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A stereoselective synthetic entry to β-substituted α-[(*trans*)-vinyl] phosphonamides

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ABSTRACT

α-(*trans*-Vinyl) phosphonamides with different substituents at the β-position were stereoselectively synthesized in high yields by treatment of β-substituted α-epoxy-α-trimethylsilyl phosphines with oxidizing agents. The corresponding phosphonamides were unstable in most cases and underwent reductive elimination affording desilylated vinyl derivatives. In turn, α-epoxy phosphines resulted from the [1+2] addition of [bis(diisopropylamino)phosphino](trimethylsilyl)carbene **2** to aliphatic, aromatic, and heteroaromatic aldehydes. In this way, a great variety of vinyl compounds have been efficiently prepared through one-pot procedure.

1. Introduction

α-Vinyl phosphonamides are interesting and versatile building blocks in organic synthesis. They have been synthesized by addition of a β-vinyl phosphonamide anion to an α,β-unsaturated ketone,[1] and by palladium-catalyzed coupling of diazaphospholidines with vinyl halides,[2] respectively. The products obtained have been used, for instance, in the preparation of antibacterial agents[3] and as dienophiles in Diels–Alder cycloadditions.[4] The α-vinyl phosphonamide unit is also present in the structure of some nucleoside analogs for antiviral treatment.[5] Moreover, in some cases, alcohols and aldehydes have been prepared from α-vinyl phosphonamides.[6]

Recently, we reported on the stereoselective synthesis of alkyl,[7] aryl,[8] and heteroaryl[9] β-substituted α-epoxy thiophosphonamides through the [1+2] addition of [bis(diisopropylamino)phosphino]-(trimethylsilyl)carbene **2** to aliphatic, aromatic, and heteroaromatic aldehydes, respectively. Carbene **2** is a nucleophilic and stable species, which is photochemically generated from the corresponding diazo compound **1** (Scheme 1).[10] The resultant α-epoxy phosphines **3** afforded, under thiolation, the corresponding α-epoxy thiophosphonamides **4**, which are stable products.

In this paper, we describe synthetic routes to α-vinyl derivatives **6** from the intermediate α-epoxy phosphines. When these compounds were oxidized by using different oxygen sources instead of thiolation, the resultant epoxy phosphonamides **5** were unstable and rearranged in situ to vinyl compounds **6**.

2. Results and discussion

The reaction of carbene **2** with benzaldehyde was carried out at room temperature, under previously described conditions,[8] and the appearance of a peak in the ^{31}P NMR spectrum at 53 ppm, attributable to the epoxy phosphine, was observed. After 10 min, a dichloromethane solution of bis(trimethylsilyl)peroxide was added and the mixture was stirred for 30 min. The signal at 53 ppm disappeared at the same rate that a new signal at 24 ppm appeared. This is a typical chemical shift for an oxidized phosphorus derivative. Nevertheless, after working-up, the ^{1}H NMR spectrum of the crude reaction did not show the signal at 4.5 ppm attributable to the α-oxirane proton in the expected epoxy derivative. Instead, a doublet of doublet at 6.8 ppm was observed with $^{2}J_{P-H}$=18.8 Hz and $^{3}J_{H-H}$=17.2 Hz. The second vinyl proton could not be differentiated from the absorption of some aromatic protons at very close chemical shifts. The obtained product was purified by column chromatography affording a solid in 70% yield whose structure **6e** was unambiguously assigned by an X-ray diffraction analysis (Scheme 1, Fig. 1). This product was also

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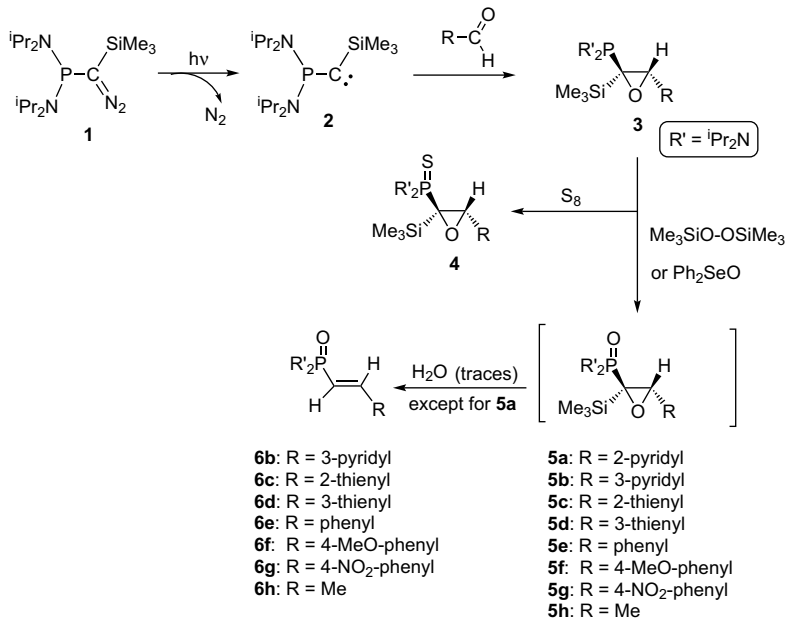


Scheme 1.

obtained in 74% yield after purification, employing diphenylselenoxide as oxidizing agent.

To verify if these results could be extensive to other different aldehydes, the reaction was carried out with 2- and 3-pyridinecarboxaldehyde, 2- and 3-thiophenecarboxaldehyde, 4-methoxy- and 4-nitrobenzaldehyde, and acetaldehyde, as representative examples of heteroaromatic, aromatic, and aliphatic aldehydes. As a result, vinyl phosphonamides **6b**–**h** were, respectively, produced in good yields (Table 1). In the case of acetaldehyde, the yield was lower due to the competition with a secondary process that we had been previously observed.[7]

Interestingly, epoxide **5a**, which has been obtained using 2-pyridincarbaldehyde, could be isolated and fully characterized. This compound remained unaltered for weeks when stored at the refrigerator under nitrogen atmosphere. However, vinyl phosphonamide **6a** was efficiently produced when **5a** was treated with hydrated tetrabutylammonium fluoride, which is an usual reagent in desilylation reactions, at room temperature for 4 h (Scheme 2).

Desilylation occurs easily in these type of products in the presence of humidity or acid traces. Then the resultant species, probably an oxiranyl anion,[11] must evolve to the vinyl derivative under the reaction conditions. The active role in this process of the

Table 1
Melting points and isolated yields for epoxide **5a** and vinyl derivatives **6b**–**h**

Compound	R	Melting point (°C)	Isolated yield (%)
5a	2-Pyridyl	60–62[a]	76
6b	3-Pyridyl	161–162[a]	95[b]
6c	2-Thienyl	155–157[c]	63[b]
6d	3-Thienyl	161–162[a]	85[b]
6e	Phenyl	150–153[a]	70[b]
6f	4-Methoxyphenyl	148–150[a]	90[b]
6g	4-Nitrophenyl	230 (dec)[a]	52[b]
6h	Methyl	83–86[a]	12[b]

[a] From pentane.
[b] Oxidation with bis(trimethylsilyl)peroxide.
[c] From ether.

phosphoranyl versus thiophosporanyl group is manifested by considering the stability of epoxide **7**, which was prepared by desilylation of the corresponding parent compound **4e** under similar conditions that in the case of **5a** (Scheme 2). The reaction took place with retention of configuration[11] as shown by the spectroscopic data. Any vinyl product was not observed in this instance.

Oxygen transfer from phosphoranyl epoxides **5** was manifested when desilylation of **5a** was carried out in the presence of trimethylphosphine. The ^{31}P NMR spectrum of the reaction mixture showed that the signal of the phosphine at −60 ppm was shifted to +30 ppm according to the presence of trimethylphosphine oxide. In contrast, no change was observed when desilylation of **4e** was

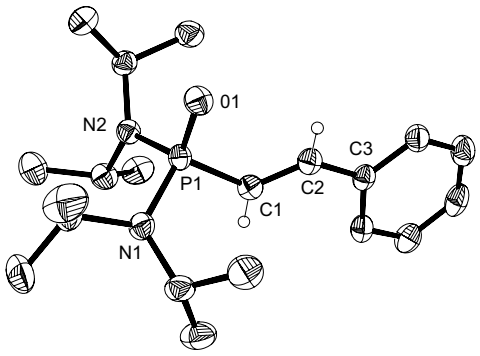
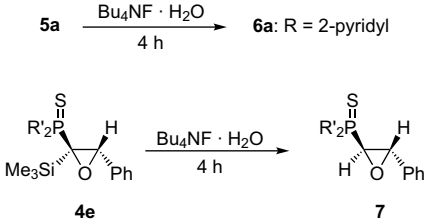


Figure 1. Structure of vinyl phosphonamide **6e** as determined by X-ray structural analysis.



Scheme 2.

achieved in the presence of trimethylphosphine, even when reaction went on overnight.

The reductive formation of vinyl derivatives from epoxides has also been observed in their reactions with alkyllithium reagents,[12] but, as far as we know, there are not precedents on oxygen transfer from epoxides to yield vinyl derivatives. Active investigation is carried out in our laboratories to explain the mechanism of this process.

3. Concluding remarks

In this work, we offer an efficient one-pot synthetic pathway for the stereoselective preparation of vinyl phosphonamides from the reaction between aldehydes and [bis(diisopropylamino)-phosphino](trimethylsilyl)carbene. This new protocol involves the oxidation of the resultant epoxy phosphine with bis(trimethylsilyl)-peroxide or diphenylselenoxide instead of thiolation with elemental sulfur that affords stable epoxy thiophosphonamides.

4. Experimental section

4.1. General

All manipulations were performed under an inert atmosphere of nitrogen by using standard Schlenk techniques. Dry, oxygen-free solvents were employed. Carbene **2** was prepared according to Ref. 10. All employed aldehydes were distilled before each reaction. ^{31}P NMR downfield chemical shifts are expressed with a positive sign, in parts per million, relative to external 85% H_3PO_4. Microanalysis of the synthesized compounds used to afford erratic results since combustion of carbon was systematically incomplete. Purity criterion was assessed from cut-range melting points and homogeneity of ^{31}P, ^{1}H, and ^{13}C NMR spectra of these products.

4.1.1. Crystal data for **6e**

$C_{20}H_{35}N_2OP$, M=350.47, monoclinic, $P2_1/c$, a=12.427(2) Å, b=11.472(1) Å, c=15.280(2) Å, β=108.253(2)°, V=2068.7(4) Å^3, Z=4, T=193(2) K. 11,847 reflections (4246 independent, R_{int}=0.0407) were collected. Largest electron density residue: 0.339 e Å^{-3}, R_1 (for $I>2\sigma(I)$)=0.0453 and wR_2=0.1201 (all data) with $R_1=\Sigma||F_o|-|F_c||/\Sigma|F_o|$ and $wR_2=(\Sigma w\ (F_o^2-F_c^2)^2/\Sigma w(F_o^2)^2)^{0.5}$. All data for **6h** were collected at low temperatures using an oil-coated shock-cooled crystal on a Bruker-AXS CCD 1000 diffractometer with Mo Kα radiation (λ=0.71073 Å). The structure was solved by direct methods[13] and all non-hydrogen atoms were refined anisotropically using the least-squares method on F^2.[14] CCDC 625421 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/conts/retrieving.html (or from the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033; e-mail: deposit@ccdc.cam.ac.uk).

4.2. General procedure for the synthesis of epoxide 5a and vinyl phosphonamides 6b–h

Dried and freshly distilled aldehyde (2 mmol) was added to a solution of carbene **2**[10] (2 mmol) in THF (2 mL) and the resultant solution was stirred at room temperature for 10 min under nitrogen atmosphere. Then bis(trimethylsilyl)peroxide in dichloromethane (0.93 mL, 3 mmol) or, alternatively, diphenylselenoxide (500 mg, 2.0 mmol) in 3 mL of THF was added. The mixture was stirred for 30 min and solvents were removed. The residue was chromatographed on neutral silica gel (mixtures of hexane–EtOAc as eluents) to provide the pure product.

4.2.1. (2RS,3RS)-3-(2-Pyridyl)-2-trimethylsilyl-2-oxiran-2-yl-N,N,N′,N′-tetraisopropylphosphonodiamide **5a**

Crystals, mp 60–62 °C (from pentane). ^{31}P NMR (101.2 MHz, acetone-d_6): δ 23.8. ^{1}H NMR (250 MHz, acetone-d_6): δ −0.12 (s, 9H, Si(CH_3)$_3$), 0.77 (s, 3H, (CH_3)$_2$CHN–), 0.79 (s, 3H, (CH_3)$_2$CHN–), 1.23–1.35 (6s, 18H, (CH_3)$_2$CHN–), 3.37 (m, 2H, (CH_3)$_2$CHN–), 3.58 (m, 2H, (CH_3)$_2$CHN–), 5.24 (d, $^3J_{P-H}$=7.0 Hz, 1H, H_3), 7.27 (m, 1H, $H_{5'}$), 7.70 (ddd, J=J'=7.7 Hz, J''=1.8 Hz, 1H, $H_{arom.}$), 8.02 (m, 1H, $H_{arom.}$), 8.48 (m, 1H, $H_{arom.}$). ^{13}C NMR (62.5 MHz, acetone-d_6): δ 0.86 (Si(CH_3)$_3$), 23.6–24.6 (8 (CH_3)$_2$CHN–), 46.4 (d, $^2J_{P-C}$=5.8 Hz, C_3), 47.6 (2(CH_3)$_2$CHN), 75.8 (d, $^1J_{P-C}$=134.5 Hz, C_2), 124.2 ($C_{3'}$), 127.8 ($C_{5'}$), 136.8 ($C_{4'}$), 148.9 ($C_{6'}$), 160.3 ($C_{2'}$). MS (m/z): 440.2 (M+H$^+$).

4.2.2. (E)-2-(3-Pyridyl)-1-ethenyl-N,N,N′,N′-tetraisopropylphosphonodiamide **6b**

Crystals, mp 161–162 °C (from pentane). ^{31}P NMR (101.2 MHz, acetone-d_6): δ 23.1. ^{1}H NMR (250 MHz, acetone-d_6): δ 1.22 (s, 6H, (CH_3)$_2$CHN–), 1.24 (s, 6H, (CH_3)$_2$CHN–), 1.30 (s, 6H, (CH_3)$_2$CHN–), 1.32 (s, 6H, (CH_3)$_2$CHN–), 3.64–3.76 (m, 4H, (CH_3)$_2$CHN–), 6.96 (dd, $^2J_{P-H}$=$^3J_{H-H}$=18.2 Hz, 1H, H_1), 7.42 (dd, $^3J_{P-H}$=18.6 Hz, $^3J_{H-H}$=18.2 Hz, 1H, H_2), 7.44 (m, 1H, $H_{5'}$), 8.09 (m, 1H, $H_{4'}$), 8.57 (m, 1H, $H_{6'}$), 8.83 (m, 1H, $H_{2'}$). ^{13}C NMR (62.5 MHz, acetone-d_6): δ 22.1 and 22.3 ((CH_3)$_2$CHN–), 44.8 and 44.9 (2(CH_3)$_2$CHN), 123.5 ($C_{5'}$), 127.0 (d, $^1J_{P-C}$=142.1 Hz, C_1), 139.7 (d, $^3J_{P-C}$=19.1 Hz, $C_{3'}$), 133.2 ($C_{6'}$), 139.7 (d, $^2J_{P-C}$=5.7 Hz, C_2), 148.7 ($C_{6'}$), 149.7 ($C_{2'}$). MS (m/z): 352.2 (M+H$^+$), 374.2 (M+Na$^+$), 390.1 (M+K$^+$).

4.2.3. (E)-2-(2-Thienyl)-1-ethenyl-N,N,N′,N′-tetraisopropylphosphonodiamide **6c**

Crystals, mp 155–157 °C (from ether). ^{31}P NMR (101.2 MHz, methanol-d_4): δ 25.3. ^{1}H NMR (250 MHz, methanol-d_4): δ 1.22 (s, 6H, (CH_3)$_2$CHN–), 1.25 (s, 6H, (CH_3)$_2$CHN–), 1.30 (s, 6H, (CH_3)$_2$CHN–), 1.32 (s, 6H, (CH_3)$_2$CHN–), 3.59–3.77 (m, 4H, (CH_3)$_2$CHN–), 6.34 (dd, $^2J_{P-H}$=19.0 Hz, $^3J_{H-H}$=17.0 Hz, 1H, H_1), 7.11 (m, 1H, H′), 7.26 (m, 1H, H′), 7.48 (m, 2H, H_2 and H′). ^{13}C NMR (62.5 MHz, methanol-d_4): δ 22.1, 23.2, 23.5, and 23.6 ((CH_3)$_2$CHN–), 46.6 and 46.7 (2(CH_3)$_2$CHN), 123.0 (d, $^1J_{P-C}$=148.8 Hz, C_1), 128.4, 129.2, and 130.1 ($C_{3'}$, $C_{4'}$, and $C_{5'}$), 138.1 (d, $^2J_{P-C}$=5.7 Hz, C_2), 143.0 (d, $^3J_{P-C}$=21.9 Hz, $C_{3'}$). MS (m/z): 357.1 (M+H$^+$), 379.2 (M+Na$^+$), 395.1 (M+K$^+$).

4.2.4. (E)-2-(3-Thienyl)-1-ethenyl-N,N,N′,N′-tetraisopropylphosphonodiamide **6d**

Crystals, mp 161–162 °C (from pentane). ^{31}P NMR (101.2 MHz, acetone-d_6): δ 24.0. ^{1}H NMR (250 MHz, acetone-d_6): δ 1.21 (s, 6H, (CH_3)$_2$CHN–), 1.24 (s, 6H, (CH_3)$_2$CHN–), 1.29 (s, 6H, (CH_3)$_2$CHN–), 1.31 (s, 6H, (CH_3)$_2$CHN–), 3.59–3.76 (m, 4H, (CH_3)$_2$CHN–), 6.61 (dd, $^2J_{P-H}$=19.2 Hz, $^3J_{H-H}$=17.5 Hz, 1H, H_1), 7.46 (dd, $^3J_{P-H}$=19.6 Hz, $^3J_{H-H}$=17.5 Hz, 1H, H_2), 7.53 (m, 2H, $H_{2'}$ and $H_{5'}$), 7.70 (m, 1H, $H_{4'}$). ^{13}C NMR (62.5 MHz, acetone-d_6): δ 22.0–22.4 ((CH_3)$_2$CHN–), 44.8 (2(CH_3)$_2$CHN), 124.1 (d, $^1J_{P-C}$=144.0 Hz, C_1), 124.9 and 125.1 ($C_{2'}$ and $C_{5'}$), 125.5 ($C_{4'}$), 137.0 (d, $^2J_{P-C}$=5.7 Hz, C_2), 139.8 (d, $^3J_{P-C}$=21.1 Hz, $C_{3'}$). MS (m/z): 357.2 (M+H$^+$), 379.2 (M+Na$^+$), 395.1 (M+K$^+$).

4.2.5. (E)-2-Phenyl-1-ethenyl-N,N,N′,N′-tetraisopropylphosphonodiamide **6e**

Crystals, mp 150–153 °C (from pentane). ^{31}P NMR (101.2 MHz, acetone-d_6): δ 23.8. ^{1}H NMR (250 MHz, acetone-d_6): δ 1.18 (s, 6H, (CH_3)$_2$CHN–), 1.21 (s, 6H, (CH_3)$_2$CHN–), 1.26 (s, 6H, (CH_3)$_2$CHN–), 1.29 (s, 6H, (CH_3)$_2$CHN–), 3.57–3.75 (m, 4H, (CH_3)$_2$CHN–), 6.75 (dd, $^2J_{P-H}$=18.8 Hz, $^3J_{H-H}$=17.2 Hz, 1H, H_1), 7.34–7.41 (m, 4H, H_2, $H_{3'}$, and $H_{4'}$), 7.62 (d, $^3J_{H-H}$=6.7 Hz, 2H, $H_{2'}$). ^{13}C NMR (62.5 MHz, acetone-d_6): δ 22.9 and 23.5 ((CH_3)$_2$CHN–), 45.9 (2(CH_3)$_2$CHN), 125.6 (d, $^1J_{P-C}$=144.0 Hz, C_1), 127.0, 129.7, and 129.9 ($C_{2'}$, $C_{3'}$, and $C_{4'}$), 137.6 (d, $^3J_{P-C}$=19.9 Hz, $C_{1'}$), 144.1 (d, $^2J_{P-C}$=5.8 Hz, C_2). MS (m/z): 351.2 (M+H$^+$), 372.2 (M+Na$^+$).

4.2.6. (*E*)-2-(4′-Methoxyphenyl)-1-ethenyl-*N*,*N*,*N*′,*N*′-tetraisopropylphosphonodiamide **6f**

Crystals, mp 148–150 °C (from pentane). ^{31}P NMR (101.2 MHz, methanol-d_4): δ 24.4. ^{1}H NMR (250 MHz, methanol-d_4): δ 1.20 (s, 6H, (CH_3)$_2$CHN–), 1.23 (s, 6H, (CH_3)$_2$CHN–), 1.27 (s, 6H, (CH_3)$_2$CHN–), 1.30 (s, 6H, (CH_3)$_2$CHN–), 3.55–3.76 (m, 4H, (CH$_3$)$_2$C*H*N–), 3.83 (s, 3H, –OCH_3), 6.46 (dd, $^{2}J_{P-H}$=20.1 Hz, $^{3}J_{H-H}$=17.2 Hz, 1H, H$_1$), 6.96 (dd, $^{3}J_{H-H}$=8.7 Hz, 2H, H$_{2'}$), 7.28 (dd, $^{3}J_{P-H}$=20.4 Hz, $^{3}J_{H-H}$=17.2 Hz, 1H, H$_2$), 7.49 (d, $^{3}J_{H-H}$=8.7 Hz, 2H, H$_{3'}$). ^{13}C NMR (62.5 MHz, methanol-d_4): δ 23.2 and 23.6 ((*C*H$_3$)$_2$CHN–), 46.6 and 46.7 (2(CH$_3$)$_2$*C*HN), 55.8 (*C*H$_3$O–), 115.4 (C$_{2'}$), 121.3 (d, $^{1}J_{P-C}$=148.8 Hz, C$_1$), 129.8 (C$_{3'}$), 130.2 (d, $^{3}J_{P-C}$=21.0 Hz, C$_{4'}$), 145.2 (d, $^{2}J_{P-C}$=5.7 Hz, C$_2$), 162.5 (C$_{1'}$). MS (*m*/*z*): 381.2 (M+H$^+$), 403.2 (M+Na$^+$).

4.2.7. (*E*)-2-(4′-Nitrophenyl)-1-ethenyl-*N*,*N*,*N*′,*N*′-tetraisopropylphosphonodiamide **6g**

Crystals, mp 230 °C (from pentane). ^{31}P NMR (101.2 MHz, methanol-d_4): δ 24.7. ^{1}H NMR (250 MHz, methanol-d_4): δ 1.22 (s, 6H, (CH_3)$_2$CHN–), 1.24 (s, 6H, (CH_3)$_2$CHN–), 1.29 (s, 6H, (CH_3)$_2$CHN–), 1.32 (s, 6H, (CH_3)$_2$CHN–), 3.61–3.79 (m, 4H, (CH$_3$)$_2$C*H*N–), 6.92 (dd, $^{2}J_{P-H}$=18.9 Hz, $^{3}J_{H-H}$=17.3 Hz, 1H, H$_1$), 7.44 (dd, $^{3}J_{P-H}$=20.0 Hz, $^{3}J_{H-H}$=17.3 Hz, 1H, H$_2$), 7.81 (d, $^{3}J_{H-H}$=8.9 Hz, 2H, H$_{2'}$), 8.28 (d, $^{3}J_{H-H}$=8.9 Hz, 2H, H$_{3'}$). ^{13}C NMR (62.5 MHz, methanol-d_4): δ 23.2, 23.3, and 23.6 ((*C*H$_3$)$_2$CHN–), 46.8 (2(CH$_3$)$_2$*C*HN), 125.2 (C$_{2'}$), 129.2 (C$_{3'}$), 129.5 (d, $^{1}J_{P-C}$=144.0 Hz, C$_1$), 142.9 (d, $^{2}J_{P-C}$=5.7 Hz, C$_2$), 143.7 (d, $^{3}J_{P-C}$=20.0 Hz, C$_{4'}$), 149.6 (C$_{1'}$). MS (*m*/*z*): 396.2 (M+H$^+$), 418.2 (M+Na$^+$).

4.2.8. (*E*)-1-Propenyl-*N*,*N*,*N*′,*N*′-tetraisopropylphosphonodiamide **6h**

Crystals, mp 83–86 °C (from pentane). ^{31}P NMR (101.2 MHz, acetone-d_6): δ 23.8. ^{1}H NMR (250 MHz, acetone-d_6): δ 1.14 (s, 6H, (CH_3)$_2$CHN–), 1.17 (s, 6H, (CH_3)$_2$CHN–), 1.22 (s, 6H, (CH_3)$_2$CHN–), 1.24 (s, 6H, (CH_3)$_2$CHN–), 1.87 (ddd, $^{3}J_{H-H}$=6.7 Hz, $^{4}J_{P-H}$=2.2 Hz, $^{4}J_{H-H}$=1.7 Hz, 1H, CH_3–), 3.48–3.66 (m, 4H, (CH$_3$)$_2$C*H*N–), 6.04 (ddq, $^{2}J_{P-H}$=21.9 Hz, $^{3}J_{H-H}$=16.6 Hz, $^{4}J_{H-H}$=1.7 Hz, 1H, H$_1$), 6.56 (ddq, $^{3}J_{P-H}$=17.4 Hz, $^{3}J_{H-H}$=16.6 Hz, $^{3}J_{H-H}$=6.5 Hz, 1H, H$_2$). ^{13}C NMR (62.5 MHz, acetone-d_6): δ 19.9 (*C*H$_3$–), 23.0 and 23.4 ((CH$_3$)$_2$CHN–), 45.8 (2(CH$_3$)$_2$*C*HN), 129.6 (d, $^{1}J_{P-C}$=142.1 Hz, C$_1$), 143.3 (d, $^{2}J_{P-C}$=4.8 Hz, C$_2$). MS (*m*/*z*): 289.1 (M+H$^+$), 311.2 (M+Na$^+$).

4.3. Desilylation of 5a and 4e: synthesis of 6a and 7

Preparation of **7** is described. A mixture of epoxide **5h** (40 mg, 0.09 mmol) and TBAF·H$_2$O (90 mg, 0.3 mmol) in 2 mL of THF was stirred at room temperature for 4 h. Solvent was removed at reduced pressure and the residue was poured into ether (15 mL). The resultant solution was successively washed with water (5×15 mL) and dried over anhydrous MgSO$_4$, and solvent was evaporated. The residue was chromatographed on neutral silica gel (EtOAc as eluent) to afford pure **7** (27 mg, 78% yield).

4.3.1. (*E*)-2-(2-Pyridyl)-1-ethenyl-*N*,*N*,*N*′,*N*′-tetraisopropylphosphonodiamide **6a**

Dense oil. ^{31}P NMR (101.2 MHz, acetone-d_6): δ 24.1. ^{1}H NMR (250 MHz, acetone-d_6): δ 1.20–1.31 (4s, 24H, (CH_3)$_2$CHN–), 3.61 (m, 4H, (CH$_3$)$_2$C*H*N–), 6.86 (dd, $^{2}J_{P-H}$=16.1 Hz, $^{3}J_{H-H}$=7.5 Hz, H$_1$), 7.19 (dd, $^{3}J_{P-H}$=7.5 Hz, $^{3}J_{H-H}$=7.5 Hz, H$_2$), 7.35 (m, 1H, H$_{heterocycle}$), 7.80 (m, 1H, H$_{heterocycle}$), 8.07 (m, 1H, H$_{heterocycle}$), 8.56 (m, 1H, H$_{heterocycle}$). ^{13}C NMR (62.5 MHz, acetone-d_6): δ 22.1, 22.3, and 22.9 ((*C*H$_3$)$_2$CHN–), 44.1 and 45.6 ((CH$_3$)$_2$*C*HN–), 116.9 (d, $^{1}J_{P-C}$=242 Hz, C$_1$), 122.4 (C$_{3'}$), 123.8 (C$_{5'}$), 129.2 (C$_2$), 135.9 (C$_{4'}$), 146.6 (C$_{6'}$), 156.3 (C$_{2'}$). MS (*m*/*z*): 352.2 (M+H$^+$), 374.2 (M+Na$^+$), 390.1 (M+K$^+$).

4.3.2. (2*RS*,3*RS*)-3-Phenyl-2-oxiran-2-yl-*N*,*N*,*N*′,*N*′-tetraisopropylthiophosphonodiamide **7**

Crystals, mp 109 °C (from ethyl acetate). ^{31}P NMR (101.2 MHz, CDCl$_3$): δ 69.4. ^{1}H NMR (250 MHz, CDCl$_3$): δ 1.13 (s, 3H, (CH_3)$_2$CHN–), 1.16 (s, 3H, (CH_3)$_2$CHN–), 1.24, 1.35, 1.37, 1.38, 1.40, and 1.43 (6s, 18H, (CH_3)$_2$CHN–), 3.15 (dd, $^{2}J_{P-H}$=27.2 Hz, $^{3}J_{H-H}$=2.3 Hz, 1H, H$_2$), 4.48 (dd, $^{3}J_{P-H}$=4.7 Hz, $^{3}J_{H-H}$=2.3 Hz, 1H, H$_3$), 7.31 (m, 5H, H$_{phenyl}$). ^{13}C NMR (62.5 MHz, CDCl$_3$): δ 22.7–23.9 ((CH$_3$)$_2$CHN–), 46.3 (d, $^{2}J_{C-P}$=4.8 Hz, (CH$_3$)$_2$CHN), 46.5 (d, $^{2}J_{C-P}$=4.8 Hz, (CH$_3$)$_2$CHN), 60.2 (d, $^{1}J_{C-P}$=158.3 Hz, C$_2$), 61.5 (C$_3$), 125.8, 128.5, 128.6 (CH$_{phenyl}$), 136.0 (C$_{quaternary}$). MS (*m*/*z*): 405.1 (M+Na$^+$).

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