

Insertion of Benzynes into the P=N Bond of *P*-Alkenyl(alkynyl)- λ^5 -phosphazenes

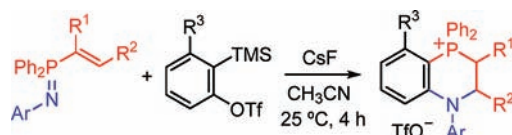
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ABSTRACT



Benzynes, generated from 2-(trimethylsilyl)phenyl triflates, have been found to react with *P*-Alkenyl- λ^5 -phosphazenes via a formal π -insertion into the P=N bond. A subsequent retro [2 + 2] cycloaddition/6 π electrocyclization/protonation cascade explains the formation of the resulting 1,4-benzazaphosphorinium triflates. *P*-Alkynyl λ^5 -phosphazenes and phosphane sulfides undergo similar transformations.

In the past decade, aryne chemistry has undergone an unprecedented revival.¹ The introduction of 2-(trimethylsilyl)phenyl triflates as mild aryne precursors,² and a variety of further reactions applied to these reactive intermediates, have facilitated access to various *ortho*-disubstituted arenes, which are otherwise difficult to prepare.

Arynes are highly strained and kinetically unstable electrophilic intermediates. Most of their reactions start by the addition of nucleophiles and are completed by a subsequent trapping step with electrophiles.³ When a nucleophile and

electrophile belong to the same molecule, these processes usually lead to benzoannulated systems either by [3 + 2] or [4 + 2] cycloaddition reactions,^{4,5} by insertion into σ -bonds,⁶ or by other tandem processes triggered by the initial nucleophilic addition.⁷

Up to now, limited success has been achieved in the insertion reactions of arynes into π -bonds, also classified as

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[2 + 2] cycloadditions, although some reports with C=C bonds have been disclosed leading to stable benzocyclobutenes.⁸ A number of insertions into carbon–heteroatom double bonds are also known,⁹ but to our knowledge, similar processes involving heteroatom–heteroatom double bonds have not been yet reported.

Some of our recent investigations have been devoted to the chemistry of λ^5 -phosphazenes (iminophosphoranes, $R^1R^2P=N-R^3$).¹⁰ These organophosphorus compounds exhibit considerable *N*-nucleophilicity due to their P^+-N^- ylidic nature.¹¹ In the particular case of *P*-alkenyl- λ^5 -phosphazenes, we have demonstrated their ability to undergo a variety of 1,4-additions to its conjugated $N=P-C=C$ heterobutadienyl fragment (Figure 1).¹²

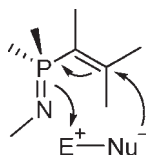
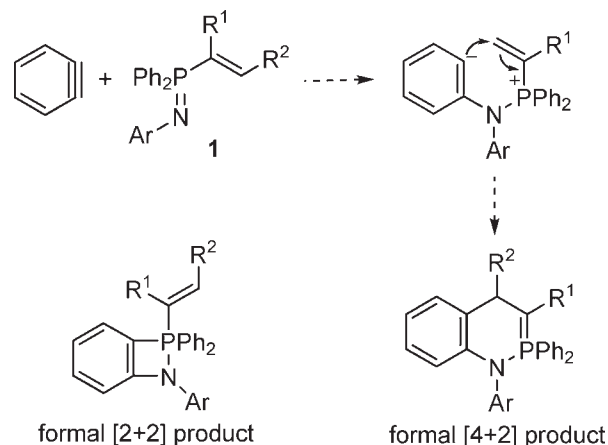


Figure 1. Schematic representation of 1,4-additions to *P*-alkenyl- λ^5 -phosphazenes.

By combining the reactive characteristics of arynes and *P*-alkenyl- λ^5 -phosphazenes **1**, we reasoned that a formal [4 + 2] cycloaddition between both chemical entities is

conceivable. This process is best visualized as a stepwise mechanism initiated by the nucleophilic attack of the phosphazene N atom onto the aryne, followed by a subsequent dipolar cyclization step, as represented in Scheme 1. A priori, the alternative formation of the formal [2 + 2] cycloadduct and the concerted nature of both classes of cycloadditions should not be ruled out.

Scheme 1. Possible Products of the Reaction of Benzyne and *P*-Alkenyl- λ^5 -phosphazenes



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The reaction of the *N*-(4-anisyl)- λ^5 -phosphazene **1a** with 2-(trimethylsilyl)phenyl triflate **2a** (3 equiv) and CsF (4 equiv) in refluxing acetonitrile under a nitrogen atmosphere for 2 h gave a 54% yield of a product, whose analytical and spectral data showed it to be a phosphonium triflate containing a P–CH₂–CH₂–N fragment instead of the expected protonated form of the [4 + 2] cycloadduct (Scheme 1). In fact, an X-ray crystal structure determination confirmed that the obtained compound was the 1,4-benzazaphosphorinium triflate **3a** (Scheme 2). The source of the proton that becomes incorporated into the ethylene fragment of **3a** should be the acetonitrile used as solvent, a circumstance that is not uncommon in the reactions of benzyne.^{3c,9k,13}

After some optimization experiments, alternative solvents (1,4-dioxane, benzene) proved to be unsuitable

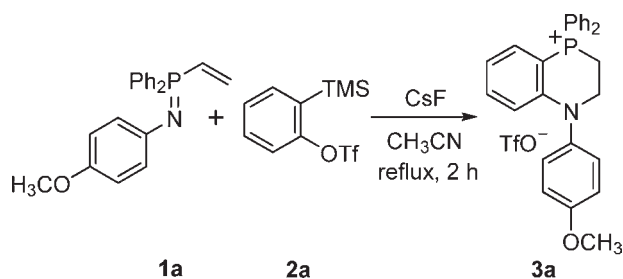
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Scheme 2. Reaction of *P*-Vinyl- λ^5 -phosphazene **1a** with Benzyne Affording 1,4-Benzazaphosphorinium Triflate **3a**



whereas the best reaction conditions were established as those in which the phosphazene/CsF/**2a** ratio is 1:2:1.2, and the reaction is run for 4 h in acetonitrile at 25 °C. The yield of **3a** was thus improved up to 90%.

Next we examined the scope of this reaction under these optimal reaction conditions by using various *N*-aryl-*P*-vinyl- λ^5 -phosphazenes bearing both electronreleasing and electronwithdrawing substituents at the aryl nucleus (entries 1–6, Table 1). We extended the substrate scope to other *P*-alkenyl counterparts,^{12,14} such as the *P*-(1-phenylvinyl) derivatives ($R^2 = \text{Ph}$, $R^3 = \text{H}$) of entries 7 and 8, and the *P*-(*E*-1-propenyl) derivatives ($R^2 = \text{H}$, $R^3 = \text{Me}$) of entries 9 and 10. In these latter cases, prolonged reaction times of up to 20 h afforded the best yields. It is noteworthy that the use as reagent of the unsymmetrical 3-methoxybenzyne provided a single reaction product in all the tested cases (entries 11–14). Regioselective reactions of 3-methoxybenzyne are well-known and have been rationalized as involving the more favorable nucleophilic attack at the *meta* position for electronic and steric reasons.^{4c,7d,15} Interestingly, our results show that in these reactions electronic factors dominate over steric ones with isomers **3k–n** being the only reaction products (Figure 2). The structure of **3k** was unambiguously confirmed by single-crystal X-ray analysis (Figure 3).

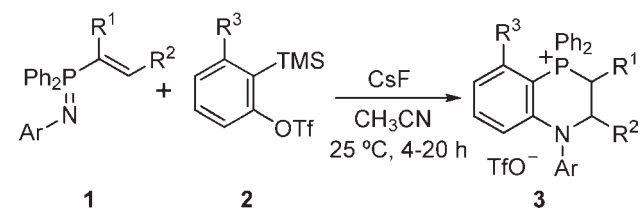
A reasonable mechanism for explaining the formation of species **3** is represented in Scheme 3. First, the λ^5 -phosphazene **1** reacts with the in situ generated benzyne **2** to yield the formal [2 + 2] cycloadduct, which then undergoes a retro [2 + 2] cycloaddition and a further 6π electrocyclic ring closure to build the 1,4-benzazaphosphorine ring system in the form of a cyclic alkylidenephosphorane. This basic intermediate is subsequently protonated by the acetonitrile used as solvent to furnish the final cationic part of triflate **3**.

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Table 1. Reaction of *P*-Alkenyl- λ^5 -phosphazenes and Aryne Precursors in the Presence of CsF^a



entry	Ar	R ¹	R ²	R ³	product	yield (%) ^b
1	4-CH ₃ OC ₆ H ₄	H	H	H	3a ^c	90
2	C ₆ H ₅	H	H	H	3b	80
3	4-CH ₃ C ₆ H ₄	H	H	H	3c	85
4	2- ^{<i>i</i>} PrC ₆ H ₄	H	H	H	3d	95
5	4-BrC ₆ H ₄	H	H	H	3e	75
6	2-CH ₃ -5-NO ₂ C ₆ H ₃	H	H	H	3f	70
7	4-CH ₃ C ₆ H ₄	C ₆ H ₅	H	H	3g	76
8	4-BrC ₆ H ₄	C ₆ H ₅	H	H	3h	59
9	4-CH ₃ C ₆ H ₄	H	CH ₃	H	3i	81
10	4-CH ₃ OC ₆ H ₄	H	CH ₃	H	3j	94
11	4-CH ₃ C ₆ H ₄	H	H	OCH ₃	3k ^c	66
12	4-CH ₃ OC ₆ H ₄	H	H	OCH ₃	3l	57
13	4-BrC ₆ H ₄	H	H	OCH ₃	3m	76
14	2-CH ₃ -5-NO ₂ C ₆ H ₃	H	H	OCH ₃	3n	57

^a Reactions Conditions: **1** (0.3 mmol), **2** (0.36 mmol), CsF (0.6 mmol), CH₃CN (10 mL), 25 °C, nitrogen atmosphere, 4 h for the synthesis of **3a–f**, and 20 h for the synthesis of **3g–n**. ^b Yield of purified product. ^c Structure confirmed by X-ray crystallography.

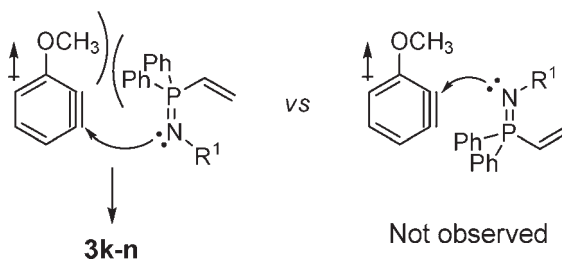


Figure 2. Electronic and steric factors in the reaction of *P*-vinyl- λ^5 -phosphazenes and 3-methoxybenzyne.

We next tested related *P*-alkynyl derivatives, such as the *N*-aryl-*P*-phenylethynyl- λ^5 -phosphazenes **4**¹⁶ and the *P*-phenylethynylphosphane sulphide **5**,¹⁷ in their reaction with the benzyne precursor **2a** in the presence of CsF under similar reaction conditions. As shown in Table 2, triflates **6** resulting from the λ^5 -phosphazenes **4** (entries 1–3) were obtained in moderate yields, whereas compound **7** (entry 4), derived from the initial [2 + 2] cycloaddition of benzyne

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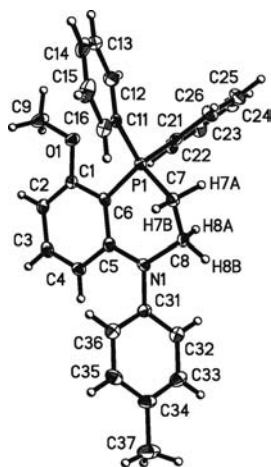
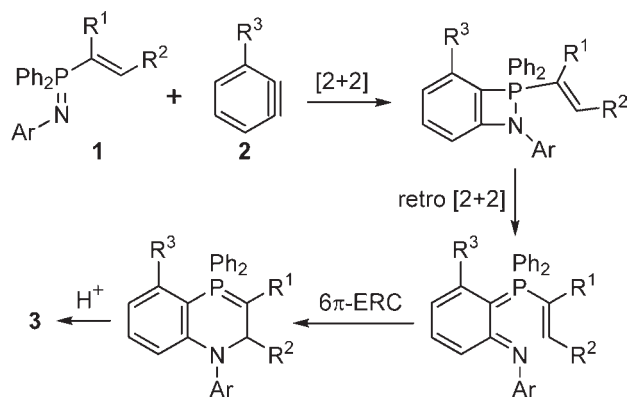


Figure 3. Crystal structure of the 1,4-benzazaphosphorinium cation of triflate **3k**.

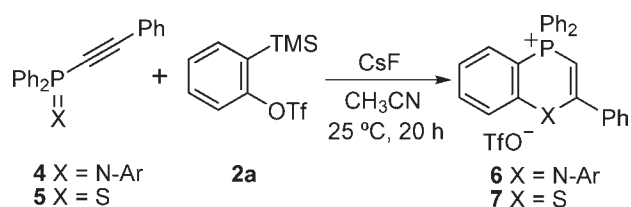
Scheme 3. Proposed Mechanism for the Reaction of *P*-Alkenyl- λ^5 -phosphazenes and Arynes



with the P=S double bond of the sulphide **5**, was also conveniently obtained.

In summary, we have successfully developed a method for the preparation of 1,4-benzazaphosphorinium salts by

Table 2. Reaction of *P*-Alkynyl- λ^5 -phosphazenes **4** and *P*-Alkynylphosphane Sulphide **5** with in-situ Generated Benzynes^a



entry	X	product	yield (%) ^b
1	4-CH ₃ C ₆ H ₄ N	6a	69
2	4-BrC ₆ H ₄ N	6b	65
3	2-CH ₃ -5-NO ₂ C ₆ H ₃ N	6c ^c	59
4	S	7	82

^a Reactions Conditions: **1** (0.3 mmol), **2** (0.36 mmol), CsF (0.6 mmol), CH₃CN (10 mL), 25 °C, nitrogen atmosphere, 20 h. ^b Yield of purified product. ^c Structure confirmed by X-ray crystallography.

reacting benzynes with *P*-alkenyl and *P*-alkynyl- λ^5 -phosphazenes. These reactions apparently involve the initial π -insertion of benzynes into the P=N bond of the organo-phosphorus reagent, followed by a retro [2 + 2] cycloaddition/ 6π electrocyclization/protonation cascade. Under this mechanistic scheme, these results show for the first time the insertion of benzynes into a heteroatom-heteroatom double bond. Further investigations on similar reactions with more simple λ^5 -phosphazenes and related P(V) species are currently underway.

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Supporting Information Available. Detailed experimental procedures, characterization data, copies of ¹H, ¹³C, and ³¹P NMR, and crystallographic information file (CIF) for compounds **3d**, **3k**, and **6c**. This material is available free of charge via the Internet at <http://pubs.acs.org>.