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Photocatalytic Defluorinative Borylation of α-(Trifluoromethyl)-styrenes

Chiara Stavagna
Cornelia S. Buettner*

Institute of Organic Chemistry, RWTH Aachen University, Landoltweg 1, 52074 Aachen, Germany
cornelia.buettner@rwth-aachen.de

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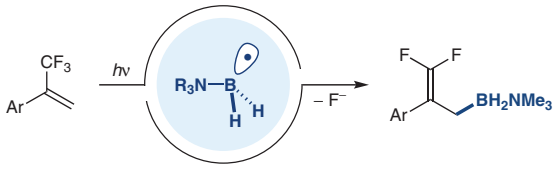

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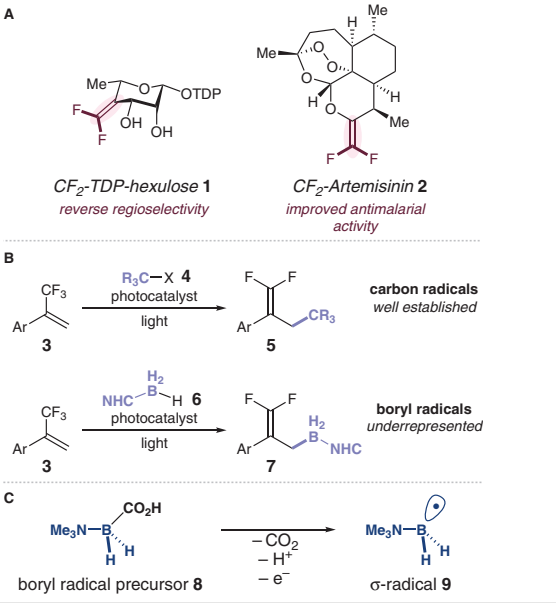
Abstract The defluorinative radical borylation of α-(trifluoromethyl)styrenes is a novel access to diverse difluoroalkene-aminoboranes in good yields. Using the boryl radical precursor borobetaine gives the key boryl radical that reacts with the α-(trifluoromethyl)styrene forming the initial C–B bond. Then a radical-polar crossover mechanism releases fluoride to provide a difluoroalkene product bearing the aminoborane synthetic handle. The difluoroalkene motif is of interest as a potent carbonyl bioisostere that has been shown to enhance biological activity and reactivity. The presence of the aminoborane moiety allows further functionalization such as Suzuki–Miyaura cross-coupling of the borylated products, which is demonstrated using complex aryl bromides. Various post-functionalizations demonstrate difluoroalkene-aminoboranes to be valuable building blocks for the construction of complex, high-value molecules.

Key word boryl radicals, photoredox catalysis, radical-polar crossover, difluoroalkenes, borylation



Scheme 1 (A) Examples of difluoroalkenes **1** and **2** as ketone bioisosteres. (B) Precedent for the addition of carbon and boron-centered radicals to α-(trifluoromethyl)styrenes **3**. (C) Boryl radical **9** generation from borobetaine **8** via oxidative decarboxylation.

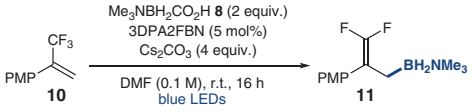
The decoration of organic motifs with fluorine atoms is regularly employed to improve the properties of high-value molecules across pharmaceuticals, agrochemicals, and materials science.[1–3] gem-Difluoroalkenes specifically have emerged as valuable bioisosteres for ketones, playing key roles in molecular recognition and biological mimicry.[4] Two prominent examples of this are the difluoroalkene derivative of TDP-6-deoxy-L-*lyxo*-4-hexulose **1** demonstrating reverse regioselectivity of enzymatic reduction,[5] and improved antimalarial activity of CF_2-artemisinin **2** *versus* artemisinin (Scheme 1A).[6]

While defluorinative functionalization of α-(trifluoromethyl)styrenes **3** to generate difluoroalkenes has been demonstrated by transition metal catalysis with B_2Pin_2 as a boron source,[7,8] recent reports focused on photoredox initiated approaches instead. Most examples utilizing radical pathways, such as those by Molander, T. Wang, and Q. Wang, focus on the addition of carbon-centered radicals to α-(trifluoromethyl)styrenes **3** to give difluoroalkenes **5** (Scheme 1B).[9–11] Heteroatomic radicals, such as boryl radicals, have been significantly less explored and have been

limited entirely to NHC-ligated boranes **6**. For these reactions, the key boryl radical is generated via hydrogen atom transfer (HAT), furnishing planar, π-radicals through the stabilizing effect of the NHC π-system.[12] Precisely this effect leads to stable products **7** that are too unreactive for direct participation in cross-coupling processes, hence they need to be derivatized further for engagement in such reactions.[13] As boron-bearing motifs are particularly interesting for the synthesis of complex organic scaffolds,[14,15] their installation is most valuable as a synthetic handle for further derivatization, namely the Suzuki–Miyaura cross-coupling, which is among the most common reactions performed in medicinal chemistry.[16] Based on our previous work on the use of amine-ligated boryl radicals,[17,18] we wanted to expand the borylation process to α-(trifluoromethyl)styrenes, forming difluoroalkenes bearing an aminoborane group, for direct further functionalization. To our knowledge, boryl radicals such as **9** have not previously been employed in the radical formation of difluoroalkenes.

An initial hit showed the defluorinative borylation was feasible with electron-donating group substituted 4-methoxy-α-(trifluoromethyl)styrene (**10**), a limitation in our previous work.[17] Encouraged by this finding, we began our endeavor using styrene **10** and boryl radical precursor borobetaine (**8**). Initial experiments revealed the organic photocatalyst 2,4,6-tris(diphenylamino)-3,5-difluorobenzonitrile (3DPA2FBN) to give the best yields of difluoroalkene **11** when compared to other photocatalysts screened, moving away from expensive metal-based photocatalysts. Importantly, control reactions omitting light (Table 1, entry 6) and photocatalyst (Table 1, entry 7) confirmed a photocatalytic process to be operative (see the Supporting Information for full details of the optimization).

Table 1 Selected Entries for the Optimization of Photocatalytic Borylation

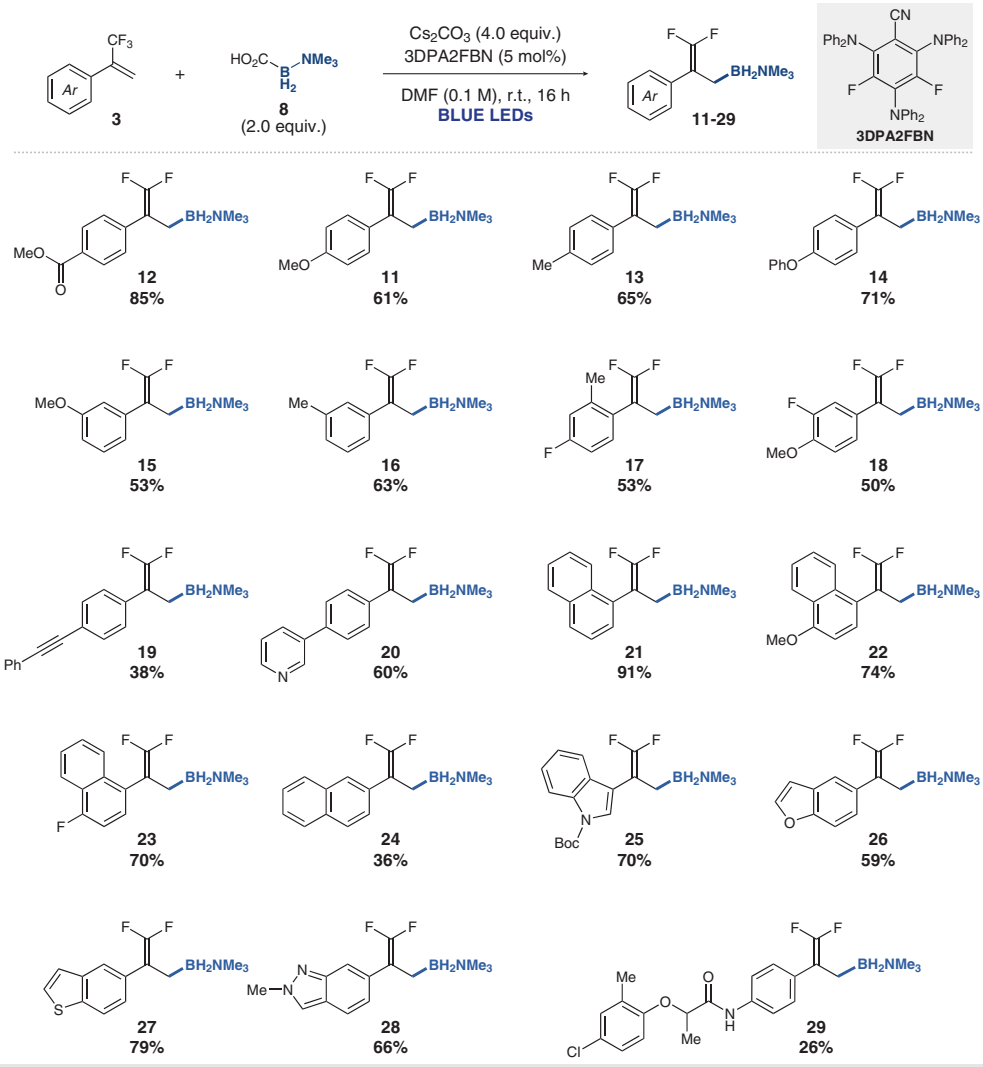


Entry	Deviation from std conditions	Yield[a] (%)
1	–	64 (61[b])
2	Cs_2CO_3 (2 equiv.)	54
3	4CzIPN	44
4	eosin Y	31
5	[Ir(ppy)$_3$]	18
6	no light	0
7	no photocatalyst	0

[a] NMR yield.
[b] Isolated yield.

Having found conditions that provided us with good yield of the borylated difluoroalkenes, we examined the tolerance of the borylation to various other α-(trifluoromethyl)styrenes **3** bearing a range of functional groups (Scheme 2). We observed very good yields of products for the borylation of α-(trifluoromethyl)styrenes **3** bearing *para*-substitutions such as ester **12**, methyl and phenyl ethers **11** and **14**, and methyl **13**. Similarly *meta*-methoxy and *meta*-methyl provide good yields of difluoroalkenes **15** and **16**. Disubstituted aryl substrates efficiently underwent borylation/defluorination providing products **17** and **18**. An alkyne-containing α-(trifluoromethyl)styrene was successfully borylated to give **19** in 38% yield with no borylation or reduction of the alkyne group, therefore showing complete chemoselectivity for the desired radical addition. Substituted naphthyls also provided very good yields of **21**, **22**, and **23**, with a lower yield observed for borylation, to give 2-styryl-naphthalene **24**. α-(Trifluoromethyl)styrenes **3** bearing more complex heteroaromatic groups gave products such as pyridine **20**, indole **25**, benzofuran **26**, benzothiophene **27**, and indazole **28** thus demonstrating that a wide range of functionalities are conducive to the developed reaction. To further highlight the tolerance of this method, mecoprop derivative **29** was synthesized in 26% yield.

We propose that the developed defluorinative borylation of α-(trifluoromethyl)styrenes occurs via a radical-polar crossover mechanism (Scheme 3). Excitation of 3DPA2FBN provides the excited state photocatalyst (PC*), this in turn undergoes single electron transfer (SET) with deprotonated borobetaine **30** as confirmed by Stern–Volmer quenching studies (see the Supporting Information). Control experiments show the requirement for light and photocatalyst. The measured potential for the deprotonated borobetaine ([**30**$^-$/**9**$^\bullet$] = +0.38 V vs SCE) (see the Supporting Information) is within range of the reported excited state reduction potential of 3DPA2FBN ([PC*/PC$^{\bullet-}$] = +0.92 V vs SCE).[19] Rapid decarboxylation furnishes the boryl radical **9** that undergoes addition to the α-(trifluoromethyl)styrene **10**, to provide the stabilized benzylic radical **31**. Reduction (by SET) of this intermediate radical occurs through concomitant oxidation of the photocatalyst radical anion (3DPA2FBN$^{\bullet-}$). Literature reported reduction potentials of benzyl radicals depend on the substitution on the aromatic ring [–1.75 V (4-MeO) and –0.77 V (4-CN)],[20] however, they fall within range of the employed photocatalyst (3DPA2FBN [PC/PC$^{\bullet-}$] = –1.92 V). Moreover, addition of TEMPO to the reaction inhibits product formation, indicative of a radical process being operative (see the Supporting Information). This mechanism is further supported by literature employing 3DPA2FBN in radical-polar crossover reactions, proceeding by reduction of the intermediate benzyl radical by the reduced form photocatalyst.[21,22] Release of fluoride from the pendant trifluoromethyl group of the benzylic anion **32** furnishes the difluoroalkene product **11**. Competi-

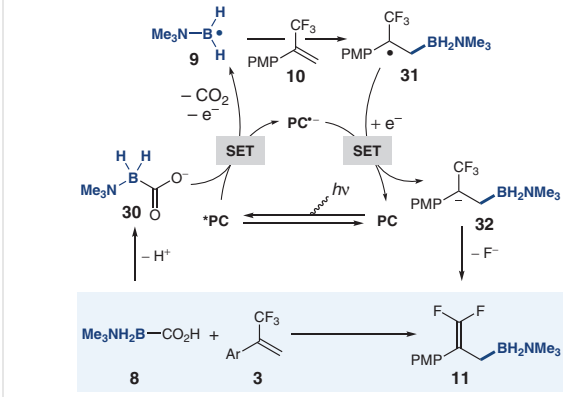


Scheme 2 Substrate scope for the photocatalytic borylation of α-(trifluoromethyl)styrenes screened

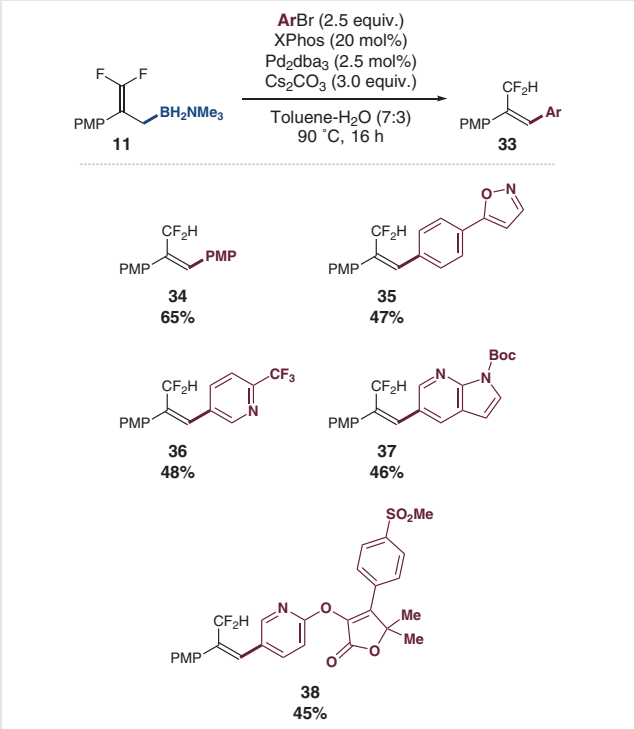
tive protonation, seen with substrates lacking the trifluoromethyl substitution, is not presumably competitive with the unimolecular elimination observed for this process.[23]

With our process to furnish aminoborane bearing difluoroalkenes in hand, we wanted to explore further reactivity. Specifically, we wanted to investigate the cross-coupling using the alkyl aminoborane as a reaction partner with various aryl bromides.

Traditionally the use of boryl radicals has focused on NHC-ligated boron species **7** that do not directly undergo cross-coupling but first require derivatization (*vide supra*). The Leonori group has demonstrated that both alkyl and aryl aminoboranes are effective reaction partners in the Suzuki–Miyaura cross-coupling owing to their hydrolysis to afford the highly reactive boronic acids in situ.[17] We were



Scheme 3 Mechanism of photocatalytic borylation of α-(trifluoromethyl)styrenes

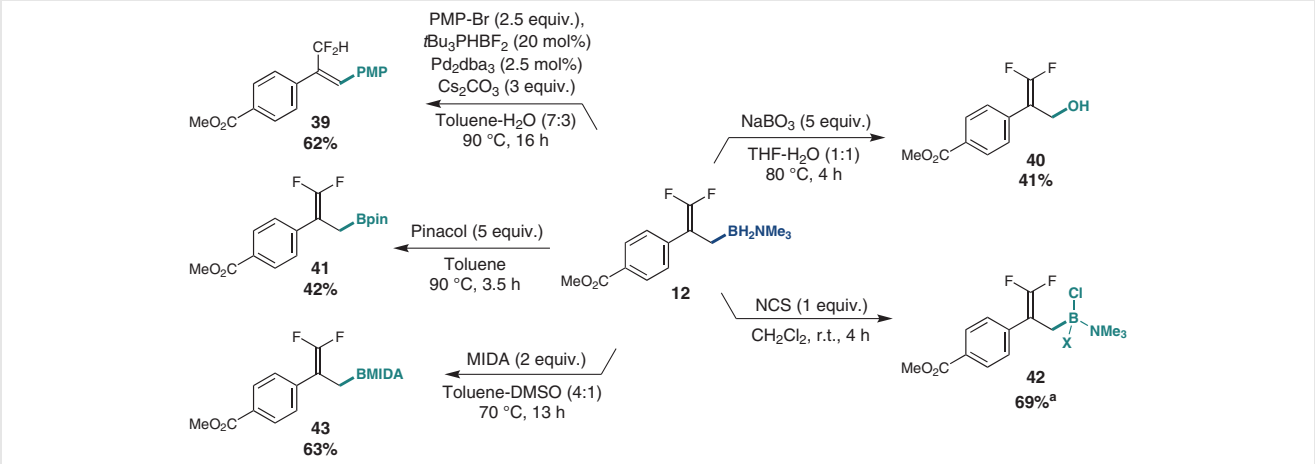


Scheme 4 Suzuki–Miyaura cross-coupling of an aminoborane to afford bis-aryl alkenes

able to demonstrate the Suzuki–Miyaura cross-coupling of aminoborane **11** with a selected range of aryl bromides showing a high degree of complexity (Scheme 4). In all cases, we observed the isomerization of the alkene to afford the difluoromethyl bis-arylated alkenes **33**. Analogous products bearing the medicinally interesting difluoromethyl group have recently been synthesized through the use of Ni catalysis and bromodifluoromethane, or through a hydroboration/cross-coupling sequence of alkynes using dicyclohexylborane, a rather challenging-to-handle reagent.[24–26] As the interest towards the introduction of difluoromethyl and other fluorinated substitution patterns in biologically relevant molecules has risen due to their improved metabolic properties, we were pleased to access this substitution pattern with convenient and mild conditions.[27–29] Difluoroalkene-aminoborane **11** underwent cross-coupling in moderate to good yields, demonstrating the formation of simpler products, such as **34**, but also using hetaryl bromides to give products containing oxazole **35**, pyridine **36**, and protected azaindole **37**. Remarkably, we could also show cross coupling of aminoborane **11** with an example from the Merck informer library (X3) to afford complex Suzuki–Miyaura product **38** in a synthetically useful yield.[30]

To elaborate on the synthetic potential of these novel difluoroalkene-aminoboranes, substrate **12** was selected for a range of initial derivatization reactions to afford secondary products from the borylated substrates (Scheme 5). Thus, the cross-coupling afforded a good yield of the Suzuki–Miyaura product **39**, demonstrating that both electron-donating and electron-withdrawing groups in the borylated substrate are tolerated. The aminoborane moiety of **12** could be post-functionalized to give both the BPin **41** and BMIDA **43**, providing alternative boron handles. Further, oxidation of aminoborane **12** provided the terminal alcohol **40**. Finally, chlorination of the borane to furnish aminoborane **42** was demonstrated to be possible; attempts at fluorination returned the starting α-(trifluoromethyl)styrene **12**.

To conclude, we have demonstrated the photocatalytic borylation of α-(trifluoromethyl)styrenes using borobetaine (**8**) as the boryl radical precursor to afford difluoroalkene-aminoboranes **11**–**29**. Further, we have shown these borylated products to undergo efficient Suzuki–Miyaura cross-coupling with various complex aryl bromides to deliver difluoromethyl bis-arylated alkenes **34**–**38**. Additionally, we have shown that the novel difluoroalkene-aminob-



Scheme 5 Post-functionalization of borylated product **12**. [a] 1:1.4 mono/dichlorination

oranes can undergo a range of post-functionalization transformations, proving again their value as synthetic building blocks for academic and industry chemists alike.

All required fine chemicals were used directly without purification unless stated otherwise. All air and moisture sensitive reactions were carried out under N_2 atmosphere using standard Schlenk manifold technique. All solvents were bought from Acros as 99.8% purity and degassed by N_2 bubbling. ^1H and ^{13}C NMR spectra were acquired at various field strengths as indicated and were referenced to $CHCl_3$ (δ = 7.27 and 77.16 for ^1H and ^{13}C, respectively). ^1H NMR coupling constants are reported in Hertz and refer to apparent multiplicities and not true coupling constants. In the ^1H NMR measurements, the BH_2 hydrogens were usually not observed due to the broad character of the quartet (J_{H-B} ~ 90 Hz). In the ^{13}C NMR, the carbon α-B was not always detected as consequence of the boron quadrupolar relaxation; when visible it is specified. The spectra measurements are specified when decoupled (e.g., $^{19}F\{^1H\}$). Proton assignment (determined by 2D NMR experiments: COSY, HSQC and HMBC) where possible. HRMS were obtained using a JEOL JMS-700 spectrometer or a Fissions VG Trio 2000 quadrupole mass spectrometer. Spectra were obtained using electron impact ionization (EI) and chemical ionization (CI) techniques, or positive electrospray (ESI). Analytical TLC: aluminum backed plates pre-coated (0.25 mm) with Merck Silica Gel 60 F254. Compounds were visualized by exposure to UV-light or by dipping the plates in permanganate ($KMnO_4$) stain followed by heating. Flash column chromatography was performed using Merck Silica Gel 60 (40–63 μm). The LEDs used are Kessil PR 160 440 nm. All the reactions were conducted in CEM 9-mL glass microwave tubes capped with a LABSOLUTE crimp seal with septum (PTFE/butyl) purchased from Th. Geyer.

Information on the synthesis of α-(trifluoromethyl)styrenes **3** and borobetaine (**8**), photographs of the photochemical reaction setup, and details of the chromatographic purification of the products and full yield data for **11–39** together with procedures and all relevant information for **40–43** are available in the Supporting Information.

Borylation of α-(Trifluoromethyl)styrenes To Give Borane–Amine Complexes 11–29; General Procedure

A microwave vial equipped with a stirring bar was charged with Me_3N-BH_2CO_2H (**8**; 2.0 equiv.), base (4.0 equiv.), photocatalyst (5 mol%), and olefin **3** (1.0 equiv.). The tube was capped with a Supelco aluminum crimp seal with septum (PTFE/butyl), evacuated and refilled with N_2 (3 ×), then degassed DMF (1 mL, 0.1 M) was added. N_2 was bubbled through the reaction mixture for 10 s. The lid was sealed with parafilm and the vial was placed under blue LEDs. The light was switched on and the mixture was stirred under irradiation at r.t. for 16 h with a fan. The reaction was diluted with EtOAc and H_2O. The aqueous phase was washed with EtOAc (3 ×), and the organic layers were filtered through a layer of Celite and $MgSO_4$. The combined organic layers were concentrated in vacuo and then purified as specified (see the Supporting Information).

Cross-Coupling of Amine–Boranes; General Procedure

A microwave vial equipped with a stirring bar was charged with the amine-borane (0.1 mmol, 1.0 equiv.), the aryl bromide (2.5 equiv., if solid), Cs_2CO_3 (98 mg, 0.3 mmol, 3.0 equiv.), XPhos (9.5 mg, 0.02 mmol, 20 mol%), and Pd_2dba_3 (2.3 mg, 0.003 mmol, 2.5 mol%). The tube was capped with a Supelco aluminum crimp seal with septum (PTFE/butyl), evacuated and refilled with N_2 (3 ×), then toluene (0.7 mL) was added. The aryl bromide (2.5 equiv., if liquid) was added, followed by H_2O (0.3 mL). The reaction was stirred at 90 °C for 16 h. The reaction was diluted with EtOAc and H_2O. The aqueous phase was washed with EtOAc (3 ×) and the organic layers were filtered through a layer of Celite and $MgSO_4$. The combined organic layers were concentrated in vacuo and purified by flash chromatography as specified.

(3,3-Difluoro-2-(4-methoxyphenyl)allyl)borane–trimethylamine Complex (11)

Oil (31 mg, 0.12 mmol, 61%); R_f = 0.33 [30% EtOAc/pentane].

IR (film): 3419, 2951, 2347, 1813, 1714, 1607, 1511, 1247, 1030, 833 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.34 (d, J = 8.4 Hz, 2 H), 6.85 (d, J = 8.4 Hz, 2 H), 3.79 (s, 3 H), 2.55 (s, 9 H), 1.52 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 158.0, 152.0 (dd, J_{C-F} = 286.4, 280.5 Hz), 129.5 (t, J_{C-F} = 3.6 Hz), 129.2 (dd, J_{C-F} = 3.4, 1.8 Hz), 113.5, 94.7 (dd, J_{C-F} = 23.6, 9.7 Hz), 55.3, 52.0, 16.2.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.55 (t, J = 99.1 Hz).

$^{19}F\{^1H\}$ NMR ($CDCl_3$, 565 MHz): δ = –96.00 (d, J = 57.9 Hz), –96.62 (d, J = 57.9 Hz).

HRMS (ESI): m/z $[M + Na]^+$ calcd for $C_{13}H_{20}ONBF_2Na$: 278.1498; found: 278.1492.

Methyl 4-(3-Boranyl-1,1-difluoroprop-1-en-2-yl)benzoate–trimethylamine Complex (12)

Oil (46 mg, 0.17 mmol, 85%); R_f = 0.15 [20% EtOAc/cyclohexane].

IR (film): 2952, 2342, 2102, 1831, 1714, 1465, 1437, 1279, 1101, 986 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.97 (d, J = 8.4 Hz, 2 H), 7.48 (d, J = 8.4 Hz, 2 H), 3.89 (s, 3 H), 2.56 (s, 9 H), 1.55 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 167.3, 152.5 (dd, J_{C-F} = 290.0, 283.4 Hz), 142.0 (t, J_{C-F} = 4.3 Hz), 129.3, 128.4 (t, J_{C-F} = 3.6 Hz), 127.9, 95.1 (dd, J_{C-F} = 24.5, 8.2 Hz), 52.1, 52.0, 16.0.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.70 (t, J = 98.6 Hz).

$^{19}F\{^1H\}$ NMR ($CDCl_3$, 565 MHz): δ = –92.58 (d, J = 49.2 Hz), –93.38 (d, J = 49.2 Hz).

HRMS (ESI): m/z $[M + Na]^+$ calcd for $C_{14}H_{20}O_2NBF_2Na$: 306.1447; found: 306.1449.

(3,3-Difluoro-2-(*p*-tolyl)allyl)borane–trimethylamine Complex (13)

Oil (31 mg, 0.13 mmol, 65%); R_f = 0.21 [20% EtOAc/cyclohexane].

IR (film): 2924, 2691, 2117, 1994, 1812, 1715, 1608, 1512 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.30 (d, J = 7.8 Hz, 2 H), 7.12 (d, J = 7.8 Hz, 2 H), 2.56 (s, 9 H), 2.33 (s, 3 H), 1.54 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 152.1 (dd, J_{C-F} = 287.0, 280.4 Hz), 135.9, 133.9 (dd, J_{C-F} = 5.5, 3.6 Hz), 128.8, 128.3 (t, J_{C-F} = 3.3 Hz), 95.1 (dd, J_{C-F} = 23.3, 9.4 Hz), 52.0, 21.3, 16.2.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.57 (t, J = 97.7 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –95.60 (d, J = 56.2 Hz), –96.14 (d, J = 56.2 Hz).

HRMS (ESI): m/z $[M + Na]^+$ calcd for $C_{13}H_{20}NBF_2Na$: 262.1549; found: 262.1541.

(3,3-Difluoro-2-(4-phenoxyphenyl)allyl)borane–trimethylamine Complex (14)

Oil (45 mg, 0.14 mmol, 71%); R_f = 0.39 [30% EtOAc/pentane].

IR (film): 2920, 2340, 1713, 1588, 1486, 1232, 1093, 995, 840 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.39 (d, *J* = 8.3 Hz, 2 H), 7.33 (t, *J* = 7.5 Hz, 2 H), 7.09 (t, *J* = 7.5 Hz, 1 H), 7.03 (d, *J* = 7.5 Hz, 2 H), 6.95 (d, *J* = 8.3 Hz, 2 H), 2.57 (s, 9 H), 1.54 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 157.4, 155.5, 152.2 (dd, J_{C-F} = 287.0, 281.0 Hz), 131.9 (dd, J_{C-F} = 5.4, 3.7 Hz), 129.8, 129.7 (dd, J_{C-F} = 4.3, 3.8 Hz), 123.2, 119.0, 118.4, 94.7 (dd, J_{C-F} = 23.6, 9.1 Hz), 52.0, 16.4.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.54 (t, *J* = 93.3 Hz).

$^{19}F\{^1H\}$ NMR ($CDCl_3$, 565 MHz): δ = –95.10 (d, *J* = 56.0 Hz), –95.80 (d, *J* = 56.0 Hz).

HRMS (ESI): *m*/*z* $[M + Na]^+$ calcd for $C_{18}H_{22}ONBF_2Na$: 340.1655; found: 340.1653.

(3,3-Difluoro-2-(3-methoxyphenyl)allyl)borane–trimethylamine Complex (15)

Oil (27 mg, 0.11 mmol, 53%); R_f = 0.29 [20% EtOAc/cyclohexane].

IR (film): 2941, 2337, 2092, 1581, 1483, 1230, 1103, 998 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.22 (t, *J* = 7.8 Hz, 1 H), 7.01 (t, *J* = 7.8 Hz, 1 H), 6.99 (s, 1 H), 6.75 (d, *J* = 8.1 Hz, 1 H), 3.80 (s, 3 H), 2.56 (s, 9 H), 1.53 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 159.4, 152.3 (dd, J_{C-F} = 287.9, 281.3 Hz), 138.5 (td, J_{C-F} = 5.4, 3.2 Hz), 128.8, 121.2 (t, J_{C-F} = 3.9 Hz), 114.5 (t, J_{C-F} = 3.4 Hz), 111.9, 95.3 (dd, J_{C-F} = 23.6, 9.7 Hz), 55.3, 52.1, 16.2.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.52 (t, *J* = 94.8 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –94.65 (d, *J* = 54.2 Hz), –95.01 (d, *J* = 54.2 Hz).

HRMS (ESI): *m*/*z* $[M + Na]^+$ calcd for $C_{13}H_{20}ONBF_2Na$: 278.1498; found: 278.1497.

(3,3-Difluoro-2-(*m*-tolyl)allyl)borane–trimethylamine Complex (16)

Oil (30 mg, 0.13 mmol, 63%); R_f = 0.30 [20% EtOAc/cyclohexane].

IR (film): 3025,2955, 2924, 2687, 2115, 1996, 1835, 1722, 1606, 1481 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.24–7.15 (m, 3 H), 7.10–6.97 (m, 1 H), 2.56 (s, 9 H), 2.34 (s, 3 H), 1.54 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 152.1 (dd, J_{C-F} = 287.0, 281.0 Hz), 137.4, 136.9 (dd, J_{C-F} = 5.4, 3.1 Hz), 129.3 (t, J_{C-F} = 3.3 Hz), 127.9, 127.2, 125.6 (t, J_{C-F} = 3.3 Hz), 95.3 (dd, J_{C-F} = 23.3, 9.4 Hz), 52.1, 21.7, 16.5.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.57 (t, *J* = 95.9 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –95.36 (d, *J* = 55.2 Hz), –95.96 (d, *J* = 56.2 Hz).

HRMS (ESI): *m*/*z* $[M + Na]^+$ calcd for $C_{13}H_{20}NBF_2Na$: 262.1549; found: 262.1543.

(3,3-Difluoro-2-(4-fluoro-2-methylphenyl)allyl)borane–trimethylamine Complex (17)

Oil (27 mg, 0.11 mmol, 53%); R_f = 0.27 [20% EtOAc/cyclohexane].

IR (film): 2921, 2337, 1995, 1915, 1733, 1586, 1494, 1231, 1144, 1090, 997 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ = 7.15 (dd, *J* = 8.4, 6.1 Hz, 1 H), 6.90–6.78 (m, 2 H), 2.53 (s, 9 H), 2.28 (s, 3 H), 1.40 (s, 2 H).

^{13}C NMR ($CDCl_3$, 101 MHz): δ = 161.7 (d, J_{C-F} = 244.1 Hz), 151.0 (dd, J_{C-F} = 282.8, 280.7 Hz), 139.1 (ddd, J_{C-F} = 7.7, 2.4, 1.2 Hz), 132.7 (ddd, J_{C-F} = 5.7, 3.1, 1.1 Hz), 131.3 (ddd, J_{C-F} = 8.0, 3.4, 1.2 Hz), 116.3 (d, J_{C-F} = 21.1 Hz), 112.1 (d, J_{C-F} = 21.1 Hz), 93.0 (dd, J_{C-F} = 24.0, 14.5 Hz), 54.3, 52.0, 17.9.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.97 (t, *J* = 100.1 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –94.95 (d, *J* = 58.2 Hz), –98.99 (d, *J* = 57.2 Hz), –117.07 (ddd, *J* = 15.6, 9.6, 6.1 Hz).

HRMS (ESI): *m*/*z* $[M + Na]^+$ calcd for $C_{13}H_{19}NBF_3Na$: 280.1455; found: 280.1455.

(3,3-Difluoro-2-(3-fluoro-4-methoxyphenyl)allyl)borane–trimethylamine Complex (18)

Oil (28 mg, 0.1 mmol, 50%); R_f = 0.21 [20% EtOAc/cyclohexane].

IR (film): 2939, 2336, 2111, 1832, 1714, 1517, 1464, 1272, 1223, 1130, 1024, 840 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.18 (dd, *J* = 13.1, 1.5 Hz, 1 H), 7.14–7.09 (m, 1 H), 6.89 (t, *J* = 8.8 Hz, 1 H), 3.87 (s, 3 H), 2.57 (s, 9 H), 1.49 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 152.2 (dd, J_{C-F} = 287.8, 281.4 Hz), 152.1 (d, J_{C-F} = 243.4 Hz), 146.0 (d, J_{C-F} = 10.3 Hz), 130.0, 124.2 (q, J_{C-F} = 3.3 Hz), 116.2 (dt, J_{C-F} = 19.0, 3.8 Hz), 112.9 (d, J_{C-F} = 1.9 Hz), 94.2 (dd, J_{C-F} = 23.8, 9.8 Hz), 56.4, 52.1, 15.9.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.64 (t, *J* = 97.4 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –94.69 (d, *J* = 55.2 Hz), –95.32 (d, *J* = 55.2 Hz), –136.29 (dd, *J* = 13.6, 8.5 Hz).

HRMS (ESI): *m*/*z* $[M + Na]^+$ calcd for $C_{13}H_{19}ONBF_3Na$: 296.1404; found: 296.1402.

(3,3-Difluoro-2-(4-(phenylethynyl)phenyl)allyl)borane–trimethylamine Complex (19)

Oil (25 mg, 0.08 mmol, 38%); R_f = 0.50 [30% EtOAc/pentane].

IR (film): 3440, 2920, 2337, 2253, 1712, 1461, 1383, 1225, 1028, 908, 733, 650 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.53 (d, *J* = 7.5 Hz, 2 H), 7.47 (d, *J* = 8.0 Hz, 2 H), 7.41 (d, *J* = 8.0 Hz, 2 H), 7.36–7.30 (m, 3 H), 2.56 (s, 9 H), 1.55 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 152.3 (dd, J_{C-F} = 289.1, 282.5 Hz), 137.1 (dd, J_{C-F} = 5.7, 4.0 Hz), 131.7, 131.3, 128.4, 128.4 (dd, J_{C-F} = 4.4, 3.6 Hz), 128.2, 123.7, 121.0, 95.1 (dd, J_{C-F} = 24.0, 8.6 Hz), 89.9, 89.2, 52.0, 15.9.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.64 (t, *J* = 92.1 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –93.43 (d, *J* = 51.2 Hz), –94.11 (d, *J* = 52.2 Hz).

HRMS (ESI): *m*/*z* $[M + Na]^+$ calcd for $C_{20}H_{22}NBF_2Na$: 348.1706; found: 348.1699.

3-(4-(3-Boranyl-1,1-difluoroprop-1-en-2-yl)phenyl)pyridine–trimethylamine Complex (20)

Oil (36 mg, 0.12 mmol, 60%); R_f = 0.33 [EtOAc].

IR (film): 3001, 2923, 2855, 2340, 2088, 1914, 1708, 1475, 1220, 1097, 997, 842 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ = 8.87 (br s, 1 H), 8.57 (br s, 1 H), 7.88 (t, *J* = 7.7 Hz, 1 H), 7.54 (s, 4 H), 7.35 (dd, *J* = 7.7, 4.8 Hz, 2 H), 2.59 (s, 9 H), 1.58 (br s, 4 H).

^{13}C NMR ($CDCl_3$, 101 MHz): δ = 152.3 (dd, *J* = 288.3, 282.1 Hz), 148.3, 136.9 (dd, *J* = 5.4, 3.7 Hz), 136.6, 135.6, 134.3, 129.1 (t, *J* = 3.8 Hz), 126.7, 123.6, 94.9 (dd, *J* = 24.0, 8.7 Hz), 52.0, 16.0.

^{11}B NMR ($CDCl_3$, 128 MHz): δ = –3.60 (t, *J* = 90.2 Hz).

^{19}F{^{1}H} NMR ($CDCl_3$, 565 MHz): δ = –93.84 (d, *J* = 53.2 Hz), –94.68 (d, *J* = 53.2 Hz).

HRMS (ESI): *m*/*z* [M + H]$^+$ calcd for $C_{17}H_{22}N_2BF_2$: 303.1834; found: 303.1837.

(3,3-Difluoro-2-(naphthalen-1-yl)allyl)borane–trimethylamine Complex (21)

Oil (50 mg, 0.18 mmol, 91%); R_f = 0.30 [20% EtOAc/cyclohexane].

IR (film): 2916, 2340, 1731, 1590, 1481, 1223, 1127, 1075, 990, 907 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.04 (dd, *J* = 8.0, 1.1 Hz, 1 H), 7.84 (dd, *J* = 8.1, 1.6 Hz, 1 H), 7.76 (d, *J* = 2.8 Hz, 1 H), 7.55–7.38 (m, 4 H), 2.49 (s, 9 H), 1.61 (br s, 2 H).

^{13}C NMR ($CDCl_3$, 101 MHz): δ = 151.6 (dd, $J_{C–F}$ = 283.3, 281.6 Hz), 135.1 (dd, $J_{C–F}$ = 5.8, 1.1 Hz), 133.8, 132.0, 131.9, 128.4, 127.3, 126.0, 125.7, 125.5, 125.4, 93.1 (dd, $J_{C–F}$ = 24.2, 14.4 Hz), 52.0, 18.3.

^{11}B{^{1}H} NMR ($CDCl_3$, 193 MHz): δ = –3.80.

^{19}F{^{1}H} NMR ($CDCl_3$, 565 MHz): δ = –93.89 (d, *J* = 57.2 Hz), –97.85 (d, *J* = 57.2 Hz).

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{16}H_{20}NBF_2Na$: 298.1549; found: 298.1551.

(3,3-Difluoro-2-(4-methoxynaphthalen-1-yl)allyl)borane–trimethylamine Complex (22)

Oil (45 mg, 0.15 mmol, 74%); R_f = 0.12 [20% EtOAc/pentane].

IR (film): 3343, 2300, 1878, 1597, 1460, 1028, 843, 780 cm^{-1}.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 8.27 (dd, *J* = 8.3, 0.7 Hz, 1 H), 7.96 (d, *J* = 8.3 Hz, 1 H), 7.50 (ddd, *J* = 8.2, 6.8, 1.4 Hz, 1 H), 7.45 (ddd, *J* = 8.2, 6.8, 1.4 Hz, 1 H), 7.32 (d, *J* = 7.9 Hz, 1 H), 6.80 (d, *J* = 7.9 Hz, 1 H), 3.99 (s, 3 H), 2.49 (s, 9 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 154.7, 151.9 (dd, $J_{C–F}$ = 283.6, 280.8 Hz), 132.8 (d, $J_{C–F}$ = 2.8 Hz), 127.2 (dd, $J_{C–F}$ = 3.5, 1.0 Hz), 126.2, 125.8, 125.8, 124.9, 122.3, 103.4, 92.9 (dd, $J_{C–F}$ = 24.0, 14.3 Hz), 55.5, 52.0, 18.2.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.68 (t, *J* = 89.6 Hz).

^{19}F{^{1}H} NMR ($CDCl_3$, 565 MHz): δ = –94.44 (d, *J* = 57.2 Hz), –97.99 (d, *J* = 57.2 Hz).

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{17}H_{22}ONBF_2Na$: 328.1655; found: 328.1569.

(3,3-Difluoro-2-(4-fluoronaphthalen-1-yl)allyl)borane–trimethylamine Complex (23)

Solid (41 mg, 0.14 mmol, 70%); R_f = 0.44 [25% EtOAc/pentane]; mp 85–87 °C.

IR (film): 3343, 2923, 1878, 1597, 1460, 1028, 843, 780 cm^{-1}.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 8.10 (d, *J* = 8.0 Hz, 1 H), 8.00 (d, *J* = 8.0 Hz, 1 H), 7.56–7.49 (m, 2 H), 7.35–7.31 (m, 1 H), 7.13–7.06 (m, 1 H), 2.50 (s, 9 H), 1.54 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 158.1 (d, $J_{C–F}$ = 251.0 Hz), 151.8 (dd, $J_{C–F}$ = 282.8, 282.2 Hz), 133.2, 131.0 (t, $J_{C–F}$ = 4.8 Hz), 127.0 (ddd, $J_{C–F}$ = 3.2, 2.3, 1.2 Hz), 126.7, 126.0 (d, $J_{C–F}$ = 2.8 Hz), 125.9 (d, $J_{C–F}$ = 2.0 Hz), 123.9 (d, $J_{C–F}$ = 16.3 Hz), 120.8 (d, $J_{C–F}$ = 5.4 Hz), 109.0 (d, $J_{C–F}$ = 19.4 Hz), 92.6 (dd, $J_{C–F}$ = 24.8, 13.9 Hz), 52.0, 18.4.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.81 (t, *J* = 98.8 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –93.79 (d, *J* = 55.2 Hz), –97.56 (d, *J* = 56.2 Hz), –124.92 (dd, *J* = 11.0, 5.0 Hz).

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{16}H_{19}NBF_3Na$: 316.1455; found: 316.1448.

(3,3-Difluoro-2-(naphthalen-2-yl)allyl)borane–trimethylamine Complex (24)

Oil (20 mg, 0.07 mmol, 36%); R_f = 0.21 [20% EtOAc/cyclohexane].

IR (film): 3016, 2946, 2351, 1829, 1715, 1484, 1247, 1078, 985, 823, 750 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 7.85 (s, 1 H), 7.82–7.76 (m, 3 H), 7.59–7.53 (m, 1 H), 7.46–7.39 (m, 2 H), 2.57 (s, 9 H), 1.65 (br s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 152.4 (dd, $J_{C–F}$ = 287.6, 281.6 Hz), 134.5 (dd, $J_{C–F}$ = 5.5, 3.6 Hz), 133.5, 132.3, 128.1, 127.6, 127.4, 127.3 (t, $J_{C–F}$ = 3.6 Hz), 127.0 (t, $J_{C–F}$ = 3.3 Hz), 125.8, 125.5, 95.5 (dd, $J_{C–F}$ = 23.6, 9.1 Hz) 52.1, 16.2.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.56 (t, *J* = 94.8 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –94.47 (d, *J* = 53.2 Hz), –95.44 (d, *J* = 54.2 Hz).

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{16}H_{20}NBF_2Na$: 298.1549; found: 298.1548.

***tert*-Butyl 3-(3-Boranyl-1,1-difluoroprop-1-en-2-yl)-1*H*-indole-1-carboxylate–trimethylamine Complex (25)**

Oil (50 mg, 0.14 mmol, 70%); R_f = 0.23 [20% EtOAc/cyclohexane].

IR (film): 2979, 2931, 2364, 1831, 1729, 1453, 1371, 1249, 1153, 1074, 988 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 8.13 (d, *J* = 6.8 Hz, 1 H), 7.60 (s, 1 H), 7.57 (d, *J* = 7.9 Hz, 1 H), 7.29 (ddd, *J* = 8.4, 7.1, 1.4 Hz, 1 H), 7.24–7.17 (m, 1 H), 2.55 (s, 9 H), 1.66 (s, 9 H), 1.58 (s, 2 H).

^{13}C NMR ($CDCl_3$, 101 MHz): δ = 152.0 (dd, $J_{C–F}$ = 286.1, 282.1 Hz), 149.9, 135.3, 129.9, 124.4 (dd, $J_{C–F}$ = 4.7, 1.3 Hz), 124.1, 122.5, 120.7 (d, $J_{C–F}$ = 4.4 Hz), 117.0 (dd, $J_{C–F}$ = 5.6, 1.8 Hz), 115.3, 87.7 (dd, $J_{C–F}$ = 27.2, 12.0 Hz), 83.6, 52.1, 28.4, 16.9.

^{11}B{^{1}H} NMR ($CDCl_3$, 128 MHz): δ = –3.70.

^{19}F NMR ($CDCl_3$, 376 MHz): δ = –91.63 (d, *J* = 55.4 Hz), –95.88 (d, *J* = 53.6 Hz).

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{19}H_{27}O_2N_2BF_2Na$: 387.2026; found: 387.2022.

(2-(Benzofuran-5-yl)-3,3-difluoroallyl)borane–trimethylamine Complex (26)

Oil (31 mg, 0.12 mmol, 59%); R_f = 0.19 [30% EtOAc/pentane].

IR (film): 2919, 2328, 2096, 1942, 1718, 1466, 1304, 1212, 1096, 997, 840, 739 cm^{-1}.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.61 (s, 1 H), 7.58 (s, 1 H), 7.43 (d, *J* = 8.6 Hz, 1 H), 7.34 (d, *J* = 8.6 Hz, 1 H), 6.73 (s, 1 H), 2.56 (s, 9 H), 1.59 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 153.9, 151.5 (dd, J_{C-F} = 285.9, 280.2 Hz), 145.1, 131.7 (dd, J_{C-F} = 5.4, 2.9 Hz), 127.3, 125.2, 121.2, 110.8, 106.9, 95.4 (dd, J_{C-F} = 23.5, 9.7 Hz), 52.1, 17.3.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.86 (t, J = 102.2 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –96.18 (d, J = 58.2 Hz), –96.97 (d, J = 58.2 Hz).

HRMS (ESI): m/z [M + Na]$^+$ calcd for $C_{14}H_{18}ONBF_2Na$: 278.1342; found: 288.1340.

(2-(Benzo[*b*]thiophen-5-yl)-3,3-difluoroallyl)borane–trimethylamine Complex (27)

Oil (22 mg, 0.08 mmol, 79%); R_f = 0.66 [40% EtOAc/pentane].

IR (film): 3420, 2922, 2342, 2093, 1829, 1715, 1480, 1440, 1220, 1052, 989, 702 cm^{-1}.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.84 (s, 1 H), 7.80 (d, J = 8.4 Hz, 1 H), 7.43–7.35 (m, 2 H), 7.30 (d, J = 5.3 Hz, 1 H), 2.56 (s, 9 H), 1.61 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 152.2 (dd, J_{C-F} = 286.3, 280.9 Hz), 139.7, 137.9, 133.2 (dd, J_{C-F} = 5.8, 3.5 Hz), 126.3, 125.2 (t, J_{C-F} = 3.3 Hz), 124.2, 123.6 (d, J_{C-F} = 3.6 Hz), 121.9, 95.3 (dd, J_{C-F} = 23.9, 9.4 Hz), 52.1, 16.6.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.87 (t, J = 102.4 Hz).

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –95.33 (d, J = 56.2 Hz), –96.17 (d, J = 56.2 Hz).

HRMS (ESI): m/z [M + Na]$^+$ calcd for $C_{14}H_{18}NSBF_2Na$: 304.1119; found: 304.1107.

(3,3-Difluoro-2-(2-methyl-2*H*-indazol-6-yl)allyl)borane–trimethylamine Complex (28)

Oil (37 mg, 0.13 mmol, 66%); R_f = 0.21 [40% EtOAc/pentane].

IR (film): 2999, 2924, 2336, 1715, 1631, 1464, 1208, 994, 840 cm^{-1}.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.79 (s, 1 H), 7.70 (s, 1 H), 7.54 (d, J = 8.7 Hz, 1 H), 7.16 (d, J = 8.7 Hz, 1 H), 4.17 (s, 3 H), 2.54 (s, 9 H), 1.60 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 152.2 (dd, J_{C-F} = 287.3, 281.5 Hz), 149.5, 134.8 (dd, J_{C-F} = 5.0, 3.4 Hz), 123.6 (dd, J_{C-F} = 3.6, 3.6 Hz), 123.3, 121.0, 119.0, 116.4 (dd, J_{C-F} = 3.7, 3.7 Hz), 95.8 (dd, J_{C-F} = 23.2, 9.5 Hz), 52.0, 40.3, 16.7.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.58 (t, J = 99.8 Hz).

^{19}F{^{1}H} NMR ($CDCl_3$, 565 MHz): δ = –94.90 (d, J = 54.3 Hz), –95.20 (d, J = 55.1 Hz).

HRMS (ESI): m/z [M + H]$^+$ calcd for $C_{14}H_{21}N_3BF_2$: 278.1791; found: 278.1793.

***N*-(4-(3-boraneyl-1,1-difluoroprop-1-en-2-yl)phenyl)-2-(4-chloro-2-methylphenoxy)propanamide–trimethylamine Complex (29)**

Oil (23 mg, 0.05 mmol, 26%); R_f = 0.29 [40% EtOAc/pentane].

IR (film): 2924, 2339, 1686, 1593, 1522, 1485, 1404, 1293, 1238, 1186, 1094, 1039, 996, 839 cm^{-1}.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 8.07 (s, 1 H), 7.40 (d, J = 8.5 Hz, 2 H), 7.30 (d, J = 8.5 Hz, 2 H), 7.11 (d, J = 2.5 Hz, 1 H), 7.03 (dd, J = 8.7, 2.5 Hz, 1 H), 6.68 (d, J = 8.7 Hz, 1 H), 4.63 (q, J = 6.8 Hz, 1 H), 2.47 (s, 9 H), 2.24 (s, 3 H), 1.57 (d, J = 6.8 Hz, 3 H), 1.45 (s, 2 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 169.9, 155.1, 153.7, 152.2 (dd, J_{C-F} = 287.6, 281.4 Hz), 135.1, 133.5 (dd, J_{C-F} = 5.5, 3.6 Hz), 131.2, 129.3, 129.2 (t, J_{C-F} = 3.7 Hz), 127.1, 119.5, 114.5, 94.7 (dd, J_{C-F} = 23.8, 9.2 Hz), 76.3, 52.0, 18.8, 16.5, 16.1.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = –3.69 (t, J = 81.1 Hz).

^{19}F{^{1}H} NMR ($CDCl_3$, 565 MHz): δ = –94.90 (d, J = 55.2 Hz), –95.51 (d, J = 54.4 Hz).

HRMS (ESI): m/z [M + Na]$^+$ calcd for $C_{22}H_{28}O_2NBClF_2Na$: 459.1793; found: 459.1796.

4,4′-(3,3-Difluoroprop-1-ene-1,2-diyl)bis(methoxybenzene) (34)

Oil (19 mg, 0.07 mmol, 65%); R_f = 0.26 [cyclohexane].

IR (film): 2935, 2838, 2109, 1609, 1511, 1246, 1178, 1028, 988 cm^{-1}.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 7.43 (d, J = 9.0 Hz, 2 H), 7.27 (d, J = 8.9 Hz, 2 H), 6.89 (d, J = 9.0 Hz, 2 H), 6.80 (d, J = 8.9 Hz, 2 H), 5.65 (s, 1 H), 5.58 (s, 1 H), 3.81 (s, 3 H), 3.78 (s, 3 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 160.8, 159.6, 145.0 (t, J_{C-F} = 26.3 Hz), 129.5, 129.1, 128.9 (t, J_{C-F} = 27.9 Hz), 127.6 (t, J_{C-F} = 5.4 Hz), 120.8 (t, J_{C-F} = 241.6 Hz), 118.0 (t, J_{C-F} = 7.9 Hz), 113.7, 113.7, 55.4, 55.3.

^{19}F{^{1}H} NMR ($CDCl_3$, 565 MHz): δ = –89.30.

HRMS (EI): m/z [M]$^+$ calcd for $C_{17}H_{16}O_2F_2$: 290.1112; found: 290.1113.

5-(4-(3,3-Difluoro-2-(4-methoxyphenyl)prop-1-en-1-yl)phenyl)-isoxazole (35)

Oil (15 mg, 0.05 mmol, 47%); R_f = 0.14 [10% EtOAc/pentane].

IR (film): 2926, 2322, 1740, 1603, 1509, 1458, 1290, 1239, 1183, 1029, 836, 793 cm^{-1}.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 8.31 (d, J = 1.8 Hz, 1 H), 7.82 (d, J = 8.1 Hz, 2 H), 7.60 (d, J = 8.3 Hz, 2 H), 7.29–7.25 (m, 2 H), 6.83–6.79 (m, 2 H), 6.57 (d, J = 1.9 Hz, 1 H), 5.71 (s, 1 H), 5.62 (s, 1 H), 3.79 (s, 3 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 168.6, 159.7, 151.0, 144.6 (t, J_{C-F} = 25.5 Hz), 138.4 (t, J_{C-F} = 28.3 Hz), 129.5, 128.7, 128.6, 126.8 (t, J_{C-F} = 5.5 Hz), 125.9, 120.2 (t, J_{C-F} = 242.3 Hz), 118.5 (t, J_{C-F} = 8.2 Hz), 113.8, 99.6, 55.4.

^{19}F{^{1}H} NMR ($CDCl_3$, 565 MHz): δ = –91.86.

HRMS (ESI): m/z [M + Na]$^+$ calcd for $C_{19}H_{15}O_2NF_2Na$: 350.0963; found: 350.0966.

5-(3,3-Difluoro-2-(4-methoxyphenyl)prop-1-en-1-yl)-2-(trifluoromethyl)pyridine (36)

Oil (16 mg, 0.05 mmol, 48%); R_f = 0.48 [10% EtOAc/pentane].

IR (film): 2936, 2307, 1738, 1608, 1512, 1335, 1251, 1139, 1034, 989, 837 cm^{-1}.

^{1}H NMR ($CDCl_3$, 600 MHz): δ = 8.81 (s, 1 H), 7.94 (dd, J = 8.2, 1.1 Hz, 1 H), 7.68 (d, J = 8.2 Hz, 1 H), 7.24 (d, J = 8.9 Hz, 2 H), 6.82 (d, J = 8.8 Hz, 2 H), 5.75 (s, 1 H), 5.64 (s, 1 H), 3.79 (s, 3 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 160.0, 149.5 (q, J_{C-F} = 35.9 Hz), 147.9 (t, J_{C-F} = 6.1 Hz), 143.8 (t, J_{C-F} = 24.7 Hz), 135.4, 135.3, 129.6, 127.7, 121.5 (q, J = 273.1 Hz), 120.1 (q, J_{C-F} = 2.7 Hz), 119.3 (t, J_{C-F} = 8.3 Hz), 119.1 (t, J_{C-F} = 242.0 Hz), 114.1, 55.4.

^{19}F{^{1}H} NMR ($CDCl_3$, 565 MHz): δ = –68.11, –92.57.

HRMS (ESI): m/z [M + Na]$^+$ calcd for $C_{16}H_{12}ONF_5Na$: 352.0731; found: 352.0732.

tert-Butyl 5-(3,3-Difluoro-2-(4-methoxyphenyl)prop-1-en-1-yl)-1*H*-pyrrolo[2,3-*b*]pyridine-1-carboxylate (37)

Oil (18 mg, 0.05 mmol, 46%); R_f = 0.30 [20% Et_2O/pentane].

IR (film): 2980, 2083, 1732, 1608, 1514, 1375, 1319, 1252, 1157, 1029, 838, 736 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 8.61 (d, *J* = 2.1 Hz, 1 H), 8.00 (d, *J* = 2.2 Hz, 1 H), 7.68 (d, *J* = 4.1 Hz, 1 H), 7.26 (d, *J* = 8.7 Hz, 2 H), 6.77 (d, *J* = 8.9 Hz, 2 H), 6.52 (d, *J* = 4.0 Hz, 1 H), 5.73 (s, 1 H), 5.62 (s, 1 H), 3.76 (s, 3 H), 1.66 (s, 9 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 159.7, 148.8, 147.9, 144.7 (t, J_{C-F} = 25.5 Hz), 143.4 (t, J_{C-F} = 5.6 Hz), 129.5, 128.5, 128.0, 127.5 (t, J_{C-F} = 27.9 Hz), 127.1 (d, J_{C-F} = 5.8 Hz), 122.4, 120.4 (t, J_{C-F} = 242.7 Hz), 118.5 (t, *J* = 8.0 Hz), 113.8, 104.8, 84.7, 55.3, 28.2.

$^{19}F\{^1H\}$ NMR ($CDCl_3$, 565 MHz): δ = –89.61.

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{22}H_{22}O_3N_2F_2Na$: 423.1491; found: 423.1491.

3-((5-(3,3-Difluoro-2-(4-methoxyphenyl)prop-1-en-1-yl)pyridin-2-yl)oxy)-5,5-dimethyl-4-(4-(methylsulfonyl)phenyl)furan-2(5*H*)-one (38)

Oil (25 mg, 0.05 mmol, 45%); R_f = 0.36 [50% EtOAc/pentane].

IR (film): 2934, 2306, 2088, 1769, 1603, 1513, 1479, 1313, 1241, 1150, 1094, 1030, 838, 771 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 8.26 (d, *J* = 1.3 Hz, 1 H), 7.99 (d, *J* = 8.5 Hz, 2 H), 7.77 (dd, *J* = 8.6, 2.5 Hz, 1 H), 7.70 (d, *J* = 8.5 Hz, 2 H), 7.26 (d, *J* = 8.9 Hz, 2 H), 6.98 (d, *J* = 8.6 Hz, 1 H), 6.82 (d, *J* = 8.8 Hz, 2 H), 5.65 (s, 1 H), 5.60 (s, 1 H), 3.79 (s, 3 H), 3.06 (s, 3 H), 1.75 (s, 6 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 165.7, 162.1, 159.9, 149.2, 145.8 (t, J_{C-F} = 6.1 Hz), 144.3, 144.1, 141.7, 138.0 (t, J_{C-F} = 4.9 Hz), 137.6, 134.9, 129.5, 129.0, 128.7 (t, J_{C-F} = 29.2 Hz), 128.2 (t, J_{C-F} = 26.2 Hz), 128.1, 119.7 (t, J_{C-F} = 244.7 Hz), 119.0 (t, J_{C-F} = 8.0 Hz), 113.9, 110.8, 84.6, 55.4, 44.5, 26.4.

$^{19}F\{^1H\}$ NMR ($CDCl_3$, 565 MHz): δ = –90.32.

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{28}H_{25}O_6NF_2SNa$: 564.1263; found: 564.1260.

Methyl 4-(3,3-Difluoro-1-(4-methoxyphenyl)prop-1-en-2-yl)benzoate (39)

Oil (20 mg, 0.06 mmol, 62%); R_f = 0.31 [20% EtOAc/cyclohexane].

IR (film): 2953, 2323, 2087, 2009, 1929, 1721, 1610, 1514, 1436, 1278, 1180, 1107, 1033, 988 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.93 (d, *J* = 8.4 Hz, 2 H), 7.40 (t, *J* = 8.1 Hz, 4 H), 6.88 (d, *J* = 8.9 Hz, 2 H), 5.79 (s, 1 H), 5.68 (s, 1 H), 3.90 (s, 3 H), 3.81 (s, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 166.7, 160.8, 145.0 (t, J_{C-F} = 26.9 Hz), 141.1, 129.7, 129.4, 128.2, 127.4 (t, J_{C-F} = 5.4 Hz), 120.4 (t, J_{C-F} = 242.2 Hz), 120.2 (t, J_{C-F} = 7.9 Hz), 113.7, 55.3, 52.1.

$^{19}F\{^1H\}$ NMR (565 MHz, $CDCl_3$): δ = –89.50.

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{18}H_{16}O_3F_2Na$: 341.0960; found: 341.0954.

Methyl 4-(1,1-Difluoro-3-hydroxyprop-1-en-2-yl)benzoate (40)

Oil (15 mg, 0.041 mmol, 41%); R_f = 0.14 [20% acetone/cyclohexane].

IR (film): 3440, 2954, 2329, 2091, 1709, 1610, 1437, 1281, 1191, 1108, 1010, 900 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 8.05 (d, *J* = 8.4 Hz, 2 H), 7.54 (d, *J* = 8.4 Hz, 2 H), 4.66–4.40 (m, 2 H), 3.93 (s, 3 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 166.8, 155.4 (dd, J_{C-F} = 298.5, 292.8 Hz), 137.0, 130.0, 129.5, 128.2 (t, J_{C-F} = 3.6 Hz), 93.1 (dd, J_{C-F} = 11.4, 8.7 Hz), 59.0 (dd, J_{C-F} = 4.8, 2.4 Hz), 52.3.

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –85.67 (dt, *J* = 28.1, 2.6 Hz), –85.81 (d, *J* = 28.1 Hz).

HRMS (EI): *m*/*z* [M]$^+$ calcd for $C_{11}H_{10}O_3F_2$: 228.0593; found: 228.0593.

Methyl 4-(1,1-Difluoro-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)prop-1-en-2-yl)benzoate (41)

Colorless oil (10 mg, 0.03 mmol, 42%); R_f = 0.45 [20% EtOAc/cyclohexane].

IR (film): 2981, 2316, 2095, 1930, 1815, 1719, 1610, 1437, 1350, 1277, 1105, 961 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.99 (d, *J* = 8.3 Hz, 2 H), 7.43 (d, *J* = 8.3 Hz, 2 H), 3.91 (s, 3 H), 1.97 (s, 2 H), 1.14 (s, 12 H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 167.0, 153.7 (dd, J_{C-F} = 292.2, 286.7 Hz), 140.3, 129.6, 128.6, 127.9 (t, J_{C-F} = 3.9 Hz), 88.8 (dd, J_{C-F} = 24.2, 13.9 Hz), 83.9, 52.2, 24.7, 11.5.

$^{11}B\{^1H\}$ NMR (193 MHz, $CDCl_3$): δ = 32.90.

^{19}F NMR ($CDCl_3$, 565 MHz): δ = –88.05 (d, *J* = 40.2 Hz), –89.53 (d, *J* = 39.2 Hz).

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{17}H_{21}O_4BF_2Na$: 361.1393; found: 361.1390.

Methyl 4-(3-(Chloro(trimethylamino)-λ^4-boranyl)-1,1-difluoroprop-1-en-2-yl)benzoate (42)

Oil (22 mg, 0.07 mmol, 69%, mixture 1:1.4 mono- and disubstituted); R_f = 0.41 [50% EtOAc/pentane].

IR (film): 2952, 2923, 2424, 2094, 1718, 1609, 1438, 1282, 1230, 1110, 836 cm^{-1}.

^1H NMR ($CDCl_3$, 600 MHz): δ = 7.98 (d, *J* = 8.5 Hz, 2 H), 7.45 (d, *J* = 7.1 Hz, 2 H), 3.90 (s, 3 H), 2.65 (s, 9 H), 1.73 (s, 1 H).

^{13}C NMR ($CDCl_3$, 151 MHz): δ = 167.2, 153.2 (dd, J_{C-F} = 289.2, 284.3 Hz), 141.1 (d, J_{C-F} = 3.9 Hz), 129.4, 128.7 (t, J_{C-F} = 3.6 Hz), 128.3, 93.3 (dd, J_{C-F} = 23.1, 12.1 Hz), 52.1, 49.8.

^{11}B NMR ($CDCl_3$, 193 MHz): δ = 4.33 (d, *J* = 122.9 Hz).

$^{19}F\{^1H\}$ NMR ($CDCl_3$, 565 MHz): δ = –91.37 (d, *J* = 46.2 Hz), –92.58 (d, *J* = 46.6 Hz).

HRMS (ESI): *m*/*z* [M + Na]$^+$ calcd for $C_{14}H_{19}O_2NBClF_2Na$: 340.1058; found: 340.1062.

Methyl 4-(1,1-Difluoro-3-(4-methyl-2,6-dioxotetrahydro-2*H*-4λ^4,8λ^4-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)prop-1-en-2-yl)benzoate (43)

Solid (23 mg, 0.06 mmol, 63%); mp 206–208 °C.

IR (film): 2961, 1748, 1706, 1605, 1437, 1278, 1231, 1100, 1033, 956, 863, 777 cm^{-1}.

^1H NMR (DMSO-d_6, 600 MHz): δ = 7.91 (d, *J* = 8.1 Hz, 2 H), 7.51 (d, *J* = 8.0 Hz, 2 H), 4.15 (d, *J* = 17.0 Hz, 2 H), 3.97 (d, *J* = 17.0 Hz, 2 H), 3.84 (s, 3 H), 2.87 (s, 3 H), 1.80 (s, 2 H).

^{13}C NMR (DMSO-d_6, 151 MHz): δ = 168.5, 166.0, 153.2 (t, J_{C-F} = 288.3 Hz), 139.9 (d, J_{C-F} = 1.9 Hz), 129.0, 128.6 (t, J_{C-F} = 3.4 Hz), 128.1, 90.7 (d, J_{C-F} = 12.6 Hz), 90.6 (d, J_{C-F} = 12.3 Hz), 61.6, 52.1, 45.5.

^{19}F NMR (DMSO-d_6, 565 MHz): δ = –89.87 (d, J = 44.0 Hz), –91.56 (d, J = 43.8 Hz).

HRMS (ESI): m/z [M + Na]$^+$ calcd for $C_{16}H_{16}BF_2NO_6Na$: 390.0936; found: 390.0932.

Conflict of Interest

The authors declare no conflict of interest.

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