Sequence of Reactant Combination Alters the Course of the Staudinger Reaction of Azides with Acyl Derivatives. Bimanes. 30.

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The Staudinger reaction of azides has now been followed by NMR and other spectroscopic techniques. *syn*-(Azidomethyl,methyl)(methyl,methyl)bimane (**1**) and Ph_3P form a triazaphosphadiene intermediate **2** and then the bimane *P*-triphenyliminophosphorane **3**. The iminophosphorane reacts with an acyl chloride to yield an iminophosphonium salt **4** which then forms the oxazaphosphetane **13**. The latter undergoes an electrocyclic reversion to form the phosphine oxide and the chloroimines **7*E*** and **7*Z***, the last being hydrolyzed to the (acylamido)bimane **6**. This set of reactions constitutes the "iminophosphorane pathway". A significant diversion of the reaction path to an (*N*-alkylamino)-phosphonium chloride **8** occurs through reaction of **4** with H_2O present in the $CDCl_3$ and through reaction of **3** with HCl. A different azide (α-azido-*o*-xylene **1b**) produces the (acylamido)-*o*-xylene as the sole product. A less sterically hindered phosphine (tri-2-furylphosphine) reacts more slowly to form the iminophosphorane **3a** from the azidobimane **1**. Reaction of the bimane *P*-tri-2-furyliminophosphorane with acyl chloride gives only the (acylamido)bimane **6**. If the acyl chloride is mixed with **1**, followed by addition of the Ph_3P, the triazaphosphadiene adduct **5** is formed via the triazaphosphadiene. The adduct **5** is converted rapidly into a six-membered cyclic compound **11**. The latter either loses nitrogen to yield **6** via **7*Z*** and **7*E*** and the phosphine oxide or loses chloride **10** through a novel chloride-induced elimination reaction from its protonated form. The change in procedure thus results in a dramatic change in the reaction pathway, a reaction set that constitutes the "triazaphosphadiene adduct pathway". In the case of α-azido-*o*-xylene, α-chloro-*o*-xylene (**10b**) is the only product. The reactions of the azides **1** or **1b** with tri-2-furylphosphine also produce chlorides as the major products accompanied by some acetamido derivatives. The nucleophile-induced reaction explains a "surprising result" (formation of ester rather than amide) reported by Sahlberg et al. (Sahlberg, C.; Jackson, A. M.; Claesson, A. *Acta Chem. Scand.* **1988**, *B42*, 556−562). The intramolecular "aza-Wittig" reaction may depend on the nucleophilicity of the triazaphosphadiene. A comprehensive mechanistic scheme for the Staudinger reaction of azides is conveniently divided into the following: (A) formation of the triazaphosphadiene (Scheme 1), (B) reactions of the triazaphosphadiene (Scheme 2), and (C) reactions via the iminophosphorane (Scheme 3). Some approximate kinetic parameters are reported for some of the reactions.

Introduction

The Staudinger reaction between trialkyl- or triarylphosphines and alkyl azides[1−3] is useful in synthesis.[4−8] The iminophosphorane product of the reaction (eq 1) is a phosphorus−nitrogen ylide, which reacts with appropriate acyl derivatives (eq 2) to yield an amide after hydrolysis.[9,10] The iminophosphorane is formed via a triazaphosphadiene intermediate, frequently isolated[1,11−21] and characterized by infrared spectroscopy[17,18] and X-ray crystallography.[22,23] We have confirmed that description by means of ^{1}H NMR, ^{31}P NMR, FT-IR, and UV−vis spectrometry. Approximate kinetics for the successive stages of the reaction are more easily and more precisely measured by these methods than through the rate of nitrogen evolution.[4,11,24] Azidobimanes (easily prepared

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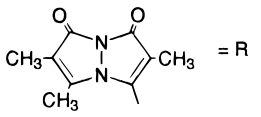
from bromobimanes[25,26]) were selected as reactants with the objective of creating fluorescent amides. The NMR results are the most important in elucidating the course of the reactions and are emphasized in our report.



$$(C_6H_5)_3P + \underset{\mathbf{1}}{RCH_2N_3} \rightarrow \underset{\mathbf{2}}{RCH_2N{=}NN{=}P(C_6H_5)_3} \xrightarrow{-N_2} \underset{\mathbf{3}}{RCH_2N{=}P(C_6H_5)_3} \quad (1)$$

$$\underset{\mathbf{3}}{RCH_2N{=}P(C_6H_5)_3} \xrightarrow{R'COX} \underset{\mathbf{4}}{RCH_2N(XCO^-R')^+P(C_6H_5)_3} \quad (2)$$

$$\underset{\mathbf{2}}{RCH_2N{=}N{-}N{=}P(C_6H_5)_3} \xrightarrow{R'COX} \underset{\mathbf{5}}{RCH_2N(XCO^-R')N{=}N^+P(C_6H_5)_3} \quad (3)$$

Our interest in the reaction pathways of the azidobimane stems from the fact that an increase in the yield of acyl derivative is observed if the reaction is carried out with the acyl chloride present before addition of the Ph_3P.[27] We now report that the course of the reaction is altered by changing the sequence of combining the reactants. The triazaphosphadiene reacts directly with the acylating agent (eq 3) to form a new intermediate, termed the triazaphosphadiene adduct. No iminophosphorane is detected under these conditions. An understanding of why certain side products form leads to additional insights into the mechanisms of both pathways for the Staudinger reaction of azides.

Results

The Staudinger reaction of azides was carried out in two ways. In the "normal reaction", the *P*-triaryliminophosphorane was formed by reaction of the azide with a triarylphosphine, followed by the addition of the acylating agent. In the "triazaphosphadiene adduct" ("TPD adduct") reaction, the triarylphosphine was added to a mixture of the azide and the acylating agent. ^{1}H NMR and some ^{31}P NMR spectroscopy as well as the identification of products gave the most information about the nature of the reaction. A typical experiment of the "TPD adduct" type involved the addition of AcCl in $CDCl_3$ to a $CDCl_3$ solution of the azide in an NMR sample tube, addition of a phosphine, mixing, and placing the tube into the probe as quickly as possible. A typical experiment of the "normal" type involved two steps. First, the phosphine was added to a $CDCl_3$ solution of the azide in an NMR tube, and NMR spectra were taken. The evolution of intermediates and products can be clearly seen in a stack plot of the spectra (Figure 1). At the point when no further change in NMR signals was noted, the acylating agent was added, and another set of measurements was made. Successive ^{1}H NMR spectra showed that the various species in the respective reaction mixtures changed during the course of the reaction. The first spectrum was taken about 45 s after the reactants were mixed. Half-lives were estimated from the changes in the relative peak integrations. The kinetics of these reactions were followed either independently or sequentially by ^{1}H and ^{31}P NMR.

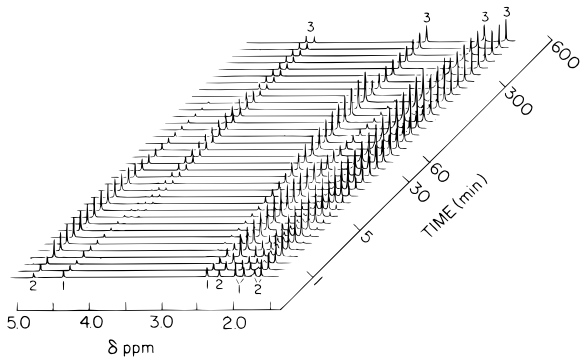
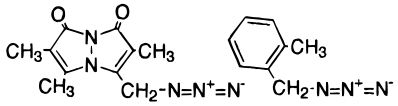
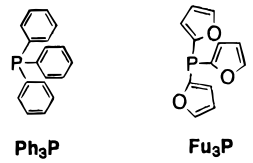


Figure 1. Stack plot of the bimane region in the ^{1}H NMR spectra of the reaction mixture of *syn*-(azidomethyl,methyl)-(methyl,methyl)bimane (**1**) (0.022 M) and Ph_3P (0.023 M) in $CDCl_3$. The time for each spectrum is shown at the right. The sequence for the conversion of **1** to triazaphosphadiene **2** to iminophosphorane **3** can be seen in the progressive changes in the peaks: α_1-CH_3, 1.96 (**1**), 1.60 (**2**), 1.49 (**3**); α_2-CH_3, 1.85, 1.69, 1.79; β-CH_3, 2.35, 2.17, 2.58; β-CH_2, 4.35 (**1**), 4.76 (**2**), 4.15 and 4.26 (**3**). The first spectrum shows both **1** and **2**. The final shows only **3** whereas the spectra taken between 3 and ca. 200 min show all three species.

Reactions carried out on a larger scale under the same conditions as those used for the NMR spectrometric measurements provided material for separation and identification by NMR spectra, mass spectra, and direct comparison with material prepared by alternative syntheses. The most detailed studies were done on the reaction of AcCl with *syn*-(azidomethyl,methyl)(methyl,-methyl)bimane (**1**) and triphenylphosphine (Ph_3P). A second azide, α-azido-*o*-xylene (**1b**), sterically similar to **1**, and a second phosphine, tri-2-furylphosphine (Fu_3P), sterically less hindered[28] and less nucleophilic than Ph_3P, were also investigated. UV and IR spectroscopic measurements yielded some evidence on the changes in the composition of the reaction mixtures.



1 **1b**



Ph_3P **Fu_3P**

"Normal" Staudinger Reaction. As noted above, the study of the "normal" Staudinger reaction of azides and phosphines was divided into stages, the first involving a study of iminophosphorane formation and the

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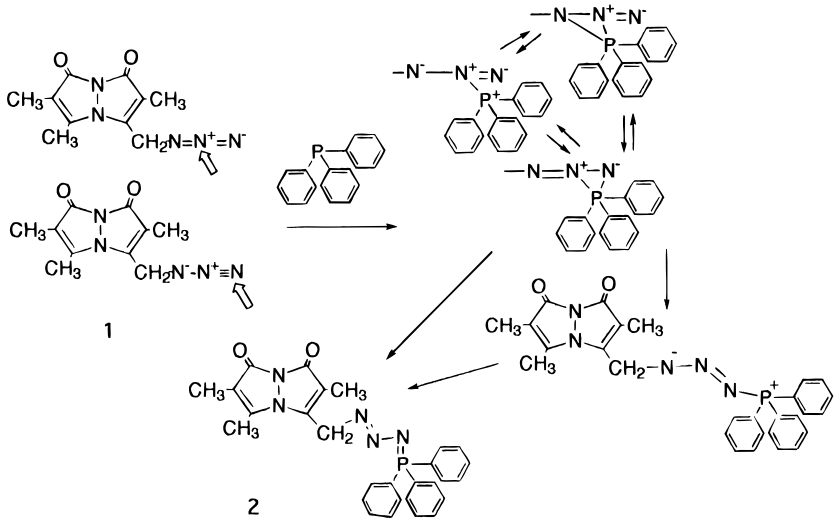
(28) Steric effects of substituents on phosphorus appear to have little influence on the rates of reactions. Kasukhin, L. F.; Ponomarchuk, M. C.; Yurchenko, R. J.; Klepa, T. I.; Yurchenko, A. G.; Gololobov, Yu. G. *J. Gen. Chem. USSR* **1982**, *52*, 691.

Scheme 1[a]



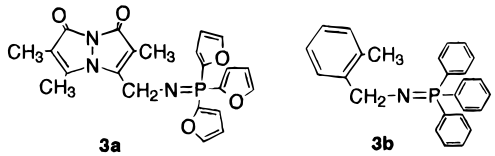
[a] Plausible mechanisms are shown for the first stage of the reaction of an azide and Ph_3P, leading to formation of the triazaphosphadiene **2**. The pathway which involves initial attack on the central nitrogen is suggested on two grounds: (a) the positive charge on the central nitrogen should promote initial attack at that position and (b) the analogy between azide and carbodiimide. The rearrangement of the triphenylphosphonio group from the central to the end nitrogen must occur by way of a three-membered ring. The second pathway is visualized at attack on a diazonium nitrogen, yielding a transition state or intermediate that can relax to the triazaphosphadiene **2**.

second an examination of the acylation of the iminophosphoranes.

Iminophosphorane Formation. *syn*-(Azidomethyl,-methyl)(methyl,methyl)bimane[26,29] (**1**) was reacted with triphenylphosphine (Ph_3P) (NMR $t_{1/2}$ 95 s) to give the triazaphosphadiene **2**, which was transformed (NMR $t_{1/2}$ 50 min) with loss of N_2 into the iminophosphorane **3** (Figure 1). The ^1H NMR signals (δ, ppm) for the sequence **1** → **2** → **3** are (1) α_1-CH_3, 1.85 → 1.60 → 1.49; (2) α_2-CH_3, 1.96 → 1.69 → 1.79; (3) β-CH_3, 2.35 → 2.17 → 2.58; (4) β-CH_2, 4.35 → 4.76 → 4.15 (1H) and 4.26 (1H). The ^{31}P NMR signals (δ, ppm) are −4.71 for Ph_3P, 25.00 for **2**, and 13.76 for **3**. The reaction is shown in eq 1 with full formulas given in Schemes 1 and 3 below. The iminophosphorane starts to appear after 2.8 min, and the quantitative reaction is complete in ca. 5 h. The iminophosphorane **3** could be stored in solution or in the dry state for a few days before decomposition products could be observed by NMR spectroscopy. Attempts at purification of **3** by chromatography (TLC or column) led to the (aminomethyl)bimane.

The reaction was followed by FTIR, using solutions similar to those used to obtain NMR spectra. The azido band at 2130 cm^{-1} disappeared quickly, with the appearance of a band a 1119 cm^{-1} assigned to P═N (of the P═NN═N group), to be replaced by the iminophosphorane P═N band at 1114 cm^{-1}. The corresponding changes in the C═O stretching band were from 1753 to 1746 to 1742 cm^{-1}. The UV absorption of the bimane around 360 nm is scarcely affected by the various chemical changes, but short wavelength absorption due to the triazaphosphadiene moiety around 250−260 nm can be seen to grow and then disappear. A blue or blue-green color (visible absorption λ_{max} 596 nm (ϵ 90)) appeared in many reactions but was shown to be a byproduct by the fact that the absorption appeared later than the TPD (**2**) in dioxane. The color was destroyed by small amounts (ca. 2 mol %) of AcCl, suggesting a true absorption coefficient of ca. 3000.

The reaction of azide **1** with tri-2-furylphosphine (Fu_3P)[30,31] to give the bimane *P*-tri-2-furyliminophosphorane **3a** [^1H NMR, δ 1.82, 1.88, 2.46 and 3.88 (s) ppm] proceeded at a much lower rate (3−4 d) than that with Ph_3P; an intermediate triazaphosphadiene **2a** corresponding to **2** was not observed.



3a **3b**

The *o*-xylyl-*P*-triphenyliminophosphorane **3b** derived from *o*-xylyl azide (**1b**) and Ph_3P is formed slowly (∼4 d); the intermediate triazaphosphadiene **2b** can be observed. The ^1H NMR signals noted in the course of the reaction for the CH_3 and CH_2 groups are as follows [sequence: **1b** → **2b** → **3b**]: (1) CH_3, 2.35, 2.19 and 2.34; (2) CH_2, 4.32 (s), 4.29 (s), and 3.86 (s). There was no evidence for the reaction of **1b** and Fu_3P over a period of 1 week.

Acylation of Iminophosphorane. Three different concentrations of AcCl were reacted with bimane *P*-(triphenylimino)phosphorane, as follows: (1) (excess) 10% AcCl/$CDCl_3$, (2) (large excess) pure AcCl, and (3) (200% excess) AcCl/$CDCl_3$ added in small increments.

(1) An "instantaneous" change in the NMR spectrum was observed when a 2-fold excess of AcCl in solution was added all at once to bimane *P*-(triphenylimino)-phosphorane (**3**). The two new sets of peaks which appeared in the region associated with bimanes were unaffected by the addition of either water or ammonium hydroxide. The integrated intensity of one set of signals was enhanced by the addition of (acetylamido)bimane **6** [^1H NMR, δ 1.74, 1.80, 2.17, 2.27, 4.40 (d, 2H, J = 4.6 Hz), 7.38 (broad t, 1H, J ∼ 4−5 Hz) ppm]. Careful integration of the peaks for the methyl protons showed that there was no acetyl-type methyl moiety in the second compound ("**X**") [^1H NMR, δ α_1-CH_3 1.34, α_2-CH_3 1.78, β-CH_3 2.53, β-CH_2 4.45 (d, 1H, J = 5.4 Hz), 4.54 (d, 1H,

(29) The nomenclature for the bimanes is explained in ref 25.

(30) Marom-Albeck, O.; Litman-Gershon, N. Unpublished results. Tri-2-furylphosphine was prepared according to ref 34; tri-2-furylphosphine oxide was identified by ^1H NMR and mass spectra.

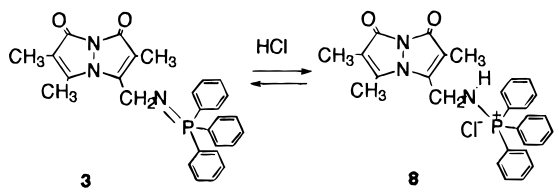
(31) Allen, D. W.; Hutley, B. G.; Mellor, M. T. J. *J. Chem. Soc., Perkin Trans. 2* **1972**, 63.

J = 5.2 Hz) ppm]. The low field region of the spectrum with the Ph protons extended down to δ 7.95 ppm; neither TPD (**2**) nor the iminophosphorane **3** nor $Ph_3P{=}O$ exhibit Ph proton signals lower than 7.65 ppm. Low-field Ph signals were not observed for a mixture of (acetylamido)bimane **6**, $Ph_3P{=}O$, and AcCl, nor were the signals for **6** altered in the mixture.

(2) When a 15-fold excess of AcCl was injected neat into a solution of iminophosphorane **3**, the NMR spectrum showed a set of signals for **X** (cf. previous paragraph) and, in addition, a new set of NMR peaks (^{1}H NMR, δ 1.84, 1.91, 2.34, 2.47, 4.59 ppm). The new peaks are assigned to the chloroimine[32] **7**. After evaporation of the sample solution, a $CDCl_3$ solution of the residue exhibited an NMR spectrum with the signals of **6** in place of **7**. The spectrum of **X** was unaffected by this procedure.

(3) Aliquot of AcCl were added over 1 h to the iminophosphorane **3** until a 2-fold excess had been reached. Both ^{1}H and ^{31}P NMR spectra were taken after each addition. In the ^{1}H NMR spectra, the bimane chloroimine **7** [δ 1.84, 1.91, 2.34, 2.47, and 4.56 ppm] was the major compound to appear from the onset. (Acetylamido)bimane **6** signals became pronounced by the last addition and almost superseded those of **7** after a 1 h interval. After several hours, the signals of **7** had vanished. The signals for **3** remained constant in intensity, once 1 equiv of AcCl had been added. However, the signal for α_1-CH_3 gradually moved upfield from 1.461 to 1.306 ppm while the positions of the α_2-CH_3 and β-CH_3 signals remained almost unchanged. The peaks for the two methylene protons of **3** [4.154 (1H) and 4.234 (1H)] diminished in intensity and coalesced to form a broad signal at lower field which then gradually redivided into the two doubles for **X** [4.444, 4.454 (1H) and 4.479, 4.488 (1H)]. During the course of the reaction, the bimane methyl region exhibited a number of low-intensity peaks ranging from 1.7 to 2.9 ppm. In the β-methylene region, three possible weak intermediate signals were observed: a triplet or two overlapping doublets centered at 3.710, a singlet at 4.296, and a triplet or two overlapping doublets at 4.472 ppm. The Ph region (lowest field peak for **3** was at 7.65 ppm) exhibited, in addition to the signals for $Ph_3P{=}O$, downfield signals (as low as 7.91 ppm) which developed at higher AcCl concentrations. There was another signal at 9.893 ppm. In the ^{31}P NMR spectra, the signal for $Ph_3P{=}O$ (29.73 ppm) appeared after the first addition and grew rapidly in intensity. The peak for **3** broadened and diminished quickly to zero while simultaneously a broad peak emerged at 38.96 ppm, narrowing as its intensity increased. Toward the end of the addition of AcCl a minor peak at 22.52 ppm made a brief appearance.

Protonation of Iminophosphorane. As a control, HCl in $CDCl_3$ was added in small increments to a $CDCl_3$ solution of iminophosphorane **3**. Changes were followed by both ^{1}H and ^{31}P NMR spectrometry (eq 4).



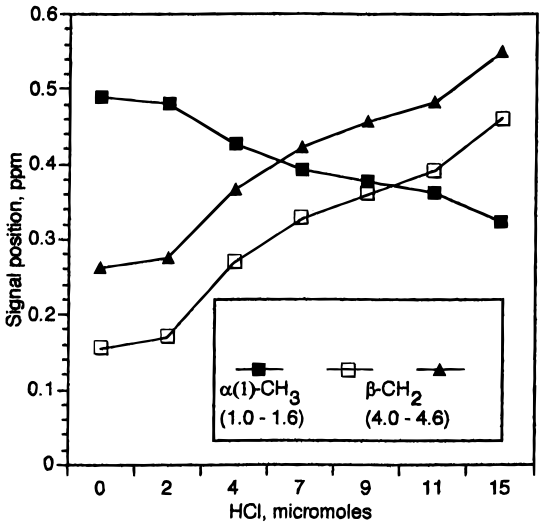


Figure 2. ^{1}H NMR peak positions for the α_1-methyl and β-methylene protons (two peaks) of the bimane *P*-triphenyliminophosphorane **3** as a function of the quantity of HCl added.

(1) ^{1}H NMR: As successive aliquots of a solution of HCl in $CDCl_3$ (total 1.25 equiv) were added to iminophosphorane **3**, the signal for one α-methyl moiety shifted gradually from 1.491 to 1.322 ppm. The two peaks for the β-methylene protons shifted from 4.156 and 4.262 to 4.461 and 4.552 ppm, respectively. The correlation between the changes is illustrated in Figure 2. The signals for the second α-methyl (1.789−1.784) and the β-methyl (2.588−2.570 ppm) protons showed minimal changes. The lowest peak in the Ph proton region moved from 7.674 to 7.950 ppm. A broad singlet appeared at 9.879 ppm.

(2) ^{31}P NMR: As successive aliquots of a solution of HCl in $CDCl_3$ (total 1.25 equiv) were added to iminophosphorane **3** (total 2 equiv), the sharp iminophosphorane peak at 13.71 ppm broadened, decreased, and was barely discernible after 1.3 equiv of HCl had been added. A broad absorption at 38.0 ppm appeared after 0.5 equiv of HCl had been added, gradually grew in height, and became a sharp peak at 38.61 ppm in the final solution.

Compound **X** was isolated in pure form by chromatography from a large-scale reaction and was identified as *syn*-((*N*-(triphenylphosphinio)amino)methyl,methyl)-(methyl,methyl)bimane chloride, *syn*-[$CH_2NHP^+(C_6H_5)_3$,-CH_3][CH_3,CH_3]B Cl^- (**8**).[11] The compound gave a positive chloride ion test, was very polar (low R_f with polar eluants), but was soluble in most solvents, including CH_2-Cl_2. The compound was stable in aqueous solution. The equivalent weight was 503.5 by titration of chloride ion with coulometrically generated mercurous ions.[33] The ^{1}H NMR spectrum in the Ph proton region showed three multiplets ranging from 7.65 to 7.95 ppm; the ratio of Ph protons to high-field bimane protons was 15:1. Similarly, low field pH signals were found in the ^{1}H NMR spectrum of $(C_6H_5)_3P^+CH_2COOCH_3$ Cl^-. The α-methyl signal [δ 1.31 ppm ($CDCl_3$)] was at much higher field than found in simple bimane derivatives; the shielding was found to decrease with rising solvent polarity as shown in Table 1. The two signals for the β-methylene protons were also seen in the spectrum of a D_2O solution, with each peak split (J = 5.3 Hz).

Although not noted in any NMR studies, some amine hydrochloride **9** was formed by hydrolysis of **8** in the

(32) The reaction of *N*-alkyl- and *N*-aryliminophosphoranes and acyl halides has been shown to give C-chloro-, C-bromo-, and C-iodoimines via at least one "salt-like" intermediate. Zbiral, E.; Bauer, E. *Phosphorus* **1972**, *2*, 35.

(33) Kirowa-Eisner, E.; Markovsky, D.; Brand, M.; Yarnitsky, Ch. *Experiments in Electroanalytical Chemistry*; manuscript in preparation.

Table 1. Effect of Solvent Polarity on the Chemical Shifts of *syn*-((*N*-(Triphenylphosphinio)amino)methyl,methyl)(methyl,methyl)bimane Chloride (8)[a]

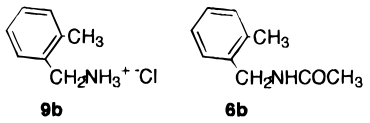
Solvent	δ values in ppm			
	α_1-CH_3	α_2-CH_3	β-CH_3	β-CH_2
$CDCl_3/CCl_4$ (6:5.5)	1.283	1.773	2.558	4.498, 4.580
$CDCl_3/CCl_4$ (2:1)	1.290	1.776	2.560	4.496, 4.581
$CDCl_3/CCl_4$ (4:1)	1.302	1.777	2.561	4.497, 4.584
$CDCl_3/CCl_4$ (6:0.5)	1.313	1.778	2.559	4.495, 4.586
$CDCl_3$	1.320	1.780	2.560	4.499, 4.589
CD_3CN	1.480	1.690	2.259	4.243, 4.308
D_2O (HDO δ 5 ppm)	1.716	1.931	2.448	4.668, 4.734

[a] The signals for the aromatic protons did not alter in position appreciably with solvent change.

preparative reaction. When the acylating agent was acetic anhydride, only the acetamidobimane **6** was formed. The yields of **6** and **8** varied from 10 to 60%, depending on the reaction conditions.

Acylation of the Bimane *P*-(Tri-2-furylimino)-phosphorane. The slow addition of AcCl to an NMR tube containing the bimane *P*-(tri-2-furylimino)phosphorane (**3a**) gave a solution which showed only the NMR peaks of the (acylamido)bimane **6**. The peaks of neither the tri-2-furyl analogue of **8** nor those of reaction intermediates were evident. The presence of **6** in the NMR tube was confirmed by the increase in the assigned peaks after addition of authentic material.

Acylation of *o*-Xylyl-*P*-triphenyliminophosphorane. Addition of AcCl to *o*-xylyl *P*-triphenyliminophosphorane (**3b**) yielded an immediate precipitate of α-amino-*o*-xylene hydrochloride (**9b**); the solution contained acetamido-*o*-xylene and $Ph_3P{=}O$. The acetamido derivative coeluted with $Ph_3P{=}O$ and could not be purified by chromatography. Identification was confirmed by the increase in the assigned peaks after addition of authentic α-(acylamido)-*o*-xylene (**6b**) [^{1}H NMR, δ 2.02, 2.33, 4.43 (d, 2H, J = 5.2 Hz), 5.54 (broad, 1H), 7.20 ppm], prepared via the Ritter reaction[34] from acetonitrile, sulfuric acid, and α-hydroxy-*o*-xylene.



9b **6b**

"Triazaphosphadiene Adduct" Reaction. Reactions in which the phosphine is added to a solution of the azido compound and a reactive acylating agent (such as AcCl) do not proceed via an iminophosphorane and lead to either both acetamido and chloro derivatives or only a chloro compound, depending on the nature of the azido compound. In the presence of the less reactive acetic anhydride, the azidobimane **1** is completely transformed to the iminophosphorane **3** before the formation of the acetamido product **6** begins.

Reactions in which 1 equiv of Ph_3P was added to azidobimane **1** and 2 equiv of AcCl in $CDCl_3$ were followed by both ^{1}H and ^{31}P NMR. ^{1}H NMR signals for two intermediates, a triazaphosphine adduct **5** and the chloroimine **7** (see next paragraph), and a final product (acetamido)bimane **6** were evident in a first spectrum ca. 45 s after mixing.

In the initial ^{31}P NMR spectrum, two signals, one at 29.79 ppm for $Ph_3P{=}O$ and another for **5** at 34.10 ppm, appeared. Both ^{1}H and ^{31}P peaks for the triazaphosphadiene **5** disappeared after 45 min. Two other products began to appear after 11 min. One was *syn*-(chloromethyl,methyl)(methyl,methyl)bimane (**10**),[26] identified after a preparative scale reaction. The second compound was assigned as *P*-triphenyloxaphosphatriazine (**12**) on the basis of ^{1}H NMR (2.40 ppm and multiplets like those of $Ph_3P{=}O$, but at 0.25 ppm lower field) and ^{31}P NMR (25.00 ppm). The NMR spectra as a function of time are illustrated in Figures 3 (^{1}H NMR) and 4 (^{31}P NMR). The relative yields of **6** and **10** were dependent on the chloride concentration: the ratio of the NMR peaks for **6** and **10** decreased from 1:0.49 to 1:0.60 in the presence of added chloride. No changes in the NMR spectra were seen after addition of ammonium hydroxide at the end of the experiment.

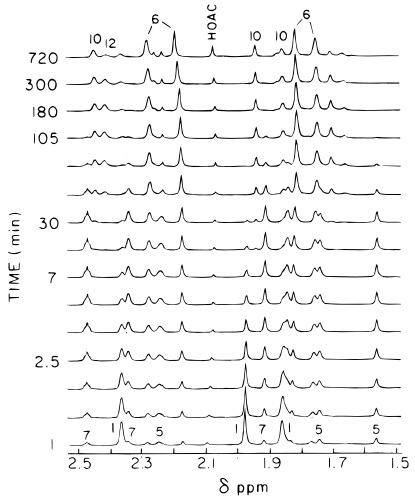


Figure 3. Stack plot of the bimane α-methyl region in the ^{1}H NMR spectra of the reaction mixture of *syn*-(azidomethyl,-methyl)(methyl,methyl)bimane (**1**) (0.022 M) and AcCl (0.044 M) with Ph_3P (0.023 M) in $CDCl_3$. The time for each spectrum is shown on the right. The peaks are identified by number. Small shifts in individual peaks with time are ascribed to small solvent effects.

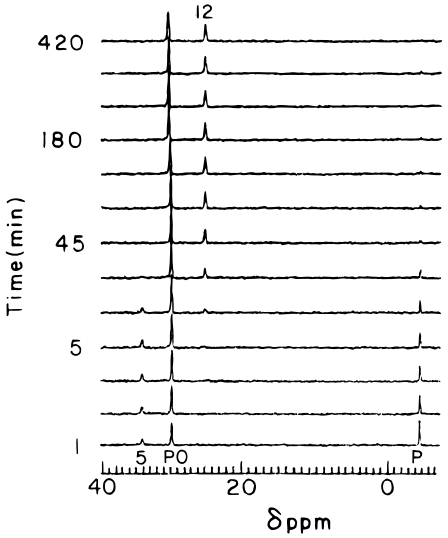
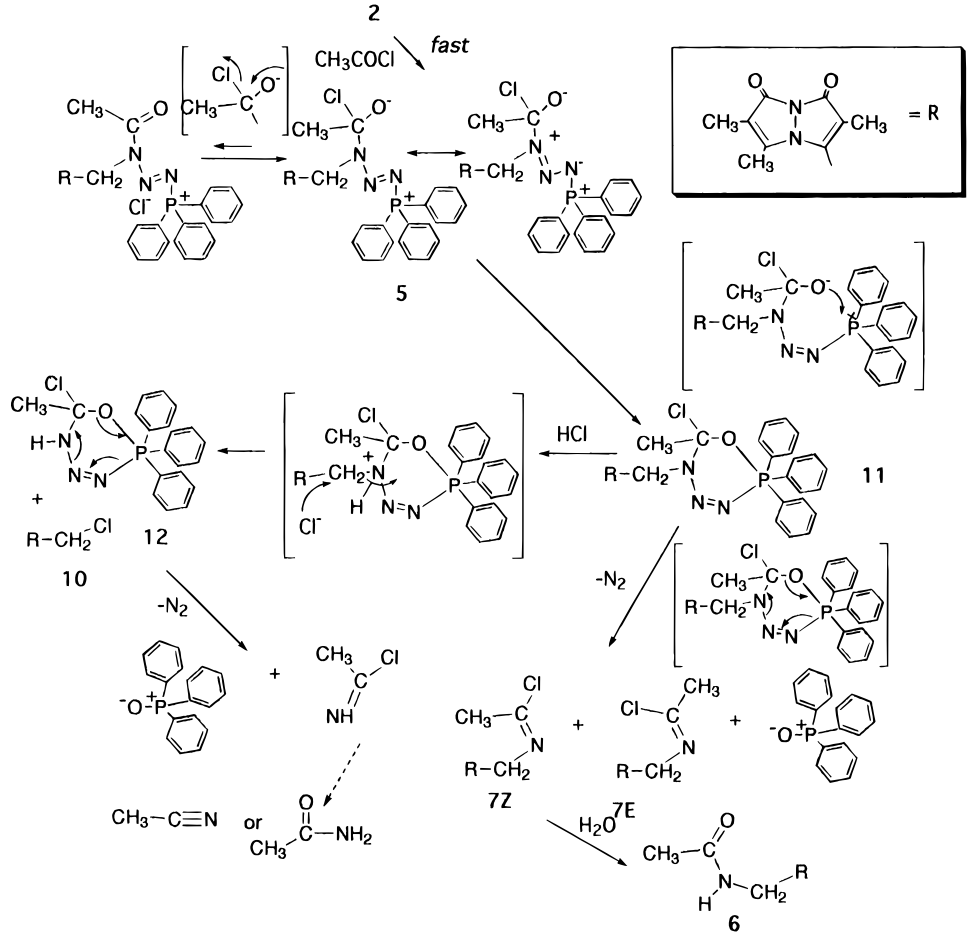


Figure 4. Stack plot for ^{31}P NMR spectra of the reaction of azidobimane **1** with Ph_3P in the presence of AcCl in $CDCl_3$. The initial peak for **P** (= Ph_3P) (−4.71 ppm) disappears, while that for the triazaphosphine adduct **5** (34.1 ppm) appears in the first spectrum and then disappears. The peak for **PO** (= $Ph_3P{=}O$) is present in the first spectrum (at 29.73 ppm) and grows thereafter. The peak for the oxaphosphatriazine **12** appears at 25.00 ppm after 11 min.

(34) Parris, C. L.; Christenson, R. M. *J. Org. Chem.* **1960**, *25*, 331.

Scheme 2. "The Triazaphosphadiene Adduct" Pathway[a]



[a] The triazaphosphadiene **2** (Scheme 1) reacts rapidly with an acyl chloride to give an triazaphosphadiene adduct **5** that may be in equilibrium with some triazenophosphonium salt. (Lack of low field signals in the Ph region favors 5 as the predominant form.) The adduct **5** is converted into the six-membered cyclic oxaphosphatriazine **11**. The cisoid form of **5** arises via rotation of the triphenylphosphonium group around a "single" bond (see resonance form). The oxaphosphatriazine **11** disappears in two ways, either via a pericyclic reaction to form phosphine oxide and chloroimine **7** [*E*- and/or *Z*-isomers] or through a chloride-induced elimination reaction of protonated **11** to form chlorobimane **10**, acetimidyl chloride, and phosphine oxide via a dealkylated oxaphosphatriazine **12**.

The first intermediate is the triazaphosphadiene adduct **5** (^{1}H, δ 1.55, 1.73, 2.22, and 4.92 ppm; ^{31}P δ 34.1 ppm) and *not* the triazaphosphadiene **2** (^{1}H NMR, δ 1.60, 1.69, 2.17, and 4.76 ppm; ^{31}P NMR, δ 25.00 ppm). The peak for the acetyl methyl group was obscured by the AcCl methyl peak at 2.66 ppm. The position of the signal for an acetyl methyl bound to nitrogen is confirmed by the chemical shift for 2-methyl-*N*-acetylimidazole at 2.65 ppm.[35] The structural assignment was based on the mode of formation, the relatively deshielded β-methylene chemical shift, and the position of the ^{31}P signal. The α-methyl position is intermediate between that of the triazaphosphadiene **2** (1.60 ppm) and the iminophosphorane **3** (1.50 ppm). The second intermediate is the chloroimine **7** (^{1}H, δ 1.84, 1.91, 2.34, 2.47 and 4.59 ppm) (see formula, Scheme 2). The assignment of 2.33 ppm to the bimane β-CH_3 and 2.66 ppm to the acetyl CH_3 was confirmed by an experiment in which acetyl-d_3 chloride was used; only the 2.33 ppm peak was observed. The oxaphosphatriazine **12** (^{31}P NMR signal like that of the earlier intermediate **2**, in which the electronic environment is similar) was hydrolyzed to $Ph_3P{=}O$ and acetonitrile or acetamide on the chromatographic column. Neither the ^{31}P NMR signal nor ^{1}H signals for $Ph_3P{=}O$ shifted in the presence of HCl.

Because of the number of peaks in the methyl regions of the NMR spectra, the correlation of methyl integrations for each species was difficult (Figure 3); the sequence of reactant peaks was easier to follow in the β-methylene proton region. A normalized set of integrated peak intensities for the methylene protons as a function of time is listed in Table 2 and plotted in figure 5. The integrated intensities for the various reactants, intermediates and products are plotted in Figure 6. The half-life of intermediate adduct **5** was estimated from the NMR intensities versus time as 2 min. The stability of chloroimine **7** seemed to depend on the amount of water present in the reaction mixture. Throughout the course of the reaction the methylene region showed no signals that could be attributed to other species.

A reaction in which tri-2-furylphosphine (Fu_3P) was added to a solution of **1** and AcCl in $CDCl_3$ gave both acetamidobimane **6** and chlorobimane **10** (0.39:1). The reaction took 2 d, resulting in 95% conversion of Fu_3P to $Fu_3P{=}O$; no reaction intermediates were observed.

A reaction in which Ph_3P was added to α-azido-*o*-xylene (**1b**) and AcCl in $CDCl_3$ led to α-chloro-*o*-xylene (**10b**) as the sole product in 2 d; no intermediates were noted by NMR. Isolation of pure **10b** was difficult on a small scale. Authentic **10b** (^{1}H NMR, δ 2.43, 4.61, 7.18−7.32 ppm), prepared from thionyl chloride and α-hydroxy-*o*-xylene, augmented the peaks assigned to **10b**, thus confirming the structural assignment. Reaction of Fu_3P with α-azido-

(35) Reddy, J. S.; Mandell, L.; Goldstein, J. H. *J. Chem. Soc.* **1963**, 1414.

Table 2. Normalized Integrated NMR Signals for Reactant, the Intermediates, and Products in the Reaction of the Azidobimane 1, Acetyl Chloride, and Triphenylphosphine by the "TPD Adduct" Pathway

	compounds				
time (s)	**1**[a]	**5**[b]	**7**[c]	**6**[d]	**10**[e]
60	67.0	14.6	9.2	9.2	0.4
85	55.0	17.0	15.0	12.0	1.0
110	43.9	21.1	19.3	15.2	0.5
135	36.9	24.0	21.8	16.9	0.4
160	31.3	24.6	24.5	18.5	1.1
210	22.2	27.2	29.1	21.0	0.6
260	21.3	27.2	29.0	21.7	0.7
360	15.7	28.1	31.9	23.5	1.4
700	13.9	28.5	31.8	24.2	1.8
1020	9.2	29.5	32.9	26.1	2.2
1340	6.6	28.4	34.6	27.1	3.4
1660	4.9	28.5	33.4	27.8	7.4
1980	4.2	26.0	33.0	30.8	5.9
3720	1.9	19.0	21.6	42.0	15.4
5560	0.0	7.6	12.5	55.4	24.5
7400	0.0	4.5	6.7	59.6	29.2
13 780	0.0	0.0	5.5	64.0	30.4
43 100	0.0	0.0	0.0	72.0	28.0

[a] *syn*-(Azidomethyl,methyl)(methyl,methyl)bimane. [b] Triazaphosphadiene adduct. [c] Chloroimine. [d] *syn*-(Acetamidomethyl, methyl)(methyl,methyl)bimane. [e] *syn*-(Chloromethyl,methyl)-(methyl,methyl)bimane.

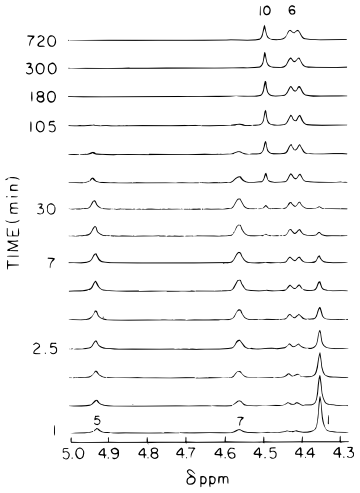
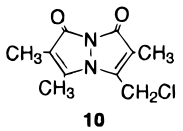
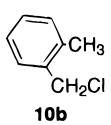


Figure 5. Stack plot of the bimane β-CH_2 region in the ^1H NMR spectra of the reaction mixture of *syn*-(azidomethyl,-methyl)(methyl,methyl)bimane (**1**) (0.022 M) and AcCl (0.044 M) with Ph_3P (0.023 M) in $CDCl_3$. The time for each spectrum is shown on the right. The disappearance of **1** (4.35 ppm) is accompanied by an increase in the triazenophosphonium adduct **5** (4.93). Subsequently, the chloroimine **7** (4.56) appears followed by the acetamidobimane **6** (4.40, 4.42) and the chlorobimane **10** (4.47 ppm).

o-xylene (**1b**) and AcCl in $CDCl_3$ also led to α-chloro-*o*-xylene (**10b**).



10



10b

Discussion

To clarify the somewhat complex scheme needed to describe the Staudinger reaction of azides, we have divided the presentation of reaction sequences into three schemes. In Scheme 1, the formation of triazaphosphadiene is considered. In Scheme 2, the course of the reaction of the triazaphosphadiene **2** with acyl chloride

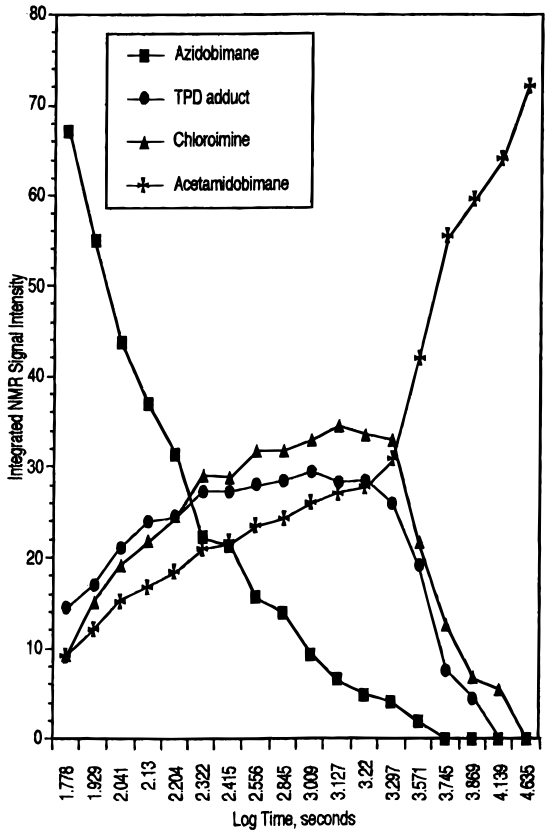


Figure 6. Plot of the integrations (β-CH_2 ^1H NMR peaks) of the azidobimane **1**, the "triazaphosphadiene (TPD) adduct" **5**, the chloroimine intermediate **7**, and the acetamidobimane **6** as a function of time for a solution obtained by the addition of Ph_3P to a mixture of **1** and AcCl in $CDCl_3$. The disappearance of **1** (1.85, 1.96, 2.35, 4.35 ppm) is accompanied by an increase in the triazenophosphonium adduct **5** (1.55, 1.73, 2.22, 4.92 ppm). Subsequently, the chloroimine **7** (1.84, 1.91, 2.34, 2.47, 4.59 ppm) appears followed by the acetamido bimane **6** (1.74, 1.80, 2.17, 2.27, 440(d) ppm).

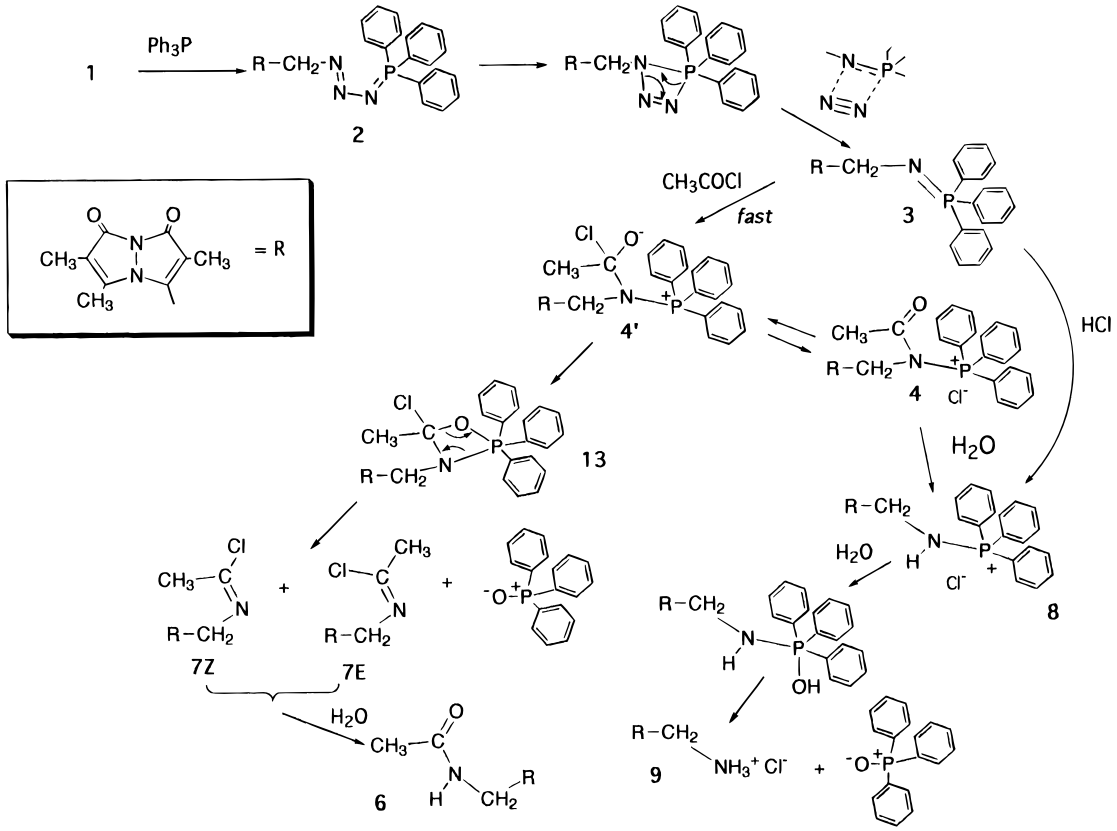
is shown (the "TPD adduct" pathway). In Scheme 3, the mechanism of the "normal" reaction is illustrated.

In Scheme 1, we address the question of how the phosphorus becomes attached to the γ-nitrogen of the azido group. The point is that the azido group has some positive charge at the middle nitrogen and, like carbodiimides, could be attacked by nucleophiles at that position. The α-azido-*o*-xylene has lower reactivity than azidobimane toward Ph_3P, a difference which is electronic in origin to judge from the minor influence of steric effects on the rate of reaction of phosphines with azides. Electron-withdrawing groups on the azide increase the rate of reaction.[28,36] An attack at either of the outer two azido nitrogens would thus be consistent with the lack of steric effects. Triazaphosphadienes are known compounds with the phosphonio group presumed bound to the end nitrogen.[17,18] If attack occurs at the central nitrogen, rearrangement of the phosphorus from the central to the end nitrogen might occur by way of a three-membered ring intermediate. Alternatively, the attack at the end nitrogen can be formulated in terms of the diazonium resonance form. Both pathways are illustrated in Scheme 1.

In Scheme 2, the course of the reaction of the triazaphosphadiene **2** with acyl chloride is analyzed. The initially formed triazaphosphadiene **2**, a nucleophilic

(36) Ponomarchuk, M. P.; Sologub, L. S.; Kasukhin, L. F.; Kukhar, V. P. *J. Gen. Chem. USSR* **1985**, *55*, 1532.

Scheme 3[a]



[a] In the "normal" Staudinger reaction, the triazaphosphadiene **2** (Scheme 1) forms the iminophosphorane **3**, presumably via a triazaphosphacyclobutene. Reaction of the iminophosphorane **3** with an acyl chloride leads to an adduct **4′**. The latter can ring close to an oxazaphosphetane **13** which undergoes cycloreversion to the chloroimine **7** (*E*- and/or *Z*-isomers). The adduct **4′** is also in equilibrium with an (*N*-alkyl-*N*-acylamino)phosphonium salt **4** which can be attacked by water to produce an (*N*-alkylamino)phosphonium chloride **8**. Further hydrolysis leads to a small amount of amine hydrochloride **9**, a process which occurs with varying ease in the conversion of iminophosphoranes to amines.[7,8,11] The chloroimine **7** produces the amide by hydrolysis.

phosphorus−nitrogen ylide, attacks the acyl chloride to give the triazaphosphadiene adduct **5**. The triazaphosphadiene reacts too rapidly under these conditions to be observed.[37−39] The adduct **5** can be considered as an extended ylide (or betaine) containing a double-bonded nitrogen bridge between $N-P^+$ and $C-O^-$. Since the low-field signals associated with the Ph protons of phosphonium salts (such as **8**) were not detected during the time that **5** and **7** were present, we infer that dissociation of chloride only occurs to a minor extent. The parallelism in the peak positions for **2** and **5** is revealed by the ^{1}H NMR chemical shifts: α_1-CH_3, 1.69 and 1.73; α_2-CH_3, 1.60 and 1.55; β-CH_3, 2.17, and 2.22; CH_2-, 4.76 and 4.92 ppm; ^{31}P NMR shifts, 24.8 and 34.1 ppm. The crystal structure of the tetrafluoroborate of an alkyl derivative of one of the unusually stable triazaphosphadienes formed from aminophosphoranes shows that reaction occurred on the α-nitrogen of the azide, as proposed for the acyl adduct **5**.[3]

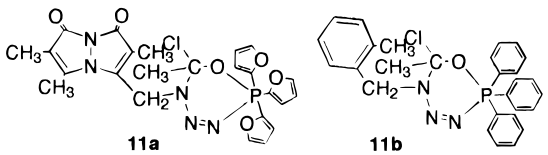
Through rotation of the triphenylphosphonium group around a "single" bond (see resonance form), the cisoid form of the "TPD adduct" **5** can be formed. This should form an oxaphosphatriazine **11** which can disappear in two ways: (1) a pericyclic reaction to form phosphine oxide and chloroimine **7** [*E*- and/or *Z*-forms] and (2) via a novel chloride-induced elimination of chlorobimane **10** from protonated **11** to form the dealkylated oxaphosphatriazine **12**. The latter undergoes a pericyclic reaction to form phosphine oxide and acetimidyl chloride (a chloroimine), which in turn can produce either acetamide or acetonitrile. The delay in the appearance of **10** (which does not form until some HCl is present in the reaction mixture), and the increase in the yield of **10** on addition of chloride support the idea that **10** is formed by the reaction of HCl with a late intermediate. Further proof is offered by the low yield of **6** as compared to **10** in the reaction with Fu_3P which points to a common intermediate for both compounds. The bimane *P*-tri-2-furyloxaphosphatriazine **11a** does not proceed to the chloroimine **7** as readily as **11** possibly because the phosphine oxide is less favored (electronegative group attached to positively charged phosphorus). Therefore, the intermediate **11a** is diverted to a greater extent to chloride formation. In the case of the "TPD adduct" pathway for α-azido-*o*-xylene (**1b**), the sole product is the α-chloro-*o*-xylene (**10b**); no intermediates are observed. The failure to observe intermediates in the reaction of **1b**, an acyl chloride, and Ph_3P may be due to the low rate of the initial reaction, coupled with higher reactivity of the intermediates (such as **11b**) and more chance to form HCl and thus, side products. Considerably greater reactivity for tri-*n*-butylphosphine over that of Ph_3P toward an α-(azidoacetyl)indole has been noted.[40] Control ex-

(37) The role of triazaphosphadiene as a synthetic intermediate (ref 34) in an intramolecular reaction with an imine is probably best explained by the authors' alternative mechanism, involving isomerization through an adjacent double bond. The same applies to the reaction of triphenylphosphine with 2,3-diazido-1,4-naphthoquinone (ref 35). In both instances, reaction occurs at the middle nitrogen of the triazeno fragment.

(38) Molina, P.; Arques, A.; Vinader, M. V. *J. Org. Chem.* **1990**, *55*, 4724.

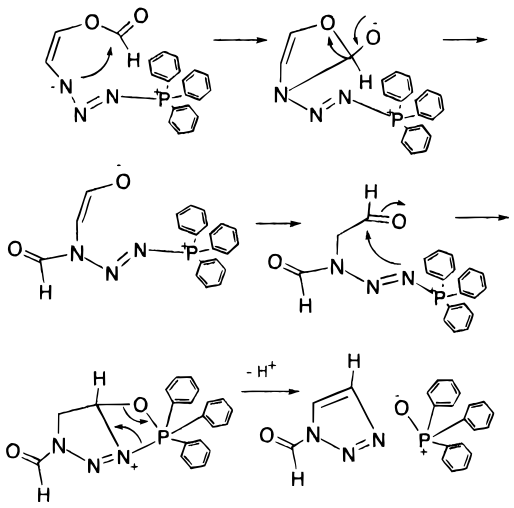
(39) Mosby, W. L.; Silva, M. L. *J. Chem. Soc.* **1965**, 1003.

periments showed that neither Ph_3P nor $Ph_3P{=}O$ reacted or complexed with HCl.



11a **11b**

The rapid reaction of CH_3COCl with **2** precludes its subsequent conversion to **3**. When a less reactive acylating agent such as acetic anhydride is present prior to the addition of Ph_3P, the iminotriphenylphosphorane **3** is formed (^{1}H NMR). The rapid formation of **5**, therefore, and its presumed swift conversion into **11**, represent a dramatic diversion of the "classical" reaction sequence for which there are both analytical and synthetic consequences.[41−44] If the acyl group is present in an appropriate part of the azide molecule, intramolecular reaction leads to ring formation (an "aza- Wittig reaction").[45−58] The intramolecular reaction course might proceed via a TPD and be different from the intermolecular reaction via **3**. Particular substituents in the azide might also divert the "aza-Wittig" product, as in the case of *N*-formyltriazole formation from a *β*-(formyloxy)vinyl phosphatriazene (see below).[59]



The course of the "normal" Staudinger reaction of azides is shown in Scheme 3. The initially formed triazaphosphadiene **2** is transformed into the iminophosphorane **3**, presumably via a triazaphosphacyclobutene. The latter has been formulated as a transition state,[23,60] even though a large number of bonding changes would be required for its formation. The nitrogen in the iminophosphorane has been shown to be derived from the α nitrogen of the azido precursor.[60] Reaction of the iminophosphorane **3** with an acyl chloride should produce a betaine, **4′**, which can form either an (*N*-alkyl-*N*-acetylamino)phosphonium salt **4** or undergo ring closure to the four-ring oxazaphosphetane **13**. An *N*-vinyl analogue of **4** has recently been isolated as a hygroscopic salt[10] [^{31}P ($CDCl_3$) δ 32.7 ppm; ^{1}H Ph protons between 7.20 and 8.09 ppm]. An oxooxazaphosphetane has been reported to form but decomposes below rt.[61] Cycloreversion of the oxaazaphosphetane **13** to the chloroimine **7** then occurs, followed by hydrolysis of the chloroimine to the final product, the acetamido compound **6**.

The provenance of the (*N*-alkylamino)phosphonium chloride **8** is uncertain but may arise either by hydrolysis of the *N*-acetylphosphonium chloride **4** or, as we have demonstrated, by reaction of HCl with the iminophosphorane **3**. A rapid equilibrium between **8** and **3** (on the NMR time scale) is shown by the gradual change in the α_1-CH_3 and β-CH_2 proton signals (Figure 2) and the broadening of the ^{31}P peaks of the two compounds. (*N*-Alkylamino)phosphonium chloride salts are well-known and are relatively stable.[11,62]

The TPD adduct pathway was initially studied using trideuterioacetyl chloride as the acyl chloride in order to simplify the ^{1}H NMR spectrum. However, the lack of information about the acetyl group caused us to use AcCl in very modest excess; we found that the byproducts of hydrolysis, acetic acid and acetic anhydride, did not interfere with our studies.

The NMR peaks for the bimane shift in the course of the "TPD adduct" reaction, **1** → **5** → **7** are as follows: α_1-CH_3, 1.97 → 1.55 → 1.91; α_2-CH_3, 2.36 → 2.22 → 2.34; β-CH_3, 1.86 → 1.73 → 1.84; β-CH_2, 4.34 → 4.93 → 4.59. An upfield shift is also noted for the α_1-CH_3 of the phosphinium chloride **8** in comparison to the iminophosphorane **3** (1.32 versus 1.49), the peak for **3** itself being at an unusually high field for a bimane. We interpret these changes as a reflection of the effect of the Ph ring current on the bimane ring, especially for the α_1 methyl group. The hydrogens of the substituents on the bimane ring, notable the α_1-CH_3, are thus sensitive probes of the local magnetic field.

In many of the "TPD adduct" reactions, substantial yields of the chlorobimane **10** were isolated. Chloride ion

(40) Molina, P.; Fresneda, P. M.; Almendros, P. *Synthesis* **1993**, 54.
(41) Ittah, Y.; Sasson, Y.; Shahak, I.; Tsaroom, S.; Blum, J. *J. Org. Chem.* **1978**, *43*, 4271.
(42) Shalev, D. E.; Radkowsky, A. E.; Kosower, E. M. Unpublished results. Acyl thioesters, acylimidazoles, the adducts of carboxylic acids and carbodiimides, and acid anhydrides react with **2** or **3** to form acyl derivatives. Carboxylic acids, reported to react slowly in refluxing toluene (refs 43 and 44), are almost certainly reacting via the anhydride, since we found no reaction with **2** under our conditions.
(43) Zaloom, J.; Calandra, M.; Roberts, D. C. *J. Org. Chem.* **1985**, *50*, 2601.
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would be unlikely to displace the azide group rapidly under our conditions, so that an intermediate must be the substrate. In addition, much of the azido compound has been consumed before chloride formation becomes significant. The delay in the appearance of chloride product is due to the requirement that the concentration of HCl must be high enough to compete for a substrate. The most likely candidate is the presumed oxaphosphatriazine intermediate **11** which can undergo either a pericyclic reaction or an elimination. In one, the expected chloroimine is formed. In the second, a chloride-induced reaction of the protonated form of **11** leads to the chlorobimane and another oxaphosphatriazine **12**.

A possible example of a displacement reaction on an intermediate is the formation of the (carbobenzoxy)alanyl ester rather than the expected [(carbobenzoxy)alanyl]-amido derivative by the treatment of an glycosyl azide with Ph_3P.[63] Other reactions to which the present work is relevant are those of Ph_3P with 1-azido-3-propyl and 2-azido-1-propyl mesylates to produce after treatment with lithium diphenylphosphide, (3-aminopropyl)- and (2-aminopropyl)diphenylphosphines.[64] The proposed three- and four-membered ring intermediates might well be five- and six-membered ring intermediates.

In the case of azidobimanes, a blue-green color (λ_{max} 596, ϵ 90 in $CHCl_3$) appears during the reaction with Ph_3P and is quite strong and persistent in some cases. Kinetic measurements as well as experiments using dioxane as solvent show that the color is due to a product that forms in the absence of the acyl halide after the iminophosphorane appears, possibly due to the reaction of **2** with **1**. No color was visible on mixing the iminophosphorane **3** and the azidobimane **1**, implying that the colored compounds arise from a reaction of the triazaphosphadiene **2**. A deep blue to purple color has been noted in the reaction of Ph_3P with 2-azido-3-vinyl-1,4-naphthoquinones at −30 °C in an unexpected conversion to 2-amino-3-acyl-1,4-naphthoquinones. The mechanism must be complex, but the authors suggest that a triazaphosphadiene might be involved without implying that the color represents an intermediate relevant to the conversion.[65] Similar color changes have been noted in the reactions of phosphines with other azido-1,4-naphthoquinones.[39]

Conclusions. The rich chemistry displayed in the Staudinger reaction of azides deserves further study in different systems. In the present case, we have shown that carrying out the reaction of a phosphine with an azide in the presence of the ultimate acylating agent leads to a change in the reaction course. We hope to study reactions in which the influence of changes in the acylating agent is examined.

Experimental Section

Spectra. ^{1}H NMR spectra: 200 MHz AM and 500 MHz spectrometers, relaxation time 3.0 s, experiments done in 5 mm tubes (ref tetramethylsilane in $CDCl_3$). ^{31}P NMR spectra: 360 MHz AMX spectrometer, relaxation delay 5.0 s, experiments done in 10 mm tubes using $CDCl_3$ as solvent (ref external 85% H_3PO_4 in H_2O). Sequential ^{31}P and ^{1}H NMR measurements were carried out using the 500 MHz spectrometer for samples in 5 mm tubes using the references as cited already. The FTIR-ATR technique for samples on AgX fibers has been described elsewhere.[66]

Solvents and Materials. THF (calcium hydride) and acetonitrile (phosphorus pentoxide) were distilled. Water was deionized and distilled. Chloroform was passed through a short alumina column before use. Bromobimane was prepared according to published procedures.[23] Other solvents (anal. or spectro. grades) and materials were used without further purification.

***syn*-(Azidomethyl,methyl)(methyl,methyl)bimane [*syn*-(CH_2N_3,CH_3)(CH_3,CH_3)B] (1).** *A shield was used; however, attempts to detonate the crystalline azide product were unsuccessful and the material is not considered hazardous. Current work is carried out without shields and evaporations are done at temperatures not exceeding 30 °C.* A solution of sodium azide (0.719 g, 11.07 mmol) in methanol−water (4:1, ∼10 mL) was added dropwise to a solution of *syn*-(bromomethyl,methyl)-(methyl,methyl)bimane[25] (2.0 g, 7.38 mmol) in THF (20 mL) over 20 min and stirred for 10 min more. After the organic solvents were evaporated, water was added (∼5 mL) and the solution was extracted with CH_2Cl_2 (5 × 25 mL). The organic extract was washed with saturated NaCl (15 mL) and evaporated and the residue flash chromatographed on silica gel [eluant, CH_2Cl_2−ethyl acetate (3:7)]. TLC on silica [eluant, ethyl acetate−1,2-dichloroethane (6:4)] was used to analyze the chromatographic fractions. The azido- and the bromobimanes are eluted close together, but the azide is fluorescent on the TLC plate while the bromobimane becomes fluorescent under irradiation over many seconds. Combining appropriate fractions gave 1.56 g of *syn*-(CH_2N_3,CH_3)(CH_3,CH_3)B (**1**) (91% yield): yellow solid; mp 135 °C (N_2 loss at 141 °C); ^{1}H NMR ($CDCl_3$) δ 1.86 (s), 1.97 (s) (6H), 2.36 (s, 3H), 4.34 (s, 2H) ppm; ^{1}H NMR (CD_3CN) δ 1.75 (s), 1.86 (s) (6H), 2.31 (s, 3H), 4.47 (s, 2H) ppm; IR (on AgX fiber) 2102, 1721, 1657, 1633, 1603, 1413, 1276, 1218 cm^{-1}; UV (dioxane) λ_{max} 366 nm (ϵ 6150); mass spectrum *m*/*z* 233 (25, M^+), 205 (30), 178 (100).

α-Azido-*o*-xylene[67] (1b). Solid NaN_3 (2.635 g, 0.041 mol) was added to α-bromo-*o*-xylene (3.621 mL, 0.027 mol) in DMSO (27 mL), and the mixture was stirred for 17 h. After water (60 mL) was added, the azido compound was extracted with ether. The organic layer was dried (Na_2SO_4) and evaporated at 10 °C (behind a shield) to yield an amber liquid. A small amount (1 mL) was purified by bulb to bulb distillation: colorless liquid; bp_{5Torr} 110 °C, density 1.13 g/mL; ^{1}H NMR ($CDCl_3$) δ 2.38 (s, 3H), 4.35 (s, 2H), 7.25 (m, 4H); mass spectrum *m*/*z* 147 (9.2, M^+), 119 (13.6), 104 (100).

Conversion of *syn*-(Azidomethyl,methyl)(methyl,methyl)bimane (1) to the Iminophosphorane 3. Reaction with Acetyl Chloride. A. *syn*-(Acetamidomethyl,methyl)(methyl,methyl)B. *syn*-(CH_2N_3,CH_3)(CH_3,CH_3)B (**1**) (0.1094 g, 0.49 mmol) and Ph_3P (0.1311 g, 0.50 mmol) were dissolved in dry acetonitrile (5 mL) and the green-blue solution stirred at rt until nitrogen evolution had ceased. The solvent was removed under vacuum at rt to give a yellow solid with a greenish tinge, *syn*-($CH_2N{=}PPh_3$,CH_3)(CH_3,CH_3)B (**3**): ^{1}H NMR ($CDCl_3$) δ 1.49 (s, 3H), 1.79 (s, 3H), 2.58 (s, 3H), 4.15 (s, 1H), 4.26 (s, 1H), 7.3−7.6 (m, 15H); ^{31}P NMR ($CDCl_3$) δ 13.83 ppm; FT-IR ($CDCl_3$) 1742, 1661, 1628, 1599, 1239, 1114 cm^{-1}. The iminophosphorane formed the amine on silica gel (TLC) and could not be purified by chromatography. A deep blue solution of **3** in CH_2Cl_2 (8 mL) was cooled to 0 °C under nitrogen, and AcCl (0.05 mL, 0.70 mmol) in CH_2Cl_2 (1 mL) was added over 25 min through a septum. The solution immediately became yellow, was stirred at 0 °C for 1 h, and was allowed to stand at rt for 1 h. Aqueous K_2CO_3 was added, and the mixture was stirred for 20 min. The organic layer was washed with water (2 × 10 mL). The combined aqueous layers were washed with CH_2Cl_2 (5 × 20 mL) until all fluorescent material had been extracted. After evaporation, the residue was flash chromatographed on silica gel [eluant, CH_2Cl_2−ethylacetate (3:7)] to give 0.039 g (0.16 mmol) of *syn*-($CH_2NHCOCH_3$,CH_3)(CH_3,CH_3)B (**6**) (32% yield) as a yellow solid: mp 204 °C; ^{1}H NMR ($CDCl_3$) δ 1.74 (s), 1.80 (s) (6H), 2.17 (s), 2.27 (s) (6H), 4.40 (CH_2, d, 2H, J = 4.6 Hz), 7.38 (NH, br t, 1H, J ∼ 4−5 Hz), (CD_3CN) 4.34 (CH_2, d, 2H, J = 5.3 Hz),

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6.84 (NH, br t, 1H, $J \sim 4-5$ Hz), ($CD_3CN + D_2O$) 4.36 (s, 2H), *no NH signal*, mass spectrum m/z 249 (M^+).

B. The iminophosphorane **3** was produced by stirring a mixture of azide **1** (0.0807 g, 0.346 mmol) and Ph_3P (0.0988 g, 0.377 mmol) overnight in $CHCl_3$ (15 mL, purified by passage through alumina). Acetyl chloride (30 μL, 0.42 mmol) in $CHCl_3$ (10 mL) was added over 10 min, the mixture was stirred overnight, stored in the freezer, and worked up a few days later (TLC on silica [eluant, methanol−acetonitrile (15:85)]). The residue showed three major compounds, $Ph_3P{=}O$, amide **6**, and a polar, fluorescent, iodine-positive material. Half of the solvent was evaporated, cyclohexane added, and the precipitate filtered off and washed successively with 0.5 mL portions of CH_2Cl_2, ethyl acetate, and acetonitrile. The solid (0.0299 g) contained chloride ion ($AgNO_3$), was soluble in water and methanol, and had the ^{1}H NMR spectrum [(CD_3OD) δ 1.83 (s, 3H), 1.95 (s, 3H), 2.47 (s, 3H), 4.33 (s, 2H), 5.49 (s, 1H) ppm] of *syn*-($CH_2NH_3^+Cl^-$,CH_3)(CH_3,CH_3)B (**9**). The residue from the filtrates was chromatographed to give (1) 0.0521 g (0.19 mmol) of $Ph_3P{=}O$ (50% yield), (2) 0.021 g (0.098 mmol) of amide **6** (eluant: acetonitrile) (28% yield), and (3) 0.0528 g of the (*N*-alkylamino)phosphonium chloride **8** [eluant, methanol−acetonitrile (1:9)] (29% yield) (positive chloride ion) which formed crystals by slow evaporation of a $CDCl_3$ solution. The molecular weight was determined by titration with coulometrically generated mercurous ions.[33] An aliquot (0.9 to 1 mL) of a methanol solution (5.05 mg/5 mL) was pipetted into the titration vessel. Perchloric acid (1.2 M, 20 drops) was added with enough methanol (~4 mL) to cover the electrodes. The end point was determined potentiometrically with two identical mercury-coated silver electrodes at constant current (0.5 μA). The current for generating Hg(I) was 2 mA. Because of the slow response of the electrodes, the end point lags behind the equivalent point. A series of titrations were performed with successive additions of new samples. The distance between the successive end points corresponds to the current used, with moles of Cl^- given by it/F (i, current; t, time). For a 0.9 mL aliquot, t was 84.6 s, equivalent to 1.76×10^{-6} mol close to the value of 1.8×10^{-6} mol for a molecular weight of 503.4, consistent with structure **8**.

***syn*-[$CH_2NHP^+(C_6H_5)_3$,CH_3][CH_3,CH_3]B Cl^- (8)**: yellow solid, mp 80−100 °C with sublimation, MW 503.4 (Cl^- titration); ^{1}H NMR ($CDCl_3$) δ 1.32 (s, 3H), 1.78 (s, 3H), 2.56 (s, 3H), 4.50 (s, 1H), 4.59 (s, 1H), 7.62−7.95 (m, 15H), 9.89 (bs, 1H); ^{31}P NMR 38.96 ppm. The δ values in a series of solvents of increasing polarity are given in Table 1.

Reaction of *syn*-(Azidomethyl,methyl)(methyl,methyl)bimane (1), Acetyl Chloride, and Triphenylphosphine (Triazaphosphadiene Adduct Pathway). Triphenylphosphine (0.0684 g, 0.261 mmol) was added all at once to a solution of azide **1** (0.0531 g, 0.228 mmol) in purified $CHCl_3$ (10.5 mL) and AcCl (30 μL, 0.422 mmol) and the mixture stirred overnight. After evaporation of the solvent, the solid residue was flash chromatographed on silica gel to give the following materials: (1) [eluant, ethyl acetate−CH_2Cl_2 (5:95)] *syn*-(CH_2Cl,CH_3)(CH_3,CH_3)B (**13**) (0.0251 g, 0.111 mmol) (50% yield), (2) (eluant, ethyl acetate) $Ph_3P{=}O$ (0.039 g, 0.14 mmol) (54%), and (3) (eluant, acetonitrile) **6** (0.0134 g, 0.054 mmol) (24% yield). The identity of the chlorobimane[26] **10** was confirmed by mp (132−4 °C), mass spectrum [m/z 226 (100), 228 (33)], ^{1}H NMR [δ 1.86 (s, 3H), 1.95 (s, 3H), 2.44 (s, 3H), 4.48 (s, 2H) ppm], and TLC comparison with authentic material.

Conversion of α-Azido-*o*-xylene (1b) to Iminophosphorane. Reaction with Acetyl Chloride. Triphenylphosphine (0.124 g, 0.473 mmol) in $CHCl_3$ (10 mL) was added to a solution of the azide **1b** (60 μL, 0.064 g, 0.43 mmol) in $CHCl_3$ (15 mL). The mixture was stirred for 1 week, and then AcCl (60 μL, 0.84 mmol) was added. After the mixture was stirred for 4 d, *o*-xylyl-α-ammonium chloride (**9b**) (25.1 mg, 0.16 mmol) (37% yield) [^{1}H NMR (DMSO-d_6) δ 2.35 (s, 3H), 4.01 (s, 2H), 7.27, 7.37 (4H), 8.27 (bs, 3H)] [positive Cl^- test] was filtered off, the filtrate evaporated, and the residue chromatographed [eluant, 10−20% ethyl acetate−CH_2Cl_2] to yield an inseparable $Ph_3P{=}O$ and α-acetamido-*o*-xylene (**6b**) (NMR spectrum identical to that of authentic **6b** in the high field region, see below).

α-Acetamido-*o*-xylene (6b). Acetonitrile (2 mL, 1.56 g, 38 mmol) and concd H_2SO_4 (0.75 mL) were stirred for 1 h at 0−10 °C. α-Hydroxy-*o*-xylene (1.222 g, 10 mmol) in acetonitrile (3 mL) was added at 0−5 °C over 30 min and the solution stirred at rt for 2 d. Some unreacted alcohol remained (TLC). Most of the solvent was evaporated, and both 10% aqueous $KHCO_3$ and solid $NaHCO_3$ were added until CO_2 evolution stopped. The precipitated sulfate was dissolved in water. This solution and the filtrate were extracted with ethyl acetate. The organic phase was washed with saturated NaCl solution (5 mL), dried ($MgSO_4$), and evaporated and the residue chromatographed [eluant, 10% ethyl acetate−CH_2Cl_2] to give α-acetamido-*o*-xylene (**6b**) (0.537 g, 3.29 mmol) (33% yield): mp 55 °C; ^{1}H NMR ($CDCl_3$) δ 2.02 (s, 3H), 2.33 (s, 3H), 4.435 (d, J = 5.2 Hz, 2H), 5.56 (bs, 1H), 7.20 (s, 4H); mass spectrum m/z 163.2 (91.6, M^+).

Reaction of α-Azido-*o*-xylene (1b), Acetyl Chloride, and Triphenylphosphine (Triazaphosphadiene Adduct Pathway). Triphenylphosphine (0.214 g, 0.82 mmol) was added to a solution of the azide **1b** (116 μL, 0.121 g, 0.82 mmol) and AcCl (60 μL, 0.066 g, 0.84 mmol) in purified $CHCl_3$ (2.5 mL), and the mixture was stirred for 1 week. A solid residue (0.03 g) was not investigated. Using precautions against water entry, the filtrate was evaporated and the residue distilled bulb to bulb, bp_{50Torr} 150 °C. The acrid odor of α-chloro-*o*-xylene permeated the apparatus; the distillate had the expected mass spectrum: m/z 40 (100), 142 (32.6) [M^+]. An NMR spectrum showed both acetic anhydride and α-chloro-*o*-xylene (see below); $Ph_3P{=}O$ remained undistilled.

α-Chloro-*o*-xylene (10b). α-Hydroxy-*o*-xylene (0.245 g, 2 mmol) was dissolved in ether (10 mL), thionyl chloride (250 μL, 0.41 g, 3.4 mmol) was added, and the solution was stirred for 2 d. After the solvent was removed, the residue was distilled bulb to bulb to give α-chloro-*o*-xylene (**10b**): bp_{55Torr} 150 °C; ^{1}H NMR ($CDCl_3$) δ 2.43 (s, 3H), 4.61 (s, 2H), 7.18−7.32 (m, 4H) ppm; mass spectrum m/z 140 (100), 142 (32.6) [M^+]. Only enough material was isolated to confirm the identify of **10b**.

Trideuterioacetyl Chloride. Thionyl chloride (9.7 g, 0.082 mol) was added dropwise to d_4-acetic acid (4.40 mL, 0.078 mol) in distilled DMF at 0 °C. The reaction was left to stir for 5 min and then distilled through a long Vigreux column and collected with a double condenser cooled by ice−water. The product, CD_3COCl (40% yield), gave no ^{1}H NMR signals in the methyl region. A quintet at 2.64 ppm, which remained unchanged during all reactions, was attributed to an impurity.

NMR Kinetics Experiments. All the experiments were carried out using 200 MHz AM, 360 MHz AMX, or 500 MHz ARX spectrometers and the Bruker kinetics program. The data were treated with the Bruker automatic Fourier transform program. Homogeneity was established for azide in the case of iminophosphorane ("normal") reactions, for azide and acyl halide in the triazaphosphadiene adduct reactions, and for Ph_3P in the case of all reactions followed by ^{31}P NMR. To minimize effects on homogeneity, concentrated reactants were added and the experiment begun. The time elapsed between these additions and the first acquired spectrum was usually 45 s. The kinetics were usually followed over a period of ca. 8 h at rt (nominally 16 °C). Each spectrum was acquired with eight scans and 5 s relaxation delay. The spectra were spaced at increasing intervals starting with 5 s periods. In some cases, ^{31}P NMR spectra were acquired alternately in the same run with ^{1}H NMR spectra for a better defined comparison.

Half-lives were estimated by using the integrated NMR peaks (A) in an uncomplicated region of the spectrum with $t_{1/2} = \ln 2/[\ln(A_0/A)(t_1 - t_2)]$. First-order (or pseudo-first-order) kinetics were assumed, and half-lives were obtained at those times for which competing reactions were minimal.

Three types of reactions were studied (200 MHz, several at 500 MHz) by means of ^{1}H and ^{31}P NMR spectroscopy: (1) the reaction of a phosphine and an azide to form an iminophosphorane, (2) the reaction of an iminophosphorane with an acylating agent ("normal" pathway), and (3) the reaction of a phosphine with a mixture of a reactive acyl derivative and an azide ("triazaphosphadiene adduct" pathway, TAP).

Kinetic Studies of Iminophosphorane Formation. A. ^{1}H NMR. (1) Ph_3P (5.9 mg, 0.023 mmol) was added to *syn*-(CH_2N_3,CH_3)(CH_3,CH_3)B (**1**) (5.0 mg, 0.021 mmol) in $CDCl_3$

(1 mL) and the formation of the triazaphosphadiene intermediate **2** and its transformation into the bimane *P*-triphenyliminophosphorane **3** followed for 8 h. A half-life of 95 s is observed for formation of **2** [δ 1.60 (s, 3H), 1.69 (s, 3H), 2.17 (s, 3H), 4.76 (s, 2H)]. A half-life of 50 min is observed for transformation of **2** to **3** [δ 1.49 (s, 3H), 1.79 (s, 3H), 2.58 (s, 3H), 4.15 (s, 1H), 4.26 (s, 1H) and 7.3−7.6 (m, 15H, Ph)]. (2) A solution of *P*-tri-2-furylphosphine (5.50 mg, 0.024 mmol) and **1** (4.86 mg, 0.021 mmol) in $CDCl_3$ (0.5 mL) was allowed to react for 4 d (spectra taken daily). Only peaks for bimane *P*-tri-2-furyliminophosphorane (**3a**) were observed [δ 1.82 (s, 3H), 1.88 (s, 3H), 2.46 (s, 3H), 3.88 (s, 2H); multiplets centered at 6.56, 7.17, and 7.74 (furyl)]. (3) Triphenylphosphine (6.51 mg, 0.025 mmol) and α-azido-*o*-xylene (**1b**) (29 μL, 10% in $CDCl_3$, 0.02 mmol) in $CDCl_3$ (0.94 mL) were allowed to react for 3 d (spectra taken daily) to obtain *o*-xylyl *P*-triphenyliminophosphorane (**3b**) [δ 2.34 (s, 3H), 3.86 (s, 2H) and Ph region 7.17−7.72 (m, 15 H)]. The formation of the xylyl triazaphosphadiene intermediate **2b** was observed [δ 2.18 (s, 3H), 4.29 (s, 2H), and 7.1−7.8 (Ph)].

B. ^{31}P NMR (360 MHz). Triphenylphosphine (25.4 mg, 0.10 mmol) was added to azide **1** (20.5 mg, 0.09 mmol) in $CDCl_3$ (2.2 mL), and the reaction was followed for 8 h. The half-lives for the formation of the intermediate **2** (25.00 ppm) and of the iminophosphorane **3** (13.76 ppm) were the same as those found in the ^{1}H NMR studies described above.

Reaction of Iminophosphoranes with Acylating Agents. "Normal" Path. A. ^{1}H and ^{31}P NMR (500 MHz). Triphenylphosphine (6.94 mg, 26 μmol) and azidobimane **1** (4.92 mg, 20.8 μmol) in $CDCl_3$ (0.5 mL) were allowed to react for 6 h. NMR spectra indicated only iminophosphorane **3** and excess Ph_3P. Using a fresh solution of AcCl in $CDCl_3$ (3.0 μmol CH_3COCl/10 μL), six aliquots of 12 μL each and then aliquots of 20, 30, 20, and 30 μL each (total 51.6 μmol CH_3COCl) were added within 1 h. Both proton and phosphorus NMR spectra were measured after each addition. After addition of 3.6 μmol, chloroimine **7** and AcCl were observed together with $Ph_3P{=}O$ (^{31}P NMR). After another 3.6 μmol had been added, the peaks of acetic anhydride and acetic acid were found. After a total of 14.4 μmol, the solution had turned orange; after another 14.4 μmol, the solution became yellow; one peak for an α-CH_3 of **3** had moved upfield, the β-CH_2 peak had broadened and shifted downfield, and the phosphorus peak of **3** had essentially been replaced by a new peak for **8** at 38.96 ppm. After the addition of 36.6 μmol, the chloroimine **7**, the phosphinamino salt **8**, the acetamido bimane **6**, and $Ph_3P{=}O$ were well represented in the spectra. The acetamidobimane **6** became discernible after 10.8 μmol had been added but remained smaller than **7** until 1 h after the final addition, when the intensity ratio of **7** and **6** reversed, the latter becoming the most prominent.

B. ^{1}H NMR. (1) Azidobimane **1** (4.99 mg, 21 μmol) and Ph_3P (6.48 mg, 25 μmol) were allowed to react in $CDCl_3$ (0.97 mL) for 12 h, and then AcCl (25 μL, 350 μmol) was added and **7** and **8** were immediately formed. Evaporation of the solvent gave a residue which contained only **6** and **8**. (2) To the bimane *P*-tri-2-furyliminophosphorane (**3a**) from the reaction of **1** (21 μmol) and *P*-tri-2-furylphosphine (24 μmol) were added successively more concentrated aliquots (0.011−0.022 M) of AcCl in $CDCl_3$. Only the acetamidobimane **6** and tri-2-furylphosphine oxide were observed. (3) Two solutions of (*o*-xylylimino)phosphorane (**3b**) were each prepared from **1b** (20 μmol) and Ph_3P (25 μmol) in $CDCl_3$ (0.94 mL). Acetyl chloride (10%)/$CDCl_3$ (22 μmol) was added to one tube and pure AcCl (280 μmol) to the other. Both solutions gave $Ph_3P{=}O$ and a precipitate of α-(acylamido)-*o*-xylene (**6b**) [δ (^{1}H) 2.02, 2.33, 4.44, 5.56 and 7.20 ppm]. (4) The azide **1** (4.85 mg, 21 μmol) and Ph_3P (6.05 mg, 23 μmol) in $CDCl_3$ (0.5 mL) were allowed to react overnight, acetic anhydride (10 μL) was added to the resulting iminophosphorane **3**, and spectra were taken over a period of days. Signals for **6** and for $Ph_3P{=}O$ appeared slowly over this time, *but reaction was incomplete with the less reactive anhydride.*

C. Control Experiments. (1) ^{1}H NMR: (a) Azidobimane **1** (0.24 mmol) and Ph_3P (0.23 mmol) in $CDCl_3$ (0.97 mL) were allowed to react overnight before 10% $CH_3COCl/CDCl_3$ (27.4 μL) was added. Ammonia ($CDCl_3$ solution) had no effect on the bimane portion of the spectrum; addition of acetamidobimane enhanced one set of signals, showing that **6** had formed. (b) A mixture of $Ph_3P{=}O$, **6**, and ammonia ($CDCl_3$) showed no change with time. (c) A mixture of $Ph_3P{=}O$, **6**, and AcCl showed no change with time. (d) (360 MHz) Iminophosphorane **3** was prepared from azide **1** (2.7 mg, 0.012 mmol) and Ph_3P (4.4 mg, 0.017 mmol in $CDCl_3$ (0.6 mL) (12 h). A fresh solution of HCl in $CDCl_3$ (0.2 M) was prepared by bubbling dry HCl into cooled solvent. Aliquots of this solution were added to the iminophosphorane **3** solution. The signals of **3** shifted gradually to those of **8** (see Figure 2). (2) ^{31}P NMR (360 MHz): (a) Iminophosphorane **3** was prepared from **1** (20.5 mg, 0.088 mmol) and Ph_3P (26.2 mg, 0.1 mmol) in $CDCl_3$ (2.2 mL). Aliquots of $HCl/CHCl_3$ (0.35 M) were added. The peak for **3** broadened and diminished while the signal at 38.6 ppm grew and became sharper. (b) In the presence of AcCl the ^{31}P peaks of Ph_3P and $Ph_3P{=}O$ in $CDCl_3$ were shifted from δ −4.90 to −4.93 and 29.87 to 29.62 ppm, respectively.

NMR Studies of the "Triazaphosphadiene Adduct" Pathway. A. Kinetics. (1) Sequential ^{1}H and ^{31}P NMR (500 MHz): acetyl chloride (200 μL, 60 μmol) in $CDCl_3$ was added to a solution of azidobimane **1** (4.91 mg, 21 μmol) in $CDCl_3$ (0.4 mL), followed by Ph_3P (7.16 mg, 27 μmol). The contents were mixed and the tube put into the probe. Starting within 35 s of mixing, spectra were taken for 7 h at increasing time intervals, with a ^{31}P spectrum 32 s after each ^{1}H spectrum. (2) ^{1}H NMR (200 MHz): CH_3COCl (27.6 μL, 10% in $CDCl_3$, 40 μmol) was added to azidobimane **1** (5.05 mg, 22 μmol) in $CDCl_3$ (0.97 mL), followed by Ph_3P (5.99 mg, 23 μmol). Starting within ca. 45 s of mixing, NMR measurements were continued for 8.5 h at increasing time intervals. Prior to phosphine addition, signals for both azide **1** and the acid chloride were unchanged but acetic anhydride and acetic acid were present. The formation and disappearance of the triazaphosphadiene adduct **5**, as well as the formation of **7**, **6**, and **10**, were followed with time. Spectra taken ca. 6 h after the last scheduled spectrum, one with, and one without added D_2O (5 μL), were identical. (3) ^{1}H NMR (360 MHz): Ph_3P (5.90 mg, 22 μmol) were added to a solution of azide **1** (5.00 mg, 200 μmol) and trideuterioacetyl chloride (6 μL, 81 μmol) in $CDCl_3$ (1 mL) and a spectrum taken after 41 s.

In ^{1}H spectra, the bimane β-methylene region was easily interpreted while the methyl region was complicated since each species had at least three methyl proton signals (four if acetyl**X** were present). Nevertheless, careful integrations of the peaks in the methyl region could be carried out. The experiments (1−3) may be summarized as follows: 1. Azide **1** decreased over ca 22 min. 2. Triazaphosphadiene adduct **5** [^{1}H δ 1.55 (s, 3H), 1.73 (s, 3H), 2.22 (s, 3H), and 4.92 (s, 2H); ^{31}P δ 34.1 ppm] formed within 1 min but disappeared over 45 min. The course of the reaction followed by ^{31}P spectra is illustrated in Figure 4. The peak for Ph_3P (−4.71 ppm) disappears, that for **5** (34.1 ppm) appears immediately then disappears, and the peak for $Ph_3P{=}O$ (29.79) grows and remains. 3. The chloroimine **7** [^{1}H δ 1.83 (s, 3H), 1.90 (s, 3H), 2.33 (s, 3H), 2.46 (s, 3H) and 4.55 (s, 2H)] formed within a few minutes and disappeared slowly over many hours. 4. The 2.46 ppm peak was absent from the spectrum of the reaction mixture containing deuterated AcCl and thus was due to the acetyl CH_3. 5. Acetamidobimane **6** was evident even in the first spectrum, and its peaks increased over the whole period. 6. Monochlorobimane, *syn*-(CH_2Cl,CH_3)(CH_3,CH_3)B (**10**) [^{1}H δ 1.86, 1.95, 2.44 and 4.48 ppm], began to appear after 11 min. 7. Ph_3P (^{31}P δ −4.7 ppm) diminished in intensity over the first 45 min. 8. $Ph_3P{=}O$ (^{31}P δ 29.8 ppm) was visible in the first ^{31}P spectrum and increased over time; the characteristic peaks for the Ph region also appeared immediately in the ^{1}H spectrum and increased over time. 9. After ca. 11 min, a new set of peaks for the oxaphosphatriazine **12** appeared, with a methyl peak at 2.40 ppm and a set of peaks similar to those of the $Ph_3P{=}O$ but at about 0.25 ppm lower field. The ^{31}P NMR peak at 25.00 ppm appeared at the same time.

B. Additional Experiments. All solutions were made up with 1 mL of $CDCl_3$. (1) Modest reactivity of acetic anhydride. Azide **1** (5.40 mg, 0.023 mmol), acetic anhydride (0.039 mmol), and Ph_3P (6.23 mg, 0.024 mmol) were reacted overnight. The

iminophosphorane **3** formed first and then slowly reacted to produce acetamidobimane **6** and $Ph_3P{=}O$.

(2) Effect of hydrogen chloride on formation of chlorobimane **10**. To one of two reaction mixtures containing **1** (5.04 mg), AcCl (27.6 μL, 10% in $CDCl_3$, 0.04 mmol), and Ph_3P (6.1 mg) was added HCl/$CDCl_3$ (60 μL, 0.2 M). After the reaction was complete, the ratio of chlorobimane **10** to acetamidobimane **6** was found to be 1:0.60, an increase of 19% in comparison to a ratio of 1:0.49 in the mixture without added HCl.

(3) Absence of intermediates in the *P*-tri-2-furylphosphine reaction. NMR spectra of a reaction mixture containing azide **1** (4.75 mg, 0.020 mmol), AcCl (0.040 mmol), and *P*-tri-2-furylphosphine (5.60 mg, 0.024 mmol) were measured over several days, the $t_{1/2}$ for the formation of iminophosphorane being about 2 min. Some 95% conversion of the phosphine to the phosphine oxide was noted, although 19% of **1** remained unreacted. The products were the acetamidobimane **6** and the chlorobimane **10**. No intermediates were observed.

(4) Absence of intermediates in the α-azido-*o*-xylene reaction. α-Azido-*o*-xylene (**1b**) (0.02 mmol), AcCl (0.04 mmol), and Ph_3P were mixed. NMR spectra showed that all starting material was consumed in 4 d to give the phosphine oxide and α-chloro-*o*-xylene (**10b**) without any indication of the presence of reaction intermediates.

(5) A solution of dry HCl in $CDCl_3$ was prepared and either Ph_3P or $Ph_3P{=}O$ added. The ^{31}P signal for the phosphine shifted from −4.8 to −4.3 ppm, while the ^1H signal shifted from 7.45 to 7.34 ppm. There was no effect on the signals of the oxide.

FTIR Kinetic Studies on *syn*-(Azidomethyl,methyl)-(methyl,methyl)bimane (1). [A] Reaction of Azide, Acid Chloride, and Triphenylphosphine ("Triazaphosphadiene Adduct" Pathway). A mixture of azide **1** (5.0 mg, 0.020 mmol) and AcCl (4.5 μL, 0.063 mmol) in $CHCl_3$ (1 mL) was prepared, and then Ph_3P (6.5 mg, 0.025 mmol) in $CDCl_3$ (1 mL) was added. FTIR spectra (KBr cell) were measured at rt at the same time intervals and concentrations as used for the NMR experiments. No significant changes in the IR spectrum were noted before the AcCl began to attack the gasket of the cell and the experiment was discontinued.

B. Reaction of Acid Chloride with Iminophosphorane ("Normal" Pathway). Ph_3P (10.5 mg, 0.04 mmol) in $CDCl_3$ (1 mL) was added to **1** (9.3 mg, 0.04 mmol) in $CHCl_3$ (1 mL). FTIR spectra of the reaction mixture in a KBr cell were measured at rt with the same time intervals and twice the concentrations as those used for the NMR experiments. A simulated initial spectrum was made by addition of the spectra of the azidobimane and Ph_3P ("spectral addition"). The initial spectrum, the solvent spectrum, and the background spectrum were all subtracted from each of the experimental spectra. (The background and solvent spectra were subtracted using a fixed factor to avoid introducing subjective errors. The spectrum of starting materials was subtracted according to the base line.) The resulting spectra were plotted over certain spectroscopic ranges. The spectrum of the intermediate was obtained through spectral subtraction of the starting material and product spectra (after 5 h reaction time).

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