Rates of Hydroxide Decomposition of Cyclic Phosphonium Salts[1]

SHELDON E. CREMER,* B. C. TRIVEDI, AND FREDERICK L. WEITL

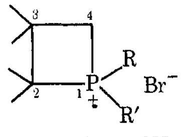
Department of Chemistry, Marquette University, Milwaukee, Wisconsin 53233

Received March 16, 1971

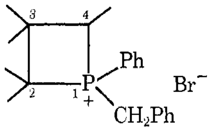
The rates of hydroxide decomposition of 1-benzyl-1-phenylphospholanium bromide (**8**), 1-benzyl-1-phenylphosphorinanium bromide (**9**), benzylethylmethylphenylphosphonium iodide (**10**) and seven substituted phosphetanium salts **1–7** have been measured in 1:1 ethanol-water at various temperatures. A marked rate enhancement was observed in going from the larger to the smaller rings; the rate of the acyclic salt **10** at 25° was comparable to the six-membered ring compound. Changes in both $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ were responsible for the rate variations; expected trends as well as apparent anomalies reflect the complexity of these overall, third-order reactions. Ring strain, the inductive effect of substituents on the ring and at phosphorus, and the degree of carbanion character adopted by the leaving group partially account for the observed activation parameters.

For the last 6 years we have been engaged in a comprehensive research program on the chemistry of phosphetanes (four-membered phosphorus heterocycles). Our studies have included the syntheses, stereochemistry, physical and spectroscopic properties, kinetic measurements, and chemical reactions of these compounds.[2] An initial report[2a] on synthetic and stereochemical aspects of phosphetanes prompted considerable activity in this field; indeed, most of the chemical literature[3] on this subject has appeared since 1967.

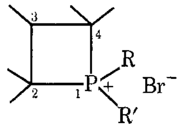
The present paper describes the rates of hydroxide decomposition of phosphetanium and other salts.[4] The rates[5] and stereochemistry[6] of base treatment of acyclic phosphonium salts was first reported by McEwen and coworkers. Shortly thereafter, Hoffmann[7] disclosed related work and several articles by Aksnes[8] then appeared. Aksnes and Bergesen[9] were the first to study the base decomposition of the cyclic compounds, 1-methyl-1-phenylphospholanium iodide and 1-methyl-1-phenylphosphorinanium iodide; the five-membered ring hydrolyzed about 1500 times faster than the six-membered ring at 75°. Thus, it was of considerable interest for us to examine the phosphetanium salts (**1–7**) and compare these to cyclic homologs **8** and **9** and an acyclic compound **10**.



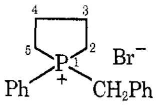
1, R = Ph; R′ = $PhCH_2$
7, R = Ph; R′ = CH_3
13, R = Ph; R′ = p-CH_3OPhCH_2



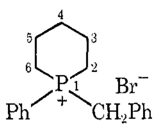
2



3, R = Ph; R′ = $PhCH_2$
4, R = R′ = $PhCH_2$
5, R = CH_3; R′ = $PhCH_2$
6, R = Ph; R′ = CH_3
14, R = *tert*-Bu; R′ = $PhCH_2$

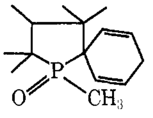


8

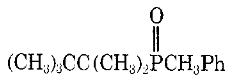


9

$PhCH_3C_2H_5P^+CH_2PhI^-$
10



11



$(CH_3)_3CC(CH_3)_2\overset{\overset{\large O}{\|}}{P}CH_2Ph$

12

Results and Discussion

Product Study.—All of the phosphonium salts with a benzyl substituent (**1–5**, **8–10**) gave the corresponding phosphine oxide and toluene on treatment with sodium hydroxide in 50% aqueous ethanol. No ring opening in competition with benzyl cleavage was observed. In the case of the phosphetanium salt **1**, in which ring opening would most likely be competitive because of formation of a primary carbanion, the salt was subjected to the kinetic reaction conditions; nmr examination of the crude reaction mixture showed only one product, 1-phenyl-2,2,3,3-tetramethylphosphetane 1-oxide.

It was not possible to check for phenyl cleavage in compounds **1–3** and **6–8** by glpc analysis because a suitable substrate which would separate a small amount of benzene in the presence of a large quantity of ethanol–water was not found. However, aqueous base decomposition of these salts followed by petroleum ether extraction and glpc analysis showed no detectible benzene. The same procedure showed toluene to be the exclusive volatile product on base treatment of **1–5** and **8**. Treatment of the phosphorinanium salt

---

[1] This work was supported by the NIH, National Cancer Institute Grant CA 11631, and in part by funds from the Marquette University Committee on Research.

[2] (a) S. E. Cremer and R. J. Chorvat, *J. Org. Chem.*, **32**, 4066 (1967); (b) *Tetrahedron Lett.*, 413 (1968); (c) S. E. Cremer, *Chem. Commun.*, 1132 (1968); S. E. Cremer, R. J. Chorvat, C. H. Chang, and D. W. Davis, *Tetrahedron Lett.*, 5799 (1968); (e) S. E. Cremer, R. J. Chorvat, and B. C. Trivedi, *Chem. Commun.*, 769 (1969); (f) S. E. Cremer and B. C. Trivedi, *J. Amer. Chem. Soc.*, **91**, 7200 (1969); (g) S. E. Cremer and C. H. Chang, *Chem. Commun.*, 1156 (1969); (h) S. E. Cremer, *ibid.*, 616 (1970).

[3] (a) K. Mislow, *Accounts Chem. Res.*, **3**, 321 (1970), and references cited therein; (b) S. E. Fishwick, J. Flint, W. Hawes, and S. Trippett, *Chem. Commun.*, 1113 (1967); (c) J. R. Corfield, J. R. Shutt, and S. Trippett, *ibid.*, 789 (1969); (d) D. J. H. Smith and S. Trippett, *ibid.*, 855 (1969); (e) J. R. Corfield, M. J. P. Harger, J. R. Shutt, and S. Trippett, *J. Chem. Soc. C*, 1855 (1970), and references cited therein; (f) J. R. Corfield and S. Trippett, *Chem. Commun.*, 1267 (1970); (g) S. Trippett, *et al.*, *ibid.*, 1350 (1970); (h) J. R. Corfield, N. J. De'Ath, and S. Trippett, *ibid.*, 1502 (1970); (i) K. Bergesen, *Acta Chem. Scand.*, **21**, 1587 (1967); (j) P. Haake, *et al.*, *J. Amer. Chem. Soc.*, **92**, 3828 (1970); (k) B. R. Ezzell, *J. Org. Chem.*, **35**, 2426 (1970); (l) T. A. Zyablikova, A. P. Panteleeva, and I. M. Shermergorn, *Izv. Akad. Nauk. SSSR, Ser. Khim.*, 373 (1969); (m) K. E. DeBruin and M. J. Jacobs, *Chem. Commun.*, 59 (1971).

[4] This research was presented in part at the 160th National Meeting of the American Chemical Society, Chicago, Ill., Sept 1970, Abstract ORGN 62; see also ref 2e and 3h for preliminary data.

[5] (a) W. E. McEwen, G. Axelrad, M. Zanger, and C. A. VanderWerf, *J. Amer. Chem. Soc.*, **87**, 3948 (1965) (b) M. Zanger, C. A. VanderWerf, and W. E. McEwen, *ibid.*, **81**, 3806 (1959).

[6] (a) W. E. McEwen, K. F. Kumli, A. Bladé-Font, M. Zanger, and C. A. VanderWerf, *ibid.*, **86**, 2378 (1964); (b) A. Bladé-Font, C. A. VanderWerf, and W. E. McEwen *ibid.*, **82**, 2396 (1960); (c) K. F. Kumli, W. E. McEwen, and C. A. VanderWerf, *ibid.*, **81**, 3805 (1959).

[7] H. Hoffmann, *Justus Liebigs Ann. Chem.*, **634**, 1 (1960).

[8] (a) G. Aksnes and L. J. Brudvik, *Acta Chem. Scand.*, **17**, 1616 (1963); (b) G. Aksnes and J. Songstad, *ibid.*, **16**, 1426 (1962).

[9] G. Aksnes and K. Bergesen, *ibid.*, **19**, 931 (1965).

TABLE I

RATE COEFFICIENTS[a] FOR OH^- DECOMPOSITION OF SALTS AND CORRESPONDING ACTIVATION PARAMETERS[b]

	Temp, °C[c]							
Compd	1.9	8.0	15.0	20.0	25.0	35.0	$\Delta H^{\ddagger}$, kcal/mol	$\Delta S^{\ddagger}$, eu
1	2.65×10^2	5.14×10^2	11.2×10^2	17.2×10^2	27.7×10^2		16.0	+10.9
2	1.79×10^1	3.70×10^1	7.07×10^1	1.11×10^2	1.65×10^2		15.0	+2.0
3	7.94		40.7	66.2	1.11×10^2		18.0	+11.0
4	3.1×10^{-1}		1.69		5.56	13.6	18.8	+7.8
5	6.06×10^{-2} (1.7°)		4.13×10^{-1}	4.56×10^{-1} (15.8°)	1.37	2.56 (30.0°)	21.2	+13.2
6	8.14×10^{-3} (0.0°)		5.93×10^{-2}		2.14×10^{-1}	6.25×10^{-1}	20.3	+6.5
7	2.54×10^{-1}		1.24		3.44	8.56	17.3	+1.9
8	8.93×10^{-3} (0.0°)		5.35×10^{-2}		1.71×10^{-1}	4.26×10^{-1}	18.2	−1.6
9			26.4×10^{-4} (45.0°)	38.6×10^{-4} (50.0°)	5.60×10^{-4}	13.4×10^{-4}	14.0	−26.4
10	1.55×10^{-3} (40.1°)	4.75×10^{-3} (50.0°)	13.1×10^{-3} (60.0°)		3.29×10^{-4}		20.2	−6.8

[a] Rate coefficients are third-order, k_3 ($l.^2$ mol^{-2} sec^{-1}). Total ionic strength equals 0.1 *M*; solvent system was 1:1 EtOH:H_2O (v/v) made at 25°. Maximum standard error in k_3 did not exceed 2.5%. [b] $\Delta H^{\ddagger}$ was calculated from the slope of a plot of log k_3/T *vs.* $1/T$. Maximum standard error in $\Delta H^{\ddagger}$ was ±2.5% and in $\Delta S^{\ddagger}$ ±1.5 eu. Value of $\Delta S^{\ddagger}$ calculated at 25°. [c] Temperature (±0.1°) for the run denoted in the top row unless otherwise given in parenthesis below the corresponding rate coefficient.

(**9**) with sodium hydroxide in aqueous ethanol gave 1-phenylphosphorinane 1-oxide as the only observable (nmr showed no $PhCH_2P{=}O$ protons) product. McEwen and coworkers had previously confirmed the absence of benzene upon aqueous base treatment of the acyclic salt **10**.[6a]

Upon aqueous base treatment, compound **6** has been shown to undergo an interesting ring expansion which results in the cyclic diene **11**.[2c,3b] Moreover, hydrolysis of **7** led to exclusive ring opening to give the open-chain oxide **12**, whose preparation is described in the Experimental Section.

Reaction Rates and Site of Cleavage.—In most cases the base decomposition of phosphonium salts has been reported to exhibit first-order dependence on the concentration of salt and second-order dependence on the concentration of hydroxide ion.[5,7–10] The data are consistent with the general mechanism advanced by McEwen.[5]

$$R_4P^+ + OH^- \rightleftharpoons R_4POH \qquad (1)$$

$$R_4POH + OH^- \rightleftharpoons R_4PO^- + H_2O \qquad (2)$$

$$R_4PO^- \longrightarrow R_3P = O + R^- \qquad (3)$$

$$R^- + H_2O \longrightarrow RH + OH^- \qquad (4)$$

In this scheme the first two steps are rapid reversible equilibria and the third step is rate determining. Alternatively, eq 2 and eq 3 can be combined into a single, concerted rate-determining step.[5a] Titration methods have been used to follow either the third-order reaction[7–9] or a pseudo-second-order reaction[5] (salt in large excess). To conveniently measure the large range of observed rates in the current study, the base was kept in excess and the resultant pseudo-first-order reaction was followed by ultraviolet spectroscopy. The hydroxide ion concentration was varied to confirm its second-order dependence; a plot of the observed rate constant *vs.* $(OH^-)^2$ was linear for all of the salts in this study. A summary of the third-order rate constants for the phosphonium salts appears in Table I.

Comparison of the rates of hydrolysis of the salts at 25° reveals substantial acceleration in going from the larger to the smaller rings. The 2,2,3,3-tetramethylphosphetanium bromide (**1**) decomposes 1.6×10^4 times faster than the phospholanium bromide (**8**), 4.9×10^6 times faster than the phosphorinanium salt (**9**), and 8.4×10^6 times faster than the acyclic compound **10**. It is likely that these multiples would increase with fewer methyl groups on the four-membered ring. Methyl substituents at ring positions 2 (or 4) and 3 decrease the rate of hydrolysis; the former position is about 1.5–2 times as effective in this regard. This is supported by the rate data from phosphetanium salts **1**, **2**, and **3** and a preliminary rate coefficient for 1-benzyl-1-phenyl-2,2,3-trimethylphosphetanium bromide of about 1.9×10^4 $l.^2$ mol^{-2} sec^{-1} at 25°. Substituents at phosphorus, other than the leaving group, also affect the rate.[5a,8a] For example, in the family of salts **3**, **4**, and **5**, a plot of log k_3 *vs.* the Taft substituent constant $(\sigma^*)^{11}$ for a phenyl, benzyl, and methyl group, respectively, is fairly linear.

In acyclic phosphonium salts the relative ease of departure for a group has been found to be benzyl > phenyl > methyl > ethyl, etc.[12] However, compounds **6** and **7**, which have 1-phenyl substituent, gave ring expansion and ring opening, respectively; the rate of cleavage in the latter is nearly as rapid as departure of a benzyl anion from the phosphetanium bromide **4**. Several factors may account for these observations. Since the bond angles[13] in **6** are $C_2PC_4 = 82.6°$, $PC_2C_3 = 83.9°$, $PC_4C_3 = 85.4°$, and $C_2C_3C_4 = 103.1°$, and those in **7** are probably similar, relief of angle strain could be achieved in the transition state leading to oxide **12** or the five-membered ring **11**. Interaction of the ring substituents (*e.g.*, axial–axial C_2–CH_3 and C_4–CH_3, etc.) may be relieved in ring opening (though

---

(10) In a few cases an overall, second-order reaction has been reported: K. Bergesen, *Acta Chem. Scand.*, **20**, 899 (1966); see also ref 8b.

(11) R. W. Taft in "Steric Effects in Organic Chemistry," M. S. Newman, Ed., Wiley, New York, N. Y., 1956, pp 590–594. A plot of log k_3 *vs.* $\Sigma\sigma^*$ (where the ring is equated to two isopropyl substituents) is also fairly linear.

(12) L. Hey and C. K. Ingold, *J. Chem. Soc.*, 531 (1933); G. W. Fenton and C. K. Ingold, *ibid.*, 2342 (1929).

(13) C. Moret and L. M. Trefonas, *J. Amer. Chem. Soc.*, **91**, 2255 (1969).

not necessarily in ring expansion), but this is likely to be less important than the strain argument. Nevertheless, competition between ring cleavage and external, substituent expulsion has occurred in specific compounds; for example, the *tert*-butylphosphetanium bromide **14** gave both 1-*tert*-butyl-2,2,3,4,4-pentamethylphosphetane 1-oxide (major product) as well as the acyclic phosphine oxide.[14] Likewise, the *p*-methoxybenzyl derivative **13** gave about 2:1 ratio of the 1-phenylphosphetane 1-oxide derivative *vs.* the ring-opened product.[14] Consequently, the site of cleavage is dependent on the nondeparting substituents on phosphorus, the degree of ring methylation, and the nature of the external leaving group. A fine energy balance may sometimes exist between ring opening and fission of an "exocyclic" phosphorus substituent.

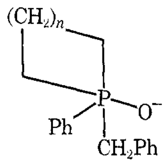
Activation Parameters.—To achieve some understanding of the substantial rate differences between the four-, five-, and six-membered rings and acyclic system, the activation enthalpies and entropies were determined (Table I). A perusal of the data indicates that both energy parameters are responsible for the observed rate differences. The following discussion is directed at pointing out a few of the factors which influence $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$.

It was anticipated that the relief of angle strain[15] in going from the four- or five- membered[16] ring compounds to a trigonal-bipyramidal intermediate (eq 1) would be reflected in relatively lower $\Delta H^{\ddagger}$ values. However, the experimental activation enthalpy and entropy are a composite from two preequilibrium steps plus the rate-determining step and are therefore not subject to straightforward analysis. Whereas angle strain may be relieved in eq 1 for salts **1–5** and **8**, this gain could be offset in the rate-determining step (eq 3) to the extent that the transition state resembles the cyclic oxide. In fact the activation enthalpies for compounds **1** and **2** are 2–3 kcal/mol and 4–5 kcal/mol less than for the five-membered ring **8** and the acyclic salt **10**, respectively. Thus, relief of angle strain achieved in the preequilibrium steps seems to be reflected in the overall $\Delta H^{\ddagger}$ value.[17] Furthermore, the effect of ring methylation would be expected to enhance $\Delta H^{\ddagger}$ (*e.g.*, compounds **3** and **8** have similar activation enthalpies) and the value for benzyl cleavage in the unmethylated, parent compound, 1-phenyl-1-benzylphosphetanium bromide, is likely to be <15 kcal/mol.

An increasing enthalpy change in the series of salts **3**, **4**, and **5** is also in qualitative accord with the change in inductive effect of the nondeparting groups[5a] on phosphorus. Similarly, the Arrhenius activation energy for the family of compounds $Ph_{4-n}P^+(CH_3)_nBr^-$, $n = 0\text{–}3$, increases with increasing methyl substitution.[8a]

The angle strain concept appears to be contradicted in the case of the phosphorinanium salt (**9**) which shows a surprisingly low $\Delta H^{\ddagger}$ and correspondingly high negative $\Delta S^{\ddagger}$. A partial explanation lies in the nature of the transition state leading to product and upon the stereochemistry of the base decomposition. Phosphetanium salts proceed with retention of configuration about phosphorus in the *rate-determining step;*[2e] likewise, phospholanium salts[16] go with complete, *overall retention*.[18] However, the decomposition of the cis and trans (phenyl *vs.* methyl) isomers of 1-benzyl-4-methyl-1-phenylphosphorinanium bromide gave 52 and 22% *overall inversion*, respectively.[19] In the open-chain salt **10**, 100% overall inversion was observed; the incoming hydroxide ion (apical) and leaving benzyl (apical) are colinear.[6]

In the trigonal-bipyramidal intermediates, the four- and five-membered rings (**15**, $n = 1\text{–}2$) assume an equatorial–apical relation (90°) due to angle constraint.[3a,15] Based on Drieding models, Marsi[19] also limited the six-membered ring ($n = 3$) to these positions.[20] Since the C_2PC_6 angle in a six-membered salt has not been determined, the degree of angle strain in the trigonal bipyramid remains uncertain. If this angle is assumed[21] to be ~105°, for example, an increase in strain results in spanning either the equatorial–equatorial (120°) or equatorial–apical positions.



15, $n = 1\text{-}3$

An important consideration follows from the geometry of the pentacovalent intermediates; namely, the degree of carbanion character of the leaving group.[22]

---

(14) S. E. Cremer, unpublished results.

(15) F. H. Westheimer, *Accounts Chem. Res.*, **1**, 70 (1968), and references cited therein.

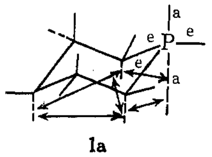
(16) For a discussion of angle strain in a five-membered ring, see K. L. Marsi, *J. Amer. Chem. Soc.*, **91**, 4724 (1969).

(17) In addition to the relief of angle strain in eq 1, a related factor may be considered: the enhanced kinetic acidity of the $P^+\text{–}CH_3$ (rate of base-catalyzed deuterium exchange) in four-membered rings[2g] relative to acyclic compounds implies a greater degree of positive charge on phosphorus, which would render the d orbitals more effective for pentacovalent bonding. See D. P. Craig, *et al.*, *J. Chem. Soc.*, 332 (1954); D. P. Craig and E. A. Magnusson, *ibid.*, 4895 (1956); D. P. Craig and C. Zauli, *J. Chem. Phys.*, **37**, 601 (1962).

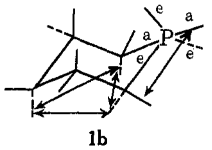
(18) As stated in ref 2e, phosphetanium salts **3** and **5** undergo rapid pseudorotation prior to decomposition; thus, equilibration of the trans and cis isomers leads predominently to *overall* retention and inversion, respectively. Likewise, compounds **2**, **6**, and **4** (*p*-D labeling in one of the benzyl groups) also undergo cis–trans equilibration (unpublished results). However, optically active **1**[3c] and 1-benzyl-1,3-dimethylphospholanium bromide[16] do not exhibit isomer equilibration.[3a]

(19) K. L. Marsi and R. T. Clark, *J. Amer. Chem. Soc.*, **92**, 3791 (1970).

(20) The Drieding models which we have made do not show any obvious angle strain when the ring is in an equatorial–equatorial (**1a**) *vs.* an equatorial–apical (**1b**) position. However, in **1a** the chair conformation is flatter (similar to cyclohexanone) than in **1b**. In addition, the number and kind of interactions (shown by double-headed arrows) are different; **1b** is energetically favored in this regard, but the energy difference may be low enough to permit interconversion at room temperature.



1a



1b

NOTE ADDED IN PROOF.—Professor Marsi recently indicated (private communication) that decomposition of the phosphorinanium salt[19] is best explained by two simultaneous reactions: inversion by the "McEwen mechanism" and retention by a mechanism similar to that forwarded for the five-membered ring.[16]

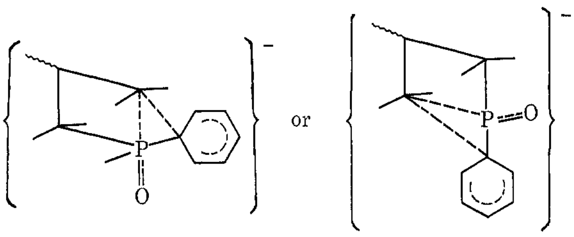
(21) The CPC internal angle in the six-membered ring, 1,2,3,4-tetrahydro-1,2,2,3,4,4-hexamethylphosphinoline 1-oxide, is 104°; see M. Haque, *J. Chem. Soc. B*, 711 (1970).

(22) The benzyl group has been placed (structure **15**) in an apical leaving position. However, because the incoming OH^- (assumed to enter apically) and benzyl anion are electronically different, the extended principle of microscopic reversibility[14] need not apply.[3a] Nevertheless, we prefer **15** in order to place the electron donor O^- equatorially. An equatorial–equatorial O^- and benzyl relation in the rate-determining step is not likely; this would result in inversion of configuration and involves more angle change[2f] during product formation.

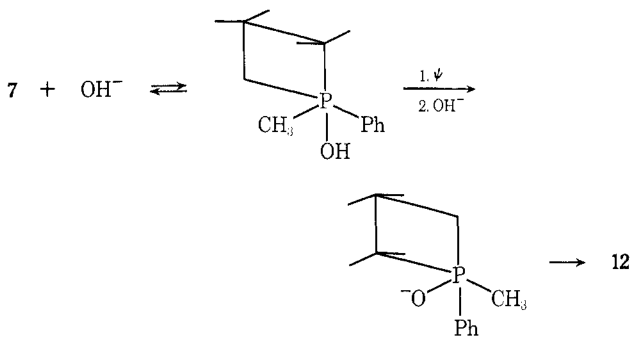
The transition state in the case of the four-membered ring (and to a lesser degree in the five-membered ring) might retain more trigonal-bipyramidal character to relieve angle strain; thus, relatively less C–P bond breaking would occur than in the acyclic or six-membered ring compounds. The more negative $\Delta S^{\ddagger}$ values for **9** and **10** would be attributed to increased protonation–solvation of the more highly developed carbanion. Furthermore, if the trigonal-bipyramidal intermediate from **9** is "strained," relief of this would be forthcoming by substantial P–CH_2Ph bond breaking in the step leading to product.

Evidence for the degree of anionic character of a substituted benzyl group in *m*- or *p*-$YC_6H_4CH_2P(CH_2Ph)_3^+X^-$[5a,23] and *m*- or *p*-$YC_6H_4CH_2PPh_3^+X^-$[7] is provided by application of the Hammett equation, which gives ρ values of +3.64 and +4.62, respectively for these systems. Moreover, a comparison of $Ph_3PCH_2Ph^+Br^-$ ($\Delta H^{\ddagger}$ = 17.2 kcal/mol, $\Delta S^{\ddagger}$ = − 6 eu) with $Ph_4P^+Br^-$ ($\Delta H^{\ddagger}$ = 26.0 kcal/mol, $\Delta S^{\ddagger}$ = +13 eu) implies that benzyl is a better leaving group than phenyl and that the more fully developed negative charge on benzyl is affiliated with greater solvent orientation (lower $\Delta S^{\ddagger}$).[24] It is apparent that the Hammett relationship should be applied to the cyclic systems in order to support or rule out any link between the degree of C–P bond breaking and entropy changes.

The origin of the low activation enthalpy observed for the six-membered ring is still not clear. If the ring adopts the geometry in **15**, then the O^- can occupy the favorable equatorial position[3a,3m,15] and a right-angle relation results between the developing P=O and leaving group. The geometry of such a transition state is considerably different from acyclic systems in which oxygen is in an apical position. Indeed, the degree of negative charge that can be assumed by oxygen in the transition state may be dictated by its apical *vs.* equatorial position. The 4-kcal/mol enthalpy difference between **8** and **9**, however, is difficult to explain *if both* achieve the geometry of **15**. The issue is further complicated by the fact that the activation energies (for loss of a phenyl group) in 1-methyl-1-phenylphospholanium iodide and 1-methyl-1-phenylphosphorinanium iodide are similar.[25]



Finally, the hydrolysis of salts **6** and **7** deserve comment. In the former the incipient tertiary carbanion can attack the aromatic ring in a concerted reaction. This feature is not present in **7**, which undergoes direct ring opening *via* a primary carbanion. Unfortunately the $\Delta H^{\ddagger}$ for departure of an alkyl CH_2^- group is unavailable for comparison. However, from $\Delta H^{\ddagger} \approx$ 37 kcal/mol for phenyl cleavage in 1-methyl-1-phenylphospholanium iodide[9] one concludes that $\Delta H^{\ddagger}$ for ring fission would be >37 kcal/mol. Consequently, an activation enthalpy of 17 kcal/mol for **7** is consistent with relief of angle strain in eq 1 as well as through P–C ring breaking in the transition state leading to product. A stereochemical study is called for to clarify the nature of the transition state. Inversion of configuration would imply a direct apical-in apical-out mechanism (OH^- and P–CH_2^- colinear). Retention could result in several ways, one of which would be



ψ ≡ pseudorotation (CH_3 pivot group)

The foregoing discussion is not meant to be definitive, but it best serves as a directive for future studies such as solvent effects, linear free energy correlations, and the rate of hydrolysis of a nonmethylated four-membered ring. This work is in progress.

Experimental Section[26]

Kinetic Procedures.—The rate measurements were made at a fixed wavelength using a Cary Model 14 ultraviolet spectrophotometer equipped with a thermostated cell compartment. The phosphonium salt was dissolved in ethanol–water (1:1 by volume, prepared at 25.0°) and equilibrated at the desired temperature. A solution of carbonate-free sodium hydroxide was prepared in distilled water and a weighed amount of sodium chloride was added to provide for a total ionic strength of 0.10 *M* in the final solution. The aqueous base was then diluted with an equal volume of ethanol at 25.0°, and equilibrated at the appropriate temperature. An aliquot of the base solution was added to an aliquot of the phosphonium salt; the mixture was shaken and transferred by a pipet to a quartz cell. In most runs 2-cm cells were used; a 10-cm cell was used for compound **9**. The reference cell contained the identical solvent system.

Comparison of the uv spectra of the salt and oxide was made to establish a wavelength which would give a suitable absorption difference. The wavelengths and typical concentrations of reagents are given in Table II. Most of the kinetic runs were followed for at least three half-lives and A_∞ was measured after ten half-lives. In those compounds such as **1** where the observed

---

[23] Trippett[3f] alluded to the "small partial rate factors for loss of *p*-substituted benzyls" and cites ref 5b. Actually, the partial rate factors vary from 0.1 to 323 for *p*-CH_3OPhCH_2 and *m*-NO_2PhCH_2, respectively.[5a] The corresponding partial rate factor for loss of *benzyl itself* in these compounds is 0.45 and 1.42, respectively.[5a]

[24] The values of $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ were computed from log k_3/T *vs.* $1/T$ from the data in ref 8b in 1:1 ethanol–water. Trippett[3f] referred to "the relatively small difference (*ca.* 100) between the rates of hydrolysis of comparable benzyl- and phenylphosphonium salts." From the activation parameters, however, it can be seen that the similarity in rate is a result of the coincidental balance in $\Delta H^{\ddagger}$ *vs.* $\Delta S^{\ddagger}$.

[25] The energy parameters of Aksnes and Bergesen[9] were determined from two temperatures (5° apart) for each compound; thus the error in the data is uncertain. From these data, for log k_3/T *vs.* $1/T$ we calculate $\Delta H^{\ddagger}$ six membered = 37.2 kcal/mol; $\Delta S^{\ddagger}$ six = 40.3 eu; $\Delta H^{\ddagger}$ five = 36.8 kcal/mol; $\Delta S^{\ddagger}$ five = +53.6 eu. The entropy values are unusually large.

[26] The nmr spectra were determined on a Varian Associates Model A-60 spectrometer with tetramethylsilane as an internal standard; the P^{31}–H^1 coupling assignments were confirmed by decoupling experiments performed with a nmr HD-60 heteronuclear spin decoupler with a frequency output near 24.3 MHz. An F & M Model 700 chromatograph was used for glpc analysis. Elemental analyses were carried out by Alfred Bernhardt, Mikroanalytisches Laboratorium, Elbach, West Germany. All boiling and melting points (Thomas–Hoover apparatus) are uncorrected. All of the preparations were conducted in the presence of nitrogen; solvents were removed during the reaction work-up with a Büchi rotating evaporator.

TABLE II

WAVELENGTHS AND CONCENTRATIONS FOR RATE MEASUREMENTS

Compd	λ, mμ[a]	[OH], *M*[b]	[Salt], *M*[c]
1	228.0	2×10^{-3}	5×10^{-5}
2	240.5	10^{-2}	5×10^{-4}
3	276.5	10^{-2}	5×10^{-4}
4	229.3	2×10^{-2}	5×10^{-4}
5	225.5	5×10^{-2}	5×10^{-4}
6	235.5	10^{-1}	5×10^{-3}
7	237.0	2×10^{-2}	5×10^{-4}
8	233.0	10^{-1}	5×10^{-3}
9	307.5[d]	10^{-1}	5×10^{-3}
10	277.9	10^{-1}	5×10^{-3}

[a] The exact value of the wavelength selected depended on the temperature of the run; this was due to the change of A_∞ of the oxide as a function of temperature. The values here are typical wavelengths and are within ±1 mμ of the actual number selected. [b] Typical, approximate concentrations. The [OH⁻] was changed from 2-to 50-fold in plots of k_{obsd} *vs.* $[\mathrm{OH}^-]^2$; most of the plots contained six points. [c] Typical and approximate values. [d] The six-membered salt has little absorption in this region, whereas the oxide has sufficient, but small absorption to follow the rate of the reaction.

rate was fast, the initial portion of the reaction (up to one half-life) was missed. In the slowest runs (such as compound **10** at 25°) A_∞ was first estimated and then varied (graphically, and then by computer) until the standard error in a plot of log $(A_t - A_\infty)$ *vs.* time was 1% or less. The calculated standard errors in Table I were determined by a least-squares analysis program using an IBM 7040 computer.

Although compounds **2**, **3**, **5**, and **6** can exist as either cis or trans isomers, it was previously found[18] that hydroxide ion caused rapid equilibration of the isomers to occur prior to decomposition to oxide. Thus, the pure isomers were not used for the kinetic experiments.

Glpc Analyses.—Aqueous solutions (250 ml) of each of the salts **1–8** were prepared to contain 5×10^{-3} *M* salt and 0.05–0.1 *M* NaOH. The solutions were covered with 10 ml of distilled petroleum ether (bp 30–40°) and allowed to stand 5–7 days in glass-stoppered flasks. A 250-μl aliquot of the petroleum ether was withdrawn and injected into a 13 ft × 0.25 in. column packed with 20% DEGS on 80–100 mesh Chromosorb W. The column was kept at 100° and the He flow rate was 100 cc/min. A control sample containing a known amount of benzene and toluene in petroleum ether over 250 ml of water was subjected to the identical conditions as the unknown; less than 1% of the theoretical maximum (based on 100% phenyl cleavage) of benzene could be detected. The retention times for benzene and toluene were 15 and 28 min, respectively. In compounds **1–3** and **8** only toluene was found; no benzene was detected from **6** or **7**. Compound **4** and **5** gave only toluene, as expected; a quantitative check (using standards of known toluene concentration) on **5** showed that >96% of the theoretical amount of toluene was formed.

Synthetic Methods.—Phosphonium salts **1** and **3** were made by quaternization of the corresponding phosphetanes;[2a] the melting points, nmr, and microanalyses of these materials are recorded here. The detailed syntheses of compounds **2** and **4** are described below. Preparation of salts **5–7**[2a] and **10**[6a] has already been reported; and the synthesis of the phospholanium salt (**8**) follows from analogy to similar literature[16] procedures. Finally, the phosphorinanium salt (**9**) was obtained by modification of the method of Grüttner and Wiernik.[27]

1-Benzyl-1-phenyl-2,2,3,3-tetramethylphosphetanium Bromide (**1**).—Quaternization of the phosphetane precursor[2a] gave the salt, mp 243–244° dec, in 60% yield. The nmr ($CDCl_3$ plus a few drops of CF_3CO_2H to increase the solubility) showed peaks at τ 1.47–2.83 (m, 10, aromatic), 5.21 (d, 2, J_{PCH} = 13 7 Hz), 5.90–7.42 (m, 2, ring hydrogens), 7.96 (d, 3, J_{PCCH} = 22.0 Hz), 8.58 (d, 3, J_{PCCH} = 22.0 Hz), 8.62 (s, 3), 8.92 (broad s, 3).

Anal. Calcd for $C_{20}H_{26}BrP$: C, 63.66; H, 6.94. Found: C, 63.42; H, 6.94.

1-Benzyl-1-phenyl-2,2,3,4,4-pentamethylphosphetanium Bromide (**3**).—Quaternization of a predominance of the trans (1-phenyl and 3-methyl) phosphetane[2a] gave a salt which was dried over P_2O_5 (100°, 0.1 mm); the melting point of the dried salt (this material tends to form a hydrate) was 212–214° dec. The nmr ($CDCl_3$) of the major isomer showed peaks at: τ 1.92–3.27 (m, 10, aromatic), 5.18 (d, 2, J_{PCH} = 13.5 Hz), 7.08–7.67 (m, 1), 8.06 (d, 6, J_{PCCH} ~20 Hz), 8.37 (d, 6, J_{PCCH} ~18.5 Hz), 8.83 (dd, 3, J_{PCCCH} ~1, J_{HCCH} = 7.0 Hz). The cis isomer showed characteristic peaks at: τ 5.03 (d, 2, J_{PCH} = 13.5 Hz), 6.02–6.80 (m, 1), 8.10 (d, 6, J_{PCCH} = 19 Hz), 8.53 (d, 6, J_{PCCH} = 18 Hz), 8.95 (broad d, 3, J_{HCCH} = 7 Hz).

The microanalysis was performed on a mixture of isomers.

Anal. Calcd for $C_{21}H_{28}BrP$: C, 64.45; H, 7.21. Found: C, 64.11; H, 7.30.

1-Benzyl-1-phenyl-2,2,3,3,4-pentamethylphosphetanium Bromide (**2**) *via* **the Corresponding Oxide.**—To 20.0 g (0.15 mol) of anhydrous aluminum chloride suspended in 100 ml of methylene chloride, 27.0 g (0.15 mol) of phenylphosphonous dichloride in 50 ml of methylene chloride was added. The homogeneous solution was cooled to 0–5° and 17.0 g (0.15 mol) of 3,4,4-trimethyl-2-pentene (Chemical Samples Co., Columbus, Ohio) in methylene chloride was added dropwise with stirring over 2 hr. The reaction stood overnight and was then cooled to 0° and treated by the dropwise addition of 200 ml of water. The organic layer was washed with saturated sodium chloride, dried, and the methylene chloride evaporated. The crude solid was recrystallized from cyclohexane and then sublimed (120°, 0.1 mm) to give 21 g (59% yield) of 1-phenyl-2,2,3,3,4-pentamethylphosphetane 1-oxide: mp 133–134°; nmr (C_6H_6) τ 6.98–7.49 (m, 1, ring proton), 8.70 (s, 3), 9.16 (s, 3) 8.85 (d, 3, J_{PCCH} = 15 Hz), 9.22 (d, 3, J_{PCCH} = 18.8 Hz), 8.93 (dd, 3, J_{PCCH} = 18.3 Hz, J_{HCCH} = 7.0 Hz); ir (CCl_4) 1190 cm^{-1} (P=O).

Anal. Calcd for $C_{14}H_{21}OP$: C, 71.15; H, 8.96; P, 13.10. Found: C, 70.88; H, 8.60; P, 13.31.

To 13.5 g (0.06 mol) of the oxide in 200 ml of dry benzene, 6.0 g (0.06 mol) of triethylamine was added. The reaction was cooled and 8.5 g (0.06 mol) of trichlorosilane was added. The mixture was stirred for 1 hr at 25° and 3 hr at reflux; it was then cooled to 0° and 150 ml of 20% NaOH was added dropwise. The benzene layer was washed with water, dried (Na_2SO_4), and evaporated to give the phosphetane:[28] bp 83–84° (0.05 mm); 94% yield; nmr (C_6H_6) τ 7.4–7.9 (m, 1, ring proton), 8.83 (s, 3), 9.23 (s, 3), 8.85 (d, 3, J_{PCCH} = 16.8 Hz), 9.22 (d, 3, J_{PCCH} = 5.2 Hz), 8.86 (dd, 3, J_{PCCH} = 14.8, J_{HCCH} = 7.0 Hz).

Anal. Calcd for $C_{14}H_{21}P$: C, 76.32; H, 9.61; P, 14.06. Found: C, 76.48; H, 9.67; P, 14.08.

To 2.47 g (0.011 mol) of the phosphetane in 15 ml of dry ether in a thick-walled flask, 2.00 g (0.012 mol) of benzyl bromide was added; the flask was stoppered and allowed to stand for 3 days. The precipitate was filtered, washed with ether, and recrystallized (acetonitrile–ethyl acetate) to give 3.0 g (67% yield) of chunky crystals: mp 209–211° dec; nmr ($CDCl_3$) τ 1.70–3.15 (m, 10, aromatic), 4.25–6.50 (m, 3, ring proton plus $PhC\mathbf{H}_2$), 8.14 (d, 3, J_{PCCH} = 20.5 Hz), ~8.67 (d, 3, J_{PCCH} ~20 Hz), ~8.37 (dd, 3, J_{PCCH} ~21 Hz, J_{HCCH} = 7.5 Hz), 8.60 (s, 3), 8.82 (s, 3).

Anal. Calcd for $C_{21}H_{28}BrP$: C, 64.45; H, 7.21. Found: C, 64.22; H, 6.92.

1,1-Dibenzyl-2,2,3,4,4-pentamethylphosphetanium Bromide (**4**) *via* **the Corresponding Oxide.**—To 38.0 g (0.20 mol) of *freshly recrystallized* 1-chloro-2,2,3,4,4-pentamethylphosphetane 1-oxide[29] in 500 ml of dry ether at 0°, a solution of benzylmagnesium chloride (0.20 mol) in 400 ml of ether was added dropwise with stirring over 2 hr. The reaction was stirred for another 12 hr and saturated ammonium chloride solution was then added. About 300 ml of benzene was added to dissolve the product (only sparingly soluble in the ether layer). The organic layer was washed three times with 5% sodium hydroxide solution and then with water. The benzene–ether was dried and evaporated to 37.5 g of crude product which was recrystallized from cyclohexane (large volume) and sublimed (160°, 0.05 mm) to give 30 g (60% yield) of 1-benzyl-2,2,3,4,4-pentamethylphosphetane 1-oxide, mp 179–181° (lit.[3k] mp 180–182°). The nmr ($CDCl_3$) showed peaks at τ

---

[27] G. Grüttner and M. Wiernik, *Ber.*, **48**, 1473 (1915); see also G. Grüttner and E. Krause, *ibid.*, **49**, 437 (1916).

[28] The stereochemistry of this isomer was determined by nmr double irradiation experiments (J. P. Albrand and J. B. Robert, private communication). A value of $^2J_{\mathrm{PCH}} \approx -7.2$ Hz was found, which implies that the 1-phenyl and 4-methyl are trans. See J. P. Albrand, D. Gagnaire, J. Martin, and J. B. Robert, *Bull. Soc. Chim. Fr.*, 40 (1969); J. P. Albrand, D. Gagnaire, M. Picard, and J. B. Robert, *Tetrahedron Lett.*, 4593 (1970).

[29] J. J. McBride, Jr., E. Jungermann, J. V. Killheffer, and R. J. Clutter, *J. Org. Chem.*, **27**, 1833 (1962).

2.4–2.9 (m, 5, aromatic), 6.75 (d, 2, J_{PCH} = 11.0 Hz), 8.26 (dq, 1, J_{PCCH} ~2 Hz, J_{HCCH} = 7.0 Hz), 8.78 (d, 6, J_{PCCH} = 16.0 Hz), 8.87 (d, 6, J_{PCCH} = 18.3 Hz), 9.12 (dd, 3, J_{HCCH} = 7.0, J_{PCCCH} = 1.7 Hz).

Anal. Calcd for $C_{15}H_{23}OP$: C, 71.97; H, 9.26. Found: C, 72.16; H, 9.08.

Reduction of the oxide (usual method, see above) and quaternization of the phosphetane (not isolated) in benzene–ether solution with benzyl bromide afforded the salt (56% overall yield) which gave needles, mp 219–222° dec, on recrystallization from acetonitrile. The nmr (CF_3CO_2H) showed absorption at τ 2.5–3.4 (m, 10, aromatic), 6.08 (d, 2, J_{PCH} = 13.0 Hz), 6.16 (d, 2, J_{PCH} = 12.5 Hz), 7.05 (dq, 1, J_{HCCH} = 7 Hz, J_{PCCH} ~3 Hz), 8.35 (d, 6, J_{PCCH} = 19 Hz), 8.41 (d, 6, J_{PCCH} = 19.7 Hz), 8.83 (d, 3, J_{HCCH} = 7, J_{PCCCH} = 1.5 Hz).

Anal. Calcd for $C_{22}H_{30}BrP$: Br, 19.71. Found: Br, 19.66, 19.85.

1-Benzyl-1-phenylphospholanium Bromide (8).—To 25 g (0.14 mol) of 1-phenyl-2-phospholene 1-oxide[30] in 300 ml of absolute ethanol, 500 mg of platinum oxide was added; the mixture was hydrogenated at room temperature in a Paar shaker at 50 psi. After 24 hr the catalyst was filtered and the solvent was evaporated. The resultant liquid was distilled to give 20 g (79%) of 1-phenyl-2-phospholane 1-oxide, bp 122–125° (0.1 mm) [lit.[31] bp 136–137° (0.3 mm)].

To a cooled solution of 18.0 g (0.10 mol) of the saturated oxide in 175 ml of benzene, 10.1 g (0.10 mol) of triethylamine was added followed by 14 g (0.10 mol) of trichlorosilane. The solution was stirred overnight at 25° and then heated at reflux for 2 hr; the usual work-up procedure (see above) gave 13 g (79%) of liquid, $n^{23}\mathrm{D}$ 1.5840, bp 68–70° (0.1 mm) [lit.[32] bp 97° (3 mm)]. The phospholane was treated with benzyl bromide in ether; the crude product (80% yield) was recrystallized repeatedly from acetonitrile to give the pure salt: mp 166–167°; nmr ($CDCl_3$) τ 1.6–3 (m, 10), 5.2 (d, 2, J_{PCH} = 16 Hz), 6.5–9.0 (broad m, 8).

Anal. Calcd for $C_{15}H_{20}BrP$: C, 60.91; H, 6.01; P, 23.84. Found: C, 61.08; H, 6.08; P, 23.83.

1-Benzyl-1-phenylphosphorinanium Bromide (9).—To 20.5 g (0.85 g-atom) of magnesium turnings covered with 100 ml of dry tetrahydrofuran,[33] 2 g of 1,5-dibromopentane was added. A crystal of iodine was added and the reaction commenced within 10 min. Then 98 g (0.43 mol) of the dibromide in 200 ml of tetrahydrofuran was slowly added over 4.5 hr to maintain the temperature at 35–40°. One-half of the Grignard solution was transferred to an addition funnel. A solution of 35 g (0.2 mol) of phenylphosphonous dichloride in 500 ml of ether was placed in a separate funnel. Each solution was added dropwise (simultaneously) at 25° to 1.5 l. of ether which was rapidly stirred in a 3-l., three-necked flask. The addition required 3 hr; the mixture was stirred overnight. A similar reaction was run with the other half of the Grignard solution; each reaction was worked up identically. Each flask was cooled and 125 ml of saturated ammonium chloride was added followed by 250 ml of water. The combined organic layers were washed (saturated NaCl solution) and dried (Mg_2SO_4); the solvent was removed to give a liquid which was distilled through a short column to afford 12.5 g (18% yield) of the 1-phenylphosphorinane, bp 80–85° (0.1 mm) [lit.[32] bp 119° (3 mm)]. The phosphine was dissolved in 175 ml of ether and treated with 12.5 g (0.073 mol) of benzyl bromide. After 60 hr, 22 g (90% yield) of product, mp 178–182° (sealed tube), was obtained; recrystallization from acetonitrile gave 17.1 g, mp 182–185° as a first crop and 3.6 g, mp 181–184° as a second crop. The nmr ($CDCl_3$) showed absorption at τ 1.8–3.0 (m, 10), 5.4 (d, 2, J_{PCH} = 15.8 Hz), and 6.3–9.0 (broad m, 10).

Anal. Calcd for $C_{18}H_{22}BrP$: C, 61.89; H, 6.35; Br, 22.88. Found: C, 62.07; H, 6.00; Br, 22.64.

Methylphenyl(1,1,2,2-tetramethylpropyl)phosphine Oxide (12).—To 3.0 g (0.01 mol) of 1-phenyl-1,2,2,3,3-pentamethylphosphetanium bromide (7)[2a] in 10 ml of water, 6 ml of 2 *N* sodium hydroxide was added. The solution was stirred at 25° for 30 min, and the heterogeneous mixture was extracted with three 50-ml portions of benzene. The benzene extracts were washed (saturated NaCl solution), dried, and evaporated to give an oil which solidified on trituration with cyclohexane. Recrystallization from cyclohexane gave 1.9 g (80% yield) of product, mp 84.5–86.5° (lit.[3e] mp 84–85°). The nmr ($CDCl_3$) showed absorption at τ 1.93–2.63 (m, 5), 8.24 (d, 3, J_{PCH} = 12.0 Hz), 8.84 (d, 3, J_{PCCH} = 17.0 Hz), 9.01 (d, 3, J_{PCCH} ~16 Hz), 8.92 (s, 9).

Anal. Calcd for $C_{14}H_{23}OP$: C, 70.54; H, 9.73; P, 13.02. Found: C, 70.94; H, 9.63; P, 12.84.

Registry No.—**1,** 31120-03-3; **2,** 31120-04-4; **3,** 19962-48-2; **4,** 31120-05-5; **5,** 16084-02-9; **6,** 16083-98-0; **7,** 16083-99-1; **8,** 31082-04-9; **9,** 31082-05-0; **10,** 31082-06-1; **12,** 28598-41-6; 1-phenyl-2,2,3,3,4-pentamethylphosphetane 1-oxide, 31082-08-3; 1-benzyl-2,2,3,4,4-pentamethylphosphetane 1-oxide, 24655-74-1.

Acknowledgment.—We are indebted to Mrs. Hai-OK Hwang for the glpc analyses and to Mr. Paul G. Elsey of the Ethyl Corporation for a generous supply of methylphosphonous dichloride.

---

[30] W. B. McCormack, U. S. Patent 2,663,737 (Dec 22, 1953); *Chem. Abstr.*, **49**, 7601 (1955). See also L. D. Quin and D. A. Mathewes, *J. Org. Chem.*, **29**, 836 (1964).

[31] W. B. McCormack, U. S. Patent 2,663,738 (Dec 22, 1953); *Chem. Abstr.*, **49**, 7602 (1955).

[32] K. Issleib and S. Haüsler, *Chem. Ber.*, **94**, 113 (1961).

[33] Considerable difficulty was encountered with diethyl ether as a solvent; the water content in this solvent seems to be an important factor: R. Brown and W. E. Jones, *J. Chem. Soc.*, 781 (1946). Use of dry THF gave consistent results; moreover, Grignard formation commenced readily and the solution contained only one phase.