Journal of Fluorine Chemistry 130 (2009) 913–921

Contents lists available at ScienceDirect

Journal of Fluorine Chemistry

journal homepage: www.elsevier.com/locate/fluor

Unexpected high regiocontrol in Heck reaction of fluorine-containing electron-deficient olefins—Highly regio- and stereoselective synthesis of β-fluoroalkyl-α-aryl-α,β-unsaturated ketones

Tsutomu Konno *, Shigeyuki Yamada, Akinori Tani, Masataka Nishida, Tomotsugu Miyabe, Takashi Ishihara

Department of Chemistry and Materials Technology, Kyoto Institute of Technology, Matsugasaki, Sakyo-ku, Kyoto 606-8585, Japan

ARTICLE INFO

Article history:
Received 17 June 2009
Received in revised form 3 July 2009
Accepted 4 July 2009
Available online 30 July 2009

Keywords:
Fluorine-containing alkenes
Heck reaction
Aryldiazonium salts
β-Fluoroalkyl-α,β-unsaturated ketones
Regioselective
Stereoselective

ABSTRACT

Treatment of (*E*)-4,4,4-trifluoro-1-aryl-2-buten-1-one with various aryldiazonium salts in the presence of palladium catalyst gave the corresponding α-arylated Heck adducts with high regio- and stereoselectivity in good to high yields.

1. Introduction

Recently, considerable interest has been focused on organofluorine compounds as pharmaceutical and agrochemical agents because the fluorine atom often alters the physiochemical properties of organic compounds, thereby modifying biological activities [1a-h]. Consequently, the development of novel and convenient methods for the preparation of fluorine-containing materials has been becoming more and more important in fluorine chemistry [2a-i].

Among various types of fluoroorganic molecules, alkenes **1** bearing a fluoroalkyl group (Rf) and an electron-withdrawing group (EWG) (Fig. 1) have been well known as one of the most valuable synthetic targets because they have wide utility as potent synthetic blocks, particularly as Michael acceptors for conjugate additions [3a-i], or dienophiles and dipolarophiles for cycloaddition reactions [4a-d]. In spite of such great utility, there have been somewhat limited studies on the stereoselective synthesis of such molecules, especially tri- or tetra-substituted alkenes thus far [5a-l]. Herein is described a novel and convenient synthesis of β-fluoroalkylated-α-aryl-α,β-unsaturated carbonyl compounds *via* a highly regio- and stereoselective Heck reaction of β-fluoroalkylated-α,β-unsaturated carbonyl compounds with various aryldiazonium salts [6a-d].

2. Results and discussion

Our initial studies were addressed to the Heck reaction of (*E*)-4,4,4-trifluoro-1-phenyl-2-buten-1-one (**2a**) with phenyldiazonium salt **3a** (Scheme 1, Table 1, Ar = Ph). Thus, treatment of **2a** with 1.2 equiv. of **3a** in the presence of 2.5 mol% of $Pd_2(dba)_3{\cdot}CHCl_3$ in THF at 40 °C for 2 h gave the corresponding α-arylated adduct **4a** in 4% yield, together with 90% of the starting material recovered (entry 1). In this case, only *Z* isomer **4aZ** was detected and neither *E* isomer **4aE** nor β-arylated product **6** was obtained [7]. As shown in entries 2–5, various sorts of solvents, such as toluene, 1,4-dioxane, ether, and methanol, did not lead to the satisfactory results (no reaction or low regioselectivity), however, the use of ethanol resulted in the formation of 9% of **4a** as a sole product (entry 6). Therefore, we next examined the reaction conditions in THF or EtOH. As described in entries 7–10, the addition of various types of phosphine ligands did not improve the yield in the reaction in THF. On the other hand, the reaction at the reflux temperature of THF afforded the Heck adducts **4aZ** and **4aE** in a ratio of 92:8 in 24%

* Corresponding author.
E-mail address: konno@chem.kit.ac.jp (T. Konno).

0022-1139/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jfluchem.2009.07.002

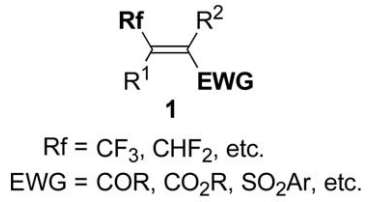


Fig. 1. Fluoroalkylated alkenes.

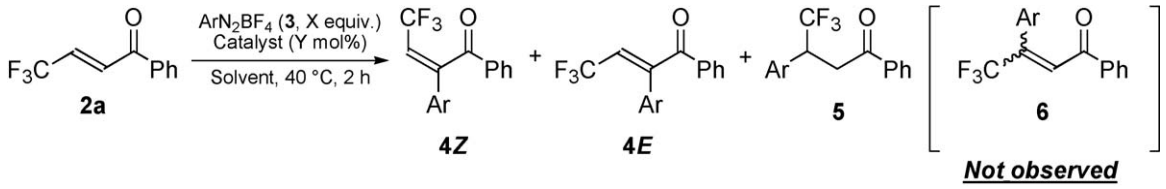
combined yield (entry 11). Though the prolonged reaction time as well as the use of 2.2 equiv. of **3a** did not bring about a significant change (entries 12 and 13), the reaction with 2.2 equiv. of **3a** in the presence of 20 mol% of palladium catalyst gave **4aZ** and **4aE** in 61% yield (entry 14). Additionally, the reaction with 4.4 equiv. of **3a** at the reflux temperature caused a significant improvement of the yield, **4aZ** and **4aE** being obtained in 79% yield in a ratio of 90:10 (entry 16).

We also investigated the reaction in EtOH as shown in entries 17–21. In sharp contrast to the reaction in THF, the ligand effect was observed significantly. Thus, when P(*o*-Tol)$_3$ was used, the starting material was completely consumed and the corresponding arylated adducts **4aZ** and **4aE** were obtained in 82% yield in a ratio of 94:6 (entry 19), though the Michael adduct **5a** was also given as a byproduct. Additionally, bulky or bidentate ligands resulted in a significant decrease of the yield (entries 20 and 21). With this best reaction conditions (entries 16 and 19), we conducted the Heck reaction with various types of aryldiazonium salts. The results are summarized in Table 2.

As shown in entries 3 and 5, *para*- and *meta*-substituted aryldiazonium salts (**3b** and **3c**) could participate well in the Heck reaction to give the corresponding adducts in good yields. In these cases, high *Z* stereoselection was observed. When the reaction was carried out in THF at the reflux temperature, a slight decrease of the yield as well as the stereoselectivity was detected (entries 4 and 6). Very interestingly, the Heck reaction with *ortho*-tolyl (**3d**) or *para*-anisyldiazonium salt (**3e**) in THF at the refluxing temperature took place smoothly to afford the corresponding Heck adducts in 75 or 71% yield, respectively (entries 8 and 10), whereas the reactions in EtOH at 40 °C resulted in very low yield of the products (entries 7 and 9). As indicated in entries 11–16, various halogen-substituted aryldiazonium salts (**3f**, **3g**, and **3h**) were applied for the Heck reaction successfully, giving the desired products in 62–74% yields with high *Z* stereoselection, though *ca.* 10–20% of Michael adducts **5** were given as byproducts. However, aryldiazonium salt substituted by more strongly electron-withdrawing group, such as cyano (**3i**), ethoxycarbonyl (**3j**), and nitro groups (**3k**), on the benzene ring, did not lead to the satisfactory results in the reaction in EtOH at 40 °C, the starting substrate **2** being almost quantitatively recovered (entries 17, 19, and 21). Interestingly, the reaction with CO_2Et-substituted aryldiazonium salt in THF at the reflux temperature gave the Heck adducts **4jZ** and **4jE** in 64% yield in a ratio of 80:20 (entry 20). On the other hand, the reaction with the CN- or NO_2-substituted aryldiazonium salts in THF did not lead to a dramatical change. (entries 18, 22 and 23). Additionally, 1-naphthyldiazonium salt (**3l**) could not also be applied for the present Heck reaction successfully (entries 24 and 25).

Next, our interest was directed toward the Heck reaction using various types of fluorine-containing electron-deficient olefins as shown in Table 3.

As described in entries 3, 4, 7, and 8, various enones having an electron-donating group (MeO) or an electron-withdrawing group



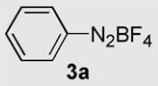
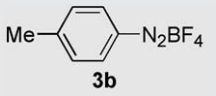
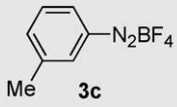
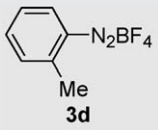
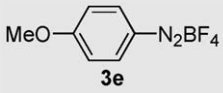
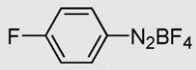
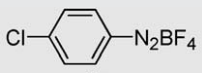
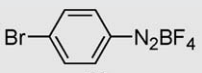
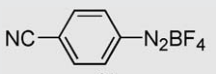
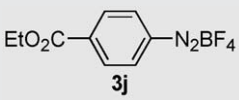
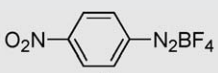
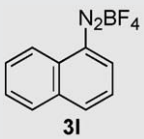
Scheme 1.

Table 1
Investigation of the reaction conditions (Ar = Ph).

Entry	X/equiv.	Catalyst	Y/mol%	Solvent	Yield[a]/% of **4a**	Ratio[a] (**4aZ**:**4aE**)	Yield[a]/% of **5a**	Recovery[a]/% of **2a**
1	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	5	THF	4	100:0	0	90
2	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	5	Toluene	0	–	0	97
3	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	5	1,4-Dioxane	10	80:20	2	67
4	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	5	Ether	0	–	0	89
5	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	5	MeOH	10	80:20	0	35
6	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	5	EtOH	9	100:0	3	90
7	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$] + 2PPh_3	5	THF	0	–	0	Quant.
8	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$] + 2P(*o*-Tol)$_3$	5	THF	0	–	0	93
9	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$] + 2PCy_3	5	THF	2	100:0	0	85
10	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$] + dppe	5	THF	0	–	0	Quant.
11[b]	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	5	THF	24	92:8	4	59
12[b,c]	1.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	5	THF	28	75:25	9	71
13[b]	2.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	5	THF	8	88:12	2	90
14[b]	2.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	20	THF	61	82:18	12	17
15[b]	3.3	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	20	THF	63	83:17	12	22
16[b]	4.4	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	20	THF	79	90:10	11	2
17	2.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$]	20	EtOH	51	92:8	3	32
18	2.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$] + 2PPh_3	20	EtOH	45	93:7	7	36
19	2.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$] + 2P(*o*-Tol)$_3$	20	EtOH	82 (69)	94:6	11	0
20	2.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$] + 2PCy_3	20	EtOH	47	89:11	4	33
21	2.2	[1/2][$Pd_2(dba)_3$·$CHCl_3$] + dppe	20	EtOH	17	88:12	0	76

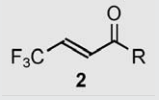
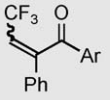
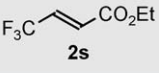
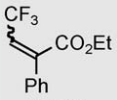
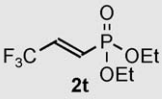
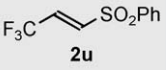
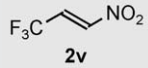
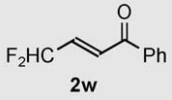
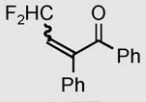
[a] Determined by ^{19}F NMR. Value in parentheses is of isolated yield.
[b] Carried out at the reflux temperature.
[c] Carried out for 12 h.

Table 2
The Heck reaction with various types of aryldiazonium salts.

Entry	Diazonium salt	Method[a]	Yield[b]/% of **4**	Ratio[b] (**4Z**:**4E**)	Yield[b]/% of **5**
1	 **3a**	A	82 (69)	94:6	11
2		B	79	90:10	11
3	 **3b**	A	57 (48)	93:7	10
4		B	35	86:14	9
5	 **3c**	A	73 (57)	95:5	9
6		B	48	88:12	10
7	 **3d**	A	9	44:56	0
8		B	75 (63)	48:52	6
9	 **3e**	A	5	100:0	4
10		B	71 (55)	92:8	17
11	 **3f**	A	74 (58)	89:11	15
12		B	69	80:20	13
13	 **3g**	A	67 (50)	89:11	10
14		B	68	79:21	19
15	 **3h**	A	65 (54)	88:12	12
16		B	62	79:21	19
17	 **3i**	A	0	–	0
18		B	0	–	Trace
19	 **3j**	A	28	86:16	6
20		B	64 (63)	80:20	15
21	 **3k**	A	11	100:0	0
22		B	38	69:31	11
23		C	41	73:27	10
24	 **3l**	A	23	88:17	0
25		B	36	58:42	9

[a] Method A: **2**, 2.2 equiv., EtOH, 40 °C, 2 h; Method B: **2**, 4.4 equiv., THF, reflux, 2 h; Method C: **2**, 4.4 equiv., THF, reflux, 10 h.
[b] Determined by ^{19}F NMR. Values in parentheses are of isolated yield.

Table 3
The Heck reaction of various substrates with phenyldiazonium salt.

Entry	Substrate		Method[a]	Product	Yield[b]/% of **4**	Ratio[a] (*Z*:*E*)	Yield[b]/% of **5**	Recovery[b]/% of **2**
1	 **2**	R = Ph (**a**)	A[c]	 **4a,m-r*Z*/*E***	82 (69)	94:6	11	0
2			B[d]		79	90:10	11	2
3		R = *p*-MeOC$_6$H$_4$ (**m**)	A		36	94:6	6	36
4			B		69 (55)	93:7	14	17
5		R = *o*-MeOC$_6$H$_4$ (**n**)	A		90 (86)	86:14	6	Trace
6			B		87	79:21	11	0
7		R = *p*-ClC$_6$H$_4$ (**o**)	A		41	93:7	7	50
8			B		70 (62)	81:19	19	10
9		R = 1-Naphthyl (**p**)	A		46	90:10	8	39
10			B		72 (48)	85:15	6	10
11		R = PhCH$_2$CH$_2$ (**q**)	A		14	71:29	4	42
12			B		41	59:41	10	23
13		R = *c*-Hex (**r**)	A		61	77:23	10	27
14			B		80 (68)	71:29	10	9
15	 **2s**		A	 **4s*Z*/*E***	13	N.D.[e]	6	81
16			B		26	97:3	8	66
17	 **2t**		A		0	–	3	76
18			B		0	–	5	68
19	 **2u**		A		4	–	3	76
20			B		0	–	3	97
21	 **2v**		A		1	–	0	22
22			B		0	–	0	17
23	 **2w**		A	 **4w*Z*/*E***	39	81:19	2	18
24			B		12	N.D.[e]	5	15

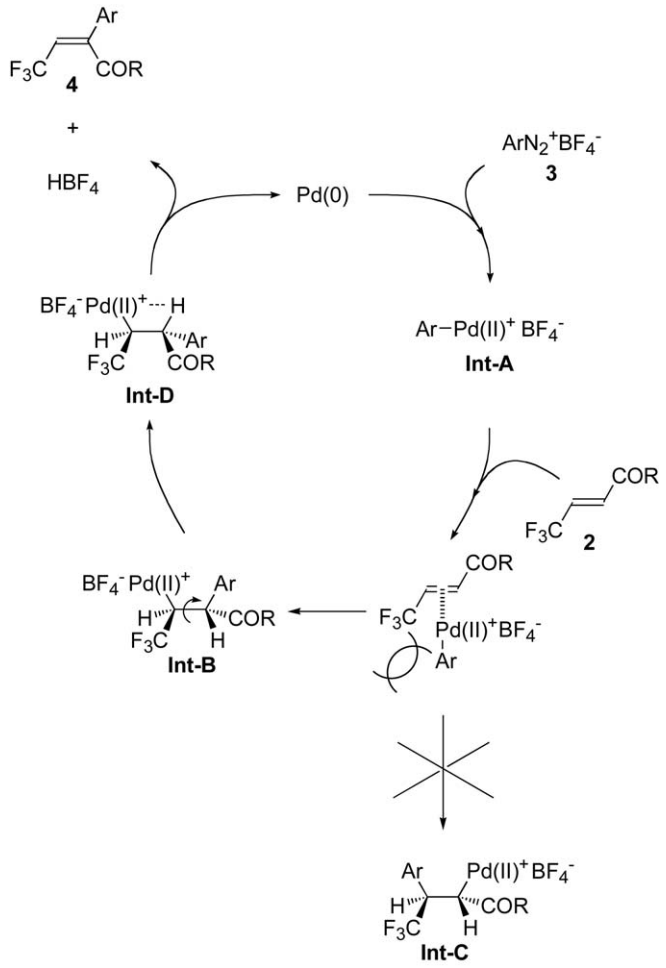
[a] Method A: **3a**, 2.4 equiv., EtOH, 40 °C, 2 h; Method B: **3a**, 4.8 equiv., THF, reflux, 2 h.
[b] Determined by ^{19}F NMR. Values in parentheses are of isolated yield.
[c] 2.2 equiv. of PhN_2BF_4 was used.
[d] 4.4 equiv. of PhN_2BF_4 was used.
[e] Not determined.

(Cl) on the benzene ring in **2** could participate nicely in the Heck reaction to give the corresponding adducts **4m**, **4o** with high regio- and stereoselectivity in good yields. In these cases, the reaction at the reflux temperature in THF (Method B) gave better results in the chemical yield as well as the stereoselectivity than the reaction at 40 °C in EtOH (Method A). *Ortho* substitution on the benzene ring in **2** also led to satisfactory results on both Methods A and B, though a slight decrease of the stereoselectivity was observed (entries 5 and 6). A naphthyl group was also found to be a good substituent (entries 9 and 10), but the use of alkyl substituent as R resulted in a significant decrease of the stereoselectivity (entries 11–14). In the case of 2-phenylethyl substituent as R, the chemical yield was also decreased significantly.

We also examined the reaction of other fluorine-containing electron-deficient olefins as described in entries 15–22. Similar to the precedent work [6c], α,β-unsaturated ester **2s** did not react with phenyldiazonium salt smoothly, giving the corresponding adduct **4s** in very low yield, together with a large amount of the starting ester [8]. Vinylphosphonate (**2t**) [9] and vinylsulfone (**2u**) [10] were also found to be very less reactive, only the starting olefins being recovered. In the case of nitroalkene (**2v**) [11a-b], neither the starting material nor the desired Heck adduct was detected, and the complex mixture was observed. Additionally, changing a fluoroalkyl group from a CF_3 to CHF_2 group caused a significant decrease of the chemical yield (entries 23 and 24), although the relatively high regioselectivity was obtained.

The reaction mechanism may be proposed as shown in Scheme 2. Thus, the reaction presumably proceeds *via* (1) oxidative addition of aryldiazonium salt **3** to Pd(0), leading to the corresponding arylpalladium complex **Int-A**, (2) coordination of the fluorine-containing electron-deficient olefin **2** to the metal center of **Int-A** and subsequent insertion into the Ar–Pd bond to form **Int-B**, not **Int-C**, (3) carbon–carbon bond rotation to produce **Int-D**, and (4) reductive elimination to give tri-substituted alkene **4** and to regenerate Pd(0).

The high regioselectivity may be attributed to a bulkiness of a CF_3 group [12]. Generally, migration of an aryl group in the insertion step of the alkene into the Ar–Pd bond favors the less substituted carbon with lower electron density, therefore β-arylation occurs in the Heck reaction of ethyl acrylate, acrylonitrile, styrene, etc. In the present reaction, a COR group is a stronger electron-withdrawing group than a CF_3 group whereas a CF_3 group is much bulkier than a COR group. Thus, α-arylation in this study indicates that the steric hindrance of the substituent is a very important factor for determining the regioselectivity, rather than an electron-withdrawing effect.



Scheme 2. A plausible mechanism.

3. Conclusion

In summary, we have developed an easy access to a variety of β-fluoroalkylated-α-aryl-α,β-unsaturated carbonyl compounds *via* a regio- and stereoselective Heck reaction with readily available aryldiazonium salts. Various aryldiazonium salts bearing an electron-donating group and halogens at the *para*, *meta* or *ortho* position of the benzene ring could participate nicely in the Heck reaction, the corresponding *Z* isomer being given preferentially. On the other hand, aryldiazonium salts having an electron-withdrawing group or bulky salts did not afford the satisfactory results. Additionally, we also found that the electron-withdrawing group (EWG) influenced largely on the efficacy of the reaction.

4. Experimental

4.1. General methods

^{1}H NMR spectra were measured with a Bruker DRX (500.13 MHz) spectrometer in a chloroform-*d* ($CDCl_3$) solution with tetramethylsilane (Me_4Si) as an internal reference. ^{13}C NMR spectra were recorded on a Bruker DRX (125.77 MHz). A JEOL JNM-EX90F (84.21 MHz, FT) or a JEOL JNM-AL400 (376.05 MHz) spectrometer was used for determining ^{19}F NMR yield with internal C_6F_6. It was used for determining regioselectivity and stereoselectivity and was used for taking ^{19}F NMR spectra in a $CDCl_3$ solution with internal $CFCl_3$ too. $CFCl_3$ was used ($\delta_F = 0$) as an internal standard for ^{19}F NMR. Infrared spectra (IR) were recorded on a Shimadzu FTIR-8200A (PC) spectrophotometer. Mass spectra (MS) were taken on a JEOL JMS-700.

4.1.1. Materials

Anhydrous tetrahydrofuran (THF) was purchased from Wako Pure Chemical Industries, Ltd. Ethanol was distilled from magnesium. All chemicals were of reagent grade and, if necessary, were purified in the usual manner prior to use. Thin layer chromatography (TLC) was done with Merck silica gel 60F_{254} plates and column chromatography was carried out with Wako gel C-200. All aryldiazonium salts were prepared according to the literature [13a-e].

4.2. Typical procedure for the preparation of 4,4,4-trifluoro-2-(4-fluorophenyl)-1-phenyl-2-buten-1-one

Method A: To a solution of $Pd_2(dba)_3{\cdot}CHCl_3$ (10 mol%) and P(*o*-Tol)$_3$ (40 mol%) in EtOH was added (*E*)-4,4,4,-trifluoro-1-phenyl-2-buten-1-one (**2**) (50 mg, 0.25 mmol) and 4-fluorophenyldiazonium tetrafluoroborate (**3f**) (115 mg, 0.55 mmol) at room temperature, and the resulting mixture was stirred at 40 °C for 2 h. After cooling to room temperature, the mixture was poured into a saturated aqueous NH_4Cl solution, and the resulting mixture was extracted three times with Et_2O. The combined organic layers were washed with a saturated solution of NaCl, dried over anhydrous Na_2SO_4, filtered, and concentrated *in vacuo*. The residue was purified by silica-gel column chromatography to give the corresponding Heck adduct (**4f**) (43 mg, 0.45 mmol: *Z*/*E* = 89:11; 58% yield).

Method B: The reaction with 4.4 equiv. of the corresponding diazonium salt in the presence of $Pd_2(dba)_3{\cdot}CHCl_3$ (10 mol%) in THF at reflux temperature for 2 h was conducted. The workup was the same as Method A.

4.2.1. 4,4,4-Trifluoro-1,2-diphenyl-2-buten-1-one (**4a**)

IR (neat) 3063, 2930, 1678, 1597, 1580, 1496, 1449, 1354, 1279, 1219, 1134, 1015 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{16}H_{12}F_3O$ 277.0841; found: 277.0853.

Z isomer: ^{1}H NMR ($CDCl_3$) δ = 6.22 (q, *J* = 8.1 Hz, 2H), 7.35–7.50 (m, 7H), 7.53–7.61 (m, 1H), 7.90–7.96 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 115.67 (q, *J* = 34.9 Hz), 122.4 (q, *J* = 271.0 Hz), 126.6, 128.8, 129.2, 129.5, 130.3, 133.8, 134.2, 135.2, 149.6 (q, *J* = 5.4 Hz), 194.2; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −59.1 (d, *J* = 8.1 Hz, 3F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 6.10 (q, *J* = 7.9 Hz, 1H), 7.35–7.50 (m, 7H), 7.53–7.61 (m, 1H), 7.90–7.96 (m, 2H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −57.3 (d, *J* = 7.9 Hz, 3F).

4.2.2. 4,4,4-Trifluoro-2-(4-methylphenyl)-1-phenyl-2-buten-1-one (**4b**)

IR (neat) 3069, 2924, 1679, 1513, 1450, 1353, 1286, 1220, 1128, 1015 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{17}H_{14}F_3O$ 291.0997; found: 291.1003.

Z isomer: M.p. 74–76 °C; ^{1}H NMR ($CDCl_3$) δ = 2.34 (s, 3H), 6.19 (q, *J* = 8.1 Hz, 1H), 7.18 (ABq, *J* = 8.2 Hz, 2H), 7.32 (ABq, *J* = 8.2 Hz, 2H), 7.43–7.60 (m, 1H), 7.90–7.96 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 21.2, 114.6 (q, *J* = 35.1 Hz), 122.5 (q, *J* = 271.0 Hz), 126.5, 128.8, 129.48, 129.9, 133.8, 134.1, 135.3, 140.7, 149.5 (q, *J* = 5.0 Hz), 194.5; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −58.9 (d, *J* = 8.1 Hz, 3F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 2.35 (s, 3H), 6.05 (q, *J* = 7.9 Hz, 1H), 7.18 (ABq, *J* = 8.2 Hz, 2H), 7.32 (ABq, *J* = 8.2 Hz, 2H), 7.43–7.60 (m, 1H), 7.90–7.96 (m, 2H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −57.2 (d, *J* = 7.9 Hz, 3F).

*4.2.3. 4,4,4-Trifluoro-2-(3-methylphenyl)-1-phenyl-2-buten-1-one (**4c**)*

IR (neat) 3062, 2924, 1681, 1597, 1450, 1347, 1288, 1264, 1231, 1134, 1038 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{17}H_{14}F_3O$ 291.0997; found: 291.0990.

Z isomer: ^1H NMR ($CDCl_3$) δ = 2.34 (s, 3H), 6.20 (q, J = 8.1 Hz, 1H), 7.19–7.28 (m, 4H), 7.42–7.48 (m, 2H), 7.55–7.60 (m, 1H), 7.91–7.96 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 21.4, 115.5 (q, J = 34.8 Hz), 122.4 (q, J = 270.9 Hz), 123.8, 127.1, 128.8, 129.1, 129.5, 131.1, 133.7, 134.1, 135.2, 139.1, 149.8 (q, J = 5.3 Hz), 194.3; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −59.1 (d, J = 8.1 Hz, 3F).

E isomer: ^1H NMR ($CDCl_3$) δ = 2.34 (s, 3H), 6.06 (q, J = 7.9 Hz, 1H), 7.19–7.28 (m, 4H), 7.42–7.48 (m, 2H), 7.55–7.60 (m, 1H), 7.91–7.96 (m, 2H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −57.8 (d, J = 7.9 Hz, 3F).

*4.2.4. 4,4,4-Trifluoro-2-(2-methylphenyl)-1-phenyl-2-buten-1-one (**4d**)*

IR (neat) 3064, 2920, 1674, 1597, 1449, 1346, 1278, 1252, 1141, 1012 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{17}H_{14}F_3O$ 291.0997; found: 291.0987.

Z isomer: ^1H NMR ($CDCl_3$) δ = 2.51 (s, 3H), 5.98 (q, J = 8.0 Hz, 1H), 7.13–7.35 (m, 4H), 7.43–7.65 (m, 3H), 7.89–7.99 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 20.4, 120.5 (q, J = 34.9 Hz), 122.0 (q, J = 271.2 Hz), 149.4 (q, J = 5.1 Hz), 193.7. The peak of aromatic carbon could not be identified; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −59.7 (d, J = 8.0 Hz, 3F).

E isomer: ^1H NMR ($CDCl_3$) δ = 2.28 (s, 3H), 6.38 (q, J = 7.6 Hz, 1H), 7.13–7.35 (m, 4H), 7.43–7.65 (m, 3H), 7.89–7.99 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 20.1, 121.1 (q, J = 26.7 Hz), 122.3 (q, J = 272.9 Hz), 149.9 (q, J = 4.8 Hz), 194.1. The one signal of aromatic carbon could not be identified; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −59.2 (d, J = 7.6 Hz, 3F).

*4.2.5. 4,4,4-Trifluoro-2-(4-methoxylphenyl)-1-phenyl-2-buten-1-one (**4e**)*

IR (neat) 2936, 2840, 1678, 1605, 1514, 1450, 1354, 1279, 1253, 1134, 1016 cm^{-1}.

HRMS (FAB) calcd for (M^+) $C_{17}H_{13}F_3O_2$ 306.0868; found: 306.0877.

Z isomer: ^1H NMR ($CDCl_3$) δ = 3.79 (s, 3H), 6.14 (q, J = 8.2 Hz, 1H), 6.88 (ABq, J = 8.9 Hz, 2H), 7.37 (ABq, J = 8.9 Hz, 2H), 7.40–7.48 (m, 2H), 7.50–7.60 (m, 1H), 7.90–7.96 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 55.3, 113.3 (q, J = 34.8 Hz), 122.6 (q, J = 270.6 Hz), 122.1, 128.8, 129.5, 130.0, 133.5, 135.3, 149.0 (q, J = 5.4 Hz), 194.7; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −58.6 (d, J = 8.2 Hz, 3F).

E isomer: ^1H NMR ($CDCl_3$) δ = 3.80 (s, 3H), 6.01 (q, J = 7.5 Hz, 1H), 6.88 (ABq, J = 8.9 Hz, 2H), 7.37 (ABq, J = 8.9 Hz, 2H), 7.40–7.48 (m, 2H), 7.50–7.60 (m, 1H), 7.90–7.96 (m, 2H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −57.2 (d, J = 7.5 Hz, 3F).

*4.2.6. 4,4,4-Trifluoro-2-(4-fluorophenyl)-1-phenyl-2-buten-1-one (**4f**)*

IR (neat) 3069, 2929, 1677, 1599, 1510, 1450, 1350, 1135, 1016 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{16}H_{11}F_4O$ 295.0747; found: 295.0745.

Z isomer: ^1H NMR ($CDCl_3$) δ = 6.17 (q, J = 8.0 Hz, 1H), 7.39–7.50 (m, 4H), 7.56–7.62 (m, 1H), 7.89–7.94 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 115.6 (q, J = 36.8 Hz), 116.4 (d, J = 22.0 Hz), 122.3 (q, J = 270.6 Hz), 128.7 (d, J = 8.4 Hz), 128.9, 129.5, 130.0, 134.1, 134.3, 148.5 (q, J = 5.4 Hz), 194.1; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −59.1 (d, J = 8.0 Hz, 3F), −110.3 to −110.2 (m, 1F).

E isomer: ^1H NMR ($CDCl_3$) δ = 6.13 (q, J = 7.8 Hz, 1H), 7.39–7.50 (m, 4H), 7.56–7.62 (m, 1H), 7.89–7.94 (m, 2H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −57.3 (d, J = 7.8 Hz, 3F), −111.9 to −111.8 (m, 1F).

*4.2.7. 2-(4-Chlorophenyl)-4,4,4-trifluoro-1-phenyl-2-buten-1-one (**4g**)*

IR (neat) 3067, 2928, 1678, 1595, 1493, 1450, 1347, 1284, 1219, 1137, 1015 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{16}H_{11}ClF_3O$ 311.0451; found: 311.0451.

Z isomer: ^1H NMR ($CDCl_3$) δ = 6.17 (q, J = 7.9 Hz, 1H), 7.33–7.40 (m, 4H), 7.44–7.50 (m, 2H), 7.57–7.62 (m, 1H), 7.89–7.93 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 116.1 (q, J = 35.3 Hz), 122.2 (q, J = 271.1 Hz), 128.0, 128.9, 129.48, 129.51, 130.0, 134.1, 134.4, 135.0, 136.6, 148.5 (q, J = 5.5 Hz), 193.9; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −59.2 (d, J = 7.9 Hz, 3F).

E isomer: ^1H NMR ($CDCl_3$) δ = 6.13 (q, J = 7.8 Hz, 1H), 7.33–7.40 (m, 4H), 7.44–7.50 (m, 2H), 7.57–7.62 (m, 1H), 7.89–7.93 (m, 2H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −57.4 (d, J = 7.8 Hz, 3F).

*4.2.8. 2-(4-Bromophenyl)-4,4,4-trifluoro-1-phenyl-2-buten-1-one (**4h**)*

IR (neat) 3066, 1678, 1596, 1489, 1345, 1285, 1138, 1074, 1012 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{16}H_{11}BrF_3O$ 354.9946; found: 354.9930.

Z isomer: ^1H NMR ($CDCl_3$) δ = 6.21 (q, J = 7.9 Hz, 1H), 7.28–7.32 (m, 2H), 7.43–7.55 (m, 4H), 7.58–7.62 (m, 1H), 7.89–7.92 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 116.1 (q, J = 35.5 Hz), 122.6 (q, J = 271.1 Hz), 124.9, 128.2, 128.9, 129.5, 132.5, 134.1, 135.0, 148.6 (q, J = 5.1 Hz), 193.8; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −59.2 (d, J = 7.9 Hz, 3F).

E isomer: ^1H NMR ($CDCl_3$) δ = 6.13 (q, J = 7.8 Hz, 1H), 7.28–7.32 (m, 2H), 7.43–7.55 (m, 4H), 7.58–7.62 (m, 1H), 7.89–7.92 (m, 2H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −57.4 (d, J = 7.8 Hz, 3F).

*4.2.9. 2-[4-(Ethoxycarbonyl)phenyl]-4,4,4-trifluoro-1-phenyl-2-buten-1-one (**4j**)*

IR (neat) 3066, 2984, 1719, 1679, 1450, 1350, 1280, 1140, 1020 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{19}H_{16}F_3O_3$ 349.1052; found: 349.1054.

Z isomer: ^1H NMR ($CDCl_3$) δ = 1.37 (t, J = 7.1 Hz, 3H), 4.36 (q, J = 7.1 Hz, 2H), 6.29 (q, J = 7.9 Hz, 1H), 7.43–7.53 (m, 4H), 7.56–7.61 (m, 1H), 7.86–7.93 (m, 2H), 8.01–8.08 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 14.2, 61.3, 117.3 (q, J = 35.1 Hz), 122.1 (q, J = 271.1 Hz), 126.6, 128.9, 129.5, 130.3, 132.0, 134.1, 134.4, 137.8, 148.8 (q, J = 4.9 Hz), 165.6, 193.6; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −58.0 (d, J = 7.9 Hz, 3F).

E isomer: ^1H NMR ($CDCl_3$) δ = 1.38 (t, J = 7.1 Hz, 3H), 4.37 (q, J = 7.1 Hz, 2H), 6.18 (q, J = 7.9 Hz, 1H), 7.43–7.53 (m, 4H), 7.56–7.61 (m, 1H), 7.86–7.93 (m, 2H), 8.01–8.08 (m, 2H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −55.6 (d, J = 7.8 Hz, 3F).

*4.2.10. 4,4,4-Trifluoro-2-(4-nitrophenyl)-1-phenyl-2-buten-1-one (**4k**)*

IR (neat) 3080, 2940, 1680, 1598, 1521, 1450, 1349, 1278, 1140, 1017 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{16}H_{11}BrF_3NO_3$ 322.0692; found: 322.0700.

Z isomer: ^1H NMR ($CDCl_3$) δ = 6.34 (q, J = 7.8 Hz, 1H), 7.45–7.54 (m, 2H), 7.58–7.68 (m, 4H), 7.89–7.93 (m, 1H), 8.17–8.28 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 118.6 (q, J = 39.7 Hz), 121.8 (q, J = 271.5 Hz), 124.4, 127.8, 129.1, 129.5, 130.0, 134.8, 139.8, 147.7 (q, J = 5.3 Hz), 148.7, 193.0; ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −59.6 (d, J = 7.8 Hz, 3F).

E isomer: ^1H NMR ($CDCl_3$) δ = 6.28 (q, J = 7.6 Hz, 1H), 7.45–7.54 (m, 2H), 7.58–7.68 (m, 4H), 7.89–7.93 (m, 1H), 8.17–8.28 (m, 2H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −57.5 (d, J = 7.6 Hz, 3F).

*4.2.11. 4,4,4-Trifluoro-2-(1-naphthyl)-1-phenyl-2-buten-1-one (**4l**)*

IR (neat) 3062, 2926, 1679, 1596, 1449, 1349, 1285, 1226, 1143, 1089, 990 cm^{-1}.

HRMS (FAB) calcd for (M^+) $C_{20}H_{13}F_3O$ 326.0918; found: 326.0927.

Z isomer: ^{1}H NMR ($CDCl_3$) δ = 6.20 (q, J = 7.9 Hz, 1H), 7.39–7.46 (m, 3H), 7.48–7.58 (m, 3H), 7.63–7.68 (m, 1H), 7.83–7.89 (m, 2H), 7.98–8.03 (m, 2H), 8.42–8.47 (m, 1H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −59.7 (d, J = 7.9 Hz, 3F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 6.56 (q, J = 7.9 Hz, 1H), 7.39–7.46 (m, 3H), 7.48–7.58 (m, 3H), 7.63–7.68 (m, 1H), 7.83–7.89 (m, 2H), 7.98–8.03 (m, 2H), 8.42–8.47 (m, 1H); ^{19}F NMR ($CDCl_3$, $CFCl_3$) δ = −58.9 (d, J = 7.6 Hz, 3F).

4.3. Preparation of various γ-trifluoromethylated α,β-unsaturated ketones 2

The γ-trifluoromethylated α,β-unsaturated ketones **2** were prepared according to the previous literature method by three steps [14a-b].

4.3.1. (E)-4,4,4-Trifluoro-1-(4-methoxyphenyl)-2-buten-1-one (2m)

IR (KBr) 3058, 2941, 1682, 1600, 1511, 1423, 1308, 1265, 1172 cm^{-1}.

HRMS (FAB) calcd for (M^+) $C_{11}H_9F_3O_2$ 230.0555; found: 230.0565.

M.p. 39–41 °C; ^{1}H NMR ($CDCl_3$) δ = 3.90 (s, 3H), 6.73 (dq, J = 15.5, 7.1 Hz, 1H), 6.99 (ABq, J = 8.9 Hz, 2H), 7.53 (dq, J = 15.5, 2.0 Hz, 1H), 7.98 (ABq, J = 8.9 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ = 55.5, 114.2, 122.7 (q, J = 270.1 Hz), 129.2, 129.4 (q, J = 35.1 Hz), 131.1 (q, J = 5.8 Hz), 131.2, 164.4, 186.1; ^{19}F NMR ($CDCl_3$) δ = −65.5 (d, J = 7.1 Hz, 3F).

4.3.2. (E)-4,4,4-Trifluoro-1-(2-methoxyphenyl)-2-buten-1-one (2n)

IR (neat) 3089, 2943, 1679, 1646, 1487, 1271, 1165, 1127, 1016 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{11}H_{10}F_3O_2$ 231.0634; found: 231.0624.

^{1}H NMR ($CDCl_3$) δ = 3.90 (s, 3H), 6.65 (dq, J = 15.6, 7.5 Hz, 1H), 6.98 (d, J = 8.4 Hz, 1H), 7.03 (ddd, J = 7.7, 7.7, 0.8 Hz, 1H), 7.47 (dq, J = 15.6, 2.1 Hz, 1H), 7.52 (ddd, J = 8.4, 7.7, 1.8 Hz, 1H), 7.70 (dd, J = 7.7, 1.8 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ = 55.5, 111.7, 121.0, 127.1 (q, J = 34.8 Hz), 122.9 (q, J = 269.6 Hz), 126.9, 131.0, 134.8, 135.7 (q, J = 5.8 Hz), 159.0, 189.5; ^{19}F NMR ($CDCl_3$) δ = −65.3 (d, J = 7.5 Hz, 3F).

4.3.3. (E)-1-(4-Chlorophenyl)-4,4,4-trifluoro-2-buten-1-one (2o)

IR (KBr) 3072, 2928, 1686, 1591, 1402, 1305, 1224, 1136, 1009 cm^{-1}.

HRMS (EI) calcd for (M^+) $C_{10}H_6ClF_3O$ 234.0059; found: 234.0065.

M.p. 46–48 °C. ^{1}H NMR ($CDCl_3$) δ = 6.83 (dq, J = 16.0, 7.5 Hz, 1H), 7.49 (dq, J = 16.0, 2.0 Hz, 1H), 7.51 (ABq, J = 8.0 Hz, 2H), 7.92 (ABq, J = 8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ = 122.4 (q, J = 270.4 Hz), 129.4, 130.2, 130.5 (q, J = 5.5 Hz), 130.7 (q, J = 37.5 Hz), 134.5, 140.8, 186.7; ^{19}F NMR ($CDCl_3$) δ = −65.7 (d, J = 7.5 Hz, 3F).

4.3.4. (E)-4,4,4-Trifluoro-1-(1-naphthyl)-2-buten-1-one (2p)

IR (neat) 3057, 1753, 1682, 1644, 1573, 1510, 1302, 1133 cm^{-1}.

HRMS (FAB) calcd for (M^+) $C_{14}H_9F_3O$ 250.0605; found: 250.0597.

^{1}H NMR ($CDCl_3$) δ = 6.79 (dq, J = 15.7, 6.6 Hz, 1H), 7.42 (dq, J = 15.7, 1.9 Hz, 1H), 7.45–7.52 (m, 1H), 7.55–7.59 (m, 1H), 7.60–7.68 (m, 1H), 7.79–7.88 (m, 1H), 7.89–7.94 (m, 1H), 8.00–8.03 (m, 1H), 8.56–8.61 (m, 1H); ^{13}C NMR ($CDCl_3$) δ = 122.6 (q, J = 270.4 Hz), 124.2, 125.4, 126.8, 128.3, 128.6, 129.2, 130.1 (q, J = 35.2 Hz), 130.3, 130.9, 133.8, 133.8, 134.7 (q, J = 5.5 Hz), 191.1; ^{19}F NMR ($CDCl_3$) δ = −65.4 (d, J = 6.6 Hz, 3F).

4.3.5. (E)-4,4,4-Trifluoro-1-(2-phenylethyl)-2-buten-1-one (2q)

IR (neat) 3029, 2958, 1714, 1661, 1497, 1303, 1266, 1128 cm^{-1}.

HRMS (EI) calcd for (M^+) $C_{12}H_{11}F_3O$ 228.0762; found: 228.0757.

^{1}H NMR ($CDCl_3$) δ = 2.97 (s, 4H), 6.58 (dq, J = 16.0, 7.5 Hz, 1H), 6.70 (dq, J = 16.0, 1.8 Hz, 1H), 7.14–7.25 (m, 3H), 7.27–7.37 (m, 2H); ^{13}C NMR ($CDCl_3$) δ = 29.4, 43.4, 122.3 (q, J = 270.1 Hz), 126.4, 128.3, 128.6, 128.6 (q, J = 35.2 Hz), 134.0 (q, J = 5.5 Hz), 140.2, 197.1; ^{19}F NMR ($CDCl_3$) δ = −65.8 (d, J = 7.5 Hz, 3F).

4.3.6. (E)-1-Cyclohexyl-4,4,4-trifluoro-2-buten-1-one (2r)

IR (neat) 2934, 2858, 1708, 1656, 1452, 1305, 1267, 1136 cm^{-1}.

HRMS (EI) calcd for (M^+) $C_{10}H_{13}F_3O$ 206.0918; found: 206.0915.

^{1}H NMR ($CDCl_3$) δ = 1.20–1.38 (m, 5H), 1.67–1.72 (m, 1H), 1.78–1.90 (m, 4H), 2.54 (tt, J = 14.3, 3.4 Hz, 1H), 6.47 (dq, J = 15.7, 6.5 Hz, 1H), 6.81 (dq, J = 15.7, 1.9 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ = 25.4, 25.7, 27.9, 50.0, 122.5 (q, J = 270.1 Hz), 128.4 (q, J = 34.9 Hz), 132.9 (q, J = 5.5 Hz), 200.6; ^{19}F NMR ($CDCl_3$) δ = −65.6 (d, J = 6.5 Hz, 3F).

4.4. Typical procedure for Heck reaction of various γ-trifluoromethylated α,β-unsaturated ketones with phenyldiazonium tetrafluoroborate

The Heck reactions were carried out using either Method A or Method B, as mentioned above.

4.4.1. 4,4,4-Trifluoro-1-(4-methoxyphenyl)-2-phenyl-2-buten-1-one (4m)

IR (neat) 3062, 2937, 1667, 1599, 1356, 1263, 1169, 1135 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{17}H_{14}F_3O_2$ 307.0947; found: 307.0951.

Z isomer: ^{1}H NMR ($CDCl_3$) δ = 3.83 (s, 3H), 6.20 (q, J = 8.0 Hz, 1H), 6.92 (ABq, J = 8.8 Hz, 2H), 7.34–7.47 (m, 5H), 7.92 (ABq, J = 8.8 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ = 55.4, 114.0, 115.2 (q, J = 34.7 Hz), 122.5 (q, J = 270.3 Hz), 126.6, 128.4, 129.1, 131.9, 132.5, 134.0, 149.9 (q, J = 5.8 Hz), 164.3, 192.7; ^{19}F NMR ($CDCl_3$) δ = −59.1 (d, J = 8.0 Hz, 3F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 3.84 (s, 3H), 6.04 (q, J = 7.6 Hz, 1H), 6.92 (ABq, J = 8.8 Hz, 2H), 7.34–7.47 (m, 5H), 7.92 (ABq, J = 8.8 Hz, 1H); ^{19}F NMR ($CDCl_3$) δ = −57.1 (d, J = 7.11 Hz, 3F).

4.4.2. 4,4,4-Trifluoro-1-(2-methoxyphenyl)-2-phenyl-2-buten-1-one (4n)

IR (neat) 3064, 2944, 1657, 1598, 1486, 1296, 1277, 1207, 1133 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{17}H_{14}F_3O_2$ 307.0947; found: 307.0950.

Z isomer: ^{1}H NMR ($CDCl_3$) δ = 3.69 (s, 3H), 5.92 (q, J = 8.0 Hz, 1H), 6.87 (d, J = 8.4 Hz, 1H), 7.02 (dd, J = 7.6, 7.6 Hz, 1H), 7.30–7.41 (m, 5H), 7.49 (ddd, J = 8.4, 8.4, 1.2 Hz, 1H), 8.01 (dd, J = 7.6, 1.2 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ = 55.2, 112.1, 112.8 (q, J = 34.7 Hz), 120.7, 122.8 (q, J = 270.3 Hz), 124.9, 126.8, 128.8, 129.6, 131.5, 134.1, 135.7, 153.1 (q, J = 5.7 Hz), 159.9, 192.5; ^{19}F NMR ($CDCl_3$) δ = −59.1 (d, J = 8.0 Hz, 3F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 3.79 (s, 3H), 6.15 (q, J = 7.1 Hz, 1H), aromatic proton could not be identified; ^{19}F NMR ($CDCl_3$) δ = −57.5 (d, J = 7.1 Hz, 3F).

4.4.3. 1-(4-Chlorophenyl)-4,4,4-trifluoro-2-phenyl-2-buten-1-one (4o)

IR (neat) 3063, 2926, 1679, 1588, 1402, 1353, 1287, 1217, 1137 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{16}H_{11}ClF_3O$ 311.0451; found: 311.0441.

Z isomer: ^{1}H NMR ($CDCl_3$) δ = 6.22 (q, J = 8.0 Hz, 1H), 7.35–7.45 (m, 7H), 7.87 (ABq, J = 8.6 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ = 115.9 (q,

J = 35.1 Hz), 122.3 (q, J = 271.1 Hz), 126.6, 129.29, 129.32, 130.3, 130.5, 130.8, 133.5, 133.6, 140.8, 149.2 (q, J = 5.4 Hz), 193.0; ^{19}F NMR ($CDCl_3$) δ = −59.1 (d, J = 8.0 Hz, 3F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 6.11 (q, J = 7.1 Hz, 1H), 7.35–7.45 (m, 7H), 7.83 (ABq, J = 8.6 Hz, 2H); ^{19}F NMR ($CDCl_3$) δ = −57.3 (d, J = 7.1 Hz, 3F).

4.4.4. 4,4,4-Trifluoro-1-(1-naphthyl)-2-phenyl-2-buten-1-one (**4p**)

IR (neat) 3060, 2932, 1666, 1509, 1447, 1344, 1287, 1134 cm^{-1}.

HRMS (FAB) calcd for (M+H) $C_{20}H_{14}F_3O$ 327.0997; found: 327.0992.

Z isomer: ^{1}H NMR ($CDCl_3$) δ = 6.23 (q, J = 8.1 Hz, 1H), 7.33–7.40 (m, 3H), 7.40–7.47 (m, 1H), 7.50–7.58 (m, 2H), 7.59–7.64 (m, 1H), 7.70–7.76 (m, 1H), 7.88–7.92 (m, 1H), 7.94–7.98 (m, 1H), 8.03–8.07 (m, 1H), 9.32–9.35 (m, 1H); ^{13}C NMR ($CDCl_3$) δ = 115.2 (q, J = 34.9 Hz), 122.6 (q, J = 270.8 Hz), 124.3, 125.4, 126.1, 126.6, 126.9, 128.3, 128.6, 129.2, 129.3, 130.2, 130.9, 133.4, 134.2, 135.3, 150.9 (q, J = 5.5 Hz), 196.0; ^{19}F NMR ($CDCl_3$) δ = −58.9 (d, J = 8.1 Hz, 3F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 6.28 (q, J = 7.1 Hz, 1H), 7.33–7.40 (m, 3H), 7.40–7.47 (m, 1H), 7.50–7.58 (m, 2H), 7.80–7.83 (m, 1H), 7.88–7.92 (m, 1H), 8.00–8.03 (m, 1H), 8.48–8.52 (m, 1H); ^{19}F NMR ($CDCl_3$) δ = −57.6 (d, J = 7.1 Hz, 3F).

4.4.5. 4,4,4-Trifluoro-1-(2-phenylethyl)-2-phenyl-2-buten-1-one (**4q**)

The titled compound could not be separated as a sole compound from Michael type adduct.

Z isomer: ^{1}H NMR ($CDCl_3$) δ = 2.95 (s, 4H), 5.86 (q, J = 8.0 Hz, 1H), 7.01–7.45 (m, 10H); ^{19}F NMR ($CDCl_3$) δ = −59.0 (d, J = 8.0 Hz, 3F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 2.96 (s, 4H), 6.54 (q, J = 6.0 Hz, 1H), 7.01–7.45 (m, 10H); ^{19}F NMR ($CDCl_3$) δ = −58.0 (d, J = 6.0 Hz, 3F).

4.4.6. 1-Cyclohexyl-4,4,4-trifluoro-2-phenyl-2-buten-1-one (**4r**)

IR (neat) 2934, 2856, 1704, 1649, 1449, 1348, 1278, 1133 cm^{-1}.

HRMS (FAB) calcd for (M^+) $C_{16}H_{18}F_3O$ 283.1310; found: 283.1309.

Z isomer: ^{1}H NMR ($CDCl_3$) δ = 1.05–1.40 (m, 5H), 1.58–1.65 (m, 1H), 1.70–1.74 (m, 2H), 1.81–1.88 (m, 2H), 2.45 (tt, J = 11.2, 3.6 Hz, 1H), 5.84 (q, J = 8.4 Hz, 1H), 7.31–7.46 (m, 5H); ^{13}C NMR ($CDCl_3$) δ = 25.61, 25.63, 28.1, 50.4, 115.0 (q, J = 35.5 Hz), 122.5 (q, J = 270.3 Hz), 126.6, 129.2, 130.1, 133.8, 152.0 (q, J = 5.8 Hz), 207.0; ^{19}F NMR ($CDCl_3$) δ = −59.1 (d, J = 8.4 Hz, 3F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 6.40 (q, J = 8.0 Hz, 1H). The other proton signal (cyclohexyl and phenyl protons) could not be identified; ^{19}F NMR ($CDCl_3$) δ = −57.7 (d, J = 8.0 Hz, 3F).

4.4.7. Ethyl 4,4,4-trifluoro-2-phenyl-2-butenoate (**4s**)

Known compound. *Z isomer*: ^{1}H NMR ($CDCl_3$) δ = 1.35 (t, J = 7.10 Hz, 3H), 4.37 (q, J = 7.10 Hz, 2H), 6.02 (q, J = 7.90 Hz, 1H), 7.42 (s, 5H); ^{19}F NMR ($CDCl_3$) δ = −60.3 (d, J = 7.90 Hz, 3F).

4.4.8. 4,4-Difluoro-1,2-diphenyl-2-buten-1-one (**4w**)

Z isomer: ^{1}H NMR ($CDCl_3$) δ = 6.20 (dt, J = 6.79, 55.6 Hz, 1H), 6.26–6.40 (m, 1H), 7.30–7.36 (m, 1H), 7.50–7.54 (m, 1H), 7.60–7.65 (m, 1H), 7.96–7.98 (m, 1H); ^{19}F NMR ($CDCl_3$) δ = −110.1 (dd, J = 9.8, 55.6 Hz, 2F).

E isomer: ^{1}H NMR ($CDCl_3$) δ = 6.21 (dt, J = 6.79, 53.8 Hz, 1H); ^{19}F NMR ($CDCl_3$) δ = −109.4 (dd, J = 9.8, 53.8 Hz, 2F).

References

[1] (a) T. Hiyama, K. Kanie, T. Kusumoto, Y. Morizawa, M. Shimizu, Organofluorine Compounds, Springer-Verlag, Berlin-Heidelberg, 2000;
(b) V.A. Soloshonok (Ed.), Enantiocontrolled Synthesis of Fluoro-Organic Compounds, Wiley, Chichester, 1999;
(c) R.D. Chambers (Ed.), Organofluorine Chemistry, Springer, Berlin, 1997;
(d) I. Ojima, J.R. McCarthy, J.T. Welch (Eds.), Biomedical Frontiers of Fluorine Chemistry, American Chemical Society, Washington, DC, 1996;
(e) R.E. Banks, B.E. Smart, J.C. Tatlow (Eds.), Organofluorine Chemistry: Principals and Commercial Applications, Plenum Press, New York, 1994;
(f) D. O'Hagen, H. Rzepa, Chem. Commun. (1997) 645–652;
(g) J. Mann, Chem. Soc. Rev. 16 (1987) 381–436;
(h) J.T. Welch, Tetrahedron 43 (1987) 3123–3197.

[2] For reviews, see:
(a) R. Dave, B. Badet, P. Meffre, Amino Acids 24 (2003) 245–261;
(b) X.-L. Qiu, W.-D. Meng, F.-L. Qing, Tetrahedron 60 (2004) 6711–6745;
(c) K. Mikami, Y. Itoh, M. Yamanaka, Chem. Rev. 104 (2003) 1–16;
(d) J.H. van Steenis, A. van der Gen, J. Chem. Soc., Perkin Trans. 1 (2002) 2117–2133;
(e) R.P. Singh, J.M. Shreeve, Tetrahedron 56 (2000) 7613–7632;
(f) S.D.R. Christie, J. Chem. Soc., Perkin Trans. 1 (1998) 1577–1588;
(g) I. Ojima, Chem. Rev. 88 (1988) 1011–1030;
(h) G.K.S. Prakash, A.K. Yudin, Chem. Rev. 97 (1997) 757–786;
(i) M.A. McClinton, D.A. McClinton, Tetrahedron 48 (1992) 6555–6666.

[3] (a) T. Konno, T. Tanaka, T. Miyabe, A. Morigaki, T. Ishihara, Tetrahedron Lett. 49 (2008) 2106–2110;
(b) T. Yamazaki, N. Shinohara, T. Kitazume, S. Sato, J. Fluorine Chem. 97 (1999) 91–96;
(c) O. Klenz, R. Evers, R. Miethchen, M. Michalik, J. Fluorine Chem. 81 (1997) 205–210;
(d) T. Konno, T. Yamazaki, T. Kitazume, Tetrahedron 52 (1996) 199–208;
(e) L. Antolini, A. Forni, I. Moretti, F. Prati, Tetrahedron: Asymmetry 7 (1996) 3309–3314;
(f) N. Shinohara, J. Haga, T. Yamazaki, T. Kitazume, S. Nakamura, J. Org. Chem. 60 (1995) 4363–4374;
(g) T. Yamazaki, J. Haga, T. Kitazume, Chem. Lett. (1991) 2175–2178;
(h) T. Yamazaki, N. Ishikawa, J. Chem. Soc., Chem. Commun. (1987) 1340–1342;
(i) P.F. Bevilacqua, D.D. Keith, J.L. Robert, J. Org. Chem. 49 (1984) 1430–1434.

[4] (a) M. Redon, Z. Janousek, H.G. Viehe, Tetrahedron 53 (1997) 6861–6872;
(b) K. Tanaka, T. Imase, S. Iwata, Bull. Chem. Soc. Jpn. 69 (1996) 2243–2248;
(c) D. Bonnet-Delpon, A. Chennoufi, M.H. Rock, Bull. Soc. Chim. Fr. 132 (1995) 402–405;
(d) Y. Hanzawa, M. Suzuki, Y. Kobayashi, T. Taguchi, Y. Iitaka, J. Org. Chem. 56 (1991) 1718–1725.

[5] Recently, several groups and we have reported the stereoselective syntheses of fluoroalkylated alkenes. See:
(a) T. Konno, A. Morigaki, K. Ninomiya, T. Miyabe, T. Ishihara, Synthesis (2008) 564–572;
(b) T. Konno, J. Chae, T. Tanaka, T. Ishihara, H. Yamanaka, J. Fluorine Chem. 127 (2006) 36–43;
(c) T. Konno, T. Daitoh, A. Noiri, J. Chae, T. Ishihara, H. Yamanaka, Tetrahedron 61 (2005) 9391–9404;
(d) S. Radix-Large, S. Kucharski, B.R. Langlois, Synthesis (2004) 456–465;
(e) T. Konno, J. Chae, T. Tanaka, T. Ishihara, H. Yamanaka, Chem. Commun. (2004) 690–691;
(f) T. Konno, T. Daitoh, A. Noiri, J. Chae, T. Ishihara, H. Yamanaka, Org. Lett. 6 (2004) 933–936;
(g) T. Konno, T. Takehana, J. Chae, T. Ishihara, H. Yamanaka, J. Org. Chem. 69 (2004) 2188–2190;
(h) M. Shimizu, T. Fujimoto, X. Liu, H. Minezaki, T. Hata, T. Hiyama, Tetrahedron 59 (2003) 9811–9823;
(i) J. Chae, T. Konno, M. Kanda, T. Ishihara, H. Yamanaka, J. Fluorine Chem. 120 (2003) 185–193;
(j) M.P. Jennings, E.A. Cork, V. Ramachanfran, J. Org. Chem. 65 (2000) 8763–8766;
(k) R.-q. Pan, X.-x. Liu, M.Z. Deng, J. Fluorine Chem. 95 (1999) 167–170;
(l) G. Prié, J. Thibonnet, M. Abarbri, A. Duchêne, J. Parrain, Synlett (1998) 839–840;
(m) Y. Shen, S. Gao, J. Fluorine Chem. 76 (1996) 37–39.

[6] Several Heck reactions of fluorine-containing alkenes were reported, see:
(a) S. Darses, M. Pucheault, J.-P. Genêt, Eur. J. Org. Chem. (2001) 1121–1128;
(b) S. Peng, F.-L. Qing, Y. Guo, Synlett (1998) 859–860;
The Heck reaction of β-fluoroalkylated α,β-unsaturated carbonyl compounds with aryl halide in the presence of palladium catalyst has been reported, however neither the high regioselectivity nor the high yields have been achieved (<48% yield, the regioselectivity = <29:71), see:
(c) Y. Gong, K. Kato, H. Kimoto, J. Fluorine Chem. 105 (2000) 169–173;
Recently, we have disclosed a preliminary finding on the Heck reaction of fluorine-containing α,β-unsaturated ketones. See:
(d) T. Konno, S. Yamada, A. Tani, T. Miyabe, T. Ishihara, Synlett (2006) 3025–3028.

[7] The stereochemistry was determined on the basis of the chemical shifts in ^{1}H NMR according to the literature. See Ref. [6c].

[8] Investigation of the reaction conditions for the Heck reaction of **2s** with phenyldiazonium salt was investigated in detail, like the case of **2a**. However, the satisfactory results were not obtained at all.

[9] T.E. Nickson, J. Org. Chem. 53 (1988) 3870–3872.

[10] H. Tsuge, T. Okano, S. Eguchi, J. Chem. Soc., Perkin Trans. 1 (1995) 2761–2766.

[11] (a) M. Moteni, A. Volonterio, M. Zanda, Org. Lett. 5 (2003) 3887–3890;
(b) S. Iwata, Y. Ishiguro, M. Utsugi, K. Mitsuhashi, K. Tanaka, Bull. Chem. Soc. Jpn. 66 (1993) 2432–2435.

[12] G. Bott, F.G. Field, S. Sternhell, J. Am. Chem. Soc. 102 (1980) 5618–5626.
[13] Arenediazonium salts were prepared according to described procedure. See:
(a) S. Darses, T. Jeffery, J.-P. Demoute, J.-P. Genêt, Bull. Chem. Chim. Fr. 133 (1996) 1095–1102;
(b) S. Darses, G. Michaud, J.-P. Genêt, Eur. J. Org. Chem. (1999) 1875–1883;
(c) M.P. Doyle, W.J. Bryker, J. Org. Chem. 44 (1979) 1572–1574;
(d) M.H. Suschitzky, Adv. Fluorine Chem. 4 (1965) 1–30;
(e) A. Roe, Org. Synth. Coll. 5 (1949) 193–228.
[14] (a) T. Yamazaki, T. Ichige, T. Kitazume, Org. Lett. 6 (2004) 4073–4076;
(b) T. Yamazaki, K. Mizutani, T. Kitazume, J. Org. Chem. 60 (1995) 6046–6056.