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Metal-Free Catalyzed Regioselective Allylic Trifluoromethanesulfonylation of Aromatic Allylic Alcohols with Sodium Trifluoromethanesulfinate

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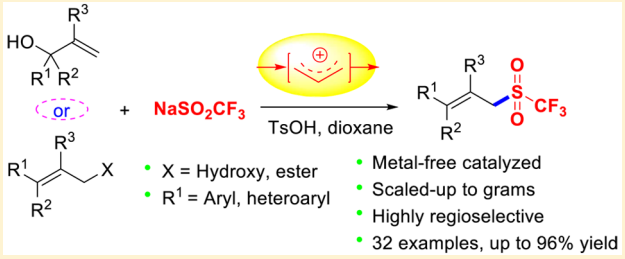
Supporting Information

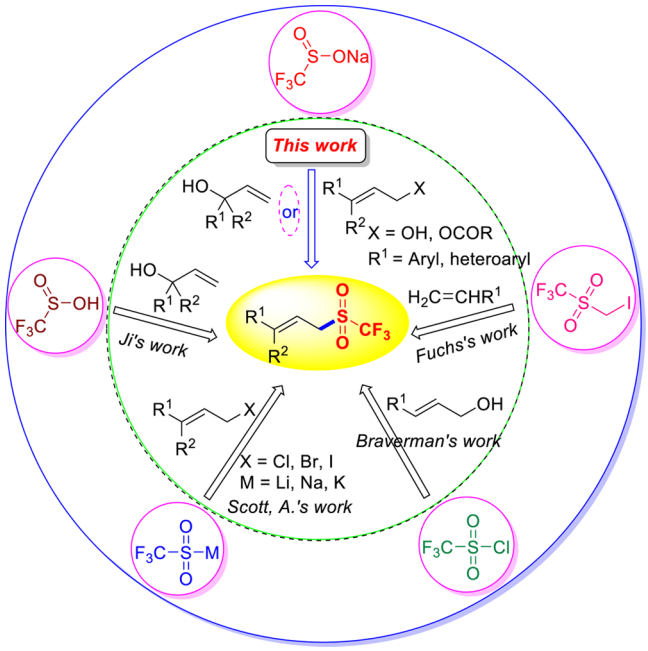
ABSTRACT: An efficient procedure for the preparation of allylic trifluoromethanesulfones with high regioselectivity from aromatic allylic alcohols/esters and $NaSO_2CF_3$ under transition-metal-free conditions is described. A wide range of functional groups were tolerated. This is the first example to realize different types of allylic alcohols, including primary, secondary, and tertiary allylic alcohols, all of which transferred to the corresponding products efficiently in good to excellent yields with readily available and inexpensive $NaSO_2CF_3$. The synthetic utility of the method was demonstrated by performing the reaction at gram scale.



The incorporation of fluorine-containing groups into organic molecules has received increasing attention in the pharmaceutical and agrochemical industries, since fluorine-containing organic molecules exhibit unique chemical, physical, and biological properties.[1] To date, the trifluoromethanesulfonyl (triflyl) group is an intensely studied fluorine-containing group for its strong electron-withdrawing power and high lipophilicity.[2] Consequently, due to their potential applications in chemistry, pharmacy, and biology, allylic trifluoromethanesulfonylated compounds have become a vibrant research area in synthetic organic chemistry.[3] However, few successful approaches have been developed over the past decades,[4−7] such as the reactions of isoprenoid perfluoroalkyl sulfones and alkyllidenemalonates,[4] radical-mediated atom-transfer addition from iodomethyl trifluoromethanesulfone (triflone) and alkynes,[5] rearrangement of cinnamyl triflinate synthesized from allylic alcohol with trifluoromethane sulfonyl chloride,[6] and substitution of a diaryl-type tertiary allylic alcohol with trifluoromethyl sulfinic acid[7] (Scheme 1). Despite these important advances, the traditional approaches to allylic triflones are limited in scope due to the limited availability of triflone reagents, prefunctionalization, harsh reaction conditions, formation of the isomeric products, low yields, and narrow substrate scope. Therefore, many attempts can still be anticipated by the creation of a new and efficient strategy capable of overcoming these limitations in current processes.

Allylic functionalization has long been intensely studied for its diversity of bond-forming types and extensive applications in chemical synthesis.[8] For most of the earlier history of allylic functionalization reactions, activated precursors of π-allyl fragments, such as allylic esters and carbonates derived from allylic alcohols and acetic acid, have predominantly been employed to accept the nucleophilic attack of nucleophiles.[9] In this respect, stoichiometric amounts of alcohols and organic waste inevitably are produced. Recently, transition-metal-

Scheme 1. Reported Methods for the Synthesis of Allylic Triflones



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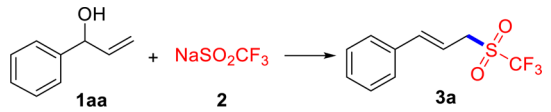
catalyzed allylic functionalization has become an attractive synthetic method via the formation of cationic η^3-allyl intermediates.[10−14] The direct use of allylic alcohols as allylating reagents would be highly active for their synthetic reliability and step economy. While significant progress in the catalysis of allylic sulfonylation with sodium arenesulfinates has been made in recent years,[15] the use of allylic alcohols as allylating reagents for the synthetic incorporation of the trifluoromethanesulfonyl moiety is still an imposing challenge for chemists.

It was noteworthy that $NaSO_2CF_3$ was developed by Langlois as a trifluoromethylating reagent at the beginning.[16] Notably, various examples of the use of $NaSO_2CF_3$ as a triflyl source have also been reported.[17] Given the increasing prevalence of triflones in medicinally relevant compounds,[18] the significant challenges in introducing the triflyl group by using the readily available and inexpensive $NaSO_2CF_3$ as a nucleophile will be of synthetic value. However, the coupling partners with $NaSO_2CF_3$ usually occur with strongly electron-withdrawing electrophilic reagents, such as diaryliodonium salts[17a] and arenediazonium tetrafluoroborates,[17b] owing to the poor nucleophilicity of $NaSO_2CF_3$. Thus, we envisioned that the allylic triflones could be prepared from the coupling reactions between allylic alcohols and $NaSO_2CF_3$, proceeding via cationic π-allyl intermediates generated by Lewis or Brønsted acid catalysis.[10d,19] As we have continuing interest in sodium sulfinates and based on our previous work with allylic alcohols,[20] we herein report a concise and efficient metal-free catalyzed method for coupling of allylic alcohols/esters using $NaSO_2CF_3$ as a trifluoromethanesulfonylation (triflylation) source to generate allylic triflones with high regioselectivity via nucleophilic substitution. To the best of our knowledge, it is the first example to realize different types of allylic alcohols, including primary, secondary, and tertiary allylic alcohols, all of which were transferred to the corresponding products efficiently in good to excellent yields.

We initiated our investigations using vinylbenzyl alcohol (**1aa**) with $NaSO_2CF_3$ (**2**) as the substrates. Performing the reaction using 2 equiv of trifluoromethanesulfonic acid (TfOH) in dioxane was expected to generate (*E*)-(3-((trifluoromethyl) sulfonyl)prop-1-en-1-yl)benzene (**3a**) in good yield (Table 1, entry 1). Disappointingly, the desired product **3a** was not obtained with recovery of starting material. To improve the yield of **3a**, various Brønsted acids were screened. To our delight, the use of the *p*-toluenesulfonic acid (TsOH) gave an excellent yield of **3a** (88%) (Table 1, entry 2). Other Brønsted acids were studied and found to be inferior in terms of product yields (Table 1, entries 3−7). Lewis acidic catalysts previously reported to activate the hydroxyl group of alcohols in nucleophilic substitution reaction were also evaluated,[16] and the results were unsatisfactory (Table 1, entries 8−11). Solvent studies revealed that the use of dioxane as solvent provided the best result (Table 1, entries 12−17). Additionally, the reaction temperatures, reactions time, and the amount of additive were also screened (Table 1, entries 18−27). At lower temperatures and with a shorter reaction time, significantly lower yields were observed, while decreasing the amount of TsOH resulted in the yields decreasing accordingly. We also investigated the effect of concentration on the reaction. A higher concentration is not beneficial to the solubility of the materials, although no further decrease in yields was observed below 0.08 M.

Having established the optimal reaction conditions (Table 1, entry 2), the scope of various allylic alcohols was investigated

Table 1. Optimization of the Reaction Conditions[a]



1aa 2 3a

entry	additive	solvent	*T* (°C)	time (h)	yield[b] (%)
1	TfOH	dioxane	100	20	n.d.
2	**TsOH**	**dioxane**	**100**	**20**	**88**
3	HBF_4	dioxane	100	20	72
4	HOAc	dioxane	100	20	68
5	TFA	dioxane	100	20	75
6	HCl	dioxane	100	20	65
7	H_2SO_4	dioxane	100	20	67
8	$PdCl_2$	dioxane	100	20	15
9	$CuCl_2$	dioxane	100	20	65
10	$ZnCl_2$	dioxane	100	20	25
11	$FeCl_3$	dioxane	100	20	51
12	TsOH	DMSO	100	20	trace
13	TsOH	DMF	100	20	trace
14	TsOH	toluene	100	20	46
15[c]	TsOH	CH_3CN	100	20	n.d.
16[c]	TsOH	THF	100	20	n.d.
17[c]	TsOH	DCE	100	20	21
18	TsOH	dioxane	110	20	86
19	TsOH	dioxane	80	20	75
20	TsOH	dioxane	50	20	<5
21	TsOH	dioxane	rt	20	n.d.
22	TsOH	dioxane	100	12	55
23	TsOH	dioxane	100	6	30
24	TsOH (1.5 equiv)	dioxane	100	20	83
25	TsOH (1.0 equiv)	dioxane	100	20	80
26	TsOH (0.5 equiv)	dioxane	100	20	68
27	TsOH (0.2 equiv)	dioxane	100	20	30

[a]Reaction conditions: unless otherwise noted, all reactions were performed with **1aa** (0.25 mmol), **2** (0.75 mmol), additive (0.5 mmol), solvent (3 mL), 100 °C, 20 h. [b]Isolated yields based on **1aa**. [c]At 65 °C.

(Table 2). A series of *para*-substituted phenyl rings with electron-donating (**1aa**−**1ac**) and electron-withdrawing (**1ad**−**1af**) groups generated products **3a**−**3f** in good to excellent yields. The presence of both a strongly electron-donating methoxy group and an electron-withdrawing trifluoromethyl group were also tolerated in moderate yields (Table 2, **3g**, **h**). Meanwhile, the substrates with a substituted phenyl ring were converted to the desired products in good yields (Table 2, **3i**−**k**). Notably, the heteroaryl substituents, such as furan and thiophene, were also compatible with the transformation, and the corresponding products could be afforded in moderate yields (Table 2, **3l**, **m**). 1-(Naphthalen-2-yl)prop-2-en-1-ol (**1an**) proceeded smoothly to give the desired product **3n** in an excellent yield of 92%. To our delight, the steric effect of substituents seemed to have no influence on the reaction, and the corresponding allylic triflones were generated in good yields (Table 2, **3o**, **p**).

To expand the substrate scope of the transformation, nonterminal allylic alcohols were screened (Table 3). In general, the phenyl substituted cinnamyl alcohols with both electron-donating and -withdrawing groups in the *para*- and *meta*-positions reacted efficiently to afford the corresponding allylic triflones in good to excellent yields (Table 3, entries 1−5). Heteroaryl substrates were also compatible under the

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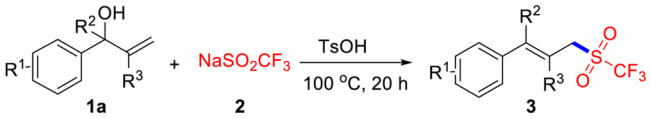
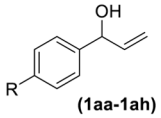
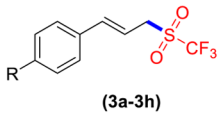
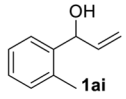
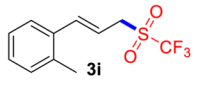
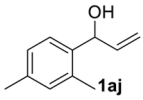
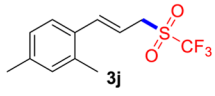
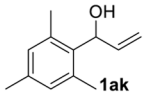
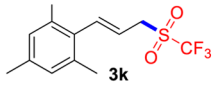
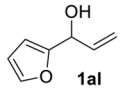
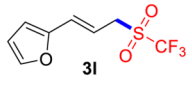
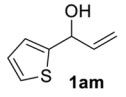
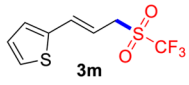
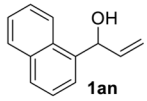
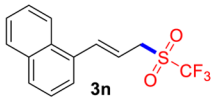
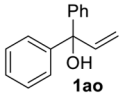
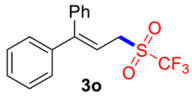
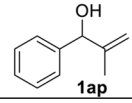
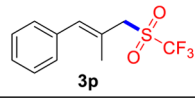
Table 2. Scope of Allyl Alcohols[a,b]



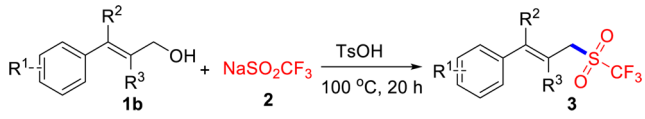
entry [a]	allylic alcohol	product	yield (%) [b]
1	 (1aa-1ah)	 (3a-3h)	**3a**, R = H 88
2			**3b**, R = CH_3 85
3			**3c**, R = $CH(CH_3)_3$ 85
4			**3d**, R = F 80
5			**3e**, R = Cl 84
6			**3f**, R = Br 88
7			**3g**, R = OCH_3 58
8			**3h**, R = CF_3 40
9	 1ai	 3i	82
10	 1aj	 3j	81
11	 1ak	 3k	86
12	 1al	 3l	51
13	 1am	 3m	68
14	 1an	 3n	92
15	 1ao	 3o	72
16	 1ap	 3p	83

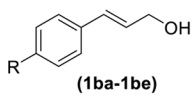
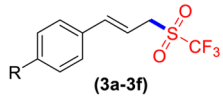
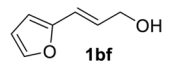
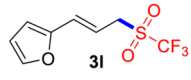
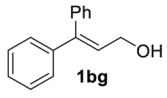
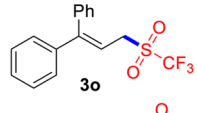
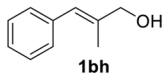
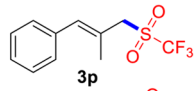
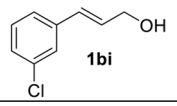
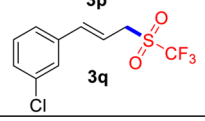
[a]Reaction conditions: **1a** (0.25 mmol), **2** (0.75 mmol), TsOH (0.5 mmol), dioxane (3 mL), 100 °C, 20 h. [b]Isolated yields based on **1a**.

standard reaction conditions (Table 3, entry 6). Additionally, the R^2, and R^3 substituted cinnamyl alcohols also worked well to finish the C−S bond transformation (Table 3, entries 7, 8).

To further demonstrate the generality of this protocol, we explored the scope of allylic esters for allylic triflone synthesis (Table 4). Delightfully, a wide range of cinnamyl esters could be converted into the corresponding product **3a** in moderate to good yields, such as cinnamyl alkyl esters, cinnamyl-2-aminobenzoate, and cinnamyl cinnamate compounds (Table 4, entries 1−7). On the basis of the our results and previous reports,[12,16] we propose that the current reaction proceeds through an S_N1-type pathway by the formation of cationic π-allyl intermediates with strongly electrophilic properties. The direct substitution of the hydroxyl group of alcohols would be activated by *p*-toluenesulfonic acid. Thus, the reaction of allylic alcohols/esters coupled with $NaSO_2CF_3$ could be realized smoothly.

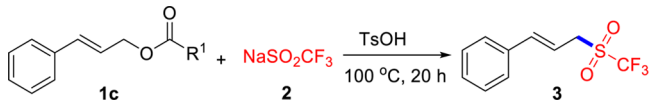
Table 3. Scope of Cinnamyl Alcohols[a,b]

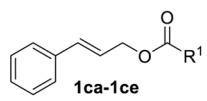
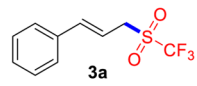
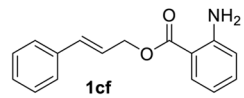
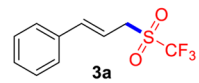
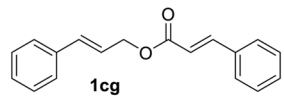
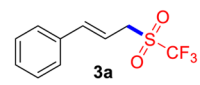


entry [a]	cinnamyl alcohol	product	yield (%) [b]
1	 (1ba-1be)	 (3a-3f)	**3a**, R = H 96
2			**3b**, R = CH_3 90
3			**3d**, R = F 89
4			**3e**, R = Cl 87
5			**3g**, R = OCH_3 80
6	 1bf	 3l	49
7	 1bg	 3o	76
8	 1bh	 3p	95
9	 1bi	 3q	70

[a]Reaction conditions: **1b** (0.25 mmol), **2** (0.75 mmol), TsOH (0.5 mmol), dioxane (3 mL), 100 °C, 20 h. [b]Isolated yields based on **1b**.

Table 4. Scope of Cinnamyl Esters[a,b]



entry [a]	cinnamyl ester	product	yield (%) [b]
1	 1ca-1ce	 3a	R = H, 90
2			R = CH_3, 89
3			R = CH_2CH_3, 79
4			R = $CH(CH_3)_2$ 61
5			R = $CH_2CH_2CH_3$ 70
6	 1cf	 3a	45
7	 1cg	 3a	65

[a]Reaction conditions: **1c** (0.25 mmol), **2** (0.75 mmol), TsOH (0.5 mmol), dioxane (3 mL), 100 °C, 20 h. [b]Isolated yields based on **1c**.

As a demonstration of the scalability of this transformation, the allylic triflylation of cinnamyl alcohol (**1ba**) with $NaSO_2CF_3$ was performed at the gram scale (Scheme 2). Analytically pure **3a** was isolated in 81% yield (1.620 g) through a pad of silica gel.

In summary, a convenient and highly efficient method for direct allylic triflylation with excellent regioselectivity from the reaction of allylic alcohols/esters with $NaSO_2CF_3$ has been developed. Both electron-rich and -poor substituted allylic alcohols provided the coupled products in good yields. The synthetic utility of the method was demonstrated by performing the reaction on a gram scale. Such a new and

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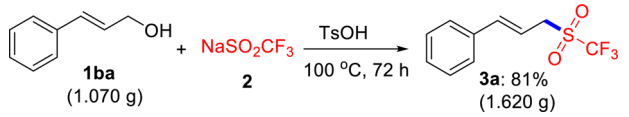
Scheme 2. Gram-Scale Allylic Triflylation of Cinnamyl Alcohol



straightforward protocol, which utilizes the commercially ready and inexpensive $NaSO_2CF_3$ reagent as a triflyl source, would extend the potential application of allylic triflones in pharmaceutical and synthetic chemistry.

EXPERIMENTAL SECTION

General Information. Melting points were measured with a melting point instrument and were uncorrected. ^{1}H and ^{13}C NMR spectra were recorded using a 400 MHz NMR spectrometer. The chemical shifts are referenced to signals at 7.26 and 77.0 ppm, respectively, with $CDCl_3$ as the solvent and TMS as the internal standard. IR spectra were obtained either as potassium bromide pellets or as liquid films between two potassium bromide pellets with a spectrometer. GC-MS was obtained using electron ionization. HRMS was obtained with an LCMS-IT-TOF mass spectrometer or recorded on an EI-ion trap High Resolution mass spectrometer. TLC was performed by using commercially prepared 100−400 mesh silica gel plates, and visualization was effected at 254 nm. Starting materials of terminal allylic alcohols were prepared according to previously reported methods.[1] Nonterminal allylic alcohols were synthesized from reduction of commercial available cinnamyl aldehydes by $NaBH_4$. $NaSO_2CF_3$, cinnamyl esters, vinylbenzyl alcohol, 1-phenylprop-2-en-1-ol, 2-methyl-1-phenylprop-2-en-1-ol, (*E*)-3-phenylprop-2-en-1-ol, and (*E*)-2-methyl-3-phenylprop-2-en-1-ol were commercially available.

General Procedure for Synthesis of Cinnamyl Trifluoromethanesulfone. In a sealed test tube, a mixture of allylic alcohol (or allylic esters), **1** (0.25 mmol), $NaSO_2CF_3$ **2** (117 mg, 0.75 mmol), TsOH (86 mg, 0.5 mmol), and 3 mL of dioxane was vigorously stirred at 100 °C for 20 h. After completion of the reaction, the mixture was quenched by saturated brines and extracted with ethyl acetate (3 × 10 mL). The combined ethyl acetate layer was then dried over sodium sulfate and concentrated in vacuum. And the resulting crude product was purified by silica gel chromatography using a mixture of EtOAc−*n*-hexane (1:50) as eluent to afford the desired product.

Procedure for Gram-Scale Allylic Trifluoromethanesulfonylation of Cinnamyl Alcohol. A mixture of cinnamyl alcohol **1ba** (8 mmol), $NaSO_2CF_3$ **2** (3.744 g, 24 mmol), TsOH (2.752 g, 16 mmol), and 60 mL of dioxane were added to a 150 mL round-bottomed flask, which was connected to a condenser and sealed with a balloon, and then vigorously stirred at 100 °C for 72 h. After completion of the reaction, the mixture was extracted with ethyl acetate (3 × 50 mL). The combined ethyl acetate layer was then dried over sodium sulfate and concentrated in vacuum. After evaporation of the solvent, the crude mixture was purified by silica gel column chromatography, to afford **3a** (1.620 g, >98% purity, 81% yield).

*(E)-(3-(Ttrifluoromethyl)sulfonyl)prop-1-en-1-yl)benzene (**3a**).* Yield: 88% (55.0 mg); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41−7.33 (m, 5H), 6.80 (d, J = 15.8 Hz, 1H), 6.15−6.08 (m, 1H), 4.12 (d, J = 7.3 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.7, 135.0, 129.3, 128.9, 127.0, 119.7 (q, J = 328.5 Hz), 110.2, 54.5; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.22 ppm; ν_{max} (KBr)/cm^{-1} 3169, 3135, 3012, 1401, 1119; HRMS (ESI) m/z: calcd for $C_{10}H_9F_3NaO_2S$ [M + Na]$^+$, 273.0168; found, 273.0169.

*(E)-1-Methyl-4-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3b**).* Yield: 85% (56.1 mg); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 (d, J = 7.3 Hz, 2H), 7.16 (d, J = 7.5 Hz, 2H), 6.77 (d, J = 15.8 Hz, 1H), 6.07 (td, J = 7.5 Hz, J = 15.4 Hz, 1H), 4.11 (d, J = 7.4 Hz, 2H), 2.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.6, 139.4, 132.3, 129.5, 126.9, 123.2 (q, J = 328.3 Hz), 108.9, 54.6, 21.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.22 ppm; ν_{max} (KBr)/cm^{-1} 3478, 3415, 1434, 1366, 618; HRMS (ESI) m/z: calcd for $C_{11}H_{11}F_3NaO_2S$ [M + Na]$^+$, 287.0324; found, 287.0321.

*(E)-1-(tert-Butyl)-4-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3c**).* Yield: 85% (65.0 mg); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (q, J = 8.5 Hz, 4H), 6.78 (d, J = 15.8 Hz, 1H), 6.09 (td, J = 7.6 Hz, J = 15.5 Hz, 1H), 4.12 (d, J = 7.6 Hz, 2H), 1.32 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.6, 141.5, 132.3, 126.8, 125.8, 119.7 (q, J = 328.3 Hz), 109.3, 54.6, 34.8, 31.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.19 ppm; ν_{max} (KBr)/cm^{-1} 3201, 2964, 1402, 1368, 1209, 1195, 620; HRMS (ESI) m/z: calcd for $C_{14}H_{17}F_3NaO_2S$ [M + Na]$^+$, 329.0794; found, 329.0794.

*(E)-1-Fluoro-4-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3d**).* Yield: 80% (53.6 mg); colorless solid, mp = 48−49 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41−7.38 (m, 2H), 7.04 (t, J = 7.9 Hz, 2H), 6.78 (d, J = 15.8 Hz, 1H), 6.09−6.02 (m, 1H), 4.13 (d, J = 7.5 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.3 (d, J = 249.5 Hz), 140.5, 131.3 (d, J = 3.4 Hz), 128.7, 128.6, 119.7 (q, J = 328.6 Hz), 116.0, 115.8, 109.9 (d, J = 2.0 Hz), 54.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.33, −111.59 ppm; ν_{max} (KBr)/cm^{-1} 3169, 1401, 1120, 622; HRMS (ESI) m/z: calcd for $C_{10}H_8F_4NaO_2S$ [M + Na]$^+$, 291.0073; found, 291.0070.

*(E)-1-Chloro-4-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3e**).* Yield: 84% (59.6 mg); colorless solid, mp = 56−57 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.39−7.30 (m, 4H), 6.77 (d, J = 15.8 Hz, 1H), 6.15−6.08 (m, 1H), 4.13 (d, J = 7.3 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.4, 135.1, 133.4, 129.1, 128.2, 119.6 (q, J = 328.3 Hz), 110.9, 54.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.26 ppm; ν_{max} (KBr)/cm^{-1} 3148, 1401, 1122; HRMS (EI) m/z: calcd for $C_{10}H_8ClF_3O_2S$ [M]$^+$, 283.9886; found, 283.9881.

*(E)-1-Bromo-4-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3f**).* Yield: 88% (72.2 mg); colorless solid, mp = 75−76 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.51 (d, J = 8.3 Hz, 2H), 7.30 (d, J = 8.4 Hz, 2H), 6.78 (d, J = 15.8 Hz, 1H), 6.16 (td, J = 7.6 Hz, J = 15.5 Hz, 1H), 4.16 (d, J = 7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.5, 133.9, 132.0, 128.4, 123.3, 119.7 (q, J = 328.6 Hz), 111.1, 54.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.29 ppm; ν_{max} (KBr)/cm^{-1} 3160, 1402, 1120, 621; HRMS (ESI) m/z: calcd for $C_{10}H_8BrF_3NaO_2S$ [M + Na]$^+$, 350.9273; found, 350.9276.

*(E)-1-Methoxy-4-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3g**).* Yield: 58% (40.6 mg); colorless solid, mp = 55−56 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36 (d, J = 8.6 Hz, 2H), 6.88 (d, J = 8.6 Hz, 2H), 6.75 (d, J = 15.7 Hz, 1H), 5.98 (td, J = 7.6 Hz, J = 15.5 Hz, 1H), 4.11 (d, J = 7.6 Hz, 2H), 3.82 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 160.5, 141.3, 128.4, 127.8, 119.7 (q, J = 328.5 Hz), 114.2, 107.4, 55.4, 54.6; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.23 ppm; ν_{max} (KBr)/cm^{-1} 3134, 1604, 1119, 622; HRMS (ESI) m/z: calcd for $C_{11}H_{11}F_3NaO_3S$ [M + Na]$^+$, 303.0273; found, 303.0273.

*(E)-1-(Trifluoromethyl)-4-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)benzene (**3h**).* Yield: 43% (34.2 mg); colorless solid, mp = 84−85 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (d, J = 8.2 Hz, 2H), 7.44 (d, J = 8.1 Hz, 2H), 6.78 (d, J = 15.9 Hz, 1H), 6.17 (td, J = 7.6 Hz, J = 15.5 Hz, 1H), 4.09 (d, J = 7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.1, 138.3, 130.9 (q, J = 31.8 Hz), 127.2, 125.8, 125.8, 121.8 (q, J = 328.3 Hz), 113.2, 54.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ −62.83, −76.30 ppm; ν_{max} (KBr)/cm^{-1} 3136, 1605, 1401, 1119, 621; HRMS (EI) m/z: calcd for $C_{11}H_8F_6O_2S$ [M]$^+$, 318.0149; found, 318.0145.

*(E)-1-Methyl-2-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3i**).* Yield: 82% (54.1 mg); colorless solid, mp = 73−74 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 (d, J = 7.2 Hz, 1H), 7.25−7.16 (m, 3H), 7.04 (d, J = 15.6 Hz, 1H), 6.00 (td, J = 7.5 Hz, J = 15.3 Hz, 1H), 4.15 (d, J = 7.4 Hz, 2H), 2.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.9, 136.0, 134.3, 130.6, 129.1, 126.4, 126.2, 119.8 (q, J = 328.5 Hz), 111.7, 54.6, 19.6; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.05 ppm; ν_{max} (KBr)/cm^{-1} 3175, 3012, 1602, 1401, 1122; HRMS (ESI) m/z: calcd for $C_{11}H_{11}F_3NaO_2S$ [M + Na]$^+$, 287.0324; found, 287.0324.

*(E)-2,4-Dimethyl-1-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3j**).* Yield: 81% (56.3 mg); colorless solid, mp = 70−71 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 (d, J = 7.7 Hz, 1H), 7.02−6.99 (m, 3H), 5.96 (td, J = 7.6 Hz, J = 15.4 Hz, 1H), 4.13 (d, J = 7.5 Hz,

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2H), 2.31 (d, J = 3.1 Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.8, 139.1, 135.9, 131.5, 131.3, 127.1, 126.1, 119.8 (q, J = 328.6 Hz), 110.5, 54.8, 21.1, 19.6; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.06 ppm; ν_{max} (KBr)/cm^{-1} 3133, 1617, 1401, 1203, 1120; HRMS (ESI) m/z: calcd for $C_{12}H_{13}F_3NaO_2S$ [M + Na]$^+$, 301.0481; found, 301.0484.

*(E)-1,3,5-Trimethyl-2-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)benzene (**3k**).* Yield: 86% (62.8 mg); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.88 (s, 2H), 6.84 (d, J = 8.2 Hz, 1H), 5.72−5.64 (m, 1H), 4.15 (d, J = 7.4 Hz, 2H), 2.27 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.5, 137.6, 136.0, 131.8, 128.9, 119.8 (q, J = 328.4 Hz), 115.4, 54.7, 21.0, 20.7; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.37 ppm; ν_{max} (KBr)/cm^{-1} 3134, 1618, 1401, 1206, 1121, 625; HRMS (ESI) m/z: calcd for $C_{13}H_{15}F_3NaO_2S$ [M + Na]$^+$, 315.0637; found, 315.0639.

*(E)-2-(3-((Trifluoromethyl)sulfonyl)prop-1-en-1-yl)furan (**3l**).* Yield: 51% (30.6 mg); colorless solid, mp = 55−56 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (s, 1H), 6.60 (d, 1H, J = 15.6 Hz), 6.40 (s, 2H), 6.04 (td, 1H, J = 7.8 Hz, J = 15.6 Hz), 4.09 (d, 2H, J = 7.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 150.7, 143.5, 129.0, 119.7 (q, J = 328.5 Hz), 112.3, 111.7, 111.2, 108.1, 54.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.35 ppm; ν_{max} (KBr)/cm^{-1} 3140, 1627, 1401, 1126; HRMS (EI) m/z: calcd for $C_8H_7F_3O_3S$ [M]$^+$, 240.0069, found, 240.0064.

*(E)-2-(3-((Trifluoromethyl)sulfonyl)prop-1-en-1-yl)thiophene (**3m**).* Yield: 68% (43.5 mg); colorless solid, mp = 89−90 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30 (t, J = 4.7 Hz, 1H), 7.11 (d, J = 2.9 Hz, 1H), 7.03 (t, J = 4 Hz, 1H), 6.95 (d, J = 15.6 Hz, 1H), 5.96 (td, J = 7.6 Hz, J = 15.4 Hz, 1H), 4.12 (d, J = 7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.7, 134.4, 128.2, 127.7, 126.6, 119.7 (q, J = 328.7 Hz), 109.0, 54.3; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.32 ppm; ν_{max} (KBr)/cm^{-1} 3142, 3010, 1600, 1401, 1120, 624; HRMS (ESI) m/z: calcd for $C_8H_8F_3O_2S_2$ [M + H]$^+$, 256.9912; found, 256.9914.

*(E)-1-(3-((Trifluoromethyl)sulfonyl)prop-1-en-1-yl)naphthalene (**3n**).* Yield: 92% (69.0 mg); colorless solid, mp = 72−73 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.01 (d, J = 8.1 Hz, 1H), 7.84 (dd, J = 7.8 Hz, J = 8.8 Hz, 2H), 7.58−7.49 (m, 4H), 7.44 (t, J = 8.0 Hz, 1H), 6.14 (td, J = 7.6 Hz, J = 15.3 Hz, 1H), 4.21 (d, J = 7.6 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 139.4, 133.6, 132.8, 130.9, 129.5, 128.7, 126.7, 126.2, 125.6, 124.7, 123.3, 119.8 (q, J = 328.7 Hz), 113.5, 54.6; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.01 ppm; ν_{max} (KBr)/cm^{-1} 3134, 1599, 1401, 1206, 1120, 777, 620; HRMS (ESI) m/z: calcd for $C_{14}H_{11}F_3NaO_2S$ [M + Na]$^+$, 323.0324; found, 323.0324.

*(3-((Trifluoromethyl)sulfonyl)prop-1-ene-1,1-diyl)dibenzene (**3o**).* Yield: 72% (58.7 mg); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45−7.39 (m, 3H), 7.33−7.29 (m, 3H), 7.27−7.25 (m, 2H), 7.23−7.19 (m, 2H), 6.12 (t, J = 7.7 Hz, 1H), 4.09 (d, J = 7.7 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.7, 140.4, 137.4, 129.5, 128.8, 128.8, 128.6, 128.5, 127.7, 119.6 (q, J = 328.3 Hz) 109.0, 51.9; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.04 ppm; ν_{max} (KBr)/cm^{-1} 3178, 3107, 1600, 1399, 1122, 625; HRMS (ESI) m/z: calcd for $C_{16}H_{13}F_3NaO_2S$ [M + Na]$^+$, 349.0481; found, 349.0484.

*(E)-(2-Methyl-3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3p**).* Yield: 83% (54.8 mg); colorless solid, mp = 86−87 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.38−7.34 (m, 2H), 7.30−7.26 (m, 3H), 6.67 (s, 1H), 4.06 (s, 2H), 2.11 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 137.3, 135.9, 129.0, 128.4, 127.8, 121.7, 119.8 (q, J = 328.5 Hz), 60.8, 18.7; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.57 ppm; ν_{max} (KBr)/cm^{-1} 3465, 3171, 3126, 1401, 1349, 1195, 1122, 620; HRMS (ESI) m/z: calcd for $C_{11}H_{11}F_3NaO_2S$ [M + Na]$^+$, 287.0324; found, 287.0325.

*(E)-1-Chloro-3-(3-((trifluoromethyl)sulfonyl)prop-1-en-1-yl)-benzene (**3q**).* Yield: 70% (49.7 mg); colorless oil; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 (s, 1H), 7.31−7.27 (m, 3H), 6.76 (d, J = 15.8 Hz, 1H), 6.19−6.11 (m, 1H), 4.14 (d, J = 7.5 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 140.2, 136.8, 134.9, 130.1, 129.2, 126.9, 125.1, 119.7 (q, J = 328.1 Hz), 112.0, 54.2; ^{19}F NMR (376 MHz, $CDCl_3$) δ −76.26 ppm; ν_{max} (KBr)/cm^{-1} 3127, 1603, 1402, 1128, 625; HRMS (ESI) m/z: calcd for $C_{10}H_8ClF_3NaO_2S$ [M + Na]$^+$, 306.9778; found, 306.9775.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b02674.

^{1}H and ^{13}C NMR spectra for all compounds prepared (PDF)

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) (a) Yuan, Z.; Wang, H. Y.; Mu, X.; Chen, P.; Guo, Y. L.; Liu, G. *J. Am. Chem. Soc.* **2015**, *137*, 2468. (b) Muller, K.; Faeh, C.; Diederich, F. *Science* **2007**, *317*, 1881. (c) Purser, S.; Moore, P. R.; Swallow, S.; Gouverneur, V. *Chem. Soc. Rev.* **2008**, *37*, 320. (d) Hagmann, W. K. *J. Med. Chem.* **2008**, *51*, 4359. (e) Meanwell, N. A. *J. Med. Chem.* **2011**, *54*, 2529. (f) Cametti, M.; Crousse, B.; Metrangolo, P.; Milani, R.; Resnati, G. *Chem. Soc. Rev.* **2012**, *41*, 31. (g) Wang, J.; Sánchez-Roselló, M.; Aceña, J. L.; del Pozo, C.; Sorochinsky, A. E.; Fustero, S.; Soloshonok, V. A.; Liu, H. *Chem. Rev.* **2014**, *114*, 2432.

(2) (a) Danoun, G.; Bayarmagnai, B.; Gruenberg, M. F.; Goossen, L. J. *Chem. Sci.* **2014**, *5*, 1312. (b) Matheis, C.; Jouvin, K.; Goossen, L. J. *Org. Lett.* **2014**, *16*, 5984. (c) Danoun, G.; Bayarmagnai, B.; Grünberg, M. F.; Gooßen, L. J. *Angew. Chem., Int. Ed.* **2013**, *52*, 7972. (d) Hansch, C.; Leo, A.; Taft, R. W. *Chem. Rev.* **1991**, *91*, 165. (e) Sheppard, W. *J. Am. Chem. Soc.* **1963**, *85*, 1314. (f) Hendrickson, J. B.; Giga, A.; Wareing, J. *J. Am. Chem. Soc.* **1974**, *96*, 2275. (g) Goumont, R.; Kizilian, E.; Buncel, E.; Terrier, F. *Org. Biomol. Chem.* **2003**, *1*, 1741.

(3) (a) Terrier, F.; Magnier, E.; Kizilian, E.; Wakselman, C.; Buncel, E. *J. Am. Chem. Soc.* **2005**, *127*, 5563. (b) Xu, X. H.; Matsuzaki, K.; Shibata, N. *Chem. Rev.* **2015**, *115*, 731. (c) El Guesmi, N. E.; Boubaker, T.; Goumont, R.; Terrier, F. *Org. Biomol. Chem.* **2008**, *6*, 4041.

(4) Scott A, B.; Cornelia, F. *Eur. Pat. Appl.* 1992, EP 0473110 A1.

(5) Mahadevan, A.; Fuchs, P. L. *J. Am. Chem. Soc.* **1995**, *117*, 3272.

(6) (a) Braverman, S.; Pechenick, T.; Zafrani, Y. *Tetrahedron Lett.* **2001**, *42*, 1391. (b) Braverman, S.; Pechenick, T.; Zafrani, Y. *ARKIVOC* **2004**, *ii*, 51−63.

(7) Chu, X. Q.; Meng, H.; Xu, X. P.; Ji, S. J. *Chem. - Eur. J.* **2015**, *21*, 11359.

(8) (a) Melpolder, J. B.; Heck, R. F. *J. Org. Chem.* **1976**, *41*, 265. (b) Chalk, A. J.; Magennis, S. A. *J. Org. Chem.* **1976**, *41*, 273. (c) Shaw, B. L.; Perera, S. D.; Staley, E. A. *Chem. Commun.* **1998**, 1361. (d) Hills, I. D.; Fu, G. C. *J. Am. Chem. Soc.* **2004**, *126*, 13178.

(9) (a) Trost, B. M.; Van Vranken, D. L. *Chem. Rev.* **1996**, *96*, 395. (b) Trost, B. M.; Crawley, M. L. *Chem. Rev.* **2003**, *103*, 2921.

(10) For Pd catalysis, see: (a) Yu, Y.; Tambar, U. K. *Chem. Sci.* **2015**, *6*, 2777. (b) Wu, H. B.; Ma, X. T.; Tian, S. K. *Chem. Commun.* **2014**, *50*, 219. (c) Wang, Y.; Kang, Q. *Org. Lett.* **2014**, *16*, 4190. (d) Huo, X.; Yang, G.; Liu, D.; Liu, Y.; Gridnev, I. D.; Zhang, W. *Angew. Chem., Int. Ed.* **2014**, *53*, 6776. (e) Li, Y. X.; Xuan, Q. Q.; Liu, L.; Wang, D.; Chen, Y. J.; Li, C. J. *J. Am. Chem. Soc.* **2013**, *135*, 12536. (f) Sundararaju, B.; Achard, M.; Bruneau, C. *Chem. Soc. Rev.* **2012**, *41*, 4467.

(11) For Au catalysis, see: (a) Muzart, J. *Tetrahedron* **2008**, *64*, 5815. (b) Uria, U.; Vila, C.; Lin, M. Y.; Rueping, M. *Chem. - Eur. J.* **2014**, *20*, 13913. (c) Barker, G.; Johnson, D. G.; Young, P. C.; Macgregor, S. A.; Lee, A. L. *Chem. - Eur. J.* **2015**, *21*, 13748. (d) Bandini, M.; Bottoni, A.;

DOI: 10.1021/acs.joc.5b02674
J. Org. Chem. 2016, 81, 1304−1309

Chiarucci, M.; Cera, G.; Miscione, G. P. *J. Am. Chem. Soc.* **2012**, *134*, 20690.
(12) For Cu catalysis, see: (a) Banerjee, D.; Junge, K.; Beller, M. *Angew. Chem., Int. Ed.* **2014**, *53*, 13049. (b) Bunescu, A.; Wang, Q.; Zhu, J. *Angew. Chem., Int. Ed.* **2015**, *54*, 3132. (c) Rokade, B. V.; Gadde, K.; Prabhu, K. R. *Eur. J. Org. Chem.* **2015**, *2015*, 2706. (d) Lei, J.; Liu, X.; Zhang, S.; Jiang, S.; Huang, M.; Wu, X.; Zhu, Q. *Chem. - Eur. J.* **2015**, *21*, 6700. (e) Lei, J.; Liu, X.; Zhang, S.; Jiang, S.; Huang, M.; Wu, X.; Zhu, Q. *Chem. - Eur. J.* **2015**, *21*, 6700.
(13) For Ru catalysis, see: (a) Neumann, P.; Dib, H.; Sournia-Saquet, A.; Grell, T.; Handke, M.; Caminade, A. M.; Hey-Hawkins, E. *Chem. - Eur. J.* **2015**, *21*, 6590. (b) Manoharan, R.; Jeganmohan, M. *Chem. Commun.* **2015**, *51*, 2929. (c) Ríos-Lombardía, N.; Vidal, C.; Cocina, M.; Morís, F.; García-Álvarez, J.; González-Sabín, J. *Chem. Commun.* **2015**, *51*, 10937. (d) Slagbrand, T.; Lundberg, H.; Adolfsson, H. *Chem. - Eur. J.* **2014**, *20*, 16102. (e) Shibahara, F.; Bower, J. F.; Krische, M. J. *J. Am. Chem. Soc.* **2008**, *130*, 6338.
(14) For other metal catalysis, see: (a) Defieber, C.; Ariger, M. A.; Moriel, P.; Carreira, E. M. *Angew. Chem., Int. Ed.* **2007**, *46*, 3139. (b) Song, R. J.; Tu, Y. Q.; Zhu, D. Y.; Zhang, F. M.; Wang, S. H. *Chem. Commun.* **2015**, *51*, 749. (c) Chu, X. Q.; Zi, Y.; Meng, H.; Xu, X. P.; Ji, S. J. *Chem. Commun.* **2014**, *50*, 7642. (d) Leung, D. H.; Bergman, R. G.; Raymond, K. N. *J. Am. Chem. Soc.* **2007**, *129*, 2746. (e) Wang, J.; Huang, W.; Zhang, Z.; Xiang, X.; Liu, R.; Zhou, X. *J. Org. Chem.* **2009**, *74*, 3299.
(15) (a) Ma, X. T.; Dai, R. H.; Zhang, J.; Gu, Y.; Tian, S. K. *Adv. Synth. Catal.* **2014**, *356*, 2984. (b) Reddy, M. A.; Reddy, P. S.; Sreedhar, B. *Adv. Synth. Catal.* **2010**, *352*, 1861. (c) Kanai, T.; Kanagawa, Y.; Ishii, Y. *J. Org. Chem.* **1990**, *55*, 3274. (d) Chandrasekhar, S.; Jagadeshwar, V.; Saritha, B.; Narsihmulu, C. *J. Org. Chem.* **2005**, *70*, 6506. (e) Li, H. H.; Dong, D. J.; Jin, Y. H.; Tian, S. K. *J. Org. Chem.* **2009**, *74*, 9501. (f) Jegelka, M.; Plietker, B. *Org. Lett.* **2009**, *11*, 3462. (g) Murakami, T.; Furusawa, K. *Synthesis* **2002**, *2002*, 479.
(16) Tordeux, M.; Langlois, B.; Wakselman, C. *J. Org. Chem.* **1989**, *54*, 2452.
(17) (a) Zhang, K.; Xu, X. H.; Qing, F. L. *J. Org. Chem.* **2015**, *80*, 7658. (b) Cullen, S. C.; Shekhar, S.; Nere, N. K. *J. Org. Chem.* **2013**, *78*, 12194.
(18) Shangary, S.; Johnson, D. E. *Leukemia* **2003**, *17*, 1470.
(19) (a) Trost, B. M.; Quancard, J. *J. Am. Chem. Soc.* **2006**, *128*, 6314. (b) Usui, I.; Schmidt, S.; Breit, B. *Org. Lett.* **2009**, *11*, 1453. (c) Jiang, G.; List, B. *Angew. Chem.* **2011**, *123*, 9643; *Angew. Chem., Int. Ed.* **2011**, *50*, 9471. (d) Tao, Z. L.; Zhang, W. Q.; Chen, D. F.; Adele, A.; Gong, L. Z. *J. Am. Chem. Soc.* **2013**, *135*, 9255.
(20) (a) Liao, J.; Zhang, Z.; Tang, X.; Wu, W.; Guo, W.; Jiang, H. *J. Org. Chem.* **2015**, *80*, 8903. (b) Huang, H.; Ji, X.; Wu, W.; Jiang, H. *Chem. Soc. Rev.* **2015**, *44*, 1155. (c) Shi, J.; Tang, X. D.; Wu, Y. C.; Li, H. N.; Song, L. J.; Wang, Z. Y. *Eur. J. Org. Chem.* **2015**, *2015*, 1193. (d) Wu, W.; Jiang, H. *Acc. Chem. Res.* **2014**, *47*, 2483. (e) Huang, L.; Qi, J.; Wu, X.; Huang, K.; Jiang, H. *Org. Lett.* **2013**, *15*, 2330. (f) Huang, L.; Wang, Q.; Qi, J.; Wu, X.; Huang, K.; Jiang, H. *Chem. Sci.* **2013**, *4*, 2665.
(21) (a) Jautze, S.; Peters, R. *Angew. Chem., Int. Ed.* **2008**, *47*, 9284. (b) Trost, B. M.; Fraisse, P. L.; Ball, Z. *Angew. Chem., Int. Ed.* **2002**, *41*, 1059.

DOI: 10.1021/acs.joc.5b02674
J. Org. Chem. 2016, 81, 1304−1309