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# Iron-Based Catalyst for Borylation of Unactivated Alkyl Halides without Using Highly Basic Organometallic Reagents

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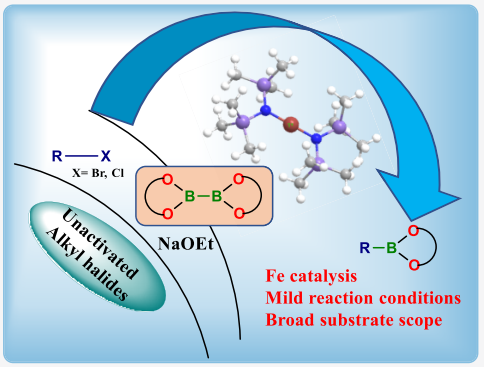
**ABSTRACT:** The mild borylation of alkyl bromides and chlorides with bis(neopentylglycolato)diborane ($B_2neop_2$) mediated by iron-bis amide is described. The reaction proceeds with a broad substrate scope and good functional group compatibility. Moreover, sufficient catalytic activity was obtained for primary and secondary alkyl halides. Mechanistic studies indicate that the reaction proceeds through a radical pathway.






Increasing attention has been devoted to the development of earth-abundant elements in catalysis for various cross-coupling reactions in recent years.[1] The importance of iron has been recognized for the functionalization and transformation of organic/inorganic substrates, because of the high efficiency, low cost, and minimal environmental impact.[2] Following seminal work by Hartwig and co-workers,[3a] iron has received greater attention for the facile C-H activation;[3b,c] however, its application in catalytic borylation reaction remains an elusive challenge in this field.[4] Alkylboronic acids and esters are imperative reagents in synthetic chemistry, pharmaceutical production, and other scientific fields because of their exclusive reactivity. They are also indispensable units used in carbon−carbon and carbon−heteroatom bond forming transformations.[5] For the synthesis of alkylboronic esters, the direct C-H borylation using alkanes was found to be more advantageous.[6] However, the product selectivity of this method is mainly controlled by steric factors.[7] An alternative method, employing an alkyl halide as starting material was developed using organolithium/magnesium reagents. This procedure has substantial limitations and low functional group tolerance.

Along this line, the nucleophile substitution reaction of boryl species with alkyl electrophiles, mainly alkyl halides, emerged as a complementary and distinct synthetic strategy for the synthesis of alkylboronic esters.[8] Several transition metal complexes containing Ir,[9] Pd,[10] Zn,[11] Cu,[12] Ni,[13] Mn,[14] and Co[15] elements have emerged as key players to catalyze this process. Although a recent report of iron catalysis yielding alkylboronic esters through hydroborylative cyclization[16] has been an interesting pathway, the reports of Fe catalysts for alkyl halide activation have been scarce.[17] In 2014, Cook[18] and Bedford[19] independently reported a direct cross-coupling of alkyl halides with bis(pinacolato)diboron, catalyzed by iron salts. These methods need a reactive organometallic reagent, EtMgBr and $^t$BuLi, respectively, to facilitate this transformation (Scheme 1). Our campaign to study the C-X borylation revealed that the use of NHC-Co catalyst was effective to cleave the C−X bond of both aryl[20] as well as alkyl halides.[15] Moreover, we have also shown iron-catalyzed hydroboration of carbonyls[21] using HBpin, where $Fe[N(Si(CH_3)_3)_2]_2$ (**A**) proved to be an effective pre-catalyst. Thus, we speculated that there is an opportunity to extend the catalytic efficiency of $Fe[N(Si(CH_3)_3)_2]_2$ to C−X (X = Cl, Br) bond activation. We herein report an iron amide catalyzed borylation of primary, secondary, and some tertiary alkyl halides with bis(neopentylglycolato)diborane ($B_2neop_2$) as borylating agent to produce alkylboronic esters from bromides and chlorides.

At first, we examined the reaction of Fe(II)amide (**A**)-catalyzed borylation reaction with 5 mol % of catalyst loading using primary alkyl bromide **1a** with $B_2neop_2$ (**2a**) in the presence of a base; the reaction proceeded in MTBE at 85 °C for 16 h to produce 63% of desired borylated product (**3a**), along with the formation of 16% protodehalogenated (**B**), and 5% homocoupled byproducts (**C**) (Table 1; entry 1). When the base was changed from Li$O^t$Bu to K$O^t$Bu, Na$O^t$Bu produced **3a** in merely comparable yields (entries 2 and 3),

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**Scheme 1. Iron-Catalyzed Borylation of Unactivated Alkyl Halides**

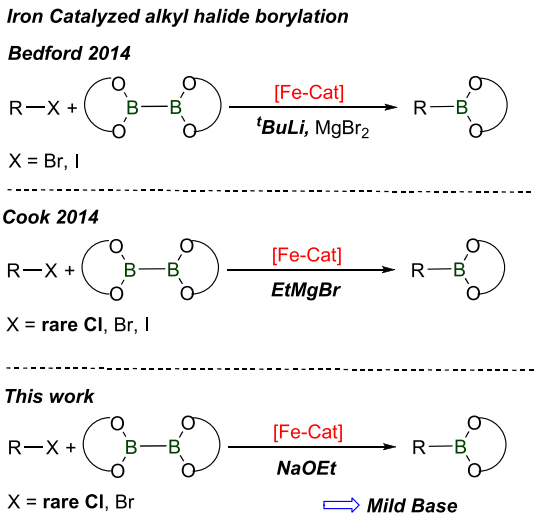
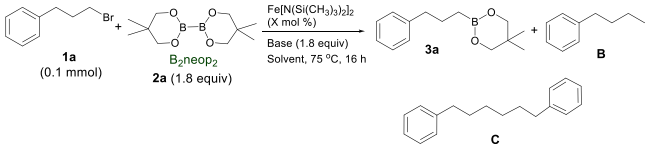



**Table 1. Optimization of Reaction Conditions for the Borylation of 1-Bromo-3-phenyl Propane (1a) Catalyzed by Iron Complex[a]**




| entry | catalyst (mol %) | base | solvent | yield[b] |
|---|---|---|---|---|
| 1 | **A** (5) | LiO$^t$Bu | MTBE | 63 |
| 2 | **A** (5) | KO$^t$Bu | MTBE | 65 |
| 3 | **A** (5) | NaO$^t$Bu | MTBE | 67 |
| 4 | **A** (5) | LiOMe | MTBE | 16 |
| 5 | **A** (5) | NaOEt | MTBE | 40 |
| 6 | **A** (10) | | MTBE | trace |
| 7 | **A** (10) | NaOEt | THF | 50 |
| 8 | **A** (10) | NaOEt | CPME | 55 |
| 9 | **A** (10) | NaOEt | hexane | 31 |
| 10 | **A** (10) | NaOEt | toluene | 44 |
| 11 | **A** (10) | NaOEt | benzene | 48 |
| 12 | **A** (10) | NaOEt | MTBE | 95 (88)[c] |
| 13 | $FeCl_2$(10) | NaOEt | MTBE | 23 |
| 14 | $FeCl_3$(10) | NaOEt | MTBE | 45 |
| 15 | $Fe(acac)_3$ (10) | NaOEt | MTBE | 46 |
| 16 | $Li[N(TMS)_2]$ (20) | NaOEt | MTBE | 6 |
| 17 | **D** (10) | NaOEt | MTBE | 67 |
| 18 | **D** (15) | NaOEt | MTBE | 98 (87)[c] |

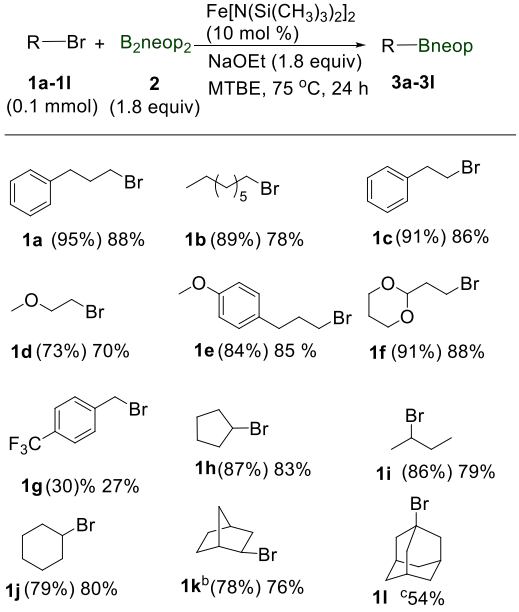
[a]Conditions: **1a** (0.1 mmol), **2a** (0.18 mmol), base (0.18 mmol), and Fe catalyst (5−10 mol %) were used at 75 °C in 750 $\mu$L of solvent. [b]Yields were determined by $^1$H NMR. [c]Isolated yield (**A** = $Fe[N(Si(CH_3)_3)_2]_2$; **D** = $Fe(N(Si(CH_3)_3)_2)_2Cl(THF)$.

and the yield reduced to 16% when LiOMe was used as a base (entry 4). When NaOEt was employed as a base, the desired ester (**3a**) was obtained in comparatively higher yield of 40% (entry 5) with less amount of protodehalogenated product (see Supporting Information (SI); Table S5). Importantly, in the absence of base, the reaction does not proceed (entry 6). Reactions in a more polar solvent like THF or less polar solvents such as CPME (cyclopentyl methyl ether), hexane, toluene, and benzene were less effective (entries 7−11). Further optimization was focused on the catalyst loading. We were pleased to observe that the catalyst loading of 10 mol % gave **3a** in 88% yield (entry 12). Use of $B_2pin_2$ as diboron reagent instead of $B_2neop_2$ led to a noticeable decrease in the yield of **3a** (66%) (see Supporting Information; Table S5, entry 6).

Encouraged by these results, we further screened various iron sources for the catalytic borylation reaction of our interest. This comprised commercially available ferrous and ferric salts, such as $FeCl_2$, $FeCl_3$, and $Fe(acac)_3$ (Table 1, entries 13−15). All of these choices of catalyst did not prove to be efficient as that of Fe(II)amide catalyst **A**. Conducting the reaction with 20 mol % of $Li[N(Si(CH_3)_3)_2]$ as catalyst caused the yield of **3a** to be 6% (entry 16). During the development of an iron based catalyst for the borylation of alkyl halides, Cook and co-workers observed that using iron(III) acetoacetate as a catalyst enables the direct cross-coupling of alkyl halides with a diboron reagent.[18] Hence, we also examined Fe(III) compound (**D**) as a catalyst. Intriguingly, compound **D** is as effective as catalyst **A**, but only with higher catalyst loading (Table 1, entries 17 and 18).

With the optimized conditions in hand, we investigated the reaction scope of this catalyst system using a variety of commercially and noncommercially available alkyl halides including alkyl chlorides (Schemes 2 and 3). Several acyclic primary alkyl bromides worked efficiently, leading to high reaction yields (**1a−1c**, 90−95% yield). Alkyl bromides bearing ether groups, such as (2-bromoethoxy)benzene (**1d**), 1-(3-bromopropyl)-4-methoxybenzene (**1e**), and 2-(2-bromoethyl)-1,3-dioxane (**1f**), afforded excellent yields of the corresponding products (**3d−3f**). *p*-Trifluoromethyl benzyl bromide (**1g**) was also suitable for this reaction, affording the

**Scheme 2. Substrate Scope of Fe-Catalyzed Borylation of Unactivated Alkyl Bromides[a]**




[a]Conditions: alkyl halide (0.1 mmol), **2a** (1.8 equiv), NaOEt (1.8 equiv), and Fe catalyst (10 mol %) were used at 75 °C in 750 $\mu$L of solvent. $^1$H NMR yields are given in parentheses. [b]*exo*-2-Bromonorbornane was used. [c](**A**) (15 mol %) and the reaction was carried out for 22 h.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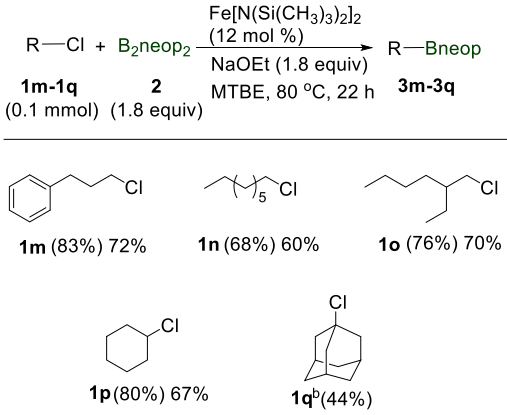
**Scheme 3. Substrate Scope of Fe-Catalyzed Borylation of Unactivated Alkyl Chlorides**[a]




[a]Conditions: alkyl chlorides (0.1 mmol), **2** (1.8 equiv), NaOEt (1.8 equiv), and **A** (12 mol %) in MTBE as a solvent at 80 °C for 22 h. $^1$H NMR yields are given in parentheses. [b](**A**) 15 mol % and the reaction was carried out for 25 h at 80 °C.

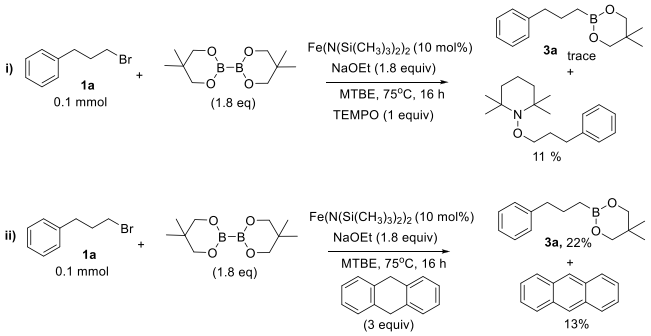
corresponding borylated product, **3g**, in moderate yield. Noticeably, when cyclic and acyclic secondary alkyl bromides were used as substrates (**1h**−**1k**), relevant alkylboronates were obtained in moderate to good yields. The tertiary bromide substrate required higher catalyst loading and reaction temperature (see SI). Reaction with 1-bromo adamantane (**1l**), gave the desired product (**3l**) in moderate yield (54%).

Since the previous reports[18,19] showed limitation toward alkyl chlorides, we were interested in investigating the scope of this reaction to the inexpensive and easily accessible alkyl chlorides, using 3-phenylpropyl chloride (**1m**) as model reacting partner. A better result was obtained with 12 mol % of **A**, 1.8 equiv of **2a** and NaOEt, using MTBE as the solvent at 80 °C for 22 h (**3a**, 82%; see SI). As shown in Scheme 3, both primary and secondary alkyl chlorides gave the corresponding alkyl boronates in moderate to good yields. The alkyl chlorides bearing acyclic substituents (**1n**−**1o**) reacted well to afford the desired products **3n**−**3o** in good yields. Cyclohexyl chloride (**1p**) was also suitable for this reaction, giving the desired product in moderate yield. Tertiary alkyl chloride, **1q**, also worked by using a higher amount of catalyst, albeit with lower yield (**3q** = 44%).

To gain some mechanistic understanding on this transformation, several control experiments were carried out. Bedford and co-workers have shown that the combination of activated borate ion and the phosphine ligated iron(I) boryl complex induces the borylation of alkyl halides. Consequently, we probed whether this catalytic reaction mechanism involved any iron boryl intermediate; reaction between an equimolar mixture of Fe-catalyst **A** and diborane on 75 °C led to a rapid change from a dark green suspension to a deep red solution. Monitoring the reaction by $^{11}$B{$^1$H} NMR spectroscopy showed that the $(Me_3Si)_2$N-Bneop is the major by product, along with the formation of an Fe-boryl complex and other boron containing species. However, this experiment proved largely uninformative, due to the paramagnetic nature of the metal center, and all our attempts to isolate an Fe-boryl complex failed due to the lack of stabilization by the labile ligand as well as their extreme sensitivity toward air and moisture.

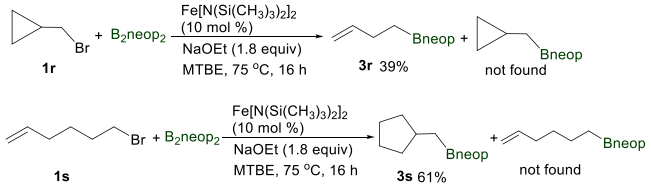
To probe the involvement of the radical, substrate **1a** was subjected to the standard reaction conditions in the presence of TEMPO; the reaction proceeded to give only a trace amount of borylated product **3a** and 11% of TEMPO coupled product. The catalytic borylation reactions of **1a** in standard reaction conditions in the presence of 9,10-dihyroanthracene also suppressed the formation of borylated product significantly and produced anthracene as side product, further verifying the radical mechanism (Scheme 4). Moreover, when

**Scheme 4. Mechanistic Investigations of Fe-Catalyzed Borylation of Unactivated Alkyl Halides on a Radical Mediated Process via Scavenger Experiments**




a radical clock experiment was conducted using **1r** as a substrate, the isolation of ring opening product (**3r**) suggests the radical-mediated process. Further, the formation of the cyclized product, cyclopentylmethyl-boronate (**3s**), from the borylation reaction of 6-bromohex-1-ene (**1s**) also confirms that the reaction proceeds via a radical-based mechanism (Scheme 5). However, detailed mechanistic studies are required to confirm the existence of the C-center radical in these reaction conditions.

**Scheme 5. Radical Clock Experiments for Fe-Catalyzed Borylation of Unactivated Alkyl Halides on a Radical Mediated Process**




The scope of boron protecting groups was examined using 1,8-diaminonaphthalene (DAN)[28] and trifluoroborate salt.[29] Alkyl-Bneop compound **3a** can be efficiently converted into the corresponding alkyl-Bdan and alkyl-$BF_3$K (82% and 99% conversion, respectively, Experiment S2 a, SI). Next, we exhibit synthetic transformations of **3a**, as the reactivity of alkyl-Bneop is not well-known, while transformations of alkyl-Bpin are very well-established. Reactions of **3a** with 0.66 equiv of alkyl halide was performed in the presence of 5 mol % of $Pd(OAc)_2$ as a catalyst[30] with 3 equiv of KO$^t$Bu as base. The coupling product was obtained in moderate yield after the mixture was refluxed at 70 °C for 24 h (Experiment S2 b, SI)

In conclusion, we have developed an Fe(II)-bis amide catalyzed borylation of alkyl halides, achieving high yields for a variety of derivatives bearing different functional groups. The methodology enables the borylation of alkyl halides, without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the use of reductive organometallic reagents. The reaction conditions are mild, and all the reagents are readily available and inexpensive. Unlike other previous methods, the system was also efficient for alkyl chloride substrates. Radical clock experiments demonstrated the involvement of a radical mechanism. Future work will focus on more detailed mechanistic studies and to find a next generation iron catalyst with improved scope and activity.

## EXPERIMENTAL SECTION

**General Information.** Unless otherwise mentioned, all the reactions are performed in a nitrogen filled MBraun glovebox or using the standard Schlenk technique. All chemicals are purchased from either Sigma-Aldrich, Alfa Aesar, or Avra-chemicals and used without further purification. Bis(neopentylglycolato)diborane ($B_2neop_2$) and bis(pinacolato)diborane ($B_2pin_2$) were obtained from AllyChem Co. Ltd., China, and were used after further purification by a sublimation process. Reagent grade solvents are purchased from SD Fine Chemicals (India), distilled according to a standard procedure, degassed by a freeze pump thaw cycle (three to four times), and stored under molecular sieves before using. MTBE was further passed through activated alumina in a nitrogen atmosphere and stored in molecular sieves. $CDCl_3$ and $C_6D_6$ were purchased from either Cambridge Isotope Laboratories or Sigma-Aldrich and deoxygenated by a freeze pump thaw cycle and stored over molecular sieves before use. NMR spectra [$^1H$ (400 MHz), $^{13}C\{^1H\}$ (100 MHz), and $^{11}B\{^1H\}$ (128 MHz) were recorded by a Bruker Avance 400 MHz NMR spectrometer at an ambient temperature. $^1H$ NMR chemical shifts are reported relative to TMS and were referenced via residual proton resonances of the corresponding deuterated solvent ($CDCl_3$: 7.26 ppm, $C_6D_6$: 7.16 ppm), whereas $^{13}C\{^1H\}$ NMR spectra are reported relative to TMS using the carbon signals of the deuterated solvent ($CDCl_3$: 77.16 ppm). $^{11}B\{^1H\}$ NMR signals are quoted relative to $BF_3$. $^1H$ NMR yield was calculated as $CH_3NO_2$ (nitromethane) as an internal standard. GC−MS data were acquired using a GCMS-QP2010 SE SHIMADZU system. Commercially available, precoated TLC sheets ALUGRAM Xtra Sil G/UV254 were purchased from MACHEREY-NAGEL GmbH & Co. KG. The removal of solvent was performed on a rotary evaporator in vacuo at a maximum temperature of 55 °C. N-Heterocyclic carbene IMes (1,3-bis(2,4,6-trimethylphenyl)midazole-2-ylidene)[22a] and iron complexes $Fe(N(Si(CH_3)_3)_2)_2$ and $Fe(N(Si(CH_3)_3)_2)_2Cl(THF)$ were synthesized similar to the reported literature procedure.[21,22b]

**General Procedure A.** *For Small Scale Catalytic Reactions.* In a glass vial equipped with a magnetic stirring bar, a catalytic amount of stock solution (0.38 M) of Fe-catalyst in hexane as $x$ mol % ($x$ = 10 for R-Br, $x$ = 12 for R-Cl, $x$ = 15 for tertiary alkylhalides) in hexane was taken; then NaOEt (1.8 equiv, 0.018 mmol, 12.3 mg) and diborane $B_2neop_2$ (1.8 equiv, 0.018 mmol, 40.5 mg) were added. To this, alkyl halide substrate (0.01 mmol) and MTBE (750 $\mu$L) were added. The vials were properly capped with an aluminum based septum before bringing out of the glovebox, further wrapped with Teflon-tape to secure the septum, and left for stirring on an oil bath at 75 °C for 16−22 h. After the completion, the reaction was quenched by being exposed to air and 3 mL of a hexane and ether mixture (7:3) was added. Further workup was done by passing the reaction mixture with a Celite and silica mixture (2:1), followed by washing the mixture with diethyl ether. The solvent was removed in vacuo, and the product was dried using reduced pressure. The NMR sample was prepared in $CDCl_3$ using nitromethane as internal standard.

**General Procedure B.** *For Larger Scale Catalytic Reactions.* In a 50 mL airtight Teflon tube equipped with a magnetic stirring bar, $Fe(N(Si(CH_3)_3)_2)_2$ catalyst, in the form of a homogeneous stock solution (0.38M) in hexane was taken in an amount as $x$ mol % ($x$ = 10 for R-Br, $x$ = 12 for R-Cl, $x$ = 15 for tertiary alkylhalides). To this, 1.8 equiv of base NaOEt (1.8 mmol, 123 mg) and diborane $B_2neop_2$ (1.8 mmol, 405 mg) were added; then 1 equiv of alkyl halides substrates (1 mmol) was added, followed by addition of 5 mL of solvent MTBE. The reaction was performed in an oil bath installed at the desired temperature for the optimized reaction time for various substrates. After completion, the reaction was quenched by exposing the mixture to air, and the mixture was diluted with the addition of 20 mL of hexane (or pentane). The mixture was filtered with paddings of Celite-silica (2:1) and washed with diethyl ether (2 × 3 mL). Solvent was evaporated under reduced pressure not more than a temperature of 55 °C. The borylated product was further purified by silica gel chromatography mostly eluted with a 2:98 solution of EtOAc and hexane.

**Experimental Procedures and Characterization Data.** *5,5-Dimethyl-2-(3-phenylpropyl)-1,3,2-dioxaborinane (**3a** and **3m**).*[10b] Compounds **3a** and **3m** were obtained following general procedure **B** as colorless oils in 88% yield (204 mg) from **1a** (199 mg, 1.0 mmol) and also in 72% yield (167 mg) with **1m** (155 mg, 1.0 mmol). Product was purified by silica gel column chromatography eluted with an EtOAc:hexane (2:98) mixture. $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.31−7.28 (m, 2H), 7.23−7.17 (m, 3H), 3.60 (s, 4H), 2.65 (t, $J$ = 7.6 Hz, 2H), 1.76 (p, $J$ = 7.8 Hz, 2H), 0.98 (s, 6H), 0.81 (t, $J$ = 7.8 Hz, 2H). $^{11}B\{^1H\}$ NMR (128 MHz, $CDCl_3$) $\delta$ 30.3. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) $\delta$ 143.1, 128.7, 128.2, 125.6, 72.0, 38.9, 31.7, 26.3, 21.8, 14.7 (C-B). GC−MS $m/z$: $(M)^+$ 232.

*5,5-Dimethyl-2-octyl-1,3,2-dioxaborinane (**3b** and **3n**).*[23] Compounds **3b** and **3n** were obtained following general procedure **B** as colorless oils in 78% yield (177 mg) from **1b** (192 mg, 1.0 mmol) and also in 60% yield (136 mg) with **1n** (149 mg, 1.0 mmol). Product was purified by silica gel column chromatography eluted with an EtOAc:hexane (2:98) mixture. $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 3.52 (s, 4H), 1.29−1.21 (m, 11H), 0.89 (s, 6H), 0.82 (m, 4H), 0.64 (t, $J$ = 7.8 Hz, 2H). $^{11}B\{^1H\}$ NMR (128 MHz, $CDCl_3$) $\delta$ 30.5. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) $\delta$ 72.0, 32.7, 32.0, 29.6, 29.4, 24.2, 22.8, 21.9, 14.1. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. GC−MS $m/z$: $(M)^+$ 226.

*5,5-Dimethyl-2-phenethyl-1,3,2-dioxaborinane (**3c**).*[24] Compound **3c** was obtained following general procedure **B** as a colorless oil in 86% yield (187 mg) from **1c** (184 mg, 1.0 mmol). Product was purified by silica gel column chromatography eluted with an EtOAc:hexane (2:98) mixture. $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.35−7.30 (m, 4H), 7.28−7.19 (m, 1H), 3.65 (s, 4H), 2.80 (t, $J$ = 8 Hz, 2H) 1.17 (t, $J$ = 8.2 Hz, 2H), 0.98 (s, 6H). $^{11}B\{^1H\}$ NMR (128 MHz, $CDCl_3$) $\delta$ 30.3. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) $\delta$ 145.1, 128.2, 128.1, 125.4, 71.9, 31.7, 30.2, 21.9. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. GC−MS $m/z$: $(M)^+$ 218.

*2-(2-Methoxyethyl)-5,5-dimethyl-1,3,2-dioxaborinane (**3d**).* Compound **3d** was obtained following general procedure **B**, using pentane and diethyl ether solution for chromatography, as a colorless oil in 70% yield (120 mg) from **1d** (139 mg, 1.0 mmol) in a 5:95 $Et_2O$ and pentane solution. Product was purified by silica gel column chromatography eluted with a $Et_2O$:pentane (10:90) mixture. $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 3.52 (s, 4H), 3.43 (m, 2H), 3.26 (s, 3H), 0.89 (s, 6H), 0.69 (m, 2H). $^{11}B\{^1H\}$ NMR (128 MHz, $CDCl_3$) $\delta$ 30.7. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) $\delta$ 72.2, 58.3, 34.3, 31.8, 22.5. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. HRMS (ESI) $m/z$ $(M + Na)^+$ calc for $C_8H_{17}BNaO_3$ 195.1168, found 195.1155.

*2-(3-(4-Methoxyphenyl)propyl)-5,5-dimethyl-1,3,2-dioxaborinane (**3e**).* Compound **3e** was obtained following general procedure **B** as a colorless oil in 85% yield (222.7 mg) from **1e** (228 mg, 1.0 mmol). Product was purified by silica gel column chromatography eluted with an EtOAc:hexane (2:98) mixture. $^1H$ NMR (400 MHz, $CDCl_3$) $\delta$ 7.10−7.08 (m, 2H), 6.82−6.80 (m, 2H), 3.78 (s, 3H), 3.57 (s, 4H), 2.54 (t, $J$ = 7.6 Hz, 2H), 1.67 (p, $J$ = 7.8 Hz, 2H), 0.95 (s, 6H), 0.75 (t, $J$ = 7.9, 2H). $^{11}B\{^1H\}$ NMR (128 MHz, $CDCl_3$) $\delta$ 30.7. $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) $\delta$ 157.7, 135.3, 129.6, 113.7, 72.1, 55.4, 37.9, 22.0, 14.2. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. HRMS (ESI) $m/z$ $(M + H)^+$ calc for $C_{15}H_{24}BO_3$ 263.1819, found 263.1798.


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*2-(2-(1,3-Dioxan-2-yl)ethyl)-5,5-dimethyl-1,3,2-dioxaborinane (**3f**).* Compound **3f** was obtained following general procedure **B** as a colorless oil in 88% yield (201 mg) from **1f** (194 mg, 1.0 mmol) in an 8:92 EtOAc and hexane solution. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 4.44 (t, $J$ = 5.2 Hz, 1H), 4.06 (dd, $J$ = 5.0 Hz, 10.7 Hz, 2H), 3.73 (dt, $J$ = 2.1 Hz, 12.4 Hz, 2H), 3.55 (s, 4H), 2.10−1.99 (m, 1H), 1.68−1.62 (m, 2H), 1.30−1.23 (m, 1H), 0.92 (s, 6H), 0.73 (t, $J$ = 7.8 Hz, 2H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 30.4. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$) $\delta$ 103.7, 72.1, 67.0, 31.7, 29.7, 26.0, 22.0. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. HRMS (ESI) $m/z$ (M + Na)$^+$ calc for $C_{11}H_{21}BNaO_4$ 251.1431, found 251.1455.

*5,5-Dimethyl-2-(4-(trifluoromethyl)benzyl)-1,3,2-dioxaborinane (**3g**).* Compound **3g** was obtained following general procedure **B** as a yellowish liquid in 27% yield (73 mg) from **1g** (239 mg, 1.0 mmol). Product was purified by flash column chromatography eluted with an EtOAc:hexane (1:99) mixture. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 7.39−7.38 (m, 2H), 7.17−7.16 (m, 2H), 3.51 (s, 4H), 2.19 (s, 2H) 0.84 (s, 6H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 30.3. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$): $\delta$ 144.5, 129.2, 125.1, 72.4, 31.8, 21.9. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. HRMS (ESI) $m/z$ (M)$^+$ calc for $C_{13}H_{16}BF_3O_2$ 272.1195, found 272.1208. GC−MS $m/z$: (M)$^+$ 272.

*2-Cyclopentyl-5,5-dimethyl-1,3,2-dioxaborinane (**3h**).*[25] Compound **3h** was obtained following general procedure **B** as a colorless oil in 83% yield (151 mg) from **1h** (151 mg, 1.0 mmol. Product was purified by silica gel column chromatography eluted with an EtOAc:hexane (2:98) mixture. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 3.59 (s, 4H), 1.74−1.68 (m, 2H), 1.57−1.48 (m, 7H), 0.95 (s, 6H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 30.8. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$) $\delta$ 72.2, 31.8, 29.8, 28.8, 27.0, 21.9. GC−MS $m/z$: (M − $CH_3$)$^+$ 167.

*2-(sec-Butyl)-5,5-dimethyl-1,3,2-dioxaborinane (**3i**).*[26] Compound **3i** was obtained following general procedure **B** as a colorless oil in 79% yield (134.2 mg) from **1i** (136 mg, 1.0 mmol. Product was purified by silica gel column chromatography eluted with an EtOAc:hexane (2:98) mixture. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 3.58 (s, 4H), 1.47−1.42 (m, 1H), 1.32−1.28 (m, 2H), 0.95 (s, 6H), 0.93−0.89 (m, 3H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 30.7. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$) $\delta$ 72.1, 31.8, 27.5, 26.2, 15.6, 13.8. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. GC−MS $m/z$: (M)$^+$ 170.

*2-Cyclohexyl-5,5-dimethyl-1,3,2-dioxaborinane (**3j** and **3p**).*[25] Compounds **3j** and **3p** were obtained following general procedure **B** as colorless oils in 80% yield (156 mg) from **1j** (162 mg, 1.0 mmol) and also in 67% yield (131 mg) with **1p** (118 mg, 1.0 mmol). Product was purified by silica gel column chromatography eluted with an EtOAc:hexane (2:98) mixture. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 3.57 (s, 4H), 1.72−1.49 (m, 9H), 1.28−1.26 (m, 2H), 0.94 (s, 6H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 30.2. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$) $\delta$ 72.1, 32.8, 28.4, 27.6, 27.1, 21.9. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. GC−MS $m/z$: (M)$^+$ 196.

*2-((1R,2R,4R)-Bicyclo[2.2.1]heptan-2-yl)-5,5-dimethyl-1,3,2-dioxaborinane (**3k**).* Compound **3k** was obtained following general procedure **B** as a colorless oil in 76% yield (158 mg) from **1k** (174 mg, 1.0 mmol). Product was purified by silica gel column chromatography eluted with an EtOAc:hexane (2:98) mixture. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 3.57 (s, 4H), 2.27−2.12 (m, 1H), 1.62−1.47 (m, 6H), 1.28−1.24 (m, 4H), 0.93 (s, 6H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 30.4. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$) $\delta$ 72.2, 38.9, 38.2, 36.8, 32.5, 32.3, 29.5, 23.5, 21.9. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. HRMS (ESI) $m/z$ (M + $CH_3OH$ + Na)$^+$ calc for $C_{13}H_{25}BNaO_3$ 263.1794, found 263.1775. GC−MS $m/z$: (M − $CH_3$)$^+$ 181.

*2-((3r,5r,7r)-Adamantan-1-yl)-5,5-dimethyl-1,3,2-dioxaborinane (**3l** and **3q**).* Compounds **3l** and **3q** were obtained following general procedure **B** as white solids in 54% yield (134 mg) from **1l** (214 mg, 1.0 mmol) and also in 44% yield (75 mg) with **1q** (170 mg, 1.0 mmol). Product was purified by flash column chromatography eluted with hexane. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 3.57 (s, 4H), 1.85(m, 3H) 1.75−1.72 (m, 12H), 0.93 (s, 6H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 29.5. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$) $\delta$ 72.1, 38.4, 37.8, 31.7, 28.1, 27.8, 21.8. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. HRMS (ESI) $m/z$ (M + Na)$^+$ calc for $C_{15}H_{25}BNaO_2$ 271.1845, found 271.1863. GC−MS $m/z$: (M)$^+$ 248.

*2-(2-Ethylhexyl)-5,5-dimethyl-1,3,2-dioxaborinane (**3o**).*[15] Compound **3o** was obtained following general procedure **B** as a colorless oil in 70% yield (158 mg) from **1o** (148 mg, 1.0 mmol). Product was purified by silica gel column chromatography eluted with an EtOAc:hexane (2:98) mixture. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 3.57 (s, 4H), 1.51−1.42 (m, 1H), 1.32−1.15 (m, 8H), 0.91 (s, 6H), 0.91−0.82 (m, 7H), 0.65 (m, 1H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 30.7. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$) $\delta$ 72.1, 36.0, 35.7, 29.4, 23.2, 22.1, 22.0, 14.3. The carbon directly attached to the boron atom was not detected, likely due to quadrupolar broadening. GC−MS $m/z$: (M − $CH_3$)$^+$ 211.

**Radical Clock Experiment.** *2-(But-3-en-1-yl)-5,5-dimethyl-1,3,2-dioxaborinane (**3r**).*[27] In a glass vial equipped with a magnetic stirring bar, a catalytic amount of a stock solution of Fe-catalyst (10 mol %; 0.38 M) in hexane was taken; then NaOEt (1.8 equiv, 0.018 mmol, 12.3 mg) and diborane $B_2neop_2$ (1.8 equiv, 0.018 mmol, 40.5 mg) were added. Following that, the substrate (bromomethyl)-cyclopropane and solvent MTBE (750 $\mu$L) were added. The vials were properly capped with an aluminum based septum before bringing out of the glovebox and left for stirring on an oil bath at 75 °C for 16 h. The reaction mixture was quenched while exposing it to air, and 3 mL of pentane was added. The mixture was further passed through a Celite and silica mixture (1:1), followed by washing with a solution of 30% ether in pentane (2 × 3 mL). Solvent was evaporated under reduced pressure, and the NMR sample was made in $CDCl_3$ using nitromethane as internal standard. Borylated product **3r** was obtained as a colorless oil in 39% yield (65 mg) from **1r** (135 mg, 1.0 mmol). Product was purified by silica gel column chromatography eluted with a $Et_2O$:pentane (2:98) mixture. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 5.90 (m, 1H), 5.02−4.97(m, 1H), 4.91−4.87(m, 1H), 3.59 (s, 4H), 2.05−2.04 (m, 2H), 0.95 (s, 6H), 0.86−0.84 (m, 2H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 30.4. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$) $\delta$ 141.5, 112.9, 72.2, 32.4, 28.2, 23.58, 22.0. GC−MS $m/z$: (M)$^+$ 168.

*2-(Cyclopentylmethyl)-5,5-dimethyl-1,3,2-dioxaborinane (**3s**).* In a glass vial equipped with a magnetic stirring bar, a catalytic amount of a stock solution of Fe catalyst (10 mol %; 0.38 M) in hexane was taken; then NaOEt (1.8 equiv, 0.018 mmol, 12.3 mg) and diborane $B_2neop_2$ (1.8 equiv, 0.018 mmol, 40.5 mg) were added. Following that, the substrate 6-bromohex-1-ene and solvent MTBE (750 $\mu$L) were added. The vials were properly capped with an aluminum based septum before bringing out of the glovebox and left for stirring on an oil bath at 75 °C for 16 h. The reaction mixture was quenched while exposing it to air, and 3 mL of pentane was added. The mixture was further passed through a Celite and silica mixture (2:1), followed by washing with a solution of 30% ether in pentane (2 × 3 mL). Solvent was evaporated under reduced pressure, and the NMR sample was made in $CDCl_3$ using nitromethane as internal standard. Borylated product **3s** was obtained as a colorless oil in 61% yield (120 mg) from **1s** (163 mg, 1.0 mmol). Product was purified by silica gel column chromatography eluted with a $Et_2O$:pentane (2:98) mixture. $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ 3.57 (s, 4H), 1.55 (m, 5H), 1.36−1.33 (m, 1H), 1.26−1.24 (m, 2H), 0.95 (s, 6H), 0.72−0.72 (d, $J$ = 7.8 Hz, 2H). $^{11}$B{$^1$H} NMR (128 MHz, $CDCl_3$) $\delta$ 30.3. $^{13}$C{$^1$H} NMR (100 MHz, $CDCl_3$) $\delta$ 72.1, 31.8, 31.0, 27.3, 27.0, 22.0. HRMS (ESI) $m/z$ (M)$^+$ calc for $C_{11}H_{21}BO_2$ 196.1635, found 196.1644.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.joc.0c02364.



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Experimental and spectroscopic data, copies of $^{1}H$, $^{13}C\{^{1}H\}$, and $^{11}B\{^{1}H\}$ NMR spectra (PDF)

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### Notes

The authors declare no competing financial interest.

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