The Staudinger Reaction between Triarylphosphines and Azides. A Study of the Mechanism

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Abstract: The reaction of substituted phenyl azides with substituted triphenylphosphines to give nitrogen and the corresponding triarylphosphine arylimide passes serially through two isomeric transition states and an intermediate complex, all having the empirical formula $Ar_3P \cdot ArN_3$. It has been shown kinetically and by means of trapping experiments that the second transition state is attainable *only* by reactivation of the intermediate complex and not by direct combination of Ar_3P with ArN_3 or by isomerization of the first transition state without deactivation. The two transition states have approximately the same energy. The differences between the transition states and possible reasons for the lack of direct interconversion are discussed in terms of momentum along the reaction coordinate, the shape of the potential energy surface, and the probability of collisional deactivation.

Most covalent azides react with triphenylphosphine and other trivalent phosphorus compounds to give nitrogen and iminophosphoranes.[2-4] Iminophosphoranes are widely used in the synthesis of amides,[5] amines,[5,6] and a variety of compounds containing carbon-to-nitrogen double bonds.[7] Rate measurements have been reported for the reactions of triphenylphosphine with trityl azide,[8] substituted benzoyl azides,[9] sulfonyl azides,[9,10] and substituted phenyl azides.[5] The mechanism for the reaction with *trityl* azide has been elucidated, but depends on the special stability of the triphenylcarbonium ion and cannot be extended to other cases. The reaction with benzenesulfonyl azide appears to be a first-order decomposition of a completely associated phosphazide complex,[9] but is accompanied by a redox side reaction in some solvents.[9,10] The reactions with substituted benzoyl azides[9] and with phenyl azides[5] have been reported to be second order over-all and accelerated by electron-withdrawing *meta* or *para* substituents in the azide.

$$RN_3 + R_3P \longrightarrow N_2 + R_3P{=}N{-}R \qquad (1)$$

Reaction of Phenyl Azides with Triphenylphosphines. A closer examination of the kinetics of the reaction of substituted phenyl azides with substituted triphenylphosphines shows that the adherence of these reactions to the second-order rate law is only approximate. The deviations are increased by electron-withdrawing substituents in the phenyl azide and by electron-releasing substituents in the triphenylphosphine. These substitutions also increase the apparent second-order rate constants (Tables II and III).

The deviations from second-order kinetics are negligible when the triphenylphosphine bears electron-withdrawing substituents, as is illustrated for the reaction of phenyl azide with tris(*p*-chlorophenyl)phosphine in Figure 1. In contrast, the second-order plot for the reaction with tris(*p*-methoxyphenyl)phosphine disperses into different lines for different initial concentrations and the early part of each line is noticeably curved (Figure 2).

Electron spin resonance spectroscopy and the addition of radical chain-transfer agents or inhibitors (trinitrotoluene, diisopropyl ether) failed to give any evidence for the participation of a free-radical process. All reactions investigated gave the expected triphenylphosphine phenylimide[3] apparently uncontaminated by side products. An isotopic tracer experiment showed that the remaining nitrogen atom in the triphenylphosphine phenylimide is exclusively the atom originally adjacent to carbon in the azide.

In view of the pattern of substituent effects and the evident lack of free-radical participation, the most probable explanation for the deviations from second-order kinetics is formation of a phosphazide complex. Such complexes are isolable from the reaction of certain phosphine–azide pairs, although in most instances they decompose to the iminophosphorane at room temperature or below.[2,5,7b] The complexes are usually yellow or orange and contain the azide and phosphine in equal proportions.

In the reactions between most aryl azides and triphenylphosphines a yellow color appears rapidly and then fades during the course of the reaction. Rapid gas evolution in solutions concentrated enough for the complex to be highly associated seriously interferes with visible or ultraviolet spectrophotometry, but we have observed an infrared band at 2310 cm^{-1}. The procedure for obtaining a sufficiently high concentration is to mix benzene solutions of the two reagents, freeze the mixture rapidly, and then observe the spectrum immediately after the mixed solution has been thawed. The frozen reaction mixture is intensely yellow. Immediately after the thawing, the band at 2310 cm^{-1} (complex) is stronger, and the azide band at 2110 cm^{-1} considerably weaker, than in similar mixtures not sub-

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[1] National Science Foundation Predoctoral Fellow.

[2] H. Staudinger and J. Meyer, *Helv. Chim. Acta*, **2**, 635 (1919).

[3] The following nomenclature is recommended by the joint British-American Nomenclature Committee [*Chem. Eng. News*, 30, 4515 (1952)]: $\equiv P{=}N{-}$ iminophosphorane, $R_3P{=}N{-}R$ trialkylphosphine alkylimide, $R_3P{=}N{-}C({=}O){-}R$ trialkylphosphine acylimide.

[4] G. I. Derkach, I. N. Zhmurova, A. V. Kirsanov, V. I. Shevchenko, and A. S. Stepanek, "Fosfazosoedineniya," Izdatel'stvo Naukova Dumka, Kiev, 1965.

[5] L. Horner and A. Gross, *Ann.*, **591**, 117 (1955).

[6] H. Zimmer and G. Singh, *J. Org. Chem.*, **28**, 483 (1963).

[7] (a) H. Staudinger and J. Meyer, *Ber.*, **53**, 72 (1920); (b) H. Staudinger and E. Hauser, *Helv. Chim. Acta*, **4**, 861 (1921); (c) H. Ulrich and A. A. Sayigh, *Angew. Chem.*, **74**, 900 (1962); (d) W. S. Wadsworth, Jr., and W. D. Emmons, *J. Am. Chem. Soc.*, **84**, 1316 (1962); *J. Org. Chem.*, **29**, 2816 (1964); (e) A. Messmer, I. Pintér, and F. Szegö, *Angew. Chem.*, **76**, 227 (1964).

[8] J. E. Leffler, U. Honsberg, Y. Tsuno, and I. Forsblad, *J. Org. Chem.*, **26**, 4810 (1961).

[9] J. E. Leffler and Y. Tsuno, *ibid.*, **28**, 902 (1963).

[10] J. E. Franz and C. Osuch, *Tetrahedron Letters*, 841 (1963).

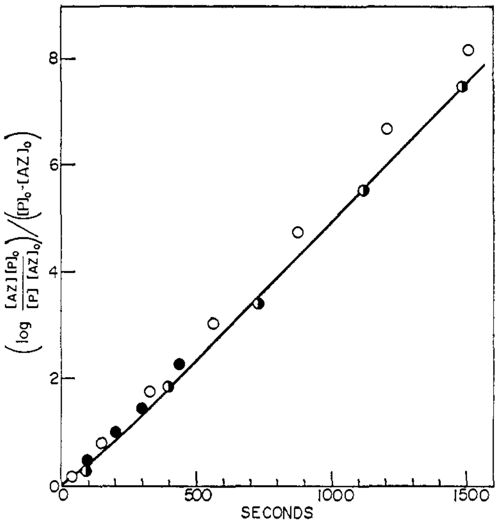

Figure 1. The line is REMECH calculated for k_1 = 0.019, k_2 = 0.042, k_3 = 0.060 (Mechanism I): ○, $[P]_0$ = 0.1654, $[AZ]_0$ = 0.0364; ◑, $[P]_0$ = 0.0116, $[AZ]_0$ = 0.1003; ●, $[P]_0$ = 0.0198, $[AZ]_0$ = 0.622. It is not resolvable into separate lines on this scale. P = tris(*p*-chlorophenyl)phosphine, AZ = phenyl azide. In benzene at 25°.

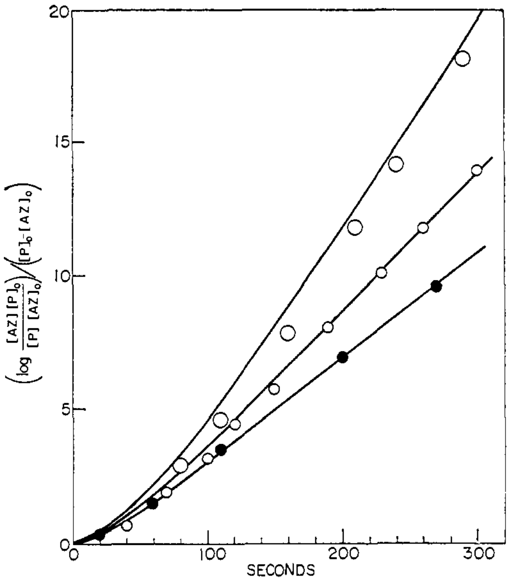

Figure 2. The lines are REMECH calculated, k_1 = 0.55, k_2 = 0.0115, k_3 = 0.010 (Mechanism I): ●, $[P]_0$ = 0.01107, $[AZ]_0$ = 0.0929; ○, $[P]_0$ = 0.0133, $[AZ]_0$ = 0.0307; ○, $[P]_0$ = 0.00902, $[AZ]_0$ = 0.0644. P = tris(*p*-methoxyphenyl)phosphine, AZ = phenyl azide. In benzene at 25°.

jected to the freeze–thaw process.[11] As the concentrated solution of the complex is allowed to stand at room temperature, the intensity of the band at 2310 cm^{-1} decreases continuously, while that of the 2110-cm^{-1} azide band first increases and then slowly decreases. The formation of the complex is therefore reversible.

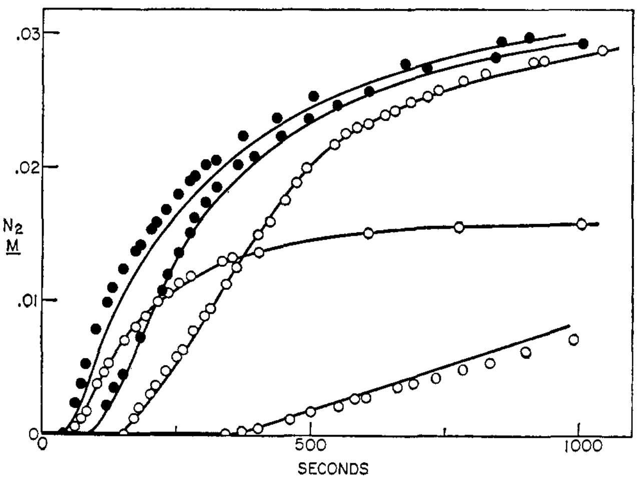

Figure 3. Nitrogen evolution in the presence of picric acid. Filled circles are runs in which part of the acid was neutralized by an initial addition of triphenylphosphine phenylimide. The lines are REMECH calculated on the basis of Mechanism I with k_1 = 0.0715, k_2 = 0.022, k_3 = 0.0238, K_4 = 10^6, K_5 = 10^8.

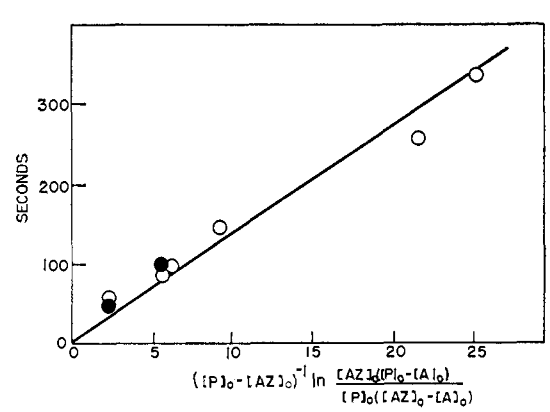

Figure 4. Induction periods in runs with picric acid. The filled circles are for runs in which triphenylphosphine phenylimide has been added initially, in which case $[A]_0$ is the remaining unneutralized acid.

The Effect of Picric Acid. The kinetics of the reaction of unsubstituted phenyl azide with unsubstituted triphenylphosphine are close to second order. However, addition of picric acid has a profound effect on the kinetics without changing the product of the reaction except for the conversion of an equivalent of the triphenylphosphine phenylimide into its picrate salt. An excess of the acid inhibits the reaction indefinitely, while lesser quantities give induction periods as illustrated in Figure 3. The rate of N_2 evolution during the induction period is too small for accurate measurement; the rate in the presence of 10% excess picric acid, measured over a long period of time, is less than 0.05% of the normal value.

The lengths of the induction periods depend on the initial concentrations as shown in Figure 4. The straight line of that figure is predicted by eq 2, derived from Mechanism I (*vide infra*). The filled circles show the effect of adding triphenylphosphine phenylimide; for those runs $[A]_0$ is the *remaining* acid, assuming 1:1 stoichiometry for the formation of triphenylphosphine phenylimide picrate.

The first evolution of nitrogen after the induction period is a zero-order process which in turn is succeeded

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[11] Freezing the solution apparently accelerates the biomolecular reaction leading to the formation of the complex, either because of small regions of highly concentrated solution in interstices of the benzene matrix or because of some other effect of the growing crystal lattice. Similar acceleration of reaction on freezing has been reported in several instances: (a) V. A. Simon, Dissertation, Florida State University, 1962; (b) N. H. Grant, D. E. Clark, and H. E. Alburn, *J. Am. Chem. Soc.*, **88**, 4071 (1966); (c) R. E. Pincock and T. E. Kiovsky, *ibid.*, **87**, 2072, 4100 (1965); **88**, 51 (1966).

rather abruptly by a second-order reaction; the rate constant of the latter is equal to that observed in the absence of picric acid. The rates of the zero-order part of the reaction are related to the initial concentrations as shown in Figure 5 and Table I.

Table I. Reaction of Phenyl Azide with Triphenylphosphine and Added Acid[a] in Benzene at 25°

Initial concn, M			Induction period, sec	$k_{\mathrm{oth}} \times 10^5$, M sec^{-1}
Phosphine	Azide	Acid[a]		
0.0903	0.0282	0.0226	260	1.53
0.1109	0.0312	0.0136	90	9.75
0.0300	0.1071	0.0136	100	9.05
0.0285	0.1273	0.0361	∞[b]	...
0.1110	0.0308	0.0187	150	5.87
0.0157	0.0746	0.0123	340	1.13
0.0161	0.1764	0.0054	60	9.3
0.1109	0.0317	0.0136[c]	50[c]	14.5[c]
0.1110	0.0313	0.0256[d]	100[d]	8.95[d]
0.1108	0.0329	0.0125[e]	50[e]	11.5[e]
0.1108	0.0320	0.0199[e]	70[e]	6.73[e]

[a] Picric acid unless otherwise noted. [b] Essentially all induction period, half-life for N_2 evolution about 6×10^4 sec. [c] Picric acid, but partially neutralized by adding 0.0068 M triphenylphosphine phenylimide. [d] Picric acid, but partially neutralized by adding 0.0119 M triphenylphosphine phenylimide. [e] Trifluoroacetic acid.

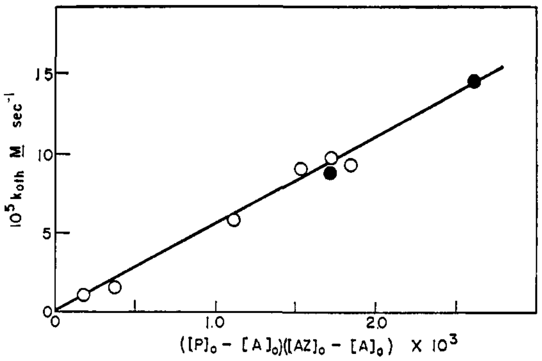

Figure 5. Dependence of zero-order constants on initial concentrations. The filled circles have the same significance as in Figure 4.

A Proposed Mechanism. The dispersion of the second-order rate constants and the kinetics in all three stages of the runs with added picric acid can be explained and reproduced quantitatively by

Mechanism I

$$\mathrm{P + AZ \xrightarrow{1} C}$$

$$\mathrm{C \xrightarrow{2} P + AZ}$$

$$\mathrm{C \xrightarrow{3} PN + N_2}$$

$$\mathrm{C + A \overset{4}{\rightleftharpoons} CA}$$

$$\mathrm{PN + A \overset{5}{\rightleftharpoons} PNA}$$

where P = triphenylphosphine, AZ = azide, C = phosphazide complex, PN = triphenylphosphine phenylimide, A = added picric acid, and CA and PNA are the corresponding salts.

The Induction Period. During the induction period, the complex C is converted immediately and completely into the salt CA and there is no possibility of nitrogen evolution until all the acid has been consumed. The length of the induction period can be obtained by integrating the rate expression for step 1 of the proposed mechanism

$$\Delta t = \frac{1}{k_1}([P]_0 - [AZ]_0)^{-1} \ln \frac{[AZ]_0([P]_0 - [A]_0)}{[P]_0([AZ]_0 - [A]_0)} \qquad (2)$$

The quantities $[P]_0$, $[AZ]_0$, and $[A]_0$ in eq 2 are the initial concentrations of triphenylphosphine, phenyl azide, and picric acid.

The fit of the picric acid data to eq 2 is probably within the error of estimating the lengths of the induction periods. A better test of the agreement for this part of the reaction is the fit of the first few points of each of the runs to the theoretical rate curves shown in Figure 3. These curves were calculated on the basis of Mechanism I using the REMECH[12] digital computer program. The value of k_1 needed for the calculation was obtained from the slope of Figure 4 and is consistent with the set of values obtained for the reactions of substituted azides with substituted triphenylphosphines, to be discussed in the section on substituent effects. The rate constants k_2 and k_3 were chosen on the basis of consistency with substituent effects and with the additional constraint that the rate of the reaction of the azide and phosphine is very sensitive to the *ratio* of these parameters. The values of K_4 and K_5 are not critical provided that they are both large and that K_5 is greater than K_4.

The Zero-Order Period. After the induction period the concentrations of phosphine (P), azide (AZ), and complex (C) remain essentially constant until all of the complex salt (CA) has been used up. The reason for this is that each molecule of the strongly basic[2,6,7b] triphenylphosphine phenylimide (PN) formed by reaction 3 immediately frees a molecule of the complex from the salt CA. Hence reaction 3 has no effect on the concentration of the complex. The concentration would be given by eq 3 if it could be assumed that the concentration of complex is small and a steady-state approximation is applicable.

$$[C] \cong \frac{k_1}{k_2}[P][AZ] = \frac{k_1}{k_2}([P]_0 - [A]_0)([AZ]_0 - [A]_0) \qquad (3)$$

The rates (k_{oth}) should then be related to the initial concentrations by eq 4. Although the form of the equation is confirmed by experiment, Figure 5, the experi-

$$k_{\mathrm{oth}} = k_3[C] = \frac{k_3 k_1}{k_2}([P]_0 - [A]_0)([AZ]_0 - [A]_0) \qquad (4)$$

mental slope is about 40% lower than predicted. This discrepancy is due to the inadequacy of the assumption that the concentration of complex is small compared to that of the phosphine and azide. A REMECH calculation using the same values of k_1, k_2, and k_3 that were used for the curves of Figure 3 and making *no* approximations shows that the concentration of complex may be as much as 30% of the concentration of the lesser of the two reagents. The k_{oth} values are the slopes of the straight portions of the lines in Figure 3, and it can be seen that the agreement between experiment and the computed lines is excellent.[13]

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(12) D. F. DeTar and C. E. DeTar, *J. Phys. Chem.*, 70, 3842 (1966).

(13) Three runs have been omitted from Figure 3 for the sake of clarity.

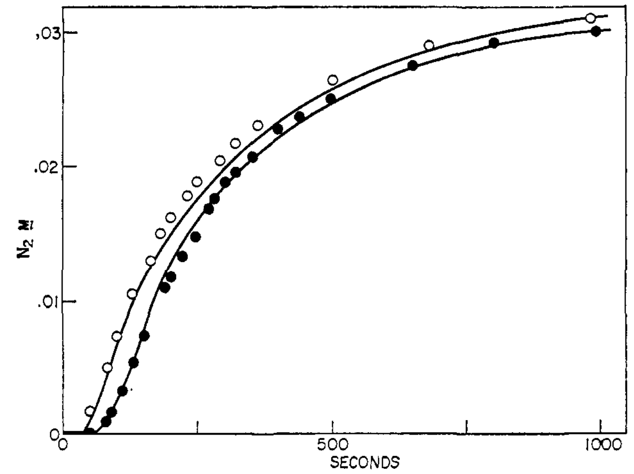

Figure 6. Phenyl azide and triphenylphosphine with trifluoroacetic acid at 25°: ○, $[P]_0 = 0.1108$, $[AZ]_0 = 0.0329$, $[F_3C\ COOH]_0 = 0.0125$; ●, $[P]_0 = 0.1108$, $[AZ]_0 = 0.0320$, $[F_3CCOOH]_0 = 0.0199$. Lines predicted by Mechanism II.

The Second-Order Period. The rate of nitrogen evolution after the reservoir of complex salt has been exhausted reverts to the approximate second-order law. The fit for reactions in which acid was initially added is shown in Figure 3. Figures 1 and 2 are typical of the fit obtained for runs without added acid. The agreement appears to be within experimental error.

Alternative Mechanisms. A mechanism in which there is a significant amount of *direct* reaction of phenyl azide and triphenylphosphine to give nitrogen and the phosphine imide can be ruled out on the basis of the kinetics and by the lack of any appreciable nitrogen evolution during the induction periods of the runs with added picric acid. The maximum effect of acid in such a mechanism would be to reduce the nitrogen evolution rate by an amount corresponding to the trapped complex. However, the existence of considerable unassociated reagent is substantiated both by the kinetics and by the changes in infrared spectrum already described. A mechanism in which the induction period is ascribed to the formation of a highly associated and unreactive complex between picric acid and one of the reagents can also be ruled out on the basis of the negligible nitrogen yield at the end of the induction period.

The Effect of Other Acids. Mechanism I suggests that other acids should have the same effect as picric acid provided that the equilibrium constants K_4 and K_5 are large enough. Trifluoroacetic acid also gives induction periods (Figure 6) but they are shorter than expected by about a factor of 2. The dimerization equilibrium constant for dichloroacetic acid in benzene at 25° is about 50 and the trend of structural effects is such that the constant for trifluoroacetic acid should be several orders of magnitude greater.[14] Trifluoroacetic acid has been shown to form both 1:1 and 2:1 salts with dibenzylamine in benzene.[14] We therefore replaced equilibria 4 and 5 of Mechanism I with those shown in Mechanism II (for use with carboxylic acids). The values 10^3, 10^4, 10^6, 10^9, and 10^4 were arbitrarily assigned to the equilibrium constants K_4, K_5, K_6, K_7, and K_8 of Mechanism II, with the results shown in Figure 6.

Mechanism II

steps 1–3 as in I

$$C + RCOOH \xrightleftharpoons{4} C{\cdot}RCOOH$$

$$2RCOOH \xrightleftharpoons{5} (RCOOH)_2$$

$$C + (RCOOH)_2 \xrightleftharpoons{6} C{\cdot}(RCOOH)_2$$

$$PN + (RCOOH)_2 \xrightleftharpoons{7} PN{\cdot}(RCOOH)_2$$

$$PN + RCOOH \xrightleftharpoons{8} PN{\cdot}RCOOH$$

This choice of values is equivalent to the use of a model involving acid dimer and dimer salt only, and makes the effect of steps 4, 5, and 8 negligible. No attempt was made to improve the fit by adjusting the values assumed for these equilibrium constants.

Dichloroacetic acid added to the phenyl azide–triphenylphosphine reaction mixture gives a slow initial reaction, but not a complete inhibition. The experimental results can be matched by assigning low values to the acid–base equilibrium constants K_4 and K_6, permitting a certain amount of free complex. In one of these experiments the acid was actually present in excess, a condition which prevents reaction entirely in the case of stronger acids. For runs with monochloroacetic acid (0.04 *M*) and acetic acid (0.156 *M*) the experimental points were within experimental error of the curve calculated by REMECH without provision for any effect of added acid.

Substituent Effects. The effects of substituents in the phenyl azide or the triphenylphosphine are shown in Tables II and III. Strongly electron-withdrawing substituents in the azide or strongly electron-releasing substituents in the phosphine cause the initial part of the second-order plot to be curved upward as in Figure 2. The apparent second-order rate constants in such cases were evaluated from the points later in the runs, after the curvature had become negligible. The substituents causing initial curvature also cause the apparent second-order rate constants to vary with concentration beyond our expected error, which is about 4–5%. The data for these runs can be recovered within experimental error by applying REMECH to the Mechanism I constants given in Table IV, and we have therefore not reported them in detail. The data for runs without the complex-favoring substituents can be reproduced by means of the apparent second-order constants.

o-Methyl or *o*-nitro substituents in the azide give slower reaction than do the corresponding substituents in the *para* position. Since the initial curvature of the second-order plot for *o*-nitrophenyl azide is less than that of the *para* isomer, the steric effect is probably to decrease the ratio k_1/k_2, *i.e.*, to make the complex less associated. The product is the normal, expected triphenylphosphine *o*-nitrophenylimide which has been made by a different route.[15] Any reaction by way of the *o*-nitrophenylnitrene should give benzofurazan oxide,[16] but this product was not detectable.

Fit to the Hammett Relationship. The correlation of $k_{\text{second order}}$ (Table II or III) with σ or $\Sigma\sigma$ is rough[17] and

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[14] S. Bruckenstein and S. Saito, *J. Am. Chem. Soc.*, **87**, 698 (1965).

[15] L. Horner and H. Oediger, *Ann.*, **627**, 142 (1959).

[16] P. A. S. Smith and B. B. Brown, *J. Am. Chem. Soc.*, **73**, 2435 (1951).

[17] The ρ value for substituents in the phenyl azide is about 1.1 (correlation coefficient 0.95); that for substituents in the triphenylphosphine is about −0.73 (correlation coefficient 0.98).

Table II. Effect of Substituents in the Azide on the Reaction of Phenyl Azide with Triphenylphosphine[a] in Benzene at 25°

Substituent	Initial concn ranges,[b] M Phosphine	Initial concn ranges,[b] M Azide	Apparent second-order constants or ranges,[b] M^{-1} sec^{-1}
p-NO$_2$[c]	0.007–0.014	0.0055–0.010	0.474–0.611[c]
p-NO$_2$[e]	0.0101	0.0309	0.233[e]
m-NO$_2$[c]	0.0077–0.024	0.0064–0.014	0.247–0.375[c]
p-CN[c]	0.0057–0.019	0.0050–0.028	0.311 0.329[c]
m-CN[c]	0.0056–0.022	0.0083–0.036	0.242–0.275[c]
m-Cl[d]	0.0099–0.031	0.0072–0.055	0.121–0.132[d]
m-F[d]	0.0056–0.042	0.0125–0.072	0.0996–0.1015[d]
p-Cl	0.0066–0.052	0.014–0.040	0.0920–0.0974
p-F	0.0145–0.085	0.0122–0.112	0.0537–0.0650
m-CH$_3$O	0.014–0.076	0.0123–0.078	0.0389–0.0393
H	0.030–0.092	0.0078–0.108	0.0331–0.0356
m-CH$_3$	0.014–0.077	0.024–0.122	0.0268–0.0281
m-t-Bu	0.011–0.16	0.015–0.086	0.0277–0.0309
p-CH$_3$	0.014–0.074	0.028–0.101	0.0275–0.0293
p-t-Bu	0.012–0.12	0.012–0.084	0.0257–0.0279
p-CH$_3$O	0.012–0.076	0.016–0.098	0.0262–0.0283
p-(CH$_3$)$_2$N	0.023–0.10	0.016–0.075	0.0143–0.0153
o-CH$_3$	0.0296–0.241	0.0293–0.343	0.00530–0.00574
o-NO$_2$	0.0333	0.0114	0.0805

[a] Except where otherwise noted. [b] Usually about four runs with an expected error of about 4–5%. Only the extreme values of the initial concentrations used and the apparent second-order rate constants obtained are tabulated. Any individual run can be reproduced within experimental error by means of the constants tabulated in Table IV in cases where the apparent second-order rate constant is dependent on the initial concentration. [c] These runs show a marked initial curvature as in Figure 2. [d] Moderate initial curvature. [e] Reaction of p-nitrophenyl azide with *p-chlorophenyldiphenylphosphine.*

Table III. Effect of Substituents in the Phosphine on the Reaction of Phenyl Azide with Triphenylphosphine in Benzene at 25°

Substituent	Initial concn or range,[a] M Phosphine	Initial concn or range,[a] M Azide	$k_{\text{second order}}$ or range,[a] M^{-1} sec^{-1}
Tris-p-Cl	0.012–0.021	0.10–0.62	0.0105–0.0117
Tris-p-Cl	0.165	0.0364	0.0123
p-Cl	0.011–0.066	0.012–0.11	0.0236–0.0238
m-CH$_3$	0.012–0.081	0.010–0.086	0.0360–0.0374
p-CH$_3$	0.012–0.061	0.0090–0.094	0.0497–0.0500
Tris-m-CH$_3$	0.0073–0.063	0.018–0.14	0.0372–0.0416[b]
p-CH$_3$O	0.016–0.086	0.012–0.093	0.0633–0.0721[b]
Tris-p-CH$_3$	0.0066–0.013	0.029–0.14	0.0560–0.0892[b]
Tris-p-CH$_3$O	0.0090–0.046	0.0087–0.093	0.0884–0.170[b]
p-N(CH$_3$)$_2$	0.011–0.056	0.013–0.075	0.130–0.158[b,c]

[a] Two to seven runs with an expected error of 4–5%. Greater variations than this are attributable to deviations from second order depending on initial concentrations. See Table IV. [b] Marked initial upward curvature of the second-order plots; see Figure 2 and Table IV. [c] In contrast, the second-order constant for tris-p-N(CH$_3$)$_2$ initially appeared to be only 0.0007 and became even smaller later in the run. This phosphine is very insoluble in benzene and cloudiness develops during the run. In chloroform the reaction appears to be even slower. In view of this extreme behavior, there may be some doubt about the structure of this compound, which was prepared by the method of E. Koenigs and H. Friedrich, *Ann.*, **509**, 138 (1934). The physical properties are different for various reported syntheses and the tris-p-N(CH$_3$)$_2$ compound has apparently never been well characterized or obtained entirely pure.

Table IV. Apparent Values of Constants for Mechanism I, Benzene, 25°[a]

Substituent	k_1	k_2	k_3
In Azide			
p-NO$_2$	0.72	0.0042	0.016
m-NO$_2$	0.54	0.0055	0.016
p-CN	0.50	0.0059	0.017
m-CN	0.40	0.0070	0.017
m-Cl	0.23	0.0115	0.019
m-F	0.18	0.0128	0.019
p-Cl	0.165	0.014	0.021
Hydrogen	0.075	0.025	0.022
In Triphenylphosphine			
Tris-m-CH$_3$	0.112	0.021	0.0175
p-CH$_3$O	0.143	0.017	0.020
Tris-p-CH$_3$	0.27	0.014	0.012
Tris-p-CH$_3$O	0.55	0.0115	0.010
p-N(CH$_3$)$_2$	0.59	0.011	0.0097

[a] These constants, with REMECH, will reproduce all the data within experimental error.

for substituents in the azide it is curved concave up, a deviation which in a simpler reaction would have been attributed either to a change in mechansim of the reaction or to the intrusion of a second important physical mechanism of interaction[18] between the substituents and the reaction zone. However, composite rate constants resulting from multistep mechanisms will, in principle, obey linear free energy relationships only under special circumstances. It was therefore desirable to test the behavior of the individual component rate constants k_1, k_2, k_3 of Mechanism I for linearity with σ. For substituents which give large deviations from second-order kinetics (marked with footnote c in Table II and b in III), fairly good estimates of the rate constants can be obtained by curve fitting using REMECH, since the shapes and slopes of the second-order plots are quite sensitive to the values used.

For hydrogen, k_1 is known from the picric acid experiments and the ratio k_2/k_3 can be obtained from eq 5.

$$k_{\text{second order}} = k_1[k_3/(k_2 + k_3)] \tag{5}$$

Equation 5 is the relationship obtained when the steady-state approximation is adequate, *i.e.*, when the complex does not attain high concentrations.

A further constraint on k_2 is a lower limit of about 0.02 below which deviation from second-order kinetics should have been noticeable. A further constraint on all three rate constants, *if linear free energy relationships are assumed*, is that each value should be compatible with *both* Hammett relationships, *i.e.*, for the azide and for the phosphine. All of these constraints or determining factors were used in selecting the k_1, k_2, and k_3 values for H given in Table IV.

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(18) J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," John Wiley and Sons, Inc., New York, N. Y., 1963.

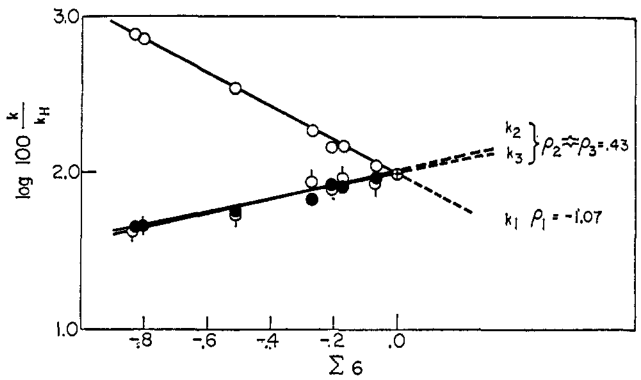

Figure 7. Effect of X in $P(C_6H_4X)_3$ on Mechanism I constants.

Figures 7 and 8 are Hammett plots of the k_1, k_2, and k_3 values for hydrogen and for the strongly complex-favoring substituents. Points for substituents near hydrogen, and hence not strongly complex favoring, are also included although rate constants for the compounds are not uniquely determined by the kinetics. The values used in such cases were chosen for compatibility with the three assumed linear Hammett relationships as well as for compatibility with the observed kinetics.

It should be noted that the ρ values for k_2 and k_3 (phosphine substituents) are small and nearly identical. This means that the ratio k_2/k_3 is nearly constant, and hence the substituent effect on $k_{\text{second order}}$ is very nearly a substituent effect on k_1 alone. This explains why the correlation coefficient for the $k_{\text{second order}}$ Hammett plot is so much better for phosphine substituents than for azide substituents.

Extrapolation of our arbitrarily linear $\rho\sigma$ relationship into the region beyond $\sigma = 0$ permits an estimation of the k_1, k_2, and k_3 for substituents whose precise adherence to second-order kinetics gives only lower limits for k_1 and k_2.[19] The estimated sets of k_1, k_2, and k_3 are then recombined according to eq 5, or by means of REMECH if necessary, to give an estimate of $k_{\text{second order}}$ which can be compared with experiment.

For phenyl azides with electron-releasing substituents the predicted $k_{\text{second order}}$ constants for reaction with triphenylphosphine are lower than the observed values by increasing amounts as the substituent becomes more electron releasing. The discrepancies range from less than 2% for *m*-methyl through 37, 55, and 92% for *p*-methyl, *p*-methoxy, and *p*-dimethylamino. This indicates that one or more of the $\rho\sigma$ relationships changes slope in the region of negative σ values. Since the predicted k_1 for the *p*-dimethylamino substituent is already lower than the observed $k_{\text{second order}}$ by about a factor of 2, at least some of the necessary curvature or dispersion can be assigned specifically to the relationship for k_1. The use of σ° rather than σ values[18] reduces the errors for *p*-methyl, *p*-methoxy, and *p*-dimethylamino to 31, 30, and 57%. The use of σ° has also been observed to improve the correlations for the reactions of substituted phenyl azides with norbornene[20] or with alkaline potassium arsenite.[21]

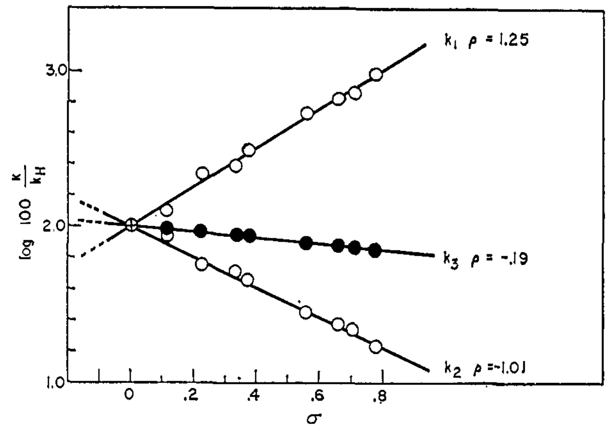

Figure 8. Effect of X in $XC_6H_4N_3$ on Mechanism I constants.

For substituted phosphines reacting with phenyl azide, the predictions from the extrapolated $\rho\sigma$ plots are 14% too low for the *p*-chloro substituent and 30% too low for tris(*p*-chloro).

The $k_{\text{second order}}$ for the reaction of *p*-nitrophenyl azide with *p*-chlorophenyldiphenylphosphine is 0.233. Assuming additivity of substituent effects in the two reagents, the REMECH-predicted value is only about 7% higher than the observed value.

Temperature Effects. We have studied the temperature dependence of the over-all rate of reaction of phenyl azide with triphenylphosphine in benzene at 14.9, 19.5, 25.0, and 32.0°. Despite the complexity of the apparent $k_{\text{second order}}$, its Arrhenius plot shows no significant deviation from linearity.[22] The spectroscopic experiments with the phenyl azide–triphenylphosphine system indicated that the phosphazide complex is favored at lower temperatures to an extent that should be detectable in the kinetics. Although deviations from second order were negligible at the upper three temperatures, the runs at 14.9° are curved for the first 5–13% of reaction. The run with the greatest excess of one of the reagents also has the greatest curvature and a significantly lower second-order constant.[23]

Solvent Effects. Table V shows the apparent second-order rate constants for the reaction of phenyl azide with triphenylphosphine in a series of solvents. The mean $k_{\text{second order}}$ values increase with two measures of solvent polarity,[24] but an increase in initial curvature and in disperison of the rate constant (for runs of sufficiently different initial concentrations) is also noted. Apparently the acceleration is due at least in part to an increase in the ratio k_1/k_2, indicating that the complex is more polar than the reagents, as already suggested from the substituent effects. The apparently normal products and normal positions of both diisopropyl ether and dimethyl sulfoxide[25] in the rate series are taken to mean that neither free-radical nor nitrene[25] intermediates are involved in the reaction.

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(19) The value of k_1 must be at least equal to $k_{\text{second order}}$ and the value for k_2 must be high enough to prevent breakdown of the steady-state approximation, about 25% of k_1 in the case of H.

(20) P. Scheiner, J. H. Schomaker, S. Deming, W. J. Libby, and G. P. Nowack, *J. Am. Chem. Soc.*, **87**, 306 (1965).

(21) I. Ugi, H. Perlinger, and L. Behringer, *Chem. Ber.*, **91**, 2330 (1958).

(22) $\Delta H^{\ddagger} = 9.6 \pm 0.9$ kcal/mole, $\Delta S^{\ddagger} = -33 \pm 3$ cal/mole/deg.

(23) $k_{\text{second order}} = 0.0156$ for $[P]_0 = 0.0774$, $[AZ]_0 = 0.4318$ in contrast to 0.0196 for $[P]_0 = 0.1932$ and $[AZ]_0 = 0.0861$.

(24) For example, the *S* constant [S. Brownstein, *Can. J. Chem.*, **38**, 1590 (1960)] and X_r [L. G. S. Brooker, A. C. Craig, D. W. Heseltine, P. W. Jenkins, and L. L. Lincoln, *J. Am. Chem. Soc.*, **87**, 2443 (1965)], both of which are defined by the effect of the solvent on the energy of a charge-transfer absorption band.

(25) L. Horner and A. Christmann, *Chem. Ber.*, **96**, 388 (1963).

Table V. Solvent Effects on the Reaction of Phenyl Azide with Triphenylphosphine at 25°

Solvent	Initial concn, M Phosphine	Initial concn, M Azide	$k_{\text{second order}}$ M^{-1} sec^{-1}
Benzene	See Table II		0.0343[a]
Isopropyl ether	0.0443	0.0890	0.0272
	0.0293	0.180	0.0242
Ethyl acetate	0.0301	0.164	0.0279
	0.0767	0.0206	0.0321
	0.0977	0.0237	0.0300
3-Pentanone[b]	0.0126	0.0877	0.0388[b]
	0.0496	0.0134	0.0413[b]
t-Butyl alcohol[b,c]	0.0248	0.114	0.0608[b]
	0.0666	0.0179	0.0742[b]
	0.0129	0.109	0.0515[b]
t-Butyl alcohol–10% H_2O (by volume)[b]	0.0237	0.0998	0.0557[b]
Acetonitrile[b,c]	0.0441	0.00887	0.0663[b]
	0.0144	0.0941	0.0604[b]
Dimethyl sulfoxide	0.0509	0.0206	0.116[d]
	0.0290	0.0476	0.110[b]
	0.0571	0.0352	0.112[b]

[a] Mean value. [b] Noticeable initial curvature. [c] Note trend toward lower rate constant with larger $|[P]_0 - [AZ]_0|$. [d] Very marked initial curvature.

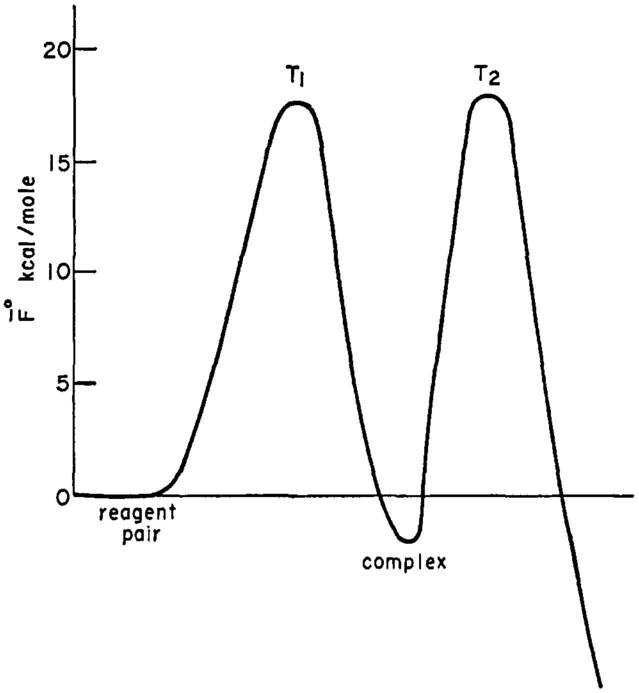
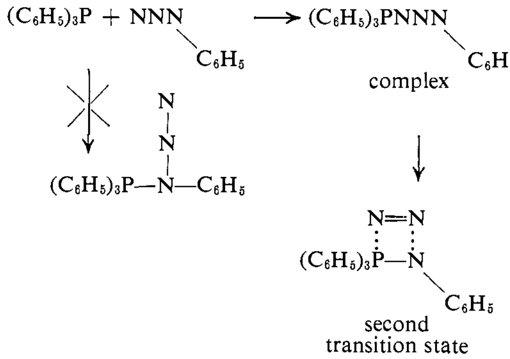


Figure 9.

Discussion of the Transition States and Intermediate. The free energies of the reagents, the complex, and the two transition states can be compared more significantly if the reagents are first converted to pairs of unlike molecules in close proximity.[26] The four species with which we are concerned are then isomeric and all three reactions can be regarded as unimolecular. Figures 9 and 10 show the reactions schematically by means of a free energy profile and a contour diagram of a hypothetical potential energy surface. The relative free energies in Figure 9 are for the unsubstituted phenyl azide and triphenylphosphine system in benzene at 25°. A significant feature of these diagrams is that the two transition states are of almost exactly the same energy. *Yet a reacting system is never able to get from the first transition state to the second without being trapped as complex.* In terms of the potential energy contour diagram, Figure 10, this is equivalent to saying that the traverse along a contour line cannot compete with deactivation.

There are in principle two possible explanations for this result. Either the surface is contoured in such a way that the reacting system arrives at the first transition state with its momentum uniquely in the direction of the complex rather than along a contour line, or the traverse along a contour line involves such a considerable spatial or conformational rearrangement of the parts of the molecule that it is slow compared to the loss of energy by collision. From either point of view the complete trapping observed supports a structure for the first transition state and the complex in which the phosphorus approaches from a preferred direction and is bonded to the *external* nitrogen atom of the azide, while in the second transition state, it is at least partly bonded to the nitrogen next to carbon and the conformation is quite different.

We note in passing that the existence of a specific reaction path favored over others having the same net change in energy is probably quite common, though experimental evidence for it is rare. For example, if the complex and its picrate had been metastable intermediates of high energy and negligible equilibrium population, the path of activation to the transition state leading to nitrogen might still have passed *uniquely* through the complex, but it would have been impossible to demonstrate this by any technique known at the present time.



Something about the distribution of charge on the internal nitrogen and on the phosphorus atoms can be deduced from the ρ values of the six Hammett relationships of Figures 7 and 8. Judging from the effects of substituents in the phosphine, the P becomes considerably more positive in attaining the first transition state, becomes slightly more positive still on descending to complex, *but then loses some positive charge so that the second transition state is about like the first by this criterion as well as by the criterion of total energy.* Judging from the effects of substituents in the azide, the nitrogen directly attached to phenyl becomes more negative in the first transition state, still more negative in the complex, *but then also suffers a slight neutralization of its negative charge on being reactivated to the second transition state.* The partial neutralization of positive charge

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[26] This can be done by simply removing the *cratic*, or mixing, part of the entropy from the quantities $\Delta F_1^{\ddagger}$ and ΔF_1°. For reactions in benzene at 25°, this is estimated to be −4.8 e.u. See R. W. Gurney, "Ionic Processes in Solution," McGraw-Hill Book Co., Inc., New York, N. Y., 1953.

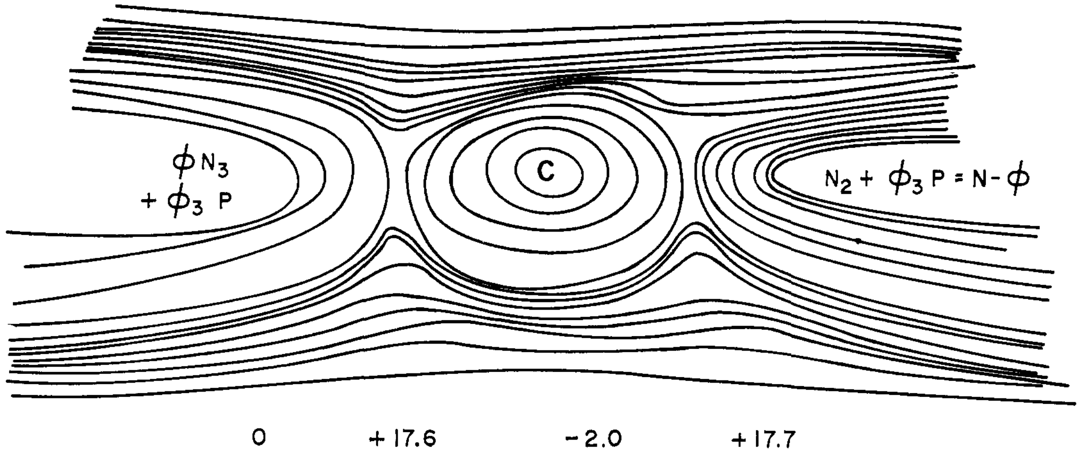
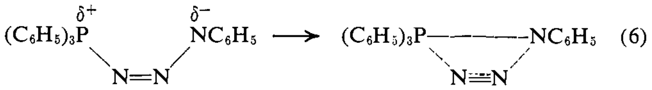


Figure 10.

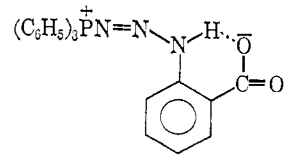
on P and of negative charge on N in the second transition state is to be expected if this is the step in which a bond forms between these two atoms.



$$\overset{\delta+}{(C_6H_5)_3P}\quad\overset{\delta-}{NC_6H_5}\;(N{=}N) \longrightarrow (C_6H_5)_3P{-}{-}{-}NC_6H_5\;(N{\equiv}N) \quad (6)$$

Four-membered cyclic transition states like that in eq 6 are by no means unusual.[27] They are also highly probable in the reaction of phosphinemethylenes[28] (or of phosphine imides) with carbonyl compounds.

Reaction of Azido Acids with Triphenylphosphine. The stabilization by acids of the phosphazide from phenyl azide and triphenylphosphine prompted us to examine the behavior of several azido acids with different spatial relationships between the azide and carbonyl groups. For example, the behavior of *p*-azidobenzoic acid is entirely normal whereas *o*-azidobenzoic acid forms a phosphazide that is unusually stable both as a solid and in solution.[5] The solid decomposes to the expected phosphine imide at 140–150° without melting. We also note that solutions of the phosphazide from *o*-azidobenzoic acid in organic solvents will evolve nitrogen at room temperature if bases are added, showing that the stabilization is in fact due to the acidic functional group. The normal behavior of *p*-azidobenzoic acid indicates an intramolecular structure for the stabilized phosphazide from *o*-azidobenzoic acid. It also supports attack of the phosphine on the γ- rather than the α-nitrogen of the azide in the formation of phosphazides.



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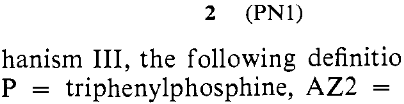
Neither azidoacetic acid nor β-azidopropionic acid gives a stable phosphazide with triphenylphosphine, and they also behave differently from each other.

The kinetics of the reaction of β-azidopropionic acid with triphenylphosphine depend on the ratio of the two reagents. With the azido acid in excess the reaction becomes second order soon after the start of a run, and the second-order rate constant (0.0031 M^{-1} sec^{-1}) is the same within experimental error as that of the ethyl ester. With the phosphine in excess the kinetics are initially about the same, but after about 40–50% reaction the apparent second-order rate constant decreases rather quickly by about an order of magnitude (Table VI). We find that these kinetics can be duplicated fairly accurately (Figure 11) by suitable assignment of constants to mechanisms such as III in which a major portion of the azido acid is in the form of a typical carboxylic acid dimer, the second azide group reacting much more slowly than the first. The slow reaction of the second azide group may be a substituent effect of the carboxylate ion substituent in some such structure as **2**.[29]

Table VI. The Reaction of Triphenylphosphine with β-Azidopropionic Acid or Its Ethyl Ester in Benzene at 25°

Initial concn, M			Second-order constant $\times 10^3$, M^{-1} sec^{-1}	
Phosphine	Azido acid	Azido ester	Initial	Final
0.398	0.0959	0	2.9	0.37
0.590	0.107	0	2.9	0.44
0.0871	0.474	0	3.03	...
0.212	0.425	0	3.02	...
0.400	0.207	0	2.8	*a*
0.154	0.611	0	3.32	...
0.242	0	0.0409	3.05	...
0.361	0	0.0745	3.20	...
0.550	0	0.0738	3.05[b]	...
0.512	0	0.0654	3.17[c]	...

[a] Could not be determined accurately. [b] 0.0772 M α-chloropropionic acid added. Run had induction period and fast reaction before becoming second-order. [c] 0.0669 M benzoic acid added.



$$(C_6H_5)_3\overset{+}{P}\overset{H}{N}CH_2CH_2COOH\cdot\overset{-}{O}\overset{O}{\overset{\|}{C}}H_2CH_2N_3$$

2 (PN1)

In Mechanism III, the following definitions are employed. P = triphenylphosphine, AZ2 = azido acid dimer, C′ = corresponding phosphazide complex, PN1 = corresponding phosphine imide, PNC = complex with remaining azide group, PN2 = corresponding

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(27) See, for example, H. G. Khorana, *Chem. Rev.*, **53**, 145 (1953); R. Huisgen and H. Reimlinger, *Ann. Chem.*, **599**, 161 (1956).

(28) S. Trippett, *Quart. Rev.* (London), 17, 406 (1963).

(29) As an example of a carboxylate ion substituent effect, we note that the rate constant for the reaction of piperidinium azidoacetate with triphenylphosphine is less than 3% that of ethyl azidoacetate.

Mechanism III

steps 1–3 as in I

$$P + AZ2 \underset{5}{\overset{4}{\rightleftharpoons}} C'$$

$$C' \xrightarrow{6} N_2 + PN1$$

$$P + PN1 \underset{8}{\overset{7}{\rightleftharpoons}} PNC$$

$$PNC \xrightarrow{9} N_2 + PN2$$

$$PN1 + C' \overset{10}{\rightleftharpoons} AZ2 + PNC$$

$$2AZ \overset{11}{\rightleftharpoons} AZ2$$

$$AZ + C \overset{12}{\rightleftharpoons} C'$$

$$PN + AZ \overset{13}{\rightleftharpoons} PN1$$

phosphine imide acid dimer, AZ = azido acid, PN = phosphine imide derived from monomeric azido acid.

We have used ethyl β-azidopropionate as a model to test some of our assumptions concerning the behavior of the acid and to provide estimates for some of the rate constants used in Mechanism III. Benzoic acid (pK_a = 4.2) has no effect on the rate of reaction of the ester, thus permitting us to ignore any effect of a molecule of β-azidopropionic acid (estimated pK_a = 4.4) on the reactivity of a second molecule of β-azidopropionic acid. That is to say, there is no such trapping of phosphazide complex by external carboxyl groups as was found for the reaction of phenyl azide with triphenylphosphine in the presence of strong acids. The second-order rate constant for the reaction of the ester in the absence of added acid provides a rough estimate for the quantity $k_1[k_3/(k_2 + k_3)]$, while the effect of added *strong* acid (α-chloropropionic, pK_a = 2.8) permits a separate estimate of k_1. Both estimates depend on the reasonable assumption that the substituent effects of $HOOCCH_2$-CH_2– and $EtOOCCH_2CH_2$– are approximately the same. Figure 11 shows the fit obtained by using this information to select constants for Mechanism III. It should be noted that the values of several of the constants used are still disposable within wide limits. We stopped varying the latter as soon as it became obvious that Mechanism III is one of the possible mechanisms since at least *one* set of constants will permit this mechanism to fit the data within experimental error. Another, but less plausible, mechanism which can be made to fit the data equally well differs from III in assuming complete dimerization of the azido acid, eliminating steps 1–3, and substituting the following equilibrium for the equilibria 11–13.

$$AZ2 + PN2 \rightleftharpoons 2PN1$$

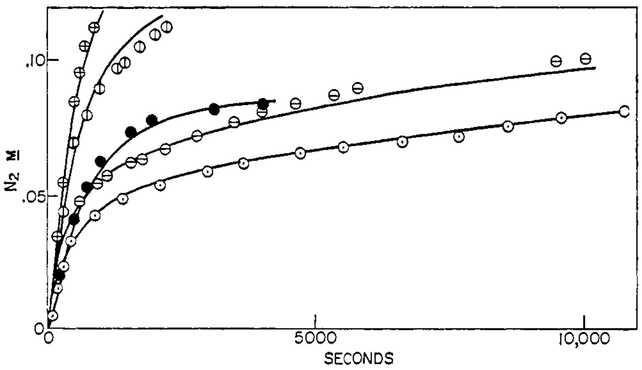

Figure 11. Triphenylphosphine and β-azidopropionic acid in benzene at 25°: ⊕, $[P]_0$ = 0.212, $[AZ]_0$ = 0.425; ⦶, $[P]_0$ = 0.400, $[AZ]_0$ = 0.207; ●, $[P]_0$ = 0.0871, $[AZ]_0$ = 0.474; ⊖, $[P]_0$ = 0.590, $[AZ]_0$ = 0.107; ○, $[P]_0$ = 0.398, $[AZ]_0$ = 0.0959. Points are experimental, lines are REMECH calculated with k_1 = 0.0075, k_2 = 0.0288, k_3 = 0.02, k_4 = 0.015, k_5 = 0.0288, k_6 = 0.02, k_7 = 0.004, k_8 = 0.02, k_9 = 0.002, K_{10} = 1.0, K_{11} = 1.0, K_{12} = 1.0, K_{13} = 10^6 (Mechanism III).

The behavior of azidoacetic acid is quite different from that of β-azidopropionic acid. Azidoacetic acid is a stronger acid (pK_a = 3.03) and the ester cannot be expected to be as good a model for the acid.

It is possible that the kinetics can still be fitted as least roughly by Mechanism III, but the relative rate constants for the monomer, dimer, and half-reacted dimer acid apparently would have to be very different from these that are successful in the case of β-azidopropionic acid. In any case, the reaction of azidoacetic acid with triphenylphosphine in benzene is further complicated by the appearance of a precipitate during the reaction. Our kinetic data for these reactions are summarized in Table VII.

Table VII. Reaction of Triphenylphosphine with Azidoacetic Acid[a] in Benzene at 25°

Initial concn, M Triphenylphosphine	Azidoacetic acid[a]	Initial zero-order constant $\times 10^4$, M sec^{-1}	Final second-order constant $\times 10^3$, M^{-1} sec^{-1}
0.212	0.0569	0.9	0.63
0.243	0.191	1.6	*b*
0.193	0.709	1.79	...
0.225	0.643	2.01	...
0.166	0.518	1.43	...
0.303	0.0967	1.7	0.85
0.130	0.0827	0.9	0.74
0.650	0.103	2.2	0.72
0.0327	0.0173[c]	...	10.0
0.191	0.0310[c]	...	9.7
0.349	0.0518[d]	3.3	11.4
0.706	0.0990[e]	...	0.26

[a] Unless otherwise noted. [b] Could not be determined accurately. [c] Ethyl ester. [d] Ester plus 0.0537 M chloroacetic acid. [e] Piperidinium salt.

The order in the presence of excess azido acid is close to zero rather than second order, and with excess phosphine the rate passes through a maximum at about 20–30% reaction. The final rate, expressed as a second-order constant, is about 0.0006–0.0008 M^{-1} sec^{-1}. For comparison, the second-order rate constant of the ethyl ester is greater by an order of magnitude, while that of the piperidinium salt is only about 0.00026. The low final rate constant suggests an azidoacetate salt-like structure for the main azide species late in runs with low azide : phosphine ratios.

Experimental Section

Azides. Most of the aryl azides were prepared by the reaction of the corresponding diazonium salt with hydrazoic acid.[30,31] A few were also made from the corresponding arylhydrazine and hydra-

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(30) E. Noelting and O. Michel, *Ber.*, **26**, 86 (1893).

Table VIII

X in $XC_6H_4N_3$[a]	Properties, mp or bp (mm), °C		Calcd,[d,m] %				Found,[d,m] %			
	Azide	Triphenylphosphine imide	C	H	N	P	C	H	N	P
p-NO_2	69.5–71[c]	Yellow, 135.5–136[e,f]	72.36	4.81	7.03	7.77	71.16	4.91	6.76	7.18
m-NO_2[g]	52–53[c]	Yellow, 138–138.5[h]								
p-CN	65–65.5[i]	Colorless, 194–195.5[h]								
m-CN	55–56.5[j]	Colorless, 150–152			7.40	8.19			7.59	8.37
m-Cl	36–37 (1)	Colorless, 119–119.5[h]								
m-F	53 (9)	Colorless, 141–142			3.77	8.34			4.09	8.40
p-Cl	32 (1), 19.5–20.5[k]	Colorless, 116–117[h]								
p-F	56 (9)	Colorless, 140.5–142			3.77	8.34			3.92	8.40
m-MeO	56–57 (1)[l]	Colorless, 125–125.5	78.31	5.78	3.65	8.08	76.73	5.91	4.06	8.86
H	44–45 (4)	Colorless, 128–130[h]								
m-CH_3	46–47 (5)	Colorless, 111.5–112.5[h]								
m-*t*-Bu	73–74 (1)	Colorless, 127.5–129			3.42				3.41	
p-CH_3	38–40 (1.5)	Yellow, 135–136[h]								
p-*t*-Bu	78–82 (2)	Lt yellow, 171–173			3.42	7.56			3.49	7.76
p-MeO	33–34[c,l]	Lt yellow, 115–117[h]								
p-$(CH_3)_2N$	Yellow, 42.5–43.5[l]									
o-CH_3	48–49 (2)	Colorless. 133.5–134.5[h]								
o-COOH	146–147 dec[n]	Tan, 215–216[o,p]								
o-NO_2	52–54[b]	150.5–152[h]								

[a] Prepared from the diazonium salt. [b] P. A. S. Smith and J. H. Boyer, "Organic Syntheses," Coll. Vol. IV, John Wiley and Sons, Inc., New York, N. Y., 1963, p 75. [c] E. Lieber, T. S. Chao, and C. N. R. Rao, *J. Org. Chem.*, **22,** 654 (1957). [d] Of the triphenylphosphine phenylimide. [e] Identified by acid hydrolysis to triphenylphosphine oxide and the corresponding aniline. [f] The melting point of this imide has previously been reported as 156–158° without analytical data. See ref 15. [g] Prepared by the method of H. H. Hodgson and W. H. H. Norris, *J. Chem. Soc.*, 762 (1949). [h] See ref 15. [i] H. Rupe and K. von Majewski (*Ber.*, **33,** 3401 (1900)) report mp 70°. [j] P. Griess, *ibid.*, **2,** 369 (1869). [k] See reference in footnote *g*. [l] See reference 21. [m] Low carbon analysis is common with compounds containing P–N bonds. See R. Belcher, J. E. Fildes, and A. J. Nutten, *Anal. Chim. Acta*, **13,** 431 (1955); I. Lysyj and J. E. Zarembo, *Microchem. J.*, **2,** 245 (1958). [n] K. A. N. Rao and P. R. Venkataraman, *J. Indian Chem. Soc.*, **15,** 194 (1938). [o] See ref 5. [p] Triphenylphosphazide, mp 147 dec, gives the imide on heating above the melting point.

zoic acid.[31,32] Table VIII lists the azides, their physical properties, and the properties of the triphenylphosphine imide.

Ethyl azidoacetate was prepared by a modification of Forster's method; the acid was obtained by hydrolysis.[33] *Anal.* Calcd for $C_2H_3N_3O_2$: neut equiv, 101.1. Found: neut equiv, 101.2, 102.1.

β-Azidopropionic acid[34] was prepared from β-propiolactone. One mole (72.0 g) of the lactone was added dropwise with stirring to a solution of 1 mole (65.0 g) of sodium azide in 200 ml of H_2O maintained at 15–25°. After stirring the mixture at room temperature for 4.5 hr, 100 ml of 37% HCl was added, the mixture extracted with ether, the extract dried over Na_2SO_4 and concentrated, and the residue distilled, yield 65.1 g, 57%, bp 74–75° (0.45 mm). *Anal.* Calcd for $C_3H_5N_3O_2$: neut equiv, 115.1. Found: neut equiv, 115.5, 116.3. The ethyl ester was made by adding $SOCl_2$ (59.5 g, 0.50 mole) dropwise to 37.6 g (0.327 mole) of the acid maintained at 20°. The excess $SOCl_2$ was distilled off after heating at 50° for 40 min, then 23 g (0.5 mole) of C_2H_5OH was added with cooling and the mixture let stand 1 hr at 25° and then distilled. The ester was obtained in 86.7% yield (40.55 g), bp 60–60.5° (7 mm).[34]

Triarylphosphines. The triarylphosphines were prepared by one of the three methods illustrated below.

Method A[35] (Example: Tris(*p*-methoxyphenyl)phosphine). The apparatus, consisting of a round-bottomed flask fitted with an efficient mechanical stirrer, a reflux condenser, dropping funnel, and gas inlet tube, was carefully dried and flushed with dry, oxygen-free nitrogen before beginning the reaction. A slow nitrogen flow through the system was continued during the course of the reaction.

The Grignard reagent was prepared from 266 g (1.42 moles) of *p*-bromoanisole and 34.4 g (1.42 g-atoms) of clean magnesium turnings in 750 ml of anhydrous ether. When all the magnesium had dissolved, a solution of 40.3 g (0.293 mole) of phosphorus trichloride in 200 ml of dry ether was added dropwise. A very exothermic reaction occurred, and efficient stirring and cooling were essential. After this addition was complete, the mixture was allowed to stand overnight at room temperature and continuously flushed with nitrogen. Next the dark, resinous reaction mixture was treated dropwise with a solution of 130 g (2.43 moles) of ammonium chloride in 400 ml of water. This hydrolysis was very exothermic and produced a light-colored solid precipitate. After stirring for several hours to complete the hydrolysis, the mixture was extracted with benzene. The extract was evaporated, and the residue was crystallized from ethanol. Four recrystallizations gave colorless needles, mp 133–134.5°, homogeneous by thin layer chromatography on alumina. The yield of pure product was 20 g (19% of theory), but large recrystallization losses were incurred.

Method B[36] (Example: Tris(*p*-chlorophenyl)phosphine). This method is similar to method A, but the phosphorus trichloride was replaced by trimethyl phosphite.[36]

The Grignard reagent was prepared from 200 g (1.05 moles) of *p*-chlorobromobenzene and 29 g (1.22 g-atoms) of magnesium in 400 ml of dry ether as in method A. Next a solution of 32.3 g (0.26 mole) of trimethyl phosphite in 300 ml of dry benzene was added dropwise with cooling and stirring. This mixture was heated at reflux for 11 hr, then allowed to cool overnight. Then the dark, resinous mixture was hydrolyzed with 400 ml of 20% aqueous ammonium chloride, as in method A. Filtration followed by separation and evaporation of the organic layer gave the desired product, which was crystallized from ethanol. Column chromatography (benzene on alumina) and four additional recrystallizations from ethanol gave pure product, mp 103–105°, in about 40% yield (large recrystallization losses).

Method C (Example: *p*-Chlorophenyldiphenylphosphine).[37] The Grignard reagent was prepared as in method A, using 105.3 g (0.550 mole) of *p*-chlorobromobenzene and 15.0 g (0.617 g-atom) of magnesium in 200 ml of dry ether and 100 ml of dry tetrahydrofuran. Then a solution of 78.0 g (0.354 mole) of diphenylphosphinous chloride (diphenylchlorophosphine, Aldrich Chemical Co.) in 250 ml of tetrahydrofuran was added dropwise with cooling and stirring. After 2 hr of heating at reflux, the mixture was hydrolyzed with aqueous ammonium chloride, as in method A. The solid precipitate was taken up in benzene. After it was washed with 10% aqueous sodium hydroxide, dried over calcium chloride, and filtered, this solution was evaporated at reduced

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(31) R. O. Lindsay and C. F. H. Allen, "Organic Syntheses," Coll. Vol. III, John Wiley and Sons, Inc., New York, N. Y., 1955, p 710.

(32) O. Dimroth, *Ber.*, **35,** 1029 (1902).

(33) M. O. Forster and H. E. Fierz, *J. Chem. Soc.*, **93,** 72 (1908); M. O. Forster and R. Müller, *ibid.*, **95,** 191 (1909).

(34) T. Curtius, *Ber.*, **45,** 1057 (1912).

(35) J. Dodonow and H. Medox, *ibid.*, **61,** 907 (1928).

(36) K. D. Berlin, I. H. Austin, and K. L. Stone, *J. Am. Chem. Soc.*, **86,** 1787 (1964).

(37) P. D. Bartlett and G. Meguerian, *ibid.*, **78,** 3710 (1956).

Table IX. Triarylphosphines

Compound	Method, yield (%)	Mp or bp (mm), °C
Tris(*p*-chlorophenyl)	B, 40	103–105[37][a] (oxide, 176–178[b,c]
p-Chlorophenyldiphenyl	C, 64	178–180 (0.25), 42–43[38]
Triphenyl	*d*	79.5–80
m-Tolyldiphenyl	C, 75	50–51, 162–166 (0.25) (oxide, 127–129)[e]
p-Tolyldiphenyl	C, 74	67–68.5[38]
Tris(*m*-tolyl)	*d*	101–102
p-Methoxyphenyldiphenyl	C, 81	67–68[f]
Tris(*p*-tolyl)	*d*	148.5–150
Tris(*p*-methoxyphenyl)	A, 20	133–134.5[g] (oxide[h] 142–145)
p-Dimethylaminophenyldiphenyl	*i*	153.5–155
Tris(*p*-dimethylaminophenyl)	*i*	

[a] F. G. Mann and E. J. Chaplin, *J. Chem. Soc.*, 527 (1937). [b] F. Challenger and J. F. Wilkinson, *ibid.*, **125,** 2675 (1924). [c] Prepared by oxidation with H_2O_2: O. Neunhoeffer and L. Lamza, *Chem. Ber.*, **94,** 2514 (1961). [d] Commercial product (Eastman Organic Chemicals) recrystallized from ethanol. [e] L. Horner, H. Hoffmann, H. G. Wippel, and G. Hassel (*Chem. Ber.*, **91,** 52 (1958)) report mp 123–124°. [f] Reported in two crystalline forms, mp 68–69° and 78–79°, by A. E. Senear, W. Valient, and J. Wirth, *J. Org. Chem.*, **25,** 2001 (1960). [g] Lit. mp 131°,[a] 130–131°,[f] 131–132°.[c] [h] Prepared by oxidation with diphenyl disulfide and air: A. Schönberg, *Ber.*, **68,** 163 (1935). [i] See text.

pressure. The residue was distilled, bp 178–180° (0.25 mm), giving 67.1 g (0.226 mole) of the desired product, 64.0% of theory. Three recrystallizations from ethanol gave long, colorless, odorless prisms, mp 42–43°.

***p*-Dimethylaminophenyldiphenylphosphine.** To a cooled, stirred mixture of 70.0 g (0.317 mole) of diphenylphosphinous chloride and 77.0 g (0.635 mole) of dimethylaniline, protected from oxygen and moisture by a current of nitrogen, 42.7 g (0.320 mole) of anhydrous aluminum chloride was added in small portions over a period of 20 min. After the initial exothermic reaction subsided, the mixture was cooled until it could just be stirred (about 80°), and a solution of 25.3 g (0.320 mole) of pyridine in 200 ml of benzene was added dropwise. The crystalline pyridine-$AlCl_3$ complex which formed was filtered off and washed with benzene. The filtrate and benzene washings were combined and washed with 400 ml of 10% aqueous sodium hydroxide, washed with water, filtered, and extracted with 500 ml of 37% hydrochloric acid in portions. The aqueous acid solution was made basic with sodium hydroxide and then extracted with chloroform. This final extract was dried (calcium oxide), filtered, and evaporated. The residue was crystallized by rubbing with ether to give 52.2 g (0.171 mole) of the phosphine, 54.0% of theoretical yield (none of the desired product could be obtained when the aluminum chloride was omitted), as colorless crystals from a large volume of ethanol, mp 153.5–155° (lit.[38] mp 153°).

Tris(*p*-dimethylaminophenyl)phosphine. A modification of the method of Koenigs and Friedrich[39] was used to prepare this compound. A mixture of 170 g (1.40 moles) of dimethylaniline, 50.0 g (0.364 mole) of phosphorus trichloride, and 100 ml (1.3 moles) of pyridine was heated at 130–135° under nitrogen for 5 hr. The resulting oil was extracted with 10% hydrochloric acid. The aqueous acid solution was filtered, then made basic with sodium hydroxide. The addition of 1 l. of ether caused a light orange solid, insoluble in both liquid phases, to separate. This solid was collected by filtration and recrystallized three times from 10:1 ethanol–chloroform to give the desired product in 20.9% yield (29.8 g, 0.0762 mole) as colorless needles from ethanol, mp 289–307° dec (depending on heating rate) (lit. mp 308°,[39] 275° [40]). The melting point is not a reliable criterion of purity. It was homogeneous by thin layer chromatography on alumina and on silica gel, but its kinetic behavior seems anomalous (see Table III) as though it might contain considerable amounts of the partly *ortho*-substituted isomers. The properties of the triarylphosphines are listed in Table IX.

Purification of Solvents. Solvents used in kinetic studies were carefully purified. References to purification methods and boiling points are given in Weissberger's monograph on solvents.[41]

Benzene. Commercial thiophene-free reagent-grade benzene was stirred or shaken with concentrated sulfuric acid for several hours, then decanted and washed repeatedly with saturated aqueous sodium bicarbonate solution and distilled water. After being dried over calcium chloride and filtered, the product was distilled twice from sodium through a 70-cm long, adiabatic fractionating column packed with glass helices. The center cut, with a boiling range of 0.5°, was collected in each case. The purified solvent was stored over sodium ribbon.

Benzene was the solvent used in most (95%) of the kinetic runs. Care was taken that each batch was purified in the same way. Different batches of solvent did not cause changes in measured rate constants.

Isopropyl Ether. Isopropyl ether, Matheson Coleman and Bell "alcohol-free" grade, was stirred for several hours with aqueous ferrous sulfate solution containing a little sulfuric acid. The separated ether layer did not oxidize aqueous potassium iodide and so was peroxide free.[41] After the ether was dried with calcium chloride and sodium ribbon, a trace of hydroquinone (inhibitor) was added, and the product was distilled through an efficient column. The fraction passing over at 69–70° was collected and stored in a brown bottle under nitrogen. All kinetic runs with this solvent were completed on the same day as its distillation.

Ethyl Acetate. Fisher Certified reagent grade ethyl acetate was used from a freshly opened bottle without further purification.

Diethyl Ketone. 3-Pentanone from Matheson Coleman and Bell contained a yellow impurity which could not be removed by distillation. Percolation through a column of Florisil (magnesium aluminum silicate chromatography material, Floridin Company) gave a water-white product, which was fractionally distilled. The fraction with bp 103.0–103.2° was used for kinetics.

***t*-Butyl Alcohol.** Baker Analyzed reagent grade *t*-butyl alcohol was refluxed over freshly cleaned magnesium turnings overnight, then fractionally distilled from the same flask. The fraction distilling at 84.0–84.5° was collected.

Acetonitrile. Eastman practical grade acetonitrile was dried over anhydrous calcium chloride, then filtered and distilled. The center cut, bp 82.6–82.8°, was used.

Dimethyl Sulfoxide. Baker Analyzed reagent grade dimethyl sulfoxide, mp 18.5°, was used without further purification.

Kinetic Measurements. Apparatus. The reaction rates of azides with trivalent phosphorus compounds were followed by monitoring the rate of nitrogen evolution. With this method, several potential sources of error are present in addition to the usual problems (such as weighing and pipetting accuracy, time measurement, and temperature measurement and control) encountered in all kinetic techniques.[42] Establishing and maintaining gas–liquid equilibrium is a major problem.[43,44] Leaks in the system can have a disastrous effect on the observations and are difficult to detect during the course of a run. Adequate temperature control in the gas measuring part of the system must be assured, since the enclosed gas is a fairly sensitive thermometer. These factors must be carefully considered in designing the apparatus.

Gas–liquid equilibrium was maintained by stirring the reaction mixture vigorously. A Teflon[45] stirring paddle was rotated at 500 to 800 rpm by a 0.10 hp (1.1 kcal/min), rheostat-controlled motor (Eberbach Corp., Ann Arbor, Mich.) with a 20:1 gear reduction drive, maximum torque 16 in. lb (0.18 kg m). The stirring shaft passed through a gas-tight ASCO Teflon[45] stirring gland (Arthur F. Smith Co., Pompano Beach, Fla.) sealed by inner and outer neoprene O rings lubricated with high-vacuum silicone grease. This

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(38) H. Goetz, F. Nerkel, and K.-H. Wiechel, *Ann.*, **665,** 1 (1963).

(39) E. Koenigs and H. Friedrich, *ibid.*, **509,** 138 (1934).

(40) H. Raudnitz, *Ber.*, **60,** 743 (1927).

(41) A. Weissberger, E. S. Proskauer, J. A. Riddick, and E. E. Toops, Jr., "Organic Solvents," 2nd ed, Interscience Publishers, Inc., New York, N. Y., 1955.

(42) R. Livingston in "Investigation of Rates and Mechanisms of Reactions," S. L. Friess, E. S. Lewis, and A. Weissberger, Ed., 2nd ed, Interscience Publishers, Inc., New York, N. Y., 1961, Chapter 3.

(43) K. J. Pedersen, *J. Am. Chem. Soc.*, **49,** 2681 (1927).

(44) D. F. DeTar, *ibid.*, **78,** 3911 (1956).

(45) Tetrafluoroethylene polymer, a trademark of E. I. duPont de Nemours and Co., Inc.

very vigorous stirring provided adequate, rapid equilibration in most cases.

The system proved to be satisfactorily gas tight in operation. Periodic tests with 100–200-mm positive or negative pressure applied in the gas-measuring buret revealed no pressure loss during the time required for a typical kinetic run. This test is severe, since the pressure differential during a run was never more than a few millimeters. The infinity point was checked for drift in every case in which an infinity volume was measured. In a few instances, drift indicating a leak was observed, and those runs were discarded. Replacing the inner O-ring seal always corrected the trouble.

The temperature of the gas collected was controlled by pumping thermostated water from the constant-temperature bath through a jacket enclosing the gas-measuring buret. The connecting lines, which were not thermostated, were mostly made of capillary tubing and had a total volume of less than 5 ml. Laboratory temperature varied no more than a few degrees during a run.

Technique. Reagents were always purified soon before use. Phenyl azide, for example, seemed to be stable for at least 2 months when stored at 10° in the dark, but it was always freshly redistilled within 1 month of use.

The reagents were weighed into small volumetric flasks, solutions were made up to volume, and aliquots were measured and transferred to the reaction flask by syringe. All but one of the reagents were placed in the reaction flask, and the mixture was stirred for 5 or 10 min to establish thermal and gas–liquid equilibria. After the mercury levels in the gas buret had been adjusted to zero, the stirrer was stopped momentarily, and the reaction was initiated by injecting the final reaction component (either azide or trivalent phosphorus compound) into the flask through an ampoule stopper. A three-way stopcock between the reaction flask and gas buret was quickly closed to the atmosphere, the timer was started, and the stirrer was restarted. This start-up operation required about 5 sec. Volume readings were begun at once and could be made very conveniently and accurately to the nearest 0.1 ml with a 50-ml gas buret. Values were measured dynamically, by moving the leveling bulb until the mercury levels in the parallel open and closed buret tubes coincided. Paralax and capillarity effects were completely eliminated by this technique.

Infinity volumes were determined by two methods. In most runs, the gas volume was observed until it became constant, at least until 12 reaction half-lives. Observed infinity volumes agreed with calculated values; lack of agreement was taken as evidence for leakage or weighing errors, and the run was discarded. With very slowly reacting compounds runs were planned to give very large infinity volumes, and the calculated values alone were used.

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Mechanistic Aspects of the Anomalous Hydride Reduction of Cyclobutene Epoxides[1]

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Abstract: The lithium aluminum hydride reduction of *exo*-bicyclo[3.2.0]hept-6-ene oxide and *exo*-2-oxabicyclo-[3.2.0]hept-6-ene oxide has been shown to afford ring-cleaved primary alcohols in addition to the derived cyclobutanols. The structures of the products have been assigned on the basis of comparison with authentic samples and further chemical transformations. Evidence was obtained by means of deuterium labeling, solvent basicity, and related experiments to suggest that the formation of the abnormal ring-opened products probably results from initial C–O bond cleavage followed by Lewis acid catalyzed opening of the strained cyclobutanoxide system.

In general, the lithium aluminum hydride (LAH) reduction of epoxides proceeds by nucleophilic attack of hydride ion from the less hindered back-side position to give rise to the more highly substituted alkoxide ion *via* carbon–oxygen bond cleavage.[3] A striking exception to this customary mode of reaction has been noted, however, in the case of certain cyclobutene epoxides.[4,5] For example, exposure of cyclobutene epoxide to the LAH reagent affords cyclobutanol and 1-butanol in approximately equal amounts.[5] Thus, a substantial degree of carbon–carbon bond cleavage, presumably caused by excessive compression of bond angles in the starting material, is found in such highly strained systems.

To ascertain whether *exo*-bicyclo[3.2.0]hept-6-ene oxide derivatives would be appropriate mechanistic probes, initial experiments were performed in which epoxide **1** was treated with LAH. When an ethereal solution of **1** and suspended hydride was heated at reflux for 4 hr, less than 5% reduction occurred as judged by vpc analysis. This surprising result was at variance with earlier reports, in particular that dealing with the rapid reduction of the closely related bicyclo[4.2.0]-oct-7-ene oxide under the same conditions,[4] and may be a reflection of greater steric hindrance to back-side attack in **1**. Accordingly, **1** was reduced in refluxing tetrahydrofuran; vpc analysis of aliquots removed at various time intervals indicated the reduction to be approximately 90–95% complete after 48 hr. The two-component product mixture was readily separated by preparative gas chromatography. The major component (64%) was assigned structure **2** on the basis of the identity of its infrared spectrum with that of an authentic sample of *exo*-bicyclo[3.2.0]heptan-2-ol.[6]

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[1] Paper XXX of the series entitled "Unsaturated Heterocyclic Systems." For previous paper in this series, see L. A. Paquette and W. C. Farley, *J. Org. Chem.*, **32**, 2725 (1967).

[2] (a) Alfred P. Sloan Foundation Fellow, 1965–1967. (b) Visiting Research Associate on leave of absence from Alexandria University, Egypt, UAR.

[3] L. A. Paquette, "Principles of Heterocyclic Chemistry," W. A. Benjamin, Inc., New York, N. Y., 1967, Chapter 1.

[4] A. C. Cope and R. W. Gleason, *J. Am. Chem. Soc.*, **84**, 1928 (1962).

[5] W. R. Moore and C. H. Beede, Abstracts, 144th National Meeting of the American Chemical Society, Los Angeles, Calif., 1963, p 11M.