showed them to be identical.

Mechanism. A most significant demand of any mechanism presented for the rearrangement of azidoquinones is an explanation of the observed stereospecificity of the reaction. The mechanism presented in Scheme I meets this stipulation provided the rate of tautomerization of the iminodiazonium ion **2** is significantly slower than its rate of bond formation to give products. This assumption is open to experimental verification for those azidoquinones (**1**) in which R_1 (Scheme I) is a proton. Rearrangement of such an azidoquinone in sulfuric acid-d_2 should give the butenolide **3** in which *no exchange* has taken place. In fact this result was observed when the azidoquinones **1a**, **1b**, and **1g** were rearranged in sulfuric acid-d_2 and the butenolides **3a**, **3b**, and **3g** were isolated from the workup in deuterium oxide. Ir and nmr analysis of the products showed no deuterium incorporation. This result supports the intermediacy of the iminodiazonium ion (**2**) and eliminates any intermediate which could incorporate deuterium before product formation (protonation at position 3, for example). The lack of deuterium incorporation also eliminates the possibility that the stereospecificity of this rearrangement is a result of an acid-catalyzed equilibration of the product.

Evidence for the protonated azidoquinone (**2**) (Scheme I) was obtained spectroscopically. To our knowledge, this is the first reported spectral detection of an iminodiazonium ion, a species commonly accepted as an intermediate in the Schmidt reaction of carbonyl compounds.[21] These intermediates were formed as highly colored species immediately upon addition of the azidoquinones to concentrated sulfuric acid. The color gradually faded as nitrogen was evolved giving finally a colorless or nearly colorless solution of the butenolide. Three of these iminodiazonium ions (**14**, **15**, and **16**) were found to have lifetimes at 5–10° long enough to allow investigation of their electronic spectra which showed, respectively, absorptions at 532, 567, and 569 nm. The corresponding azidoquinones (**1h**, **d**, **e**) in 95% ethanol show absorptions at



	R_1	R_2	Visible absorption, nm
14			532
15	H	CH_3	567
16	H	$CH(CH_3)_2$	569

390, 495, and 498 nm, respectively. It is conceivable that the colored species formed in this reaction are aminodiazonium ions, produced *via* protonation on the azide group at the nitrogen adjacent to the quinone nucleus. Such ions have been proposed in the acid-catalyzed decomposition of certain aryl azides.[21,22] However, even though a mechanism involving aminodiazonium ions or nitrenium ions can be envisaged for the rearrangement of azidoquinones, these intermediates are untenable with the observed stereospecificity of the reaction.

The mechanism presented in Scheme I predicts that the rate of disappearance of the iminodiazonium ions will follow pseudo-first-order kinetics, *i.e.*, $-d[C_6HR_3N_3O_2]/dt = k_{-1}[C_6HR_3N_3O_2] - k_1[C_6R_3N_3O_2][H^+] + k_2[C_6HR_3N_3O_2] = k[C_6HR_3N_3O_2]$. This was observed experimentally when the rates of disappearance of the iminodiazonium ions (**14**, **15**, and **16**) were measured spectrophotometrically in concentrated sulfuric acid at 25.5°. Ions **14**, **15**, and **16**, respectively, have half-lives of 34, 35, and 22 sec at 25.5° which correspond to the following observed first-order rate constants: (**14**) 2.0×10^{-2} sec^{-1}, (**15**) 1.9×10^{-2} sec^{-1}, (**16**) 3.2×10^{-2} sec^{-1}. The kinetic data for one of these (**15**) are presented in graphical form in Figure 1.

(18) B. F. Cain, *J. Chem. Soc.*, 936 (1961).

(19) A thermally induced rearrangement of **1j** is not likely for this transformation since we have found that azidoquinones pyrolytically rearrange to cyclopentene-1,3-diones. For example, 2-azido-3,6 diphenyl-1,4-benzoquinone, structurally analogous to **1j** except for the absence of the acidic hydroxy group, rearranges in refluxing toluene to give a 61% isolated yield of 2,4-diphenyl-2-cyanocyclopentene-1,3-dione.

(20) H. W. Moore and R. J. Wikholm, *Tetrahedron Lett.*, 5049 (1968).

(21) P. A. S. Smith in "Molecular Rearrangements," Vol. 1, P. de Mayo, Ed., Interscience Publishers, New York, N. Y., 1963.

(22) C. L. Arcus and J. V. Evans, *J. Chem. Soc.*, 789 (1958); C. H. Gudmundsen and W. E. McEwen, *J. Amer. Chem. Soc.*, 79, 329 (1957).

Table II. Spectral Properties of Azidoquinones

Compd	Mp, °C	Ir (cm^{-1})[a]	Nmr (ppm from TMS)[b]	Mass spectrum
1a	108–109	2140, 2120, 1670, 1650, 1580	6.57 s (1); 6.11 s (1); 1.26 s (9)	M^+, 205 (1%); 177 (24%); 162 (40%); 134 (100%); 67 (95%)
1b	133–135	2150, 2120, 1660, 1650, 1589	7.45 s (5); 6.87 s (1); 6.33 s (1)	M^+, 225 (1%); 197 (41%); 169 (18%); 141 (43%); 140 (25%); 114 (19%); 102 (100%)
1c	89–92	2150, 1680, 1660	6.60 d (1) J = 1.5 cps; 6.23 s (1); 2.05 d (3) J = 1.5 cps	M^+, 163 (1%); 135 (50%); 108 (29%); 79 (17%); 68 (57%); 52 (56%); 40 (100%)
1d	87 dec	2120, 2100, 1670, 1650	6.51 d (1) J = 1.5 cps; 2.05 d (3) J = 1.5 cps; 1.93 s (3)	M^+, 177 (3%); 149 (34%); 93 (14%); 81 (100%); 40 (57%)
1e	65–67	2125, 1665, 1610	5.49 d (1) J = 1.2 cps; 3.03 h (1) J = 6.9 cps; 1.92 s (3); 1.17 d (6) J = 6.9 cps	[c]
1f	125 dec	2110, 1640, 1600	1.95 s (6)	M^+, 218 (1%); 82 (46%); 81 (100%); 65 (15%); 53 (100%)
1h	81–82	2120, 1680, 1650, 1600, 1570	7.6–8.2 m (4); 2.05 s (3)	M^+, 213 (1%); 185 (63%); 130 (27%); 129 (27%); 104 (100%); 102 (37%); 76 (96%)
1i	117–119	2100, 1670, 1640, 1580, 1560	7.5 s (5); 7.4 s (5); 6.92 s (1)	
1j	100 dec	3440, 2100, 1630	7.3–7.4 m (10)	
1k	86–87	3460, 3320, 2120, 1650	5.23 b (2); 2.94 h (1) J = 7.1 cps; 1.86 s (3); 1.21 d (6) J = 7.1 cps	[c]
1l	97–98	3500, 3410, 2120, 1650, 1610	5.00 b (2); 3.18 h (1) J = 7 cps; 1.85 s (3); 1.19 d (6) J = 7 cps	[c]
1m		3310, 3110, 2140, 1660	6.00 s (1); 5.68 s (1)	[d]

[a] Nujol. [b] b = broad; d = doublet; s = singlet; h = heptet. [c] See ref 5. [d] See ref 13.

Experimental Section[23]

2-Azido-5-*t*-butyl-1,4-benzoquinone (1a). 2-Chloro-5-*t*-butyl-1,4-benzoquinone (6 g, 0.03 mol) was dissolved in 300 ml of hot 95% ethanol. The ethanol solution was cooled under running water until the quinone started to crystallize. Sodium azide (5.9 g, 0.09 mol) in 30 ml of water was then added in one portion. The reaction solution which changed from yellow to red was allowed to stand at ambient temperature for 15 min and then cooled to 0°. 2-Azido-5-*t*-butyl-1,4-benzoquinone (**1a**) (5.9 g, 95% yield), mp 107.5–109°, was collected. The spectral properties of this gold-yellow compound are given in Table II.

Anal. Calcd for $C_{10}H_{11}N_3O_2$: C, 58.54; H, 5.37; N, 20.48. Found: C, 58.60, H, 5.36; N, 20.17.

2-Azido-5-phenyl-1,4-benzoquinone (1b). 2-Chloro-5-phenyl-1,4-benzoquinone[24] (2.5 g, 0.012 mol) was dissolved in 200 ml of hot 95% ethanol. The solution was cooled to the point at which the quinone started to crystallize. Sodium azide (0.82 g, 0.013 mol) in 10 ml of water was then added in one portion. After 10 min the reaction solution was cooled. The resulting precipitate 2.4 g (93% yield) of 2-azido-5-phenyl-1,4-benzoquinone (**1b**), mp 133–135, was collected (see Table II for spectral properties).

Anal. Calcd for $C_{12}H_7N_3O_2$: C, 63.99; H, 3.11; N, 18.65. Found: C, 63.99; H, 3.11; N, 18.85.

2-Azido-5-methyl-1,4-benzoquinone (1c). 2-Chloro-5-methyl-1,4-benzoquinone[25] (0.86 g, 0.006 mol) was dissolved in 25 ml of 95% ethanol. To this solution was added 0.80 g (0.012 mol) of sodium azide in 10 ml of water in one portion. The reaction solution was cooled and 15 ml of water was then added, resulting in the precipitation of 0.60 g (87% yield) of 2-azido-5-methyl-1,4-benzoquinone (1c), mp 89–92°.

Anal. Calcd for $C_7H_5N_3O_2$: C, 51.52; H, 3.07; N, 25.77. Found: C, 51.72; H, 3.03; N, 25.82.

2-Azido-3,6-dimethyl-1,4-benzoquinone (1d). 2-Chloro-3,6-dimethyl-1,4-benzoquinone[26] (0.5 g, 0.003 mol) was dissolved in the minimum amount of boiling 95% ethanol. The ethanol solution was cooled under running water until the chloroquinone started to crystallize. Sodium azide (0.5 g, 0.07 mol) in 15 ml of water was then added in one portion. The reaction solution was cooled in ice resulting in the precipitation of 0.07 g (14% yield) of 2-azido-3,6-dimethyl-1,4-benzoquinone (**1d**), mp 87° dec. Satisfactory combustion analysis could not be obtained on this azide. However, its spectral properties (Table II) are in complete agreement with its formulation.

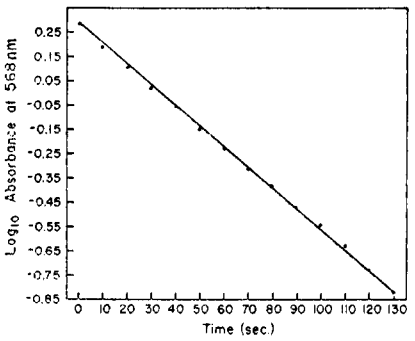


Figure 1. Plot of absorbance at 568 nm *vs.* time for the decomposition of 2-azido-3,6-dimethyl-1,4-benzoquinone in 98% sulfuric acid at 25.5°.

2-Azido-3-methyl-5-isopropyl-1,4-benzoquinone (1e). The above azidoquinone (**1e**), mp 65–67°, was prepared in 92% yield according to the method reported in ref 5.

2,5-Diazido-3,6-dimethyl-1,4-benzoquinone (1f). 2,5-Dichloro-3,6-dimethyl-1,4-benzoquinone (1.0 g, 0.005 mol) was dissolved in 100 ml of hot 95% ethanol. The solution was cooled to approximately 40° and 1.9 g (0.029 mol) of sodium azide in 10 ml of water was added in one portion. After 15 min the reaction mixture was cooled resulting in the precipitation of 0.98 g (92% yield) of the beautiful orange 2,5-diazido-3,6-dimethyl-1,4-benzoquinone (**1f**), mp 125° dec. See Table II for the spectral properties of **1f**.

Anal. Calcd for $C_8H_6N_6O_2$: C, 44.04; H, 2.75; N, 38.53. Found: C, 43.94; H, 2.79; N, 38.56.

2-Azido-1,4-naphthoquinone (1g). The above azidoquinone was prepared in 87% yield by the method reported by Fieser and Hartwell.[4]

2-Azido-3-methyl-1,4-naphthoquinone (1h). 2-Bromo-3-methyl-1,4-naphthoquinone[27] (2 g, 0.008 mol) was dissolved in 75 ml of 95%

(23) Melting points are uncorrected. Nmr spectra were obtained using a Varian Associates A-56/60 spectrometer. Ir spectra were obtained using a Perkin–Elmer Model 137 spectrophotometer. Mass spectra were obtained from West Coast Technical Service, San Gabriel, Calif., using a Hitachi-Perkin-Elmer RMU-6D mass spectrometer. Uv spectra were obtained using a Cary Model 14 spectrophotometer.

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ethanol. To the above solution was added in one portion 1.8 g (0.032 mol) of sodium azide in 10 ml of water. The solution was heated for a few minutes in order to obtain solution and then allowed to stand in the dark at room temperature for 45 min. Cooling the reaction solution in ice resulted in the precipitation of 0.5 g of 2-azido-3-methyl-1,4-naphthoquinone, mp 81–82.5°. Addition of 15 ml of water to the filtrate gave another 0.5 g of azide. Total yield of product was 1 g (60% yield). See Table II for the ir, nmr, and mass spectral data of **1h**.

Anal. Calcd for $C_{11}H_7N_3O_2$: C, 61.97; H, 3.29. Found: C, 61.56; H, 3.28.

2-Azido-3,6-diphenyl-1,4-benzoquinone (1i). 2-Chloro-3,6-diphenyl-1,4-benzoquinone[28] (1 g, 0.003 mol) was dissolved in 200 ml of hot 95% ethanol. The ethanol solution was cooled to the point where the quinone began to precipitate. At this point 0.88 g (0.014 mol) of sodium azide in 15 ml of water was added in one portion. The resulting red solution was allowed to stand for 30 min at room temperature and then cooled to 0°. The resulting precipitate, 0.71 g, of bright red 2-azido-3,6-diphenyl-1,4-benzoquinone, mp 117–119°, was collected. An additional 0.22 g of product was obtained by pouring the filtrate into water giving a total yield of 91%. The spectral properties of **1i** are listed in Table II.

Anal. Calcd for $C_{18}H_{11}N_3O_2$: C, 71.85; H, 3.67. Found: C, 71.71; H, 3.85.

2-Azido-5-hydroxy-3,6-diphenyl-1,4-benzoquinone (1j). 2-Chloro-4-hydroxy-3,6-diphenyl-1,4-benzoquinone (12) (0.9 g, 0.003 mol) was dissolved in a boiling mixture of 100 ml at 95% ethanol and 25 ml of dimethyl formamide. The solution was cooled and 0.65 g (0.01 mol) of sodium azide in 5 ml of water was added in one portion. The reaction solution which turned dark blue upon addition of the azide was heated for approximately 5 min until the color changed to dark green. This solution was then poured into water and acidified to pH 2. The resulting precipitate (0.9 g, 98% yield) of 2-azido-5-hydroxy-3,6-diphenyl-1,4-benzoquinone (**1j**) melted with gas evolution at 100° giving a new solid (**3j**) which melted at 190°. See Table II for spectral data of **1j**. Satisfactory combustion analysis could not be obtained on this compound.

2-Azido-3-methyl-5-amino-6-isopropyl-1,4-benzoquinone (1k). The above azidoquinone (**1k**) was prepared as described in ref 5.

2-Azido-3-isopropyl-5-amino-6-methyl-1,4-benzoquinone (1l). The above azidoquinone (**11**) was prepared as described in ref 5.

2-Azido-5-amino-1,4-benzoquinone (1m). The above azidoquinone (**1m**) was prepared in 75% yield as described in ref 13.

General Method for Conversion of Azidoquinones to γ-Cyanoalkylidine- (or Cyanoarylidine-) $\Delta^{\alpha,\beta}$-butenolides. The following general method was used for the rearrangement of the azidoquinones (**1a–i**). The azidoquinone was slowly added (5–10-mg portions) to cold (0–5°) concentrated sulfuric acid. During the addition the acid was *vigorously* stirred. After complete addition of the azide the reaction solution was maintained at 0–5° until all nitrogen evolution ceased. The reaction solution was then poured into ice–water and the butenolide collected by filtration. The pure products were usually obtained by recrystallization from aqueous ethanol and/or sublimation. The spectral properties for all of these butenolides are given in Table I.

β-*t*-Butyl-γ-cyanomethylene-$\Delta^{\alpha,\beta}$-butenolide (3a). 2-Azido-5-*t*-butyl-1,4-benzoquinone (0.5 g, 0.0024 mol) was converted by the general procedure to 0.41 g (95% yield) of the butenolide (**3a**), mp 89–90°.

Anal. Calcd for $C_{10}H_{11}NO_2$: C, 67.80; H, 6.22; N, 7.89. Found: C, 67.65; H, 6.20; N, 7.89.

β-Phenyl-γ-cyanomethylene-$\Delta^{\alpha,\beta}$-butenolide (3b). 2-Azido-5-phenyl-1,4-benzoquinone (0.3 g, 0.0015 mol) was converted by the general method to 0.21 g (80% yield) of the butenolide **3b,** mp 136–137°.

Anal. Calcd for $C_{12}H_7NO_2$: C, 73.10; H, 3.55; N, 7.11. Found: C, 73.30; H, 3.54; N, 7.09.

β-Methyl-γ-cyanomethylene-$\Delta^{\alpha,\beta}$-butenolide (3c). 2-Azido-5-methyl-1,4-benzoquinone (0.2 g, 0.0012 mol) was converted by the general method to 0.11 g (65% yield) of the butenolide **3c,** mp 63–64°.

Anal. Calcd for $C_7H_5NO_2$: C, 62.22; H, 3.67; N, 10.41. Found: C, 61.98; H, 3.67; N, 10.14.

β-Methyl-γ-(1-cyanoethylidine)-$\Delta^{\alpha,\beta}$-butenolide (3d). 2-Azido-3,6-dimethyl-1,4-benzoquinone (0.12 g, 0.0007 mol) was converted by the general method to 0.07 g (70% yield) of the butenolide **3d,** mp 78–80°.

Anal. Calcd for $C_8H_7NO_2$: C, 64.43; H, 4.70; N, 9.40. Found: C, 64.23; H, 4.52; N, 9.37.

α-Methyl-β-azido-γ-(1-cyanoethylidene)-$\Delta^{\alpha,\beta}$-butenolide (3f). 2,5-Diazido-3,6-dimethyl-1,4-benzoquinone (0.30 g, 0.012 mol) was converted by the general method to 0.19 g (77% yield) of the butenolide **3f,** mp 115 dec.

Anal. Calcd for $C_8H_6N_4O_2$: C, 50.53; H, 3.16; N, 29.47. Found: C, 50.81; H, 3.16; N, 29.36.

α,β-Benzo-γ-cyanomethylenebutenolide (3g). 2-Azido-1,4-naphthoquinone (2.0 g, 0.02 mol) was converted by the general method to 1.0 g (59% yield) of the butenolide **3g,** mp 170–172°.

Anal. Calcd for $C_{10}H_5NO_2$: C, 70.17; H, 2.92; N, 8.18. Found: C, 70.16; H, 2.93; N, 8.13.

α,β-Benzo-γ-(1-cyanoethylidene)butenolide (3h). 2-Azido-3-methyl-1,4-naphthoquinone (1.0 g, 0.005 mol) was converted by the general method to 0.83 g (95% yield) of the butenolide **3h,** mp 144–145°.

Anal. Calcd for $C_{11}H_7NO_2$: C, 71.35; H, 3.78; N, 7.57. Found: C, 71.68; H, 3.91; N, 7.68.

α-Phenyl-γ-cyanobenzylidene-$\Delta^{\alpha,\beta}$-butenolide (3i). 2-Azido-3,6-diphenyl-1,4-benzoquinone (0.55 g, 0.002 mol) was converted by the general method to 0.15 g (30% yield) of the butenolide **3i,** mp 190–191°.

Anal. Calcd for $C_{18}H_{11}NO_2$: C, 79.12; H, 4.03; N, 5.13. Found: C, 78.15; H, 4.30; N, 4.80.

α-Phenyl-β-hydroxy-γ-cyanobenzylidene-$\Delta^{\alpha,\beta}$-butenolide (3j). 2-Azido-4-hydroxy-3,6-diphenyl-1,4-benzoquinone (1.0 g, 0.0032 mol) was refluxed in 40 ml of chloroform for 30 min. The solvent was evaporated to a volume of 10 ml and then filtered to remove 0.35 g of insoluble residue. The remaining chloroform was removed *in vacuo* to give 0.6 g (65% yield) of the butenolide **3j,** mp 189–191°. The same product was obtained in 40% yield by the acid-catalyzed rearrangement of the azidoquinone **1j** according to the general method.

Anal. Calcd for $C_{18}H_{11}NO_3$: C, 74.74; H, 4.03; N, 4.84. Found: C, 74.44; H, 3.81; N, 4.67.

Acid-Catalyzed Rearrangement of α-Phenyl-β-hydroxy-γ-cyanobenzylidene-$\Delta^{\alpha,\beta}$-butenolide (3j) to the Azepinedione (4). The butenolide **3j** (0.13 g, 0.005 mol) was added to 10 ml of concentrated sulfuric acid at a temperature of 5°. After standing for 3 hr the reaction solution was poured into 100 ml of ice–water. The resulting precipitate was recrystallized from aqueous ethanol to give 0.1 g (77% yield) of the azepinedione **4,** mp 217 dec.

The ir spectrum (Nujol) of **4** showed characteristic absorptions at 3350, 3130, 1685, 1590, 1560, and 1515 cm^{-1}. The nmr spectrum (acetone-d_6) showed only aromatic proton absorptions as a multiplet between δ 7.3 and 7.7. The mass spectrum showed a molecular ion at 307 (3%) in accord with the formulation $C_{18}H_{13}NO_4$.

Anal. Calcd for $C_{18}H_{13}NO_4$: C, 70.36; H, 4.23; N, 4.56. Found: C, 70.44; H, 4.33; N, 4.48.

Photolytic Isomerization of β-*t*-Butyl-γ-cyanomethylene-$\Delta^{\alpha,\beta}$-butenolide (1a). Conversion of the *trans–trans* Isomer (1a) to the *cis–trans* Isomer (5) and 2-Cyano-4-*t*-butyl-1,3-cyclopentenedione (6). The *trans–trans* isomer of β-*t*-butyl-γ-cyanomethylene-$\Delta^{\alpha,\beta}$-butenolide (**3a**) (0.2 g, 0.001 mol) was dissolved in 60 ml of *n*-hexane and irradiated for 2 hr with a 2537-Å resonance lamp. The reaction was monitored by gas chromatography which indicated a steady state after 2 hr. The reaction solution was cooled in an ice bath which resulted in the precipitation of 0.1 g (50% yield) of the cyclopentenedione **6.** This base-soluble product shows characteristic absorptions in the ir spectrum at 2265 (CN), 1770, 1720 (C=O) and 1600 cm^{-1} (C=C). The nmr spectrum of **6** in $CDCl_3$ shows absorptions for a vinyl proton at δ 4.40 b (**1**) and *t*-butyl methyl protons at δ 1.38 s (**9**).

The filtrate was concentrated under vacuum to an oil. Analysis of the oil by nmr and glc showed it to contain equal amounts of the *trans–trans* butenolide **3a** and the *cis–trans* isomer 5. The latter compound was isolated by preparative glc at 200° using 20 ft × $^3/_8$ in. SE 30 columns. The solid thus isolated was recrystallized from aqueous ethanol to give analytically pure butenolide (**5**), mp 93°. See Table I for the spectral properties of this compound.

Anal. Calcd for $C_{10}H_{11}NO_2$: C, 67.80; H, 6.22; N, 7.80. Found: C, 68.09; H, 6.41; N, 7.88.

A pure sample of the *cis–trans* butenolide **5** was photolyzed in a manner analogous to that described for the *trans–trans* isomer and shown to go to the same steady-state composition of **3a, 5,** and **6.**

2,3,5,6-Diepoxy-2,5-diphenyl-1,4-benzoquinone (11). To a stirred suspension of 17.0 g (0.067 mol) of 2,5-diphenyl-1,4-benzoquinone in 400 ml of 3:1 dioxane–ethanol was added 30 ml of 30% hydrogen peroxide and 5 ml of Triton B (benzyltrimethyl ammonium

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hydroxide). As the reaction proceeded the undissolved yellow quinone went into solution and after about 1 hr the solution became nearly clear and colorless. The reaction solution was then poured into 1000 ml of ice water to give 14.8 g (0.507 mol, 75% yield) of the diepoxide **11**, mp 206–209°.

Anal. Calcd for $C_{18}H_{12}O_4$: C, 73.98; H, 4.14. Found: C, 73.94; H, 4.15.

The ir spectrum of **11** shows characteristic absorptions at 1720, 1260, 690, and 750 cm^{-1}. The nmr spectrum (DMSO-d_6) shows two absorptions in a ratio of 10:2, at, respectively, δ 7.48 and 4.18. The mass spectrum of **11** shows a molecular ion peak at *m/e* 292 in accord with the formulation $C_{18}H_{12}O_4$.

2-Chloro-5-hydroxy-3,6-diphenyl-4-benzoquinone (12). A dioxane–ethanol solution (10:1) of 8 g (0.027 mol) of 2,3,5,6-diepoxy-2,5-diphenyl-1,4-benzoquinone (**11**) was treated with 10 ml of concentrated hydrochloric acid. After heating to reflux for a few minutes to accomplish complete solution, the reaction was allowed to stand at ambient temperature for 7 days. During this time several additional 10-ml portions of acid were added. Filtration of the cooled reaction solution gave a beautiful yellow-orange dioxane complex of the quinone **12**. The dioxane was readily removed *in vacuo* to give 5.8 g (69% yield) of the known[19] 2-chloro-5-hydroxy-3,6-diphenyl-1,4-benzoquinone, mp 212° (recrystallized from dioxane).

Vulpinic Acid (13). The butenolide (**3j**) (2.0 g, 0.007 mol) was dissolved in a minimum amount of boiling methanol. To this solution was added 0.5 ml of concentrated HCl. Cooling this solution resulted in the precipitation of 2.1 g (95% yield) of vulpinic acid (**14**). This product was identical (mixture melting point and infrared) to an authentic sample of the natural product.[20]

Conversion of the Azidoquinones 1a, 1b, and 1g, Respectively, to the Butenolides 3a, 3b, and 3g in Sulfuric Acid-d_2. The azidoquinones **1a**, **1b**, and **1g** were converted to the corresponding butenolides **3a**, **3b**, and **3g**, respectively, by the general method. The acid used was 98% D_2SO_4 and the products were isolated by pouring the acid solution into 98% D_2O. The butenolides obtained under these conditions were identical in *all respects* with those obtained under protic conditions, *i.e.*, no exchange was observed.

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General Acid Catalysis and the pH-Independent Hydrolysis of 2-(*p*-Nitrophenoxy)tetrahydropyran

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Abstract: The hydrolysis of 2-(*p*-nitrophenoxy)tetrahydropyran is characterized by a pH-independent reaction at pH values greater than 4.0. This reaction has a D_2O solvent isotope effect of approximately unity; k_{D_2O}/k_{H_2O} = 1.1 for hydrolysis in solvent containing 50% dioxane and k_{D_2O}/k_{H_2O} = 0.9 for hydrolysis in H_2O or D_2O. The value of ΔS^* is +2.2 eu. The pH-independent reaction is strongly accelerated by increasing the polarity of the solvent, being 48.7 times more rapid in water than in 50% dioxane–H_2O. Thus, this reaction is most likely a unimolecular decomposition to *p*-nitrophenoxide ion and a resonance stabilized carbonium ion. Bond breaking is also relatively important in comparison to protonation in the transition state of the general acid catalyzed reaction as evidenced by the Brønsted coefficient of 0.5 and the positive value of ρ (0.9) obtained in formic acid catalyzed hydrolysis of the series of 2-(substituted phenoxy)tetrahydropyrans.

Acetals having strongly electron-withdrawing substituents in the leaving group, which reduce basicity and at the same time increase the ease of C–O bond breaking, are hydrolyzed with partially rate-determining protonation by hydronium ion and a pronounced general acid catalysis.[1] In the case of 2-(*p*-nitrophenoxy)-tetrahydropyran there is a large plateau in the pH-rate constant profile at pH values greater than 4.[1] Plateau regions have also been observed in the hydrolysis of various types of glycosides,[2] but the mechanistic significance of the pH-independent reactions is obscured by the presence of neighboring groups, hydroxyl or acetamido, which could participate in the reaction. A further complication encountered with glycosides is that hydroxide ion catalysis is observed. A fast pH-independent reaction has also been detected with tropone diethyl ketal, a ketal whose hydrolysis is catalyzed by general acids.[3] The elucidation of the mechanism of a pH-independent acetal hydrolysis reaction would be of great importance in furthering understanding of the factors influencing the hydrolysis of these compounds. Therefore, in view of the structural simplicity of 2-(*p*-nitrophenoxy)tetrahydropyran and the lack of hydroxide ion catalysis, a detailed investigation of its pH-independent hydrolysis was carried out and is reported in this paper.

Experimental Section

Materials. 2-(*p*-Nitrophenoxy)tetrahydropyran was that previously studied.[1] Dioxane was purified by the method of Fieser[4] and was stored frozen in brown bottles. Deuterium oxide (99.8%) was obtained from Bio-Rad Co.

Kinetic Measurements. The rates of hydrolysis were measured in H_2O, D_2O, and in solvent containing 10 and 50% dioxane (v/v). The rates were measured spectrophotometrically with a Zeiss PMQ 11 spectrophotometer by following the appearance of *p*-nitrophenol at 330 mμ or *p*-nitrophenoxide ion at 400 mμ. The acetal, dissolved in purified dioxane, was added directly to the thermostated solution in the cuvette by means of a calibrated dropping pipet. One drop was added and the solution was then stirred vigorously. The reactions were followed to at least 75% of completion, and infinity points were taken at greater than 10 half-lives and were stable. Values of k_{obsd} were calculated with an Olivetti Underwood Pro-

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