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Palladium- and Nickel-Catalyzed Kumada Cross-Coupling Reactions of *gem*-Difluoroalkenes and Monofluoroalkenes with Grignard Reagents

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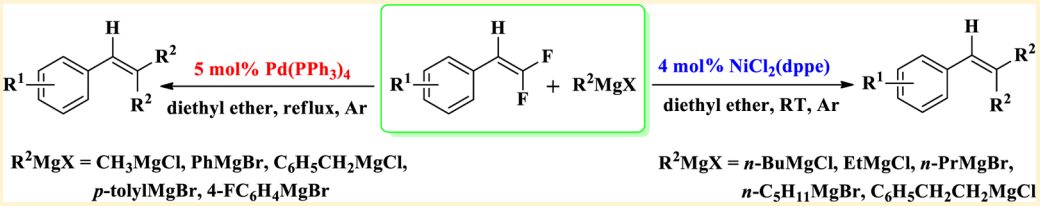
Supporting Information



ABSTRACT: A novel Kumada−Tamao−Corriu cross-coupling reaction of *gem*-di- or monofluoroalkenes with Grignard reagents, with or without *β*-hydrogen atoms, in the presence of a catalytic amount of palladium- or nickel-based catalysts has been developed. The reaction is performed under mild conditions (room temperature or reflux in diethyl ether for 1−2 h) and leads to di-cross- or mono-cross-coupled products in good to high yields.

INTRODUCTION

Transition-metal-catalyzed cross coupling of aryl or alkenyl halides with Grignard reagents (RMgX), known as the Kumada−Tamao−Corriu cross-coupling reaction, is one of the most valuable and versatile methods for the construction of carbon—carbon bonds since its discovery in the 1970s.[1] With more than 40 years of extensive investigation of Kumada reactions, it currently matters not whether coupling partners are very reactive organic bromides and iodides or unactivated alkyl chlorides, the Kumada reaction can proceed smoothly through modification of the reaction conditions.[2]

Recently, the use of aryl fluorides as the electrophile coupling partner in Kumada reactions has attracted much attention due to the importance of functionalization of the C—F bond.[3] However, cross-coupling reactions of alkenyl fluorides with Grignard reagents have been little studied, and only a few examples of C—C bond formation using alkenyl fluorides have been reported.[4] Earlier studies have demonstrated that fluoroolefins bearing a greater number of fluorine or chlorine atoms, such as 1-arylpentafluoropropene and 1,l-dichloro-2,2-difluoroethylene, could react with RMgX without a metal catalyst.[5] Ishihara and co-workers reported that the reaction of various fluorine-containing alkenes containing an electron-withdrawing group, such as pentafluorocrotonate, trifluoroacrylic ester, and trifluorovinyl sulfone, with Grignard reagents proceeds smoothly in the presence of CuCN to give their corresponding addition−elimination products in good to high yields.[6] In 2011, Nagai described nickel (Ni)- and palladium (Pd)-catalyzed coupling reactions of fluorine-containing olefins, such as tetrafluoroethylene and hexafluoropropylene, with Grignard reagents with the aid of a ligand (PPh_3); however, the yields of these reactions were not high, and a mixture of di-cross- and mono-cross-coupled products was obtained.[7] Furthermore, despite their synthetic utility, these methods suffer from several drawbacks such as narrow substrate scope, lack of stereocontrol over double-bond geometry, the presence of inseparable *E*/*Z* isomers, and a mixture of mono- and disubstitution products. Thus, the development of alternative transition-metal-catalyzed coupling reactions of alkenyl fluorides with Grignard reagents via C—F bond activation that can be performed under milder conditions is highly desirable. In continuation of our interest in the functionalization of the C—F bond of fluoroalkene and aryl fluoride,[8] we report here palladium- and nickel-catalyzed coupling reactions of *gem*-di- or monofluoroalkenes with different Grignard reagents, which afford di-cross- or mono-cross-coupled products in good to high yields (Scheme 1).

RESULTS AND DISCUSSION

Generally, the Kumada cross-coupling reaction of Grignard reagents with organohalides is achieved by using a catalytic amount of a nickel or palladium catalyst.[4b,9] Therefore, we first tested nickel catalyst $NiCl_2$(dppe) using the model reaction of

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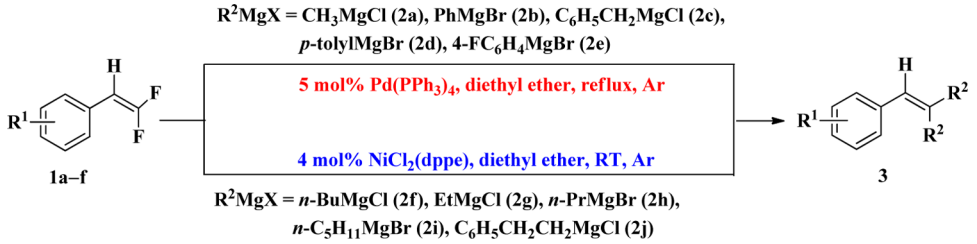
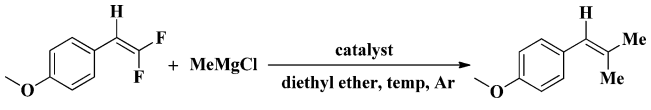
Scheme 1. Pd- or Ni-Catalyzed Cross-Coupling Reaction of *gem*-Difluoroalkenes with R^2MgX



1-(2,2-difluorovinyl)-4-methoxybenzene **1a** with methylmagnesium chloride **2a** in diethyl ether in different reaction conditions (Table 1, entries 1–6). Although the use of

Table 1. Optimization of the Reaction Conditions for the Synthesis of 3aa



entry	catalyst (mol %)	MeMgCl (equiv)	T (°C)	yield (%)[a]
1	$NiCl_2$(dppe) (5)	2.4	0	15
2	$NiCl_2$(dppe) (5)	2.4	rt	25
3	$NiCl_2$(dppe) (5)	2.4	reflux	60
4	$NiCl_2$(dppe) (5)	3.6	rt	51
5	$NiCl_2$(dppe) (5)	3.6	reflux	78
6	$NiCl_2$(dppe) (5)	1.0	reflux	0
7	$PdCl_2$(dppb) (5)	2.4	reflux	3
8	$PdCl_2$(dppf) (5)	2.4	reflux	0
9	$PdCl_2$(dppe) (5)	2.4	reflux	0
10	$Pd_2(dba)_3$ (5)	2.4	reflux	28
11	$Pd(PPh_3)_4$ (5)	2.4	reflux	95
12	$Pd(PPh_3)_4$ (5)	2.4	25	75
13	$Pd(PPh_3)_4$ (5)	2.4	15	0
14	$Pd(PPh_3)_4$ (4)	2.4	reflux	77
15	none	2.4	reflux	0
16	$Pd(PPh_3)_4$ (5)	2.0	reflux	37
17	$Pd(PPh_3)_4$ (5)	1.2	reflux	4
18	$Pd(PPh_3)_4$ (5)	0.8	reflux	0

[a]Yields refer to desired product **3aa** and are determined by GC analysis based on **1a** (1 mmol).

$NiCl_2$(dppe) resulted in the formation of the double cross-coupling product in moderate yield (78%, GC/MS, entry 5), a sizable amount of the starting material **1a** was recovered. Next, we focused on the Kumada coupling reaction of **1a** with **2a** in the presence of various Pd catalysts (entries 7–18). Among the Pd catalysts tested, $Pd(PPh_3)_4$ was found to be the most effective (entry 11). Working at lower reaction temperatures resulted in a decrease in the reaction rate (entries 12 and 13). Decreasing the amount of $Pd(PPh_3)_4$ or **2a** obviously diminished the yield (entries 14 and 16–18). In addition, the control experiment showed that no reaction occurred in the absence of a nickel or palladium catalyst (entry 15). Interestingly, only a trace amount of the monocoupled product was detected in this case, regardless of whether the reaction was performed in the presence of either a palladium or a nickel catalyst. Furthermore, no relationship could be found for the formation of the monocoupled product based on the amount of **2a** added.

Having optimized the reaction conditions (Table 1, entry 11), we next examined the scope of this $Pd(PPh_3)_4$-catalyzed cross-coupling reaction of *gem*-difluoroalkenes with Grignard reagents (Table 2, utilized substrates listed in the Supporting Information). Difluoroethenes with electron-donating substituents such as CH_3O (**1a**), BnO (**1b**), and CH_3S (**1c**) on the aromatic ring underwent coupling reactions with high yields. 1-Aryl-2,2-difluoroethenes that have a naphthyl group could also be converted to a double cross-coupling product with a good yield (**1d**). When an aliphatic difluoroalkene such as 1,1-difluoro-2-benzyl ethylene was used as the substrate, the reaction did not proceed well, and only a small amount of di-cross-coupled product was observed. The aromatic ring in difluoroalkenes seems necessary to ensure a high yield.

Unfortunately, the cross coupling of Grignard reagents bearing β-hydrogen atoms, such as *n*-BuMgCl, EtMgCl, *n*-PrMgBr, *n*-$C_5H_{11}MgBr$, and $C_6H_5CH_2CH_2MgCl$, with *gem*-difluoroalkenes in the presence of $Pd(PPh_3)_4$ afforded only disubstituted alkenes in moderate yields (60–80%, GC/MS). This might be partly attributable to facile β-hydride elimination of Grignard reagents catalyzed by $Pd(PPh_3)_4$, which leads to undesired olefin products.[10]

In the following investigation, our attention was directed toward the reaction of *gem*-difluoroalkenes with alkyl Grignard reagents containing β-hydrogen atoms. Grignard reagent *n*-BuMgCl **2f** was used as a test substrate for screening reaction conditions (Table 3). In the absence of catalyst, only a trace amount of double cross-coupling product **3af** was detected (entry 1). The use of $Co(acac)_2$ resulted in the formation of the double cross-coupled product in a very low yield; however, dehydrofluorinated cross-coupled product **3af′** was predominantly observed (entry 2).[11] It was suprising to find that when the reaction was catalyzed with $PdCl_2$(dppf), a highly effective catalyst for cross coupling of primary and secondary alkyl Grignard reagents containing β-hydrogen atoms with organic halides,[12] substrate **1a** was almost completely recovered in the reaction mixture (entry 3). Although $Pd(PPh_3)_4$ exhibited excellent catalytic activity in the cross coupling of *gem*-difluoroalkenes with Grignard reagents without β-hydrogen atoms, the $Pd(PPh_3)_4$-catalyzed coupling reaction of **1a** with **2f** was unsuccessful, giving the expected product **3af** only in moderate yield along with a considerable amount of **3af′** (entries 4 and 5). Hydrodefluorination of 1-(2,2-difluorovinyl)-4-methoxybenzene **1a** to afford 1-methoxy-4-vinylbenzene under the above-mentioned reaction conditions is difficult. The second C—F bond in **1a** reacts quickly with RMgX to form **3af′**, and no 1-methoxy-4-vinylbenzene was detected at all.

Based on the pioneering contributions of Kumada, the cross-coupling reaction of organic halides with alkylmagnesium halides bearing β-hydrogen atoms could proceed efficiently in the presence of a nickel catalyst.[13] Therefore, we next focused

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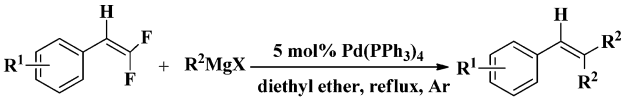
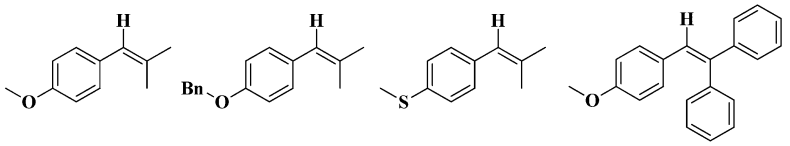
Table 2. $Pd(PPh_3)_4$-Catalyzed Cross Coupling of *gem*-Difluoroalkenes with Grignard Reagents[a]

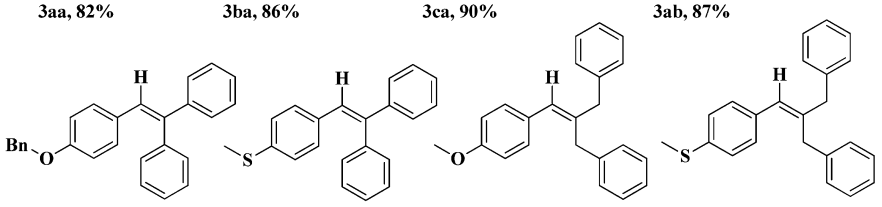


1a–d 2a–e 3aa–de

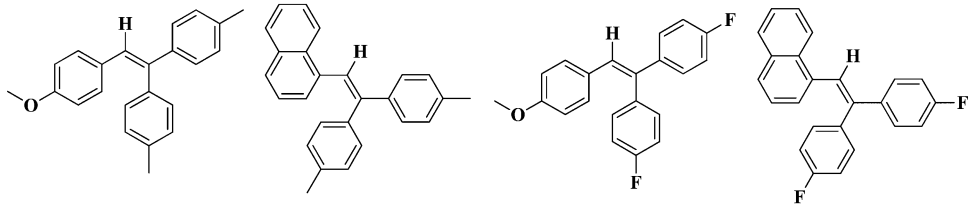
R^2MgX = CH_3MgCl (2a), PhMgBr (2b), $C_6H_5CH_2MgCl$ (2c), *p*-tolylMgBr (2d), 4-FC_6H_4MgBr (2e)



3aa, 82% 3ba, 86% 3ca, 90% 3ab, 87%



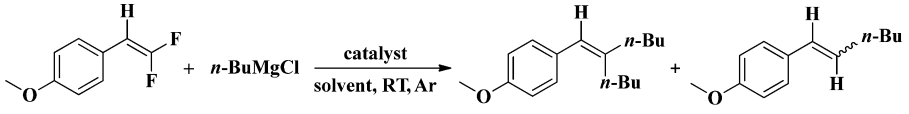
3bb, 87% 3cb, 83% 3ac, 72% 3cc, 79%



3ad, 86% 3dd, 84% 3ae, 84% 3de, 88%

[a]Reaction conditions: *gem*-difluoroalkenes **1a–d** (1.0 mmol), R^2MgX **2a–e** (2.4 mmol), diethyl ether (8 mL), 2 h.

Table 3. Optimization of the Reaction Conditions for the Synthesis of 3af



1a 2f 3af 3af'

entry	catalyst (mol %)	solvent	*n*-BuMgCl (equiv)	3af/3af' yield (%)[a]
1	none	Et_2O	2.4	4/0
2	$Co(acac)_2$ (5)	Et_2O	2.4	5/60
3	$PdCl_2(dppf)$ (5)	Et_2O	2.4	NR
4	$Pd(PPh_3)_4$ (5)	Et_2O	2.4	75/25
5	$Pd(PPh_3)_4$ (5)	Et_2O[b]	2.4	80/20
6	$NiCl_2$ (5)	Et_2O	2.4	64/27
7	$Ni(acac)_2$ (5)	Et_2O	2.4	48/51
8	$NiCl_2(PCy_3)_2$ (5)	Et_2O	2.4	40/32
9	$NiBr_2(PPh_3)_2$ (5)	Et_2O	2.4	32/69
10	$NiCl_2$(dppp) (5)	Et_2O	2.4	95/5
11	$NiCl_2$(dppe) (5)	Et_2O	2.4	99
12	$NiCl_2$(dppe) (4)	Et_2O	2.4	99
13	$NiCl_2$(dppe) (3)	Et_2O	2.4	90
14	$NiCl_2$(dppe) (5)	THF	2.4	95/2
15	$NiCl_2$(dppe) (5)	DMF	2.4	NR
16	$NiCl_2$(dppe) (5)	CH_3CN	2.4	NR
17	$NiCl_2$(dppe) (4)	Et_2O	2.0	75/5
18	$NiCl_2$(dppe) (4)	Et_2O	1.2	34/33

[a]Single yields refer to the desired product **3af** and are determined by GC analysis based on **1a** (1 mmol). [b]Reflux.

on screening various nickel-based catalysts. Different nickel complexes, such as $NiCl_2$, $Ni(acac)_2$, $NiCl_2(PCy_3)_2$, $NiBr_2(PPh_3)_2$, $NiCl_2$(dppp), and $NiCl_2$(dppe), were separately applied in the reaction (entries 6–11). The results indicated

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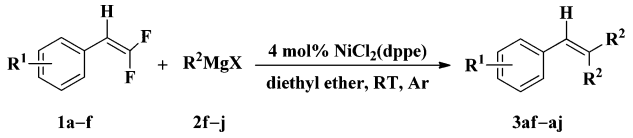
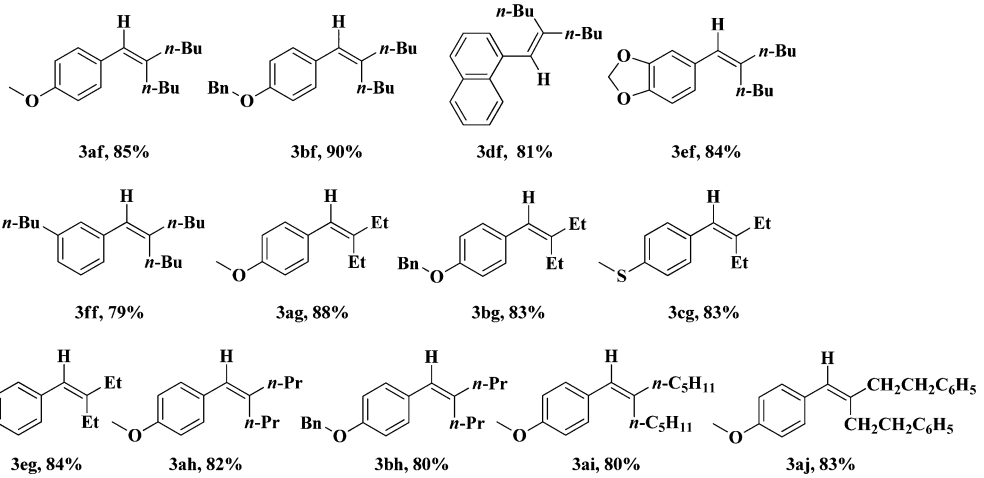
Table 4. $NiCl_2$(dppe)-Catalyzed Cross Coupling of *gem*-Difluoroalkenes with Grignard Reagents[a]



1a–f 2f–j 3af–aj

R^2MgX = *n*-BuMgCl (2f), EtMgCl (2g), *n*-PrMgBr (2h), *n*-$C_5H_{11}MgBr$ (2i), $C_6H_5CH_2CH_2MgCl$ (2j)



3af, 85% 3bf, 90% 3df, 81% 3ef, 84%

3ff, 79% 3ag, 88% 3bg, 83% 3cg, 83%

3eg, 84% 3ah, 82% 3bh, 80% 3ai, 80% 3aj, 83%

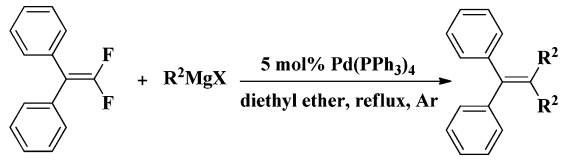
[a]Reaction conditions: *gem*-difluoroalkenes **1a–f** (1.0 mmol), R^2MgX **2f–j** (2.4 mmol), diethyl ether (8 mL), 2 h.

that $NiCl_2$(dppe) was clearly the best choice, and $NiCl_2$(dppp) provided a slightly lower yield. Catalyst loading was found to affect the yield, and 4 mol % $NiCl_2$(dppe) seemed to be optimal for this reaction (entries 11–13). The use of different solvents revealed that diethyl ether is the best reaction medium among those tested for this reaction (entries 12 and 14–16). On the other hand, a significant decrease in yield was observed when the amount of **2f** was reduced to 1.2 equiv, giving expected product **3af** in 34% yield along with 33% of the dehydrofluorinated product **3af′** (entries 17 and 18).

Using the optimized conditions described above (Table 3, entry 12), we next tried to extend the Kumada coupling reactions to other alkylmagnesium halides bearing β-hydrogen atoms. As can be seen in Table 4, in most cases, *gem*-difluoroalkenes **1a–f** could react with alkylmagnesium halides **2f–j** efficiently and transform into di-cross-coupled products with good to high yields. To our delight, only trace amounts of mono-cross-coupled and dehydrofluorinated products were observed. Difluoroalkenes bearing a halide atom on the aryl ring such as 1-bromo-3-(2,2-difluorovinyl)benzene **1f** also afforded the expected product in a good yield (**3ff**). However, when this nickel catalytic system was applied to Kumada coupling of Grignard reagents without β-hydrogen atoms, such as **2a–e**, the yield of the coupling product decreased sharply (25–72%, GC).

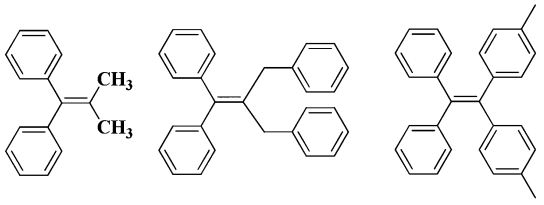
To further verify the generality of the cross-coupling reaction involving the C—F bond of fluoroalkene, symmetrical *gem*-difluoroalkene **1g** and six monofluoroalkenes, (*E*)-**1h**, (*E*)-**1i**, and **1j–m**, were subjected to cross coupling with Grignard reagents in the presence of $Pd(PPh_3)_4$ as a catalyst under the optimized reaction conditions (Table 1, entry 11). The results are shown in Tables 5–7. The coupling reaction of fluoroalkenes with Grignard reagents without β-hydrogen atoms proceeded very well to afford the desired products in good to excellent yields, regardless of whether the fluoroalkenes were symmetrical *gem*-difluoroalkenes or monofluoroalkenes. However, the reaction of (2,2-difluoroethene-1,1-diyl)-

Table 5. $Pd(PPh_3)_4$-Catalyzed Coupling Reaction of Symmetrical *gem*-Difluoroalkenes 1g with R^2MgX[a]



1g 2a, 2c, 2d 3ga, 3gc, 3gd

R^2MgX = CH_3MgCl (2a), $C_6H_5CH_2MgCl$ (2c), *p*-tolylMgBr (2d)



3ga, 87% 3gc, 81% 3gd, 43%

[a]Reaction conditions: *gem*-difluoroalkenes **1g** (1.0 mmol), R^2MgX (2.4 mmol), diethyl ether (8 mL), 2 h.

dibenzene **1g** with *p*-tolylMgBr **2d** proceeded less efficiently, affording the desired product in only 43% yield, presumably due to steric repulsion between the neighboring benzene rings (Table 5, **3gd**). An alkynyl group next to the fluoroalkene did not affect this transformation and gave the expected products in high yields (Table 7). As shown in Tables 6 and 7, the reaction of monofluoroalkenes with CH_3MgCl, PhMgBr, $C_6H_5CH_2MgCl$, *p*-tolylMgBr, and 4-FC_6H_4MgBr and catalyzed by $Pd(PPh_3)_4$ gives only cross-coupling products in high yields.

A novel $NiCl_2$(dppe) catalytic system was also expanded to the coupling reaction of *n*-BuMgCl with some fluoroalkenes, such as **1g**, (*E*)-**1i**, and **1j** (Table 8). Unfortunately, these reactions were unsuccessful; only (*E*)-**1i** afforded desired coupled product (*E*)-**3if** in moderate yield (62%).

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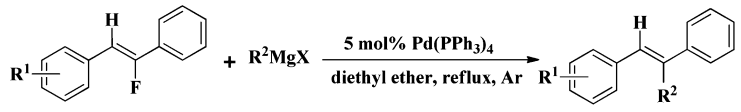
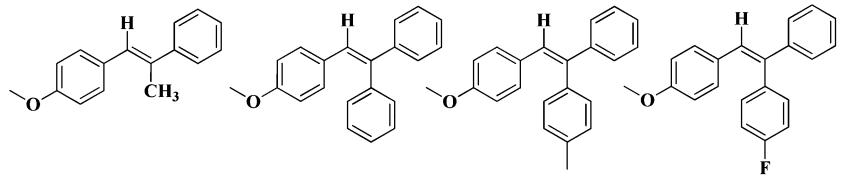
Table 6. $Pd(PPh_3)_4$-Catalyzed Coupling Reaction of Monofluoroalkenes (*E*)-1h and (*E*)-1i with R^2MgX[a]

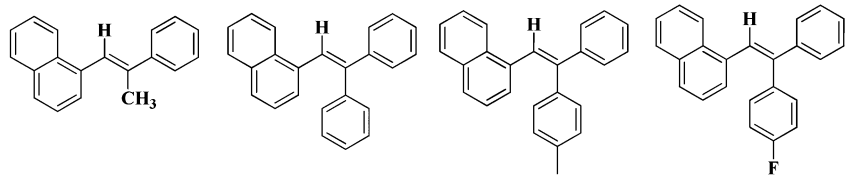


(*E*)-1h, (*E*)-1i 2a, 2b, 2d, 2e 3ha-ie

R^2MgX = CH_3MgCl (2a), PhMgBr (2b), *p*-tolylMgBr (2d), 4-FC_6H_4MgBr (2e)



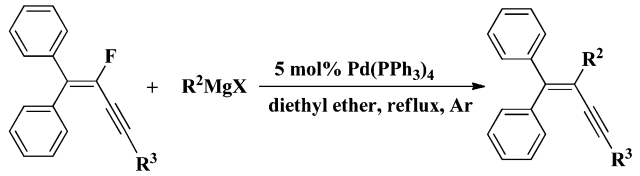
(*E*)-3ha, 89% 3ab, 96% (*Z*)-3hd, 90% (*Z*)-3he, 93%



(*E*)-3ia, 91% 3ib, 84% (*Z*)-3id, 96% (*Z*)-3ie, 90%

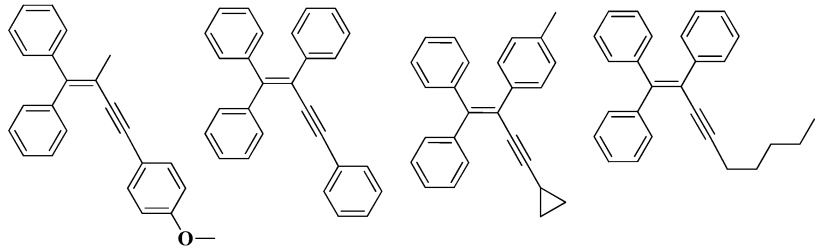
[a]Reaction conditions: (*E*)-**1h** and (*E*)-**1i** (1.0 mmol), R^2MgX (2.0 mmol), diethyl ether (8 mL), 2 h.

Table 7. $Pd(PPh_3)_4$-Catalyzed Coupling Reaction of Monofluoroalkenes 1j−m with R^2MgX[a]



1j, 1k, 1l, 1m 2a, 2b, 2d 3ja-mb

R^2MgX = CH_3MgCl (2a), PhMgBr (2b), *p*-tolylMgBr (2d)



3ja, 90% 3kb, 94% 3ld, 82% 3mb, 87%

[a]Reaction conditions: **1j−m** (1.0 mmol), R^2MgX (2.0 mmol), diethyl ether (8 mL), 2 h.

On the basis of the observations described above and related literature, we hypothesize that the reaction mechanism is essentially analogous to previous reports regarding Ni- or Pd-catalyzed coupling reactions of alkenyl halides (X = Cl, Br, I) and aryl fluorides with Grignard reagents.[1d,3a,10a] The proposed mechanism of the Ni-catalyzed coupling reaction of fluoroalkene with Grignard reagents bearing β-hydrogen atoms (**2f−j**) is depicted in Scheme 2. The Ni-catalyzed coupling reaction involves three elementary steps: oxidative addition of RF, transmetalation of RMgX, and reductive elimination of the Ni complex. The mechanism of the Pd-catalyzed coupling reaction of fluoroalkene with Grignard reagents without β-hydrogen atoms (**2a−e**) is almost the same as that of the Ni-catalyzed coupling reaction.

It has been reported that when primary and secondary alkyl Grignard reagents that have β-hydrogen atoms were used as coupling partners with organic halides, that aside from their corresponding cross-coupling products, a small amount of reduction product was observed.[1d,10b,13,14] A putative mechanism for the formation of a dicoupled product (**VII**) and a monocouple-reduced byproduct (**XI**) via a $Pd(PPh_3)_4$-catalyzed coupling reaction of difluoroalkene with *n*-BuMgCl is illustrated in Scheme 3. We tried to isolate intermediates **I** and **IV** and cultivate single crystals but failed to get them to cultivate.

In summary, we have developed two new and efficient palladium- and nickel-based catalytic systems for the coupling of *gem*-difluoroalkenes or monofluoroalkenes with Grignard reagents under simple and mild reaction conditions without any

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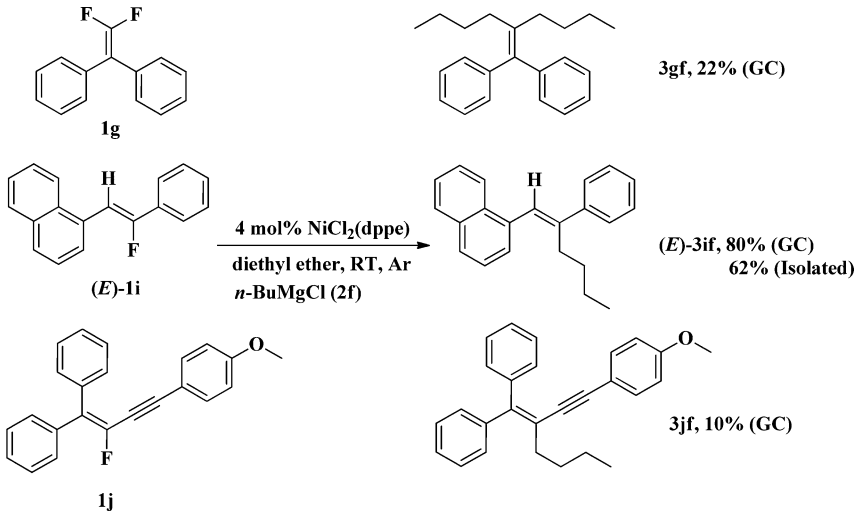
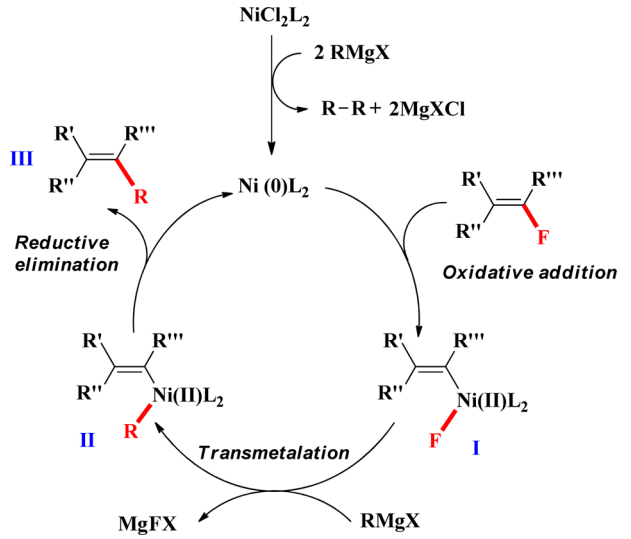
Table 8. $NiCl_2$(dppe)-Catalyzed Coupling Reaction of 1g, (*E*)-1i, and 1j with R^2MgX[a]



[a]Reaction conditions: **1g**, (*E*)-**1i**, and **1j** (1.0 mmol), *n*-BuMgCl (2.4 or 2.0 mmol), diethyl ether (8 mL), 2 h. Yields determined by GC analysis and based on **1g**, (*E*)-**1i**, and **1j** (1 mmol).

Scheme 2. Proposed Mechanism for the Ni-Catalyzed Cross-Coupling Reaction of Fluoroalkene with Grignard Reagents



additional ligands. The catalytic system involving $Pd(PPh_3)_4$ was found to be exceptionally effective for the coupling reaction of fluoroalkenes with Grignard reagents without β-hydrogen atoms to exclusively afford the corresponding dicoupled product in high yield, whereas $NiCl_2$(dppe) exhibited superior reactivity in the cross coupling of fluoroalkenes with Grignard reagents bearing β-hydrogen atoms. Using a combination of the two new catalytic systems will provide a powerful and practical tool for the synthesis of multisubstituted alkenes from fluoroalkenes.

EXPERIMENTAL SECTION

General Comments. All reagents were analytical grade, obtained from commercial suppliers, and used without further purification. ^{1}H NMR and ^{13}C NMR spectra were recorded on a 400 MHz spectrometer at 400 and 100 MHz, respectively, using TMS as an internal standard. ^{19}F NMR spectra were obtained using a 400 MHz spectrometer at 376 MHz. $CDCl_3$ was used as the NMR solvent in all cases. GC and GC/MS were calibrated by authentic standards. High-resolution mass spectra (HRMS) were acquired in electron-impact (EI) mode using a TOF mass analyzer.

Synthesis of Compounds ***1a–m.*** Substrates **1a–g** were synthesized according to literature procedures.[8d] Substrates (*E*)-**1h** and (*E*)-**1i** were synthesized according to methods in the literature.[15] Substrates **1j–m** were prepared according to reported methods.[16]

General Procedure for the Cross-Coupling Reaction. To a solution of *gem*-difluoroalkenes or monofluoroalkenes (1 mmol) and $Pd(PPh_3)_4$ (57.8 mg, 0.05 mmol) or $NiCl_2$(dppe) (21.2 mg, 0.04 mmol) in diethyl ether was added dropwise a solution of Grignard reagent in THF or Et_2O (2.4 or 2.0 mmol) at room temperature under an argon atmosphere. The mixture was stirred for 2 h at reflux or at room temperature (monitored by TLC and GC/MS). After completion of the reaction, the reaction mixture was quenched with a saturated aqueous solution of NH_4Cl (5 mL) and extracted with ethyl acetate (3 × 10 mL). The combined organic layer was washed with water and brine, then dried over anhydrous Na_2SO_4, filtered, and concentrated under vacuum. The crude residue was then purified by column chromatography on silica gel using *n*-hexane as the eluent to afford pure target compound **3**.

*1-Methoxy-4-(2-methyl-1-propen-1-yl)benzene (**3aa**, CAS: 877-99-6).*[2f] Colorless oil: yield 82% (132.9 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.14 (d, J = 8.8 Hz, 2H), 6.84 (d, J = 8.4 Hz, 2H), 6.20 (s, 1H), 3.78 (s, 3H), 1.87 (s, 3H), 1.83 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.9, 134.2, 131.6, 130.1, 124.8, 113.7, 55.5, 27.1, 19.6.

*1-(Benzyloxy)-4-(2-methylprop-1-en-1-yl)benzene (**3ba**).* White solid: yield 86% (204.8 mg); mp 66.6–67.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42–7.30 (m, 5H), 7.14 (d, J = 8.0 Hz, 2H), 6.91 (d, J = 8.0 Hz, 2H), 6.20 (s, 1H), 5.03 (s, 2H), 1.87 (s, 3H), 1.83 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.9, 137.2, 134.0, 131.6, 129.8, 128.6, 127.9, 127.5, 124.5, 114.4, 70.0, 26.8, 19.4; HRMS (EI) calcd for $C_{17}H_{18}O$ ([M]$^+$) 238.1358, found 238.1359.

*Methyl(4-(2-methylprop-1-en-1-yl)phenyl)sulfane (**3ca**).* Yellow oil: yield 90% (160.3 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.20 (d, J = 8.4 Hz, 2H), 7.14 (d, J = 8.4 Hz, 2H), 6.20 (s, 1H), 2.46 (s, 3H), 1.88 (s, 3H), 1.84 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.8, 135.5, 129.2, 126.6, 124.6, 27.0, 19.5, 16.1; HRMS (EI) calcd for $C_{11}H_{14}S$ ([M]$^+$) 178.0816, found 178.0815.

*1-(2,2-Diphenylethenyl)-4-methoxybenzene (**3ab**, CAS: 18648-74-3).*[17] White solid: yield 87% (248.9 mg); mp 81.0–82.6 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33–7.19 (m, 10H), 6.95 (d, J = 8.4 Hz, 2H), 6.91 (s, 1H), 6.65 (d, J = 8.4 Hz, 2H), 3.71 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.4, 143.6, 140.6, 130.8, 130.4, 130.0, 128.7, 128.1, 127.6, 127.4, 127.2, 113.4, 55.1.

*1-(2,2-Diphenylethenyl)-4-(phenylmethoxy)benzene (**3bb**, CAS: 18648-75-4).*[18] White solid: yield 87% (315.1 mg); mp 100.3–101.5

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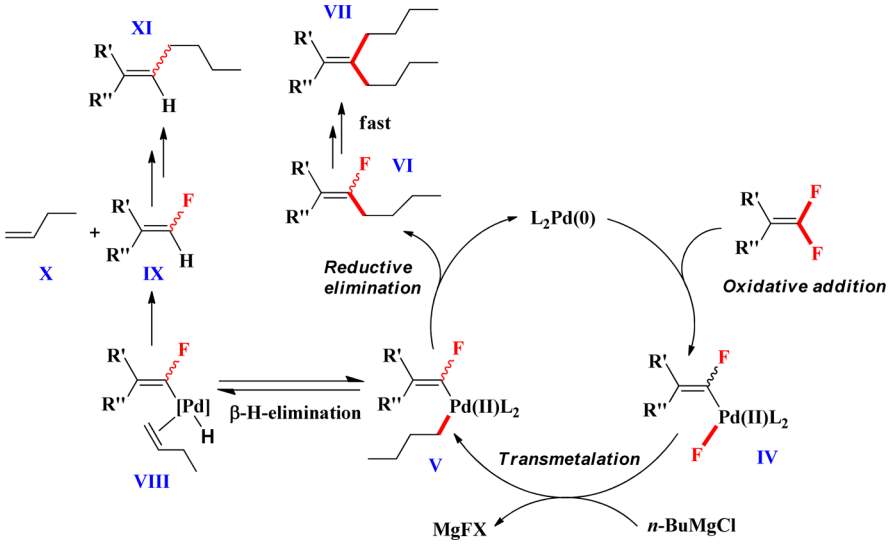
Scheme 3. Proposed Mechanism for the $Pd(PPh_3)_4$-Catalyzed Cross-Coupling Reaction of Difluoroalkene with *n*-BuMgCl



°C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34−7.19 (m, 15H), 6.93 (d, J = 8.0 Hz, 2H), 6.89 (s, 1H), 6.70 (d, J = 8.0 Hz, 2H), 4.91 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.8, 143.7, 140.9, 140.8, 137.1, 131.0, 130.6, 130.5, 128.9, 128.7, 128.4, 128.1, 127.8, 127.7, 127.6, 127.5, 127.4, 114.5, 70.0; HRMS (EI) calcd for $C_{27}H_{22}O$ ([M]$^+$) 362.1671, found 362.1672.

*1-(2,2-Diphenylethenyl)-4-(methylthio)benzene (**3cb**, CAS: 133776-80-4).*[19] Light yellow solid: yield 83% (250.8 mg); mp 106.9−108.6 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32−7.19 (m, 10H), 6.98 (d, J = 8.4 Hz, 2H), 6.92 (d, J = 8.8 Hz, 2H), 6.90 (s, 1H), 2.39 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.4, 142.2, 140.5, 137.0, 134.3, 130.4, 130.0, 128.8, 128.3, 127.6, 127.5, 125.9, 15.6.

*1-Methoxy-4-[3-phenyl-2-(phenylmethyl)-1-propenyl]benzene (**3ac**, CAS: 61022-48-8).*[20] Light yellow oil: yield 72% (226.2 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31−7.26 (m, 4H), 7.22−7.16 (m, 8H), 6.82 (d, J = 8.4 Hz, 2H), 6.51 (s, 1H), 3.76 (s, 3H), 3.53 (s, 2H), 3.36 (s, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.3, 139.8, 139.6, 138.9, 130.4, 129.7, 129.2, 128.7, 128.5, 128.4, 128.2, 126.1, 113.7, 55.3, 43.4, 36.0.

*(4-(2-Benzyl-3-phenylprop-1-en-1-yl)phenyl)(methyl)sulfane (**3cc**).* White solid: yield 79% (260.8 mg); mp 95.4−96.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.26−7.25 (m, 4H), 7.19−7.12 (m, 10H), 6.48 (s, 1H), 3.52 (s, 2H), 3.34 (s, 2H), 2.36 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.4, 139.7, 139.6, 136.8, 134.9, 129.4, 129.2, 128.9, 128.8, 128.6, 128.5, 126.7, 126.5, 126.4, 43.7, 36.3, 16.0; HRMS (EI) calcd for $C_{23}H_{22}S$ ([M]$^+$) 330.1442, found 330.1443.

*4,4′-(2-(4-Methoxyphenyl)ethene-1,1-diyl)bis(methylbenzene) (**3ad**, CAS: 1187460-27-0).*[21] White solid: yield 86% (270.2 mg); mp 75.7−77.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.21 (d, J = 8.0 Hz, 2H), 7.12 (s, 4H), 7.08 (d, J = 8.0 Hz, 2H), 6.98 (d, J = 8.8 Hz, 2H), 6.87 (s, 1H), 6.65 (d, J = 8.8 Hz, 2H), 3.67 (s, 3H), 2.36 (s, 3H), 2.32 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.4, 141.3, 140.7, 138.0, 137.1, 137.0, 131.0, 130.6, 130.5, 129.6, 129.1, 127.6, 126.9, 113.6, 55.2, 21.6, 21.3.

*1-[2,2-Bis(4-methylphenyl)ethenyl]naphthalene (**3dd**, CAS: 75078-97-6).*[4b] White solid: yield 84% (280.7 mg); mp 145.0−146.3 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15−8.12 (m, 1H), 7.81−7.79 (m, 1H), 7.62 (d, J = 8.0 Hz, 1H), 7.46−7.44 (m, 2H), 7.37 (s, 1H), 7.31 (d, J = 8.0 Hz, 2H), 7.17−7.13 (m, 3H), 7.05 (d, J = 7.2 Hz, 1H), 6.98−6.91 (m, 4H), 2.37 (s, 3H), 2.25 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.8, 141.2, 137.8, 137.6, 137.0, 135.8, 133.8, 132.9, 130.9, 129.3, 129.0, 128.8, 128.4, 127.9, 127.2, 126.2, 126.0, 125.7, 125.5, 125.0, 21.6, 21.5.

*4,4′-(2-(4-Methoxyphenyl)ethene-1,1-diyl)bis(fluorobenzene) (**3ae**, CAS: 2069-81-0).*[22] White solid: yield 84% (270.6 mg); mp 67.4−68.9 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.25−7.22 (m, 2H), 7.17−7.14 (m, 2H), 7.04−6.93 (m, 6H), 6.83 (s, 1H), 6.68 (d, J = 8.8 Hz, 2H), 3.74 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.5 (d, $^1J_{CF}$ = 245.6 Hz), 162.3 (d, $^1J_{CF}$ = 245.2 Hz), 158.7, 139.8 (d, $^4J_{CF}$ = 3.1 Hz), 138.7, 136.5 (d, $^4J_{CF}$ = 3.4 Hz), 132.3 (d, $^3J_{CF}$ = 7.9 Hz), 130.9, 129.9, 129.2 (d, $^3J_{CF}$ = 7.9 Hz), 128.1, 116.0 (d, $^2J_{CF}$ = 21.2 Hz), 115.2 (d, $^2J_{CF}$ = 19.2 Hz), 113.7, 55.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ −114.3 to −114.4 (m, 1F), −115.0 to −115.1 (m, 1F).

*1-(2,2-Bis(4-fluorophenyl)vinyl)naphthalene (**3de**).* White solid: yield 88% (301.1 mg); mp 76.5−77.9 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.12−8.10 (m, 1H), 7.85−7.83 (m, 1H), 7.67 (d, J = 8.4 Hz, 1H), 7.50−7.48 (m, 2H), 7.39−7.37 (m, 3H), 7.21−7.17 (m, 1H), 7.08−7.01 (m, 5H), 6.85−6.81 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.6 (d, $^1J_{CF}$ = 246.0 Hz), 162.0 (d, $^1J_{CF}$ = 245.4 Hz), 142.7, 139.3 (d, $^4J_{CF}$ = 3.2 Hz), 135.9 (d, $^4J_{CF}$ = 3.4 Hz), 134.9, 133.5, 132.4, 132.3 (d, $^3J_{CF}$ = 7.9 Hz), 129.8 (d, $^3J_{CF}$ = 8.0 Hz), 128.6, 127.7, 127.4, 126.5, 126.2, 125.9, 125.3, 124.6, 115.3 (d, $^2J_{CF}$ = 21.3 Hz), 115.2 (d, $^2J_{CF}$ = 21.3 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −114.3 to −114.4 (m, 1F), −114.4 to −114.5 (m, 1F); HRMS (EI) calcd for $C_{24}H_{16}F_2$ ([M]$^+$) 342.1220, found 342.1219.

*1-(2-Butyl-1-hexenyl)-4-methoxybenzene (**3af**, CAS: 836601-77-5).*[23] Colorless oil: yield 85% (209.3 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13 (d, J = 8.4 Hz, 2H), 6.84 (d, J = 8.4 Hz, 2H), 6.19 (s, 1H), 3.80 (s, 3H), 2.20 (t, J = 8.0 Hz, 2H), 2.14 (t, J = 7.6 Hz, 2H), 1.45−1.29 (m, 8H), 0.94 (t, J = 7.4 Hz, 3H), 0.89 (t, J = 7.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.9, 142.9, 131.6, 130.0, 124.4, 113.7, 55.5, 37.3, 30.9, 30.8, 30.7, 23.2, 22.9, 14.3, 14.2.

*1-(Benzyloxy)-4-(2-butylhex-1-en-1-yl)benzene (**3bf**).* Yellow oil: yield 90% (290.0 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42−7.29 (m, 5H), 7.14−7.11 (m, 2H), 6.92−6.89 (m, 2H), 6.19 (s, 1H), 5.02 (s, 2H), 2.21−2.14 (m, 4H), 1.47−1.33 (m, 8H), 0.96−0.87 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.9, 142.6, 137.1, 131.6, 129.7, 128.5, 127.8, 127.4, 124.1, 114.4, 69.9, 37.0, 30.5, 30.4, 30.3, 22.9, 22.5, 14.0, 13.9; HRMS (EI) calcd for $C_{23}H_{30}O$ ([M]$^+$) 322.2297, found 322.2295.

*1-(2-Butylhex-1-en-1-yl)naphthalene (**3df**).* Colorless oil: yield 81% (215.6 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98−7.94 (m, 1H), 7.84−7.83 (m, 1H), 7.73−7.71 (m, 1H), 7.47−7.28 (m, 4H), 6.61 (s, 1H), 2.31−2.29 (m, 2H), 2.08−2.06 (m, 2H) 1.61−1.15 (m, 8H), 1.02−0.98 (m, 3H), 0.76−0.73 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.1, 136.3, 133.5, 132.4, 128.2, 126.6, 126.4, 125.6, 125.5, 125.4, 125.3, 122.7, 36.2, 30.6, 30.5, 22.7, 14.1, 13.9; HRMS (EI) calcd for $C_{20}H_{26}$ ([M]$^+$) 266.2035, found 266.2036.

*5-(2-Butylhex-1-en-1-yl)benzo[d][1,3]dioxole (**3ef**).* Light yellow oil: yield 84% (218.6 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.76−6.64 (m, 3H), 6.15 (s, 1H), 5.93 (s, 2H), 2.19 (t, J = 7.8 Hz, 2H), 2.12 (t, J = 7.6 Hz, 2H), 1.48−1.25 (m, 8H), 0.93 (t, J = 7.2 Hz, 3H), 0.89 (t, J = 7.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 147.3, 145.5, 143.1,

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132.9, 124.2, 122.0, 109.0, 108.0, 100.8, 36.9, 30.6, 30.5, 30.4, 22.9, 22.6, 14.1, 14.0; HRMS (EI) calcd for $C_{17}H_{24}O_2$ ([M]$^+$) 260.1776, found 260.1775.

*1-Butyl-3-(2-butylhex-1-en-1-yl)benzene (**3ff**).* Yellow oil: yield 79% (215.1 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.22−7.18 (m, 1H), 7.02−6.98 (m, 3H), 6.24 (s, 1H), 2.59 (t, J = 7.8 Hz, 2H), 2.22 (t, J = 8.0 Hz, 2H), 2.15 (t, J = 7.6 Hz, 2H), 1.60−1.29 (m, 12H), 0.96−0.87 (m, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.6, 142.4, 138.6, 128.7, 127.8, 125.8, 125.7, 124.8, 37.0, 35.6, 33.6, 30.6, 30.5, 30.4, 22.9, 22.5, 22.3, 14.0, 13.9; HRMS (EI) calcd for $C_{20}H_{32}$ ([M]$^+$) 272.2504, found 272.2505.

*1-(2-Ethylbut-1-en-1-yl)-4-methoxybenzene (**3ag**).* Colorless oil: yield 88% (167.3 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.14 (d, J = 8.8 Hz, 2H), 6.85 (d, J = 8.4 Hz, 2H), 6.17 (s, 1H), 3.79 (s, 3H), 2.25 (q, J = 7.5 Hz, 2H), 2.18 (q, J = 7.5 Hz, 2H), 1.10 (t, J = 5.8 Hz, 3H), 1.06 (t, J = 6.0 Hz, 3H); ^{13}C NMR (100 M Hz, $CDCl_3$) δ 157.8, 145.3, 131.4, 129.7, 122.7, 113.6, 55.3, 29.5, 23.8, 13.1, 12.9; HRMS (EI) calcd for $C_{13}H_{18}O$ ([M]$^+$) 190.1358, found 190.1357.

*1-(Benzyloxy)-4-(2-ethylbut-1-en-1-yl)benzene (**3bg**).* Yellow oil: yield 83% (220.9 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43−7.29 (m, 5H), 7.15−7.13 (m, 2H), 6.93−6.90 (m, 2H), 6.17 (s, 1H), 5.03 (s, 2H), 2.27−2.16 (m, 4H), 1.12−1.04 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.9, 145.2, 137.1, 131.5, 129.6, 128.5, 127.8, 127.4, 122.6, 114.4, 69.9, 29.5, 23.7, 13.0, 12.8; HRMS (EI) calcd for $C_{19}H_{22}O$ ([M]$^+$) 266.1671, found 266.1672.

*(4-(2-Ethylbut-1-en-1-yl)phenyl)(methyl)sulfane (**3cg**).* Yellow oil: yield 83% (171.1 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.20 (d, J = 8.4 Hz, 2H), 7.13 (d, J = 8.0 Hz, 2H), 6.16 (s, 1H), 2.46 (s, 3H), 2.24 (q, J = 7.5 Hz, 2H), 2.17 (q, J = 7.9 Hz, 2H), 1.09 (t, J = 6.4 Hz, 3H), 1.06 (t, J = 6.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.6, 135.7, 135.4, 129.0, 126.6, 122.6, 29.5, 23.8, 16.1, 13.0, 12.8; HRMS (EI) calcd for $C_{13}H_{18}S$ ([M]$^+$) 206.1129, found 206.1128.

*5-(2-Ethylbut-1-en-1-yl)benzo[d][1,3]dioxole (**3eg**).* Light yellow oil: yield 84% (171.5 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.76−6.65 (m, 3H), 6.13 (s, 1H), 5.91 (s, 2H), 2.24 (q, J = 7.5 Hz, 2H), 2.16 (q, J = 7.7 Hz, 2H), 1.09 (t, J = 6.0 Hz, 3H), 1.05 (t, J = 6.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 147.5, 145.9, 145.8, 133.0, 123.0, 122.1, 109.1, 108.2, 101.0, 29.6, 23.9, 13.2, 13.0; HRMS (EI) calcd for $C_{13}H_{16}O_2$ ([M]$^+$) 204.1150, found 204.1149.

*1-Methoxy-4-(2-propyl-1-penten-1-yl)benzene (**3ah**, CAS: 860734-09-4).*[24] Colorless oil: yield 82% (178.9 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13 (d, J = 8.4 Hz, 2H), 6.84 (d, J = 8.8 Hz, 2H), 6.20 (s, 1H), 3.79 (s, 3H), 2.18 (t, J = 8.0 Hz, 2H), 2.11 (t, J = 8.0 Hz, 2H), 1.54−1.45 (m, 4H), 0.94 (t, J = 6.8 Hz, 3H), 0.90 (t, J = 7.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.7, 142.2, 131.4, 129.7, 124.5, 113.5, 55.2, 39.5, 32.8, 21.6, 21.4, 14.3, 14.0.

*1-(Benzyloxy)-4-(2-propylpent-1-en-1-yl)benzene (**3bh**).* Colorless oil: yield 80% (235.4 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44−7.31 (m, 5H), 7.13 (d, J = 8.4 Hz, 2H), 6.92 (d, J = 8.0 Hz, 2H), 6.20 (s, 1H), 5.04 (s, 2H), 2.18 (t, J = 7.8 Hz, 2H), 2.11 (t, J = 7.6 Hz, 2H), 1.52−1.47 (m, 4H), 0.96−0.89 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.2, 142.6, 137.5, 131.9, 130.0, 128.8, 128.2, 127.8, 124.7, 114.7, 70.3, 39.7, 33.0, 21.8, 21.6, 14.6, 14.2; HRMS (EI) calcd for $C_{21}H_{26}O$ ([M]$^+$) 294.1984, found 294.1985.

*1-Methoxy-4-(2-pentylhept-1-en-1-yl)benzene (**3ai**).* Colorless oil: yield 80% (219.4 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.12 (d, J = 8.8 Hz, 2H), 6.84 (d, J = 8.8 Hz, 2H), 6.19 (s, 1H), 3.78 (s, 3H), 2.20 (t, J = 8.0 Hz, 2H), 2.13 (t, J = 7.6 Hz, 2H), 1.51−1.42 (m, 4H), 1.36−1.27 (m, 8H), 0.91 (t, J = 6.8 Hz, 3H), 0.88 (t, J = 6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 157.7, 142.7, 131.4, 129.7, 124.2, 113.5, 55.2, 37.3, 32.1, 31.8, 30.7, 28.1, 28.0, 22.7, 22.6, 14.1, 14.0; HRMS (EI) calcd for $C_{19}H_{30}O$ ([M]$^+$) 274.2297, found 274.2295.

*(3-(4-Methoxybenzylidene)pentane-1,5-diyl)dibenzene (**3aj**).* Light yellow oil: yield 83% (284.0 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29−7.12 (m, 10H), 7.09−7.05 (m, 2H), 6.83−6.80 (m, 2H), 6.25 (s, 1H), 3.74 (s, 3H), 2.84−2.75 (m, 4H), 2.57−2.46 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.1, 142.3, 142.1, 140.5, 130.9, 129.8, 128.7, 128.6, 128.5, 128.4, 126.1, 126.0, 113.7, 55.3, 39.4, 35.1, 34.7, 33.0; HRMS (EI) calcd for $C_{25}H_{26}O$ ([M]$^+$) 342.1984, found 342.1983.

*1,1′-(2-Methyl-1-propen-1-ylidene)bisbenzene (**3ga**, CAS: 781-33-9).*[25] Colorless oil: yield 87% (181.1 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30−7.26 (m, 4H), 7.20−7.17 (m, 6H), 1.84 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.5, 137.3, 131.1, 129.9, 128.0, 126.2, 22.6.

*1,1-Dibenzyl-2,2-diphenylethylene (**3gc**, CAS: 69275-86-1).*[26] Light yellow solid: yield 81% (291.8 mg); mp 78.0−78.9 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30−7.25 (m, 12H), 7.22−7.17 (m, 4H), 7.10 (d, J = 7.6 Hz, 4H), 3.39 (s, 4H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 142.8, 141.3, 140.4, 136.1, 129.5, 128.9, 128.4, 128.3, 126.6, 126.0, 37.3.

*1,1-Diphenyl-2,2-di-p-tolylethylene (**3gd**, CAS: 32298-40-1).*[27] White solid: yield 43% (154.9 mg); mp 160.1−161.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.09−7.00 (m, 10H), 6.92−6.87 (m, 8H), 2.23 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.2, 141.0, 140.9, 140.1, 136.0, 131.4, 131.3, 128.4, 127.7, 126.2, 21.3.

*1-Methoxy-4-(2-phenyl-1-propenyl)benzene ((E)-**3ha**, CAS: 22692-69-9).*[28] White solid: yield 89% (199.5 mg); mp 83.6−84.9 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50 (d, J = 8.4 Hz, 2H), 7.37−7.23 (m, 5H), 6.91 (d, J = 8.4 Hz, 2H), 6.78 (s, 1H), 3.82 (s, 3H) ; 2.27 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.2, 144.2, 135.9, 131.0, 130.4, 128.3, 127.3, 127.0, 126.0, 113.7, 55.3, 17.5.

*1-Methoxy-4-[(1Z)-2-(4-methylphenyl)-2-phenylethenyl]benzene ((Z)-**3hd**, CAS: 780756-50-5).*[29] Colorless sticky liquid: yield 90% (270.1 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31−7.22 (m, 5H), 7.14 (d, J = 8.0 Hz, 2H), 7.09 (d, J = 8.0 Hz, 2H), 6.98 (d, J = 8.8 Hz, 2H), 6.87 (s, 1H), 6.67 (d, J = 8.8 Hz, 2H), 3.74 (s, 3H), 2.38 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.4, 143.9, 140.7, 137.6, 136.9, 130.8, 130.4, 130.3, 129.5, 128.2, 127.5, 127.2, 113.4, 55.2, 21.4; HRMS (EI) calcd for $C_{22}H_{20}O$ ([M]$^+$) 300.1514, found 300.1515.

*(Z)-1-Fluoro-4-(2-(4-methoxyphenyl)-1-phenylvinyl)benzene ((Z)-**3he**, CAS: 1619921−71−9).*[30] White solid: yield 93% (282.8 mg); mp 77.3−78.1 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.28−7.24 (m, 5H), 7.18−7.15 (m, 2H), 7.03−6.98 (m, 2H), 6.94 (d, J = 8.8 Hz, 2H), 6.90 (s, 1H), 6.68 (d, J = 8.8 Hz, 2H), 3.73 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.2 (d, $^1J_{CF}$ = 244.9 Hz), 158.6, 143.5, 139.6, 136.6 (d, $^4J_{CF}$ = 3.4 Hz), 132.2 (d, $^3J_{CF}$ = 7.9 Hz), 130.9, 130.0, 128.3, 128.1, 127.5, 127.4, 115.8 (d, $^2J_{CF}$ = 21.1 Hz), 113.6, 55.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ −114.6 to −114.7 (m, 1F); HRMS (EI) calcd for $C_{21}H_{17}FO$ ([M]$^+$) 304.1263, found 304.1262.

*1-(2-Phenyl-1-propenyl)-(E)-naphthalene ((E)-**3ia**, CAS: 131061−06−8).*[31] Colorless oil: yield 91% (222.2 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.02−8.00 (m, 1H), 7.85−7.83 (m, 1H), 7.76 (d, J = 8.4 Hz, 1H), 7.63−7.61 (m, 2H), 7.48−7.43 (m, 3H), 7.41−7.37 (m, 3H), 7.32−7.27 (m, 2H), 2.11 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 143.3, 139.0, 135.8, 133.8, 132.3, 128.6, 127.5, 127.4, 126.8, 126.1, 126.0, 125.9, 125.6, 125.5, 125.3, 17.6.

*1-(2,2-Diphenylethenyl)naphthalene (**3ib**, CAS: 22837−11−2).*[17] White solid: yield 84% (257.2 mg); mp 80.9−81.6 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15−8.13 (m, 1H), 7.82−7.79 (m, 1H), 7.63 (d, J = 8.0 Hz, 1H), 7.48−7.41 (m, 5H), 7.37−7.32 (m, 3H), 7.17−7.03 (m, 7H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.8, 143.5, 140.3, 135.3, 133.5, 132.6, 130.7, 128.5, 128.3, 128.2, 128.0, 127.7, 127.2, 126.4, 126.0, 125.8, 125.3, 124.7.

*(Z)-1-(2-Phenyl-2-(p-tolyl)vinyl)naphthalene ((Z)-**3id**).* White solid: yield 96% (307.4 mg); mp 135.9−136.1 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15−8.13 (m, 1H), 7.82−7.79 (m, 1H), 7.63 (d, J = 8.0 Hz, 1H), 7.47−7.40 (m, 5H), 7.36−7.30 (m, 3H), 7.20−7.14 (m, 1H), 7.07 (d, J = 6.8 Hz, 1H), 6.97−6.92 (m, 4H), 2.25 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.8, 143.8, 137.2, 136.8, 135.5, 133.6, 132.6, 130.6, 128.8, 128.5, 128.3, 127.7, 127.6, 127.1, 126.0, 125.9, 125.8, 125.4, 124.8, 21.3; HRMS (EI) calcd for $C_{25}H_{20}$ ([M]$^+$) 320.1565, found 320.1566.

*(Z)-1-(2-(4-Fluorophenyl)-2-phenylvinyl)naphthalene ((Z)-**3ie**).* White solid: yield 90% (291.7 mg); mp 83.4−84.2 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.08−8.05 (m, 1H), 7.79−7.76 (m, 1H), 7.61 (d, J = 8.4 Hz, 1H), 7.44−7.36 (m, 5H), 7.33−7.28 (m, 3H), 7.15−7.11 (m, 1H), 7.02−6.99 (m, 3H), 6.79−6.74 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.1 (d, $^1J_{CF}$ = 245.1 Hz), 143.9, 143.4, 136.3 (d, $^4J_{CF}$ = 3.4 Hz), 135.2, 133.7, 132.6, 132.5 (d, $^3J_{CF}$ = 7.8 Hz), 128.7,

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128.5, 128.3, 128.0, 127.8, 127.5, 126.8, 126.2, 126.0, 125.5, 124.8, 115.2 (d, $^2J_{CF}$ = 21.2 Hz); ^{19}F NMR (376 MHz, $CDCl_3$) δ −114.8 to −114.9 (m, 1F); HRMS (EI) calcd for $C_{24}H_{17}F$ ([M]$^+$) 324.1314, found 324.1315.

*(4-(4-Methoxyphenyl)-2-methylbut-1-en-3-yne-1,1-diyl)-dibenzene (**3ja**).* Yellow solid: yield 90% (291.7 mg); mp 86.3−87.8 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48−7.46 (m, 2H), 7.35−7.17 (m, 10H), 6.80−6.77 (m, 2H), 3.77 (s, 3H), 2.05 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 159.4, 146.8, 142.4, 141.5, 132.8, 130.1, 130.0, 128.1, 127.5, 127.2, 127.1, 116.4, 116.0, 114.0, 92.3, 91.3, 55.3, 22.0; HRMS (EI) calcd for $C_{24}H_{20}O$ ([M]$^+$) 324.1514, found 324.1516.

*1,1′,1″,1‴-(1-Buten-3-yne-2,4-diyl-1-ylidene)tetrakisbenzene (**3kb**, CAS: 21979−82−8).*[32] White solid: yield 94% (334.8 mg); mp 131.8−132.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58−7.55 (m, 2H), 7.38−7.30 (m, 5H), 7.22−7.10 (m, 11H), 7.02−7.00 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 149.0, 142.8, 141.4, 139.7, 131.4, 131.2, 130.6, 130.0, 128.2, 128.0, 127.9, 127.8, 127.7, 127.3, 127.1, 123.7, 121.6, 93.0, 92.5.

*(4-Cyclopropyl-2-(p-tolyl)but-1-en-3-yne-1,1-diyl)dibenzene (**3ld**).* White solid: yield 82% (274.0 mg); mp 92.5−93.2 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45−7.43 (m, 2H), 7.28−7.20 (m, 3H), 7.13 (d, J = 8.0 Hz, 2H), 7.06−7.04 (m, 3H), 6.95−6.93 (m, 2H), 6.91 (d, J = 8.0 Hz, 2H), 2.22 (s, 3H), 1.26−1.20 (m, 1H), 0.68−0.63 (m, 2H), 0.54−0.50 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 146.1, 142.5, 141.2, 136.5, 135.8, 130.4, 129.6, 129.1, 127.8, 127.1, 126.8, 126.7, 126.2, 121.2, 96.8, 77.6, 20.5, 7.8, 0; HRMS (EI) calcd for $C_{26}H_{22}$ ([M]$^+$) 334.1722, found 334.1721.

*Non-1-en-3-yne-1,1,2-triyltribenzene (**3mb**).* White solid: yield 87% (304.7 mg); mp 54.6−55.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50−7.47 (m, 2H), 7.29−7.24 (m, 5H), 7.13−7.04 (m, 6H), 6.97−6.93 (m, 2H), 2.23 (t, J = 7.0 Hz, 2H), 1.44−1.36 (m, 2H), 1.26−1.19 (m, 4H), 0.85 (t, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 147.4, 143.1, 141.8, 140.5, 131.2, 130.4, 130.0, 127.8, 127.7, 127.6, 127.0, 126.9, 122.1, 94.8, 83.1, 31.1, 28.2, 22.3, 19.8, 14.1; HRMS (EI) calcd for $C_{27}H_{26}$ ([M]$^+$) 350.2035, found 350.2032.

*1-[(1E)-2-Phenyl-1-hexen-1-yl]naphthalene ((E)-**3if**, CAS: 1469445−07−5).*[33] Colorless oil: yield 62% (177.4 mg); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.02−8.01 (m, 1H), 7.84−7.82 (m, 1H), 7.76 (d, J = 8.0 Hz, 1H), 7.57−7.55 (m, 2H), 7.47−7.36 (m, 6H), 7.32−7.28 (m, 1H), 7.09 (s, 1H), 2.56 (t, J = 7.6 Hz, 2H), 1.38−1.27 (m, 2H), 1.19−1.12 (m, 2H), 0.71−0.68 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.8, 142.7, 136.0, 133.7, 132.5, 128.6, 128.5, 127.4, 127.3, 126.9, 126.2, 126.0, 125.5, 125.4, 31.0, 30.3, 22.7, 13.9.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

^{1}H and ^{13}C NMR spectra of compounds **3aa**−**aj**, **3ba**, **3bb**, **3bf**−**bh**, **3ca**−**cc**, **3cg**, **3dd**−**df**, **3ef**, **3eg**, **3ff**, **3ga**, **3gc**, **3gd**, (*E*)-**3ha**, (*Z*)-**3hd**, (*Z*)-**3he**, (*E*)-**3ia**, **3ib**, (*Z*)-**3id**, (*Z*)-**3ie**, **3ja**, **3kb**, **3ld**, **3mb**, and (*E*)-**3if**, ^{19}F NMR spectra of compounds **3ae**, **3de**, (*Z*)-**3he**, and (*Z*)-**3ie**, and HRMS (EI) spectra of compounds **3ba**, **3ca**, **3bb**, **3cc**, **3de**, **3bf**, **3df**−**ff**, **3ag**−**cg**, **3eg**, **3bh**, **3ai**, **3aj**, (*Z*)-**3hd**, (*Z*)-**3he**, (*Z*)-**3id**, (*Z*)-**3ie**, **3ja**, **3ld**, and **3mb**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) (a) Tamao, K.; Sumitani, K.; Kumada, M. *J. Am. Chem. Soc.* **1972**, *94*, 4374. (b) Corriu, R. J. P.; Masse, J. P. *Chem. Commun.* **1972**, 144. (c) Adrio, J.; Carretero, J. C. *ChemCatChem* **2010**, *2*, 1384. (d) Smith, R. S.; Kochi, J. K. *J. Org. Chem.* **1976**, *41*, 502. (e) Chelucci, G. *Chem. Rev.* **2012**, *112*, 1344.

(2) (a) Kambe, N.; Iwasaki, T.; Terao, J. *Chem. Soc. Rev.* **2011**, *40*, 4937. (b) Wang, Z.-X.; Liu, N. *Eur. J. Inorg. Chem.* **2012**, 901. (c) Guisán-Ceinos, M.; Soler-Yanes, R.; Collado-Sanz, D.; Phapale, V. B.; Buñuel, E.; Cárdenas, D. J. *Chem.—Eur. J.* **2013**, *19*, 8405. (d) Breitenfeld, J.; Ruiz, J.; Wodrich, M. D.; Hu, X. *J. Am. Chem. Soc.* **2013**, *135*, 12004. (e) Zhang, X.-Q.; Wang, Z.-X. *Synlett* **2013**, 2081. (f) Liu, N.; Wang, Z.-X. *J. Org. Chem.* **2011**, *76*, 10031. (g) Ackermann, L.; Potukuchi, H. K.; Kapdi, A. R.; Schulzke, C. *Chem.—Eur. J.* **2010**, *16*, 3300. (h) Türkmen, H.; Kani, İ. *Appl. Organometal. Chem.* **2013**, *27*, 489. (i) Krasovskiy, A. L.; Haley, S.; Voigtritter, K.; Lipshutz, B. H. *Org. Lett.* **2014**, *16*, 4066.

(3) (a) Amii, H.; Uneyama, K. *Chem. Rev.* **2009**, *109*, 2119. (b) Sun, A. D.; Love, J. A. *Dalton Trans.* **2010**, *39*, 10362. (c) Jin, Z.; Li, Y.-J.; Ma, Y.-Q.; Qiu, L.-L.; Fang, J.-X. *Chem.—Eur. J.* **2012**, *18*, 446. (d) Soulé, J.; Miyamura, H.; Kobayashi, S. *J. Am. Chem. Soc.* **2013**, *135*, 10602. (e) Guo, W.-J.; Wang, Z.-X. *J. Org. Chem.* **2013**, *78*, 1054. (f) Mitsudo, K.; Doi, Y.; Sakamoto, S.; Murakami, H.; Mandai, H.; Suga, S. *Chem. Lett.* **2011**, *40*, 936. (g) Terao, J.; Ikumi, A.; Kuniyasu, H.; Kambe, N. *J. Am. Chem. Soc.* **2003**, *125*, 5646. (h) Sun, A. D.; Leung, K.; Restivo, A. D.; LaBerge, N. A.; Takasaki, H.; Love, J. A. *Chem.—Eur. J.* **2014**, *20*, 3162. (i) Lu, F.-G.; Sun, H.-J.; Du, A.-Q.; Feng, L.; Li, X.-Y. *Org. Lett.* **2014**, *16*, 772. (j) Page, M. J.; Lu, W. Y.; Poulten, R. C.; Carter, E.; Algarra, A. G.; Kariuki, B. M.; Macgregor, S. A.; Mahon, M. F.; Cavell, K. J.; Murphy, D. M.; Whittlesey, M. K. *Chem.—Eur. J.* **2013**, *19*, 2158.

(4) (a) Qiu, J.; Gyorokos, A.; Tarasow, T. M.; Guiles, J. *J. Org. Chem.* **2008**, *73*, 9775. (b) Saeki, T.; Takashima, Y.; Tamao, K. *Synlett* **2005**, 1771. (c) Hajduch, J.; Paleta, O. *J. Fluorine Chem.* **2011**, *132*, 143. (d) Okuhara, K. *J. Org. Chem.* **1976**, *41*, 1487. (e) Mujkic, M.; Lentz, D. *Dalton Trans.* **2012**, *41*, 839. (f) Ohashi, M.; Kambara, T.; Hatanaka, T.; Saijo, H.; Doi, R.; Ogoshi, S. *J. Am. Chem. Soc.* **2011**, *133*, 3256.

(5) (a) Dmowski, W. *J. Fluorine Chem.* **1981**, *18*, 25. (b) Tarrant, P.; Warner, D. A. *J. Am. Chem. Soc.* **1954**, *76*, 1624.

(6) (a) Yamada, S.; Takahashi, T.; Konno, T.; Ishihara, T. *Chem. Commun.* **2007**, 3679. (b) Yamada, S.; Shimoji, K.; Takahashi, T.; Konno, T.; Ishihara, T. *Chem.—Asian J.* **2010**, *5*, 1846. (c) Yamada, S.; Takahashi, T.; Konno, T.; Ishihara, T. *J. Fluorine Chem.* **2013**, *149*, 95. (d) Yamada, S.; Noma, M.; Konno, T.; Ishihara, T.; Yamanaka, H. *Org. Lett.* **2006**, *8*, 843. (e) Yamada, S.; Noma, M.; Hondo, K.; Konno, T.; Ishihara, T. *J. Org. Chem.* **2008**, *73*, 522.

(7) Nagai, T.; Shibanuma, T.; Ogoshi, S.; Ohashi, M. WO Patent 2,011,108,668, 2011.

(8) (a) Xiong, Y.; Wu, J.-J.; Xiao, S.-H.; Xiao, J.; Cao, S. *J. Org. Chem.* **2013**, *78*, 4599. (b) Jin, G.-Y.; Zhang, X.-X.; Cao, S. *Org. Lett.* **2013**, *15*, 3114. (c) Xiao, S.-H.; Xiong, Y.; Zhang, X.-X.; Cao, S. *Tetrahedron* **2014**, *70*, 4405. (d) Xiong, Y.; Zhang, X.-X.; Huang, T.; Cao, S. *J. Org. Chem.* **2014**, *79*, 6395.

(9) (a) Heravi, M. M.; Hajiabbasi, P. *Monatsh. Chem.* **2012**, *143*, 1575. (b) Terao, J.; Naitoh, Y.; Kuniyasu, H.; Kambe, N. *Chem. Commun.* **2007**, 825.

(10) (a) Knappke, C. E. I.; Wangelin, A. J. *Chem. Soc. Rev.* **2011**, *40*, 4948. (b) Murahashi, S.; Yamamura, M.; Yanagisawa, K.; Mita, N.; Kondo, K. *J. Org. Chem.* **1979**, *44*, 2408.

(11) (a) Okamoto, Y.; Yoshikawa, Y.; Hayashi, T. *J. Organomet. Chem.* **1989**, *359*, 143. (b) Santos, M. D.; Franck, X.; Hocquemiller, R.; Figadère, B.; Peyrat, J.; Provot, O.; Brion, J.; Alami, M. *Synlett* **2004**, 2697.

(12) Hayashi, T.; Konishi, M.; Kobori, Y.; Kumada, M.; Higuchi, T.; Hirotsu, K. *J. Am. Chem. Soc.* **1984**, *106*, 158.

(13) Tamao, K.; Kiso, Y.; Sumitani, K.; Kumada, M. *J. Am. Chem. Soc.* **1972**, *94*, 9268.
(14) Frisch, A. C.; Beller, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 674.
(15) Zhang, W.; Huang, W.-Z.; Hu, J.-B. *Angew. Chem., Int. Ed.* **2009**, *48*, 9858.
(16) Konno, T.; Kishi, M.; Ishihara, T.; Yamada, S. *J. Fluorine Chem.* **2013**, *156*, 144.
(17) Shimasaki, T.; Konno, Y.; Tobisu, M.; Chatani, N. *Org. Lett.* **2009**, *11*, 4890.
(18) Pedersen, C. T. *Acta Chem. Scand.* **1968**, *22*, 247.
(19) (a) Kitamura, T.; Kabashima, T.; Nakamura, I.; Fukuda, T.; Taniguchi, H. *J. Am. Chem. Soc.* **1991**, *113*, 7255. (b) Kitamura, T.; Kabashima, T.; Taniguchi, H. *J. Org. Chem.* **1991**, *56*, 3739.
(20) Rajadhyaksha, V. J.; Peck, J. V. O.; Chouw, J. J. DE Patent 2,603,541, 1976.
(21) Bolliger, J. L.; Frech, C. M. *Chimia* **2009**, *63*, 23.
(22) Funasaka, W.; Ando, T.; Kondo, K.; Kodama, S. *Yuki Gosei Kagaku Kyokaishi* **1959**, *17*, 717.
(23) Shirakawa, E.; Ikeda, D.; Masui, S.; Yoshida, M.; Hayashi, T. *J. Am. Chem. Soc.* **2012**, *134*, 272.
(24) Tiffeneau, M.; Levy, J.; Weill, P. *Bull. Soc. Chim. Fr.* **1931**, *49*, 1709.
(25) López, J. G.; Ramallal, A. M.; González, J.; Roces, L.; García-Granda, S.; Iglesias, M. J.; Oña-Burgos, P.; Ortiz, F. L. *J. Am. Chem. Soc.* **2012**, *134*, 19504.
(26) Kostikov, R. R.; Drygailova, E. A.; Morzhakova, T. M.; Ogloblin, K. A. *Vestnik Leningradskogo Universiteta, Seriya 4: Fizika, Khimiya*; 1978; *3*, 114.
(27) Banerjee, M.; Emond, S. J.; Lindeman, S. V.; Rathore, R. *J. Org. Chem.* **2007**, *72*, 8054.
(28) Zhu, G.-G.; Kong, W.; Feng, H.; Qian, Z.-S. *J. Org. Chem.* **2014**, *79*, 1786.
(29) Itami, K.; Mineno, M.; Muraoka, N.; Yoshida, J. *J. Am. Chem. Soc.* **2004**, *126*, 11778.
(30) Cahiez, G.; Moyeux, A.; Poizat, M. *Chem. Commun.* **2014**, *50*, 8982.
(31) Miura, M.; Hashimoto, H.; Itoh, K.; Nomura, M. *J. Chem. Soc., Perkin Trans. 1* **1990**, *8*, 2207.
(32) Sakai, N.; Komatsu, R.; Uchida, N.; Ikeda, R.; Konakahara, T. *Org. Lett.* **2010**, *12*, 1300.
(33) Xue, F.; Zhao, J.; Hor, T. S. A. *Chem. Commun.* **2013**, *49*, 10121.