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An Efficient Synthesis of Phospha-Morita-Baylis-Hillman Adducts *via* Michaelis-Arbuzov Reaction of the DABCO Salt of Morita-Baylis-Hillman Bromide

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An efficient synthesis of phospha-Morita-Baylis-Hillman adducts was carried out in good yields *via* the Michaelis-Arbuzov reaction of the DABCO salts of MBH bromides. Instead of a DABCO salt, a phosphonium salt could be effectively used for some substrates which showed some problems in the presence of DABCO.

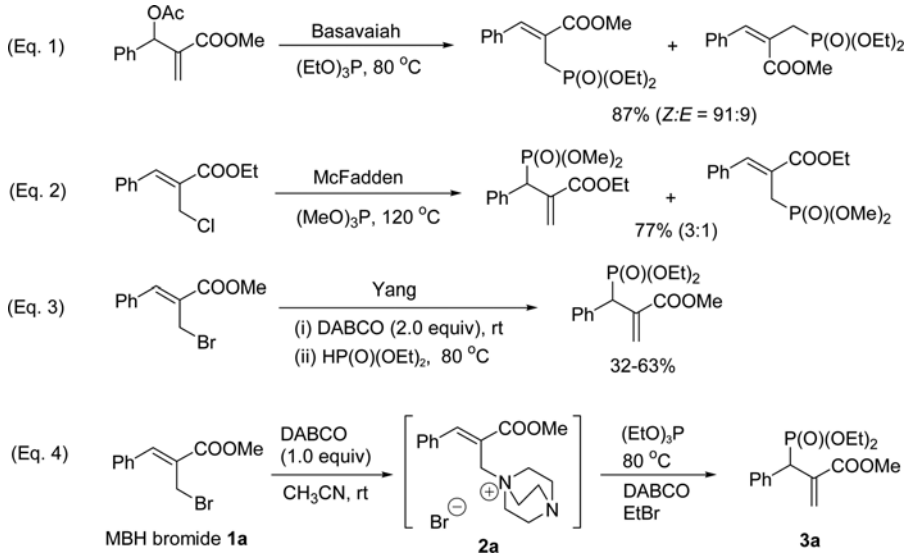
Key Words : Phospha-Morita-Baylis-Hillman adducts, Michaelis-Arbuzov reaction, DABCO salt, Allylic phosphonates

Introduction

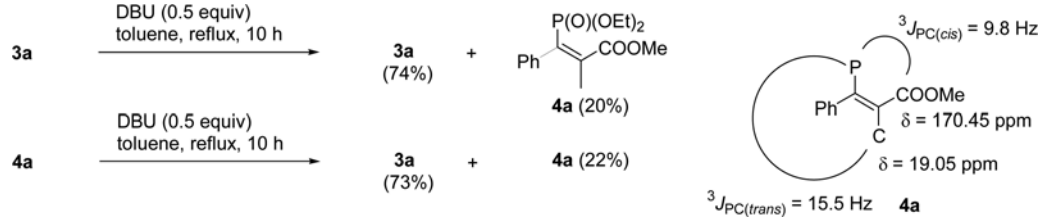
The preparation of alkyl phosphonates was carried out most frequently using alkyl halides and trialkyl phosphites *via* the Michaelis-Arbuzov reaction.[1] The Morita-Baylis-Hillman (MBH) acetates or bromides could be used efficiently for the preparation of allylic phosphonates.[2-4] Actually, the primary allylic phosphonate has been prepared from the acetate of MBH adducts by Basavaiah and Pandiaraju,[2a] as shown in Eq. (1) (Scheme 1). The preparation of a secondary phosphonate was examined with MBH bromides or chlorides by McFadden and co-workers; however, a mixture of primary and secondary phosphonates was formed (Eq. 2).[3] Yang and co-workers have reported the selective synthesis of secondary phosphonates *via* Michaelis-Becker reaction using diethyl phosphite and an excess amount of DABCO (Eq. 3).[4] However, the reaction provided low to moderate yields (32-63%) with only two examples. The reason for the low yield must be due to insufficient generation of the anion of diethyl phosphite with DABCO.[5,6] In these contexts, we decided to examine the synthesis of secondary phosphonate **3a**, namely a phospha-Morita-Baylis-Hillman (phospha-MBH) adduct, *via* the Michaelis-Arbuzov reaction using trialkyl phosphite and the DABCO salt of MBH bromide (Eq. 4).[7]

Results and Discussion

The reaction of MBH bromide **1a**[8] and DABCO (1.0 equiv) in CH_3CN readily provided a DABCO salt **2a** at room temperature within 30 min.[9] The Michaelis-Arbuzov reaction between **2a** and triethyl phosphite (2.0 equiv) at 80 °C for 3 h afforded phospha-MBH adduct **3a** in good yield (92%) along with a trace amount of alkenylphosphonate **4a** (< 3%, *vide infra*). The tetrasubstituted alkenylphosphonate **4a** must be formed *via* a double-bond isomerization of **3a** by DABCO. Thus, we examined the feasibility for the isomerization of **3a** to **4a**, as shown in Scheme 2. Actually, a treatment of **3a** with DABCO or Et_3N showed very sluggish

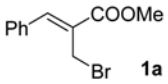
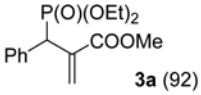
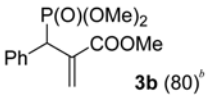
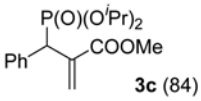
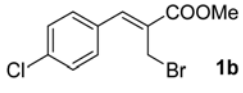
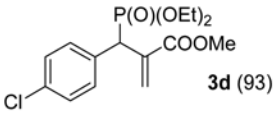
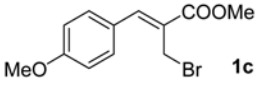
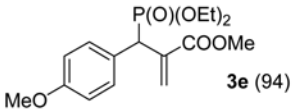
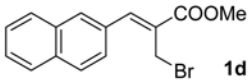
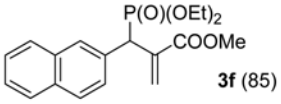
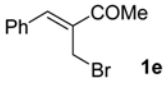
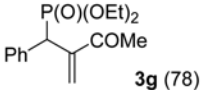


Scheme 1



Scheme 2

Table 1. Synthesis of phospha-Morita-Baylis-Hillman adducts[a]

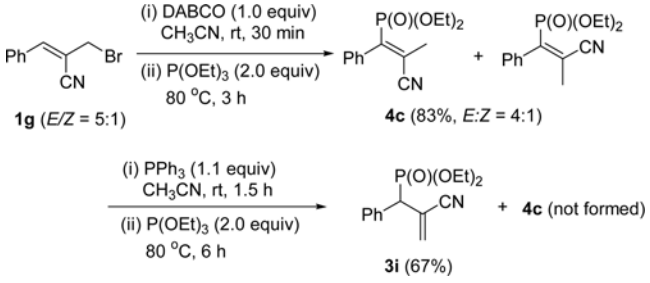
Entry	MBH bromide	Product (%)
1	 **1a**	 **3a** (92)
2	**1a**	 **3b** (80)[b]
3	**1a**	 **3c** (84)
4	 **1b**	 **3d** (93)
5	 **1c**	 **3e** (94)
6	 **1d**	 **3f** (85)
7	 **1e**	 **3g** (78)

[a]Conditions: (i) MBH bromide (0.5 mmol), DABCO (1.0 equiv), CH_3CN, rt, 30 min. (ii) Trialkyl phosphite (2.0 equiv), 80 °C, 3 h. [b]Reaction time: 8 h.

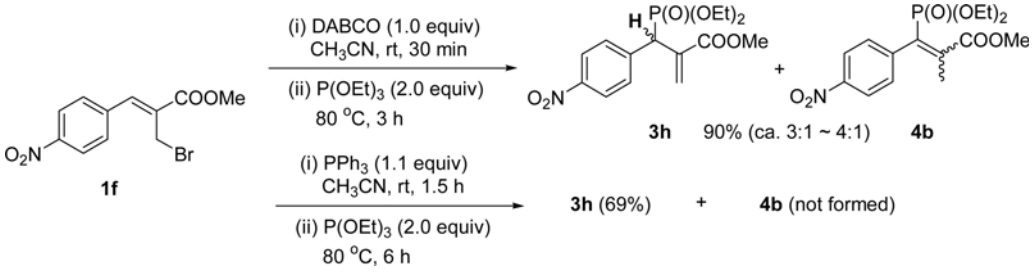
reactivity. The reaction of **3a** and DBU (0.5 equiv) in refluxing toluene showed the formation of **4a**; however, the reaction was not completed even after 10 h. The isolated yield of **4a** was 20%, and **3a** was recovered in 74%. Treatment of **4a** with DBU (0.5 equiv) afforded **3a** in 73% along with remaining **4a** in 22%. The results stated that these two compounds can be converted each other. Similar rearrangements between allylic and alkenylphosphonates have been reported.[10] The stereochemistry of **4a** was confirmed by the three-bond coupling constant between phosphorous atom and carbon atoms, as also shown in Scheme 2.[11]

Encouraged by the successful results, various phospha-MBH adducts **3b-g** were synthesized and the results are summarized in Table 1. Besides triethyl phosphite (entry 1), the reactions with trimethyl- and triisopropyl phosphites afforded the corresponding phosphonates **3b** and **3c** in good yields (entries 2 and 3). The reactions of other MBH bromides **1b-d** (entries 4-6) provided **3d-f** in good yields (85-94%). The bromide **1e** (entry 7), which was prepared from the corresponding MBH bromide of methyl vinyl ketone, [8g] also afforded **3g** in good yield (78%). As noted above, the corresponding alkenylphosphonates were observed in most of the entries; however, the amount was negligible (< 5%) and the desired products **3b-g** could be separated easily.

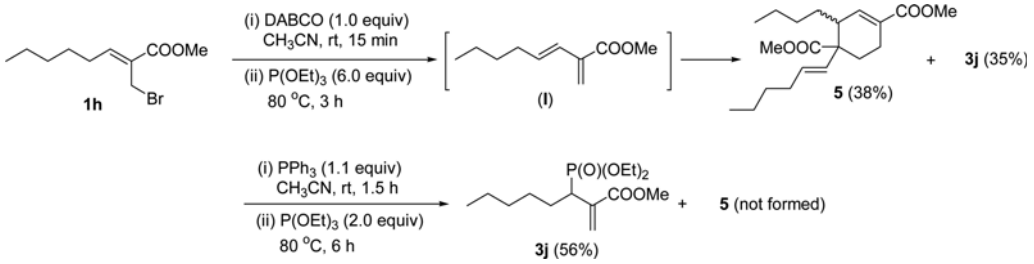
When we carried out the reaction of *p*-nitro derivative **1f**,[8h] the desired product **3h** was formed as a major product; however, an appreciable amount of alkenylphosphonate **4b** was formed together, as shown in Scheme 3. The compound **4b** must be formed *via* the double bond isomerization of **3h**.



Scheme 4



Scheme 3



Scheme 5

The benzylic proton of **3h** would be more acidic than the corresponding protons of **3a-g**, and this could be the reason for the formation of **4b** in an increased amount. In addition, the formation of **4b** made the separation of **3h** very tedious. Thus we examined the Michaelis-Arbuzov reaction of the phosphonium salt of **1f** instead of a DABCO salt.[12] To our delight, compound **3h** could be obtained in good yield (69%) without the formation of **4b**.

The reaction of a nitrile derivative **1g**[8b] also showed a severe isomerization problem, as shown in Scheme 4. The phosphonate **3i** was not formed at all when the DABCO salt was used in the Michaelis-Arbuzov reaction. Instead, an *E/Z* mixture of alkenylphosphonate **4c** (*E/Z* = 4:1) was obtained in 83%. Thus, we carried out the reaction with a phosphonium salt, and the secondary phosphonate **3i** was obtained in moderate yield (67%).

The use of a DABCO salt was also ineffective for the alkyl derivative **1h**.[8b] During the synthesis of a DABCO salt of **1h**, a slow formation of a cyclohexene derivative **5** was observed. The cyclohexene derivative **5** could be formed by an E2 elimination of **1h** or its DABCO salt to form a 1,3-diene intermediate **I** and a subsequent Diels-Alder reaction,[13] as shown in Scheme 5. In order to reduce the formation of **5**, we carried out the Michaelis-Arbuzov reaction in the presence of an excess amount (6.0 equiv) of triethyl phosphite; however, both cyclohexene **5** (38%) and phosphonate **3j** (35%) were produced together. Thus, the desired phosphonate **3j** was prepared by using a phosphonium salt in moderate yield (56%), as for the synthesis of **3h** and **3i**.

In order to compare the reactivity between DABCO salt and phosphonium salt, we examined the preparation of **3a** from **1a** *via* the phosphonium salt as in the Schemes 3-5. The yield of **3a** was low (68%) as compared to that of the DABCO salt (92%, entry 1 in Table 1). The Michaelis-Arbuzov reaction was also examined between triethyl phosphite and the DABCO salt of MBH acetate instead of MBH bromide. The phosphonate **3a** was obtained in only 48% yield under the same conditions (80 °C, 3 h), although the corresponding DABCO salt was formed quantitatively in aqueous THF. The formation of a DABCO salt in CH_3CN was so sluggish, thus the following Michaelis-Arbuzov reaction could not be carried out.

In summary, we disclosed an efficient synthesis of phospha-Morita-Baylis-Hillman adducts in good yields *via* the Michaelis-Arbuzov reaction of the DABCO salts of MBH bromides. Instead of a DABCO salt, a phosphonium salt could be effectively used for some substrates which showed some problems in the presence of DABCO.

Experimental Section

^{1}H NMR (300 MHz) and ^{13}C NMR (75 MHz) spectra were recorded using tetramethylsilane (TMS, δ = 0 ppm) as an internal standard. ^{31}P NMR (121 MHz) spectra were recorded using 85% H_3PO_4 (δ = 0 ppm) as an external standard. The preparation of MBH bromides **1a-h** was carried out according to the literature procedure.[8]

Typical Procedure for the Synthesis of 3a. A mixture of **1a** (128 mg, 0.5 mmol) and DABCO (56 mg, 0.5 mmol) in CH_3CN (2.0 mL) was stirred at room temperature for 30 min. To the solution triethyl phosphite (166 mg, 1.0 mmol) was added, and the reaction mixture was heated to 80 °C for 3 h. After the extractive aqueous workup and column chromatographic purification process (hexanes/EtOAc/CH_2Cl_2, 2:1:1), compound **3a** was isolated as a colorless oil, 144 mg (92%). Other compounds were prepared similarly. The separation of product from the side product such as triethyl phosphate and/or triphenylphosphine oxide was somewhat tedious for some entries. Thus the following solvent system during the flash column chromatographic purification step is recommended: compounds **3a-d**, **3f** and **3g** (hexanes/EtOAc/CH_2Cl_2, 2:1:1); compounds **3e**, **3h** and **3i** (toluene/EtOAc, 4:1); compound **3j** ($CHCl_3$). The spectroscopic data of **3a-j**, **4a**, **4c** and **5** are as follows.

Compound 3a: 92%; colorless oil; IR (film) 1722, 1624, 1441, 1244, 1053, 1024 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.00 (t, *J* = 7.2 Hz, 3H), 1.20 (t, *J* = 7.2 Hz, 3H), 3.56-3.69 (m, 1H), 3.64 (s, 3H), 3.76-3.89 (m, 1H), 3.96-4.05 (m, 2H), 4.52 (d, J_{PH} = 24.6 Hz, 1H), 6.46 (s, 1H), 6.47 (s, 1H), 7.15-7.27 (m, 3H), 7.37-7.40 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 16.07 (J_{PC} = 5.7 Hz), 16.25 (J_{PC} = 5.7 Hz), 44.24 (J_{PC} = 140.8 Hz), 52.26, 62.36 (J_{PC} = 6.9 Hz), 62.86 (J_{PC} = 6.9 Hz), 127.36 (J_{PC} = 2.3 Hz), 128.41 (J_{PC} = 1.7 Hz), 128.82 (J_{PC} = 6.3 Hz), 129.56 (J_{PC} = 6.9 Hz), 134.73 (J_{PC} = 6.3 Hz), 136.01 (J_{PC} = 1.7 Hz), 166.55 (J_{PC} = 14.3 Hz); ^{31}P NMR ($CDCl_3$, 121 MHz) δ 24.63; ESIMS *m/z* 313 [M$^+$+H]. Anal. Calcd for $C_{15}H_{21}O_5P$: C, 57.69; H, 6.78. Found: C, 57.92; H, 6.61.

Compound 3b: 80%; colorless oil; IR (film) 1721, 1624, 1454, 1439, 1244, 1057, 1030 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 3.40 (d, *J* = 10.8 Hz, 3H), 3.65 (s, 3H), 3.65 (d, *J* = 11.1 Hz, 3H), 4.55 (d, J_{PH} = 24.6 Hz, 1H), 6.47 (d, *J* = 3.0 Hz, 1H), 6.48 (d, *J* = 3.0 Hz, 1H), 7.16-7.28 (m, 3H), 7.35-

7.40 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 43.74 (J_{PC} = 140.8 Hz), 52.29, 53.08 (J_{PC} = 7.4 Hz), 53.57 (J_{PC} = 6.9 Hz), 127.48 (J_{PC} = 2.9 Hz), 128.52 (J_{PC} = 2.3 Hz), 128.97 (J_{PC} = 6.3 Hz), 129.44 (J_{PC} = 6.9 Hz), 134.40 (J_{PC} = 6.2 Hz), 135.72 (J_{PC} = 1.7 Hz), 166.39 (J_{PC} = 14.3 Hz); ESIMS *m/z* 285 [M^++H]. Anal. Calcd for $C_{13}H_{17}O_5P$: C, 54.93; H, 6.03. Found: C, 54.77; H, 6.34.

Compound 3c: 84%; colorless oil; IR (film) 1722, 1624, 1454, 1385, 1242, 1021, 988 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.75 (d, *J* = 6.3 Hz, 3H), 1.13 (d, *J* = 6.3 Hz, 3H), 1.16 (d, *J* = 6.3 Hz, 3H), 1.22 (d, *J* = 6.3 Hz, 3H), 3.64 (s, 3H), 4.25-4.36 (m, 1H), 4.45 (d, J_{PH} = 24.6 Hz, 1H), 4.54-4.65 (m, 1H), 6.44 (d, *J* = 3.0 Hz, 1H), 6.50 (d, *J* = 3.0 Hz, 1H), 7.13-7.25 (m, 3H), 7.37-7.41 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) d 22.93 (J_{PC} = 5.8 Hz), 23.61 (J_{PC} = 5.7 Hz), 23.97 (J_{PC} = 3.5 Hz), 24.14 (J_{PC} = 2.9 Hz), 44.73 (J_{PC} = 142.5 Hz), 52.17, 70.68 (J_{PC} = 7.4 Hz), 71.37 (J_{PC} = 6.8 Hz), 127.20 (J_{PC} = 2.3 Hz), 128.25 (J_{PC} = 1.7 Hz), 128.48 (J_{PC} = 6.3 Hz), 129.73 (J_{PC} = 6.9 Hz), 135.13 (J_{PC} = 5.7 Hz), 136.43 (J_{PC} = 1.7 Hz), 166.64 (J_{PC} = 14.3 Hz); ESIMS *m/z* 341 [M^++H]. Anal. Calcd for $C_{17}H_{25}O_5P$: C, 59.99; H, 7.40. Found: C, 60.10; H, 7.19.

Compound 3d: 93%; colorless oil; IR (film) 1722, 1626, 1491, 1439, 1242, 1053, 1026 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.04 (td, *J* = 7.2 and 0.3 Hz, 3H), 1.21 (t, *J* = 7.2 Hz, 3H), 3.62-3.75 (m, 1H), 3.65 (s, 3H), 3.79-3.92 (m, 1H), 3.96-4.06 (m, 2H), 4.48 (d, J_{PH} = 24.6 Hz, 1H), 6.45 (d, *J* = 3.0 Hz, 1H), 6.48 (d, *J* = 3.0 Hz, 1H), 7.19-7.23 (m, 2H), 7.29-7.34 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 16.14 (J_{PC} = 5.7 Hz), 16.26 (J_{PC} = 6.3 Hz), 43.68 (J_{PC} = 141.4 Hz), 52.34, 62.55 (J_{PC} = 6.9 Hz), 62.88 (J_{PC} = 6.8 Hz), 128.58 (J_{PC} = 2.3 Hz), 129.00 (J_{PC} = 6.3 Hz), 130.88 (J_{PC} = 6.8 Hz), 133.37 (J_{PC} = 2.9 Hz), 133.43 (J_{PC} = 5.7 Hz), 135.78 (J_{PC} = 1.7 Hz), 166.38 (J_{PC} = 14.3 Hz); ESIMS *m/z* 347 [M^++H]. Anal. Calcd for $C_{15}H_{20}ClO_5P$: C, 51.96; H, 5.81. Found: C, 51.89; H, 6.01.

Compound 3e: 94%; colorless oil; IR (film) 1722, 1609, 1512, 1441, 1254, 1134, 1053, 1028 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.08 (td, *J* = 7.2 and 0.3 Hz, 3H), 1.27 (td, *J* = 7.2 and 0.3 Hz, 3H), 3.64-3.77 (m, 1H), 3.71 (s, 3H), 3.77 (s, 3H), 3.83-3.96 (m, 1H), 4.01-4.12 (m, 2H), 4.52 (d, J_{PH} = 24.3 Hz, 1H), 6.50-6.51 (m, 2H), 6.81-6.86 (m, 2H), 7.33-7.38 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 16.14 (J_{PC} = 5.7 Hz), 16.25 (J_{PC} = 6.2 Hz), 43.36 (J_{PC} = 141.9 Hz), 52.22, 55.11, 62.26 (J_{PC} = 6.9 Hz), 62.81 (J_{PC} = 6.8 Hz), 113.81 (J_{PC} = 1.7 Hz), 126.59 (J_{PC} = 6.3 Hz), 128.41 (J_{PC} = 6.3 Hz), 130.61 (J_{PC} = 6.8 Hz), 136.31 (J_{PC} = 1.2 Hz), 158.85 (J_{PC} = 2.9 Hz), 166.58 (J_{PC} = 14.3 Hz); ESIMS *m/z* 343 [M^++H]. Anal. Calcd for $C_{16}H_{23}O_6P$: C, 56.14; H, 6.77. Found: C, 56.43; H, 6.96.

Compound 3f: 85%; colorless oil; IR (film) 1722, 1624, 1439, 1240, 1134, 1053, 1026 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.96 (td, *J* = 7.2 and 0.6 Hz, 3H), 1.21 (t, *J* = 7.2 Hz, 3H), 3.54-3.67 (m, 1H), 3.61 (s, 3H), 3.75-3.87 (m, 1H), 3.97-4.07 (m, 2H), 4.69 (d, J_{PH} = 24.3 Hz, 1H), 6.51 (d, *J* = 3.0 Hz, 1H), 6.54 (d, *J* = 3.0 Hz, 1H), 7.33-7.39 (m, 2H), 7.50 (dt, *J* = 8.4 and 1.8 Hz, 1H), 7.70-7.75 (m, 3H), 7.84 (t, *J* = 2.4 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 16.10 (J_{PC} = 5.7 Hz), 16.27 (J_{PC} = 5.7 Hz), 44.36 (J_{PC} = 140.8 Hz), 52.25, 62.42 (J_{PC} = 7.5 Hz), 62.85 (J_{PC} = 6.9 Hz), 125.91 (J_{PC} = 1.1 Hz), 126.00 (J_{PC} = 1.1 Hz), 127.44, 127.49 (J_{PC} = 5.2 Hz), 127.88 (J_{PC} = 1.1 Hz), 128.04 (J_{PC} = 1.1 Hz), 128.52 (J_{PC} = 8.0 Hz), 128.96 (J_{PC} = 6.8 Hz), 132.25 (J_{PC} = 6.3 Hz), 132.53 (J_{PC} = 1.7 Hz), 133.19 (J_{PC} = 2.3 Hz), 135.01 (J_{PC} = 1.7 Hz), 166.54 (J_{PC} = 13.8 Hz); ESIMS *m/z* 363 [M^++H]. Anal. Calcd for $C_{19}H_{23}O_5P$: C, 62.98; H, 6.40. Found: C, 62.65; H, 6.33.

Compound 3g: 78%; colorless oil; IR (film) 1682, 1624, 1495, 1366, 1246, 1055, 1026 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.98 (t, *J* = 7.2 Hz, 3H), 1.19 (t, *J* = 7.2 Hz, 3H), 2.27 (s, 3H), 3.57-3.71 (m, 1H), 3.76-3.89 (m, 1H), 3.93-4.03 (m, 2H), 4.74 (d, J_{PH} = 23.7 Hz, 1H), 6.31 (d, *J* = 3.3 Hz, 1H), 6.70 (d, *J* = 3.3 Hz, 1H), 7.12-7.25 (m, 3H), 7.37-7.41 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 16.04 (J_{PC} = 5.7 Hz), 16.22 (J_{PC} = 6.3 Hz), 25.29, 41.56 (J_{PC} = 140.8 Hz), 62.14 (J_{PC} = 7.4 Hz), 62.82 (J_{PC} = 7.4 Hz), 127.19 (J_{PC} = 2.9 Hz), 128.39 (J_{PC} = 1.7 Hz), 128.91 (J_{PC} = 6.9 Hz), 129.51 (J_{PC} = 7.4 Hz), 135.22 (J_{PC} = 5.8 Hz), 144.48 (J_{PC} = 2.3 Hz), 197.34 (J_{PC} = 10.3 Hz); ESIMS *m/z* 297 [M^++H]. Anal. Calcd for $C_{15}H_{21}O_4P$: C, 60.80; H, 7.14. Found: C, 60.87; H, 7.02.

Compound 3h: 69%; colorless oil; IR (film) 1722, 1597, 1524, 1441, 1348, 1244, 1051, 1024 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.05 (td, *J* = 7.2 and 0.3 Hz, 3H), 1.23 (td, *J* = 7.2 and 0.3 Hz, 3H), 3.66 (s, 3H), 3.68-3.81 (m, 1H), 3.82-3.95 (m, 1H), 3.99-4.09 (m, 2H), 4.61 (d, J_{PH} = 24.3 Hz, 1H), 6.53 (d, *J* = 3.0 Hz, 1H), 6.56 (d, *J* = 3.0 Hz, 1H), 7.53-7.59 (m, 2H), 8.09-8.13 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 16.17 (J_{PC} = 5.8 Hz), 16.32 (J_{PC} = 5.8 Hz), 44.40 (J_{PC} = 140.8 Hz), 52.55, 62.97 (J_{PC} = 6.8 Hz), 63.00 (J_{PC} = 7.5 Hz), 123.59 (J_{PC} = 2.3 Hz), 129.87 (J_{PC} = 6.3 Hz), 130.48 (J_{PC} = 6.9 Hz), 135.12 (J_{PC} = 2.3 Hz), 142.69 (J_{PC} = 6.3 Hz), 147.24 (J_{PC} = 2.9 Hz), 166.18 (J_{PC} = 14.3 Hz); ESIMS *m/z* 358 [M^++H]. Anal. Calcd for $C_{15}H_{20}NO_7P$: C, 50.42; H, 5.64; N, 3.92. Found: C, 50.33; H, 5.92; N, 3.76.

Compound 3i: 67%; colorless oil; IR (film) 2224, 1601, 1454, 1393, 1250, 1051, 1022, 968 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.05 (td, *J* = 7.2 and 0.6 Hz, 3H), 1.25 (t, *J* = 7.2 Hz, 3H), 3.65-3.79 (m, 1H), 3.84-3.97 (m, 1H), 3.90 (d, J_{PH} = 24.3 Hz, 1H), 4.01-4.11 (m, 2H), 6.07 (d, *J* = 3.0 Hz, 1H), 6.21 (dd, *J* = 3.0 and 1.2 Hz, 1H), 7.26-7.34 (m, 3H), 7.37-7.41 (m, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 16.06 (J_{PC} = 5.1 Hz,), 16.21 (J_{PC} = 6.3 Hz), 48.83 (J_{PC} = 140.9 Hz), 62.79 (J_{PC} = 7.4 Hz), 63.45 (J_{PC} = 6.8 Hz), 117.80 (J_{PC} = 10.3 Hz), 119.48 (J_{PC} = 5.1 Hz), 128.30 (J_{PC} = 2.3 Hz), 128.88 (J_{PC} = 1.7 Hz), 129.42 (J_{PC} = 6.9 Hz), 132.37 (J_{PC} = 6.3 Hz), 134.32 (J_{PC} = 8.6 Hz); ESIMS *m/z* 280 [M^++H]. Anal. Calcd for $C_{14}H_{18}NO_3P$: C, 60.21; H, 6.50; N, 5.02. Found: C, 60.46; H, 6.43; N, 4.86.

Compound 3j: 56%; colorless oil; IR (film) 1722, 1439, 1246, 1051, 1026, 959 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.79 (t, *J* = 6.9 Hz, 3H), 1.17-1.25 (m, 6H), 1.19 (t, *J* = 7.2 Hz, 3H), 1.22 (t, *J* = 7.2 Hz, 3H), 1.54-1.71 (m, 1H), 1.82-1.94 (m, 1H), 3.28 (ddd, J_{PH} = 23.4 Hz, *J* = 10.8 and 4.2 Hz,

1H), 3.72 (s, 3H), 3.93-4.07 (m, 4H), 5.83 (d, J = 5.7 Hz, 1H), 6.41 (d, J = 5.7 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 13.95, 16.30 (J_{PC} = 5.8 Hz), 16.35 (J_{PC} = 6.3 Hz), 22.32, 26.90 (J_{PC} = 13.7 Hz), 29.26 (J_{PC} = 3.4 Hz), 31.41 (J_{PC} = 1.1 Hz), 37.14 (J_{PC} = 137.3 Hz), 52.25, 62.05 (J_{PC} = 7.4 Hz), 62.17 (J_{PC} = 6.8 Hz), 127.30 (J_{PC} = 8.6 Hz), 136.12 (J_{PC} = 8.0 Hz), 167.20 (J_{PC} = 6.3 Hz); ESIMS *m/z* 307 [M^++H]. Anal. Calcd for $C_{14}H_{27}O_5P$: C, 54.89; H, 8.88. Found: C, 55.06; H, 8.69.

Compound 4a: 20%; colorless oil; IR (film) 1736, 1625, 1597, 1435, 1260, 1133, 1023, 966 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.16 (td, J = 7.2 and 0.6 Hz, 6H), 1.78 (d, J = 3.0 Hz, 3H), 3.81 (s, 3H), 3.87-4.06 (m, 4H), 7.10-7.14 (m, 2H), 7.22-7.34 (m, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 16.12 (J_{PC} = 6.3 Hz), 19.05 (J_{PC} = 15.5 Hz), 52.53, 62.22 (J_{PC} = 5.7 Hz), 127.76 (J_{PC} = 2.3 Hz), 128.39 (J_{PC} = 1.1 Hz), 128.90 (J_{PC} = 4.6 Hz), 130.67 (J_{PC} = 178.1 Hz), 135.06 (J_{PC} = 8.0 Hz), 146.27 (J_{PC} = 9.8 Hz), 170.45 (J_{PC} = 9.8 Hz); ^{31}P NMR ($CDCl_3$, 121 MHz) δ 12.98; ESIMS *m/z* 313 [M^++H]. Anal. Calcd for $C_{15}H_{21}O_5P$: C, 57.69; H, 6.78. Found: C, 57.54; H, 6.91.

Compound 4c: 83%; colorless oil; IR (film) 2218, 1643, 1445, 1236, 1051, 1020 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz, *E*-form) δ 1.15 (td, J = 7.2 and 0.3 Hz, 6H), 2.42 (d, J = 3.3 Hz, 3H), 3.85-4.11 (m, 4H), 7.19-7.23 (m, 2H), 7.29-7.37 (m, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz, *E*-form) δ 16.03 (J_{PC} = 6.3 Hz), 19.64 (J_{PC} = 5.2 Hz), 62.73 (J_{PC} = 5.7 Hz), 117.76 (J_{PC} = 30.9 Hz), 124.82 (J_{PC} = 20.6 Hz), 128.37 (J_{PC} = 4.4 Hz), 128.42 (J_{PC} = 1.1 Hz), 128.95 (J_{PC} = 1.7 Hz), 136.07 (J_{PC} = 6.8 Hz), 146.76 (J_{PC} = 176.3 Hz); ^{1}H NMR ($CDCl_3$, 300 MHz, *Z*-form) δ 1.90 (td, J = 7.2 and 0.3 Hz, 6H), 1.86 (d, J = 2.7 Hz, 3H), 3.85-4.11 (m, 4H), 7.08-7.12 (m, 2H), 7.29-7.37 (m, 3H); ^{13}C NMR ($CDCl_3$, 75 MHz, *Z*-form) δ 20.80 (J_{PC} = 13.7 Hz), 63.16 (J_{PC} = 6.3 Hz), 121.37 (J_{PC} = 3.5 Hz), 128.14 (J_{PC} = 5.1 Hz), 128.57 (J_{PC} = 1.7 Hz), 128.66 (J_{PC} = 2.3 Hz), 133.97 (J_{PC} = 6.9 Hz), 147.01 (J_{PC} = 177.4 Hz), 2 carbon signals were overlapped; ESIMS *m/z* 280 [M^++H]. Anal. Calcd for $C_{14}H_{18}NO_3P$: C, 60.21; H, 6.50; N, 5.02. Found: C, 60.37; H, 6.39; N, 4.83.

Compound 5: 38%; colorless oil; IR (KBr) 1730, 1715, 1651, 1456, 1435, 1258, 1229 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 0.81 (t, J = 7.2 Hz, 3H), 0.83 (t, J = 7.2 Hz, 3H), 0.96-1.09 (m, 1H), 1.15-1.41 (m, 8H), 1.47-1.58 (m, 1H), 1.64-1.73 (m, 1H), 1.94-2.01 (m, 2H), 2.05-2.13 (m, 1H), 2.24-2.30 (m, 2H), 2.72-2.78 (m, 1H), 3.57 (s, 3H), 3.65 (s, 3H), 5.30 (d, J = 15.6 Hz, 1H), 5.46 (dt, J = 15.6 and 6.6 Hz, 1H), 6.99 (dt, J = 5.1 and 1.8 Hz, 1H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 13.82, 13.92, 22.05, 22.14, 22.87, 25.37, 29.87, 31.29, 31.40, 32.44, 40.65, 50.47, 51.52, 52.05, 128.32, 130.12, 131.98, 142.65, 167.60, 175.50; ESIMS *m/z* 337 [M^++H]. Anal. Calcd for $C_{20}H_{32}O_4$: C, 71.39; H, 9.59. Found: C, 71.08; H, 9.51. The compound **5** was isolated as a single diastereomer presumably as a *trans* based on the reported papers;[13] however, we did not confirm the stereochemistry decisively.

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