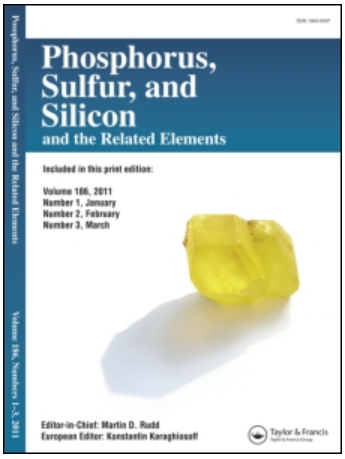

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A New Alternative for the Synthesis of Highly Functionalized Phosphoryl Derivatives

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A New Alternative for the Synthesis of Highly Functionalized Phosphoryl Derivatives

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*Nucleophilic addition of diethylphosphite to Bayllis-Hillman acetate **5** in the presence of K_2CO_3 provides E and Z-allylphosphonates **6**, which could be converted in the presence of N-bromosuccinimide (NBS) and benzoyl peroxide as catalyst into allylbromides **2**. The primary one is further converted via an efficient tandem "formylation-hydrolysis" into the corresponding primary allylalcohol **8**. The secondary allylbromides **2** react with TEAF via a β-elimination to give buta-1,3-dienes **9**.*

Keywords Functionalyzed allyl bromides; formylation-hydrolysis; N-Bromosuccinimide; phosphonates

INTRODUCTION

Development of allylic bromides, containing various functional groups and their synthetic applications, have been widely studied[1–4] because of their importance as powerful reagents for the synthesis of biologically active species.[5–8] Recently, we have reported a new stereoselective synthesis of allylic bromide[9] **1** bearing a β-phosphoric moiety and we have demonstrated that compound **1** can be used for the synthesis of allylamines[9] **3** and γ-butyrolactones[10] **4**.

The phosphoryl bromides were expected to be versatile reagents in organic synthesis since they are anticipated to act as phosphonate and/or as allylic bromide.

In continuation of our work on the synthesis of derivatives bromide, we report herein a convenient procedure for the preparation of a new

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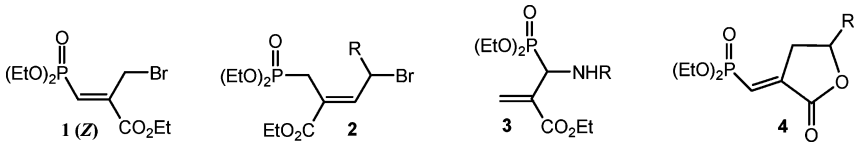
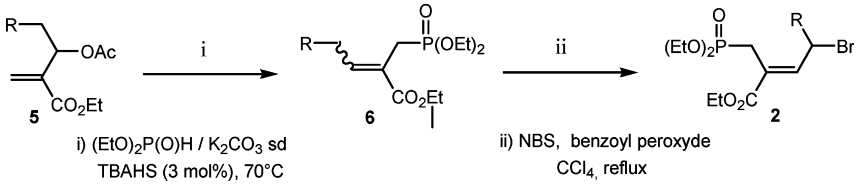


series analogous to **1** in which the phosphoryl group is changed into allyllic position leading to new functionalized allyl bromides **2**.

RESULTS AND DISCUSSION

Synthesis of 4-Bromo-2-(Diethoxyphosphorylmethyl) Alk-2-Enoic Acid Ethyl Esters 2

Starting from the Baylis-Hillman acetates **5**, the reaction coupling with diethylphosphite using anhydrous potassium carbonate as base at 70°C with or without solvent, led to the same allylphosphonates **6** reported in the literature.[11,12] The latter were converted to the functionalized *Z*-allyl bromides **2** (Scheme 1) after their treatment with N-bromosuccinimide (NBS) in carbon tetrachloride using a catalytic amount of benzoyl peroxide in good yields as indicated in Table I.



SCHEME 1

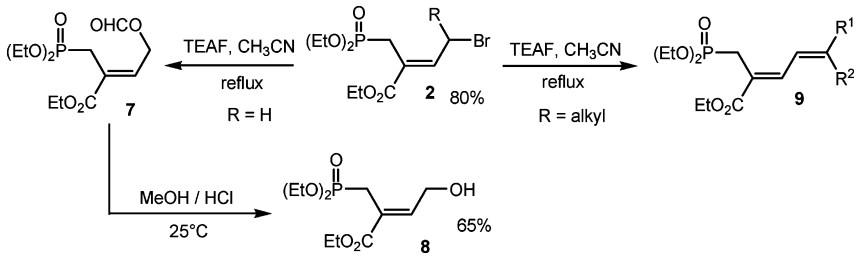
TABLE I Physical Data of Compounds 2a–d and 6a–d

Entry	*R*	Rdt (%)	(Z : E)*	Entry	Rdt (%)
6a	H	79	87 : 13	**2a**	78
6b	Me	73	87 : 13	**2b**	82
6c	^{i}Pr	72	63 : 37	**2c**	86
6d	Et	69	85 : 15	**2d**	70

*Determined by ^{1}P NMR spectral analysis.

Formylation-Hydrolysis of Functional Allyl Bromides 2

In recent publications,[13,14] we have reported a general and convenient and simple procedure for the conversion of primary allylbromides into the corresponding primary allylic alcohols in two reaction steps "formylation-hydrolysis". In this way, we found that the reaction of primary allylic bromide **2a** with triethylammonium formate (TEAF) at reflux of acetonitrile, afforded the corresponding S_N2 type product **7** in 80% yield. The obtained formiate **7** is easily converted into the corresponding β-(hydroxymethyl) acrylic acid ester **8** in methanol in the presence of one drop of concentrated hydrochloric at room temperature. Unfortunately, the formylation process of secondary allylic bromides **2(b,c)** in the same reaction conditions, led exclusively to the buta-1,3-dienes **9** *via* a β-elimination (–HBr) (Scheme 2). The obtained highly conjugated system seems to govern this reaction. The objective in the obtaining of secondary alcohols was not reached; nevertheless, the result reported here seems to have a considerable importance because the functional 1,3-butadienes **9** which have been thoroughly studied in recent years, were evaluated as potential starting materials for organic synthesis, in particular in some various cycloaddition-reactions.[15–17]



SCHEME 2

TABLE II Synthesis of Buta-1,3-dienes 9-b

Entry	R^1	R^2	Rdt (%)
9a	H	Me	55
9b	Me	Me	68

CONCLUSION

In summary, we have developed a simple and efficient method for preparation of allylbromides **2** from allylphosphonates **6,** and we have demonstrated that compounds **2** may be used as potential synthons for the synthesis of allylic alcohol **8** and functional but-1,3-dienes **9**.

EXPERIMENTAL SECTION

Apparatus

The IR spectra were recorded in chloroform on a Perkin-Elmer spectrophotometer Paragon 1000 PC. Mass spectra were recorded on a Hewlett-Packard 5989 instrument. ^{1}H, ^{13}C, and ^{31}P NMR were recorded either in $CDCl_3$ solution on a Bruker AC 300 MHz for the proton, 75 MHz for ^{13}C and 121 MHz for ^{31}P. Chemical shifts were in ppm using tetramethylsilane (TMS) as an internal standard for the ^{1}H and ^{13}C NMR and H_3PO_4 85% for ^{31}P NMR spectra as an external standard. Multiplicity of peaks is indicated by the following: *s*, singlet; *d*, doublet; *t*, triplet; *q*, quartet; *qt*, quintuplet; *br*, board; and *m*, multiplet.

Synthesis of Allylphosphonates 6(a–d)

A mixture of allyl acetate 5 (20 mmol), diethylphosphite (4.14 g, 30 mmol), potassium carbonate (4.14 g, 30 mmol), and tetrabutylammonium hydrogenosulfate (2%), was stirred at 70°C for 12 hours. After cooling, the reaction mixture was diluted with water and extracted with ether. The combined organic layers were washed with brine and dried over $MgSO_4$. After evaporation of the solvent, the residue was distilled under reduced pressure.

(Z, E)-2-(Diethoxyphosphorylmethyl) but-2-enoic acid ethyl ester 6a

IR(cm^{-1}) : $\nu_{C=O}$ = 1710, $\nu_{C=C}$ = 1640, $\nu_{P=O}$ = 1245. ^{1}H NMR: δ = 7.17 (qt, 1H, $^{4}J_{PH} = {}^{3}J_{HH}$ = 7.0 Hz,=C$\underline{H}$-*Z*), 6.32 (qt, 1H, $^{4}J_{PH} = {}^{3}J_{HH}$ = 7.0*Hz,* =C$\underline{H}$-*E*), 4.32 (q, 2H, $^{3}J_{HH}$ = 7.3 Hz, O-C$\underline{H}_2$—CH_3), 4.18 (qt, 4H, $^{3}J_{PH} = {}^{3}J_{HH}$ = 7.0 Hz,2O-C$\underline{H}_2$—CH_3), 3.08 (d, 2H, $^{2}J_{HP}$ = 22.0 Hz, =C—C$\underline{H}_2$-P-*Z*), 2.88 (d, 2H, $^{2}J_{HP}$ = 22.0 Hz, C=CH_2-P-*E*), 2.13 (m, 3H, P—CH_2-C=CH—C$\underline{H}_3$ − *E*), 1.94 (dd, 3H, $^{5}J_{HP}$ = 6.0 Hz $^{3}J_{HH}$ = 7.0 Hz, P-CH_2-C=CH—C$\underline{H}_3$ − *Z*), 1.34 (t, 3H, $^{3}J_{HH}$ = 7.0 Hz, CH_2-C$\underline{H}_3$), 1.28 (t, 6H, $^{3}J_{HH}$ = 7.0 Hz, 2CH_2-C$\underline{H}_3$). RMN ^{13}C: δ = 166.6 (d, P-CH_2—C—$\underline{C}$=O, $^{3}J_{CP}$ = 2.8 Hz), 141.4 (d, P-CH_2—C=$\underline{C}$H-*E*, $^{3}J_{CP}$ = 10.3 Hz), 140.6 (d, P-CH_2-C=$\underline{C}$H-*Z*, $^{3}J_{CP}$ = 10.2 Hz), 124.2 (d, =$\underline{C}$—CH_2—P,$^{2}J_{CP}$ = 11.4

Hz), 61.9 (d, 2P-O-$\underline{C}H_2$, $^2J_{CP}$ = 6.7 Hz), 60.5 ($\underline{C}H_2$), 30.1 (d, $\underline{C}H_2$-P-*E*, $^1J_{C-P}$ = 140.2 Hz), 23.6 (d, $\underline{C}H_2$-P-*Z*, $^1J_{CP}$ = 140.4 Hz), 16.3 (d, 2$\underline{C}H_3$-CH_2-O-P, $^3J_{CP}$ = 6.2 Hz), 15.1 ($\underline{C}H_3$), 14.2 ($\underline{C}H_3$). RMN ^{31}P: δ = 25.83-*Z*, 26.04-*E*.

(Z, E)-2-(Diethoxyphosphorylmethyl) Pent-2-enoic Acid Ethyl Ester 6b

IR: $\nu_{C=O}$ = 1714, $\nu_{C=C}$ = 1645, $\nu_{P=O}$ = 1245. ^{1}H NMR: δ = 7.0 (q, 1H, $^4J_{PH}$ = $^3J_{HH}$ = 6.0 Hz, = C$\underline{H}$-Z), 6.14 (q, 1H, $^4J_{PH}$ = $^3J_{HH}$ = 6.0 Hz, = C$\underline{H}$-*E*), 4.33 (q, 2H, $^3J_{HH}$ = 7.3 Hz, O-C$\underline{H}_2$-CH_3), 4.08 (qt, 4H, $^3J_{PH}$ = $^3J_{HH}$ = 7.0 Hz,2P-O-C$\underline{H}_2$—CH_3), 3.02 (d, 2H, $^2J_{PH}$ = 22.1 Hz, =C-C$\underline{H}_2$-P-*Z*), 2.86 (d, 2H, $^2J_{HP}$ = 22.1 Hz, =C-C$\underline{H}_2$-P-*E*), 2.3 (m, 2H, CH_3-C$\underline{H}_2$-CH-*E*), 2.25 (m, 2H, CH_3-C$\underline{H}_2$-CH-*Z*), 1.32 (t, 3H, $^3J_{HH}$ = 7.3 Hz, O-CH_2-C$\underline{H}_3$), 1.28 (t, 6H, $^3J_{HH}$ = 7.0 Hz, 2C$\underline{H}_3$-CH_2-O), 0.95 (t, 3H, $^3J_{HH}$ = 6.5 Hz, CH_2-C$\underline{H}_3$ – *Z*), 0.91 (t, 3H, $^3J_{HH}$ = 6.5 Hz, CH_2-C$\underline{H}_3$ – *E*). ^{13}C NMR: δ = 166.8 (d, P-CH_2-C-$\underline{C}$=O, $^3J_{CP}$ =2.8 Hz), 146.4 (d, P-CH_2-C = $\underline{C}$H-*E*, $^3J_{CP}$ = 10.4 Hz), 145.9 (d, P-CH_2-C=$\underline{C}$H-*Z*, $^3J_{CP}$ = 10.4 Hz), 123.1 (d, =$\underline{C}$-CH_2-P, $^2J_{CP}$ = 11.4 Hz), 61.9 (d, 2P-O-$\underline{C}H_2$, $^2J_{CP}$ = 6.7 Hz), 60.5 (O-$\underline{C}H_2$), 32.1 ($\underline{C}H_2$), 24.6 (d, $\underline{C}H_2$-P-*E*, $^1J_{CP}$ = 140.6 Hz), 29.86 (d, $\underline{C}H_2$-P-*Z*, $^1J_{CP}$ = 140.8 Hz), 16.3 (d, 2$\underline{C}H_3$-CH_2-O-P, $^3J_{CP}$ = 6.2 Hz), 14.2 ($\underline{C}H_3$), 14.1 ($\underline{C}H_3$).

(Z, E)-2-(Diethoxyphosphorylmethyl)-5-methylhex-2-enoic Acid Ethyl Ester 6c

IR: $\nu_{C=O}$ = 1705, $\nu_{C=C}$ = 1638, $\nu_{P=O}$ = 1243. ^{1}H NMR: δ = 6.95 (q, 1H, $^4J_{PH}$ = $^3J_{HH}$ = 6.3 Hz, =C$\underline{H}$-*Z*), 6.15 (q, 1H, $^4J_{PH}$ = $^3J_{HH}$ = 6.3 Hz, =C$\underline{H}$-*E*), 4.23 (q, 2H, $^3J_{HH}$ = 7.3 Hz, O-C$\underline{H}_2$-CH_3), 4.08 (qt, 4H, $^4J_{PH}$ = $^3J_{HH}$ = 7.3 Hz,2P-O-C$\underline{H}_2$-CH_3), 2.95 (d, 2H, $^2J_{PH}$ = 22.0 Hz, =C-C$\underline{H}_2$-P-*Z*), 2.86 (d, 2H, $^2J_{PH}$ = 22.1 Hz, =C-C$\underline{H}_2$-P-*E*), 2.41 (q, 2H, $^3J_{HH}$ = 6.9 Hz, CH-C$\underline{H}_2$-CH-*E*), 2.18 (q, 2H, $^3J_{HH}$ = 6.9 Hz, CH-C$\underline{H}_2$-CH-*Z*), 1.8 (m, 1H, CH_2-C$\underline{H}$), 1.31 (t, 3H, $^3J_{HH}$ = 7.3 Hz, O—CH_2—C$\underline{H}_3$), 1.29 (t, 6H, $^3J_{HH}$ = 7.3 Hz, 2O-CH_2—C$\underline{H}_3$), 0.93 (d, 6H, $^3J_{HH}$ = 6.5 Hz, 2CH-C$\underline{H}_3$ – *Z*), 0.92 (d, 6H, $^3J_{HH}$ = 6.6 Hz, 2CH-C$\underline{H}_3$ – *E*). ^{13}C NMR: δ = 166.7 (d, , P-CH_2—C-$\underline{C}$=O, $^3J_{CP}$ = 3.8 Hz), 146.0 (d, P-CH_2-C=$\underline{C}$H–*E*, $^3J_{CP}$ = 10.5 Hz), 144.9 (d, P-CH_2-C=$\underline{C}$H-*Z*, $^3J_{CP}$ = 10.3 Hz), 122.9 (d, =$\underline{C}$-CH_2-P-*E*, $^2J_{CP}$ = 10.6 Hz), 123.6 (d, =$\underline{C}$-CH_2-P-*Z*, $^2J_{CP}$ = 11.6 Hz), 61.9 (d, 2P-O-$\underline{C}H_2$, $^2J_{CP}$ = 6.6 Hz), 60.5 (O-$\underline{C}H_2$), 38.6 ($\underline{C}$H), 28.8 (d, $\underline{C}H_2$-P-*E*, $^1J_{CP}$ = 140.5 Hz), 24.1 (d, $\underline{C}H_2$-P-*Z*, $^1J_{CP}$ = 140.5 Hz), 22.4 ($\underline{C}H_2$), 16.3 (d, 2$\underline{C}H_3$-CH_2-O-P, $^3J_{CP}$ = 4.8 Hz), 14.2 ($\underline{C}H_3$).

(Z, E)-2-(Diethoxyphosphorylmethyl) Hex-2-enoic Acid Ethyl ester 6d

IR: $\nu_{C=O} = 1716$, $\nu_{C=C} = 1645$, $\nu_{P=O} = 1247$. ^{1}H NMR: $\delta = 6.91$ (q, 1H, $^4J_{PH} = {}^3J_{HH} = 6.0$ Hz, $=C\underline{H}$-*Z*), 6.14 (q, 1H, $^4J_{PH} = {}^3J_{HH} = 6.0$ Hz, $=C\underline{H}$-*E*), 4.32 (q, 2H, $^3J_{HH} = 7.3$ Hz, O–C$\underline{H}_2$–CH_3), 4.08 (qt, 4H, $^3J_{PH} = {}^3J_{HH} = 7.0$ Hz, 2P–O–C$\underline{H}_2$-CH_3), 2.98 (d, 2H, $^2J_{HP} = 22.1$ Hz, C$\underline{H}_2$-P-*Z*), 2.84 (d, 2H, $^2J_{PH} = 22.1$ Hz, C$\underline{H}_2$-P-*E*), 2.5 (m, 2H, =CH–C$\underline{H}_2$ – *E*), 2.28 (m, 2H, =CH–C$\underline{H}_2$ – *Z*), 1.5 (m, 2H, CH_2-C$\underline{H}_2$-CH_3), 1.32 (t, 3H, $^3J_{HH} = 7.3$ Hz, O–CH_2–C$\underline{H}_3$), 1.28 (t, 6H, $^3J_{HH} = 7.0$ Hz, 2 O–CH_2–C$\underline{H}_3$), 0.93 (t, 3H, $^3J_{HH} = 6.5$ Hz, CH_2–C$\underline{H}_3$ – *Z*), 0.90 (t, 3H, $^3J_{HH} = 6.5$ Hz, CH_2–C$\underline{H}_3$ – *E*). ^{13}C NMR: $\delta = 166.8$ (d, P–CH_2–C–$\underline{C}$=O, $^3J_{CP} = 2.8$ Hz), 146.9 (d, P–CH_2–C=$\underline{C}$H-*E*, $^3J_{CP} = 10.5$ Hz), 145.8 (d, P-CH_2–C=$\underline{C}$H-*Z*, $^3J_{CP} = 10.3$ Hz), 123.1 (d, =$\underline{C}$–CH_2-P, $^2J_{CP} = 11.5$ Hz), 61.9 (d, 2P-O-$\underline{C}H_2$, $^2J_{CP} = 6.7$ Hz), 60.5 (O-$\underline{C}H_2$), 31.8 ($\underline{C}H_2$), 30.1 (d, $\underline{C}H_2$-P-*E*, $^1J_{CP} = 140.5$ Hz), 24.0 (d, $\underline{C}H_2$-P-*Z*, $^1J_{CP} = 140.6$ Hz), 22.4 ($\underline{C}H_2$), 16.3 (d, 2$\underline{C}H_3$-CH_2-O-P, $^3J_{CP} = 6.7$ Hz), 14.0 ($\underline{C}H_3$), 13.7 ($\underline{C}H_3$). ^{31}P NMR: δ =: 25.04-Z, 25.4-*E*.

Synthesis of Allylbromides 2(a–d)

A solution of allylic phosphonate 6 (5 mmol), 4.5 mmol (0.8 g) of N-bromosuccinimide, 0.01 g (4.128 10^{-2} mmol) of benzoyl peroxide, and 15 mL of dry carbon tetrachloride was heated under reflux for 8 h. After the mixture was cooled, the succinimide was filtered off and washed once with dry CCl_4. The solvent was removed to leave an oil, which was purified by column chromatography on silica gel (CH_2Cl_2 / AcOEt : 7 / 3).

(Z)-4-Bromo-2-(diethoxyphosphorylmethyl) But-2-enoic Acid Ethyl Ester 2a

^{1}H NMR: $\delta = 7.17$ (q, 1H, $^4J_{PH} = {}^3J_{HH} = 7.0$ Hz, $=C\underline{H}$), 4.25 (q, 2H, $^3J_{HH} = 7.3$ Hz, O-C$\underline{H}_2$- CH_3), 4.12 (m, 2H, C$\underline{H}_2$-Br), 4.05 (qt, 4H, $^3J_{PH} = {}^3J_{HH} = 7.0$ Hz, 2P–O–C$\underline{H}_2$–CH_3), 2.98 (d, 2H, $^2J_{PH} = 22.0$ Hz, CH_2-P), 1.34 (t, 3H, $^3J_{HH} = 7.0$ Hz, O–CH_2–C$\underline{H}_3$), 1.28 (t, 6H, $^3J_{HH} = 7.0$ Hz, 2O–CH_2–C$\underline{H}_3$). ^{13}C NMR: $\delta = 165.8$ (d, P-CH_2–C–$\underline{C}$=O, $^3J_{CP} = 3.3$ Hz), 138.4 (d, P-CH_2–C=$\underline{C}$H, $^3J_{CP} = 10.5$ Hz), 124.2 (d, =$\underline{C}$–CH_2-P, $^2J_{CP} = 11.8$ Hz), 62.3 (d, 2P-O-$\underline{C}H_2$, $^2J_{CP} = 6.6$ Hz), 61.5 (O-$\underline{C}H_2$), 26.3 ($\underline{C}H_2$-Br), 23.7 (d, $\underline{C}H_2$-P, $^1J_{CP} = 139.7$ Hz), 16.3 (d, 2$\underline{C}H_3$–CH_2-O-P, $^3J_{CP} = 6.2$ Hz), 14.2 ($\underline{C}H_3$).

(Z)-4-Bromo-2-(Diethoxyphosphorylmethyl) Pent-2-enoic Acid Ethyl Ester 2b

^{1}H NMR: $\delta = 6.97$ (dd, 1H, $^4J_{PH} = 11.4$ Hz $^3J_{HH} = 6.2$ Hz, $=C\underline{H}$), 5.05 (m, 1H, C$\underline{H}$-Br), 4.25 (q, 2H, $^3J_{HH} = 7.0$ Hz, O-C$\underline{H}_2$-CH_3), 4.09 (2q,

4H, $^3J_{HH}$ = 7.3 Hz,2 O–C<u>H</u>$_2$–CH$_3$), 3.03 (AB d, 2H, $^2J_{PH}$ = 23.0 Hz $^2J_{HH}$ = 14.0 Hz C<u>H</u>$_2$-P), 1.84 (d, 3H, $^3J_{HH}$ = 6.6 Hz, CH–C<u>H</u>$_3$), 1.34 (t, 3H, $^3J_{HH}$ = 7.0 Hz, O–CH$_2$–C<u>H</u>$_3$), 1.3, 1.27 (2t, 6H, $^3J_{HH}$ = 7.0 Hz, 2 OCH$_2$–C<u>H</u>$_3$). ^{13}C NMR: δ = 165.9 (d, P–CH$_2$–C–<u>C</u>=O, $^3J_{CP}$ = 3.2 Hz), 144.1 (d, P–CH$_2$–C=<u>C</u>H, $^3J_{CP}$ = 10.5 Hz), 122.9 (d, =<u>C</u>–CH$_2$-P, $^2J_{CP}$ = 11.8 Hz), 62.2 (d, 2P-O-<u>C</u>H$_2$-CH$_3$, $^2J_{CP}$ = 6.8 Hz), 61.2 (O-<u>C</u>H$_2$), 43.0 (<u>C</u>H-Br), 25.2 (<u>C</u>H$_3$), 23.7 (d, <u>C</u>H$_2$-P, $^1J_{CP}$ = 139.6 Hz), 16.2 (d, 2<u>C</u>H$_3$–CH$_2$–O–P,$^3J_{CP}$ = 6.2 Hz), 14.0 (<u>C</u>H$_3$).

(Z)-4-Bromo-2-(Diethoxyphosphorylmethyl)-5-mehylhex-2-enoic Acid Ethyl Ester 2c

^{1}H NMR: δ = 6.97 (dd, 1H, $^4J_{PH}$ = 11.4 Hz $^3J_{HH}$ = 5.9 Hz, =CH), 4.84 (dd, 1H, $^3J_{HH}$ = 11.0 Hz $^5J_{PH}$ = 5.9 Hz, C<u>H</u>-Br), 4.23 (q, 2H, $^3J_{HH}$ = 7.3 Hz, O–C<u>H</u>$_2$–CH$_3$), 4.12 (2q, 4H, $^3J_{HH}$ = 7.3 Hz $^3J_{HH}$ = 7.3 Hz,2O–C<u>H</u>$_2$–CH$_3$), 3.08, 2.94 (AB d, 2H, $^2J_{PH}$ = 23.2 Hz $^2J_{HH}$ = 15.0 Hz, CH$_2$-P), 2.02 (m, 1H, Br–CH–C<u>H</u>), 1.33 (t, 3H, $^3J_{HH}$ = 7.3 Hz, O–CH$_2$–C<u>H</u>$_3$), 1.30, 1.28 (2t, 6H, $^3J_{HH}$ = 7.3 Hz, 2O–CH$_2$–C<u>H</u>$_3$), 1.05, 1.09 (2d, 6H, $^3J_{HH}$ = 6.3 Hz $^3J_{HH}$ = 7.0 Hz, C<u>H</u>$_3$–CH). ^{13}C NMR: δ = 166.1 (d, P-CH$_2$–C–<u>C</u>=O, $^3J_{CP}$ = 3.7 Hz), 141.8 (d, P–CH$_2$–C=<u>C</u>H, $^3J_{CP}$ = 10.6 Hz), 124.2 (d, =<u>C</u>–CH$_2$-P, $^2J_{CP}$ = 11.6 Hz), 62.1 (d, 2P-O-<u>C</u>H$_2$, $^2J_{CP}$ = 6.8 Hz), 61.5 (O-<u>C</u>H$_2$), 56.7 (<u>C</u>H-Br), 34.4 (<u>C</u>H), 21.0 (d, <u>C</u>H$_2$-P, $^1J_{CP}$ = 139.8 Hz), 20.2 (<u>C</u>H$_3$), 19.5 (<u>C</u>H$_3$),16.5 (d, 2<u>C</u>H$_3$-CH$_2$-O-P,$^3J_{CP}$ = 6.1 Hz), 14.2 (<u>C</u>H$_3$).

(Z)-4-Bromo-2-(Diethoxyphosphorylmethyl) Hex-2-enoic Acid Ethyl Ester 2d

^{1}H NMR: δ = 6.97 (dd, 1H, $^3J_{PH}$ = 11.4 Hz $^3J_{HH}$ = 6.2 Hz, =C<u>H</u>), 4.83 (m, 1H, C<u>H</u>-Br), 4.25 (q, 2H, J = 7.0 Hz, O-C<u>H</u>$_2$–CH$_3$), 4.09 (2q, 4H, $^3J_{HH}$ = 7.3 Hz $^3J_{HH}$ = 7.3 Hz,2O-C<u>H</u>$_2$-CH$_3$), 3.04 (AB d, 2H, $^2J_{HP}$ = 23.0 Hz $^2J_{HH}$ = 14.0 Hz, C<u>H</u>$_2$-P), 1.95 (m, 2H, Br-CH-C<u>H</u>$_2$), 1.33 (t, 3H, $^3J_{HH}$ = 7.0 Hz, C<u>H</u>$_3$- CH$_2$), 1.28, 1.24 (2t, 6H, $^3J_{HH}$ = 7.3 Hz $^3J_{HH}$ = 7.3 Hz, 2C<u>H</u>$_3$-CH$_2$), 1.08 (t, $^3J_{HH}$ = 7.3 Hz, 3H, C<u>H</u>$_3$-CH$_2$). ^{13}C NMR: δ = 166.1 (d, P-CH$_2$-C-<u>C</u>=O, $^3J_{CP}$ = 3.3 Hz), 144.1 (d, P-CH$_2$-C=<u>C</u>H, $^3J_{CP}$ = 10.6 Hz), 123.9 (d, =<u>C</u>-CH$_2$-P, $^2J_{CP}$ = 11.6 Hz), 62.3 (d, 2P-O-<u>C</u>H$_2$-CH$_3$, $^2J_{CP}$ = 6.8 Hz), 61.5 (O-<u>C</u>H$_2$), 50.9 (<u>C</u>H-Br), 31.3 (<u>C</u>H$_2$), 23.9 (d, <u>C</u>H$_2$-P, $^1J_{CP}$ = 139.6 Hz), 16.3 (d, 2<u>C</u>H$_3$-CH$_2$-O-P, $^3J_{CP}$ = 6.1 Hz), 14.2 (<u>C</u>H$_3$), 12.0 (<u>C</u>H$_3$). MS: m/z (%): 373 (M$^+$+2, 50), 371 (M$^+$, 55), 291 (83), 245 (93), 29 (100).

Synthesis of Allyl Formate 7

Allyl bromide 2a (3.43 g, 10 mmol) was added to a solution of triethylammonium formate (3.67 g, 25 mmol) in MeCN (10 mL) and the solution

was stirred at reflux for 6 h. The mixture was extracted with ether (3 x 30 mL). The combined organic layers were dried over $MgSO_4$ and evaporated at reduced pressure to give the crude formate 7 which was purified by chromatography (CH_2Cl_2 / AcOEt : 7 / 3).

(Z)-2-(Diethoxyphosphorylmethyl)-4-formyloxybut-2-enoic Acid Ethyl Ester 7

IR: $\nu_{C=O} = 1726$, $\nu_{C=C} = 1634$. ^{1}H NMR: $\delta = 8.1$ (s, 1H,O—C<u>H</u>), 6.97 (q, 1H, $^4J_{PH} = {}^3J_{HH} = 7.0$ Hz, =C<u>H</u>), 4.81 (t, 2H, $^3J_{HH} = 7.0$ Hz, =CH—C<u>H</u>$_2$—O), 4.28 (q, 2H, $^3J_{HH} = 7.3$ Hz, O—C<u>H</u>$_2$—CH$_3$), 4.12 (qt, 4H, $^3J_{PH} - {}^3J_{HH} = 7.0$ Hz,2P-O-C<u>H</u>$_2$—CH$_3$), 2.95 (d, 2H, $^2J_{HP} = 22.0$ Hz, C<u>H</u>$_2$-P), 1.34 (t, 3H, $^3J_{HH} = 7.0$ Hz, O—CH$_2$—C<u>H</u>$_3$), 1.28 (t, 6H, $^3J_{HH} = 7.0$ Hz, 2 O—CH$_2$—C<u>H</u>$_3$). ^{13}C NMR: $\delta = 165.4$ (d, P—CH$_2$-C—<u>C</u>=O, $^3J_{PH} = 3.1$ Hz), 161.1 (O=<u>C</u>H), 137.4 (d, P-CH$_2$-C=<u>C</u>H, $^3J_{CP} = 10.7$ Hz), 125.7 (d, =<u>C</u>-CH$_2$-P, $^2J_{CP} = 11.7$ Hz), 62.3 (d, 2P-O-<u>C</u>H$_2$-CH$_3$, $^2J_{CP} = 6.8$ Hz), 61.2 (O-<u>C</u>H$_2$), 64.3 (<u>C</u>H$_2$-O), 22.8 (d, <u>C</u>H$_2$-P, $^1J_{CP} = 140.0$ Hz), 16.3 (d, 2<u>C</u>H$_3$-CH$_2$-O-P,$^3J_{CP} = 6.1$ Hz), 14.1 (<u>C</u>H$_3$).

Synthesis of Allyl Alcohol 8

One drop of concentrated HCl was added to a solution of formate 7 (0.61 g, 2 mmol) in 10 mL MeOH and the solution was stirred at r.t. for 2 h. The mixture was diluted with Et_2O and dried ($MgSO_4$). The solvent was removed in vacuo to give the allylic alcohol 8 which was purified by column chromatography (CH_2Cl_2/AcOEt: 6/4).

(Z)-2-(Diethoxyphosphorylmethyl)-4-Hydroxybut-2-enoic Acid Ethyl Ester 8

IR: $\nu_{OH} = 3594$, $\nu_{C=O} = 1715$, $\nu_{C=C} = 1648$. ^{1}H NMR: $\delta = 7.01$ (q, 1H, $^4J_{PH} = {}^3J_{HH} = 6.2$ Hz, =C<u>H</u>), 4.54(br, 1H,O<u>H</u>), 4.26 (m, 2H, C<u>H</u>$_2$-OH), 4.16 (q, 2H, $^3J_{HH} = 7.0$ Hz, O-C<u>H</u>$_2$- CH$_3$), 4.01 (qt, 4H, $^3J_{PH} = {}^3J_{HH} = 7$ Hz,2P—O—C<u>H</u>$_2$—CH$_3$), 2.97 (d, 2H, $^2J_{HP} = 22.0$ Hz, C<u>H</u>$_2$-P), 1.24 (t, 3H, $^3J_{HH} = 7.0$ Hz, O-CH$_2$-C<u>H</u>$_3$), 1.22 (t, 6H, $J = 7.0$ Hz, 2O-CH$_2$-C<u>H</u>$_3$). ^{13}C NMR: $\delta = 166.5$ (d, P-CH$_2$—C—<u>C</u>=O, $^3J_{CP} = 3.0$ Hz), 144.2 (d, P-CH$_2$-C=<u>C</u>H, $^3J_{CP} = 10.4$ Hz), 123.2 (d, =<u>C</u>-CH$_2$-P, $^2J_{CP} = 11.1$ Hz), 62.5 (d, 2P-O-<u>C</u>H$_2$-CH$_3$, $^2J_{CP} = 6.8$ Hz), 61.2 (O-<u>C</u>H$_2$), 59.4 (<u>C</u>H$_2$-OH), 22.7 (d, <u>C</u>H$_2$-P, $^1J_{CP} = 139.3$ Hz), 16.3 (d, 2<u>C</u>H$_3$-CH$_2$-O-P,$^3J_{CP} = 6.2$ Hz), 14.0 (<u>C</u>H$_3$).

Synthesis of Buta-1,3-dienes 9(a,b)

Allyl bromide 2(a,b) (10 mmol) was added to a solution of triethylammonium formate (3.67 g, 25 mmol) in MeCN (10 mL) and the solution

was stirred at reflux for 6 h. The mixture was extracted with ether (3 × 30 mL). The combined organic layers were dried over $MgSO_4$ and evaporation at reduced pressure to give buta-1,3-diène 9, which was purified by chromatography (CH_2Cl_2 / AcOEt: 7/3).

2-(Diethoxyphosphorylmethyl) hexa-2,4-dienoice acid ethyl ester 9a

^{1}H NMR: $\delta = 7.29$ (m, 1H, =C$\underline{H}$), 6.42 (m, 1H, =C$\underline{H}$), 6.14 (m, 1H, =C$\underline{H}$), 4.23 (q, 2H, $^3J_{HH} = 7.0$ Hz, O-C$\underline{H}_2$- CH_3), 4.08 (qt, 4H, $^3J_{PH} = {}^3J_{HH} = 7.0$ Hz,P-O—C$\underline{H}_2$—CH_3), 3.03 (d, 2H, $^2J_{PH} = 22.4$ Hz,C$\underline{H}_2$-P), 1.88 (d, 3H, $^3J_{HH} = 6.9$ Hz, =CH—C$\underline{H}_3$), 1.30 (t, 3H, $^3J_{HH} = 7.0$ Hz, CH_2-C$\underline{H}_3$), 1.27 (t, 6H, $^3J_{HH} = 7.0$ Hz, 2CH_2-C$\underline{H}_3$). ^{13}C NMR: $\delta = 167.2$ (C=O), 141.2 (d, P-CH_2-C=C$\underline{H}$, $^3J_{CP} = 10.2$ Hz), 139.1 (=C$\underline{H}$), 127.6 (=C$\underline{H}$), 119.2 (d, =C-CH_2-P, $^2J_{CP} = 12.4$ Hz), 62.1 (d, 2P-O-C$\underline{H}_2$, $^2J_{CP} = 6.5$ Hz), 60.9 (O-C$\underline{H}_2$), 24.0 (d, C$\underline{H}_2$-P, $^1J_{CP} = 140.6$ Hz), 18.9 (C$\underline{H}_3$), 16.3 (d, 2C$\underline{H}_3$-CH_2-O-P,$^3J_{CP} = 6.4$ Hz), 14.3 (C$\underline{H}_3$). MS: m/z (%): 290 (M^+, 4), 249 (10), 216 (100), 188 (60).

2-(Diethoxyphosphorylmethyl)-5-methylhexa-2,4-dienoic Acid Ethyl Ester 9b

^{1}H NMR: $\delta = 7.62$ (dd, 1H, $^3J_{HH} = 12.0$ Hz $^4J_{HP} = 5.9$ Hz, CH=C$\underline{H}$-C-CH_2-P), 6.19 (d, 1H, $^3J_{HH} = 12.0$ Hz, C=C$\underline{H}$—CH=), 4.23 (q, 2H, $^3J_{HH}$ = 6.9 Hz, O—C$\underline{H}_2$—CH_3), 4.08 (qt, 4H, $^3J_{HH} = 7.0$ Hz,2 O—C$\underline{H}_2$-CH_3), 3.03 (d, 2H, $^2J_{HP}$ − 22.4 Hz,C$\underline{H}_2$-P), 1.91 (s, 6H, C$\underline{H}_3$-C=), 1.32 (t, 3H, $^3J_{HH} = 6.9$ Hz, C$\underline{H}_3$—CH_2-O), 1.27 (t, 6H, $^3J_{HH}$ − 7.0 Hz, 2C$\underline{H}_3$-CH_2-O). ^{13}C NMR: $\delta = 167.5$ (C—O), 146.7 (=C), 132.9 (d, P-CH_2—C=C$\underline{H}$, $^3J_{CP} = 10.2$ Hz), 121.5 (=C$\underline{H}$), 118.9 (d, =C—CH_2-P, $^2J_{CP} = 12.4$ Hz), 61.9 (d, 2P-O-C$\underline{H}_2$, $^2J_{CP} = 6.6$ Hz), 60.8 (O-C$\underline{H}_2$), 25.8 (C$\underline{H}_3$), 23.9 (d, C$\underline{H}_2$-P, $^1J_{CP} = 140.6$ Hz), 19.0 (C$\underline{H}_3$), 16.3 (d, 2C$\underline{H}_3$-CH_2-O-P,$^3J_{CP} = 6.4$ Hz), 14.3 (C$\underline{H}_3$). MS: m/z (%): 304 (M^+, 6), 249 (100), 221 (38), 176 (60), 29 (27).

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