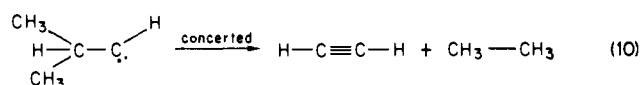
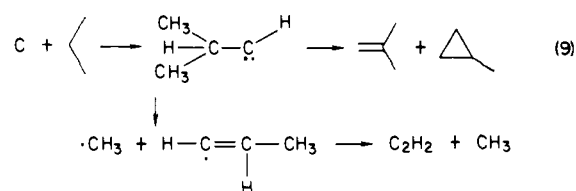


cleavage, a carbene with enough internal energy to undergo this cleavage will be generated. Since it has been observed that an increase in pressure of added hydrocarbon reactant does not lower C_2H_2 yields,⁶ we must assume that cleavage of vibrationally excited **16** and **18** occurs rapidly before collisional deactivation can occur.

A major drawback to experimental studies involving nucleogenic ^{11}C atoms is the fact that only products bearing the ^{11}C label are detected. Thus, while labeled acetylene is observed, the remaining fragments from the cleavage are undetected.¹ However when C atoms are generated by the chemical decomposition of 5-diazo-tetrazole,³⁷ yields are high enough to permit detection of all products. Experiments of this type support the contention that cleavage of the bond β to the carbene carbon occurs in a stepwise manner. Thus reaction of carbon with propane gives mainly products which may be rationalized by assuming initial insertion into the 2° C-H bond to generate isopropyl carbene, which may either cleave or rearrange (eq 9). The major products from the cleavage reaction are C_2H_2 and CH_4 . The CH_4 results from hydrogen abstraction by methyl radicals. A concerted cleavage of the two C-C bonds β to the carbene carbon (eq 10) would lead

to ethane rather than methane.



Acknowledgment. We thank the Auburn University Computation Center for a generous allotment of computer time. M.L.M. thanks Auburn University for the award of a Grant-in-Aid (82-54). P.B.S. gratefully acknowledges support of this research by the National Science Foundation under Grant CHE-8401198. An insightful comment by a referee regarding the possibility of reaction on the $^3A'$ potential energy surface is acknowledged.

Registry No. C, 7440-44-0; CH_4 , 74-82-8; $CH\equiv CH$, 74-86-2; ethylidene, 4218-50-2.

(37) Shevlin, P. B.; Kammula, S. J. *Am. Chem. Soc.* 1977, 99, 2627.

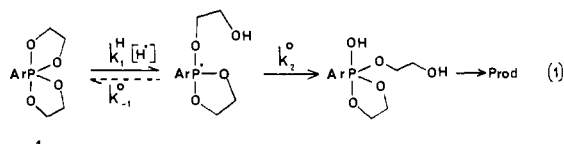
Oxyphosphorane Hydrolysis. Reversible Ring Opening of Spirophosphoranes Containing Six-Atom Rings

Glenn H. McGall and Robert A. McClelland*

Contribution from the Department of Chemistry, University of Toronto, Toronto, Ontario, Canada M5S 1A1. Received December 17, 1984

Abstract: A kinetic and mechanistic study is reported for the hydrolysis of two spirooxyphosphoranes containing six-atom rings (6-phenyl-1,5,7,11-tetraoxa-6-phosphospiro[5.5]undecane (**2a**) and the 3,3,9,9-tetramethyl-substituted compound (**2b**)). An intermediate is observed at pH < 9, which had been synthesized and characterized as a ring-opened phosphonium ion (**3**). Kinetic and spectral analysis show that the hydrolysis mechanism involves reversible formation of this phosphonium ion, with $K_1 = [2a][H^+]/[3a] = 3 \times 10^{-9}$, followed by rate-limiting addition to the cation of water and, at high pH, hydroxide ion. Reversibility of the ring opening is unambiguously established by the observation that addition of the cation to a solution of high pH results in ring closure to the phosphorane.

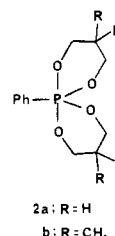
Alkoxyphosphoranes are phosphoryl group analogues of acetals and ortho esters¹ and also serve as models of hydroxyphosphoranes, the postulated intermediates in the hydrolysis of phosphate esters.² Although alkoxyphosphoranes are well established,³ investigations of their hydrolyses have been limited.⁴ We recently have initiated a program of study of the mechanisms of hydrolyses and have reported kinetic⁵ and isomerization⁶ data for spirophosphoranes **1**. The hydrolysis is characterized by an H^+ -catalyzed reaction



extending from acidic pH to about pH 9.5 where there is an abrupt

changeover to an OH^- catalyzed reaction. The latter was concluded to involve an associative process with formation of a hexacoordinated phosphoroxanide ion. For the former a dissociative mechanism with a phosphonium ion intermediate was proposed (eq 1).

In this paper we report a kinetic study of the hydrolysis of the spirophosphoranes **2** with six-membered rings in place of five.



Despite the structural similarities of **1** and **2**, considerable differences are observed, the most notable being that the phosphonium ion intermediates from **2** are observable at pH < 9. This observation permits kinetic and spectral analyses, which show that the cations and phosphoranes are in equilibrium prior to the overall hydrolysis.

Experimental Section

1H NMR spectra were obtained at 60 MHz, unless otherwise stated. ^{31}P NMR spectra were obtained at 32.3 MHz with chemical shifts relative to 85% H_3PO_4 , downfield shifts being reported as positive. Con-

(1) Fife, T. H. *Acc. Chem. Res.* 1972, 5, 264-272. Cordes, E. H.; Bull, H. G. *Chem. Rev.* 1974, 74, 581-604.

(2) Westheimer, F. H. *Acc. Chem. Res.* 1968, 1, 70-78.

(3) Holmes, R. R. "Pentacoordinated Phosphorus"; American Chemical Society: Washington, D.C., 1980; Vol. 1 and 2, ACS Monographs 175 and 176.

(4) (a) Archie, W. C.; Westheimer, F. H. *J. Am. Chem. Soc.* 1973, 95, 5955-5959. (b) Queen, A.; Lemire, A. E.; Janzen, A. F. *Int. J. Chem. Kinet.* 1981, 13, 411-416. (c) Belskii, V. E.; Khismatullina, L. A.; Bykova, T. G.; Burykina, A. V.; Ivanov, B. E. *J. Gen. Chem. USSR* 1979, 49, 298-302.

(5) McClelland, R. A.; Patel, G.; Cirinna, C. *J. Am. Chem. Soc.* 1981, 103, 6432-6436.

(6) McGall, G.; McClelland, R. A. *Chem. Soc., Chem. Commun.* 1982, 1222-1223.

ventional UV spectra and kinetic measurements were obtained with a Cary 2390 spectrophotometer linked to an Apple IIe microcomputer. Stopped-flow kinetic measurements were carried out with a Durrum-Gibson apparatus linked to a Tektronix 4050 microcomputer.

Synthesis. 6-Phenyl-3,3,9,9-tetramethyl-1,5,7,11-tetraoxa-6-phosphaspiro[5.5]undecane (**2b**),⁷ 2-oxo-2-phenyl-1,3,2-dioxaphosphorinane (**5a**),⁸ and 5,5-dimethyl-2-oxo-2-phenyl-1,3,2-dioxaphosphorinane (**5b**)⁹ were prepared by literature methods.

6-Phenyl-1,5,7,11-tetraoxa-6-phosphaspiro[5.5]undecane (2a) was prepared in the same way as **2b** with 1,3-propanediol. The white crystals from ether had mp 151–153 °C: ³¹P NMR (CDCl₃) δ -50.2; ¹H NMR (CDCl₃) δ 7.8–7.1 (5 H, multiplet), 4.05 (8 H, d, *J* = 15 Hz) of *t* (*J* = 6.5 Hz), 1.92 (4 H, quintet, *J* = 6.5 Hz). Anal. Calcd for C₁₂H₁₇O₄P: C, 56.25; H, 6.69; P, 12.09. Found: C, 56.28; H, 6.75; P, 12.11.

5,5-Dimethyl-2-methoxy-2-phenyl-1,3,2-dioxaphosphorinane-2-ylum Trifluoromethanesulfonate (6b). **5b** (0.23 g, 1 mmol) and 1.7 g (10 mmol) of methyl trifluoromethanesulfonate were dissolved in 3 mL of methylene chloride. After 6 h of standing 8 mL of carbon tetrachloride were added and the solid product collected by filtration. **6b** had mp 89–91 °C: ³¹P NMR (CDCl₃) δ +31.5; ¹H NMR (200 MHz, CDCl₃) δ 8.0–7.5 (5 H, m), 4.93 (2 H, dd, *J*_{P-H} = 6.4 Hz, *J*_{H-H} = 10.8 Hz), 4.51 (2 H, dd, *J*_{P-H} = 15.6 Hz, *J*_{H-H} = 10.8 Hz), 4.26 (3 H, d, *J*_{P-H} = 11 Hz), 1.27 (3 H, s), 1.19 (3 H, s). A small amount of unreacted **5b** is present in this sample. The phosphonium ion **6a** was prepared in CH₂Cl₂ solution in the same way and used directly as the solution.

Phosphonium Ion 3b. One equivalent of trifluoromethanesulfonic acid was slowly added to the phosphorane **2b** dissolved in methylene chloride at -80 °C under nitrogen. The mixture was allowed to come to room temperature. This solution was used directly in further experiments since attempts to precipitate salts resulted in oils. The ion **3b** in CD₂Cl₂ had ³¹P NMR δ +30.5; ¹H NMR (200 MHz) δ 8.0–7.5 (5 H, m), 4.96 (2 H, dd, *J*_{P-H} = 5.6 Hz, *J*_{H-H} = 11.0 Hz), 4.44 (2 H, dd, *J*_{P-H} = 16.2 Hz, *J*_{H-H} = 11.1 Hz), 4.34 (2 H, d, *J*_{P-H} = 5.1 Hz), 3.48 (2 H, s), 1.23 (3 H, s), 1.16 (3 H, s), 0.95 (6 H, s).

Products. Product analysis for **2b** was carried out by dissolving a small quantity of the phosphorane in a D₂O solution of the appropriate pH. ³¹P NMR spectra were obtained directly on this solution, and ¹H NMR spectra were obtained in CDCl₃ after removal of the D₂O by lyophilization. The major product, the ester bis(2,2-dimethyl-3-hydroxypropyl) phenylphosphonate (**4b**), had ³¹P NMR δ +22.0; ¹H NMR δ 8.0–7.5 (5 H, m), 3.85 (4 H, d, *J*_{P-H} = 7 Hz), 3.38 (4 H, s), and 0.92 (12 H, s). The minor product (³¹P NMR, δ +18.8) was the cyclic ester **5b**, as shown by direct comparison with the synthetic sample.

Kinetic Measurements. Solutions for kinetic studies were prepared by adding to a volumetric flask half the volume of dioxane and then filling to the mark with aqueous solutions of the desired acid, base, or buffer concentration. In all solutions an ionic strength of 0.5 was maintained with sodium chloride as the added electrolyte. The dioxane employed was spectrograde quality further purified by being passed through a short column of Fisher adsorption alumina followed by distillation from lithium aluminum hydride prior to use. The pH was measured with a Corning Model 130 pH meter and combination electrode, with calibration with standard aqueous buffers. An empirical correction factor of 0.12 was added to all measured pH.¹⁰ This factor was obtained from the measured pH of 1.88 observed for 50% aqueous dioxane containing 0.0100 M HCl and 0.49 M NaCl. The pH values of sodium hydroxide solutions were calculated with a *pK*_w of 15.8 obtained for this solvent composition at 25 °C.¹¹

Kinetic measurements for solutions with pH below 13 were conducted as follows. A small quantity of a 1 M solution of the phosphorane in dry methylene chloride was dissolved in a 0.002 M NaOH solution in 50% aqueous dioxane previously thermostated at 25 °C. The phosphorane concentration was of the order 10⁻³ M. The NaOH solution was rapidly loaded into one syringe of the stopped-flow spectrophotometer, where it was mixed with the appropriate acid or buffer also in 50% dioxane. Absorbance changes at 265 nm were monitored. The photomultiplier output of the spectrometer was connected to a digitizing device, and the digitized absorbance-time data were transferred to a microcomputer for analysis. First-order rate constants were calculated as slopes of plots of ln(*A*_∞ - *A*) or ln(*A* - *A*_∞) vs. time except for the fast kinetic phase observed between pH 7 and 8. Due to the incursion of a subsequent

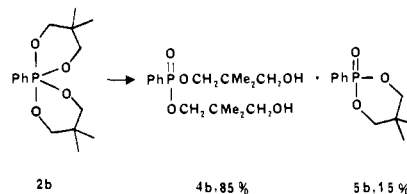
process, a stable infinity absorbance for this initial rapid phase is not achieved. Rate constants were calculated with use of the Guggenheim method. All kinetic plots displayed excellent linearity over several half-lives. The pH values of all solutions were measured immediately after mixing on the stopped-flow apparatus.

In more concentrated sodium hydroxide solutions, absorbance changes associated with the subsequent hydrolysis of the phosphonate ester products prevented direct spectrophotometric determination of rate constants for the phosphorane hydrolysis. The approach described previously⁵ to obtain rate constants for the hydrolysis of **1** at high pH was therefore employed. A solution of the phosphorane having the appropriate NaOH concentration is prepared at 25 °C. This solution is rapidly loaded into one syringe of the stopped-flow apparatus where it is mixed with an HCl solution such that the final solution after mixing is acidic. Unreacted phosphorane remaining in the base solution at the time of each mixing is quantified by the total absorbance change observed for the much more rapid hydrolysis which occurs after the pH jump. Rate constants for the base hydrolysis were obtained from the slopes of plots of ln(*A*₀ - *A*_∞) vs. *t* where *t* is the time of mixing and *A*₀ and *A*_∞ are the initial and final absorbances after each mixing.

Rates of hydrolysis in aqueous sulfuric acid solutions were measured by conventional UV spectroscopy, following absorbance decreases at 270 nm.

Results

Products of Hydrolysis. Hydrolysis products were determined for **2b**, the substrate with the simpler ¹H NMR pattern. As summarized below, a mixture of phosphonate esters is formed.



The major product (+22.0 ppm ³¹P chemical shift) had a ¹H NMR spectrum corresponding to the acyclic diester **4b**. A minor product (+18.8 ppm ³¹P) was the cyclic ester **5b**, which was synthesized independently for comparison. Integration of the NMR spectra showed that the ratio **5b**:**4b** was 15.85. This does not vary appreciably with the pH of the solution.

Kinetics. Kinetic studies were conducted following changes in UV spectra, with a wavelength of 265 nm being employed for the majority of the rate measurements. The phosphoranes, phosphonate ester products, and intermediate phosphonium ions exhibit similar UV spectra (see Figure 1 of ref 5 and Figure 1 of the accompanying paper), since there is not a strong interaction between the phenyl ring and the phosphorus atom. There is, however, an intensity difference, with the phosphonium ion the most strongly adsorbing and the phosphorane the least. Extinction coefficients at 265 nm are 4.5 × 10² for the phosphorane **2a**, 6.5 × 10² for the product mixture (mainly **4a**), and 9.5 × 10² for the phosphonium ion **3a**.

At any pH in wholly aqueous solution the hydrolysis of both **2a** and **2b** is complete within a few seconds. In consequence kinetic measurements were performed in dioxane:water mixtures prepared as described in the Experimental Section. In dilute solutions of NaOH in this mixture, the phosphoranes have half-lives of about 2 min. This provides sufficient time to carry out the stopped-flow pH jump experiments necessary to obtain kinetic data at lower pH. The phosphorane **2a** was studied in the most detail. Rate constants were measured at 25 °C with the ionic strength being maintained constant at 0.5. In buffer solutions, catalysis by the buffer is observed, and intercept rate constants were obtained by extrapolation to zero buffer concentration. The rate-pH profile for **2a** is shown in Figure 1. This exhibits four distinct regions of kinetic behavior.

pH > 12. The hydrolysis in very dilute NaOH solutions shows up spectrally as a first-order increase in absorbance in the region 250 to 275 nm, very similar to the spectral change which occurs in the hydrolysis of the phosphorane **1**, Ar = Ph.⁵ That this change does represent conversion of the phosphorane to the ester products was demonstrated in the present case by recording ¹H NMR

(7) Antczak, S.; Bone, S. A.; Briery, J.; Trippett, S. *J. Chem. Soc., Perkin Trans. 1*, 1977, 278–281.

(8) Edmunson, R. S.; Wrigley, J. O. *L. Tetrahedron* 1967, 23, 283–290.

(9) Majoral, J. P.; Navech, J. *Bull. Soc. Chim. Fr.* 1971, 95–104.

(10) Van Viter, L. G.; Haas, C. G. *J. Am. Chem. Soc.* 1953, 75, 451–454.

(11) Wooley, E. M.; Hurkot, D. G.; Hepler, L. G. *J. Phys. Chem.* 1970, 74, 3908–3913.

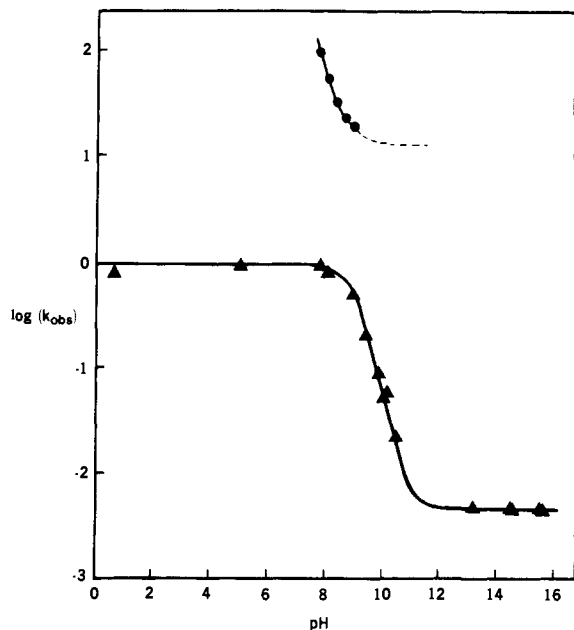


Figure 1. Rate-pH profiles in the hydrolysis of the phosphorane **2a**. The lower curve refers to formation of phosphonate ester products from an equilibrating mixture of phosphorane **2a** and phosphonium ion **3a**. The upper curve refers to establishment of this equilibrium approaching from the phosphorane side. See text for a detailed discussion and dissection into individual regions.

Table I. Observed and Derived Rate Constants for the Hydrolysis of the Phosphorane **2a**

constant	value
k_b°	$4.9 \times 10^{-3} \text{ s}^{-1}$
k_s^{H}	$3.9 \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$
$k_a^\circ = k_2^\circ$	1.1 s^{-1}
$k_2^{\text{OH}} = k_b^\circ \cdot K_a / K_w$	$1.0 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$
$k_f^{\text{H}} = k_1^{\text{H}}$	$4.1 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$
$k_f^\circ = k_{-1}^\circ$	13 s^{-1}
$K_1 = k_{-1}^\circ / k_1^{\text{H}}$	3.2×10^{-9}
$K_1 = k_a^\circ / k_s^{\text{H}}$	2.8×10^{-9}
$K_1 = K_a$ (spect)	3.3×10^{-9}

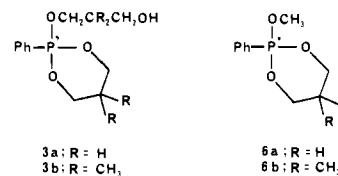
spectra as a function of time in a solvent mixture containing 0.005 M NaOD (Figure 2). In this experiment the disappearance of the phosphorane NMR signals occurs simultaneously with the rise of the spectrum corresponding to the ester products. A first-order rate constant was determined by integration of the spectra obtained at various times. This was within experimental error identical with the value obtained by UV spectroscopy. In more concentrated NaOH solutions (>0.01 molar) the phosphonate ester products, once formed, undergo further hydrolysis due to the high hydroxide ion concentration. This interferes with the kinetic study of the phosphorane hydrolysis since it is seen in the UV spectra as a decrease in absorbance, as was confirmed by isolating the product mixture from dilute acids where no hydrolysis occurs, and adding this to the same NaOH solutions. A pH-jump technique (ref 5 and Experimental Section) has been developed to measure rate constants for the phosphorane when this further hydrolysis interferes. As can be seen in Figure 1, the rate of phosphorane hydrolysis is independent of pH above pH 12. The constant k_b° in Table I is the first-order rate constant in this region. This rate constant refers to the noncatalyzed conversion of the phosphorane to the mixture of phosphonate products.

pH 9–11. In this region the same absorbance increase is observed as that seen at higher pH. Now, however, a first-order dependency on H^+ concentration is observed. The second-order rate constant ($k_{\text{obs}}/[\text{H}^+]$) is listed in Table I as k_s^{H} . General acid catalysis by the buffer is also observed. A crude Brønsted plot using NH_4^+ , Et_3NH^+ , and H_3O^+ has a slope of 0.65. The kinetics in this region refer to an acid-catalyzed conversion of the phosphorane to the phosphonate mixture.



Figure 2. ^1H NMR spectra for the phosphorane **2b**. The top spectrum has been recorded in CDCl_3 , and the doublet at δ 3.6 represents the four equivalent CH_2 groups. The remaining spectra have been recorded in 0.005 M NaOD/ D_2O (HOD resonance at δ 4) at approximately 30 s, 2 min, 5 min, and 15 min after phosphorane addition. The bottom spectrum represents the diester **4b** and is characterized by a CH_2 doublet at δ 3.7 (POCH_2) and a CH_2 singlet at δ 3.2 (CH_2OH).

pH < 7. Hydrolysis below pH 7 is characterized by a first-order absorbance decrease, in contrast to the situation at pH > 9. The rate constant for the decrease is dependent on the base component of the buffer. At zero buffer concentration the rate constant (k_a° of Table I) is independent of pH. We suspected that, under these acidic conditions, the phosphorane was being rapidly converted to an intermediate phosphonium ion **3** and that what was being observed in the kinetics was the hydrolysis of this cation to the phosphonate products. (See Figure 1 of the accompanying paper for an example of the spectral change which occurs in the hydrolysis of an alkoxyphosphonium ion.) This was verified by



preparing the model cations **6**, by methylation of the cyclic phosphonate esters. In aqueous sulfuric acid solutions¹² these undergo hydrolysis with a UV spectral change very similar to that exhibited by the phosphorane. Moreover the rate constant for the model ion is virtually identical with that of the corresponding phosphorane. It also proved possible to form the cations **3** in the absence of nucleophiles,¹³ by addition of 1 equiv of trifluoro-

(12) 20% H_2SO_4 –50% H_2SO_4 . It was necessary to use these more concentrated acids to retard the rate of the cation hydrolysis in order to perform kinetic experiments with the model cations.

(13) For other examples where phosphonium ions have been prepared by ring opening of phosphoranes see: (a) van Aken, D. Paulissen, L. M. C.; Buck, H. M. *J. Org. Chem.* **1981**, *46*, 3189–3193. (b) Granoth, I.; Martin, J. C. *J. Am. Chem. Soc.* **1981**, *103*, 2711–2715. (c) Hellwinkel, D.; Krapp, W. *Chem. Ber.* **1978**, *111*, 13–41.

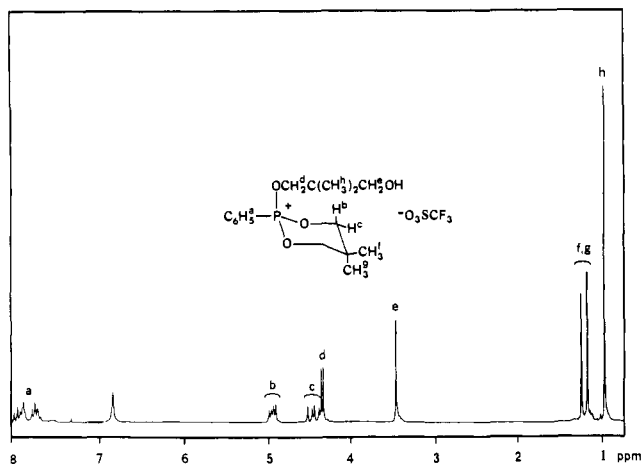


Figure 3. ^1H NMR spectrum (200 MHz) of the cation **3b** in CD_2Cl_2 . Assignment of the ring protons has been made on the basis¹⁴ of P-H coupling constants ($J_{\text{H}^b\text{-P}} = 5.6$ Hz, $J_{\text{H}^c\text{-P}} = 16.2$ Hz).

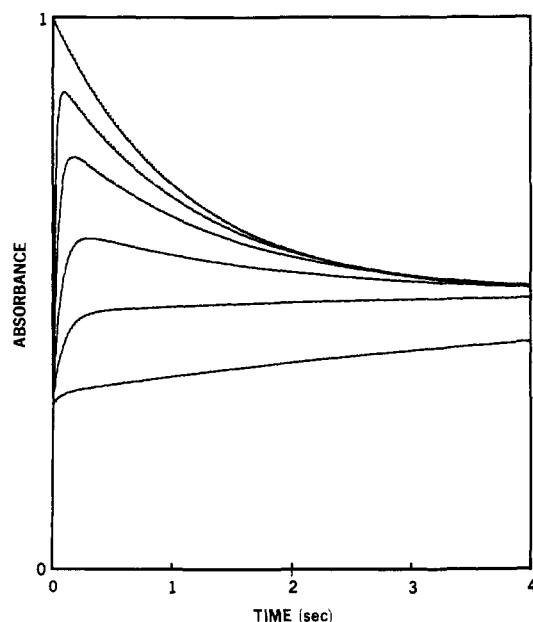


Figure 4. Absorbance vs. time curves for the hydrolysis of the phosphorane **2a**. Experiments were conducted on the stopped-flow spectrophotometer at a wavelength of 265 nm and with an initial phosphorane concentration of 5×10^{-4} molar. The final pH (from top to bottom) is 5.0, 7.28, 7.7, 8.2, 8.7, and 9.2.

methanesulfonic acid to the phosphoranes **2** in anhydrous CD_2Cl_2 . The cation **3b** displays the expected low-field ^{31}P NMR resonance at +30.5 ppm and a ^1H NMR spectrum (Figure 3) consistent with the proposed structure. Addition of solutions of this cation to sulfuric acid results in an absorbance decrease, with rate constants identical with those obtained from the phosphorane **2b**. Addition of the cation to sodium hydroxide results in an absorbance increase, again with a rate constant identical with that for the phosphorane. In other words, in base solution the cation undergoes ring closure, regenerating its phosphorane precursor.

pH 7–10. More complex kinetic behavior is exhibited in this region. The absorbance–time curves reveal two processes (Figure 4), the first characterized by a rapid rise in absorbance and the second characterized by a slower change giving the absorbance of the ester products. As seen in the upper curve of Figure 1 the first change follows the rate law

$$k_{\text{obsd}}(\text{fast}) = k_f^{\circ} + k_f^{\text{H}}[\text{H}^+] \quad (2)$$

(14) For P-H coupling constants in 1,3,2-dioxaphosphorinanes see: Maryanoff, B. E.; Hutchins, R. O.; Maryanoff, C. A. *Top. Stereochem.* **1979**, *5*, 187–326.

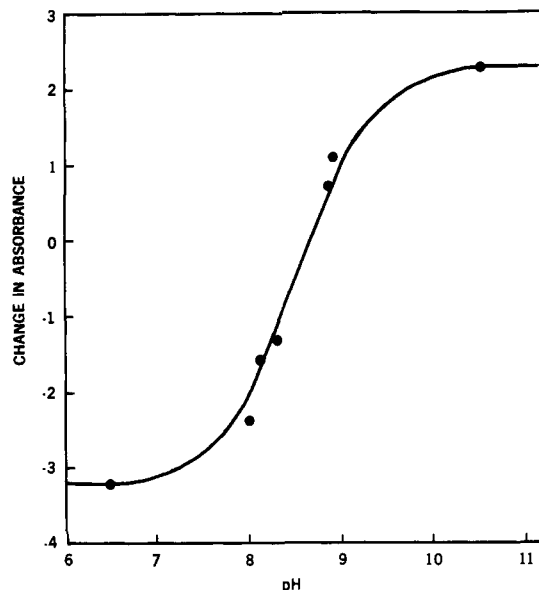


Figure 5. Absorbance change occurring during the slow kinetic phase. For conditions see caption to Figure 4.

with constants k_f° and k_f^{H} listed in Table I. The second phase has rate constants which connect the H^+ -dependent region at pH 10 to the pH-independent region at pH 7, so that one continuous curve is obtained from high pH and low pH.

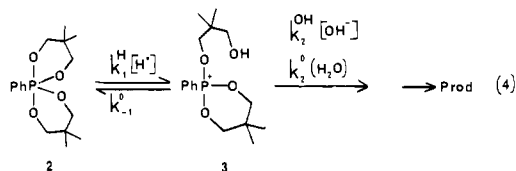
As seen in Figure 4, the absorbance level attained after completion of the fast phase varies with pH such that the subsequent slow phase undergoes a changeover from a negative absorbance change at pH 7 to a positive change at pH 10. Figure 5 shows a plot vs. pH of the total absorbance change which occurs in the slow phase. The result is a spectroscopic titration curve, and an acidity constant $K_a(\text{spect})$ (Table I) can be calculated according to eq 3, where ΔA , ΔA_{acid} , and ΔA_{base} are the absorbance changes at intermediate pH and in acid and in base, respectively.

$$K_a(\text{spect}) = \frac{\Delta A - \Delta A_{\text{acid}}}{\Delta A_{\text{base}} - \Delta A} [\text{H}^+] \quad (3)$$

It can be noted that the behaviors at higher pH and lower pH represent simplified versions of this more complex behavior. At $\text{pH} > 10$ the initial rapid phase has a negligible amplitude, so that only the relatively slow absorbance increase is observed. At $\text{pH} < 7$, the initial rise is present but it has become sufficiently fast that it cannot be observed even by stopped-flow spectroscopy. In consequence only the slower absorbance decrease is observed.

Discussion

The mechanism which we propose for the hydrolysis of the phosphoranes **2** is shown in eq 4. In this mechanism the phos-



phonium ion **3** is an intermediate at all pH, being formed reversibly from the phosphorane. The rate-limiting step at all pH is the cation hydrolysis, which occurs with water addition and, in base, hydroxide addition. The intermediacy of the phosphonium ion is obviously well established in neutral and acid solutions where it can in fact be observed as an intermediate. In basic solutions it is not observed but its presence can be inferred from the kinetic analysis.

The most direct evidence for the reversibility in base of the first step is the observation that the phosphonium ion ring closes to the neutral phosphorane in these solutions. It is also possible at intermediate pH to observe the phosphorane:phosphonium ion

equilibration as a rapid process preceding the overall hydrolysis and on the basis of the spectroscopic changes calculate the equilibrium constant (eq 5). It can be noted that if ring opening

$$K_a(\text{spect}) = K_1 = \frac{[\text{phosphorane}][\text{H}^+]}{[\text{phosphonium ion}]} \quad (5)$$

were not truly reversible throughout the pH range of the measurement of this value, a titration curve would not be produced.

According to this model, the lower k_{obsd} -pH profile in Figure 1 refers to the formation of the phosphonate ester products¹⁵ from an equilibrating mixture of phosphorane **2** and phosphonium ion **3**. The assumptions that this equilibration is rapid and that the phosphonium ion hydrolyzes by addition of water, the k_2° process, and hydroxide ion, the k_2^{OH} process, produce the following kinetic

$$k_{\text{obsd}} = \frac{k_2^\circ [\text{H}^+] + k_2^{\text{OH}} K_w}{[\text{H}^+] + K_1} \quad (6)$$

expression. This equation has the correct form to account for the rate-pH profile. In acid solutions where $[\text{H}^+] \gg K_1$, the phosphonium ion predominates in the initial equilibrium and the observed kinetics refer to the addition of water to this cation. Thus k_{obsd} is independent of pH and $k_a^\circ = k_2^\circ$. At higher pH where $[\text{H}^+] \ll K_1$, the phosphorane is the major species present in the initial equilibrium, and the observed kinetics represent the conversion of this species to the phosphonate products. This hydrolysis still proceeds by way of the intermediate cation, with the rate-limiting step being the hydrolysis of this latter species. Where this occurs with water addition (pH 9–11), k_{obsd} shows a first-order dependency on H^+ concentration, as is observed, with $k_s^{\text{H}} = k_2^\circ / K_1$. The H^+ dependency arises because of the requirement for cation formation. It can be noted that the ratio $k_a^\circ / k_s^{\text{H}}$ provides a kinetic measurement of the equilibrium constant K_1 ; this is in excellent agreement with the spectroscopic value (Table I). At higher pH k_{obsd} levels again. This can be explained by the involvement at these high pH values of hydroxide ion in the phosphonium ion hydrolysis, with the overall pH independency arising because hydronium ion is required to generate this species. The observed rate constant k_b° in this region is equal to $k_2^{\text{OH}} K_w / K_1$. It can be noted that the lower curve drawn in Figure 1 is a calculated curve based on eq 6 and the derived constants. This shows excellent agreement with the experimental k_{obsd} values.

At intermediate pH the kinetics of the equilibrium process can also be observed. The observed rate constants represent an approach to equilibrium so that the following expression applies,

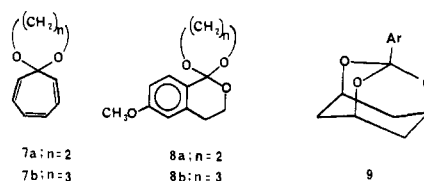
$$k_{\text{obsd}}(\text{fast}) = k_1^{\text{H}}[\text{H}^+] + k_{-1}^\circ \quad (7)$$

and we can set $k_1^{\text{H}} = k_f^{\text{H}}$ and $k_{-1}^\circ = k_r^\circ$. This provides a second kinetic value for K_1 as the ratio $k_{-1}^\circ / k_1^{\text{H}}$ and again excellent agreement is obtained with the spectroscopic value. The observation of this process provides further support to the idea of the reversible first step, since it establishes that $k_{-1}^\circ > k_2^\circ$. That is, the cation ring closes preferentially over water addition. This fast kinetic phase is not observed at lower pH, although it must occur. With $k_1^{\text{H}} = 4 \times 10^9 \text{ M}^{-1} \text{ s}^{-1}$, however, ring opening is complete even on the stopped-flow time scale. The equilibration phase is not observed at higher pH as well since starting with phosphorane the ring stays closed. In principle, kinetics could have been obtained by starting with the ring-opened cation. In practice, however, this experiment could not be carried out since the cation has a half-life of less than one second on the acid side of the equilibrium. Thus solutions of the cation cannot be prepared to allow it to be mixed in the stopped-flow apparatus with base, as would be required to observe the ring closure.

The buffer dependency which is observed in acid solutions represents general base catalysis of the hydrolysis of the phosphonium ion.¹⁶ This same process appears as general acid ca-

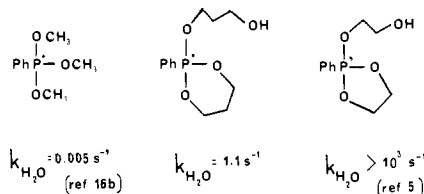
talysis (specific acid-general base) in more basic solutions where the phosphorane predominates in the initial equilibrium. The measured Brønsted α of 0.65 in these solutions thus corresponds to a β value of 0.35 for the base catalysis.

The mechanism of eq 4 is the same as that previously proposed⁵ for the acid hydrolysis of the phosphoranes **1** and is also directly analogous to the mechanism of acetal and ortho ester hydrolysis.¹ In this general mechanism a ring opening in the cation-forming step raises the question of reversibility of this step.¹⁷ This is determined by the relative magnitudes of the rate constants for the reverse ring closure and water addition, or in terms of eq 1 and 2 the relative magnitudes of the constants k_{-1}° and k_2° . When the cation cannot be observed, the question of reversibility generally cannot be unambiguously answered since regardless of the k_{-1}° / k_2° ratio the observed rate expression has the same form.¹⁸ With the phosphorane of this study, it is the observation of the cation which allows a distinction to be made. With carbonyl derivatives the intermediate oxocarboxonium ion is considerably less stable.¹⁹ There are, however, three systems **7**,²⁰ **8**,²¹ and **9**²² with particularly stable cations where reversibility of the ring opening has been established by using an approach similar to that of the present study. The tropone ketal **7b** and spiro lactone ortho ester



8b are analogous to the phosphorane **2** in that all systems are derivatives of 1,3-propanediol. The k_{-1}° / k_2° ratios are 1.6 for **7b** and 3.8 for **8b**. As with the phosphorane there is a preference for ring closure over water addition. In no case is the preference overwhelmingly large.

Perhaps the most striking difference between the two spiro-phosphoranes **1** and **2** is that the phosphonium ion is readily observed with the latter while with the former it cannot be detected at any pH. In fact for the five-cycle system we concluded that the cation half-life was less than 1 ms.⁵ This difference undoubtedly reflects phosphonium ion stability. A comparison of the hydrolytic lability of structurally analogous cations is given below. The reactivity order parallels that generally observed for



the hydrolysis of cyclic and acyclic phosphate esters.¹ With the phosphonium ions the actual magnitude of the difference between the six cycle and the acyclic compound is somewhat larger than

(16) (a) A detailed study of the base catalysis of the hydrolysis of acyclic phosphonium ions has been carried out.^{15b} (b) McClelland, R. A.; Patel, G.; McGall, G. *J. Am. Chem. Soc.*, following paper in this issue.

(17) In principle reversibility is also a consideration when the departing OH is not joined to the cation. Under hydrolytic conditions, however, there is a large excess of water and reversion of the cation formation is unimportant.

(18) (a) Since the cation remains a steady-state intermediate at all acidities so that rate = $(k_1^{\text{H}} k_2^\circ / (k_{-1}^\circ + k_2^\circ)) [\text{H}^+] [\text{substrate}]$ or rate $\propto [\text{H}^+]$ regardless of the relative magnitudes of k_{-1}° and k_2° .^{18b} (b) Willi, A. V. In "Comprehensive Chemical Kinetics", Vol. 8, "Proton Transfer"; Bamford, C. H., Tipper, C. F. H., Eds.; Elsevier: Amsterdam, 1977; pp 49–52.

(19) McClelland, R. A.; Ahmad, M. *J. Am. Chem. Soc.* **1978**, *100*, 7027–7031, 7031–7035. Young, J. R.; Jencks, W. P. *Ibid.* **1977**, *99*, 8238–8248.

(20) McClelland, R. A.; Ahmad, M.; Mandrapilas, G. *J. Am. Chem. Soc.* **1979**, *101*, 970–974.

(21) McClelland, R. A.; Moreau, C. *Can. J. Chem.*, in press.

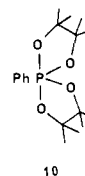
(22) McClelland, R. A.; Lam, P. W. K. *Can. J. Chem.* **1984**, *62*, 1068–1073.

(15) The two phosphonate ester products are formed in parallel first-order reactions. The observed rate constant k_{obsd} is the sum of the first-order rate constants for these two processes.

that normally observed with esters.²³

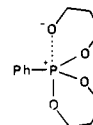
Because the phosphonium ion intermediate cannot be detected in the hydrolysis of the spirophosphoranes **1** with five atom rings, the question of the reversibility of the ring-opening step in their acid hydrolysis cannot be answered unambiguously.¹⁸ In our report of these compounds, we did propose an irreversible ring opening, principally on the basis of a near zero entropy of activation. This suggestion is obviously at variance with the conclusion of the present study, although it is clearly possible that the two systems, being structurally different, might behave differently. Our current interpretation, however, is that both types of compounds do have the same mechanism, with ring-opening reversible in each.²⁴ Cyclizations of 2-hydroxyethyl phosphates where five-atom rings are formed show large effective molarities (10^4 M),²⁵ much larger than those found with cyclizations of 3-hydroxypropyl analogues where six-atom rings are formed. Thus it seems reasonable that if a six-atom cyclization is faster than water addition as in the present study, a five-atom cyclization is also likely to be faster, possibly significantly faster. Moreover, we have recently prepared the phosphorane **10**, an octamethyl derivative of **1**. This compound undergoes acid-catalyzed methyl isomerization orders of magnitude faster than it undergoes acid-catalyzed hydrolysis, an observation which can be interpreted in terms of highly reversible ring opening.²⁶ Because of the *gem*-dialkyl effect, this system is ideally set up for facile ring closure of the phosphonium ion. What is interesting, however, is that the entropy of activation for the

hydrolysis is also slightly positive. Thus the previous argument⁵ that such values are inconsistent with reversibility is incorrect.²⁷



10

One additional feature of the hydrolysis of the spirophosphorane **2** which deserves comment is the very large rate constant 4×10^9 $\text{M}^{-1} \text{s}^{-1}$ for the H^+ -catalyzed ring opening. Numbers of this order of magnitude are without precedent in the hydrolysis of acetals and ortho esters, even for tropone ketals^{19,28} and amide acetals²⁹ where very stable cations are produced. The rate constant is in fact very close to the diffusion limit, making the ring-opening process appear as if it were a simple proton transfer in the thermodynamically favored direction. One possible interpretation involves a very polar P-O bond in the phosphorane, which is prevented from breaking because of the cyclic system. This



polarity makes the oxygen basic. Proton transfer therefore occurs on virtually every collision with a strong acid such as H_3O^+ and the bond completely breaks.

Acknowledgment. The continued financial support of the Natural Sciences and Engineering Research Council is gratefully acknowledged.

Registry No. **2a**, 97210-53-2; **2b**, 34736-78-2; **3b**, 97210-54-3; **4b**, 97210-56-5; **5a**, 7191-13-1; **5b**, 882-69-9; **6a**, 97210-57-6; **6b**, 97210-55-4; methyl trifluoromethanesulfonate, 333-27-7; trifluoromethanesulfonic acid, 1493-13-6.

(27) The equilibrium ring-opening step will have associated with it a positive ΔS^\ddagger , while water addition will have a negative ΔS^\ddagger . What apparently happens is that the two cancel one another.

(28) Anderson, E.; Fife, T. H. *J. Am. Chem. Soc.* **1969**, *91*, 7163-7166.

(29) McClelland, R. A. *J. Am. Chem. Soc.* **1978**, *100*, 1844-1849.

(23) Asknes, G.; Bergeson, K. *Acta Chem. Scand.* **1966**, *20*, 2508-2514.

(24) Although several other mechanistic criteria were also employed in the study of **1**, these point only to the general dissociative mechanism, and are consistent with either reversible or irreversible ring opening to the cation. Thus, if the ring opening were highly reversible so that hydration were rate limiting, (i) the rate law would be the same,¹⁸ (ii) the observed general acid catalysis would represent the kinetically equivalent specific acid-catalyzed ring opening; general base-catalyzed water addition, the latter a common feature of phosphonium ion hydrolysis,¹⁶ (iii) the observed negative ρ value would simply mean that the substituent effect on the equilibrium ring opening were more important than the substituent effect for the water addition, as is found with the thioxaadamantanes **9**,²² and (iv) the slightly inverse solvent isotope effect is exactly what is expected, since this is now an A2 reaction which is characterized by such isotope effects.^{24b} (b) Wiberg, K. *Chem. Rev.* **1955**, *55*, 713.

(25) Kirby, A. J. *Adv. Phys. Org. Chem.* **1980**, *17*, 183.

(26) McGall, G.; McClelland, R. A. *J. Chem. Soc., Chem. Commun.* **1985**, 560-561.