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Microwave-Assisted Synthesis of the (*E*)-α-Methylalkenoate Framework from Multifunctionalized Allylic Phosphonium Salts

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ABSTRACT: *A convenient and general microwave-assisted method for the synthesis of stereochemically defined α-methylalkenoic acids and esters from allylic phosphonium salts in a basic aqueous medium is described. A selective preparation of acids or esters was dependent on the base (NaOH or $NaHCO_3$) employed in the reaction and could be achieved with good to excellent yields under mild conditions in the absence of hydrides and reducing agents.* © 2012 Wiley Periodicals, Inc. Heteroatom Chem 23:179–186, 2012; View this article online at wileyonlinelibrary.com. DOI 10.1002/hc.21001

INTRODUCTION

Phosphonium salts have great versatility in chemical reactions and are used as advanced building blocks for the synthesis of a wide variety of novel compounds [1]. In particular, phosphonium salts **P** bearing an allylic appendage, which are often prepared in situ by reacting triaryl (or trialkyl) phosphines with allyl acetates **A** or bromides **B**, are useful intermediates in annulation reactions (with the intermediacy of phosphorus ylides) [2] and have also been occasionally used in Wittig olefination [3] (Scheme 1). The multifunctional allylic moiety found in **P** is readily available from the Morita–Baylis–Hillman (MBH) reaction [4], which gives allylic alcohols **S** as precursors of acetates **A** and bromides **B**.

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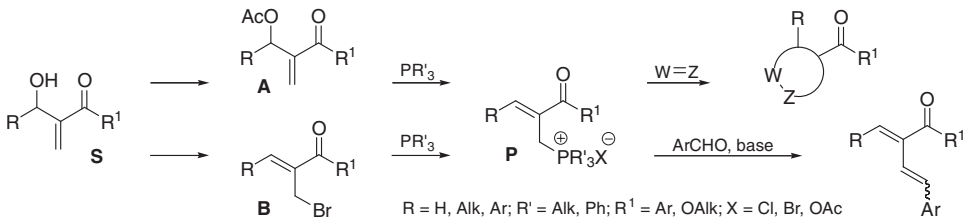
The α-alkylpropenoate backbone generated in the MBH reaction is an important structural unit present in insect pheromones and also in many other biologically active molecules [5]. Consequently, there are several reports describing the stereoselective synthesis of α-methylalkenoic acids by chemical reduction of the corresponding allylic alcohols **S** [6], acetates **A** [7], and bromides **B** [8]. While many of these methods furnish the expected α-methylalkenoates in good yields, there are generally one or more drawbacks involved such as the use of metal hydrides or reagents that are not readily accessible, the need for anhydrous conditions, or the formation of side products.

It is known that semistabilized ylides originating from base-induced deprotonation of allylic and benzylic phosphonium salts may undergo reduction in the presence of water to give the corresponding hydrocarbon and phosphine oxide through a mechanism where a phosphonium hydroxide **H** is invoked [9] (Scheme 2).

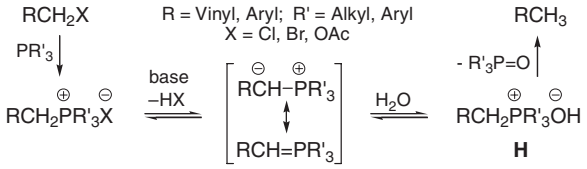
Herein, we report the development of a simple and efficient methodology for the synthesis of α-methylalkenoic acids and esters with high diastereoselectivity from a sequential base-mediated redox reaction of type-**P** phosphonium salts in an aqueous medium under microwave irradiation, as described below.

RESULTS AND DISCUSSION

Initially, the phosphonium salts **1a–1m** were prepared in nearly quantitative yields by mixing an

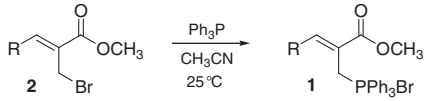


SCHEME 1



SCHEME 2

TABLE 1 Preparation of Phosphonium Salts **1** from Allylic Bromides **2**



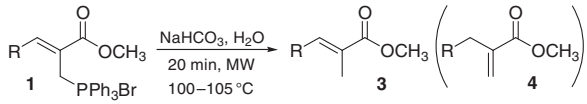
Entry	*R*	*Time (h)*[a]	*Yield (%)*[b]	*δ 31P (ppm)*[c]
1	C_6H_5 (a)	28 [0.5]	99	22.5
2	4-$CH_3OC_6H_4$ (b)	30	98	22.5
3	3,4-$(OCH_2O)C_6H_3$ (c)	30 [0.5]	98	22.1
4	4-$CH_3C_6H_4$ (d)	30	95	22.6
5	4-ClC_6H_4 (e)	24	98	22.2
6	2-ClC_6H_4 (f)	24	97	21.7
7	2,4-$Cl_2C_6H_3$ (g)	24	98	21.4
8	4-BrC_6H_4 (h)	24	96	22.3
9	4-$NO_2C_6H_4$ (i)	24 [0.5]	99	22.1
10	3-$NO_2C_6H_4$ (j)	24	95	21.9
11	2-$NO_2C_6H_4$ (k)	24	96	20.9
12	2-$C_{10}H_7$ (l)	30	96	22.4
13	(*E*)-C_6H_5CH=CH (m)	30	97	21.1

[a]Numbers in brackets refer to reactions carried out by heating in an oil bath (kept at a temperature of 100–105°C) or in a microwave reactor (T_{max} = 105°C, maximum potency = 50 W, maximum pressure = 50 PSI, t = 1 min ramp, 30 min hold, stirring mode "on").
[b]Isolated yields.
[c] ^{31}P NMR spectra were recorded at 81 MHz ($CDCl_3$, 85% H_3PO_4 as external standard).

equimolar mixture of allylic bromide **2** (readily available [8a,10] from the bromination of MBH adducts [4] with LiBr in an acidic medium) and Ph_3P in CH_3CN at room temperature for the appropriate period (Table 1). The reaction time can be dramatically reduced to 30 min by heating the solution under reflux or, alternatively, in a microwave reactor to give comparable results (Table 1, entries 1, 3, and 9).

Subsequently, a representative number of phosphonium salts **1** were submitted to different combinations of base ($NaHCO_3$, Et_3N, DABCO, HMTA) and solvent (water alone or in mixtures with DMSO or CH_3CN) for the selective reduction to α-methylalkenoates **3**. The best results were achieved with the use of inexpensive sodium bicarbonate (5 equiv) in water (Table 2).

TABLE 2 Preparation of α-Methylalkenoates **3** from Phosphonium Salts **1**



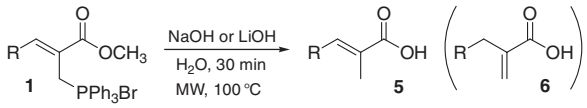
Entry	*R*	*Yield (%)*[a]	***3*:*4* (%)**[b]
1	C_6H_5 (a)	69	90:10
2	4-$CH_3OC_6H_4$ (b)	80	100:0
3	3,4-$(OCH_2O)C_6H_3$ (c)	76	100:0
4	4-$CH_3C_6H_4$ (d)	63	90:10
5	4-ClC_6H_4 (e)	72	95:5
6	2-ClC_6H_4 (f)	78	90:10
7	2,4-$Cl_2C_6H_3$ (g)	71	80:20
8	4-BrC_6H_4 (h)	74	85:15
9	4-$NO_2C_6H_4$ (i)	62	35:65
10	2-$C_{10}H_7$ (l)	74	90:10
11	(*E*)-C_6H_5CH=CH (m)	76	100:0

[a]Isolated yields of **3**:**4**, after column chromatography on silica gel (9:1 hexane/EtOAc).
[b]Ratio **3**:**4** (%) was determined by ^{1}H NMR integration (400 MHz, $CDCl_3$).

In all cases studied, the transformation was slow (20–40 h) at room temperature, but at 100°C the reaction time was reduced to 20 min, either by heating with an oil bath or using microwave irradiation. The presence of strongly electron-donating R groups favored the exclusive formation of the desired product **3** (Table 2, entries 2, 3, and 11), whereas the substitution with electron-withdrawing groups on the aromatic ring caused the generation of the rearranged isomer **4** in nonnegligible amounts (Table 2, entries 7–9).

As expected, in the absence of a base no appreciable reaction was observed, with the starting phosphonium **1** being recuperated almost entirely. However, replacing $NaHCO_3$ as the base with NaOH or LiOH also led to the redox reaction of phosphonium

TABLE 3 Preparation of α-Methylalkenoic Acids **5** from Phosphonium Salts **1**



Entry	*R*	*Yield[a](%) NaOH (**5:6**)[b]*	*Yield[a](%) LiOH (**5:6**)[b]*
1	C_6H_5 (a)	71 (80:20)	79 (90:10)
2	4-$CH_3OC_6H_4$ (b)	82 (95:5)	77 (95:5)
3	3,4-(OCH_2O)C_6H_3 (c)	81 (80:20)	80 (85:15)
4	4-$CH_3C_6H_4$ (d)	90 (90:10)	88 (90:10)
5	4-ClC_6H_4 (e)	85 (80:20)	91 (90:10)
6	2-ClC_6H_4 (f)	85 (80:20)	88 (85:15)
7	2,4-$Cl_2C_6H_3$ (g)	75 (75:25)	
8	4-BrC_6H_4 (h)	92 (85:15)	86 (80:20)
9	4-$NO_2C_6H_4$ (i)	*c*	*c*
10	2-$C_{10}H_7$ (l)	76 (90:10)	
11	(*E*)-C_6H_5CH═CH (m)	84 (>99:1)[d]	79 (>99:1)[d]

[a]Isolated yields.
[b]Ratio **5**:**6** (%) was determined by ^{1}H NMR integration (400 MHz, $CDCl_3$).
[c]Complex mixture of products.
[d]Reaction was carried out for 50 min.

salts **1**, but in these cases the concurrent hydrolysis of the ester group took place to furnish the corresponding α-methylalkenoic acids **5** (Table 3). No difference between NaOH and LiOH was evident from the data in Table 3, and both bases were effective in terms of mediating the reaction. In most cases, the isolated yields for the α-methylalkenoic acids **5** were higher than those observed for the corresponding α-methylalkenoates **3** (compare Tables 2 and 3). In addition, acid **5** was more easily separated from the side product (Ph_3PO) than ester **3** because the former was soluble in the aqueous basic medium (as a free carboxylate), whereas the latter (as well as Ph_3PO) was not, requiring purification by chromatography. However, the regioselectivity in favor of the more substituted alkenoic acid **5** was compromised due to the formation of the rearranged isomer **6** in all but one case (Table 3, entry 11).

This trend was particularly accentuated for the products carrying electron-withdrawing groups (Table 3, entries 5–8), although the selectivity for the electron-rich piperonyl derivative was also low (Table 3, entry 3). Modification of the reaction conditions, including time, temperature, amount of base, and addition of cosolvents, did not lead to any significant improvement in the regioselectivity.

Finally, we investigated the direct transformation of allylic bromides **2** into the corresponding α-methylalkenoic esters **3** and acids **5** through the one-pot reaction, without isolation of phosphonium salts **1**. Accordingly, substrate **2**, Ph_3P, and the base ($NaHCO_3$ or NaOH) in H_2O—CH_3CN were heated under microwave irradiation at 100°C (Table 4). Notably, all steps involved in this operation (nucleophilic displacement of bromine with Ph_3P, reduction of phosphonium salt **1**, and, depending on the base employed, ester hydrolysis) occurred smoothly to give the expected mixture of unsaturated esters **3**:**4** or carboxylic acids **5**:**6** with regioselectivity comparable to the stepwise process from salt **1** (see Tables 2 and 3). However, in a few cases, the use of $NaHCO_3$ led to a partial hydrolysis of the ester group with concurrent formation of acid **5** (Table 4, entry 6) or its isomer **6** (Table 4, entry 2).

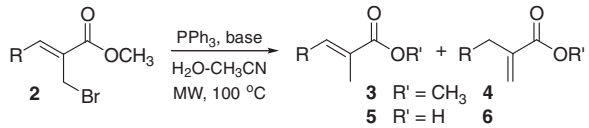
In conclusion, this methodology describes a convenient and general microwave-assisted synthesis of α-methylalkenoate derivatives in an aqueous medium from allylic bromides **2** or phosphonium salts **1**. Depending on the base employed in this redox process, the α-methylalkenoates **3** or α-methylalkenoic acids **5** can be easily accessed. Important advantages of this transformation include fast reactions, mild conditions, application of inexpensive and readily available reagents, operational simplicity, high yields, and moderate-to-high selectivity.

EXPERIMENTAL

General

Allylic bromides **2** were prepared according to literature procedures [10a,b]. Bromides **2a–g,i–m** are known compounds, and their infrared (IR) and ^{1}H NMR spectra were in accordance with the reported data [10a,b]. CH_3CN was freshly distilled from CaH_2. All chemicals were of reagent grade and were used as received. Column chromatography was performed using silica gel (70–230 mesh) and hexane/ethyl acetate as the eluent. TLC analysis was performed in silica gel plates, using a UV lamp for visualization. ^{1}H NMR spectra were recorded at 400 MHz, and coupling constants (J) are measured in hertz (Hz). ^{13}C NMR spectra were recorded at 100 MHz. Chemical shifts were recorded in parts per million (ppm, δ) relative to TMS at 0.00 ppm or solvent ($CDCl_3$ at 7.26 ppm or DMSO-d_6 at 2.50 ppm for ^{1}H NMR, and $CDCl_3$ at 77.2 ppm or DMSO-d_6 at 39.5 ppm for ^{13}C NMR) as the internal standard. ^{31}P NMR spectra were recorded at 81 MHz, and chemical shifts were recorded in parts per million (ppm, δ) relative to 85% H_3PO_4 at 0.00 ppm. IR spectra were recorded with the use of KBr (range 4000–400 cm^{-1}). Elemental analysis was conducted in a CHNS analyzer instrument. Melting points were determined by using a hot plate apparatus and are uncorrected.

TABLE 4 One-Pot Preparation of α-Methylalkenoic Esters **3** and Acids **5** from Allylic Bromides **2**



Entry	*R*	*Base*	*Time (min)*	***3:4*** *(%)*[a] *R′ = CH₃*	***5:6*** *(%)*[a] *R′ = H*
1	C_6H_5 (a)	$NaHCO_3$	30	80:20	
2	4-$CH_3OC_6H_4$ (b)	$NaHCO_3$	30	100:0[b]	
3	3,4-$(OCH_2O)C_6H_3$ (c)	$NaHCO_3$	30	100:0	
4	2-ClC_6H_4 (f)	$NaHCO_3$	60	80:20	
5	2,4-$Cl_2C_6H_3$ (g)	$NaHCO_3$	30	80:20	
6	(*E*)-$C_6H_5CH{=}CH$ (m)	$NaHCO_3$	30	100:0[c]	
7	C_6H_5 (a)	NaOH	40		95:5
8	C_6H_5 (a)	LiOH	40		90:10
9	3,4-$(OCH_2O)C_6H_3$ (c)	NaOH	60		90:10
10	4-$CH_3C_6H_4$ (d)	NaOH	60		95:5
11	2-ClC_6H_4 (f)	NaOH	60		85:15
12	2,4-$Cl_2C_6H_3$ (g)	NaOH	40		80:20

[a]The relative product distribution (%) was determined by ^{1}H NMR integration (400 MHz, $CDCl_3$).
[b]The crude reaction product contained ca. 15% of the rearranged acid **6b**.
[c]The crude reaction product contained ca. 15% of the acid **5m**.

Microwave-assisted reactions were performed in 10-mL sealed tubes in a monomode microwave CEM Explorer reactor instrument with IR temperature monitoring and a noninvasive pressure transducer.

*Methyl (Z)-2-(bromomethyl)-3-(4-bromophenyl)-2-propenoate (***2h***).* Yield 83%, white solid; mp: 58.5–60.0°C; IR (KBr) ν_{max} 3431, 3054, 2995, 2948, 1712, 1615, 1582, 1490, 1431, 1283, 1202, 1155, 1072 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 3.87 (s, 3H), 4.33 (s, 2H), 7.43 (d, $J = 8.6$ Hz, 2H), 7.58 (d, $J = 8.6$ Hz, 2H), 7.73 (s, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 26.6 (CH_2), 52.9 (OCH_3), 124.4 (C), 129.5 (C), 131.4 (2 × CH), 132.4 (2 × CH), 133.3 (C), 141.9 (CH), 166.6 (C); Anal. Calcd for $C_{11}H_{10}Br_2O_2$ (%): C, 39.56; H, 3.02. Found: C, 39.72; H, 3.41.

General Procedure for the Preparation of Phosphonium Salts **1**

Allylic bromide **2** (1.0 mmol) and Ph_3P (1.0 mmol) were added to CH_3CN (3.0 mL), and the solution was stirred at 25°C for the time given in Table 1. Concentration under reduced pressure gave salt **1** in 95%–99% yields and high purity. Recrystallization with CH_3CN gave **1** as a crystalline solid with analytical purity.

*[(Z)-2-Methoxycarbonyl-3-phenyl-2-propenyl]triphenylphosphonium Bromide (***1a***).* White solid; mp: 156.5–158.0°C; IR (KBr): ν_{max} 3445, 3042, 2992, 2949, 1700, 1625, 1586, 1436, 1268, 1111 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 3.39 (s, 3H), 5.01 (d, $J = 14.8$ Hz, 2H), 7.27–7.33 (m, 5H), 7.58–7.62 (m, 12H), 7.72–7.77 (m, 3H), 7.94 (d, $J = 5.1$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 24.8 (d, $J = 50.6$ Hz, CH_2), 52.6 (CH_3), 117.5 (d, $J = 85.0$ Hz, 3 × C_P), 121.1 (d, $J = 9.6$ Hz, C), 128.5 (2 × CH), 129.3 (2 × CH), 129.7 (s, CH), 130.2 (d, $J =$ 12.5 Hz, 6 × C_PH), 133.4 (d, $J = 3.7$ Hz, C), 133.8 (d, $J = 10.3$ Hz, 6 × C_PH), 135.1 (3 × C_PH), 146.4 (d, $J = 10.3$ Hz, CH), 166.4 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as the external standard): δ 22.5; Anal. Calcd for $C_{29}H_{26}BrO_2P$ (%): C, 67.32; H, 5.07. Found: C, 66.93; H, 5.10.

*[(Z)-2-Methoxycarbonyl-3-(4-methoxyphenyl)-2-propenyl]triphenylphosphonium Bromide (***1b***).* White solid; mp: 178.0–180.0°C; IR (KBr): ν_{max} 3462, 3396, 3058, 2948, 2908, 1699, 1629, 1601, 1512, 1439, 1261, 1112 cm^{-1}; ^{1}H NMR ($CDCl_3$): δ 3.38 (s, 3H), 3.82 (s, 3H), 5.12 (d, $J = 14.8$ Hz, 2H), 6.86 (d, $J = 8.6$ Hz, 2H), 7.39 (d, $J = 8.6$ Hz, 2H), 7.57–7.62 (m, 6H), 7.65–7.76 (m, 9H), 7.88 (d, $J = 4.9$ Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 24.9 (d, $J = 49.4$ Hz, CH_2), 52.4 (CH_3), 55.6 (CH_3), 114.8 (2 × CH), 118.0 (d, $J = 85.0$ Hz, 3 × C_P), 118.3 (d, $J = 10.3$ Hz, C), 125.6 (d, $J =$ 2.9 Hz, C), 130.1 (d, $J = 12.4$ Hz, 6 × C_PH), 130.9 (2 × CH), 134.0 (d, $J = 9.5$ Hz, 6 × C_PH), 135.0 (3 × C_PH), 146.2 (d, $J = 10.2$ Hz, CH), 160.9 (C), 166.9 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as the external standard): δ 22.5; Anal. Calcd for $C_{30}H_{28}BrO_3P$ (%): C, 65.82; H, 5.16. Found: C, 65.70; H, 5.30.

*[(Z)-2-Methoxycarbonyl-3-(3,4-methylenedioxyphenyl)-2-propenyl]triphenylphosphonium Bromide (**1c**).* White solid; mp: 192.0–194.0°C; IR (KBr): ν_{max} 3443, 3404, 3057, 2899, 1700, 1610, 1491, 1436, 1234, 1113 cm^{-1}; ^1H NMR ($CDCl_3$): δ 3.38 (s, 3H), 5.07 (d, J = 14.8 Hz, 2H), 5.97 (s, 2H), 6.62 (s, 1H), 6.80 (d, J = 8.0 Hz, 1H), 7.03 (d, J = 8.0 Hz, 1H), 7.60–7.71 (m, 12H), 7.75–7.79 (m, 3H), 7.82 (d, J = 4.7 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 25.3 (d, J = 50.3 Hz, CH_2), 52.8 (CH_3), 101.9 (CH_2), 108.6 (CH), 109.5 (CH), 118.1 (d, J = 84.6 Hz, 3 × C_P), 119.5 (d, J = 10.0 Hz, C), 124.3 (CH), 127.4 (C), 130.4 (d, J = 12.2 Hz, 6 × C_PH), 134.2 (d, J = 9.2 Hz, 6 × C_PH), 135.3 (3 × C_PH), 146.3 (d, J = 9.9 Hz, CH), 148.5 (C), 149.3 (C), 166.9 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 22.1; Anal. Calcd for $C_{30}H_{26}BrO_4P$ (%): C, 64.18; H, 4.67. Found: C, 64.37; H, 5.05.

*[(Z)-2-Methoxycarbonyl-3-(4-methylphenyl)-2-propenyl]triphenylphosphonium Bromide (**1d**).* White solid, mp 180.0–181.0°C; IR (KBr): ν_{max} 3450, 3396, 3056, 3006, 2951, 2897, 1710, 1631, 1586, 1436, 1263, 1110 cm^{-1}; ^1H NMR ($CDCl_3$): δ 2.34 (s, 3H), 3.39 (s, 3H), 5.10 (d, J = 14.8 Hz, 2H), 7.13 (d, J = 8.0 Hz, 2H), 7.23 (d, J = 8.0, 2H), 7.57–7.70 (m, 12H), 7.72–7.77 (m, 3H), 7.92 (d, J = 4.9 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 21.1 (CH_3), 24.5 (d, J = 49.3 Hz, CH_2), 52.3 (CH_3), 117.5 (d, J = 84.9 Hz, 3× C_P), 119.8 (d, J = 9.1 Hz, C), 128.4 (2 × CH), 129.7 (2 × CH), 129.9 (d, J = 11.4 Hz, 6 × C_PH), 133.6 (6 × C_PH), 134.0 (C), 134.8 (3 × C_PH), 139.9 (C), 146.2 (d, J = 8.3 Hz, CH), 166.3 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 22.6; Anal. Calcd for $C_{30}H_{28}BrO_2P$ (%): C, 67.80; H, 5.31. Found: C, 67.90; H, 5.50.

*[(Z)-3-(4-Chlorophenyl)-2-methoxycarbonyl-2-propenyl]triphenylphosphonium Bromide (**1e**).* White solid; mp: 169.5–171.5°C; IR (KBr): ν_{max} 3435, 3408, 3048, 3003, 2948, 1701, 1623, 1588, 1436, 1293, 1110 cm^{-1}; ^1H NMR ($CDCl_3$): δ 3.38 (s, 3H), 5.22 (d, J = 15.2 Hz, 2H), 7.31 (d, J = 8.2 Hz, 2H), 7.43 (d, J = 8.2 Hz, 2H), 7.55–7.60 (m, 6H), 7.64–7.75 (m, 9H), 7.90 (d, J = 4.8 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 24.3 (d, J = 49.8 Hz, CH_2), 52.6 (CH_3), 117.5 (d, J = 85.0 Hz, 3 × C_P), 121.4 (d, J = 9.6 Hz, C), 129.4 (2 × CH), 130.0 (d, J = 12.5 Hz, 6 × C_PH), 130.1 (2 × CH), 131.8 (C), 133.8 (d, J = 9.6 Hz, 6 × C_PH), 134.9 (3 × C_PH), 135.5 (C), 144.9 (d, J = 8.8 Hz, CH), 166.1 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 22.2; Anal. Calcd for $C_{29}H_{25}BrClO_2P$ (%): C, 63.12; H, 4.57. Found: C, 63.10; H, 4.60.

*[(Z)-3-(2-Chlorophenyl)-2-methoxycarbonyl-2-propenyl]triphenylphosphonium Bromide (**1f**).* White solid; mp: 127.0–128.5°C; IR (KBr): ν_{max} 3418, 3375, 3004, 2950, 2889, 1716, 1634, 1587, 1437, 1265, 1111 cm^{-1}; ^1H NMR ($CDCl_3$): δ 3.32 (s, 3H), 5.00 (d, J = 15.2 Hz, 2H), 7.07 (d, J = 7.8 Hz, 1H), 7.25 (t, J = 7.8 Hz, 1H), 7.47–7.60 (m, 13H), 7.67–7.71 (m, 3H), 7.88 (d, J = 7.4 Hz, 1H), 7.98 (d, J = 5.5 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 24.1 (d, J = 50.0 Hz, CH_2), 52.9 (CH_3), 117.7 (d, J = 85.7 Hz, 3 × C_P), 122.8 (d, J = 9.6 Hz, C), 128.9 (CH), 130.0 (CH), 130.4 (d, J = 12.4 Hz, 6× C_PH), 131.0 (CH), 131.3 (CH), 132.6 (C), 133.4 (C), 134.1 (d, J = 10.2 Hz, 6 × C_PH), 135.2 (3 × C_PH), 144.2 (d, J = 9.6 Hz, CH), 166.0 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 21.7; Anal. Calcd for $C_{29}H_{25}BrClO_2P$ (%): C, 63.12; H, 4.57. Found: C, 62.90; H, 4.70.

*[(Z)-3-(2,4-Dichlorophenyl)-2-methoxycarbonyl-2-propenyl]triphenylphosphonium Bromide (**1g**).* White solid; mp: 178.0–180.0°C; IR (KBr): ν_{max} 3415, 3059, 3006, 2949, 1715, 1641, 1586, 1438, 1289, 1255, 1109 cm^{-1}; ^1H NMR ($CDCl_3$): δ 3.36 (s, 3H), 5.28 (d, J = 15.6 Hz, 2H), 7.01 (d, J = 2.0 Hz, 1H), 7.52–7.57 (m, 6H), 7.62–7.73 (m, 10H), 7.97 (d, J = 5.6 Hz, 1H), 8.25 (d, 8.2 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 24.1 (d, J = 49.5 Hz, CH_2), 52.9 (CH_3), 117.6 (d, J = 84.6 Hz, 3 × C_P), 123.3 (d, J = 10.0 Hz, C), 129.3 (CH), 129.4 (CH), 130.3 (d, J = 13.0 Hz, 6 × C_PH), 131.0 (C), 132.8 (CH), 133.8 (C), 134.0 (d, J = 10.0 Hz, 6 × C_PH), 135.0 (3 × C_PH), 136.1 (C), 142.9 (d, J = 10.0 Hz, CH), 165.7 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 21.4; Anal. Calcd for $C_{29}H_{24}Cl_2BrO_2P$ (%): C, 59.41; H, 4.14. Found: C, 59.10, H, 4.43.

*[(Z)-3-(4-Bromophenyl)-2-methoxycarbonyl-2-propenyl]triphenylphosphonium Bromide (**1h**).* White solid; mp: 118.0–120.0°C; IR (KBr): ν_{max} 3489, 3428, 3054, 3006, 2952, 1713, 1634, 1584, 1437, 1264, 1111 cm^{-1}; ^1H NMR ($CDCl_3$): δ 3.36 (s, 3H), 5.09 (d, J = 15.0 Hz, 2H), 7.31 (d, J = 8.6 Hz, 2H), 7.43 (d, J = 8.6 Hz, 2H), 7.54–7.64 (m, 12H), 7.70–7.75 (m, 3H), 7.86 (d, J = 5.5 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 24.6 (d, J = 48.8 Hz, CH_2), 52.9 (CH_3), 118.0 (d, J = 84.5 Hz, 3 × C_P), 121.8 (d, J = 10.0 Hz, C), 124.2 (C), 130.3 (d, J = 12.2 Hz, 6 × C_PH), 130.6 (2 × CH), 132.5 (C), 132.7 (2 × CH), 134.2 (d, J = 10.0 Hz, 6 × C_PH), 135.2 (3 × C_PH), 145.4 (d, J = 10.7 Hz, CH), 166.5 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 22.3; Anal. Calcd for $C_{29}H_{25}Br_2O_2P$ (%): C, 58.41; H, 4.23. Found: C, 58.10; H, 4.40.

*[(Z)-2-Methoxycarbonyl-3-(4-nitrophenyl)-2-propenyl]triphenylphosphonium Bromide (***1i***).* Yellow solid; mp: 128.0–130.0°C; IR (KBr): ν_{max} 3421, 3042, 3003, 2987, 1707, 1593, 1518, 1437, 1347, 1316, 1110 cm^{-1}; ^1H NMR ($CDCl_3$): δ 3.41 (s, 3H), 5.34 (d, J = 15.4 Hz, 2H), 7.54–7.59 (m, 6H), 7.66–7.74 (m, 9H), 7.77 (d, J = 8.6 Hz, 2H), 7.98 (d, J = 5.1 Hz, 1H), 8.16 (d, J = 8.6 Hz, 2H); ^{13}C NMR ($CDCl_3$): δ 24.8 (d, J = 50.3 Hz, CH_2), 53.1 (CH_3), 117.7 (d, J = 84.5 Hz, 3 × C_P), 124.1 (d, J = 10.0 Hz, C), 124.5 (2 × CH), 130.3 (2 × CH), 130.4 (d, J = 13.0 Hz, 6 × C_PH), 134.2 (d, J = 10.0 Hz, 6 × C_PH), 135.3 (3 × C_PH), 140.0 (C), 143.9 (d, J = 10.7 Hz, CH), 148.0 (C), 166.0 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 22.1; Anal. Calcd for $C_{29}H_{25}BrNO_4P$ (%): C, 61.93; H, 4.48; N, 2.49. Found: C, 61.70; H, 4.40; N, 2.50.

*[(Z)-2-Methoxycarbonyl-3-(3-nitrophenyl)-2-propenyl]triphenylphosphonium Bromide (***1j***).* Yellow solid; mp: 126.5–127.5°C; IR (KBr): ν_{max} 3459, 3387, 3048, 2992, 1712, 1615, 1586, 1526, 1437, 1355, 1314, 1113 cm^{-1}; ^1H NMR ($CDCl_3$): δ 3.36 (s, 3H), 5.07 (d, J = 15.4 Hz, 2H), 7.50–7.70 (m, 16H), 7.73 (appt, J = 8.0 Hz, 1H), 7.92 (d, J = 5.3 Hz, 1H), 8.03 (dd, J = 8.2 and 2.0 Hz, 1H), 8.34 (d, J = 7.6 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 24.6 (d, J = 49.0 Hz, CH_2), 53.1 (CH_3), 117.6 (d, J = 85.5 Hz, 3 × C_P), 122.9 (CH), 123.9 (d, J = 10.0 Hz, C), 124.0 (CH), 130.4 (d, J = 13.0 Hz, 6 × C_PH), 131.7 (CH), 134.1 (d, J = 9.2 Hz, 6 × C_PH), 135.1 (C), 135.3 (3 × C_PH), 135.9 (CH), 143.8 (d, J = 9.0 Hz, CH), 148.2 (C), 166.0 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 21.9; Anal. Calcd for $C_{29}H_{25}BrNO_4P$ (%): C, 61.93; H, 4.48; N, 2.49. Found: C, 61.80; H, 4.60; N, 2.50.

*[(Z)-2-Methoxycarbonyl-3-(2-nitrophenyl)-2-propenyl]triphenylphosphonium Bromide (***1k***).* Yellow solid; mp: 144.0–146.0°C; IR (KBr): ν_{max} 3445, 3053, 3007, 2989, 2950, 1715, 1638, 1586, 1522, 1435, 1345, 1270, 1111 cm^{-1}; ^1H NMR ($CDCl_3$): δ 3.36 (s, 3H), 5.30 (d, J = 15.6 Hz, 2H), 7.48–7.75 (m, 16H), 7.87 (dd, J = 8.0 and 1.0 Hz, 1H), 8.19 (dt, J = 8.0 and 1.0 Hz, 1H), 8.26 (d, J = 5.7 Hz, 1H), 8.28 (d, J = 8.0 Hz, 1H); ^{13}C NMR ($CDCl_3$, DMSO-d_6 as internal standard): δ 23.3 (d, J = 50.6 Hz, CH_2), 52.8 (CH_3), 116.9 (d, J = 85.0 Hz, 3 × C_P), 120.5 (d, J = 10.2 Hz, C), 125.6 (CH), 130.1 (C), 130.2 (d, J = 12.5 Hz, 6 × C_PH), 130.6 (CH), 131.4 (CH), 133.8 (d, J = 9.5 Hz, 6 × C_PH), 135.3 (3 × C_PH), 136.1 (CH), 144.4 (d, J = 10.3 Hz, CH), 145.8 (C), 165.5 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 20.9; Anal. Calcd for $C_{29}H_{25}BrNO_4P$ (%): C, 61.93; H, 4.48; N, 2.49. Found: C, 61.70; H, 4.60; N, 2.50.

*[(Z)-2-Methoxycarbonyl-3-(2-naphthyl)-2-propenyl]triphenylphosphonium Bromide (***1l***).* White solid; mp: 159.5–160.5°C; IR (KBr): ν_{max} 3454, 3394, 3051, 3000, 2948, 1705, 1626, 1586, 1434, 1341, 1270, 1110 cm^{-1}; ^1H NMR ($CDCl_3$): δ 3.40 (s, 3H), 5.21 (d, J = 15.0 Hz, 2H), 7.35–7.38 (m, 2H), 7.43–7.66 (m, 16H), 7.75–7.79 (m, 2H), 7.94–7.96 (m, 1H), 8.01 (s, 1H), 8.09 (d, J = 5.5 Hz, 1H); ^{13}C NMR ($CDCl_3$): δ 24.5 (d, J = 49.5 Hz, CH_2), 52.6 (CH_3), 117.7 (d, J = 85.5 Hz, 3 × C_P), 121.0 (d, J = 10.0 Hz, C), 125.5 (CH), 126.8 (CH), 127.5 (2 x CH), 128.6 (CH), 128.9 (CH), 129.1 (CH), 130.0 (d, J = 13.0 Hz, 6 × C_PH), 130.8 (C), 133.1 (C), 133.3 (C), 133.9 (d, J = 9.2 Hz, 6 × C_PH), 134.9 (3 × C_PH), 146.5 (d, J = 10.0 Hz, CH), 166.5 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 22.4; Anal. Calcd for $C_{33}H_{28}BrO_2P$ (%): C, 69.85; H, 4.97. Found: C, 69.60; H, 5.10.

*[(2Z,4E)-2-Methoxycarbonyl-5-phenyl-2,4-pentadienyl]triphenylphosphonium Bromide (***1m***).* White solid; mp >198.0°C (dec); IR (KBr): ν_{max} 3447, 3402, 3047, 3005, 2980, 2878, 1711, 1618, 1602, 1591, 1439, 1256, 1110, 970 cm^{-1}; ^1H NMR ($CDCl_3$, DMSO-d_6 as internal standard): δ 3.34 (s, 3H), 4.81 (d, J = 15.2 Hz, 2H), 6.75 (d, J = 15.2 Hz, 1H), 6.89 (dd, J= 15.2 and 11.5 Hz, 1H), 7.24–7.31 (m, 5H), 7.48 (dd, J = 11.5 and 5.5 Hz, 1H), 7.57–7.61 (m, 6H), 7.67–7.72 (m, 9H); ^{13}C NMR ($CDCl_3$, DMSO-d_6 as internal standard): δ 24.3 (d, J = 50.5 Hz, CH_2), 52.4 (CH_3), 117.0 (d, J= 11.7 Hz, C), 117.4 (d, J = 85.0 Hz, 3 × C_P), 122.9 (d, J = 5.1 Hz, CH), 128.0 (2 × CH), 128.7 (2 × CH), 129.9 (CH), 130.2 (d, J = 12.5 Hz, 6 × C_PH), 134.2 (d, J = 9.5 Hz, 6 × C_PH), 135.3 (C), 135.4 (3 × C_PH), 144.0 (d, J = 4.4 Hz, CH), 145.8 (d, J = 9.5 Hz, CH), 166.6 (C); ^{31}P NMR ($CDCl_3$, 85% H_3PO_4 as external standard): δ 21.1; Anal. Calcd for $C_{31}H_{28}BrO_2P$ (%): C, 68.52; H, 5.19. Found: C, 68.30; H, 5.30.

General Procedure for the Microwave-Assisted Synthesis of α-Methylalkenoates **3**

Phosphonium salt **1** (1.0 mmol), $NaHCO_3$ (5.0 m mol), and water (5.0 mL) were placed in a 10-mL glass tube. The vessel was sealed with a septum, placed into the microwave cavity of the monomode reactor (CEM-Explorer, with IR temperature and noninvasive pressure transducer) and irradiated by a single pulse (T_{max} = 100–105°C, maximum potency = 50 W, maximum pressure = 50 PSI, t = 1 min ramp, 20 min hold, stirring mode "on") under the conditions given in Table 2. After the mixture had cooled to room temperature, the reaction vessel was opened and the contents were treated with 1 M HCl until

pH ~7.0. The aqueous mixture was extracted with CH_2Cl_2 and the organic extracts were washed with water, dried over Na_2SO_4, filtered, and concentrated under reduced pressure. The crude product was purified by column chromatography on silica gel (9:1 hexane/EtOAc) to give ester **3** and, in some cases, **3** and **4** as a mixture of isomers that we were unable to separate by conventional silica gel chromatography; their spectroscopic characterizations were in agreement with the published data [6e,7a,b,8a].

General Procedure for the Microwave-Assisted Synthesis of α-Methylalkenoic Acid **5**

Phosphonium salt **1** (1.0 mmol), NaOH (or LiOH) (5.0 mmol), and water (5.0 mL) were placed in a 10-mL glass tube. The vessel was sealed with a septum, placed into the microwave cavity of the monomode reactor (CEM-Explorer, with IR temperature and noninvasive pressure transducer) and irradiated by a single pulse ($T_{max} = 100°C$, maximum potency = 50 W, maximum pressure = 50 PSI, $t = 1$ min ramp, 30 min hold, stirring mode "on") under the conditions given in Table 3. After the mixture had cooled to room temperature, the reaction vessel was opened, the neutral contents were extracted with CH_2Cl_2, and the organic extract was discharged. The aqueous layer was acidified with 6 M HCl until pH 1.0 and the acid formed was extracted with CH_2Cl_2, dried over Na_2SO_4, filtered, and concentrated to give the isomeric products **5** and **6** as a mixture of isomers that we were unable to separate by conventional silica gel chromatography; their spectroscopic characterizations were in agreement with the published data [6e,7c,11].

General Procedure for the Microwave-Assisted Synthesis of α-Methylalkenoates **3** *or α-Methylalkenoic Acids* **5** *Directly from Bromides* **2**

Allylic bromide **2** (1.0 mmol), Ph_3P (1.0 mmol), $NaHCO_3$ or NaOH (5.0 mmol), CH_3CN (3.0 mL), and water (5.0 mL) were placed in the microwave tube, and the mixture was irradiated with stirring under the conditions given in Table 4. After the usual workup, the esters **3**:**4** or the acids **5**:**6** were obtained in high yields; their spectroscopic characterizations were in agreement with the published data [6e,7a–c,8a,11].

SUPPORTING INFORMATION

Copies of IR and NMR (^1H, ^{13}C, and ^{31}P) spectra for all phosphonium salts associated with this article are available from the corresponding author (e-mail: msa@qmc.ufsc.br) on request.

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