Wittig Olefination of Trifluoromethyl Ketones and Allylic Carbonates Mediated by Phosphines

Tong Wang, Li-Tao Shen, Song Ye*

Beijing National Laboratory for Molecular Sciences, CAS Key Laboratory of Molecular Recognition and Function, Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, P. R. of China
Fax +86(10)62554449; E-mail: songye@iccas.ac.cn

Received 20 June 2011; revised 15 July 2011

Abstract: The Wittig olefination of trifluromethyl ketones and allylic carbonates mediated by tributylphosphine was realized to give corresponding trifluoromethyl dienes in good yields with excellent *E*-selectivities.

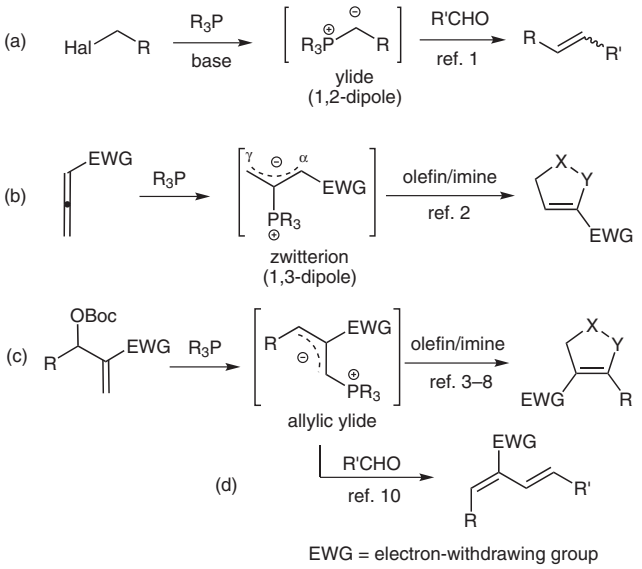
Key words: Wittig, trifluoromethyl ketones, trifluoromethyl olefins, ylides, allylic carbonate

The phosphonium ylide has become established as a classic reagent for the olefination of carbonyl groups.[1] Generally, phosphonium ylides are generated from the salt of phosphine and haloalkanes in the presence of base (Scheme 1, equation a). In 1995, Lu et al. reported their pioneering phosphine-catalyzed [3+2] annulation of allenoates with electron-deficient olefins, involving phosphonium zwitterions (1,3-dipole) as the key intermediate (Scheme 1, equation b).[2a] The phosphine-catalyzed annulation of allenoate then becomes a powerful tool for the construction of (hetero)cycles.[2] In 2003, the same group reported the generation of phosphonium allylic ylides from allylic carbonates and the application of these intermediates in annulation reactions (Scheme 1, equation c).[3]

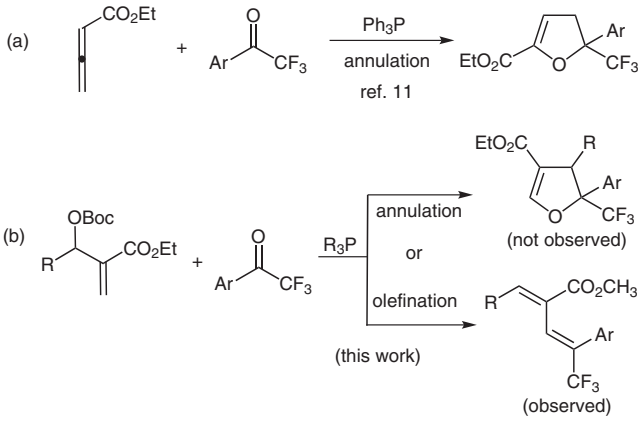
In the past decade, allylic carbonates[4] were successfully used as C_3 synthons in phosphine-catalyzed [3+2] annulations with olefins[5] and imines,[6] in [3+4] annulation with coumalate,[7] and in [3+6] annulation[8] with tropone. In addition, allylic carbonates were also used as C_1 synthons for phosphine-catalyzed [4+1] annulation.[9] Interestingly, a phosphine-mediated Wittig olefination reaction of allylic carbonates and aldehydes was reported recently by He et al. (Scheme 1, equation d).[10]

Recently, we have reported an oxygen-version of the [3+2] annulation of allenoates with trifluoromethyl ketones, previously developed by Lu et al. (Scheme 2, equation a).[11] The use of trifluoromethyl ketones was the key to the success of the annulation reaction, compared with previously reported use of aldehydes.[12] Considering the many applications of fluorinated compounds[13] and the ready availability of the allylic carbonates through Morita–Baylis–Hillman reaction,[14] we were interested in exploring the phosphine-catalyzed (or mediated) reaction of allylic carbonates and trifluoromethyl ketones. The possible competition between annulation and olefination[15] was also interesting (Scheme 2, equation b).

Initially, the model reaction of allylic carbonate **1a** and trifluoromethyl ketone **2a** with 10 mol% triphenylphosphine as the catalyst was investigated. No annulation product and only a trace of olefination product **3aa** was observed, along with the recovery of the substrates, for the 'catalytic' reaction. Based on an analysis of the mechanism (see below), it is clear that phosphine acts as the reagent for the olefination reaction. Thus, significantly more phosphine



Scheme 1 Generation of phosphonium ylides and their reactions



Scheme 2 Comparison of the reactions of allenoates and allylic carbonates with trifluoromethyl ketones

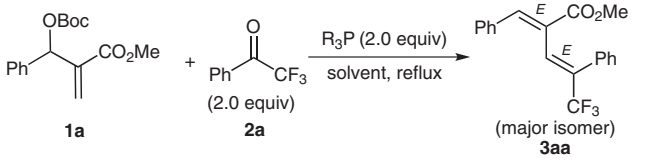
SYNTHESIS 2011, No. 20, pp 3359–3363
Advanced online publication: 24.08.2011
DOI: 10.1055/s-0030-1260185; Art ID: H62511SS
© Georg Thieme Verlag Stuttgart · New York

Downloaded by: Florida International University. Copyrighted material.

was employed to optimize the reaction conditions (Table 1). It was found that 69% total yield of the olefination products was obtained when two equivalents of triphenylphosphine (Ph_3P) was used, albeit with poor *E*/*Z*-selectivity (Table 1, entry 1). Solvent screening resulted in varied yields without improvement of *E*/*Z*-selectivities (Table 1, entries 2–6). Several phosphines were then tested in the reaction (Table 1, entries 7–13). Besides triphenylphosphine, other triarylphosphines with either electron-withdrawing (4-F, Cl) or electron-donating (4-Me, MeO) groups gave olefination products in similar yields and *E*/*Z*-selectivity (Table 1, entries 7–10). Better *E*/*Z*-selectivity resulted when methyldiphenylphosphine was used (Table 1, entry 11). Finally, trimethylphosphine and tri(*n*-butyl)phosphine were identified as optimal; application of these reagents gave the dienes in good yield with excellent *E*/*Z*-selectivity (Table 1, entries 12 and 13). In addition, no loss of yield or selectivity was observed when the amount of phosphine was reduced from 2 to 1.5 equivalents (Table 1, entry 14).

With the optimized reaction conditions in hand, the reaction scope was then briefly investigated (Table 2). It was found that both aryltrifluoromethyl ketones with electron-donating (Ar = 4-Me, 4-$MeOC_6H_4$) and electron-withdrawing (Ar = 4-ClC_6H_4) substituents worked well, to furnish the corresponding dienes in good yields (Table 2, entries 2–4). Ketone **2e**, with a *meta*-methylphenyl group worked well to give the corresponding diene **3ae** in 69% yield (Table 2, entry 5). Ketone **2f**, with a 2-thienyl group, also worked but with somewhat low yield (Table 2, entry 6). Several allylic carbonates with a range of aryl groups were also tested (Table 2, entries 7–10). Substrates with both electron-donating (Ar = 4-Me C_6H_4) and electron-withdrawing substituents (Ar = 4-ClC_6H_4) were tolerated (Table 2, entries 7–8). Both *meta*- and *ortho*-substituted substrates (**1d** and **1e**, R = 3-ClC_6H_4, 2-ClC_6H_4) showed comparable results to those obtained with *para*-substituted substrates (**1c**, R = 4-ClC_6H_4; Table 2, entries 9, 10 vs. 8). The structure of the diene **3aa** was unambiguously established by X-ray analysis of its crystal (Figure 1).

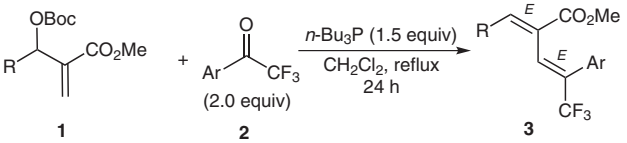
Table 1 Optimization of Reaction Conditions



Entry	R_3P	Solvent	dr ratio[a]	Yield (%)[b]
1	Ph_3P	CH_2Cl_2	1:0.17:0.1	69
2	Ph_3P	toluene	1:0.14:0.21	66
3	Ph_3P	THF	1:0.13:0.17	66
4	Ph_3P	MeCN	1:1.36:0.12	42
5	Ph_3P	EtOAc	1:1.0:0.44	48
6	Ph_3P	MeOH	N.D.[c]	0
7	$(4\text{-}FC_6H_4)_3P$	CH_2Cl_2	1:0.14:0.26	53
8	$(4\text{-}ClC_6H_4)_3P$	CH_2Cl_2	1:0.14:0.23	47
9	$(4\text{-}MeOC_6H_4)_3P$	CH_2Cl_2	1:0.19:0.13	52
10	$(4\text{-}MeC_6H_4)_3P$	CH_2Cl_2	1:0.19:0.13	54
11	Ph_2PMe	CH_2Cl_2	1:0.10:0.03	53
12	Me_3P	CH_2Cl_2	1:0:0.04	49
13	$(n\text{-}Bu)_3P$	CH_2Cl_2	1:0:0.03	57
14	$(n\text{-}Bu)_3P$[d]	CH_2Cl_2	1:0:0.03	65

[a] Determined by ^1H NMR (300 MHz) analysis of the isolated product with (*E*,*E*)-**3aa** as the major isomer.
[b] Isolated yield.
[c] N.D. = not determined.
[d] 1.5 equivalents were used.

Table 2 Wittig Olefination of Morita–Baylis–Hillman Carbonates with Trifluoromethylketones



Entry	1	R	2	Ar	3	Yield (%)[a]
1	**1a**	Ph	**2a**	Ph	**3aa**	65
2	**1a**	Ph	**2b**	4-MeC_6H_4	**3ab**	58
3	**1a**	Ph	**2c**	4-$MeOC_6H_4$	**3ac**	69
4	**1a**	Ph	**2d**	4-ClC_6H_4	**3ad**	61
5	**1a**	Ph	**2e**	3-MeC_6H_4	**3ae**	69
6	**1a**	Ph	**2f**	2-thienyl	**3af**	58
7	**1b**	4-MeC_6H_4	**2a**	Ph	**3ba**	67
8	**1c**	4-ClC_6H_4	**2a**	Ph	**3ca**	72
9	**1d**	3-ClC_6H_4	**2a**	Ph	**3da**	66
10	**1e**	2-ClC_6H_4	**2a**	Ph	**3ea**	76

[a] Isolated yield of (*E*,*E*)-**3** with dr >20:1 in all cases.

A possible mechanism for the olefination reaction is depicted in Scheme 3. The phosphonium allylic ylide **A** is initially generated from the phosphine and allylic carbonate. Addition of the ylide to the trifluoromethyl ketone gives the adduct **B**, which collapses to furnish the dienes and phosphine oxide. The vicinal position of the oxygen and phosphine in adduct **B** may then facilitate the formation of phosphine oxide, which gives dienes as the product rather than dihydrofuran as for the reaction of allenoate with ketone.[11] The better *E*-selectivity for the olefination catalyzed by $(n\text{-}Bu)_3P$ rather than Ph_3P may be due to the favored formation of trialkylphosphine oxide over triarylphosphine oxide.

Downloaded by: Florida International University. Copyrighted material.

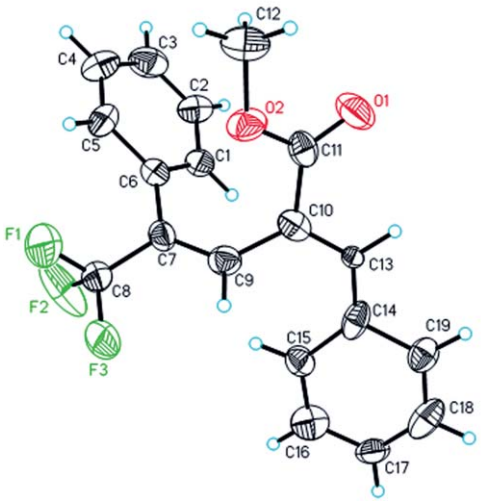
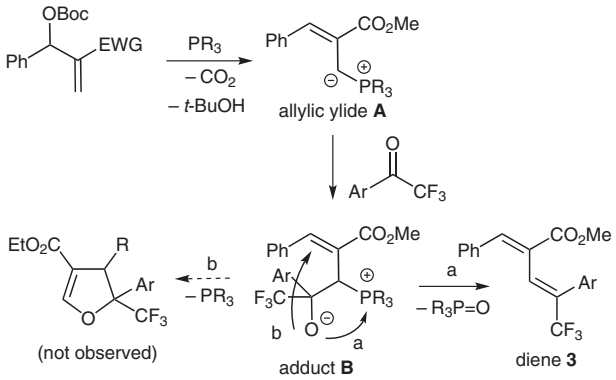


Figure 1 X-ray structure of diene **3aa**



Scheme 3 Proposed reaction mechanism

In conclusion, the trialkylphosphine-mediated Wittig olefination of trifluoromethyl ketones gives the corresponding trifluoromethyl dienes in good yields with good *E*-selectivities. The formation of olefins is different to the reported formation of dihydrofuran for the phosphine-catalyzed annulation of allenoates and ketones.

Unless otherwise indicated, all starting materials were obtained from commercial suppliers and used as received. The allylic carbonates were prepared according to literature methods.[3,5–8] Anhydrous THF and toluene were distilled from sodium and benzophenone. Anhydrous CH_2Cl_2 was distilled from CaH_2. Anhydrous EtOAc and MeCN were dried over molecular sieves. All reactions utilizing air- or moisture-sensitive reagents were performed in oven-dried glassware with magnetic stirring under a nitrogen atmosphere. Column chromatography was performed with silica gel 200–300 mesh.

Wittig Olefination of Allylic Carbonates with Trifluoromethylketones; Typical Procedure

To a stirred solution of allylic carbonate **1** (0.25 mmol) and trifluoromethylketone **2** (0.5 mmol) in CH_2Cl_2 (5 mL), was added tributylphosphine (0.375 mmol). The solution was stirred at reflux temperature for 24 h. The reaction mixture was concentrated under reduced pressure, and the residue was purified by column chromatography on silica gel (CH_2Cl_2–petroleum ether, typically 3:1) to furnish the corresponding diene **3**.

(2*E*,3*E*)-Methyl 2-Benzylidene-5,5,5-trifluoro-4-phenylpent-3-enoate (3aa)

Yield: 76 mg (65%); white solid; mp 92–93 °C; R_f = 0.4 (petroleum ether–EtOAc, 10:1).

IR (KBr): 1716, 1645, 1494, 1358, 1259, 1167, 953, 898, 765 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.48 (d, *J* = 1.5 Hz, 1 H), 7.28–7.15 (m, 8 H), 7.07–7.05 (m, 2 H), 7.01–7.00 (m, 1 H), 3.31 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 166.9, 143.3, 134.62 (q, *J* = 29.3 Hz), 134.58, 132.7, 130.2, 129.9, 128.8, 128.75, 128.73, 128.6 (q, *J* = 6.2 Hz), 128.4, 126.9, 123.6 (q, *J* = 272 Hz), 52.0.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –64.8.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{19}H_{15}F_3O_2$: 332.1024; found: 332.1027.

(2*E*,3*E*)-Methyl 2-Benzylidene-5,5,5-trifluoro-4-*p*-tolylpent-3-enoate (3ab)

Yield: 70 mg (58%); white solid; mp 76–77 °C; R_f = 0.4 (petroleum ether–EtOAc, 10:1).

IR (KBr): 1711, 1591, 1119, 892, 739 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.48 (d, *J* = 1.2 Hz, 1 H), 7.34–7.28 (m, 5 H), 7.01–6.95 (m, 5 H), 3.32 (s, 3 H), 2.21 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 167.1, 143.1, 138.8, 134.70 (q, *J* = 29.2 Hz), 134.67, 130.2, 129.9, 129.8, 128.7, 128.6, 128.2 (q, *J* = 6.2 Hz), 127.8, 127.1, 123.6 (q, *J* = 272 Hz), 52.0, 21.3.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –64.8.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{20}H_{17}F_3O_2$: 346.1181; found: 346.1185.

(2*E*,3*E*)-Methyl 2-Benzylidene-5,5,5-trifluoro-4-(4-methoxyphenyl)pent-3-enoate (3ac)

Yield: 85 mg (69%); white solid; mp 88–89 °C; R_f = 0.3 (petroleum ether–EtOAc, 10:1).

IR (KBr): 1718, 1607, 1514, 1254, 1169, 1114 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.49 (d, *J* = 1.5 Hz, 1 H), 7.35–7.29 (m, 5 H), 7.03–6.95 (m, 3 H), 6.74–6.69 (m, 2 H), 3.69 (s, 3 H), 3.37 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 167.2, 159.9, 143.0, 134.7, 134.4 (q, *J* = 29.2 Hz), 132.9 (q, *J* = 2.1 Hz), 130.2, 130.1, 129.9, 128.8, 127.9 (q, *J* = 6.2 Hz), 127.2, 123.7 (q, *J* = 272 Hz), 113.8, 55.3, 52.1.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –64.9.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{20}H_{17}F_3O_3$: 362.1130; found: 362.1134.

(2*E*,3*E*)-Methyl 2-Benzylidene-4-(4-chlorophenyl)-5,5,5-trifluoropent-3-enoate (3ad)

Yield: 76 mg (61%); white solid; mp 53–54 °C; R_f = 0.5 (petroleum ether–EtOAc, 10:1).

IR (KBr): 1722, 1636, 1492, 1286, 1172, 764 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.52 (d, *J* = 1.5 Hz, 1 H), 7.32–7.28 (m, 5 H), 7.17–7.12 (m, 2 H), 7.03–7.02 (m, 1 H), 6.96–6.93 (m, 2 H), 3.43 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 166.7, 143.8, 134.9, 134.5, 133.5 (q, *J* = 29.6 Hz), 131.1, 130.2, 130.12, 130.09, 129.2 (q, *J* = 6.2 Hz), 128.8, 128.7, 126.3, 123.3 (q, *J* = 272 Hz), 52.2.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –65.0.

Downloaded by: Florida International University. Copyrighted material.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{19}H_{14}ClF_3O_2$: 366.0634; found: 366.0638.

(2*E*,3*E*)-Methyl 2-Benzylidene-5,5,5-trifluoro-4-*m*-tolylpent-3-enoate (3ae)

Yield: 84 mg (69%); colorless oil; R_f = 0.4 (petroleum ether–EtOAc, 10:1).

IR (KBr): 1719, 1636, 1260, 1119, 693 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.47 (d, *J* = 1.5 Hz, 1 H), 7.30 (m, 5 H), 7.07 (t, *J* = 7.5 Hz, 1 H), 7.01–6.98 (m, 2 H), 6.88–6.81 (m, 2 H), 3.34 (s, 3 H), 2.17 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 167.0, 143.2, 138.0, 134.69 (q, *J* = 29.2 Hz), 134.68, 132.6, 130.2, 129.8, 129.6, 129.2, 128.8, 128.6, 128.4 (q, *J* = 6.2 Hz), 127.1, 125.9, 123.6 (q, *J* = 272 Hz), 52.0, 21.5.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –64.8.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{20}H_{17}F_3O_2$: 346.1181; found: 346.1184.

(2*E*,3*Z*)-Methyl 2-Benzylidene-5,5,5-trifluoro-4-(thiophen-2-yl)pent-3-enoate (3af)

Yield: 69 mg (58%); white solid; mp 70–71 °C; R_f = 0.4 (petroleum ether–EtOAc, 10:1).

IR (KBr): 1716, 1596, 1433, 1286, 1257, 1172, 1121, 765 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.65 (d, *J* = 1.5 Hz, 1 H), 7.38–7.30 (m, 5 H), 7.24 (dd, *J* = 5.1, 1.2 Hz, 1 H), 7.00–6.96 (m, 2 H), 6.89 (dd, *J* = 8.1, 3.6 Hz, 1 H), 3.44 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 166.7, 144.3, 134.5, 133.2, 130.9, 130.2, 129.1, 128.9, 128.7, 128.3 (q, *J* = 6.1 Hz), 127.9, 127.2, 126.6, 123.1 (q, *J* = 272 Hz), 52.2.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –65.6.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{17}H_{13}F_3O_2S$: 338.0588; found: 338.0592.

(2*E*,3*E*)-Methyl 5,5,5-Trifluoro-2-(4-methylbenzylidene)-4-phenylpent-3-enoate (3ba)

Yield: 81 mg (67%); white solid; mp 121–122 °C; R_f = 0.4 (petroleum ether–EtOAc, 10:1).

IR (KBr): 1711, 1603, 1261, 1162, 1106, 811, 739 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.48 (s, 1 H), 7.26–7.11 (m, 9 H), 7.00 (s, 1 H), 3.29 (s, 3 H), 2.30 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 167.1, 143.5, 140.5, 134.4 (q, *J* = 29.5 Hz), 132.9, 131.9, 130.4, 129.6, 128.9 (q, *J* = 6. 2 Hz), 128.85, 128.79, 128.4, 125.9, 123.7 (q, *J* = 272 Hz), 51.9, 21.6.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –64.8.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{20}H_{17}F_3O_2$: 346.1181; found: 346.1184.

(2*E*,3*E*)-Methyl 2-(4-Chlorobenzylidene)-5,5,5-trifluoro-4-phenylpent-3-enoate (3ca)

Yield: 90 mg (72%); white solid; mp 118–119 °C; R_f = 0.4 (petroleum ether–EtOAc, 10:1).

IR (KBr): 2962, 1711, 1489, 1437, 1257, 1164, 823, 766 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.41 (s, 1 H), 7.28–7.14 (m, 7 H), 7.04–7.01 (m, 2 H), 6.96–6.95 (m, 1 H), 3.36 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 166.7, 141.8, 135.9, 135.1 (q, *J* = 29.5 Hz), 133.0, 132.5, 131.3, 129.1, 128.9, 128.7, 128.4, 128.1 (q, *J* = 6.2 Hz), 127.4, 123.5 (q, *J* = 272 Hz), 52.1.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –64.8.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{19}H_{14}ClF_3O_2$: 366.0634; found: 366.0637.

(2*E*,3*E*)-Methyl 2-(3-Chlorobenzylidene)-5,5,5-trifluoro-4-phenylpent-3-enoate (3da)

Yield: 84 mg (66%); white solid; mp 74–75 °C; R_f = 0.4 (petroleum ether–EtOAc, 10:1).

IR (KBr): 1723, 1434, 1288, 1172, 1120, 786 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.38 (s, 1 H), 7.24–7.23 (m, 1 H), 7.20–7.11 (m, 6 H), 7.00–6.96 (m, 3 H), 3.40 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 166.6, 141.5, 136.3, 135.2 (q, *J* = 29.5 Hz), 134.7, 132.3, 129.9, 129.8, 129.7, 128.7, 128.4, 128.3, 128.2, 127.94 (q, *J* = 6.3 Hz), 127.93, 123.4 (q, *J* = 272 Hz), 52.2.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –65.0.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{19}H_{14}ClF_3O_2$: 366.0634; found: 366.0637.

(2*E*,3*E*)-Methyl 2-(2-Chlorobenzylidene)-5,5,5-trifluoro-4-phenylpent-3-enoate (3ea)

Yield: 95 mg (76%); colorless oil; R_f = 0.4 (petroleum ether–EtOAc, 10:1).

IR (KBr): 1715, 1594, 1435, 1250, 1171, 1119 cm^{-1}.

^1H NMR ($CDCl_3$, 300 MHz): δ = 7.62 (s, 1 H), 7.30–7.11 (m, 7 H), 6.92–6.90 (m, 3 H), 3.44 (s, 3 H).

^{13}C NMR ($CDCl_3$, 75 MHz): δ = 166.7, 139.9, 134.82 (q, *J* = 29.4 Hz), 134.81, 133.0, 132.3, 130.8, 130.7, 129.9, 128.9, 128.8, 128.6, 128.4, 127.8 (q, *J* = 6.2 Hz), 126.6, 123.4 (q, *J* = 272 Hz), 52.3.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –65.0.

HRMS (EI): *m/z* $[M]^+$ calcd for $C_{19}H_{14}ClF_3O_2$: 366.0634; found: 366.0638.

Supporting Information for this article is available online at http://www.thieme-connect.com/ejournals/toc/synthesis.

Primary Data for this article are available online at http://www.thieme-connect.com/ejournals/toc/synthesis and can be cited using the following DOI: 10.4125/pd0015th

Acknowledgment

Financial support from the National Natural Science Foundation of China (20932008), the Ministry of Science and Technology of China (2011CB808600) and the Chinese Academy of Sciences is gratefully acknowledged.

References

(1) Maryanoff, B. E.; Reitz, A. B. *Chem. Rev.* **1989**, *89*, 863.
(2) (a) Zhang, C.; Lu, X. *J. Org. Chem.* **1995**, *60*, 2906. (b) Lu, X.; Lu, Z.; Zhang, X. *Tetrahedron* **2006**, *62*, 457. (c) Lu, Z.; Lu, X. *Tetrahedron Lett.* **1997**, *38*, 3461. For reviews, see: (d) Lu, X.; Zhang, C.; Xu, Z. *Acc. Chem. Res.* **2001**, *34*, 535. (e) Methot, J. L.; Roush, W. R. *Adv. Synth. Catal.* **2004**, *346*, 1035. (f) Lu, X.; Du, Y.; Lu, C. *Pure Appl. Chem.* **2005**, *77*, 1985. (g) Nair, V.; Menon, R. S.; Sreekanth, A. R.; Abhilash, N.; Biju, A. T. *Acc. Chem. Res.* **2006**, *39*, 520. (h) Ye, L.-W.; Zhou, J.; Tang, Y. *Chem. Soc. Rev.* **2008**, *37*, 1140. (i) Cowen, B. J.; Miller, S. J. *Chem. Soc. Rev.* **2009**, *38*, 3102. (j) Marinetti, A.; Voituriez, A. *Synlett* **2010**, 174.

Downloaded by: Florida International University. Copyrighted material.

(3) Du, Y.; Lu, X.; Zhang, C. *Angew. Chem. Int. Ed.* **2003**, *42*, 1035.
(4) The group of Krische has used this class of compound as effective allylic alkylating agents, see: (a) Cho, C.-W.; Krische, M. *Angew. Chem. Int. Ed.* **2004**, *43*, 6689. (b) Cho, C.-W.; Kong, J.-R.; Krische, M. *Org. Lett.* **2004**, *6*, 1337. (c) Park, H.; Cho, C.-W.; Krische, M.; Jiang, Y.-Q.; Shi, Y.-L.; Shi, M. *J. Am. Chem. Soc.* **2008**, *130*, 7202.
(5) (a) Feng, J.; Lu, X.; Kong, A.; Han, X. *Tetrahedron* **2007**, *63*, 6035. (b) Tan, B.; Candeias, N. R.; Barbas, C. F. *J. Am. Chem. Soc.* **2011**, *133*, 4672. (c) Deng, H.-P.; Wei, Y.; Shi, M. *Org. Lett.* **2011**, *13*, 3348. For intramolecular, see: (d) Ye, L.-W.; Sun, X.-L.; Wang, Q.-G.; Tang, Y. *Angew. Chem. Int. Ed.* **2007**, *46*, 5951. (e) Wang, Q.-G.; Zhu, S.-F.; Ye, L.-W.; Zhou, C.-Y.; Sun, X.-L.; Tang, Y.; Zhou, Q.-L. *Adv. Synth. Catal.* **2010**, *352*, 1914. (f) Han, X.; Ye, L.-W.; Sun, X.-L.; Tang, Y. *J. Org. Chem.* **2009**, *74*, 3394.
(6) Zheng, S.; Lu, X. *Org. Lett.* **2008**, *10*, 4481.
(7) Zheng, S.; Lu, X. *Org. Lett.* **2009**, *11*, 3978.
(8) Du, Y.; Feng, J.; Lu, X. *Org. Lett.* **2005**, *7*, 1987.
(9) (a) Chen, Z.; Zhang, J. *Chem. Asian J.* **2010**, *5*, 1542. (b) Xie, P.; Huang, Y.; Chen, R. *Org. Lett.* **2010**, *12*, 3768. (c) Zhou, R.; Wang, J.; Song, H.; He, Z. *Org. Lett.* **2011**, *13*, 580. (d) Tian, J.; Zhou, R.; Sun, H.; Song, H.; He, Z. *J. Org. Chem.* **2011**, *76*, 2374.
(10) Zhou, R.; Wang, C.; Song, H.; He, Z. *Org. Lett.* **2010**, *12*, 976.
(11) (a) Wang, T.; Ye, S. *Org. Lett.* **2010**, *12*, 4168. (b) Wang, T.; Ye, S. *Org. Biomol. Chem.* **2011**, *9*, 5260.
(12) (a) Zhu, X.-F.; Henry, C. E.; Wang, J.; Dudding, T.; Kwon, O. *Org. Lett.* **2005**, *7*, 1387. (b) Zhu, X.-F.; Schaffner, A.-P.; Li, R. C.; Kwon, O. *Org. Lett.* **2005**, *7*, 2977. (c) Creech, G. S.; Kwon, O. *Org. Lett.* **2008**, *10*, 429. (d) Creech, G. S.; Zhu, X.-F.; Fonovic, B.; Dudding, T.; Kwon, O. *Tetrahedron* **2008**, *64*, 6935.
(13) For selected synthesis of heterocycles containing a trifluoromethyl group, see: (a) Burstein, C.; Glorius, F. *Angew. Chem. Int. Ed.* **2004**, *43*, 6205. (b) Abid, M.; Torok, B. *Adv. Synth. Catal.* **2005**, *347*, 1797. (c) Zhu, J.; Cheng, Z.; Xie, H.; Li, S.; Wu, Y. *Org. Lett.* **2010**, *12*, 2434. (d) Morandi, B.; Carreira, E. M. *Angew. Chem. Int. Ed.* **2010**, *49*, 4294. (e) Matoba, K.; Kawai, H.; Furukawa, T.; Kusuda, A.; Tokunaga, E.; Nakaura, S.; Shiro, M.; Shibata, N. *Angew. Chem. Int. Ed.* **2010**, *49*, 5762. (f) Kobatake, T.; Fujino, D.; Yoshida, S.; Yorimitsu, H.; Oshima, K. *J. Am. Chem. Soc.* **2010**, *132*, 11838. (g) Jiang, H.; Wang, Y.; Wan, W.; Hao, J. *Tetrahedron* **2010**, *66*, 2746. For reviews, see: (h) Ma, J.-A.; Cahard, D. *Chem. Rev.* **2008**, *108*, PR1. (i) Nie, J.; Guo, H.-C.; Cahard, D.; Ma, J.-A. *Chem. Rev.* **2011**, *111*, 455.
(14) (a) Basavaiah, D.; Reddy, B. S.; Badsara, S. S. *Chem. Rev.* **2010**, *110*, 5447. (b) Basavaiah, D.; Rao, A. J.; Satyanarayana, T. *Chem. Rev.* **2003**, *103*, 811.
(15) For the synthesis and application of olefins with the trifluoromethyl group, see: (a) Shimojuh, N.; Imura, Y.; Moriyama, K.; Togo, H. *Tetrahedron* **2011**, *67*, 951. (b) Pedro, M. F.; Hirner, S.; Kühn, F. E. *Tetrahedron Lett.* **2005**, *46*, 7777. (c) Chen, Y.; Huang, L.; Zhang, X. P. *J. Org. Chem.* **2003**, *68*, 5925. (d) Lebel, H.; Paquet, V. *Org. Lett.* **2002**, *4*, 1671. (e) Nader, B. S.; Cordova, J. A.; Karen, E.; Reese, K. E.; Powell, C. L. *J. Org. Chem.* **1994**, *59*, 2898. (f) Eguchi, T.; Aoyama, T.; Kakinuma, K. *Tetrahedron Lett.* **1992**, *33*, 5545.

Downloaded by: Florida International University. Copyrighted material.