Supplementary Information

Genetically programmed chiral organoborane synthesis

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This PDF includes:

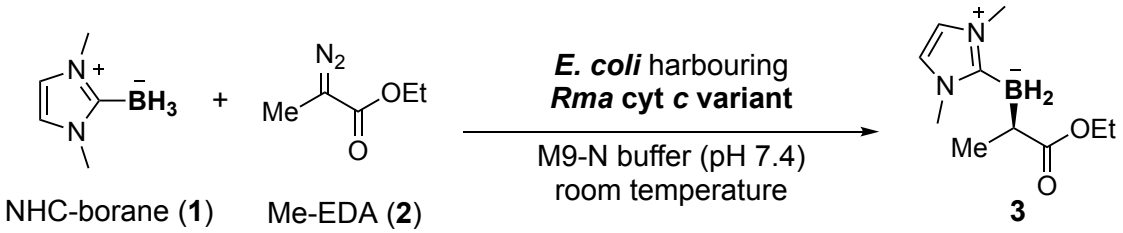
I. Materials and Methods

Unless otherwise noted, all chemicals and reagents were obtained from commercial suppliers (Sigma-Aldrich, VWR, Alfa Aesar, Acros) and used without further purification. Bovine serum albumin (BSA) was purchased from Sigma-Aldrich. Silica gel chromatography was carried out using AMD Silica Gel 60, 230-400 mesh. ^{1}H and ^{13}C NMR spectra were recorded on a Bruker Prodigy 400 MHz instrument (400 MHz for ^{1}H and 100 MHz for ^{13}C). Chemical shifts (δ) are reported in ppm downfield from tetramethylsilane, using the solvent resonance as the internal standard (^{1}H NMR: $\delta = 7.26$, ^{13}C NMR: $\delta = 77.36$ for $CDCl_3$). ^{19}F NMR and ^{11}B NMR data were collected on a VARIAN 300 MHz spectrometer (101 MHz for ^{19}F NMR) and a Bruker Prodigy 400 MHz instrument (128 MHz for ^{11}B NMR), respectively. Sonication was performed using a Qsonica Q500 sonicator. High-resolution mass spectra were obtained at the California Institute of Technology Mass Spectral Facility. Chemical reactions were monitored using thin layer chromatography (Merck 60 gel plates) using a UV-lamp for visualization. Gas chromatography (GC) analyses were carried out using a Shimadzu GC-17A gas chromatograph, a FID detector, and J&W HP-5 column (30 m x 0.32 mm, 0.25 μm film). Gas chromatography-mass spectrometry (GC-MS) analyses were carried out using Shimadzu GCMS-QP2010SE system and J&W HP-5ms column. Analytical chiral supercritical fluid chromatography (SFC) was performed with a JACSO 2000 series instrument using *i*-PrOH and supercritical CO_2 as the mobile phase. Chiral normal-phase HPLC analyses were performed using an Agilent 1200 series instrument with *i*-PrOH and hexanes as the mobile phase. Chiral GC was performed on an Agilent 6850 GC with FID detector using a Chiraldex GTA column (30.0 m × 0.25 mm) at 1.0 mL/min He carrier gas flow.

Biological materials and methods are described in the Methods section of the manuscript.

II. Kinetic Studies

Comparison of carbon–boron bond forming rates of BOR^{WT} and BOR^{R1} as whole-cell catalysts, cell lysates, or purified proteins.



NHC-borane (**1**) Me-EDA (**2**) **3**

Biocatalysts	turnover frequency (TOF) / h^{-1}
BOR^{WT} purified protein	3 ± 2
BOR^{WT} cell lysate	4 ± 1
BOR^{WT} whole cell	410 ± 250
BOR^{R1} purified protein	30 ± 2
BOR^{R1} cell lysate	160 ± 100
BOR^{R1} whole cell	6100 ± 700

TOFs reported represent mean values averaged over four experiments. Errors quoted indicate one standard deviation.

Whole cell-catalysed reaction: Experiments were performed using whole *E. coli* cells harbouring BOR^{WT} or BOR^{R1} (with the BOR protein concentration normalised to 10 μM), 10 mM borane, 10 mM diazo ester, 5 vol% MeCN, M9-N buffer at room temperature under anaerobic conditions for various time intervals.

Cell lysate-catalysed reaction: Experiments were performed using cell lysate of *E. coli* harbouring BOR^{WT} or BOR^{R1} (with the BOR protein concentration normalised to 10 μM), 10 mM borane, 10 mM diazo ester, 10 mM $Na_2S_2O_4$, 5 vol% MeCN, M9-N buffer at room temperature under anaerobic conditions for various time intervals. See Methods section of the manuscript for cell lysate preparation procedure.

Purified protein-catalysed reaction: Experiments were performed using purified BOR^{WT} or BOR^{R1} (10 μM), 10 mM borane, 10 mM diazo ester, 10 mM $Na_2S_2O_4$, 5 vol% MeCN, M9-N buffer at room temperature under anaerobic conditions for various time intervals. See Methods section of the manuscript for purified protein preparation procedure

General procedure for carrying out timed experiments: In an anaerobic chamber, 3.8 mL of whole *E. coli* cells harboring BOR variant, or a solution of 3.4 mL of BOR variant cell lysate / purified protein and 0.4 mL $Na_2S_2O_4$ (100 mM in M9-N buffer), was added to a 10 mL glass vial. After charging NHC-borane **1** (100 μL, 400 mM in MeCN) and Me-EDA **2** (100 μL, 400 mM in MeCN), the vial was capped and the reaction was shaken at 600 rpm on an orbital shaker. At regular time intervals (see table below), 400 μL of the reaction mixture was removed from the vial and added to a 2 mL microcentrifuge tube containing 600 μL cyclohexane / EtOAc

(1:1 v/v) and internal standard (20 μL, 20 mM 1,2,3-trimethoxybenzene in toluene). After vortexing for 20 seconds, 200 μL of the organic layer was immediately removed for GC analysis.

Biocatalysts	Sampling time
BOR^{WT} purified protein	Every hour from t = 1 to 4 h
BOR^{WT} cell lysate	Every hour from t = 1 to 4 h
BOR^{WT} whole cell	Every minute from t = 1 to 4 min
BOR^{R1} purified protein	Every minute from t = 1 to 4 min
BOR^{R1} cell lysate	Every minute from t = 0.5 to 3.5 min
BOR^{R1} whole cell	Every minute from t = 0.5 to 3.5 min

Table above shows time points at which the biocatalytic reaction was sampled to determine the reaction initial rate.

III. Inactivation Studies

Inactivation studies of BOR^{R1} were carried out using purified protein or whole cell *E. coli* harbouring BOR^{R1}. Effects of NHC-borane **1**, Me-EDA **2**, or organoborane **3** were determined by preincubating the biocatalyst with either one of these reagents (10 mM) for 15 min before the catalyst was used for borylation, and by comparing the TTN of the resulting catalyst (TTN^{incub}) with that of an untreated biocatalyst ($TTN^{control}$), as described in Figure 2f.

Purified protein-catalysed reactions were performed using purified BOR^{R1} (10 μM), 10 mM borane, 10 mM diazo ester, 10 mM $Na_2S_2O_4$, 5 vol% MeCN, M9-N buffer at room temperature under anaerobic conditions for 30 min. See Methods section of the manuscript for purified protein preparation procedure

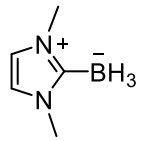
Whole cell-catalysed reactions were performed using whole *E. coli* cells harboring BOR^{R1} (with the BOR protein concentration normalised to 10 μM), 10 mM borane, 10 mM diazo ester, 5 vol% MeCN, M9-N buffer at room temperature under anaerobic conditions for 30 min.

IV. Substrate Synthesis and Characterization

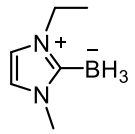
Picoline borane substrate was obtained from Sigma-Aldrich. Ethyl 2-diazopropanoate (Me-EDA) was obtained from Arch Bioscience. All commercially available reagents were used as received. The following diazo compounds are known and prepared according to literature procedures: methyl 2-diazopropanoate [1], isopropyl 2-diazopropanoate [2], benzyl 2-diazopropanoate[3], ethyl 2-phenyldiazoacetate (Ph-EDA)[4], ethyl 2-diazo-3,3,3-trifluoropropanoate (CF_3-EDA)[5], and (1-diazo-2,2,2-trifluoroethyl)benzene (CF_3-DMB)[6].

Other NHC-BH_3 substrates were synthesized from corresponding imidazolium iodide salts as reported[7]. Namely, imidazolium iodide salts (5 mmol) were resuspended in 5 mL THF. A solution of NaHMDS (1M in THF, 1.05 equiv.) was then added at –78 °C under Ar and shaken for 1 h at –78 °C. Afterwards, a solution of BH_3-THF (1M in THF, 1 equiv.) was added to the reaction

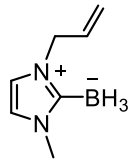
and the reaction mixture was allowed to warm from –78 °C to rt and stirred overnight. The solvent was removed under reduced pressure and the residue was purified by flash column chromatography to give the NHC-BH_3 complexes. The ^{1}H NMR resonances of the B–H protons are broad (due to geminal coupling with boron) and generally in the range of 0.4 – 1.6 ppm. The ^{13}C NMR resonances of the boron-binding NHC quarternary carbons usually appear at around 170 ppm and are typically broad (due to germinal coupling with boron) and weak; these signals are sometimes not visible in the ^{13}C NMR spectra.



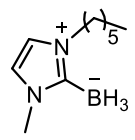
This compound is known[8]. ^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.91 – 6.66 (m, 2H), 3.71 (s, 6H), 0.99 (dd, *J* = 172.7, 86.3 Hz, 3H).



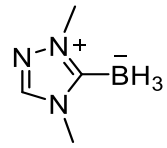
This compound is known[9]. ^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.87 – 6.65 (m, 2H), 4.00 (q, *J* = 7.3 Hz, 2H), 3.57 (s, 3H), 1.22 (t, *J* = 7.3 Hz, 3H), 1.44 – 0.30 (m, 3H).



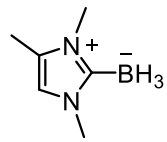
This compound is known[8]. ^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.84 – 6.79 (m, 2H), 5.91 (ddt, *J* = 17.1, 10.2, 6.1 Hz, 1H), 5.30 – 5.06 (m, 2H), 4.71 (dt, *J* = 6.1, 1.5 Hz, 2H), 3.71 (s, 3H), 1.43 – 0.35 (m, 3H).



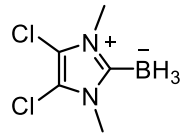
^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.82 – 6.76 (m, 2H), 4.13 – 3.97 (m, 2H), 3.69 (s, 3H), 1.83 – 1.63 (m, 2H), 1.42 – 1.19 (m, 6H), 0.97 – 0.75 (m, 3H), 1.46 – 0.41 (m, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 171.0, 119.9, 118.7, 48.8, 35.8, 31.3, 30.1, 26.1, 22.5, 14.0; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –37.4 (q, *J* = 86 Hz); MS (FAB) *m/z* [$(M + H)^+ - H_2$] calcd for $C_{10}H_{20}N_2B$: 179.1720, found: 179.1707.



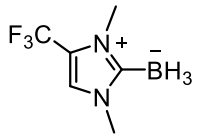
This compound is known[8]. ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.85 (s, 1H), 3.94 (s, 3H), 3.74 (s, 3H), 1.45 – 0.42 (m, 3H).



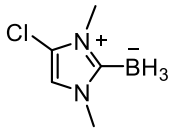
This compound is known[10]. ^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.49 (q, *J* = 1.2 Hz, 1H), 3.56 (s, 3H), 3.50 (s, 3H), 2.07 (d, *J* = 1.3 Hz, 3H), 1.31 – 0.43 (m, 3H).



This compound is known[11]. ^{1}H NMR (400 MHz, Chloroform-*d*) δ 3.72 (s, 6H), 1.44 – 0.41 (m, 3H).



^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.23 (q, *J* = 1.5 Hz, 1H), 3.82 (s, 3H), 3.77 (s, 3H), 1.49 – 0.54 (m, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 177.1, 122.2, 121.8, 119.40 (q, *J* = 267.3 Hz), 36.5, 34.0. ^{11}B NMR (128 MHz, Chloroform-*d*) δ –37.4 (q, *J* = 88 Hz). ^{19}F NMR (282 MHz, Chloroform-*d*) δ –61.2 (d, *J* = 3 Hz); MS (FAB) *m/z* [$(M+H)^+$–H_2] calcd for $C_6H_9F_3N_2B$: 177.0811, found: 177.0815.

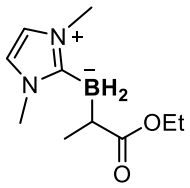


^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.78 (s, 1H), 3.71 (s, 3H), 3.67 (s, 3H), 1.45 – 0.51 (m, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ ^{13}C NMR (101 MHz, $CDCl_3$) δ 173.5, 119.3, 116.9, 36.4, 33.0. ^{11}B NMR (128 MHz, Chloroform-*d*) δ –36.9 (q, *J* = 87 Hz); MS (FAB) *m/z* [$(M+H)^+$–H_2] calcd for $C_5H_9N_2BCl$: 143.0547, found: 143.0547.

V. Synthesis and Characterization of Authentic Organoborane Products

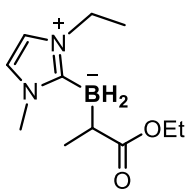
Racemic standard references of organoborane products were prepared *via* Rh-catalyzed B–H insertion reactions with procedures slightly modified from a previously reported method[8]. Namely, a 4 mL vial with screw cap and PTFE septum was charged with a borane substrate (1.0 mmol, 1 equiv.) and $Rh_2(OAc)_4$ (11 mg, 2.5 mol%). The vial was evacuated and backfilled with Ar three times and 2 mL of anhydrous CH_2Cl_2 was added. The vial was placed in a 38 °C water bath. A CH_2Cl_2 solution (1 mL) of diazo compound (1.0 mmol) was slowly added to the reaction mixture over 4 hours. Afterwards, the reaction mixture was allowed to further react overnight. The crude reaction mixture was purified by flash chromatography (dry loading) using EtOAc and hexanes as eluents and afforded organoborane products in 30 - 75% yield. The ^{1}H NMR resonances of the B–H protons are broad (due to geminal coupling with boron) and generally in the range of 0.4 – 1.6 ppm. The ^{13}C NMR resonances of the boron-binding NHC quarternary carbons usually appear at around 170 ppm and are typically broad (due to germinal coupling with boron) and weak; these signals are sometimes not visible in the ^{13}C NMR spectra.

(1,3-Dimethyl-1*H*-imidazol-3-ium-2-yl)(1-ethoxy-1-oxopropan-2-yl)dihydroborate (3)



^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.82 (s, 2H), 3.98 – 3.78 (m, 2H), 3.75 (s, 6H), 1.95 – 1.10 (m, 2H), 1.88 (br s, 1H), 1.10 (d, *J* = 6.2 Hz, 3H), 1.06 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.5, 120.4, 58.7, 36.2, 30.5, 17.8, 14.6. The boron-bound NHC quarternery carbon was not resolved; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.6 (t, *J* = 90 Hz); MS (FAB) *m/z* [$(M + H)^+ – H_2$] calcd for $C_{10}H_{18}O_2N_2B$: 209.1461, found: 209.1456.

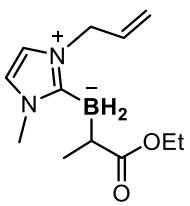
(1-Ethoxy-1-oxopropan-2-yl)(3-ethyl-1-methyl-1*H*-imidazol-3-ium-2-yl)dihydroborate (4)



^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.91 – 6.82 (m, 2H), 4.28 – 3.97 (m, 2H), 3.93 – 3.73 (m, 2H), 3.70 (s, 3H), 1.84 (br s, 1H), 1.95 – 1.10 (br m, 2H), 1.34 (t, *J* = 7.3 Hz, 3H), 1.05 (d, *J* = 6.7 Hz, 3H), 0.98 (t, *J* = 7.2 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.3, 170.0, 120.7, 118.2, 58.4, 43.5, 35.9, 30.4, 17.6,

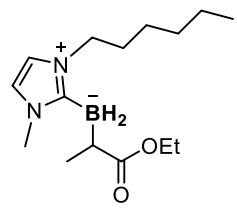
15.8, 14.4; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.5 (t, *J* = 89 Hz). MS (FAB) *m/z* [$M^{+\cdot}$]calcd for $C_{11}H_{21}O_2N_2B$: 224.1696, found: 224.1693.

(3-Allyl-1-methyl-1*H*-imidazol-3-ium-2-yl)(1-ethoxy-1-oxopropan-2-yl)dihydroborate (5)



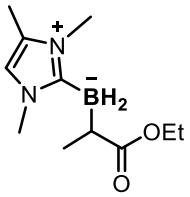
^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.85 (AB q, *J* = 2.0 Hz, 2H), 5.94 (ddt, *J* = 17.1, 10.2, 6.1 Hz, 1H), 5.39 – 5.17 (m, 2H), 4.82 (ddt, *J* = 15.3, 6.0, 1.5 Hz, 1H), 4.68 (ddt, *J* = 15.3, 6.2, 1.4 Hz, 1H), 3.99 – 3.78 (m, 2H), 3.76 (s, 3H), 1.92 – 1.05 (m, 2H), 1.87 (br s, 1H), 1.09 (d, *J* = 6.6 Hz, 3H), 1.05 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.6, 132.9, 120.9, 119.7, 119.0, 58.8, 51.4, 36.4, 32.0, 17.9, 14.8. The boron-bound NHC quarternery carbon was not resolved; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.6 (t, *J* = 90 Hz). MS (FAB) *m/z* [M + H^+]calcd for $C_{12}H_{22}O_2N_2B$: 237.1774, found: 237.1783.

(1-Ethoxy-1-oxopropan-2-yl)(3-hexyl-1-methyl-1*H*-imidazol-3-ium-2-yl)dihydroborate (6)



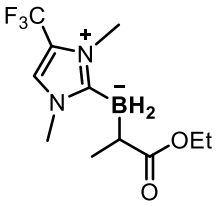
^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.88 – 6.79 (m, 2H), 4.20 – 4.06 (m, 1H), 3.99 (m, 1H), 3.93 – 3.74 (m, 2H), 3.72 (s, 3H), 1.93 – 1.79 (m, 1H), 1.72 (dt, *J* = 13.8, 6.9 Hz, 2H), 1.71 – 1.20 (m, 8H), 1.12 – 1.05 (m, 3H), 1.01 (td, *J* = 7.2, 2.4 Hz, 3H), 0.90 – 0.80 (m, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.6, 120.7, 119.0, 58.7, 48.9, 36.2, 31.6, 30.8, 30.5, 26.5, 22.7, 17.9, 14.7, 14.2. The boron-bound NHC quarternery carbon was not resolved; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.5 (t, *J* = 90 Hz); MS (FAB) *m/z* [$M^{+\cdot}$]calcd for $C_{15}H_{29}O_2N_2B$: 280.2322, found: 280.2330.

(1-Ethoxy-1-oxopropan-2-yl)(1,3,4-trimethyl-1*H*-imidazol-3-ium-2-yl)dihydroborate (7)



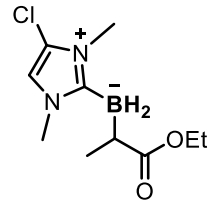
^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.55 (q, *J* = 1.2 Hz, 1H), 3.95 – 3.77 (m, 2H), 3.66 (s, 3H), 3.61 (s, 3H), 2.16 (d, *J* = 1.1 Hz, 3H), 1.84 (br s, 1H), 1.93 – 1.10 (m, 2H), 1.07 (s, 3H), 1.12 – 1.02 (m, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.7, 170.0, 128.3, 117.6, 58.7, 35.9, 32.7, 32.0 – 29.5 (m), 17.9, 14.7, 9.7; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.2 (t, *J* = 89 Hz); MS (FAB) *m/z* [$M^{+\cdot}$] calcd for $C_{11}H_{21}O_2N_2B$: 224.1696, found: 224.1695.

(1,3-Dimethyl-4-(trifluoromethyl)-1*H*-imidazol-3-ium-2-yl)(1-ethoxy-1-oxopropan-2-yl)dihydroborate (8)



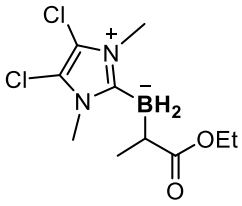
^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.29 (q, *J* = 1.3 Hz, 1H), 4.00 – 3.70 (m, 2H), 3.85 (s, 3H), 3.81 (s, 3H), 1.88 (br s, 1H), 1.85 – 1.05 (m, 2H), 1.12 (d, *J* = 6.6 Hz, 3H), 1.05 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.2, 123.6, 122.8 – 122.5 (m), 119.6 (q, *J* = 267.6 Hz), 59.0, 36.9, 34.4, 30.0, 17.9, 14.7. The boron-bound NHC quarternery carbon was not resolved; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.7 (t, *J* = 91 Hz). ^{19}F NMR (282 MHz, Chloroform-*d*) δ –61.1; MS (FAB) *m/z* [$M^{+\cdot}$] calcd for $C_{11}H_{18}O_2N_2BF_3$: 278.1414, found: 278.1405.

(4-Chloro-1,3-dimethyl-1*H*-imidazol-3-ium-2-yl)(1-ethoxy-1-oxopropan-2-yl)dihydroborate (9)



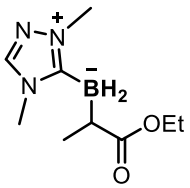
^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.83 (s, 1H), 3.97 – 3.79 (m, 2H), 3.73 (s, 3H), 3.70 (s, 3H), 2.00 – 1.10 (m, 2H), 1.94 – 1.76 (m, 1H), 1.13 – 1.02 (m, 6H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.4, 173.0, 119.9, 117.3, 58.9, 36.6, 33.3, 30.3, 17.9, 14.7; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.2 (t, *J* = 90 Hz); MS (FAB) *m/z* [$M^{+\cdot}$] calcd for $C_{10}H_{18}O_2N_2BCl$: 244.1150, found: 244.1154.

(4,5-Dichloro-1,3-dimethyl-1*H*-imidazol-3-ium-2-yl)(1-ethoxy-1-oxopropan-2-yl)dihydroborate (10)



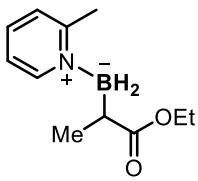
^{1}H NMR (400 MHz, Chloroform-*d*) δ 3.95 – 3.78 (m, 2H), 3.72 (s, 6H), 1.83 (br s, 1H), 1.99 – 1.05 (m, 2H), 1.10 (d, *J* = 11.9 Hz, 3H), 1.05 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.1, 172.0, 116.6, 59.0, 34.1, 30.0, 17.8, 14.7; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –23.9 (t, *J* = 91 Hz); MS (FAB) *m/z* [M + H^+] calcd for $C_{10}H_{18}O_2N_2BCl_2$: 279.0838, found: 279.0846.

(1,4-Dimethyl-4*H*-1,2,4-triazol-1-ium-5-yl)(1-ethoxy-1-oxopropan-2-yl)dihydroborate (11)



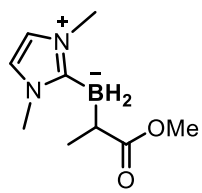
^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.92 (s, 1H), 3.95 (s, 3H), 3.94 – 3.79 (m, 2H), 3.78 (s, 3H), 1.89 (br s, 1H), 2.00 – 1.05 (m, 2H), 1.13 – 1.09 (m, 3H), 1.05 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.2, 141.7, 59.0 (d, *J* = 8.0 Hz), 38.6, 34.1, 30.0, 17.9, 14.7. The boron-bound NHC quarternery carbon was not resolved; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –25.0 (t, *J* = 91 Hz). MS (FAB) *m/z* [M + H^+] calcd for $C_9H_{19}O_2N_3B$: 212.1570, found: 212.1570.

Ethyl 2-((2-methyl-pyridin-1-yl)boraneyl)propanoate (12)



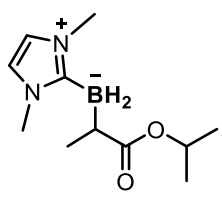
^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.53 (dd, *J* = 6.0, 1.6 Hz, 1H), 7.84 (td, *J* = 7.7, 1.7 Hz, 1H), 7.42 – 7.36 (m, 1H), 7.33 – 7.28 (m, 1H), 3.79 (AB qq, *J* = 10.8, 7.1 Hz, 2H), 3.30 – 2.15 (m, 2H), 2.77 (s, 3H), 2.05 – 1.92 (m, 1H), 1.05 (d, *J* = 6.8 Hz, 3H), 0.94 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 182.1, 157.9, 149.4, 140.2, 127.7, 122.6, 58.8, 32.8, 22.8, 15.2, 14.6; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –5.1 (t, *J* = 103 Hz); MS (FAB) *m/z* [$M^{+\cdot}$] calcd for $C_{11}H_{18}O_2NB$: 207.1431, found: 207.1431.

(1,3-Dimethyl-1*H*-imidazol-3-ium-2-yl)(1-methoxy-1-oxopropan-2-yl)dihydroborate (13)



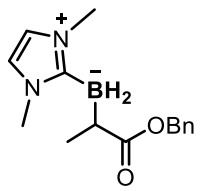
^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.82 (s, 1H), 3.72 (s, 6H), 3.43 (s, 2H), 1.99 – 1.08 (m, 3H), 1.06 (d, *J* = 6.8 Hz, 2H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.9, 170.0, 120.6, 50.7, 36.2, 30.5, 17.8; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.6 (t, *J* = 90 Hz); MS (FAB) *m/z* [$M^{+\cdot}$] calcd for $C_9H_{17}O_2N_2B$: 196.1383, found: 196.1388.

(1,3-Dimethyl-1*H*-imidazol-3-ium-2-yl)(1-isopropoxy-1-oxopropan-2-yl)dihydroborate (14)



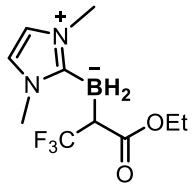
^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.81 (s, 2H), 4.76 (hept, *J* = 6.2 Hz, 1H), 3.75 (s, 6H), 1.86 (br s, 1H), 2.00 – 1.10 (m, 2H), 1.09 (d, *J* = 6.2 Hz, 6H), 0.94 (d, *J* = 6.3 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.3, 170.0, 120.6, 65.1, 36.4, 30.7, 22.5, 22.2, 18.1; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.5 (t, *J* = 90 Hz); MS (FAB) *m/z* [$M^{+\cdot}$] calcd for $C_{11}H_{21}O_2N_2B$: 224.1696, found: 224.1703.

(1-(Benzyloxy)-1-oxopropan-2-yl)(1,3-dimethyl-1*H*-imidazol-3-ium-2-yl)dihydroborate (15)



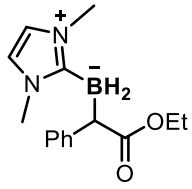
^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.36 – 7.17 (m, 5H), 6.71 (s, 2H), 4.92 (s, 2H), 3.62 (s, 6H), 2.10 – 1.15 (m, 2H), 1.97 (br s, 1H), 1.16 (d, *J* = 6.5 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.2, 170.0, 137.6, 128.4, 128.1, 127.7, 120.5, 64.7, 36.1, 30.8, 17.9; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.5 (t, *J* = 88 Hz); MS (FAB) *m/z* [$(M + H)^{+} - H_2$] calcd for $C_{15}H_{20}O_2N_2B$: 271.1618, found: 271.1616.

(1,3-Dimethyl-1*H*-imidazol-3-ium-2-yl)(3-ethoxy-1,1,1-trifluoro-3-oxopropan-2-yl)dihydroborate (16)



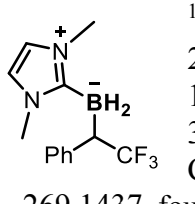
^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.88 (s, 2H), 4.15 – 3.97 (m, 2H), 3.76 (s, 6H), 2.65 (s, 1H), 2.10 – 1.25 (m, 2H), 1.18 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 174.2 (d, *J* = 5.2 Hz), 168.0, 128.7 (q, *J* = 276.2 Hz), 121.2, 60.0, 42.6, 36.3, 14.6; ^{11}B NMR (128 MHz, Chloroform-*d*) δ −28.6 (t, *J* = 92 Hz). ^{19}F NMR (282 MHz, Chloroform-*d*) δ −62.5 (d, *J* = 10 Hz); MS (FAB) *m/z* [$(M + H)^{+} - H_2$] calcd for $C_{10}H_{15}O_2N_2BF_3$: 263.1179, found: 263.1167.

(1,3-Dimethyl-1*H*-imidazol-3-ium-2-yl)(2-ethoxy-2-oxo-1-phenylethyl)dihydroborate (17)



^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.35 – 7.24 (m, 2H), 7.19 – 7.11 (m, 2H), 7.07 – 6.99 (m, 1H), 6.77 (s, 2H), 4.24 – 3.93 (m, 2H), 3.46 (s, 6H), 3.35 – 3.22 (m, 1H), 2.34 – 1.41 (m, 2H), 1.21 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 179.7, 145.8, 127.9, 127.8, 124.1, 120.7, 120.2, 59.3, 45.6 (d, *J* = 44.3 Hz), 36.0, 14.8, (the NHC quarternary carbon was too broad to be visible due to coupling with B); ^{11}B NMR (128 MHz, Chloroform-*d*) δ –23.2 (t, *J* = 93 Hz); MS (FAB) *m/z* [$M^{+\cdot}$] calcd for $C_{15}H_{21}O_2N_2B$: 272.1696, found: 272.1687.

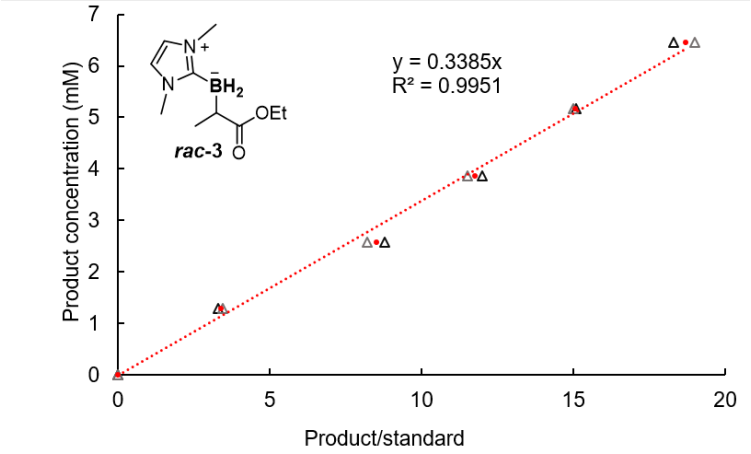
(1,3-Dimethyl-1*H*-imidazol-3-ium-2-yl)(2,2,2-trifluoro-1-phenylethyl)dihydroborate (18)

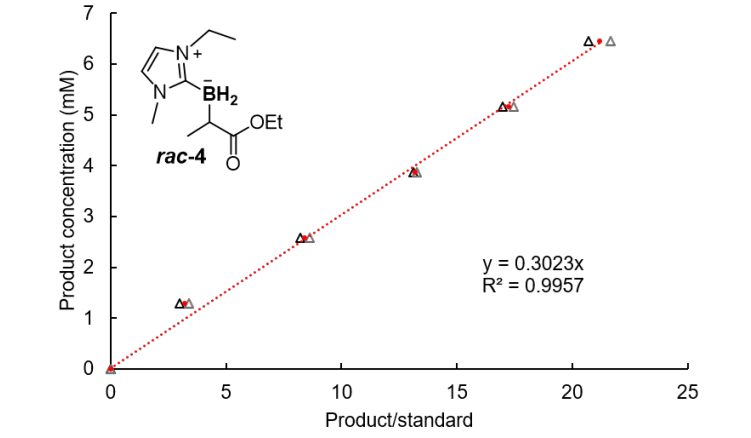


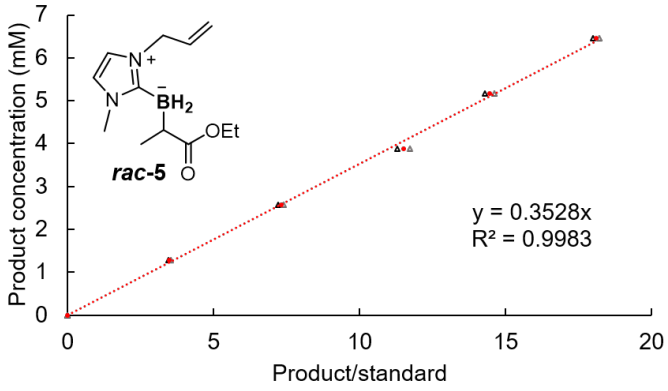
^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.23 – 7.05 (m, 5H), 6.76 (s, 2H), 3.52 (s, 6H), 2.90 – 2.60 (m, 1H), 2.25 – 1.40 (m, 2H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 169.1, 143.7 (d, *J* = 3.5 Hz), 131.4 (q, *J* = 278.0 Hz), 128.4, 128.3, 125.2, 120.8, 43.5, 36.0; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –26.7 (t, *J* = 90 Hz); ^{19}F NMR (282 MHz, Chloroform-*d*) δ –61.8 (d, *J* = 13 Hz); MS (ESI) *m/z* [$M + H^{+}$] calcd for $C_{13}H_{17}N_2BF_3$: 269.1437, found: 269.1440.

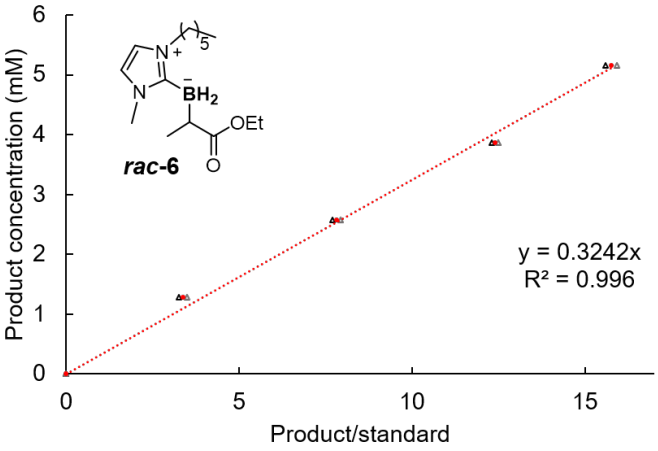
VI. GC-MS Standard Curves for Organoborane Products

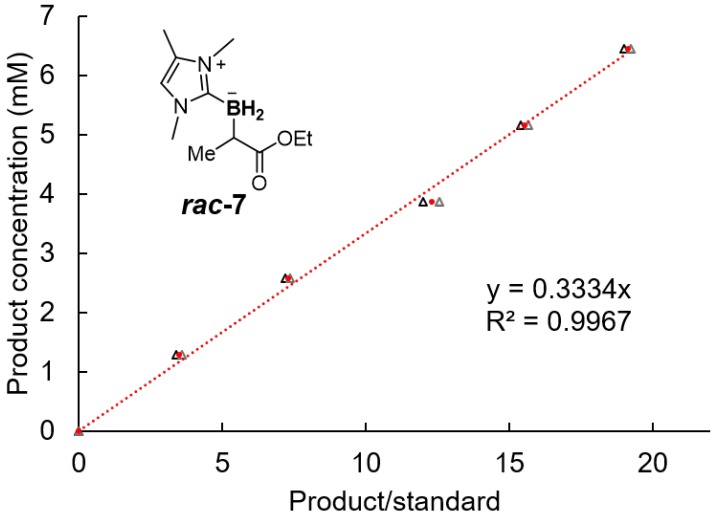
Product formation in enzymatic reactions was quantified by GC-MS based on standard curves. To determine the standard calibration curves, stock solutions of chemically synthesized organoborane products were prepared at various concentrations (1 - 7 mM in 4:6 hexanes/EtOAc) with added internal standard 1,2,3-trimethoxybenzene with a final concentration of 6.45 mM in the stock solutions of organoborane products. Individual data point for each duplicate run is marked as triangle, the average of duplicate runs is marked as red dot. The standard curves plot product concentration in mM (y-axis) against the average ratio of product area to internal standard area on GC-MS (x-axis). The quantification of organoborane **12** was determined by preparative scale reactions as this compound cannot be identified by GC-MS.

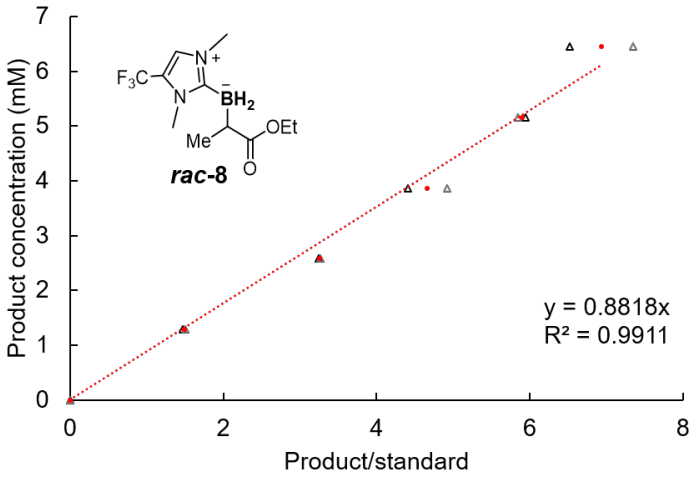


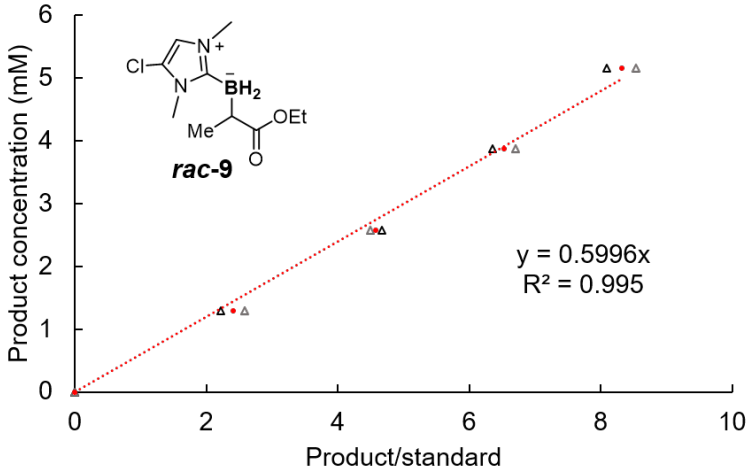


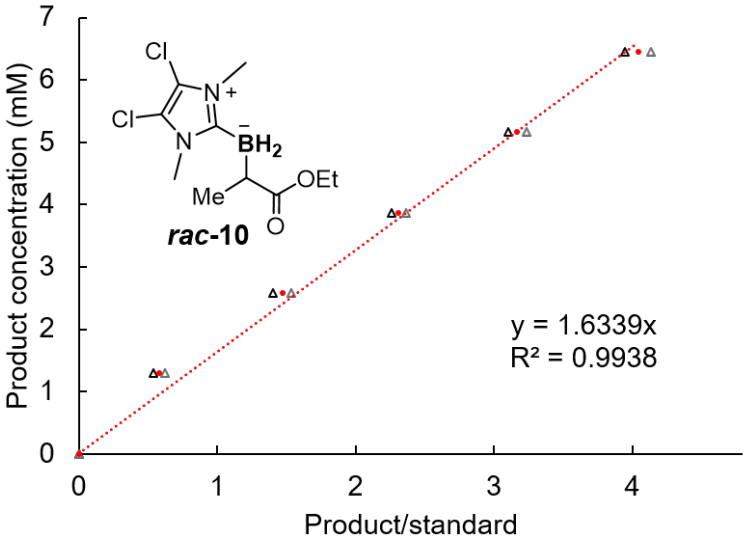

Product concentration (mM)
Product/standard
y = 0.3528x
R² = 0.9983
rac-5

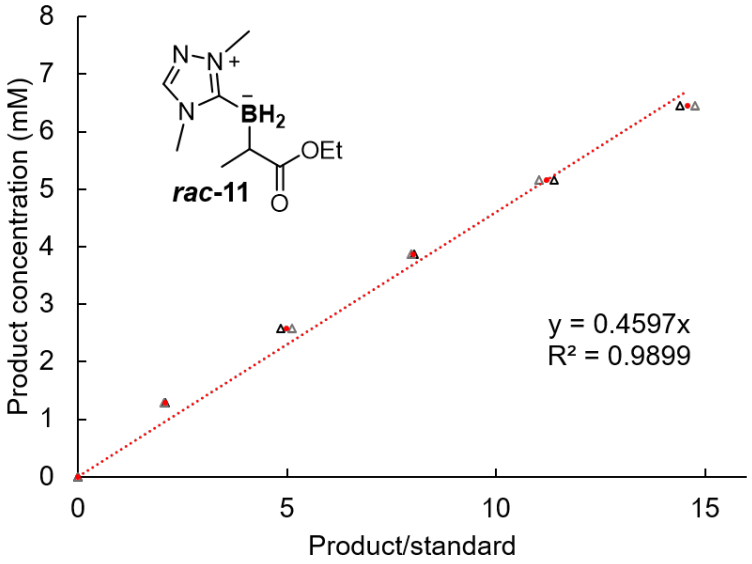

Product concentration (mM)
Product/standard
y = 0.3242x
R² = 0.996
rac-6

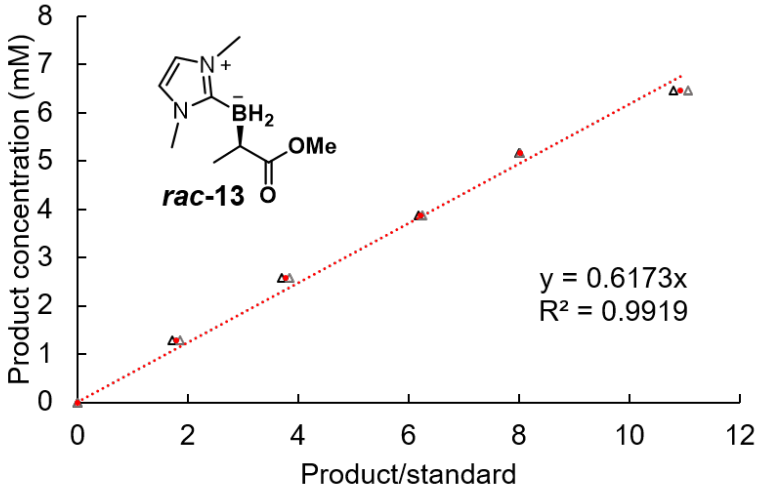

Product concentration (mM)
Product/standard
y = 0.3334x
R² = 0.9967
rac-7

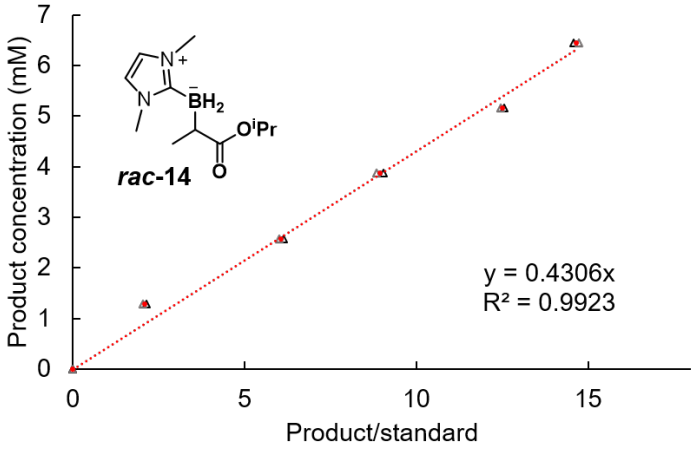

Product concentration (mM)
Product/standard
y = 0.8818x
R² = 0.9911
rac-8

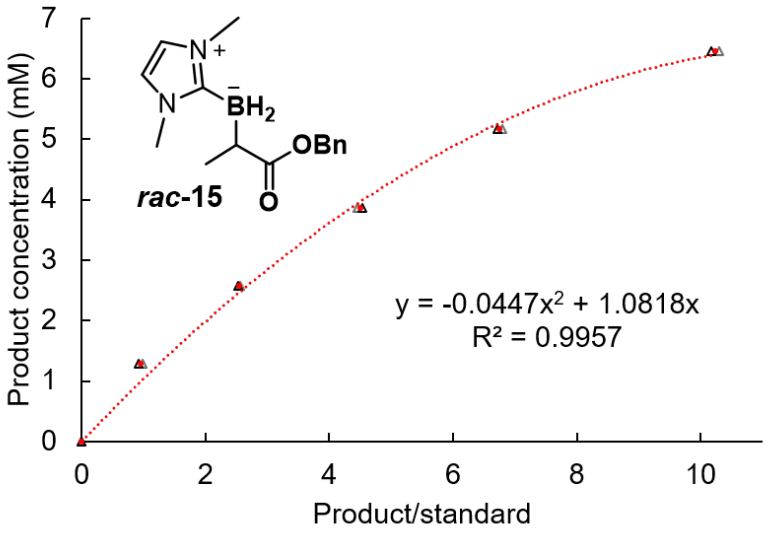

Product concentration (mM)
Product/standard
y = 0.5996x
R² = 0.995
rac-9

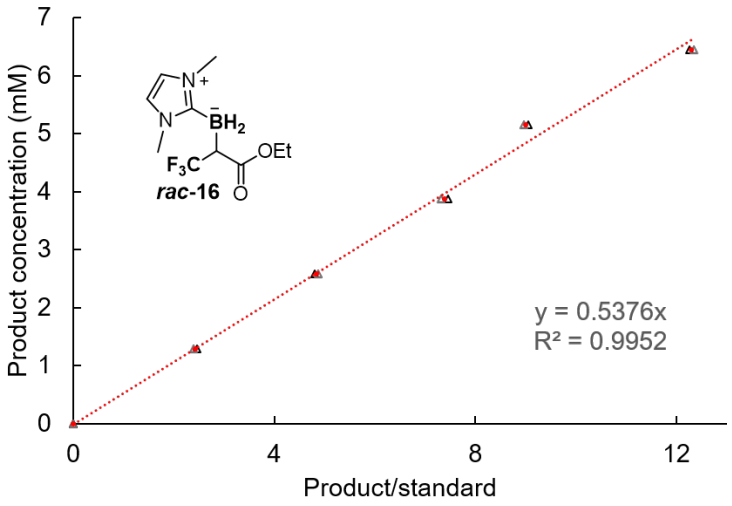

Product concentration (mM)
Product/standard
y = 1.6339x
R² = 0.9938
rac-10

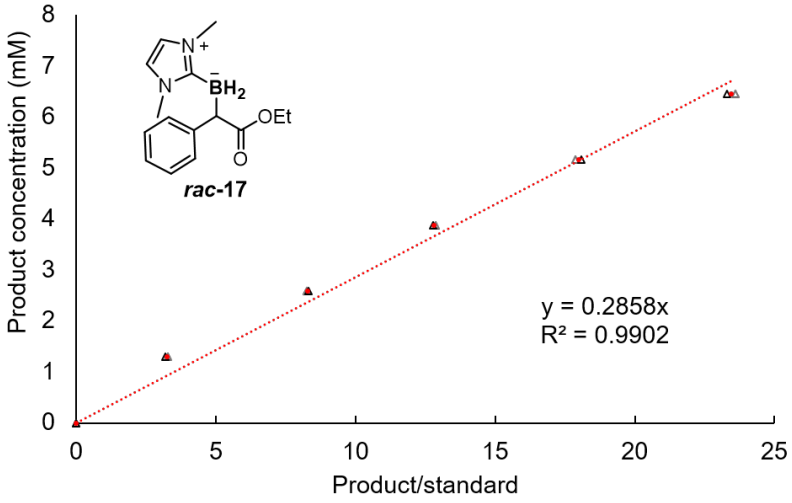

Product concentration (mM)
Product/standard
y = 0.4597x
R² = 0.9899
rac-11
BH2
OEt
O

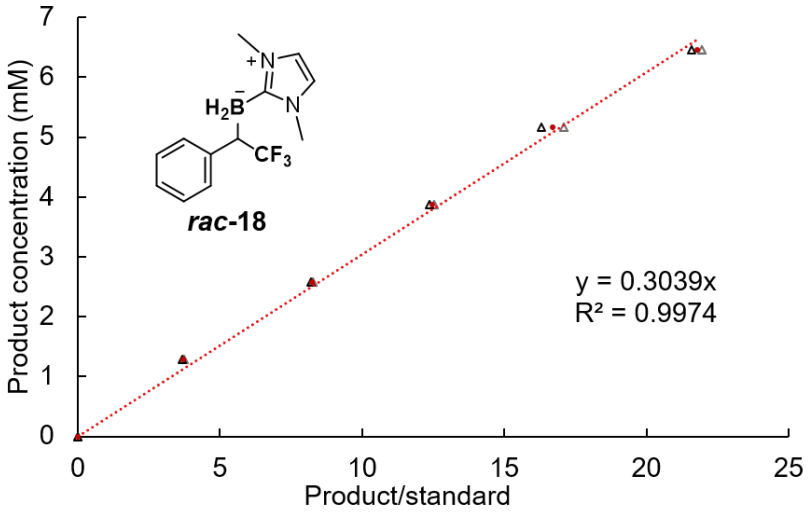

Product concentration (mM)
Product/standard
y = 0.6173x
R² = 0.9919
rac-13
BH2
OMe
O


Product concentration (mM)
Product/standard
y = 0.4306x
R² = 0.9923
rac-14
BH2
OiPr
O


Product concentration (mM)
Product/standard
y = -0.0447x² + 1.0818x
R² = 0.9957
rac-15

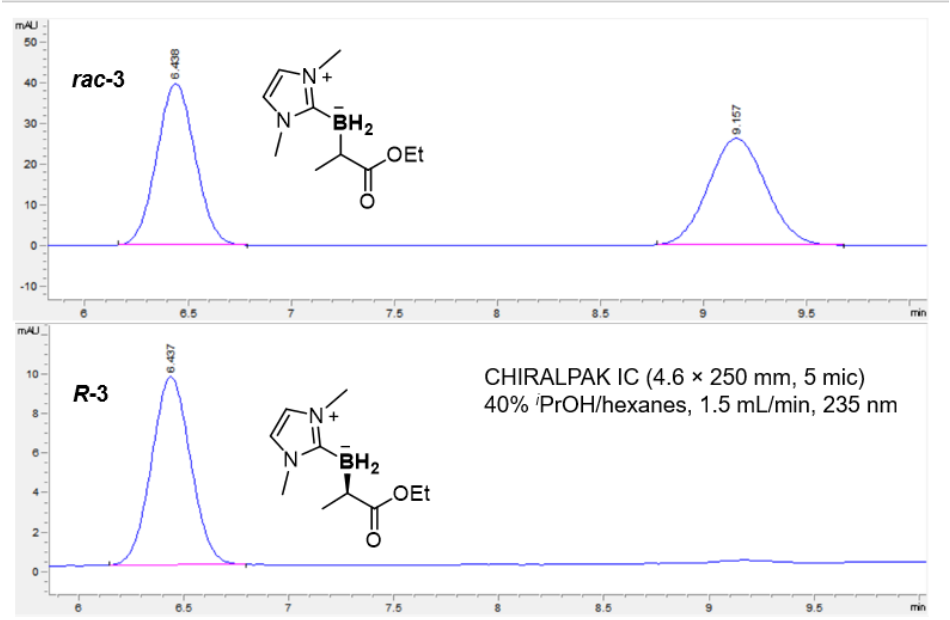

Product concentration (mM)
Product/standard
y = 0.5376x
R² = 0.9952
rac-16


Product concentration (mM)
Product/standard
y = 0.2858x
R² = 0.9902
rac-17

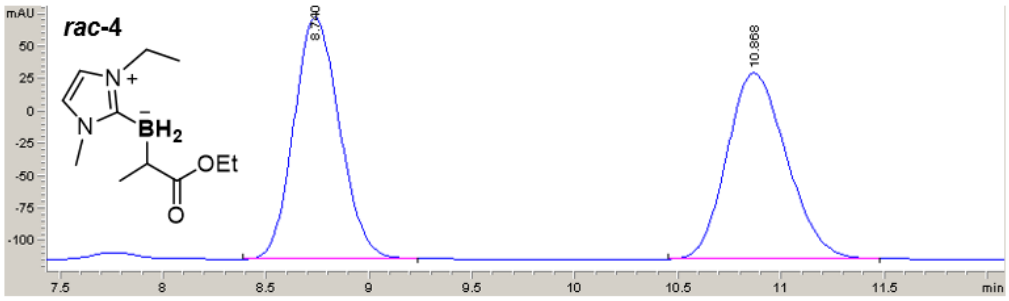

Product concentration (mM)
Product/standard
y = 0.3039x
R² = 0.9974
rac-18

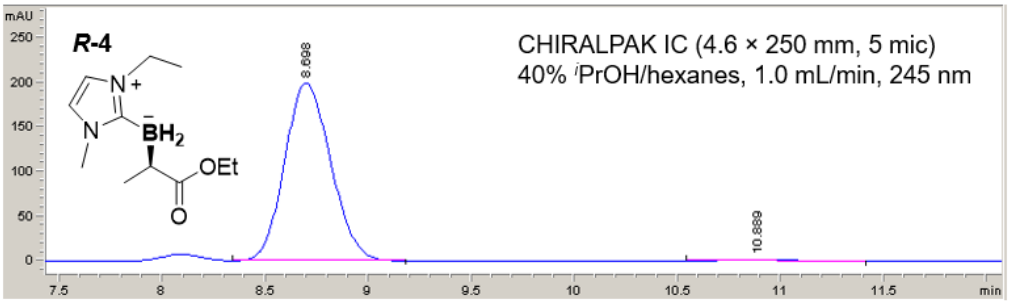
VII. Determination of Enantioselectivity

All e.r. values of enzymatically synthesized borane products were determined using chiral SFC or normal-phase chiral HPLC. The absolute configurations of enzymatically synthesized borane products **3**, **12**, and **18** were determined to be *R via* X-ray crystallography. The absolute configurations of organoborane products **4-11**, **13-16** were inferred by analogy, assuming the facial selectivity of the diazo reagents from which these products were made remains the same as that of Me-EDA.

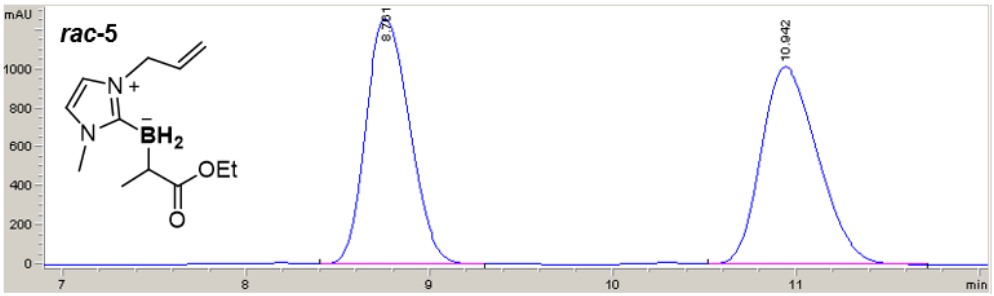


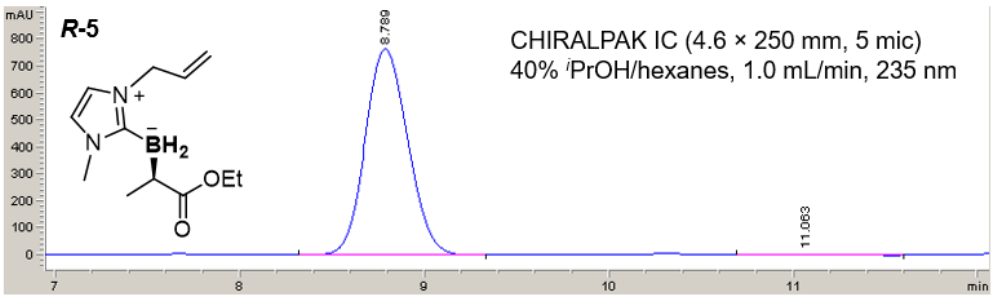
rac-3			*R*-3		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
6.438	519.0	50.3	6.437	123.5	97.6
9.157	512.4	49.7	9.168	3	2.4



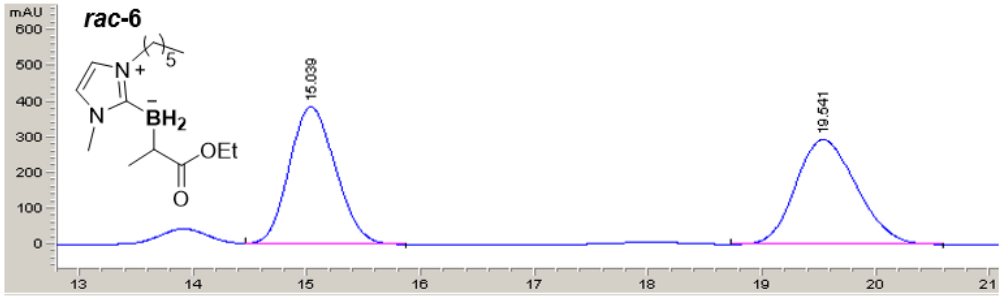


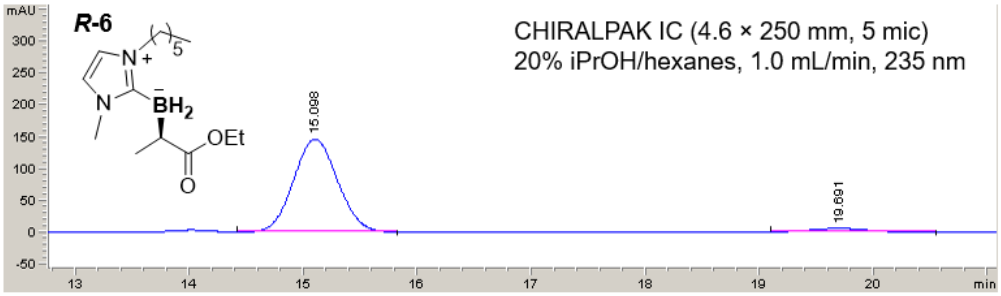
rac-4			*R*-4		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
8.74	2890.3	49.8	8.698	3105.2	98.6
10.868	2910.5	50.2	10.889	42.7	1.3



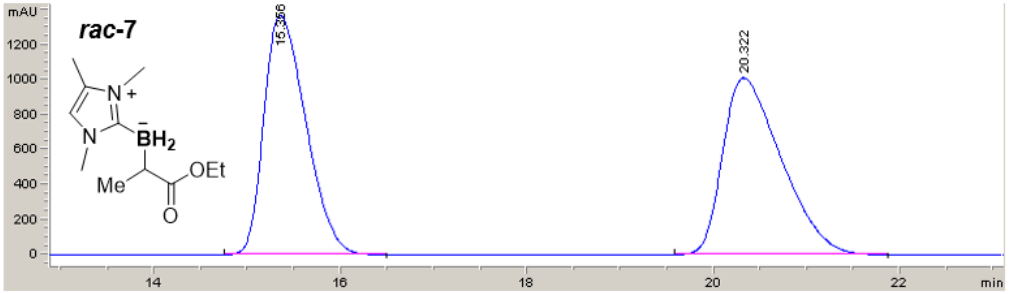


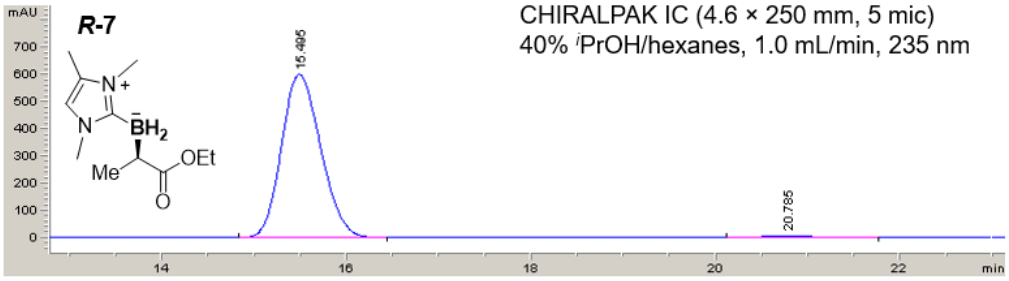
rac-5			*R*-5		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
8.761	21036	49.2	8.789	12279.6	99.4
10.942	21752	50.8	11.063	81.3	0.6



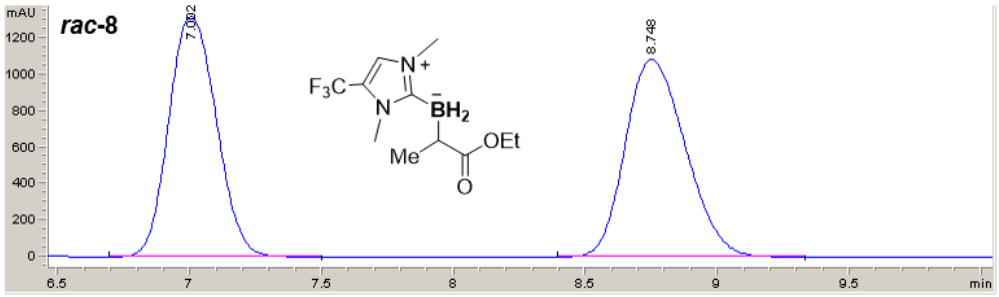


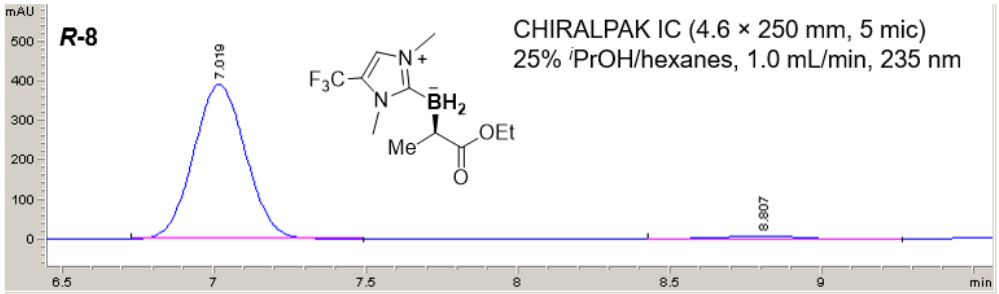
rac-6			*R*-6		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
15.039	10916.7	50.0	15.098	3940.4	95.6
19.541	10905.3	50.0	19.691	181.6	4.4



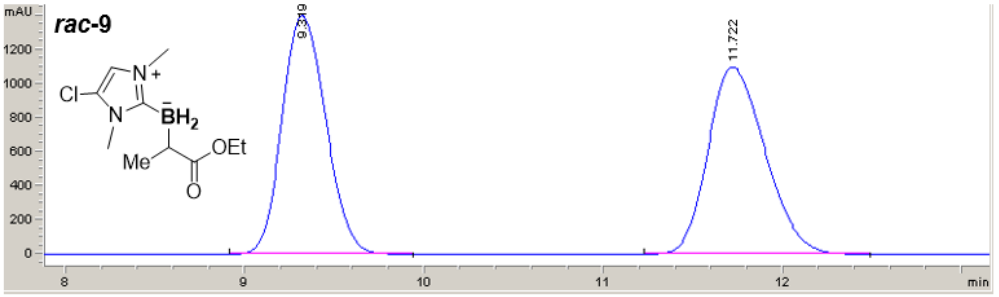


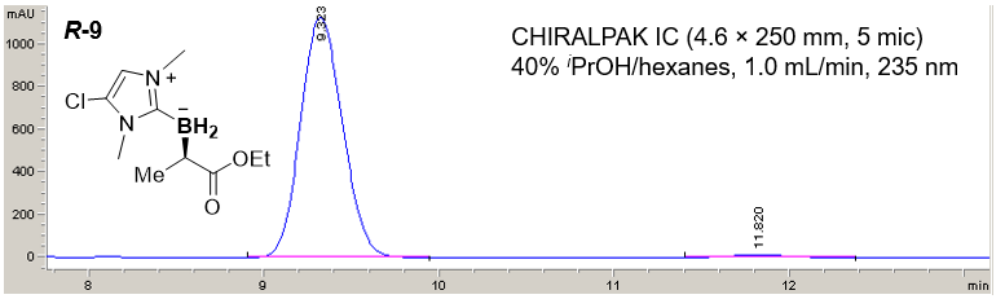
rac-7			*R*-7		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
15.356	42847.9	49.3	15.495	17552.6	98.6
20.322	44076.6	50.7	20.785	252.7	1.4



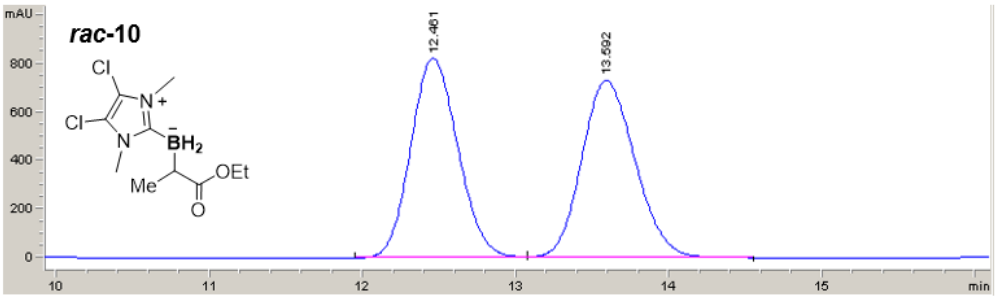


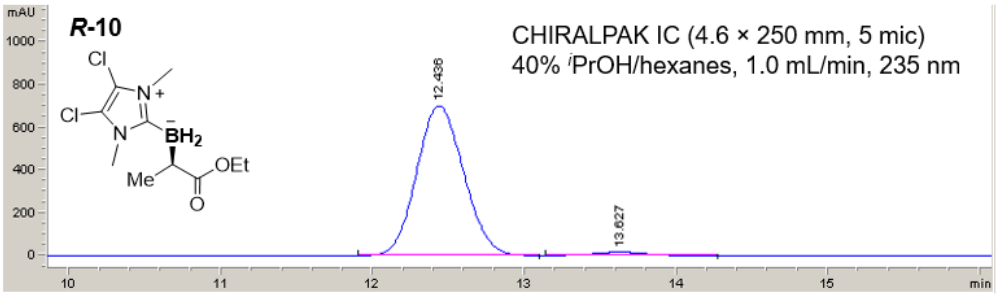
rac-8			*R*-8		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
7.002	16485.6	49.0	7.019	4675.3	97.1
8.748	17138.5	51.0	8.807	140.6	2.9



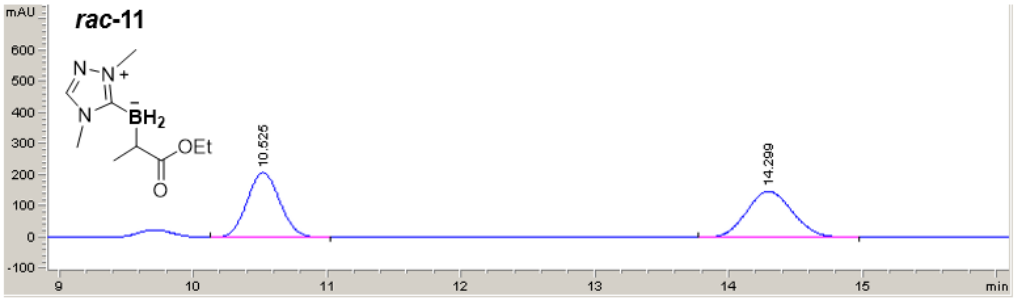


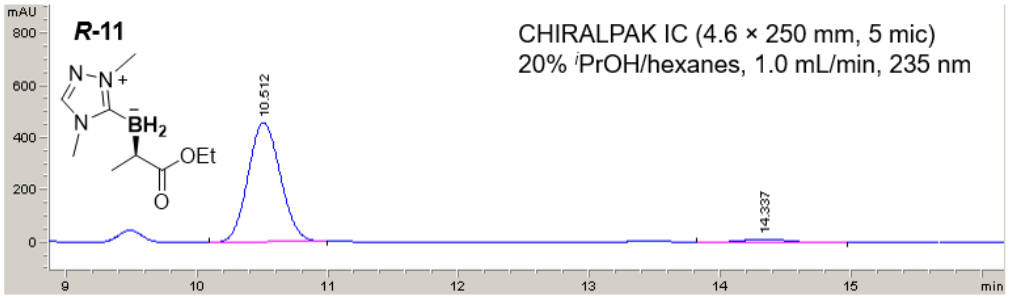
rac-9			*R*-9		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
9.319	23716.2	49.4	9.323	18767.6	98.7
11.722	24243.2	50.5	11.82	245.9	1.3



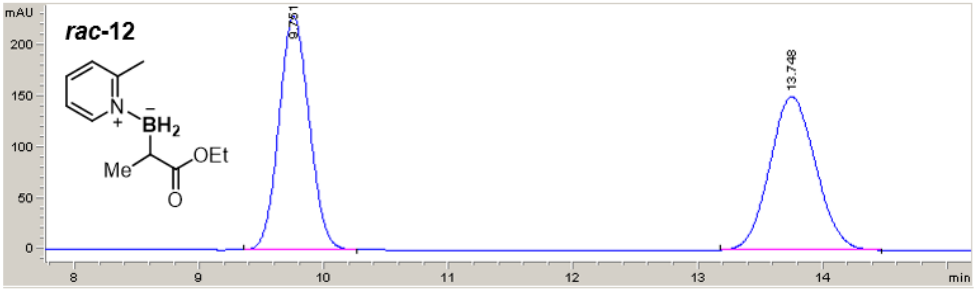


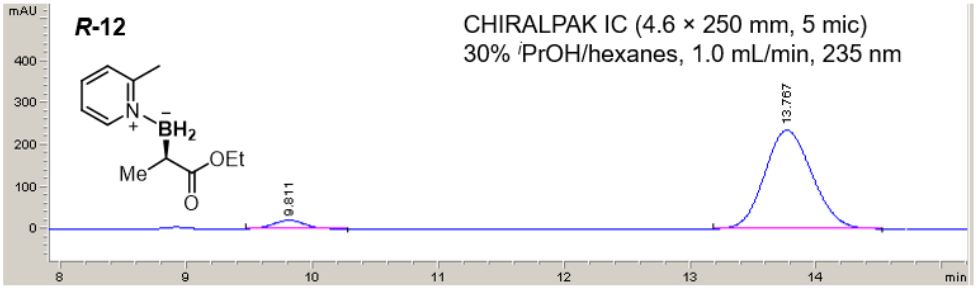
rac-10			*R*-10		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
12.461	17593.3	49.8	12.436	15102.1	97.5
13.592	17704.5	50.2	13.627	394.2	2.5



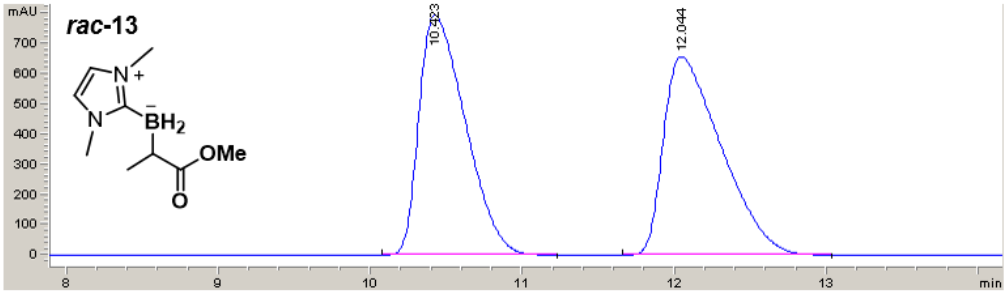


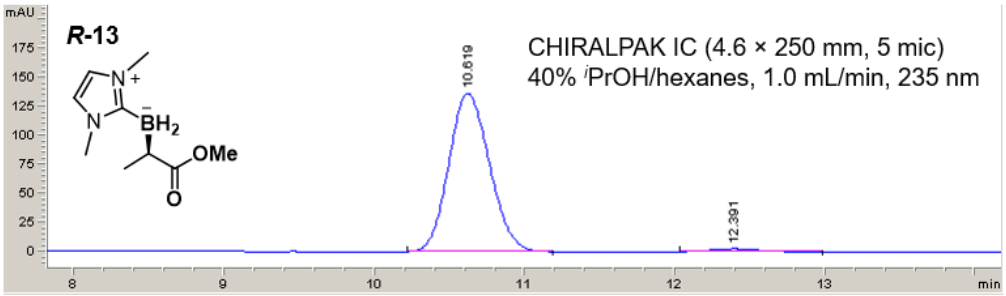
rac-11			*R*-11		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
10.525	3548.2	50.0	10.512	7851.9	96.3
14.299	3548	50.0	14.377	303.5	3.7



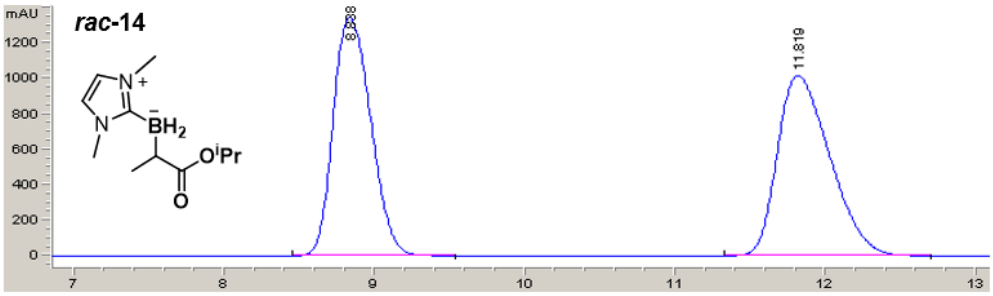


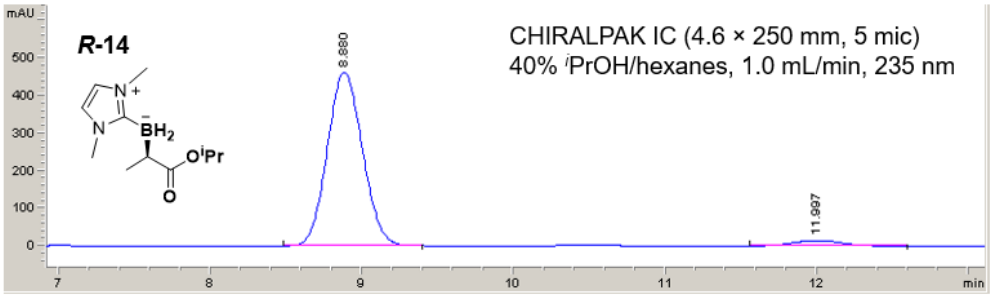
rac-12			*R*-12		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
9.751	3855	50.0	9.811	300.4	4.4
13.748	3856.4	50.0	13.767	6600.1	95.6



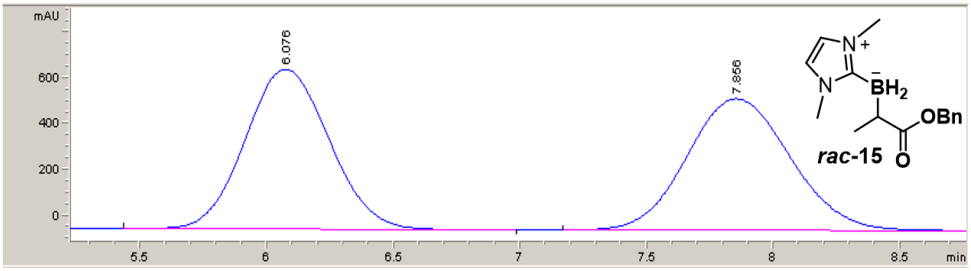


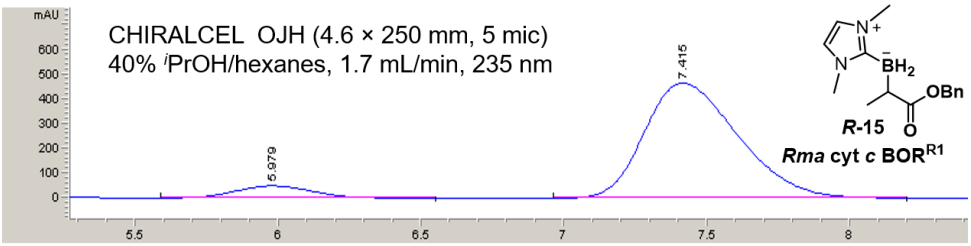
rac-13			*R*-13		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
10.423	792.9	49.2	10.619	2569.9	98.0
12.044	655.8	50.8	12.391	54.3	2.0



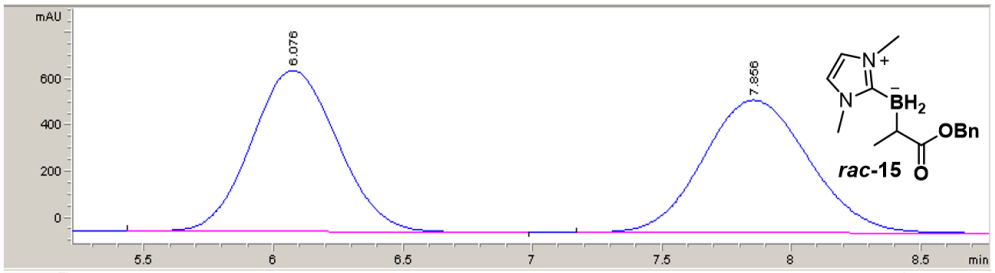


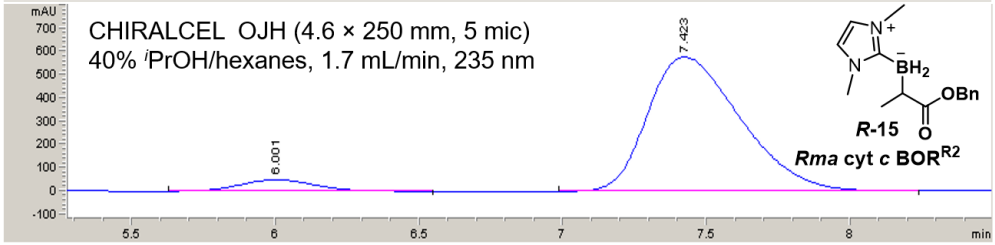
rac-14			*R*-14		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
8.838	23352.5	49.0	8.88	7453.1	95.9
11.819	24689.3	51.0	11.997	323.1	4.1



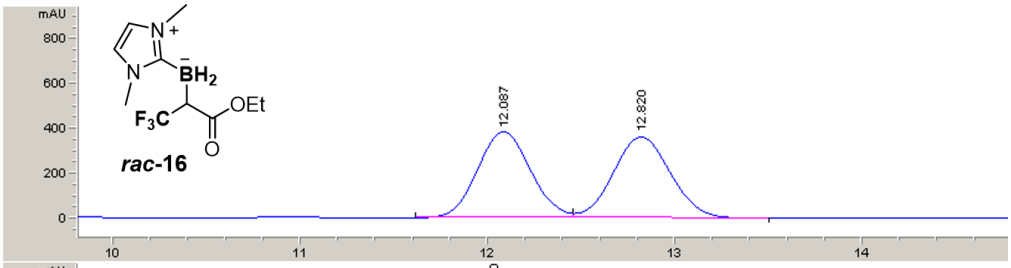


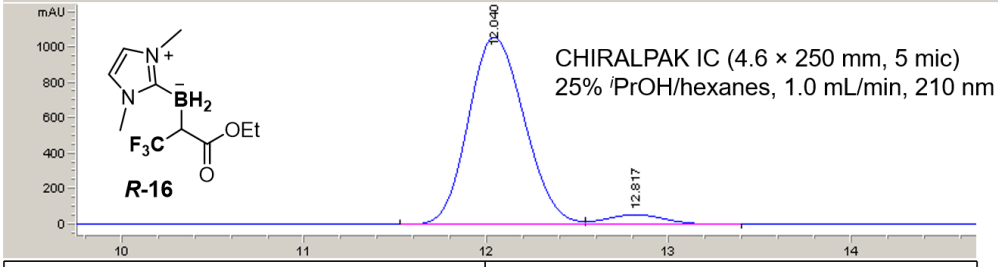
rac-15			*R*-15 (*Rma* cyt *c* BOR^{R1})		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
6.076	16251.2	49.7	5.979	920	8.0
7.856	16497.4	50.3	7.415	10567.3	92.0



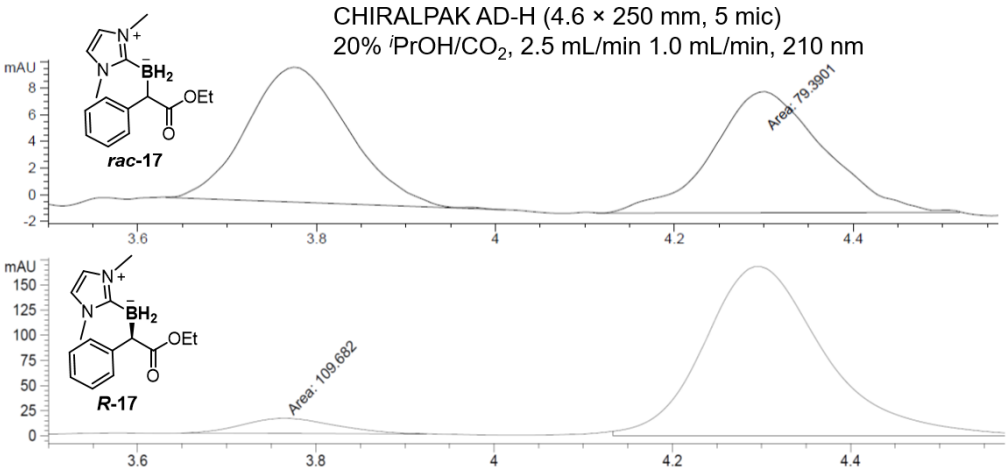


***rac*-15**			***R*-15 (*Rma* cyt *c* BOR^{R2})**		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
6.076	16251.2	49.7	6.001	884.1	6.0
7.856	16497.4	50.3	7.423	12965.3	94.0

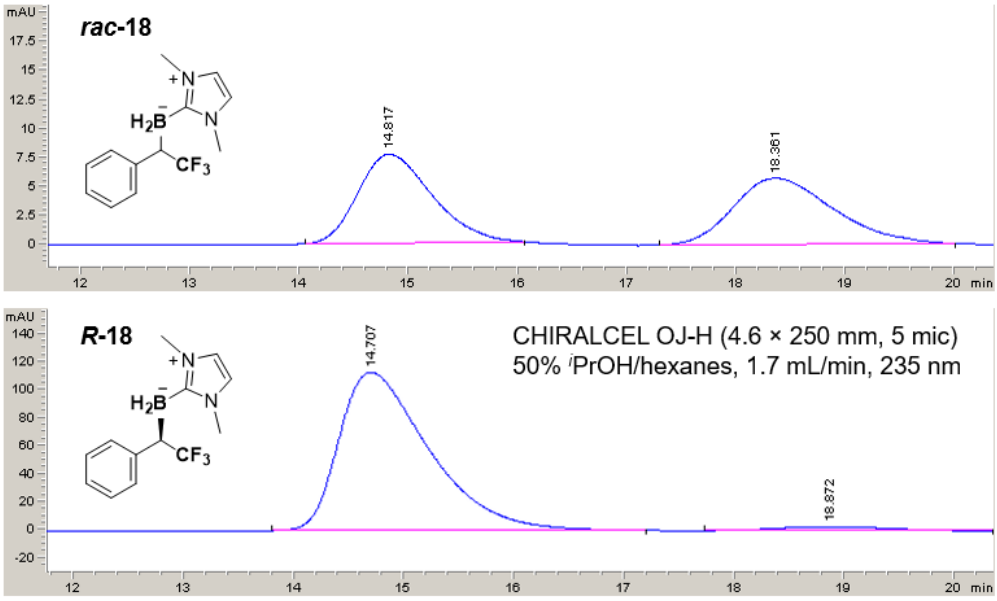




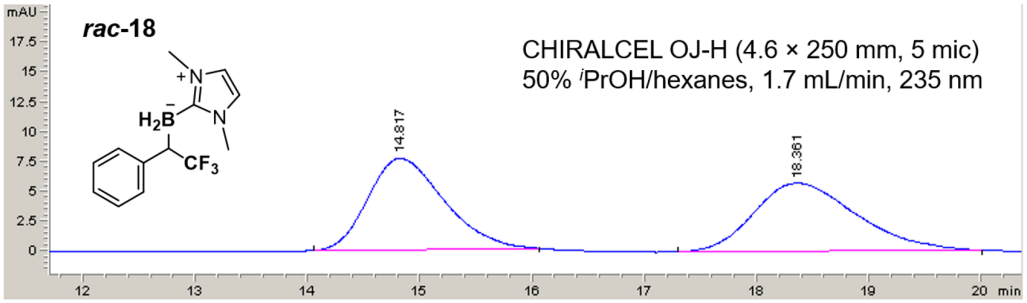
***rac*-16**			***R*-16**		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
12.087	7583.9	49.6	12.04	22545.6	94.9
12.82	7718.3	50.4	12.817	1222.6	5.1

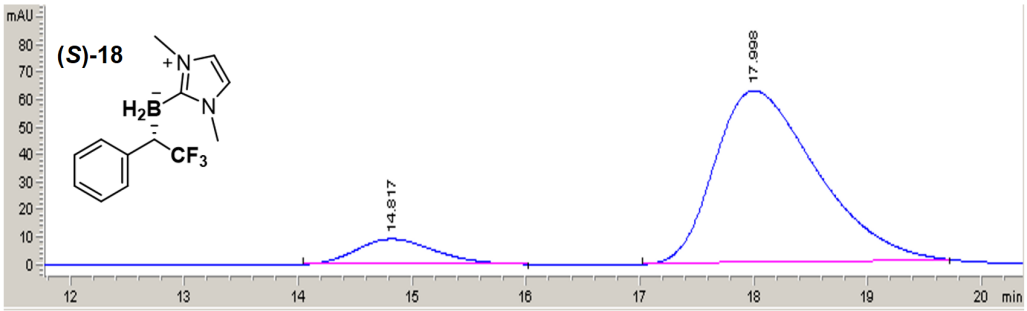


rac-17			*R*-17		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
3.775	79.9	50.1	3.765	109	6.0
4.299	79.4	49.9	4.296	1583	94.0



rac-18			*R*-18		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
14.817	370	50.1	14.707	6420.3	96.7
18.361	367.8	49.9	18.872	215.8	3.3

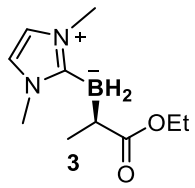




***rac*-18**			**(*S*)-18**		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
14.817	370	50.1	14.817	452	10.0
18.361	367.8	49.9	17.998	3949	90.0

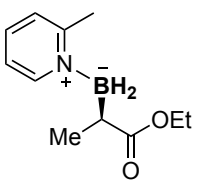
VIII. Preparative Scale Enzymatic Reactions

Preparation of whole-cell suspensions for borylation reactions: $HB_{amp/chlor}$ (200 mL) in a 1 L flask was inoculated with an overnight culture (4 mL, $LB_{amp/chlor}$) of recombinant *E. cloni*® EXPRESS BL21(DE3) cells containing a pET22b(+) plasmid encoding *Rma* cyt *c* variant, and the pEC86 plasmid. The culture was shaken at 37 °C and 250 rpm (no humidity control) until the OD_{600} was 0.7 (typically 2 - 3 hours). The culture was placed on ice for 30 minutes, and IPTG and ALA were added to final concentrations of 20 μM and 200 μM, respectively. The incubator temperature was reduced to 20 °C, and the culture was allowed to shake for 22 hours at 140 rpm. Cells were pelleted by centrifugation (4 °C, 5 min, 4,000xg), resuspended in M9-N buffer and adjusted to OD_{600} = 30. The whole-cell suspension was placed on ice and bubbled with Ar for 30 min.



3

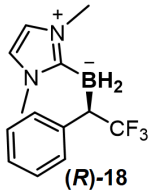
Biocatalytic synthesis of (1,3-dimethyl-1*H*-imidazol-3-ium-2-yl)(1-ethoxy-1-oxopropan-2-yl)dihydroborate (3) (0.5 mmol scale reaction). Under anaerobic conditions, to a 40 mL vial were added 12 mL *Rma* cyt *c* BOR^{R1} whole-cell suspension (OD_{600} = 30), 3 mL glucose solution (250 mM), *di*MeNHC-BH_3 solution (125 μL, 2 M in MeCN) and Me-EDA (125 μL, 2 M in MeCN). The vial was capped and shaken at 520 rpm in an anaerobic chamber at room temperature. After 4 hours, another portion of *di*MeNHC-BH_3 (125 μL, 2 M in MeCN) and Me-EDA (125 μL, 2 M in MeCN) were added and the vial was shaken for 8 more hours at 520 rpm. The reaction mixture was then transferred to a 50 mL Falcon tube and extracted by 30 mL 3:7 hexanes/EtOAc *via* vortexing (30 s for three times). Centrifugation (5,000xg, 5 min) was used to completely separate the organic and aqueous layers. After removal of the organic layers, two additional rounds of extraction were performed. The combined organic extracts were dried over anhydrous Na_2SO_4, concentrated, and purified by flash chromatography (dry loading) with EtOAc/hexanes (5% to 60% EtOAc/hexanes gradient) to afford pure organoborane product **3** (79 mg, 0.376 mmol, 75% yield). The protein concentration of OD_{600} = 30 whole-cell solution was determined to be 10.41 μM by hemochrome assay after cell lysis by sonication. The total turnover number for this reaction was 3000. The stereoselectivity of the product was determined as 97.5:2.5 e.r. by normal-phase chiral HPLC. $[\alpha]_D^{23}$ = + 114.5 (*c* 0.19, EtOAc). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 6.82 (s, 2H), 3.98 – 3.78 (m, 2H), 3.75 (s, 6H), 1.95 – 1.10 (m, 2H), 1.88 (br s, 1H), 1.10 (d, *J* = 6.2 Hz, 3H), 1.06 (t, *J* = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 183.5, 120.4, 58.7, 36.2, 30.5, 17.8, 14.6. The boron-bound NHC quarternery carbon was not resolved; ^{11}B NMR (128 MHz, Chloroform-*d*) δ –24.55 (t, *J* = 90 Hz).



12

Biocatalytic synthesis of ethyl 2-((2-methyl-pyridin-1-yl)boraneyl)propanoate (12) on gram scale. Under anaerobic conditions, to a 250 mL conical flask were added 50 mL *Rma* cyt *c* BOR^{R1} whole-cell solution (OD_{600} = 30), glucose (2.6 mL, 1 M), picoline borane (1.4 mL, 2 M in MeCN) and Me-EDA (1.4 M in MeCN). The flask was shaken at 240 rpm in an anaerobic chamber. At 3 h intervals, two additional batches of whole-cell solution (50 mL), glucose (2.6 mL, 1 M), picoline borane (1.4 mL, 2 M in MeCN) and Me-EDA (1.4 M in MeCN) were added. The reaction mixture was shaken for a total of 24 hours and then divided between six 50 mL Falcon tubes. 25 mL 3:7 hexanes/EtOAc was added to each tube to

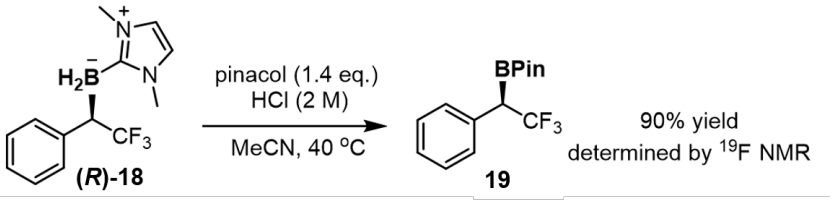
extract the borylation product via vortexing (30 s for three times) and centrifugation (5,000xg, 5 min). After removal of the organic layers, two additional rounds of extraction were performed. The combined organic extracts were dried over anhydrous Na_2SO_4, concentrated, and purified by flash chromatography (dry loading) with EtOAc/hexanes (5% to 40% EtOAc/hexanes gradient) to afford pure organoborane product **12** (0.74 g, 3.57 mmol, 42% yield). The protein concentration of OD_{600} = 30 whole-cell solution was determined to be 8.18 μM by hemochrome assay after cell lysis by sonication. The total turnover number for this reaction was 2910. The stereoselectivity of the product was determined as 96:4 e.r. by normal-phase chiral HPLC. $[\alpha]_D^{23}$ = + 117.2 (*c* 0.37, EtOAc). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.53 (dd, *J* = 6.0, 1.6 Hz, 1H), 7.84 (td, *J* = 7.7, 1.7 Hz, 1H), 7.42 – 7.36 (m, 1H), 7.33 – 7.28 (m, 1H), 3.79 (AB qq, *J* = 10.8, 7.1 Hz, 2H), 3.30 – 2.15 (m, 2H), 2.77 (s, 3H), 2.05 – 1.92 (m, 1H), 1.05 (d, *J* = 6.8 Hz, 3H), 0.94 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 182.13, 157.92, 149.35, 140.26, 127.67, 122.60, 58.83, 32.78, 22.76, 15.16, 14.61. ^{11}B NMR (128 MHz, Chloroform-*d*) δ –5.10 (t, *J* = 103 Hz).



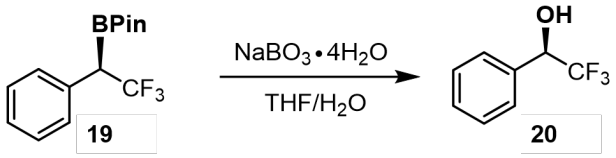
(*R*)-18

Biocatalytic synthesis of (1,3-Dimethyl-1H-imidazol-3-ium-2-yl)(2,2,2-trifluoro-1-phenylethyl)dihydroborate ((*R*)-18) at (1 mmol scale reaction). To a 250 mL conical flask were added 40 mL *Rma* cyt *c* BOR^{P1} whole-cell solution (OD_{600} = 30), glucose (2.6 mL, 1 M), *di*MeNHC-BH_3 (1.2 mL, 0.6 M in MeCN) and CF_3-DMB (1.0 mL, 0.6 M in MeCN). The flask was shaken at 240 rpm in the anaerobic chamber. After 6 hours, another batch of whole-cell solution (40 mL, OD_{600} = 30), glucose (2.6 mL, 1 M), *di*MeNHC-BH_3 (1.2 mL, 0.6 M in MeCN) and CF_3-DMB (1.0 mL, 0.6 M in MeCN) were added to the reaction mixture. The reaction mixture was shaken for a total of 30 hours and then divided between four 50 mL Falcon tubes. 25 mL 3:7 hexanes/EtOAc was added to each tube to extract the borylation product via vortexing (30 s for three times) and centrifugation (5,000xg, 5 min). After removal of the organic layers, two additional rounds of extraction were performed. The combined organic extracts were dried over anhydrous Na_2SO_4, concentrated, and purified by silica column chromatography (dry loading) with EtOAc/hexanes (5% to 50% EtOAc/hexanes gradient) to afford pure organoborane product **(*R*)-18** (130 mg, 0.485 mmol, 40% yield). Recovered borane starting material is 82 mg. The yield based on consumed starting material is 70%. The protein concentration of OD_{600} = 30 whole-cell solution was determined to be 6.06 μM by hemochrome assay after cell lysis by sonication. The total turnover number (TTN) for this reaction was 1000. The stereoselectivity of the product was determined as 96:4 e.r. by normal-phase chiral HPLC. $[\alpha]_D^{23}$ = – 81.3 (*c* 0.67, EtOAc). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.23 – 7.05 (m, 5H), 6.76 (s, 2H), 3.52 (s, 6H), 2.90 – 2.60 (m, 1H), 2.25 – 1.40 (m, 2H); ^{13}C NMR (101 MHz, Chloroform-*d*) δ 169.1, 143.7 (d, *J* = 3.5 Hz), 131.4 (q, *J* = 278.0 Hz), 128.4, 128.3, 125.2, 120.8, 43.5, 36.0; ^{11}B NMR (128 MHz, Chloroform-*d*) δ – 26.72 (t, *J* = 90 Hz); ^{19}F NMR (282 MHz, Chloroform-*d*) δ –61.80 (d, *J* = 13 Hz).

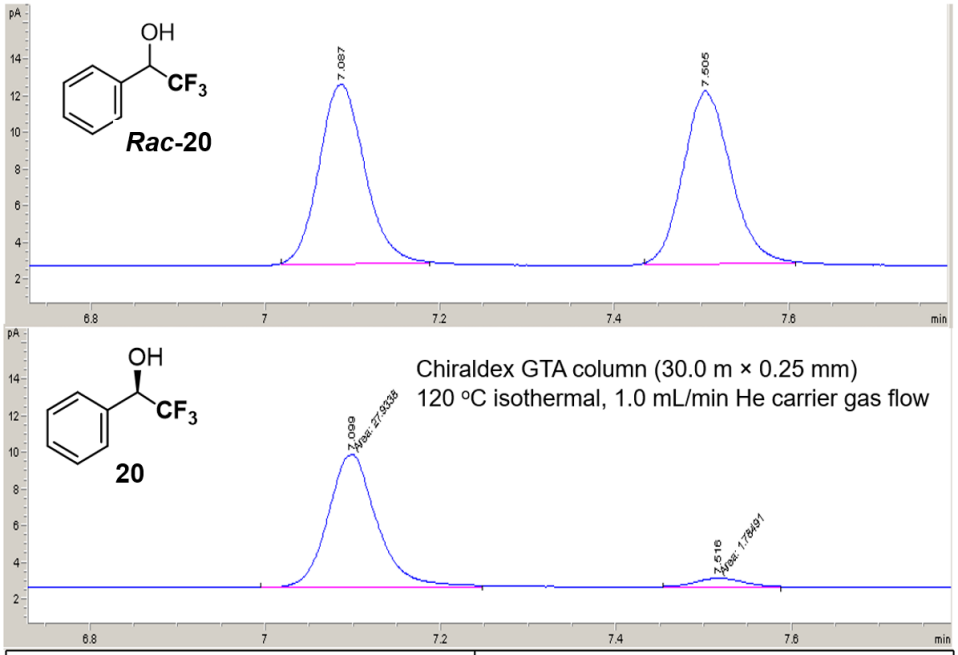
IX. Derivatization of Enzymatic Borylation Product (*R*)-18



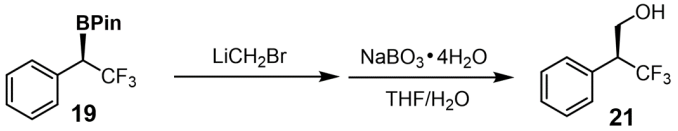
(A) Conversion of (*R*)-18 to the corresponding pinacol boronate ester 19. The protocol was modified from that reported by Zhou *et al.*[12]. To a 40 mL vial with screw cap were added 54 mg enzymatic product **(*R*)-18** (0.2 mmol) and a stir bar. The vial was evacuated and backfilled with argon three times. 4 mL acetonitrile solution of pinacol (33 mg, 0.28 mmol, 1.4 eq.) was added to the vial *via* syringe. The resulting solution was stirred for 5 min for **(*R*)-18** to dissolve, followed by the addition of 300 μL of 2 M HCl. The vial was stirred at 40 °C. The reaction can be monitored by GC-MS (usual reaction time is 10 - 12 hours) or ^{19}F NMR (**19** has a chemical shift at δ –62.75 ppm (d, J = 12 Hz)). After reaction completion, 10 μL fluorobenzene was added to the reaction mixture. An aliquot of reaction mixture was diluted with $CDCl_3$ to measure the yield via ^{19}F NMR. The formation of **19** was confirmed by GC-MS, and by conversion of **19** to alcohol **20** (see section **B** below).



(B) Conversion of 19 to alcohol 20. To the reaction mixture obtained after ligand exchange with pinacol in step **A**, 5 mL of water was added, and the mixture was extracted with 15 mL of 1:1 hexanes:EtOAc three times. The solvent was removed under reduced pressure and the vial was backfilled with argon. The crude product **19** was dissolved in 15 mL of pentane and passed through a syringe filter to remove the insoluble materials. This process was repeated two additional times to ensure all soluble materials were extracted. The combined organic extracts were dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. Under argon, THF (1 mL) was added to the vial to dissolve the crude product **19** followed by the addition of H_2O (1 mL) and 154 mg of $NaBO_3$•$4H_2O$. The reaction mixture was stirred for 6 hours and extracted with EtOAc (15 mL) three times. The combined organic extracts were concentrated under reduced pressure and purified by flash column chromatography to yield alcohol **20** (0 - 30% hexanes/EtOAc). 27.4 mg alcohol **1** was obtained (78% yield). The e.r. was confirmed by chiral GC with FID detector using a Chiraldex GTA column (30.0 m × 0.25 mm) (conditions: 120 °C isothermal at 1.0 mL/min He carrier gas flow). Retention time: 7.09 min for *R* enantiomer, 7.52 min for *S* enantiomer). This compound is known[13]. ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.56 – 7.34 (m, 5H), 5.03 (qd, J = 6.7, 4.4 Hz, 1H), 2.57 (dd, J = 4.5, 1.5 Hz, 1H) ^{13}C NMR (101 MHz, Chloroform-*d*) δ 134.3, 130.0, 129.0, 127.8, 124.6 (q, J = 282.1) Hz, 73.2 (q, J = 32.0 Hz). ^{19}F NMR (282 MHz, Chloroform-*d*) δ –78.40 (d, J = 7 Hz).

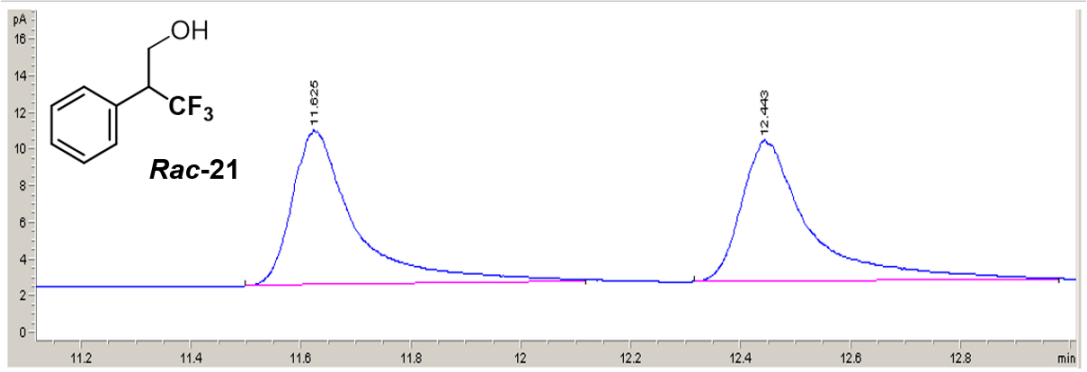


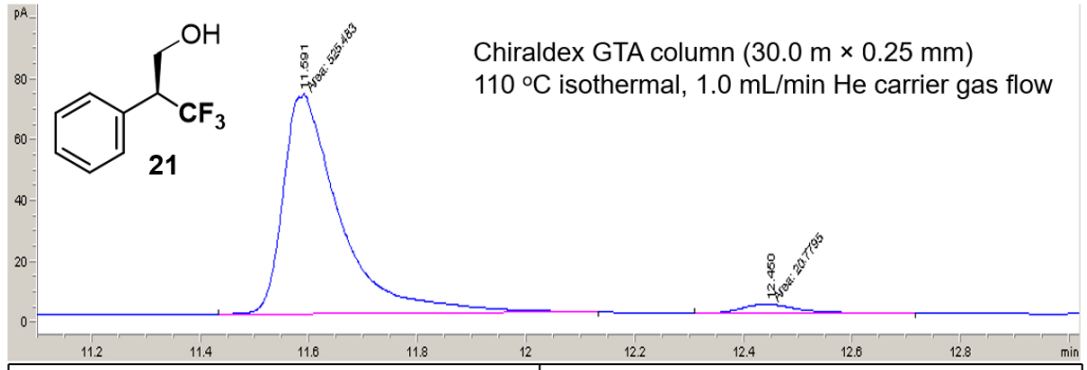
***Rac*-20**			**20**		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
7.087	36	50.1	7.099	27.9	94.0
7.505	35.9	49.9	7.516	1.8	6.0



(C) Conversion of 19 to alcohol 21 *via* Matteson homologation and oxidation. To the reaction mixture obtained after ligand exchange with pinacol in step **A**, 5 mL of water was added and the mixture was extracted with 15 mL of 1:1 hexanes:EtOAc three times. The solvent was removed under reduced pressure and the vial was backfilled with argon. The crude product **19** was dissolved in 15 mL of pentane and passed through a syringe filter to remove the insoluble materials. This process was repeated two additional times to ensure all soluble materials were extracted. The combined organic extracts were concentrated under reduced pressure. Under argon, 2 mL of anhydrous THF and dibromomethane (35 µL, 2.5 eq.) were added and the vial was cooled in a dry ice/acetone bath. *n*-BuLi (160 µL, 2.5 M in hexanes, 2.0 eq.) was added dropwise over 30 min. The solution was allowed to warm to room temperature slowly. The reaction mixture was then diluted with 3 mL *sat.* NH_4Cl and extracted with EtOAc (15 mL) for three times. The combined organic extracts were dried over anhydrous Na_2SO_4 and concentrated under reduced pressure. The resulting crude mixture was dissolved in THF (1 mL). 1 mL of H_2O and $NaBO_3$•$4H_2O$ (154 mg) were then added and the reaction mixture was stirred for 6 hours. The reaction was then extracted with EtOAc. The organic extracts were dried, concentrated under reduced pressure, and purified by flash column chromatography to yield alcohol **21** (0 - 30%

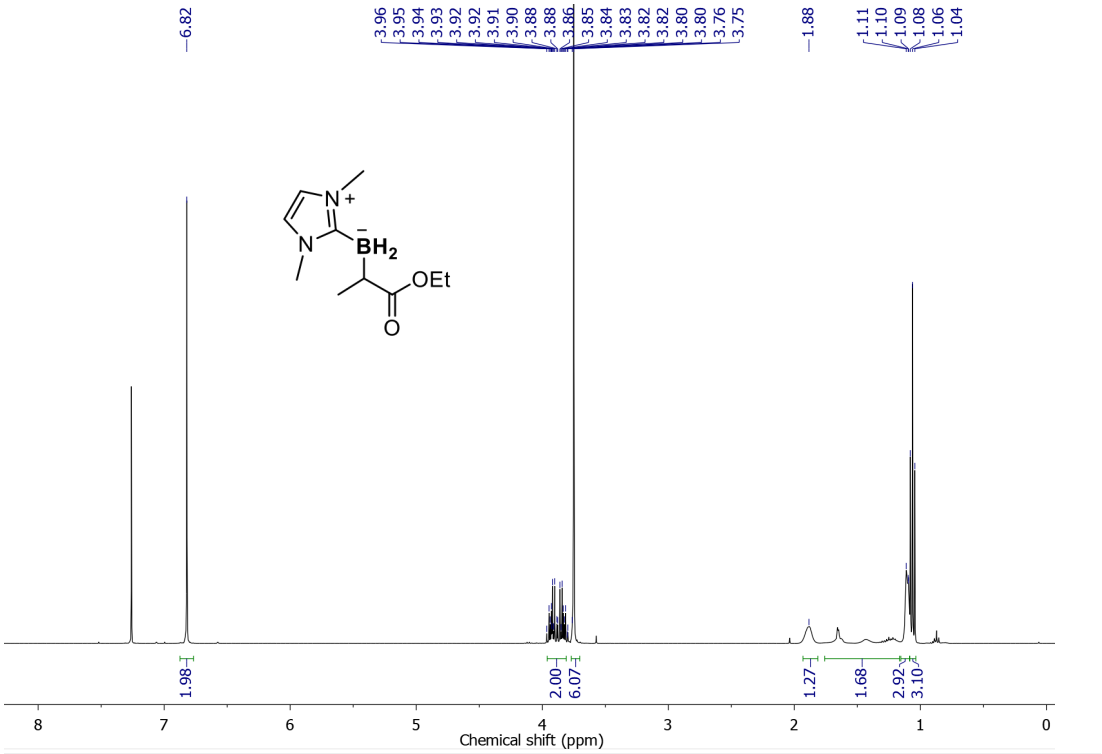
hexanes/EtOAc). 12.6 mg alcohol **21** was obtained (33% overall yield, 38% for the Matteson homologation and oxidation steps). The e.r. was confirmed by chiral GC with FID detector using a Chiraldex GTA column (30.0 m × 0.25 mm) (conditions: 110 °C isothermal at 1.0 mL/min He carrier gas flow). Retention time: 11.625 min for *S* enantiomer, 12.443 min for *R* enantiomer). This compound is known[14]. ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.44 – 7.31 (m, 5H), 4.20 (dd, *J* = 11.7, 5.7 Hz, 1H), 4.04 (dd, *J* = 11.4, 7.8 Hz, 1H), 3.56 (qdd, *J* = 9.4, 7.8, 5.8 Hz, 1H), 1.57 (s, 1H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 132.8 (d, *J* = 2.2 Hz), 129.5, 129.4, 129.0, 126.4 (q, *J* = 280.5 Hz), 61.7 (q, *J* = 2.9 Hz), 52.9 (q, *J* = 25.5 Hz). ^{19}F NMR (282 MHz, Chloroform-*d*) δ –67.47 (d, *J* = 9 Hz).

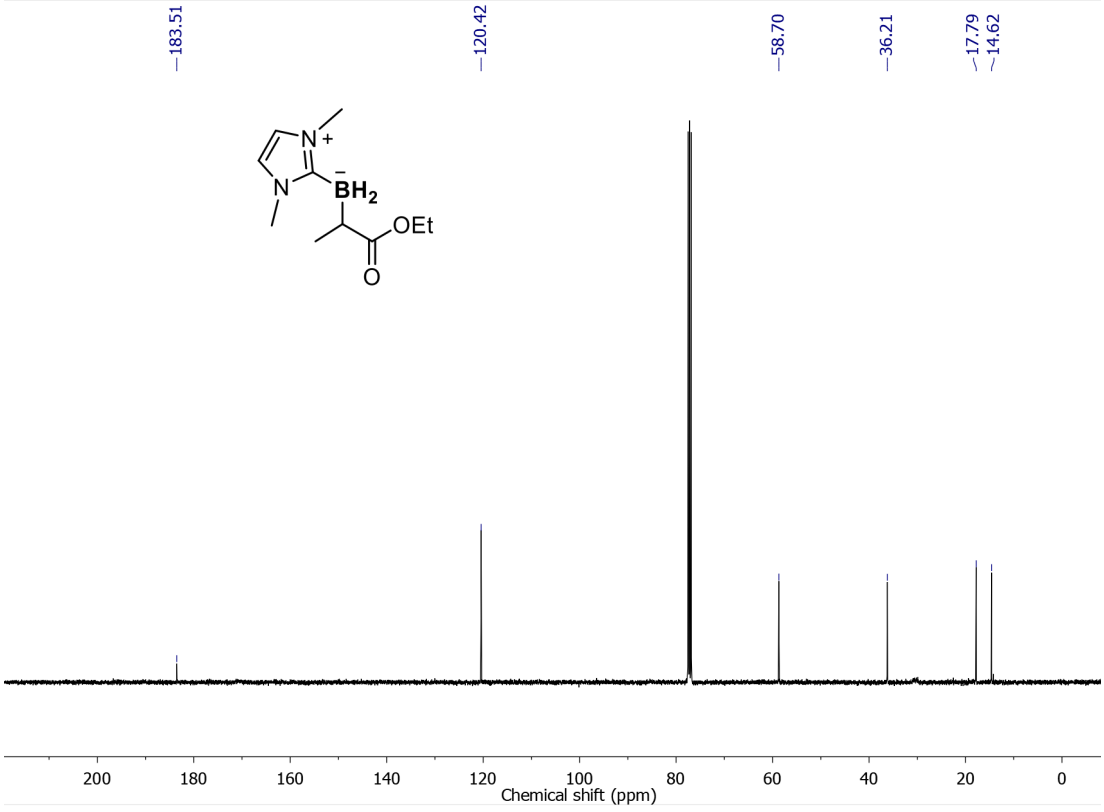


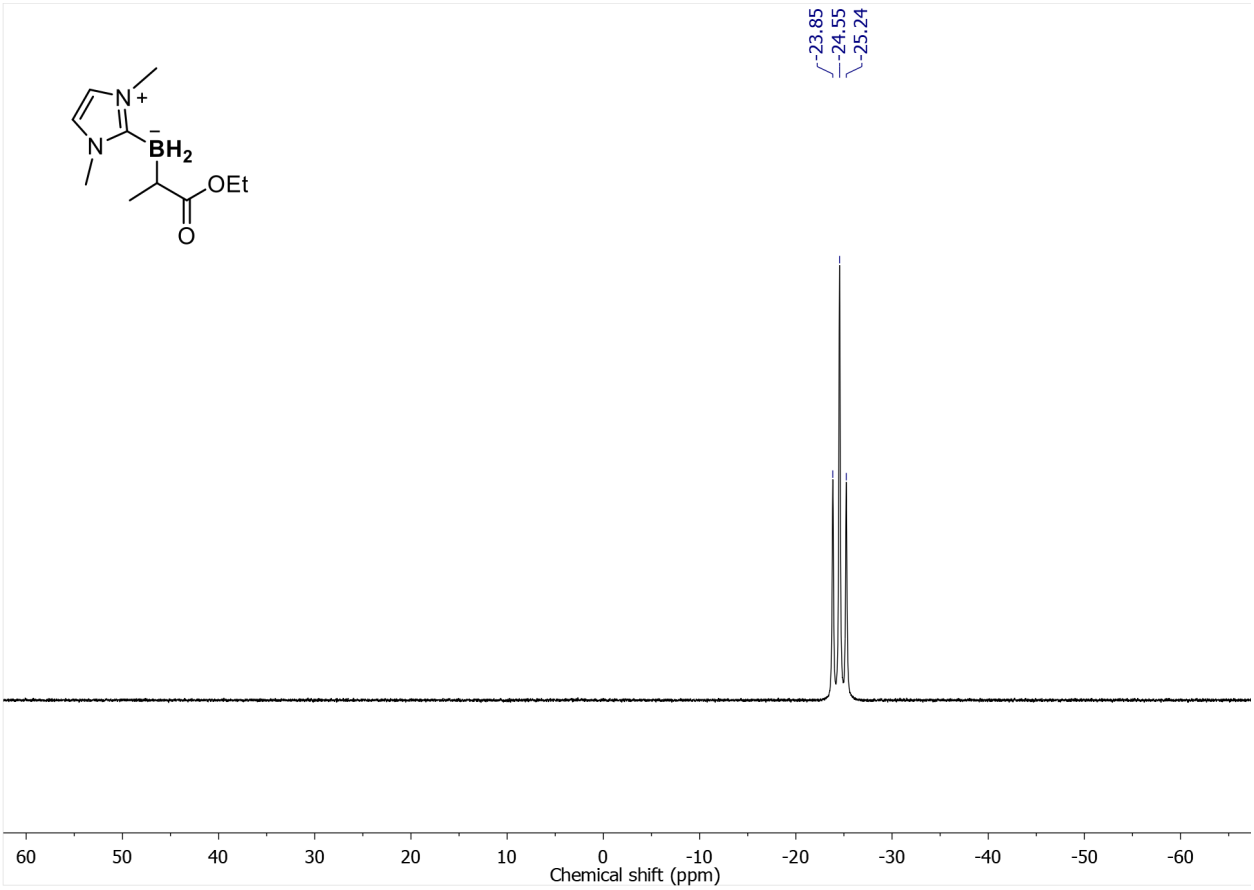


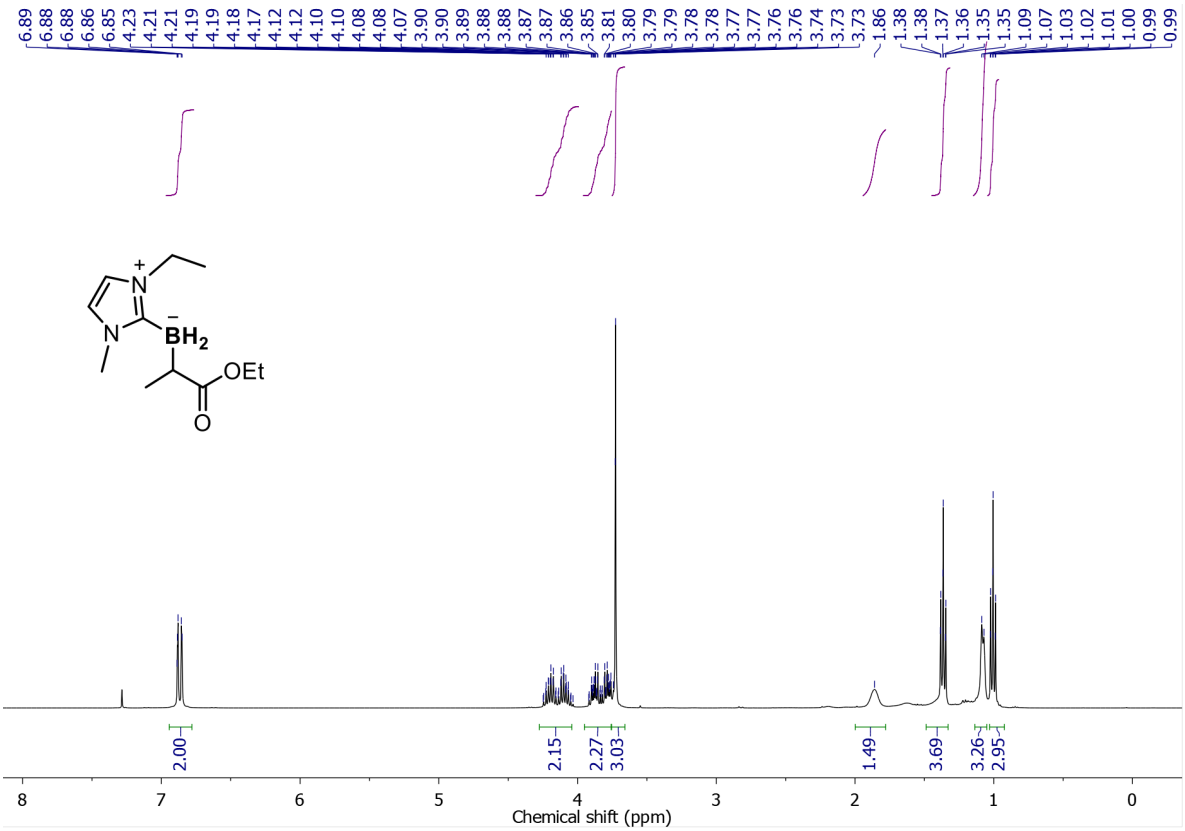
***Rac*-21**			**21**		
Retention Time (min)	Area (mAu)	Area%	Retention Time (min)	Area (mAu)	Area%
11.625	66.7	50.3	11.591	525.5	96.2
12.443	65.8	49.7	12.450	20.8	3.8

X. NMR Spectra






-23.85
-24.55
-25.24
BH2
OEt
O
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Chemical shift (ppm)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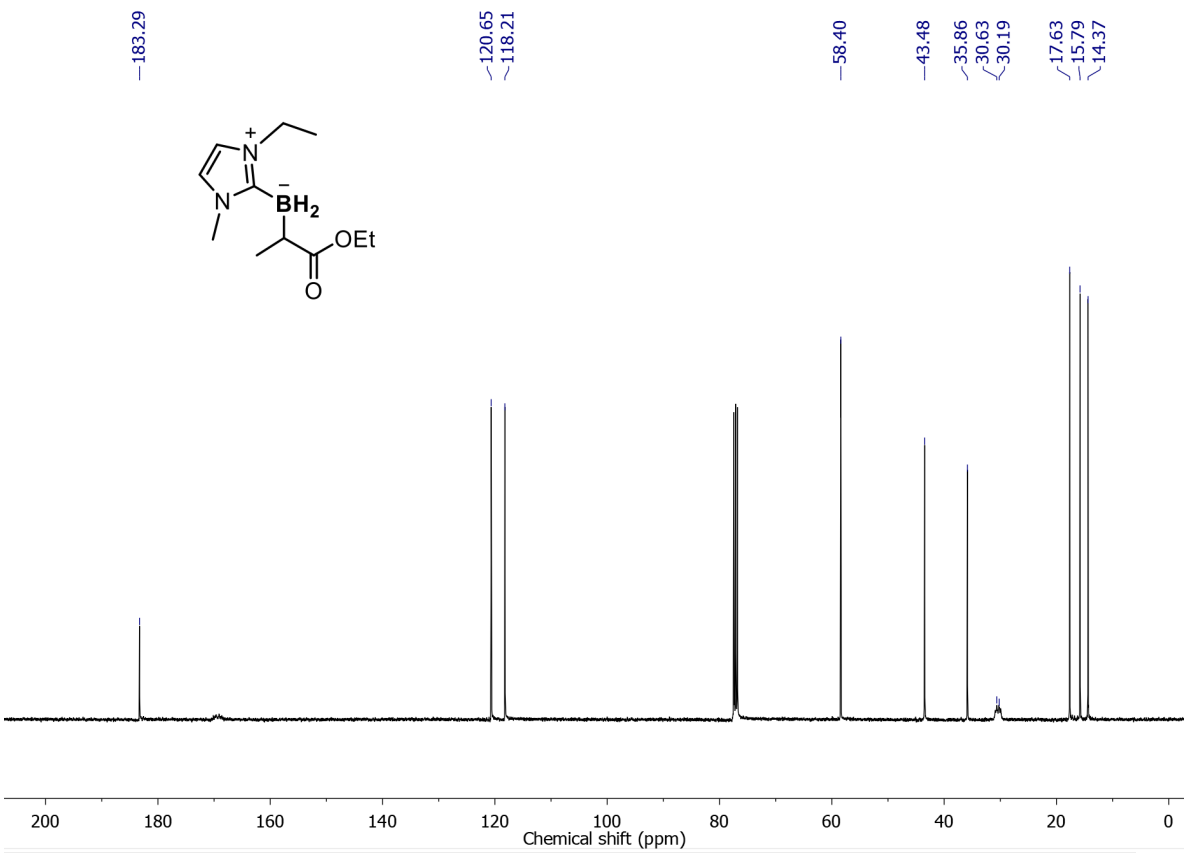
6.88
6.88
6.86
6.85
4.23
4.21
4.21
4.19
4.19
4.18
4.17
4.12
4.12
4.10
4.10
4.08
4.08
4.07
3.90
3.90
3.89
3.88
3.88
3.87
3.87
3.86
3.85
3.81
3.80
3.79
3.79
3.78
3.78
3.77
3.77
3.76
3.76
3.74
3.73
3.73
1.86
1.38
1.38
1.37
1.36
1.35
1.35
1.09
1.07
1.03
1.02
1.01
1.00
0.99
0.99
BH2
OEt
O
2.00
2.15
2.27
3.03
1.49
3.69
3.26
2.95
8
7
6
5
4
3
2
1
0
Chemical shift (ppm)


183.29
120.65
118.21
58.40
43.48
35.86
30.63
30.19
17.63
15.79
14.37
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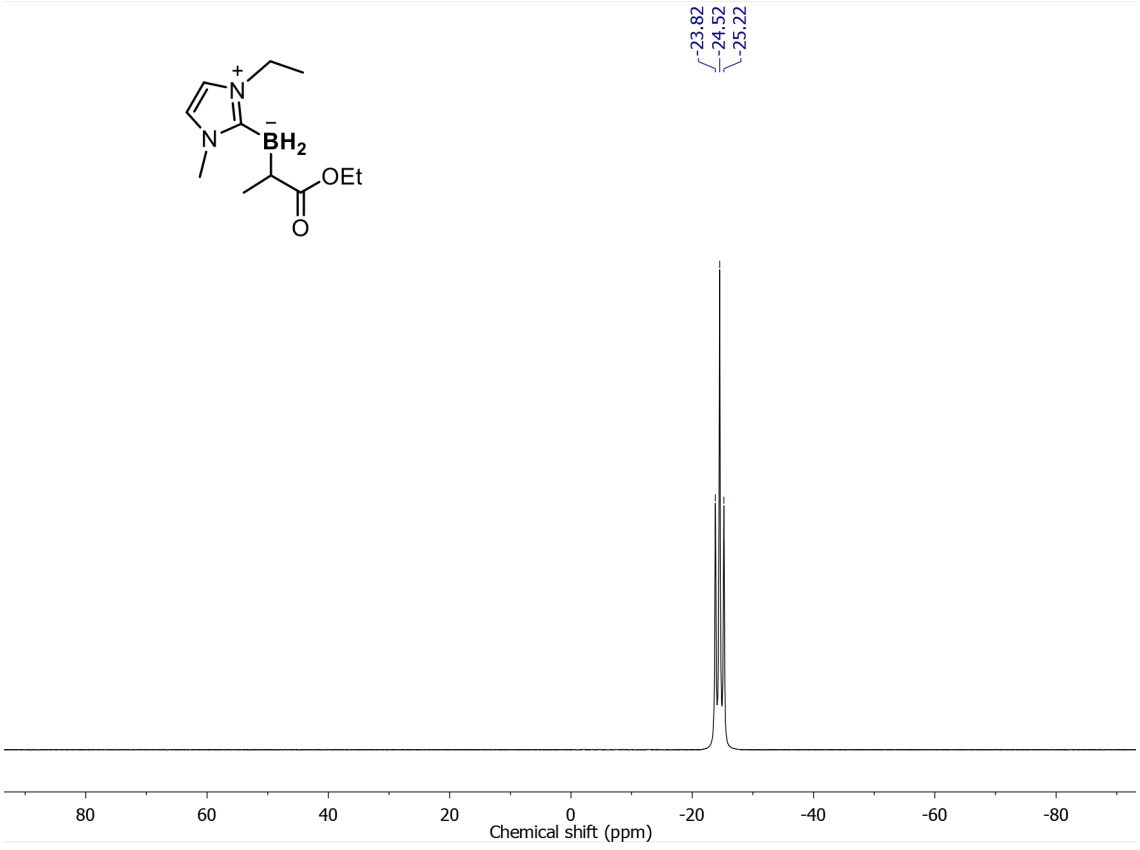
OEt
O
200
180
160
140
120
100
80
60
40
20
0
Chemical shift (ppm)


-23.82
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-25.22
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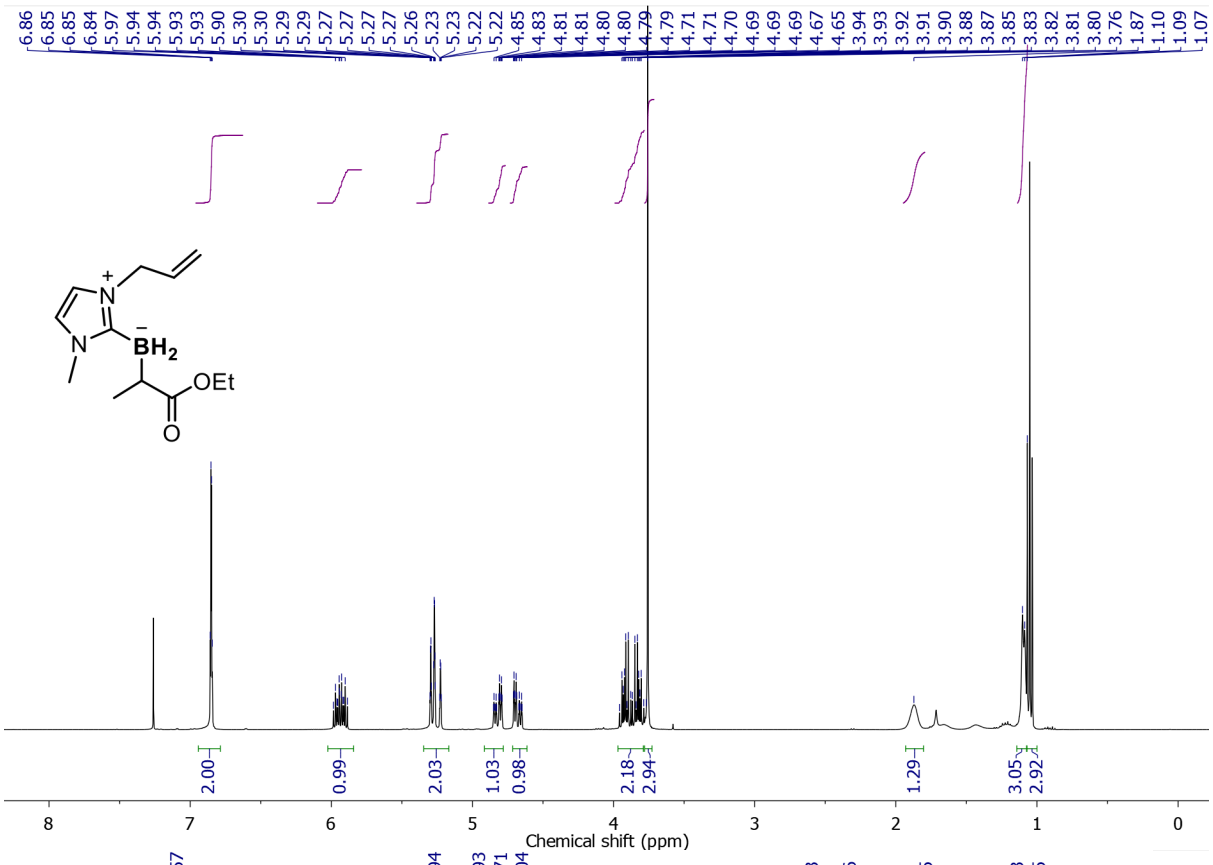
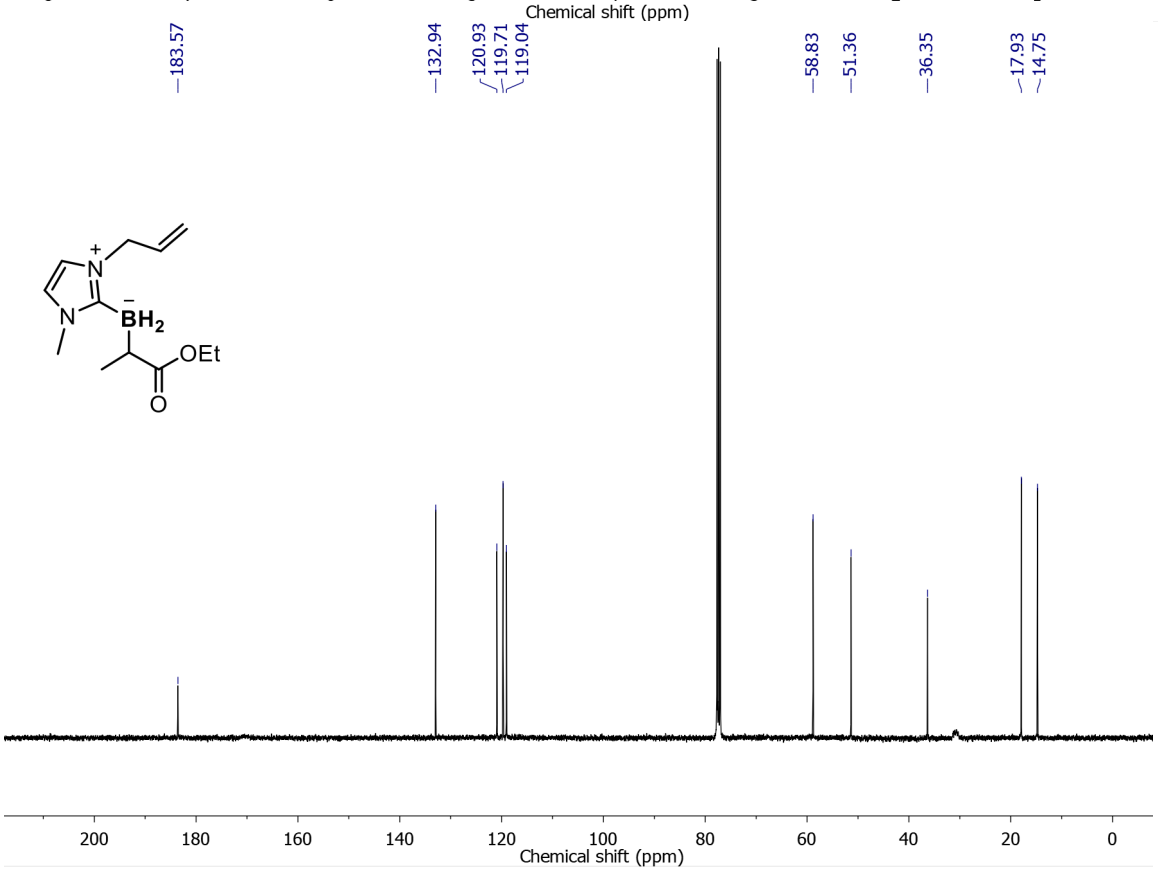
OEt
O
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)


6.86 6.85 6.85 6.84 5.97 5.94 5.94 5.93 5.93 5.90 5.30 5.29 5.29 5.27 5.27 5.27 5.27 5.26 5.23 5.23 5.22 5.22 4.85 4.83 4.81 4.81 4.80 4.80 4.79 4.79 4.71 4.70 4.69 4.69 4.67 4.65 3.94 3.93 3.92 3.91 3.90 3.88 3.87 3.85 3.83 3.82 3.81 3.80 3.76 1.87 1.10 1.09 1.07
2.00 0.99 2.03 1.03 0.98 2.18 2.94 1.29 3.05 2.92
8 7 6 5 4 3 2 1 0
Chemical shift (ppm)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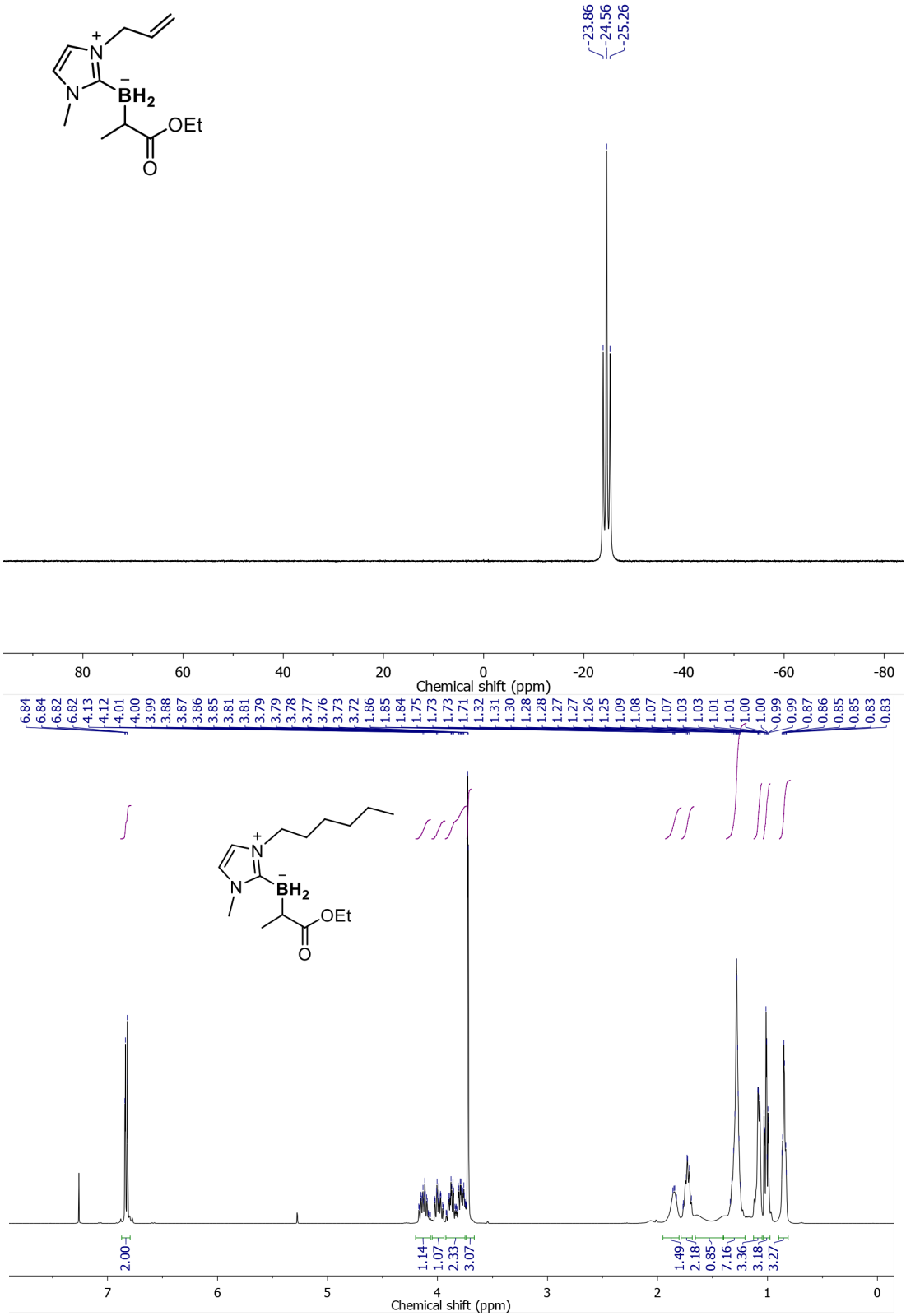
Chemical shift (ppm)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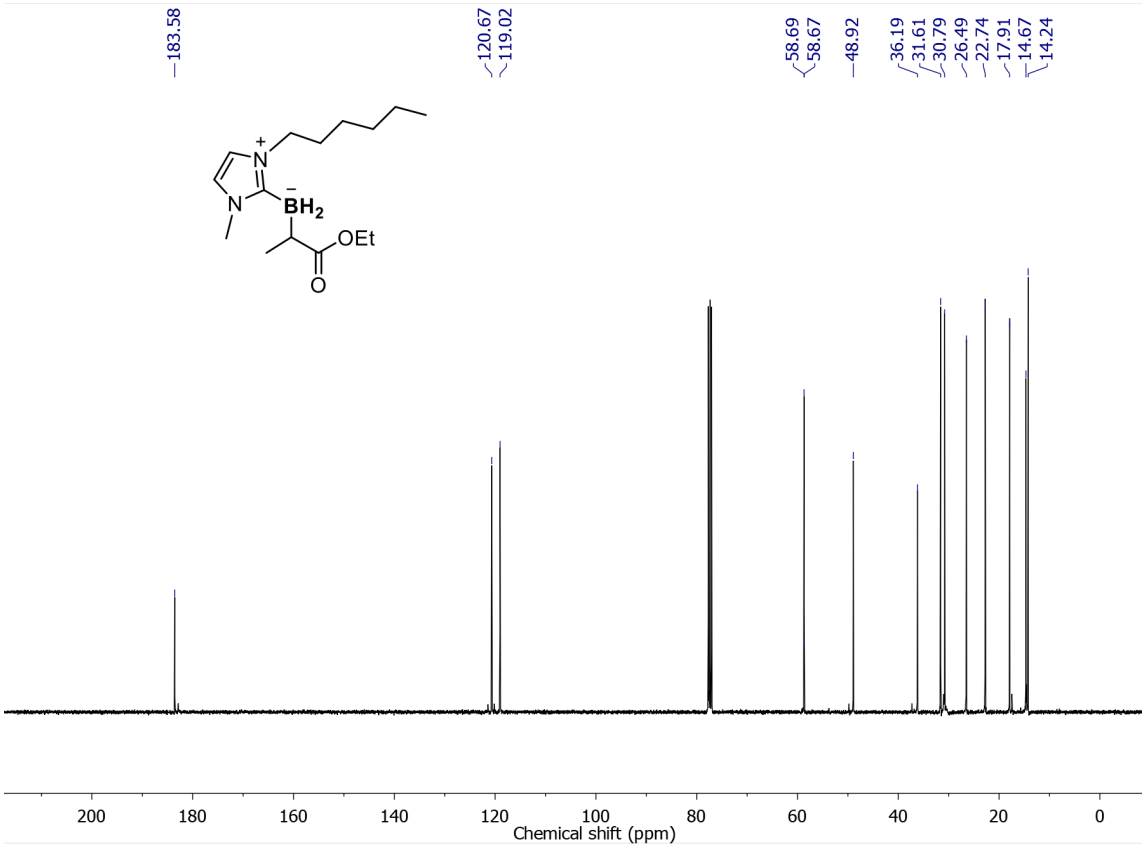
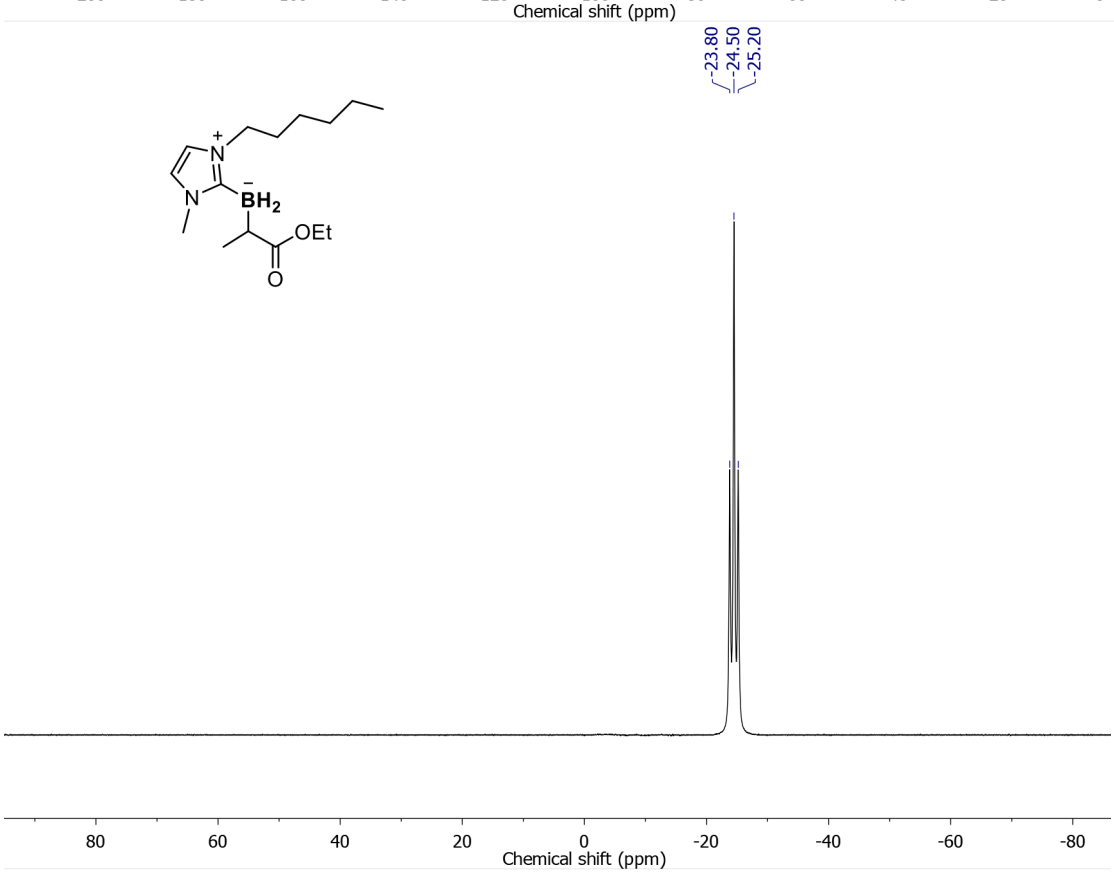
-24.56
-25.26
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)
2.00
1.14
1.07
2.33
3.07
1.49
2.18
0.85
7.16
3.36
3.18
3.27
7
6
5
4
3
2
1
0
Chemical shift (ppm)


183.58
120.67
119.02
58.69
58.67
48.92
36.19
31.61
30.79
26.49
22.74
17.91
14.67
14.24
OEt
200
180
160
140
120
100
80
60
40
20
0
Chemical shift (ppm)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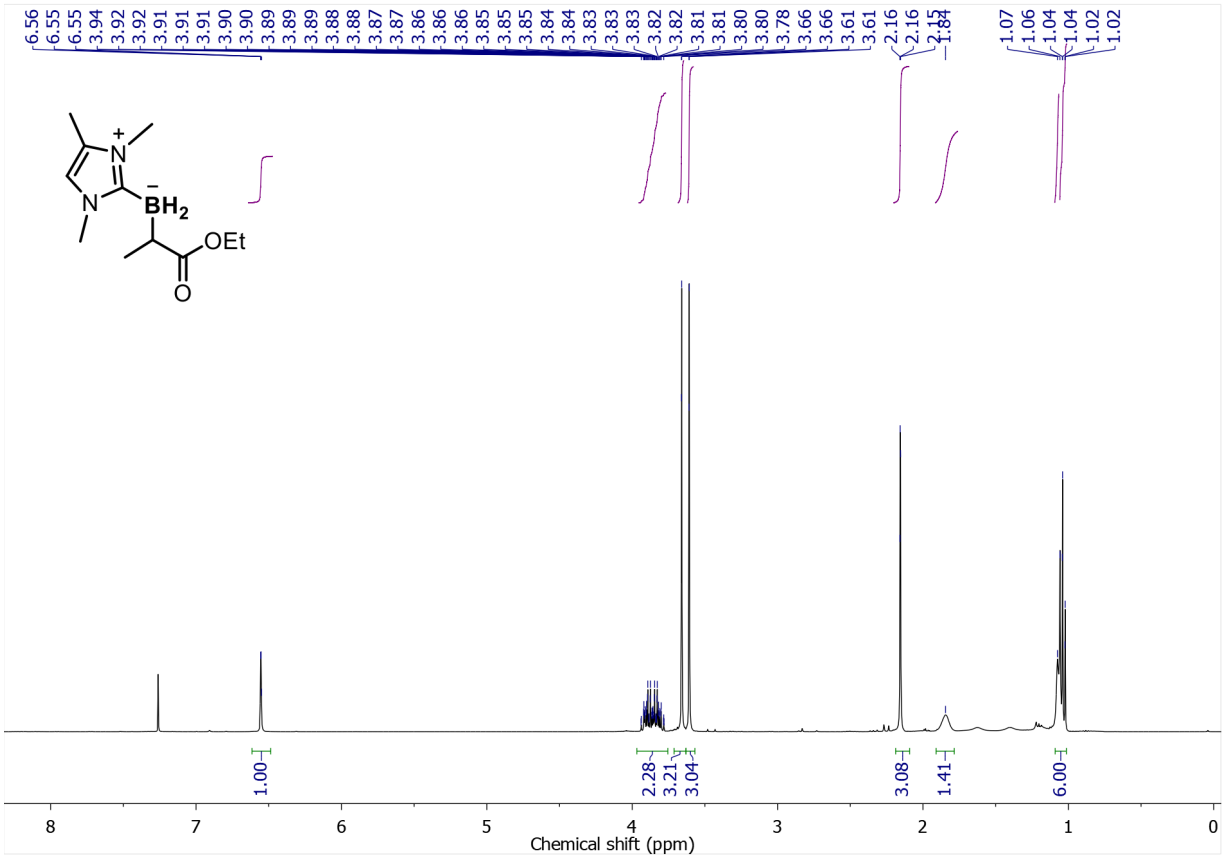
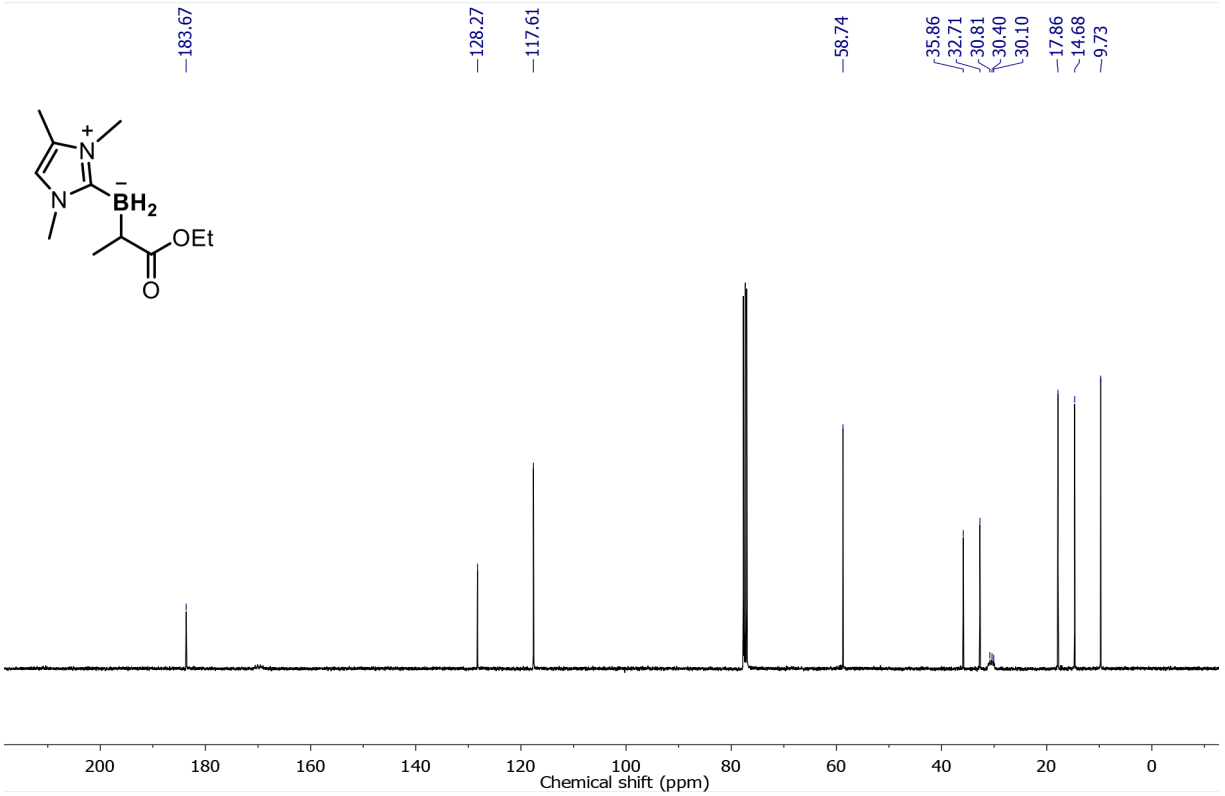
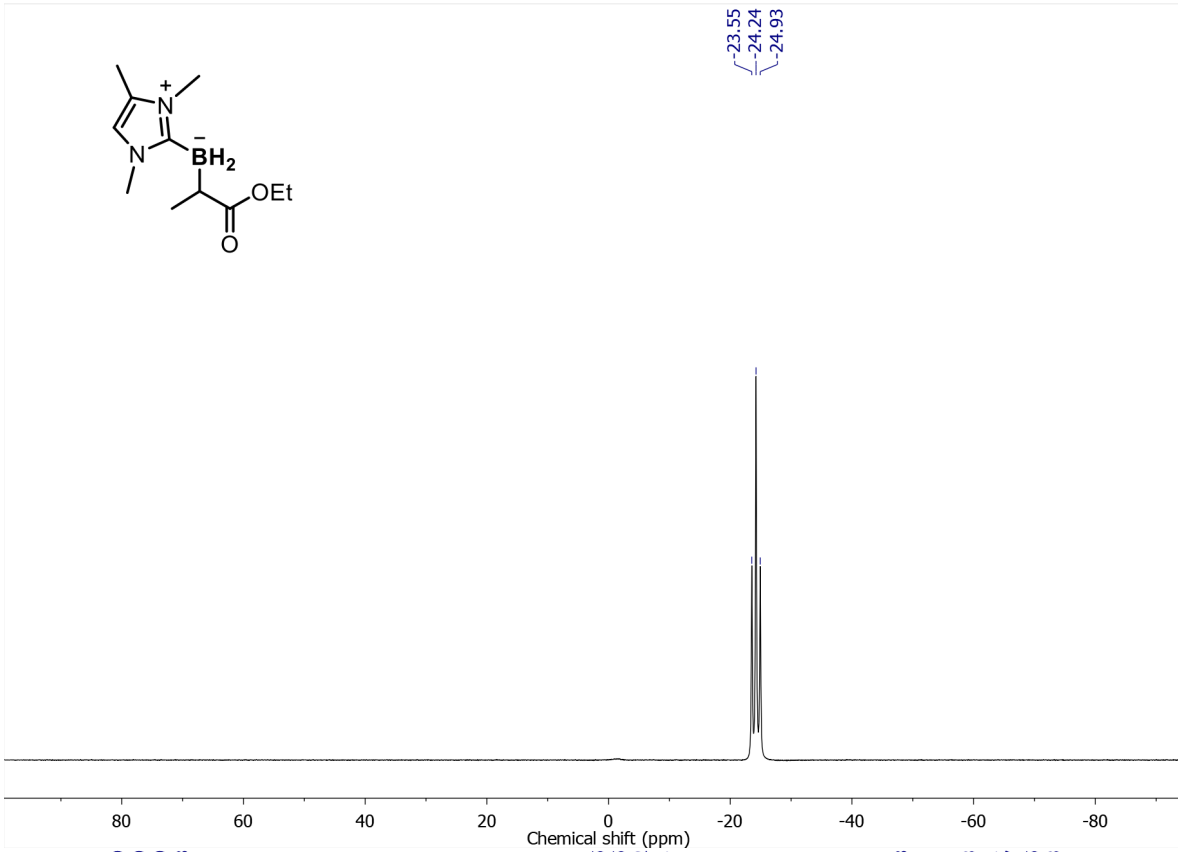
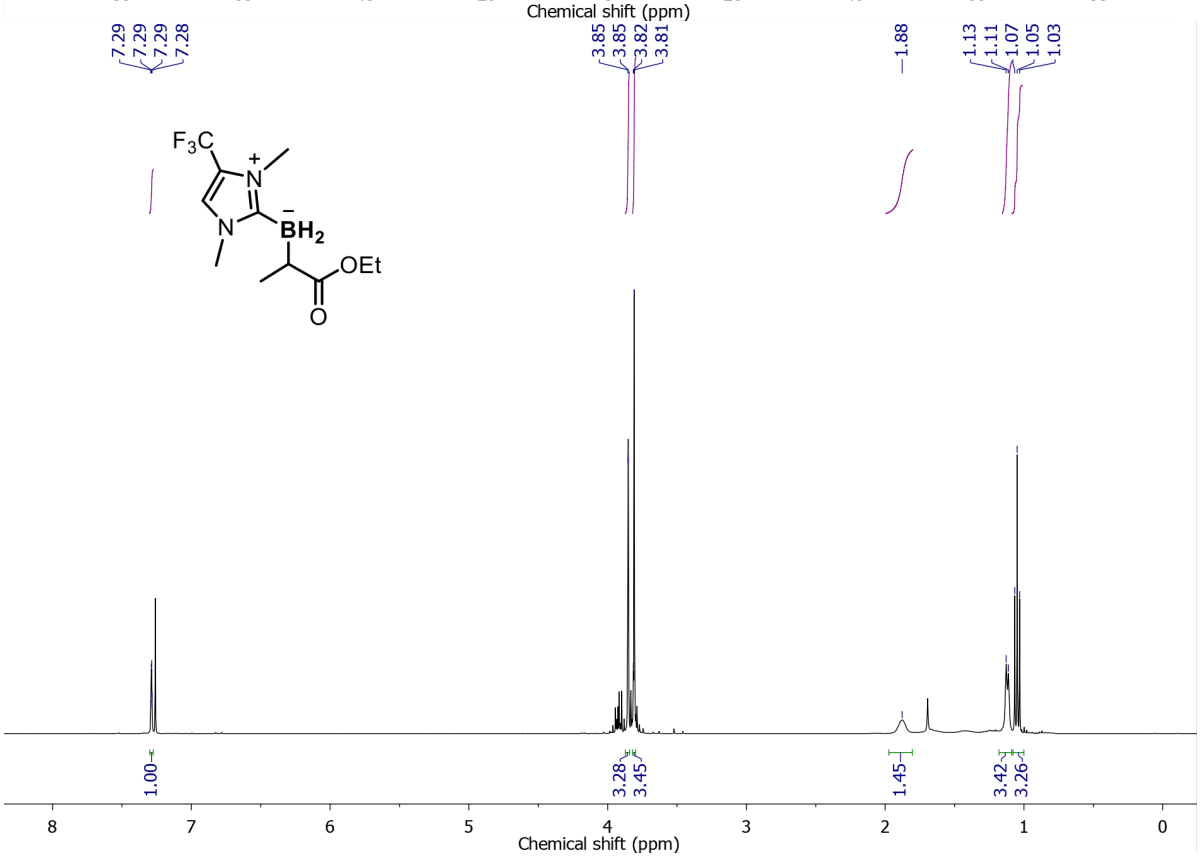
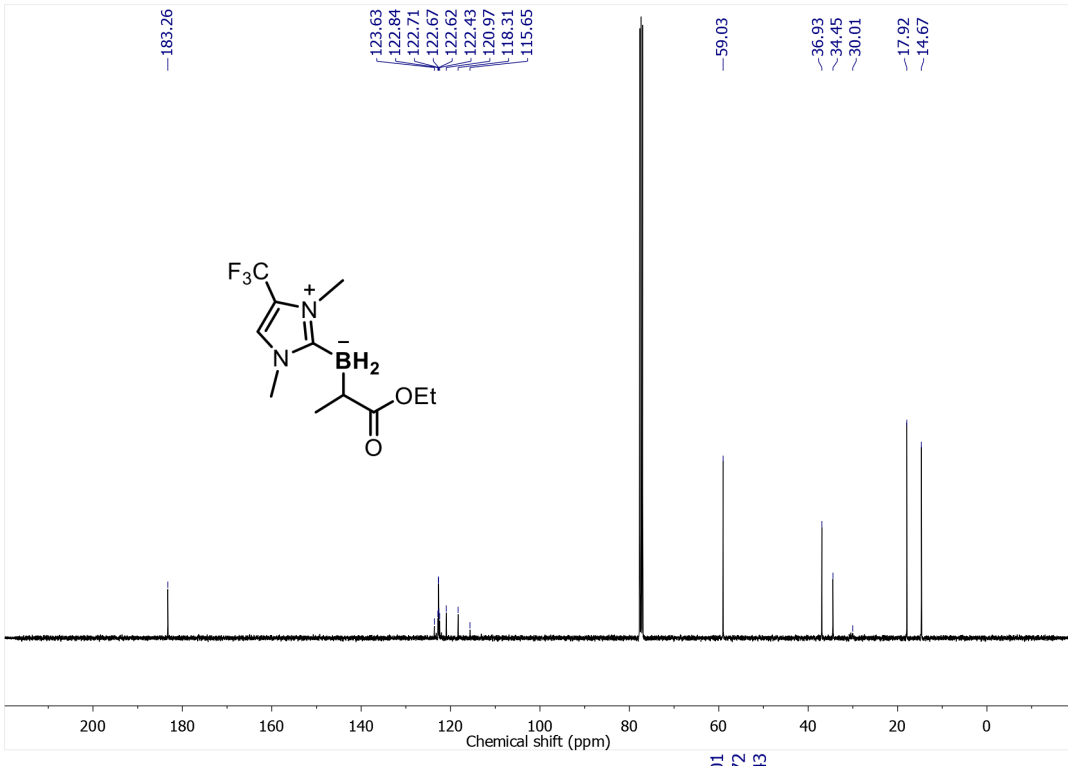
-25.20
OEt
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

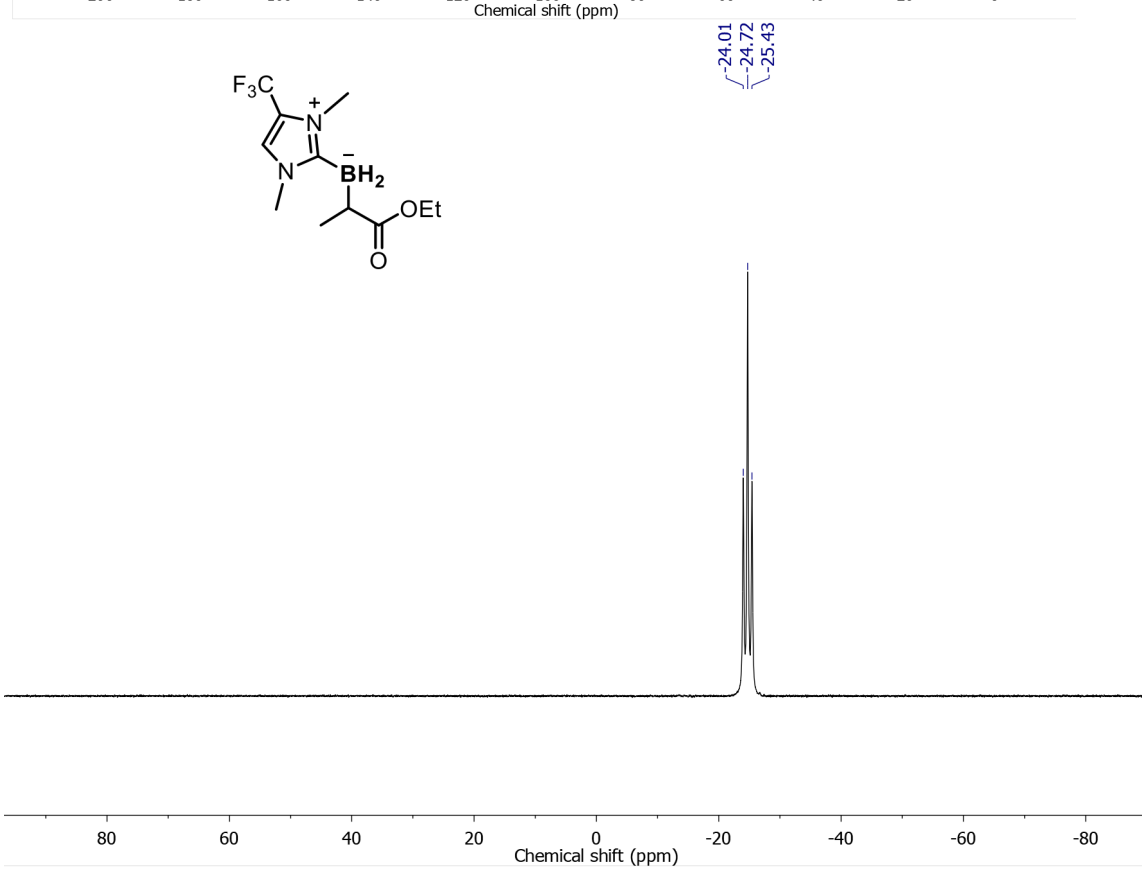

6.56 6.55 6.55 3.94 3.92 3.92 3.91 3.91 3.91 3.90 3.90 3.89 3.89 3.89 3.88 3.88 3.87 3.87 3.86 3.86 3.86 3.85 3.85 3.85 3.84 3.84 3.83 3.83 3.82 3.82 3.81 3.81 3.80 3.80 3.78 3.66 3.66 3.61 3.61 2.16 2.16 2.15 1.84 1.07 1.06 1.04 1.04 1.02 1.02
BH2
OEt
O
1.00 2.28 3.21 3.04 3.08 1.41 6.00
8 7 6 5 4 3 2 1 0
Chemical shift (ppm)

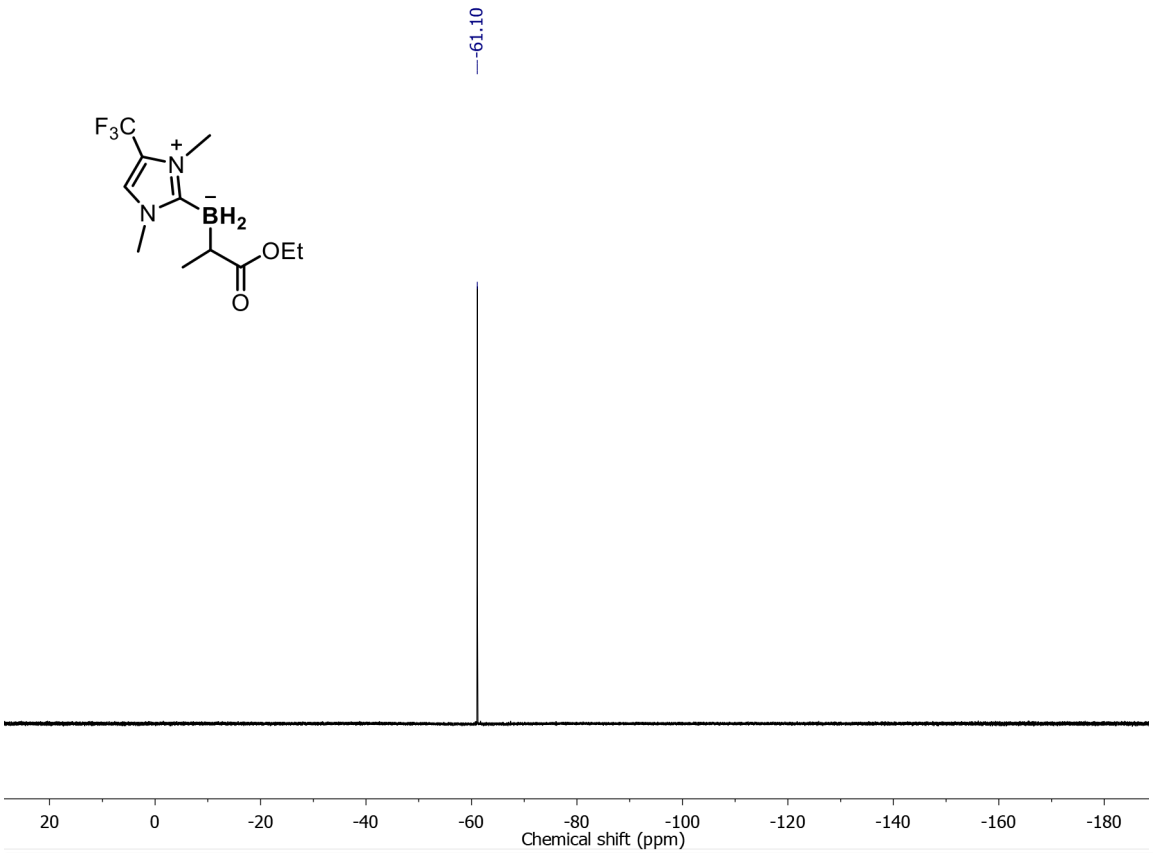

183.67 128.27 117.61 58.74 35.86 32.71 30.81 30.40 30.10 17.86 14.68 9.73
BH2
OEt
O
200 180 160 140 120 100 80 60 40 20 0
Chemical shift (ppm)

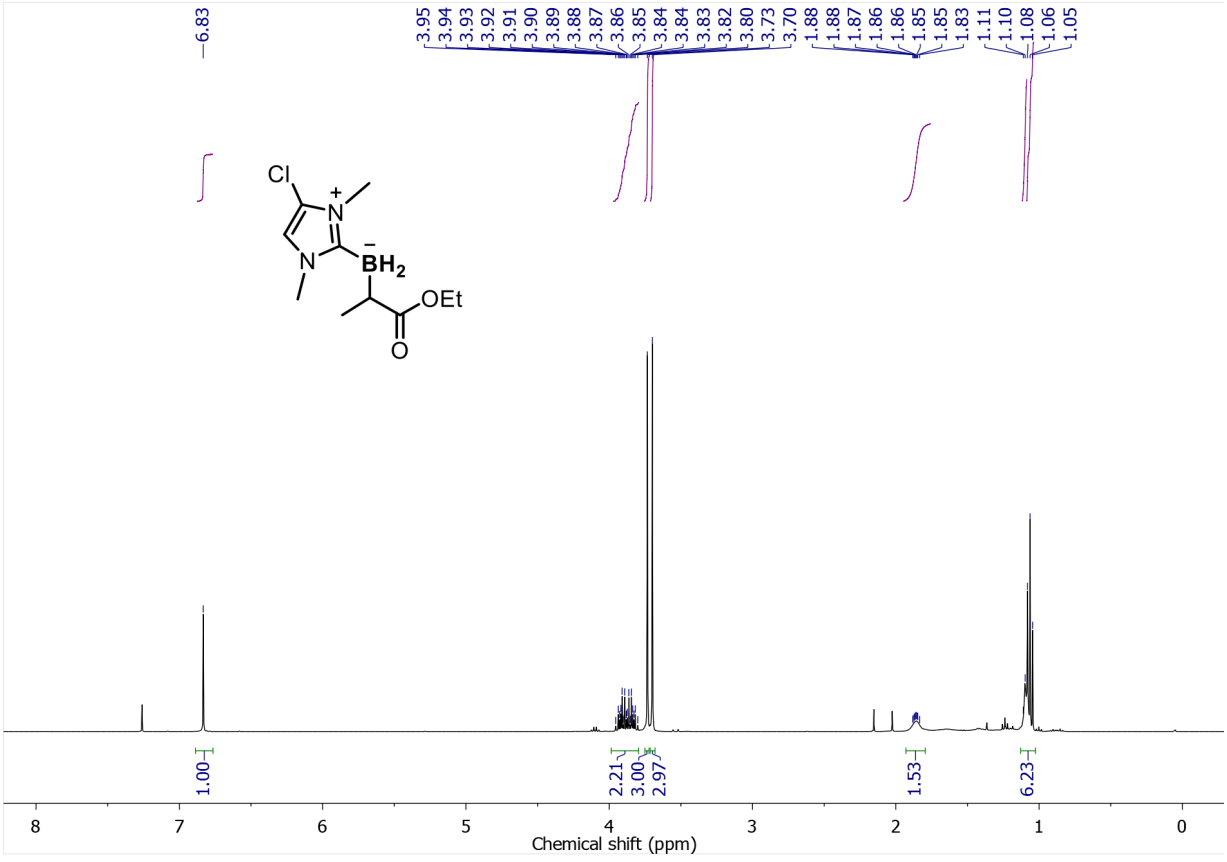

-23.55
-24.24
-24.93
BH2
OEt
O
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

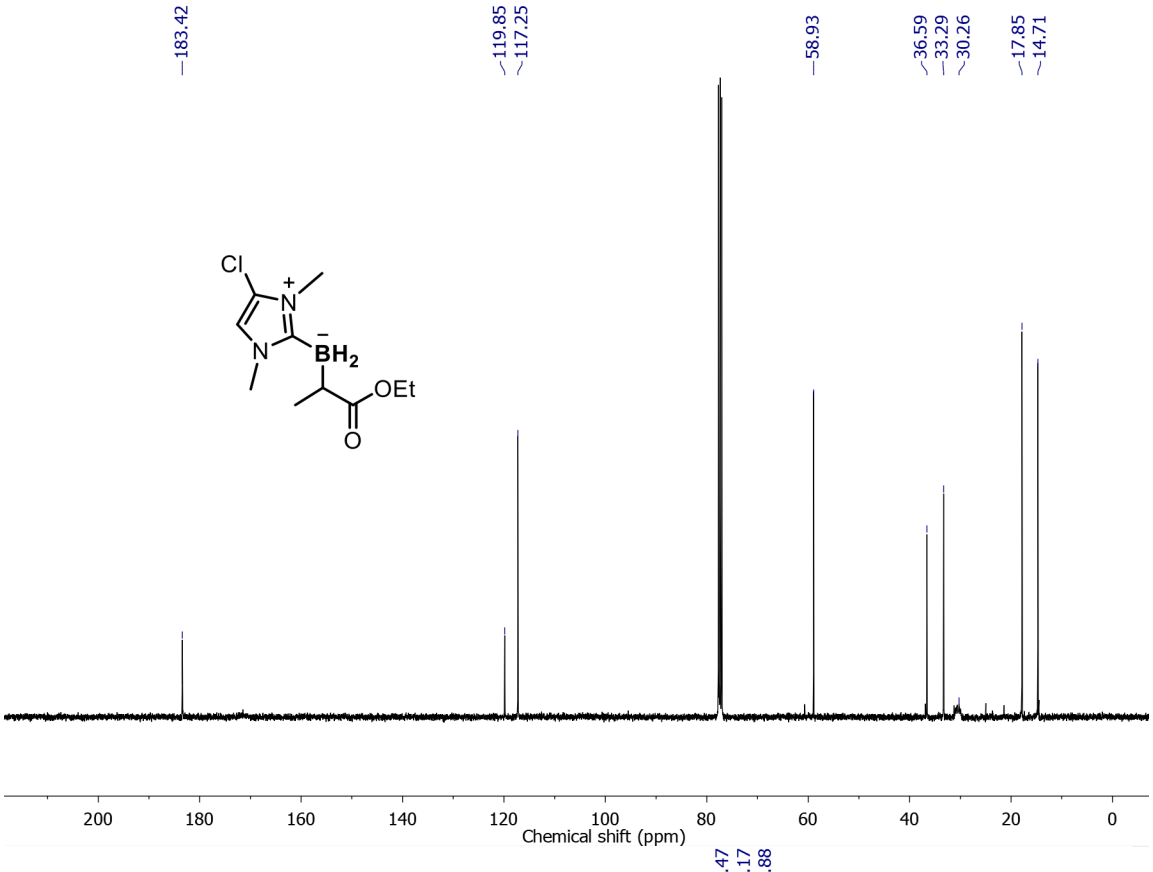

7.29
7.29
7.29
7.28
3.85
3.85
3.82
3.81
1.88
1.13
1.11
1.07
1.05
1.03
F3C
BH2
OEt
O
1.00
3.28
3.45
1.45
3.42
3.26
8
7
6
5
4
3
2
1
0
Chemical shift (ppm)

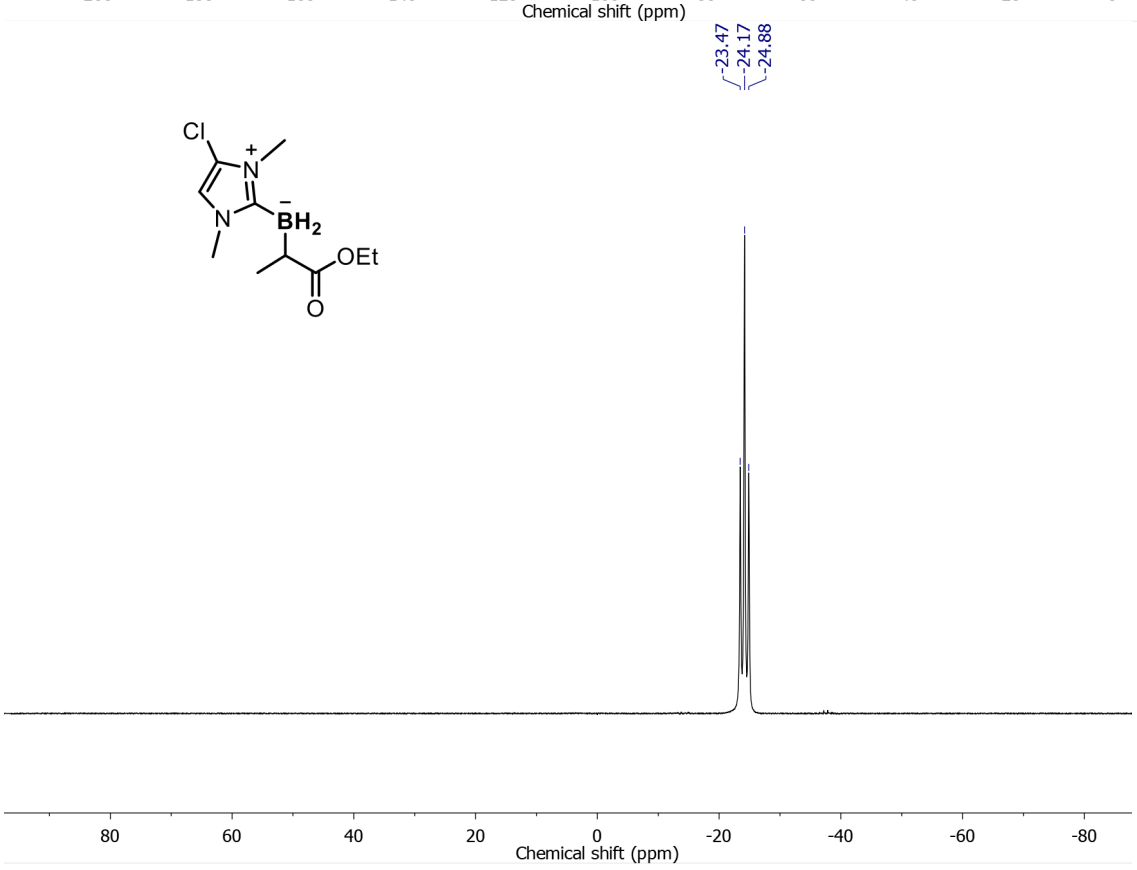

183.26
123.63
122.84
122.71
122.67
122.62
122.43
120.97
118.31
115.65
59.03
36.93
34.45
30.01
17.92
14.67
F3C
BH2
OEt
O
200
180
160
140
120
100
80
60
40
20
0
Chemical shift (ppm)

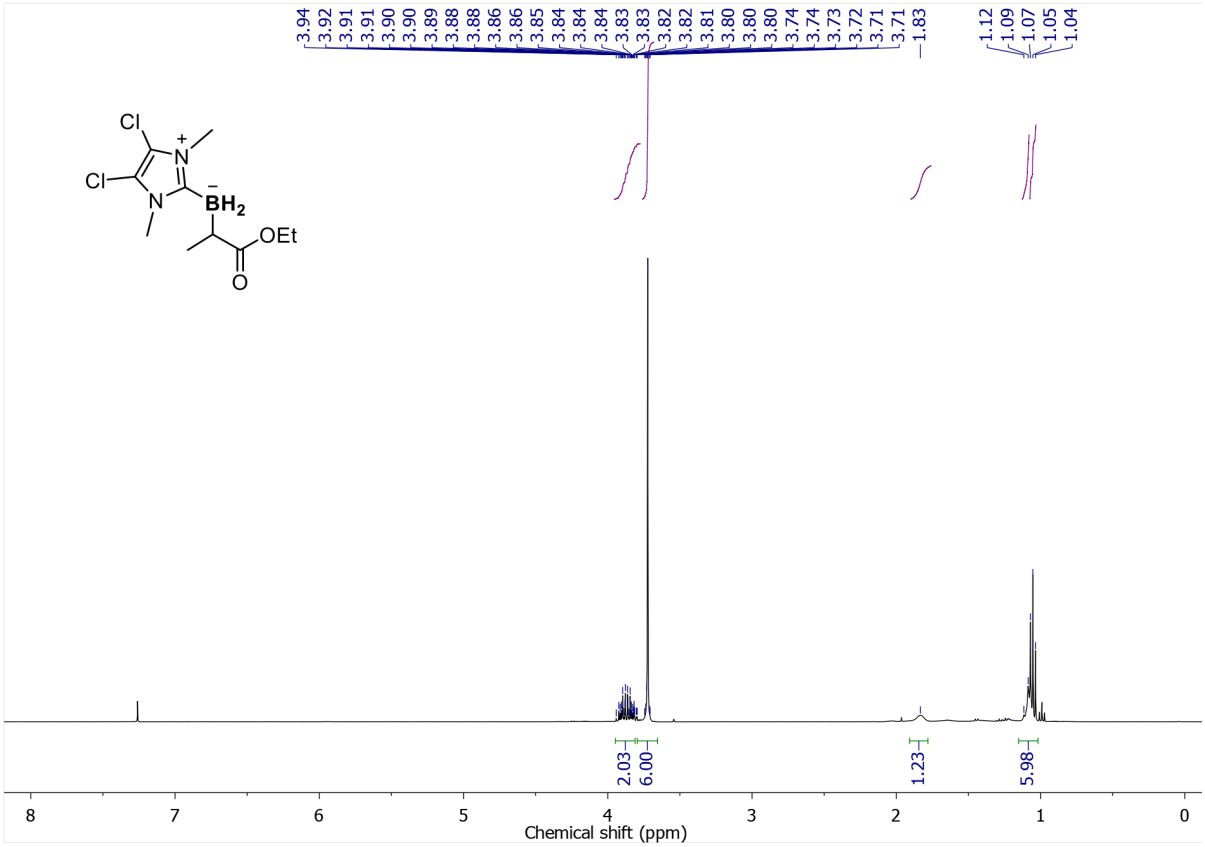

24.01
24.72
25.43
F3C
BH2
OEt
O
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

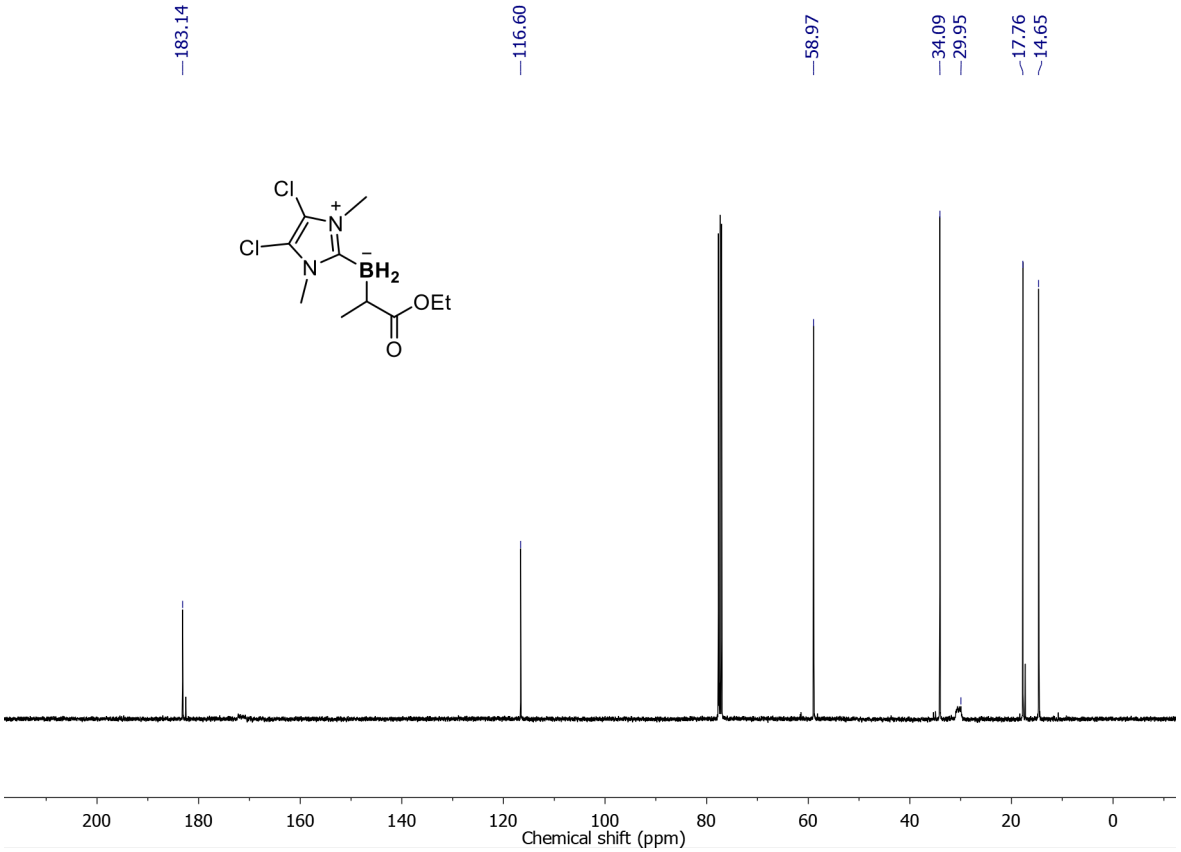

-61.10
F3C
N
N
BH2
OEt
O
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
Chemical shift (ppm)

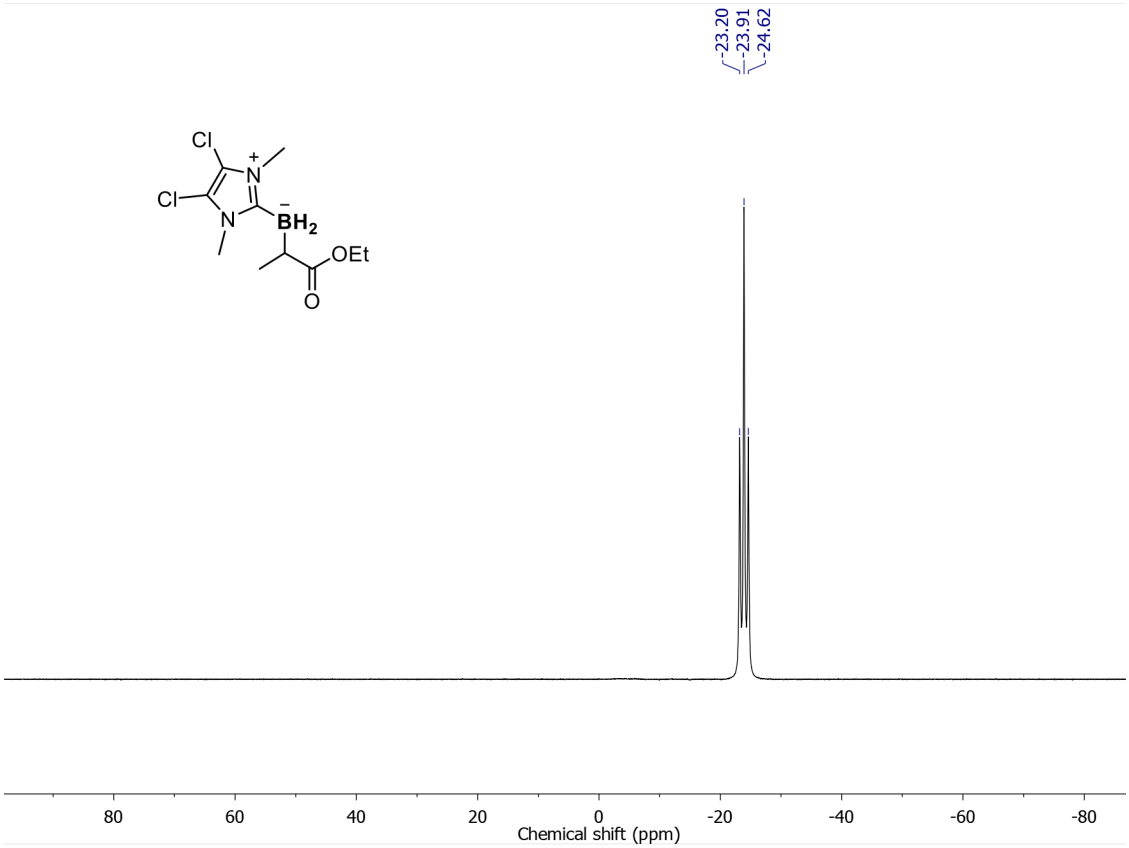

6.83
3.95
3.94
3.93
3.92
3.91
3.90
3.89
3.88
3.87
3.86
3.85
3.84
3.84
3.83
3.82
3.80
3.73
3.70
1.88
1.88
1.87
1.86
1.86
1.85
1.85
1.83
1.11
1.10
1.08
1.06
1.05
Cl
N
N
BH2
OEt
O
1.00
2.21
3.00
2.97
1.53
6.23
8
7
6
5
4
3
2
1
0
Chemical shift (ppm)

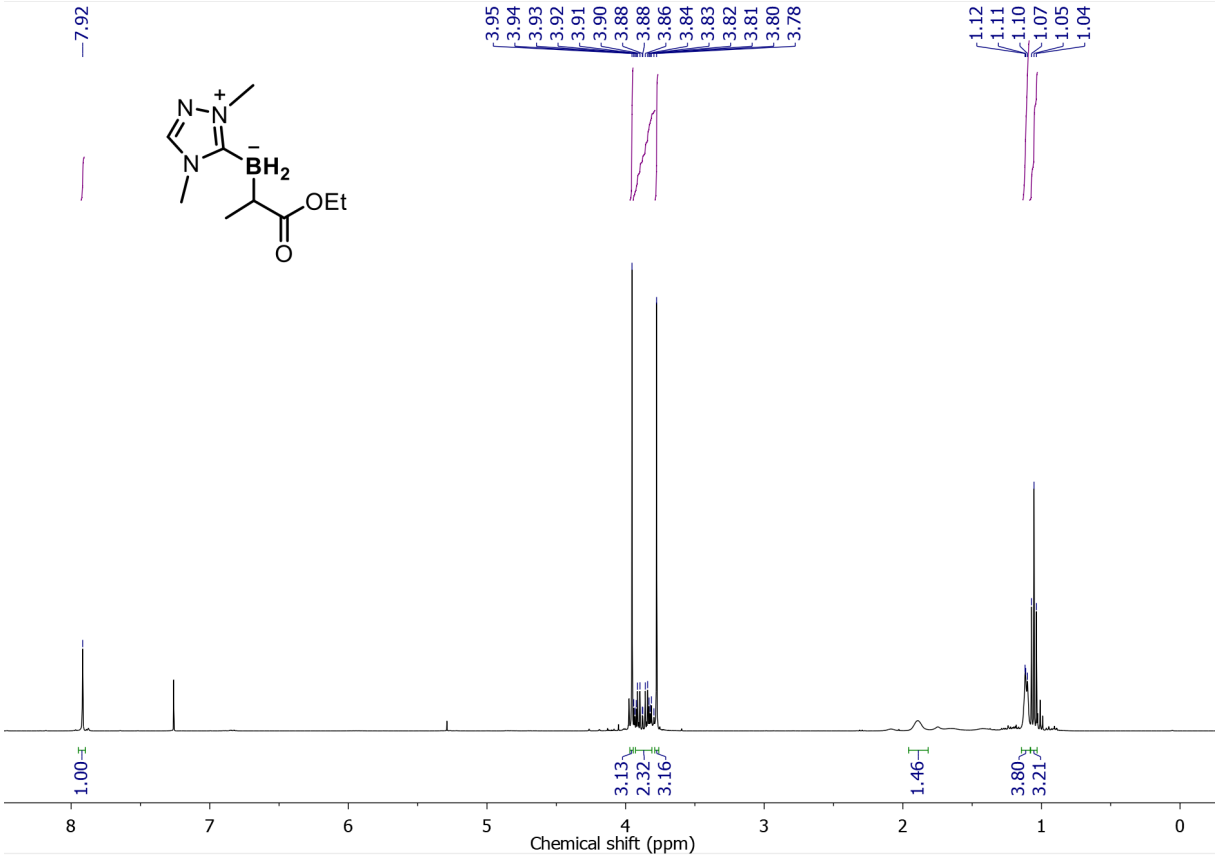

183.42
119.85
117.25
58.93
36.59
33.29
30.26
17.85
14.71
Cl
N
N
BH2
OEt
O
200
180
160
140
120
100
80
60
40
20
0
Chemical shift (ppm)

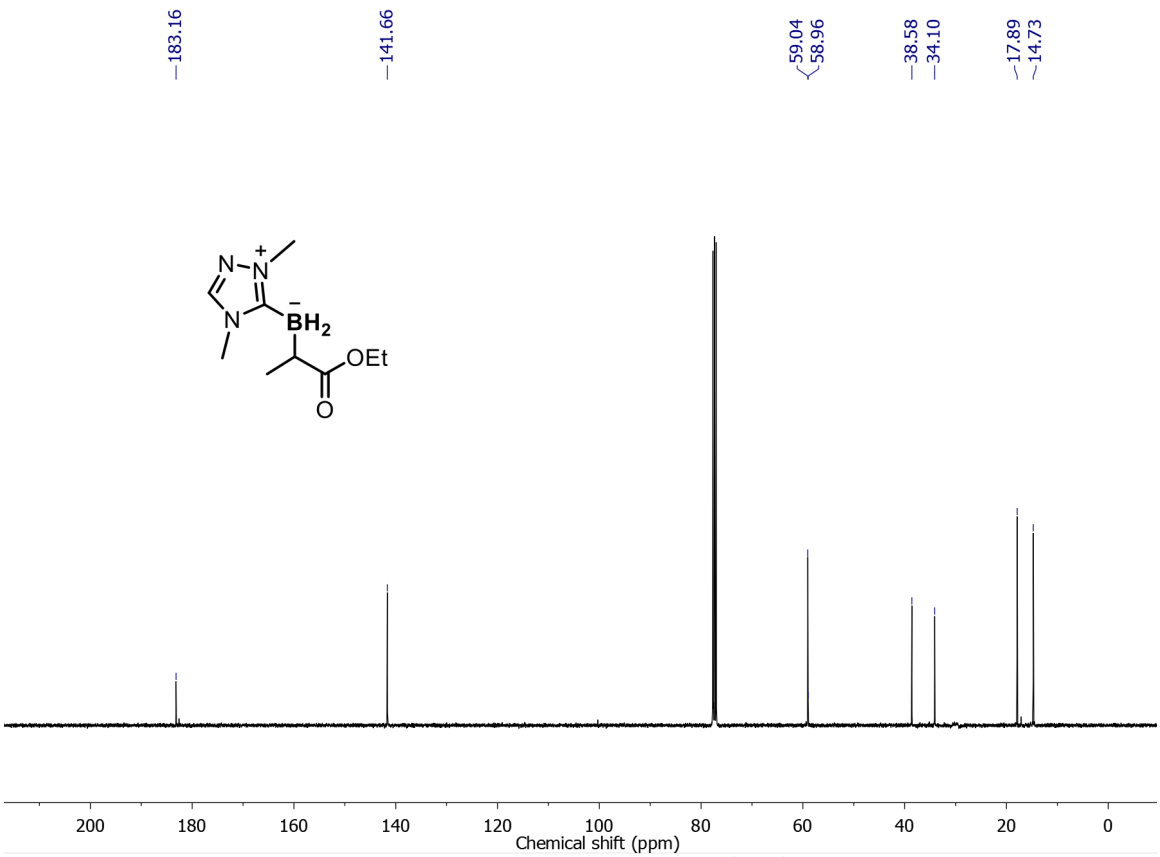

-23.47
-24.17
-24.88
Cl
N
N
BH2
OEt
O
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

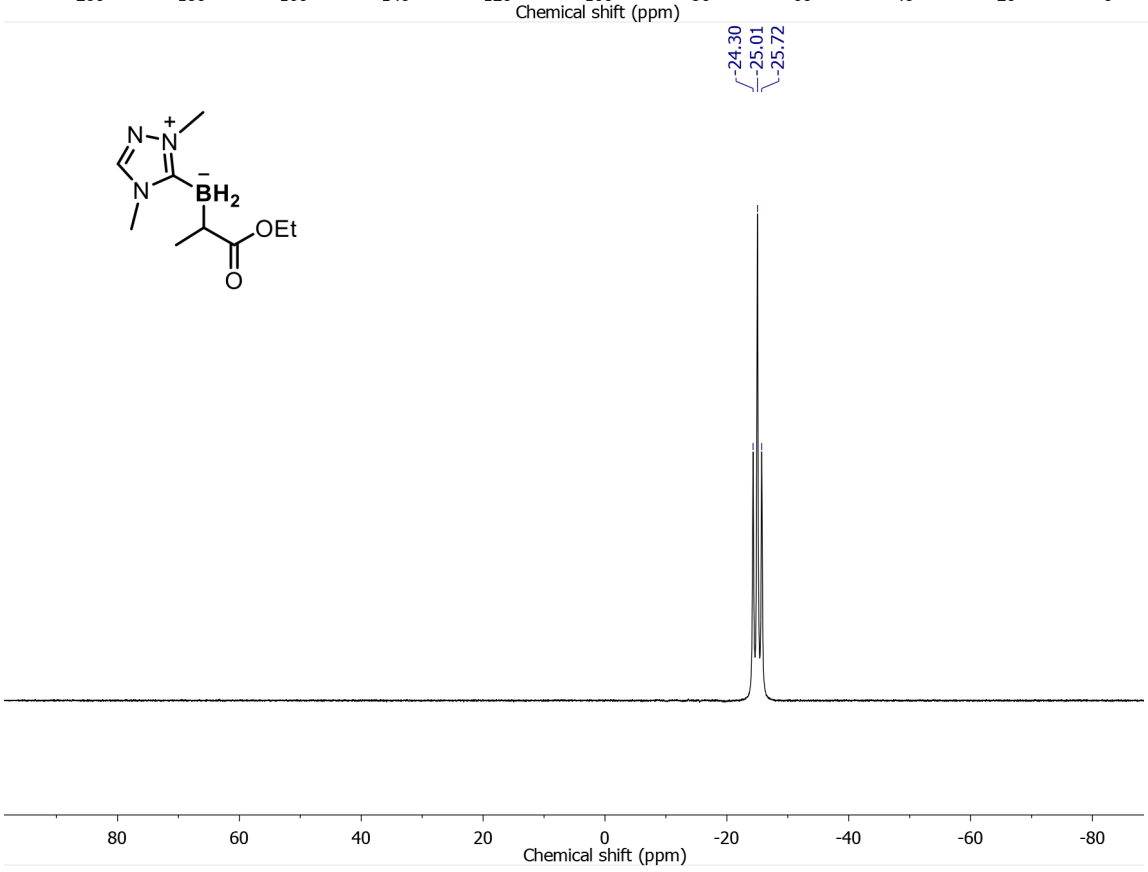

3.94 3.92 3.91 3.91 3.90 3.90 3.89 3.88 3.88 3.86 3.86 3.85 3.84 3.84 3.84 3.83 3.83 3.82 3.82 3.81 3.80 3.80 3.80 3.74 3.74 3.73 3.72 3.71 3.71 1.83
1.12 1.09 1.07 1.05 1.04
Cl
Cl
N
N
BH2
OEt
O
2.03
6.00
1.23
5.98
8 7 6 5 4 3 2 1 0
Chemical shift (ppm)

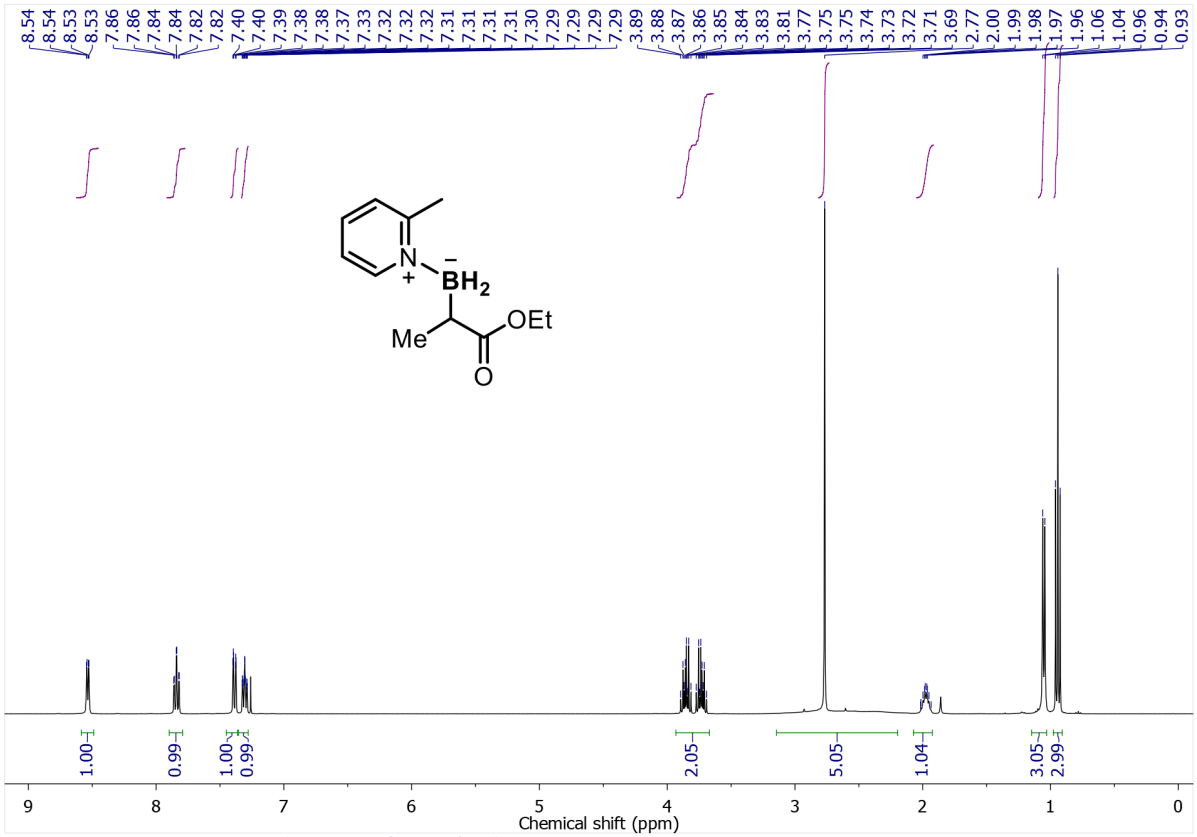

183.14
116.60
58.97
34.09
29.95
17.76
14.65
Cl
Cl
N
N
BH2
OEt
O
200 180 160 140 120 100 80 60 40 20 0
Chemical shift (ppm)

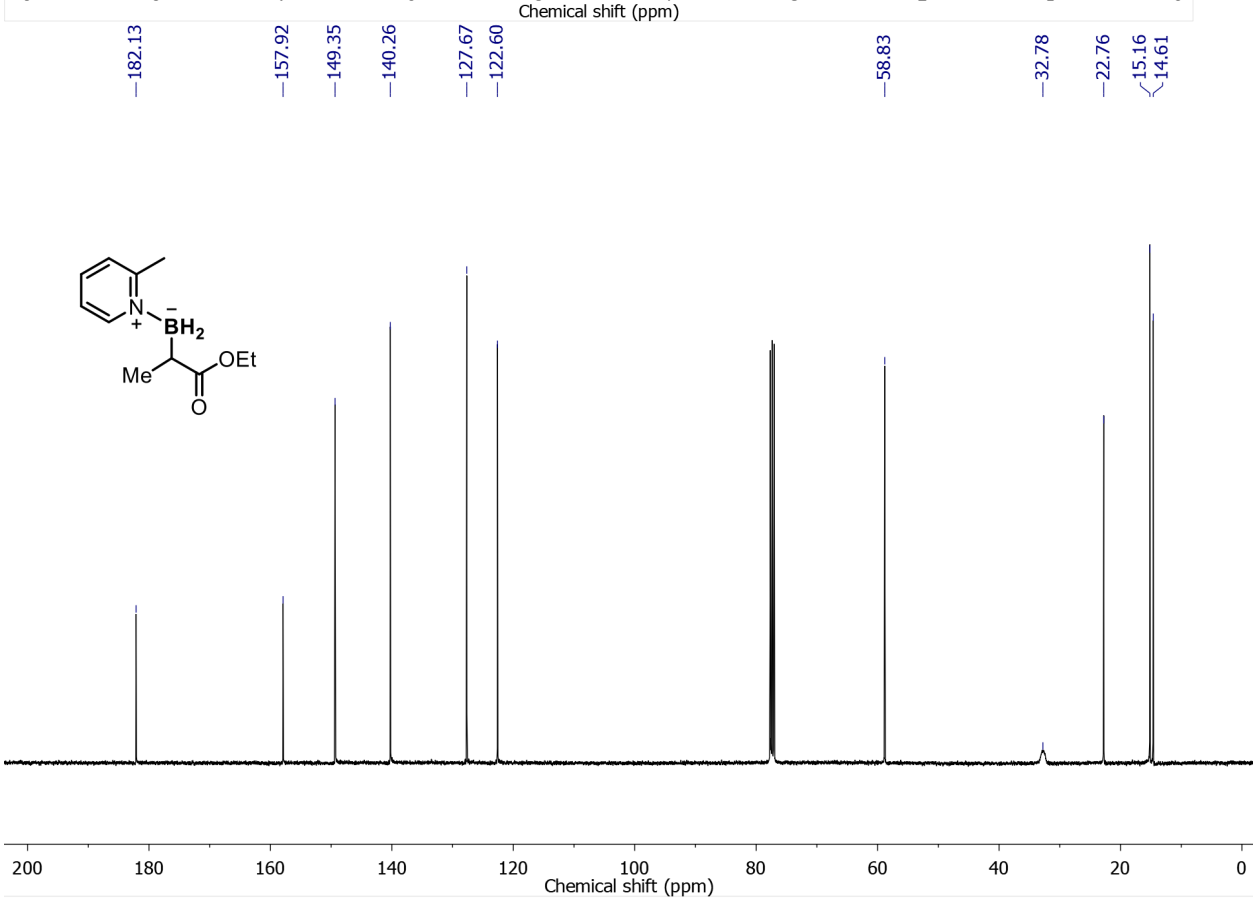

-23.20
-23.91
-24.62
Cl
Cl
N
N
BH2
OEt
O
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

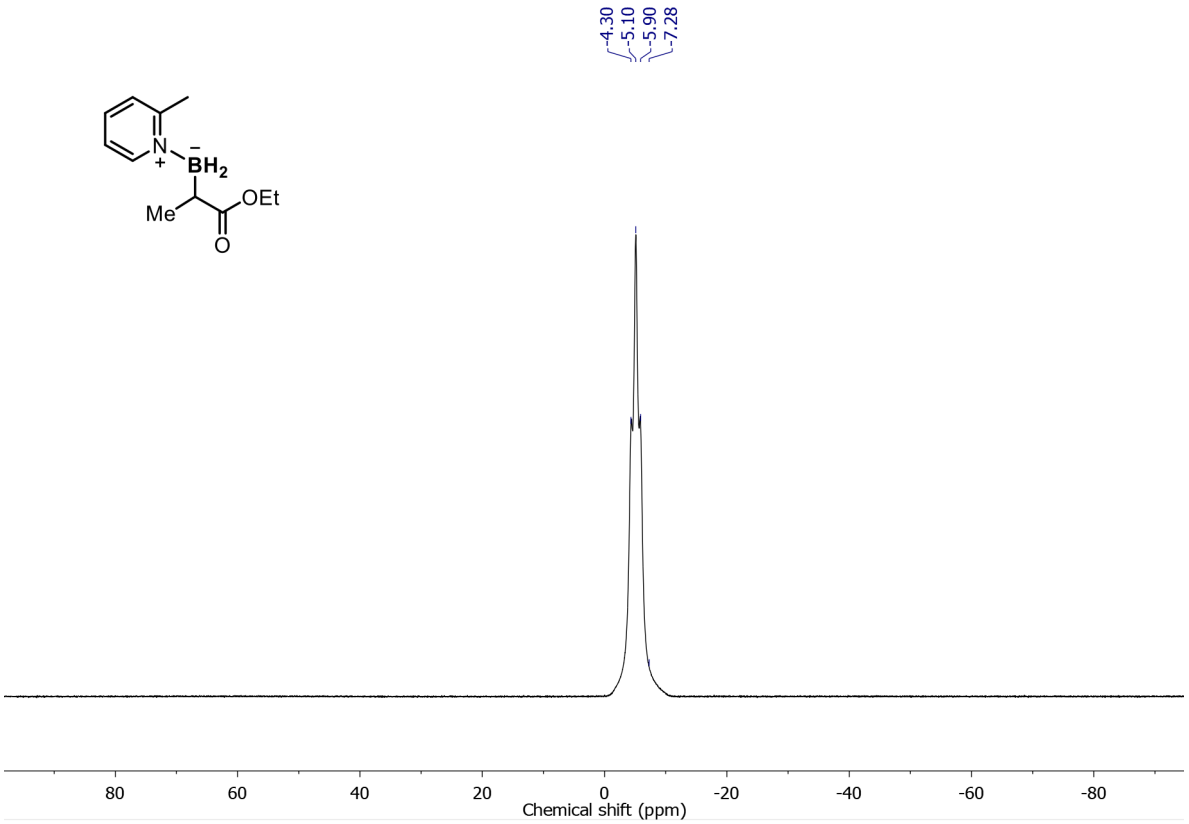

7.92
3.95
3.94
3.93
3.92
3.91
3.90
3.88
3.88
3.86
3.84
3.83
3.82
3.81
3.80
3.78
1.12
1.11
1.10
1.07
1.05
1.04
N
N
BH2
OEt
O
1.00
3.13
2.32
3.16
1.46
3.80
3.21
8
7
6
5
4
3
2
1
0
Chemical shift (ppm)

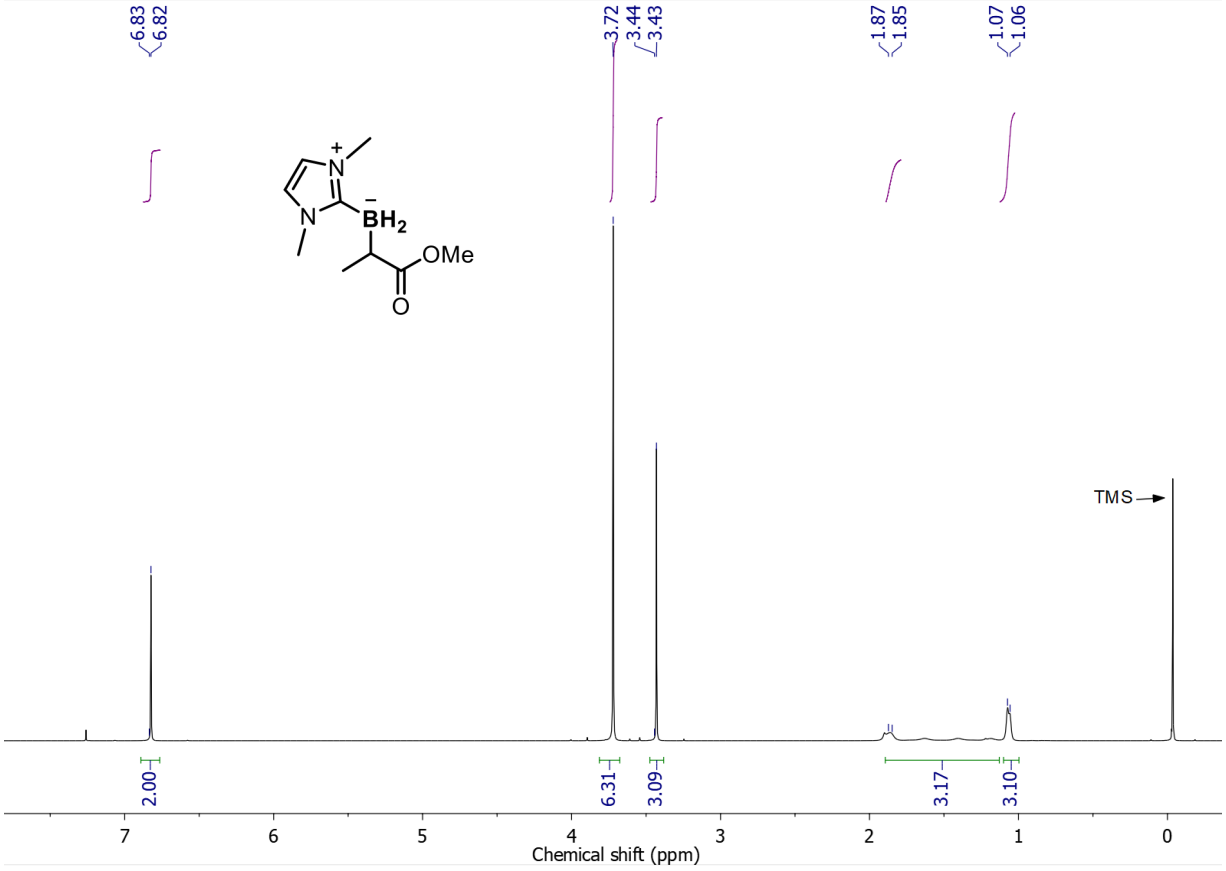

183.16
141.66
59.04
58.96
38.58
34.10
17.89
14.73
OEt
O
200
180
160
140
120
100
80
60
40
20
0
Chemical shift (ppm)

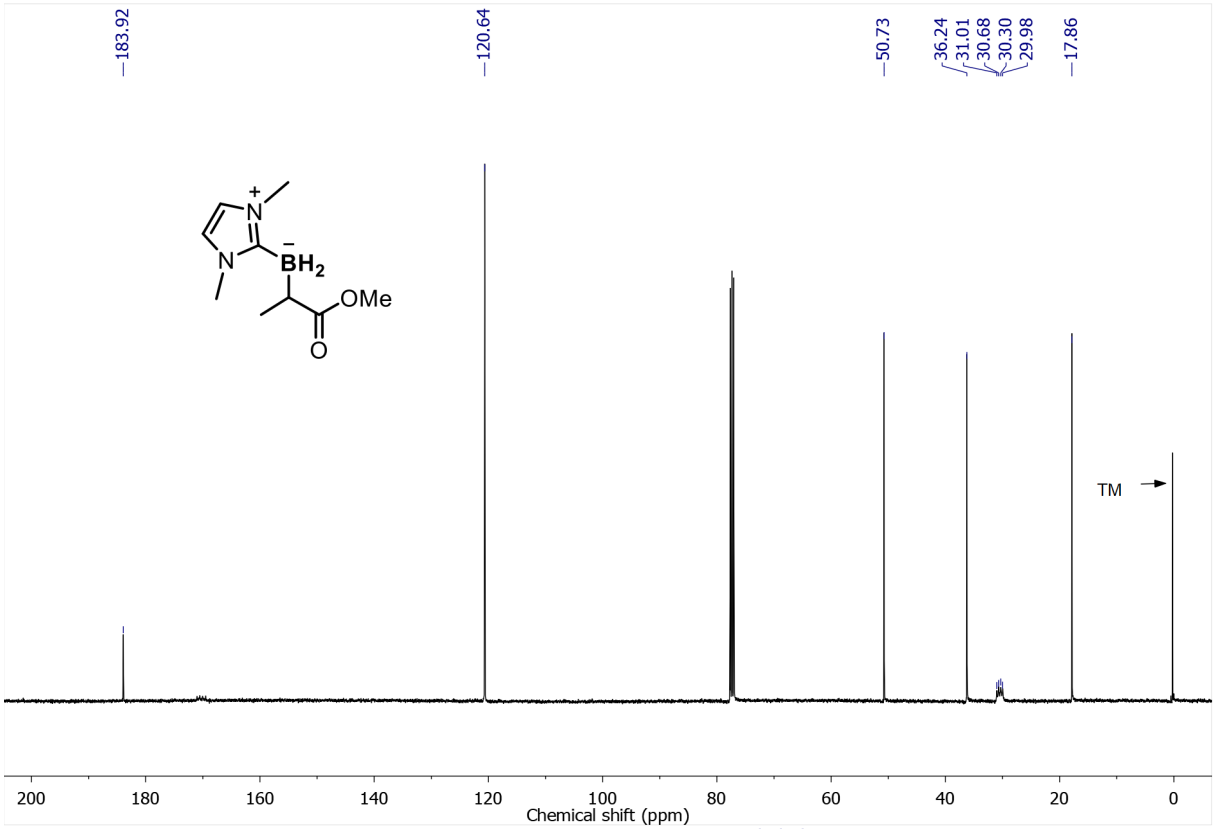

-24.30
-25.01
-25.72
OEt
O
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

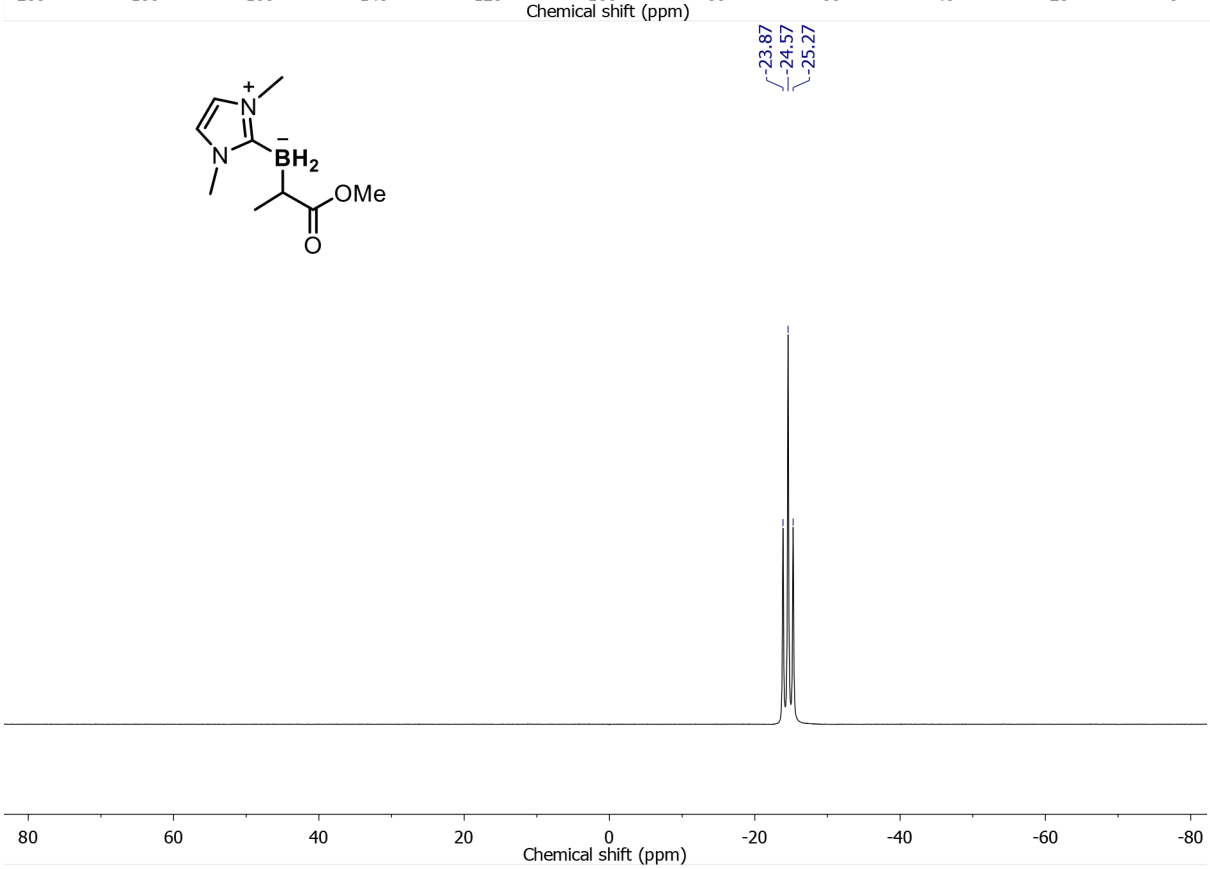

8.54 8.54 8.53 8.53 7.86 7.86 7.84 7.84 7.82 7.82 7.40 7.40 7.39 7.38 7.38 7.37 7.33 7.32 7.32 7.32 7.31 7.31 7.31 7.31 7.30 7.29 7.29 7.29 3.89 3.88 3.87 3.86 3.85 3.84 3.83 3.81 3.77 3.75 3.75 3.74 3.73 3.72 3.71 3.69 2.77 2.00 1.99 1.98 1.97 1.96 1.06 1.04 0.96 0.94 0.93
BH2
Me
OEt
O
1.00 0.99 1.00 0.99 2.05 5.05 1.04 3.05 2.99
9 8 7 6 5 4 3 2 1 0
Chemical shift (ppm)

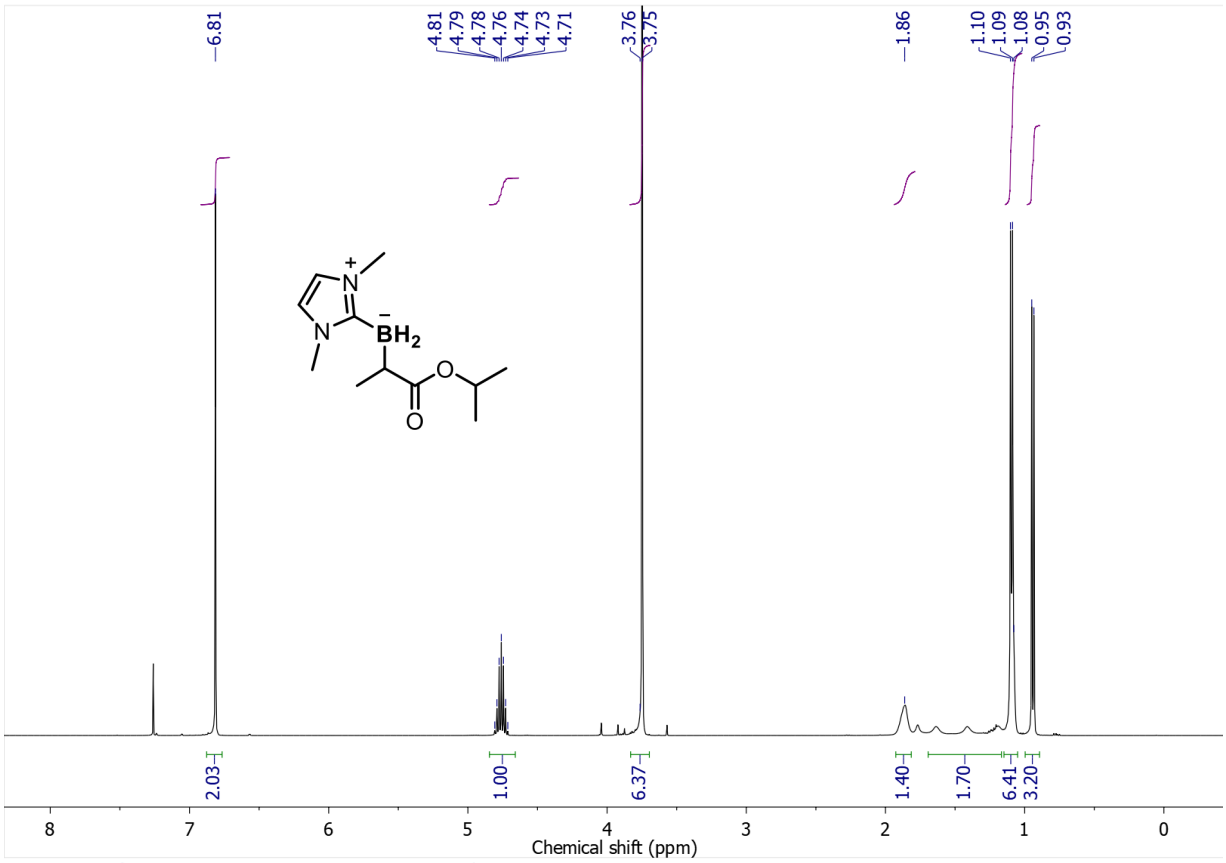

182.13 157.92 149.35 140.26 127.67 122.60 58.83 32.78 22.76 15.16 14.61
BH2
Me
OEt
O
200 180 160 140 120 100 80 60 40 20 0
Chemical shift (ppm)

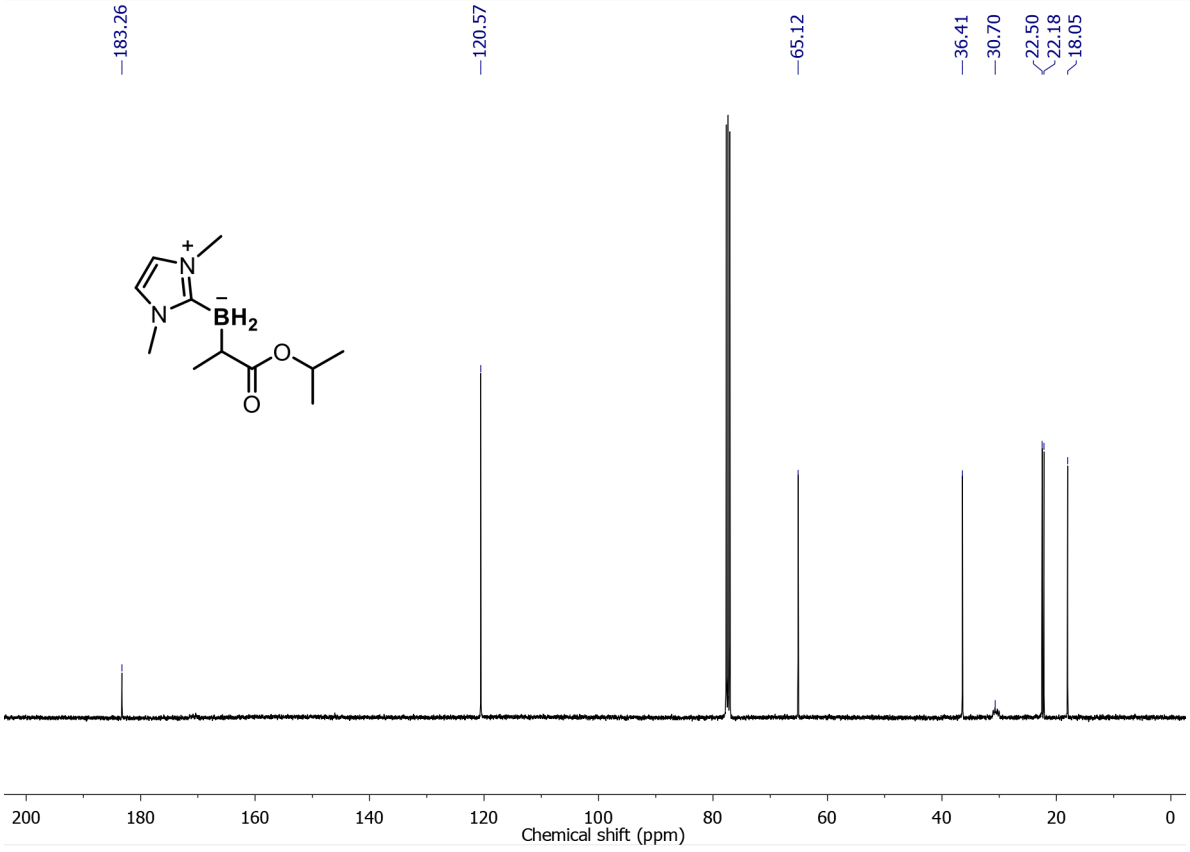

-4.30
-5.10
-5.90
-7.28
Me
OEt
O
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

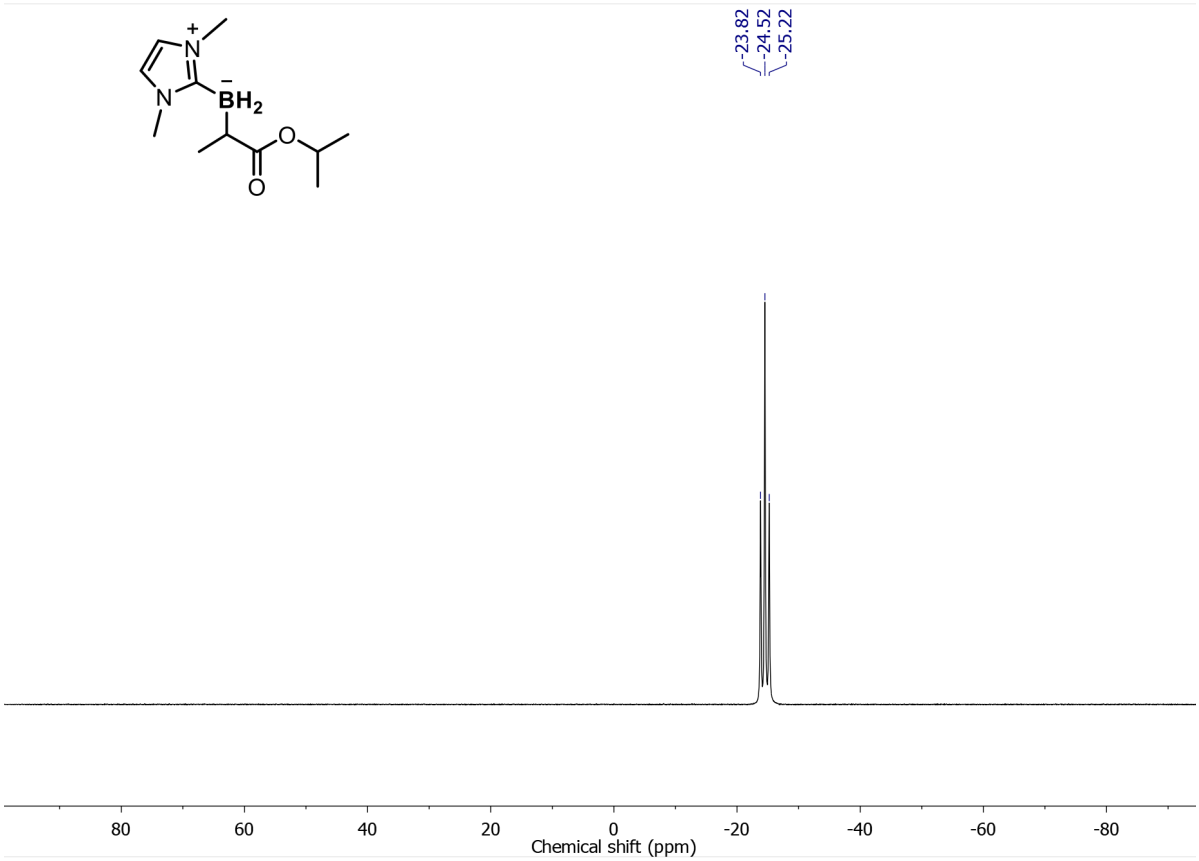

6.83
6.82
3.72
3.44
3.43
1.87
1.85
1.07
1.06
OMe
O
TMS
2.00
6.31
3.09
3.17
3.10
7
6
5
4
3
2
1
0
Chemical shift (ppm)

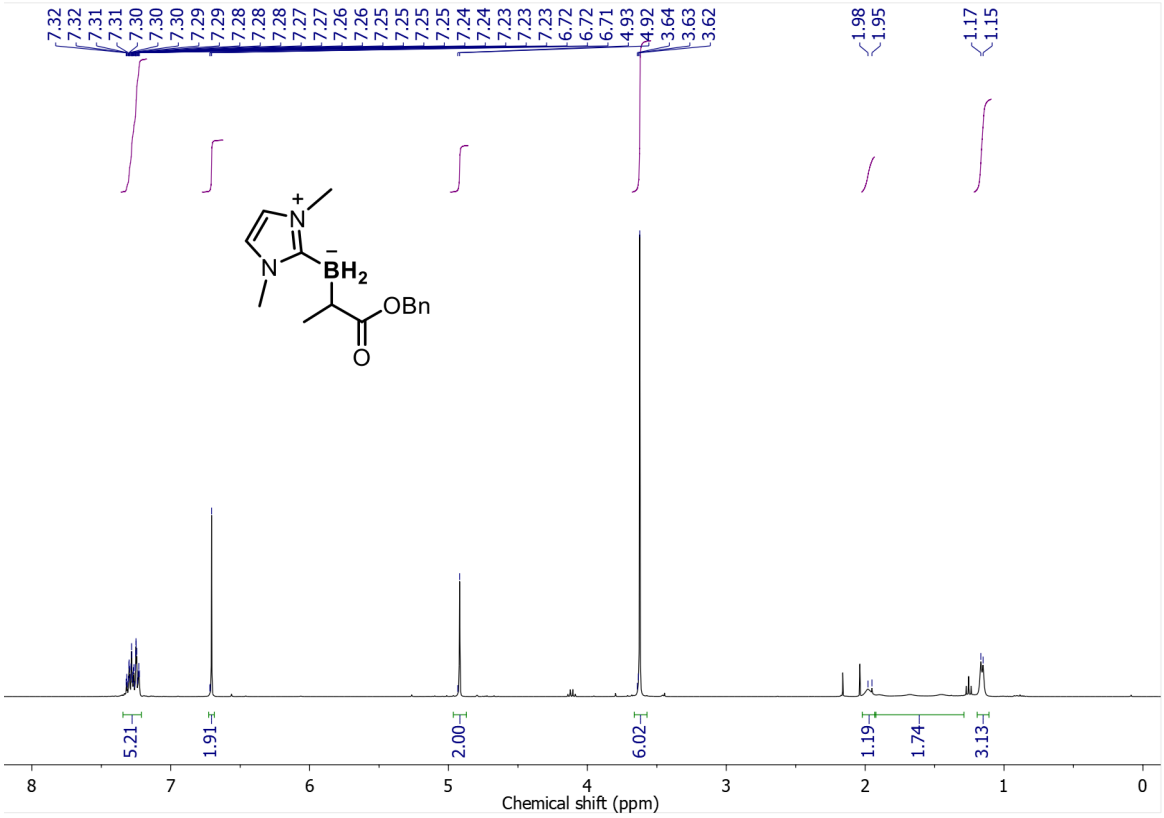

183.92
120.64
50.73
36.24
31.01
30.68
30.30
29.98
17.86
TM
200
180
160
140
120
100
80
60
40
20
0
Chemical shift (ppm)

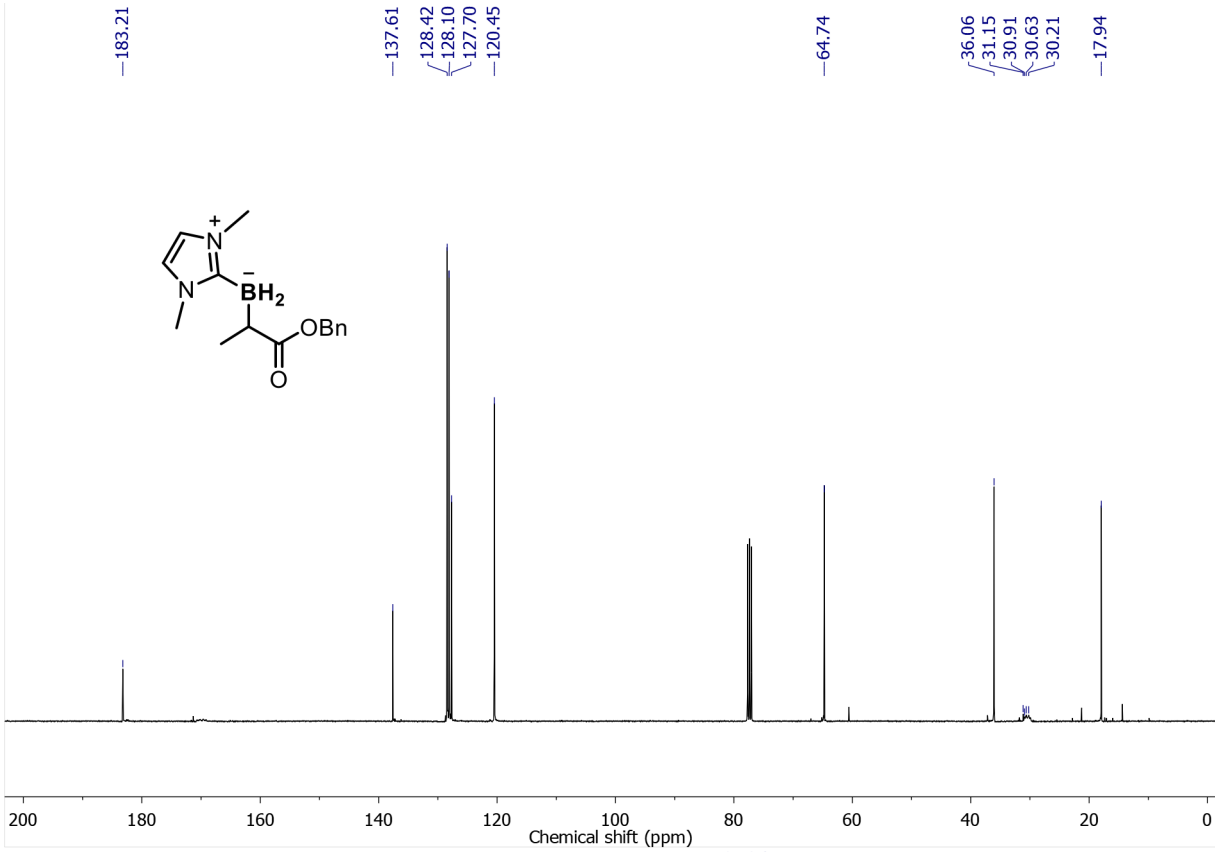

-23.87
-24.57
-25.27
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

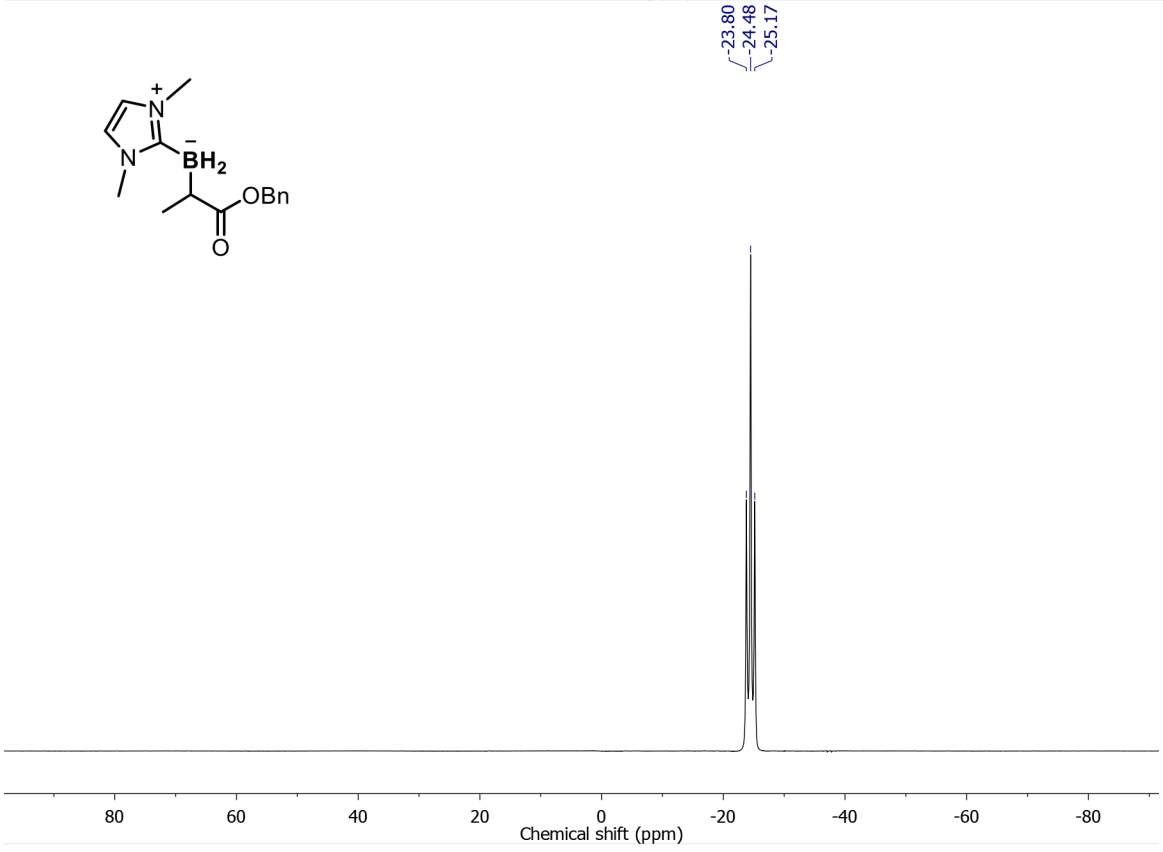

6.81
4.81
4.79
4.78
4.76
4.74
4.73
4.71
3.76
3.75
1.86
1.10
1.09
1.08
0.95
0.93
2.03
1.00
6.37
1.40
1.70
6.41
3.20
Chemical shift (ppm)

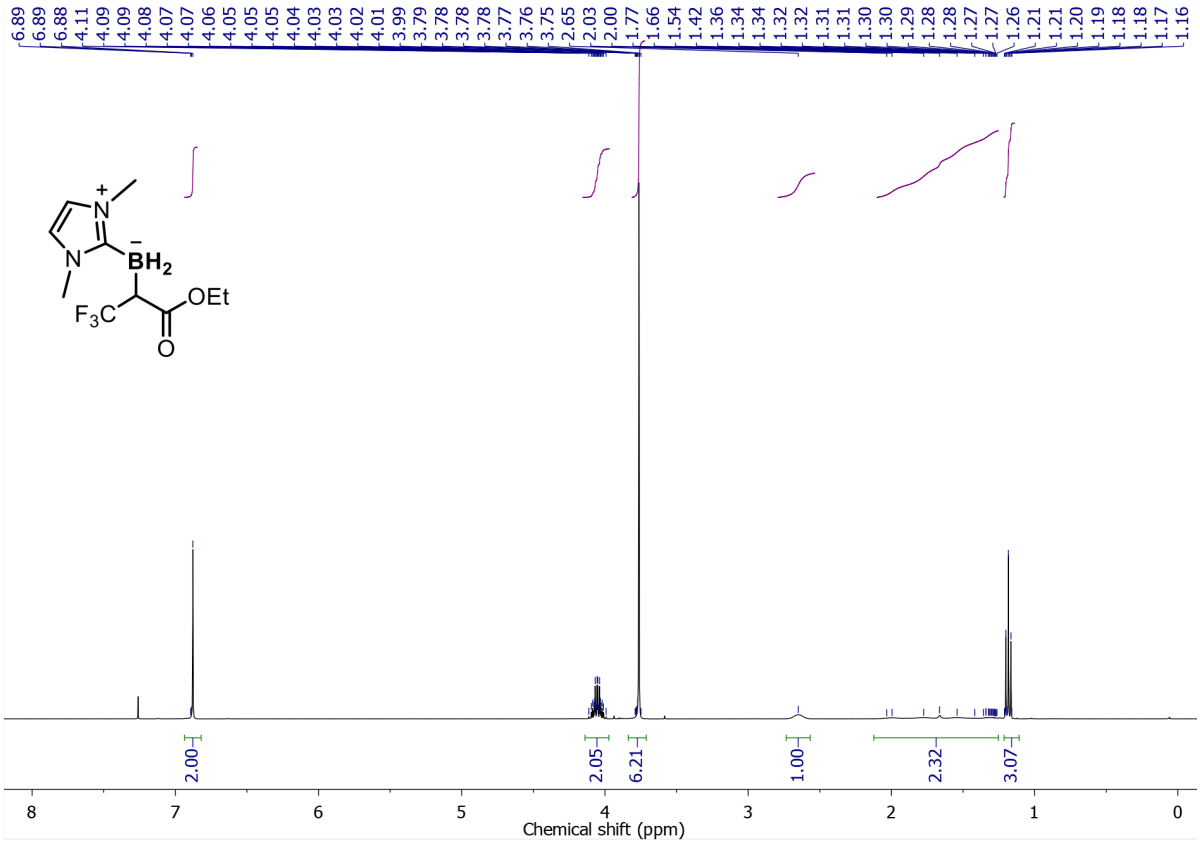

183.26
120.57
65.12
36.41
30.70
22.50
22.18
18.05
Chemical shift (ppm)

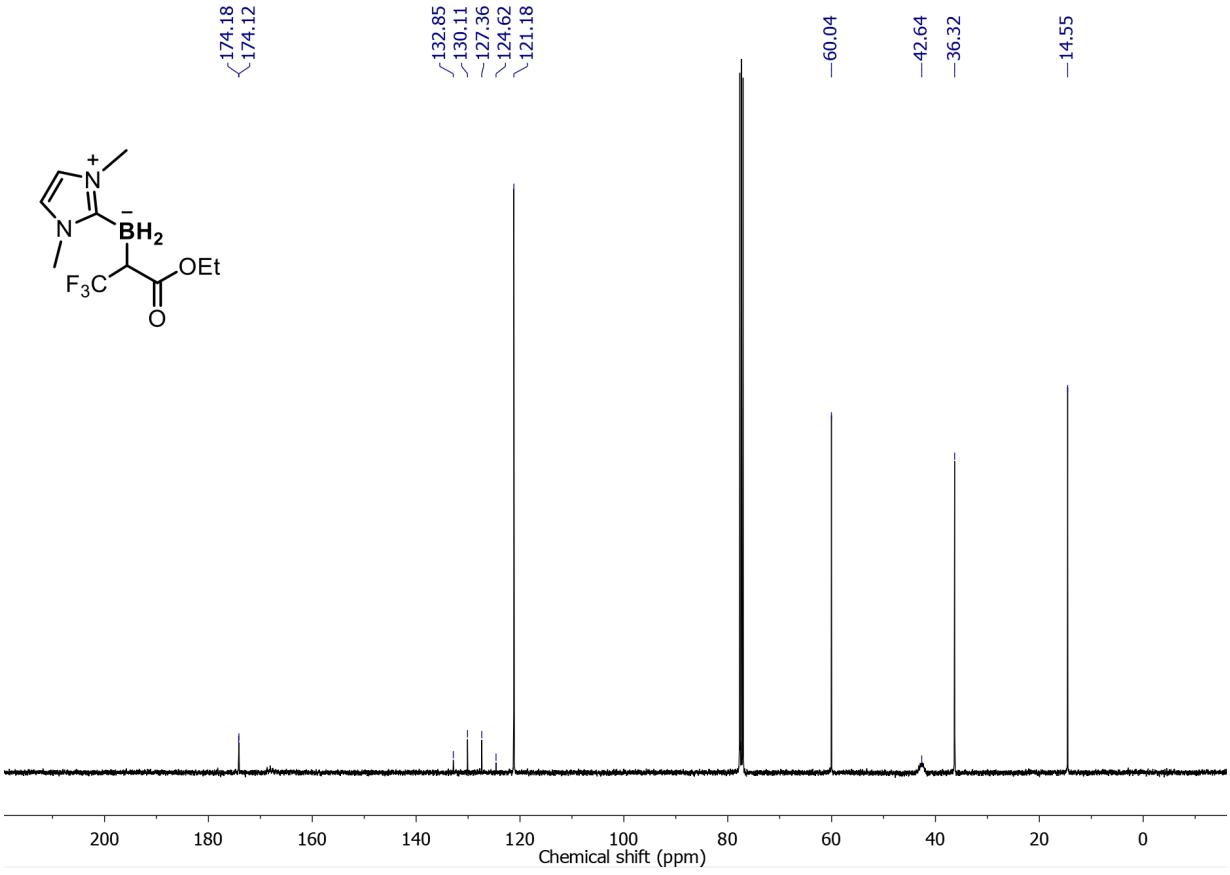

-23.82
-24.52
-25.22
Chemical shift (ppm)

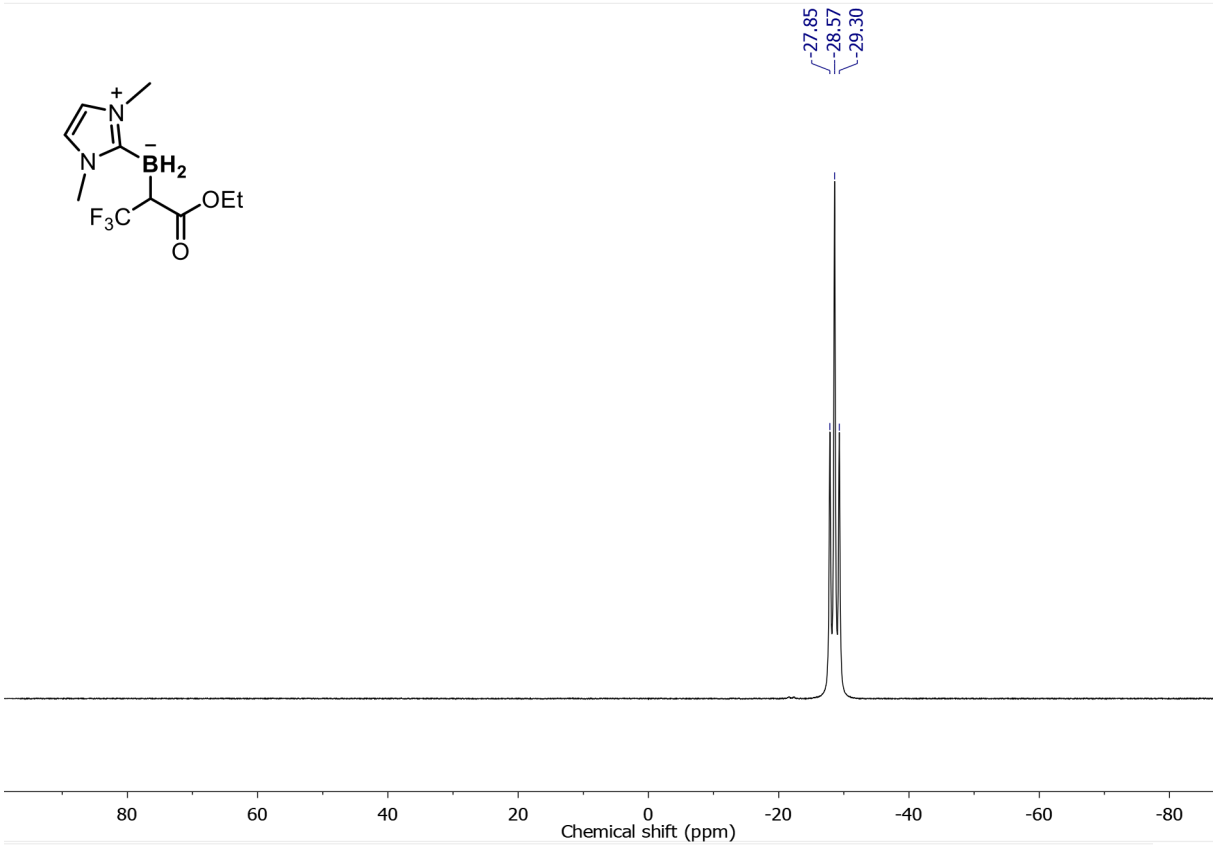

7.32
7.32
7.31
7.31
7.30
7.30
7.30
7.29
7.29
7.28
7.28
7.28
7.27
7.27
7.26
7.26
7.25
7.25
7.25
7.25
7.24
7.24
7.23
7.23
7.23
6.72
6.72
6.71
4.93
4.92
3.64
3.63
3.62
1.98
1.95
1.17
1.15
OBn
5.21
1.91
2.00
6.02
1.19
1.74
3.13
Chemical shift (ppm)

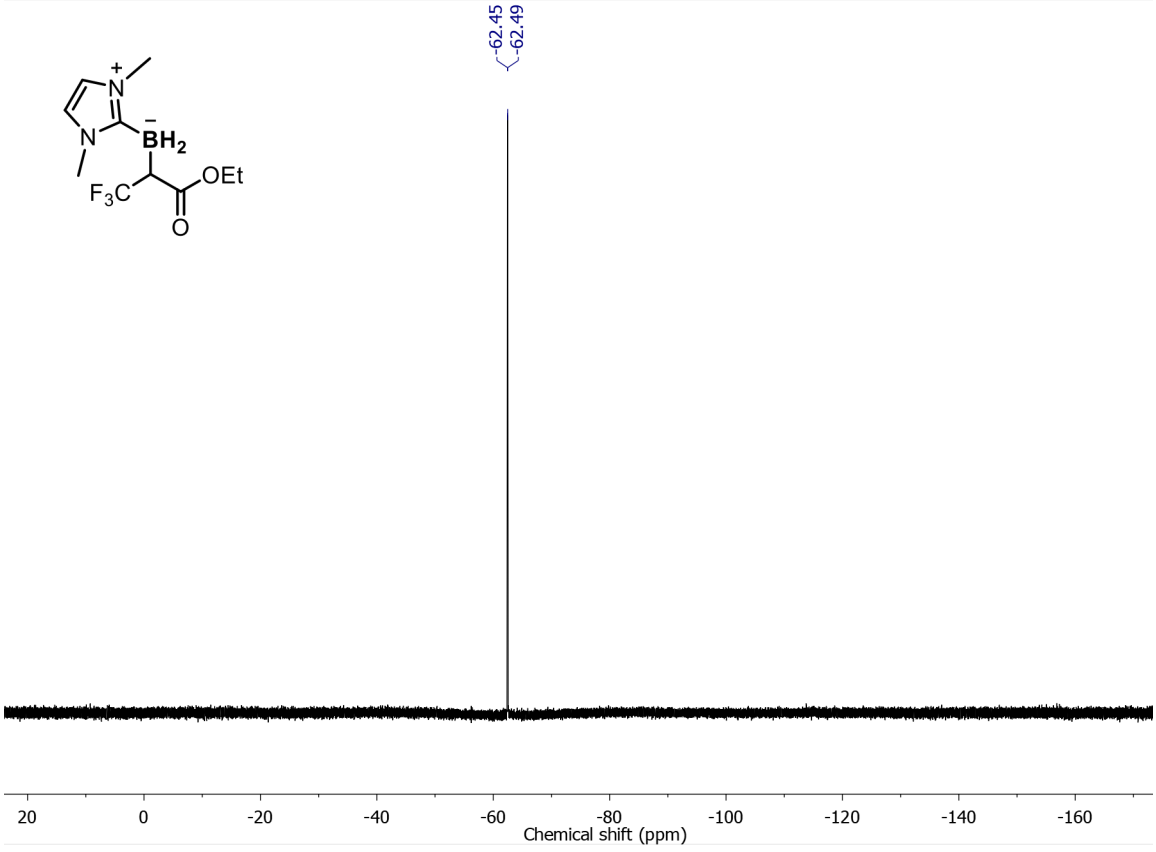

183.21
137.61
128.42
128.10
127.70
120.45
64.74
36.06
31.15
30.91
30.63
30.21
17.94
BH2
OBn
O
200
180
160
140
120
100
80
60
40
20
0
Chemical shift (ppm)

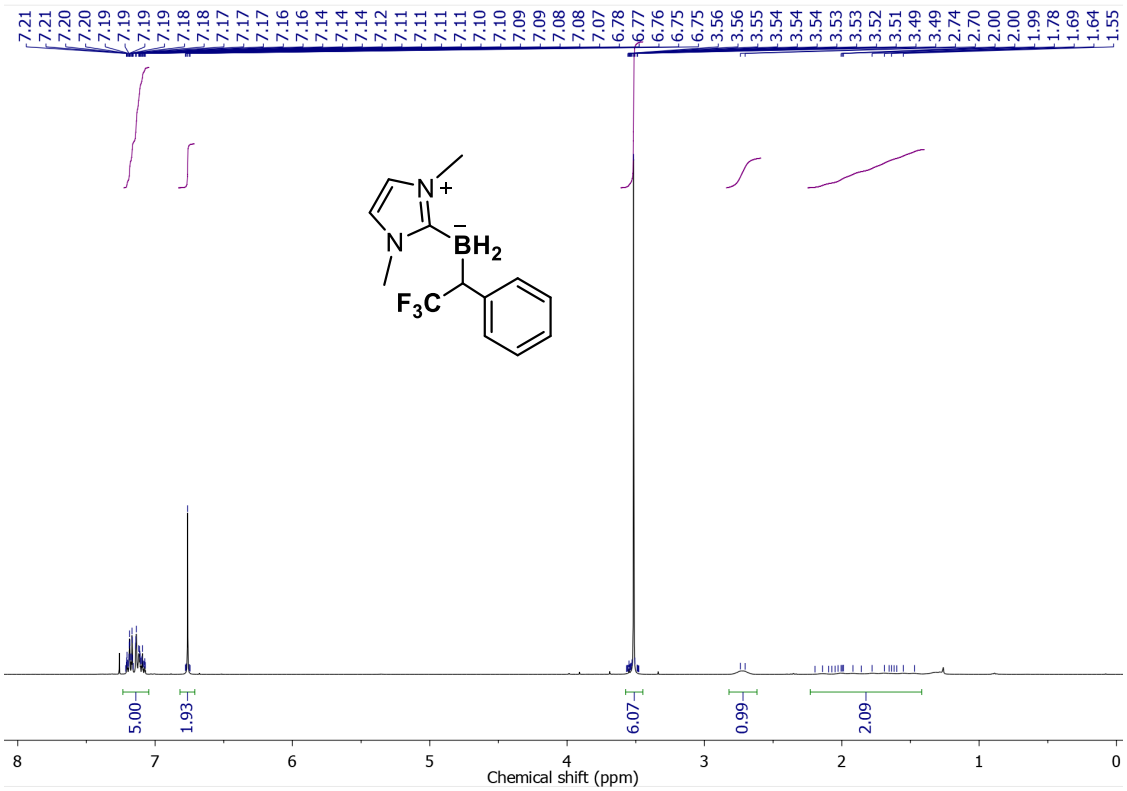

-23.80
-24.48
-25.17
BH2
OBn
O
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

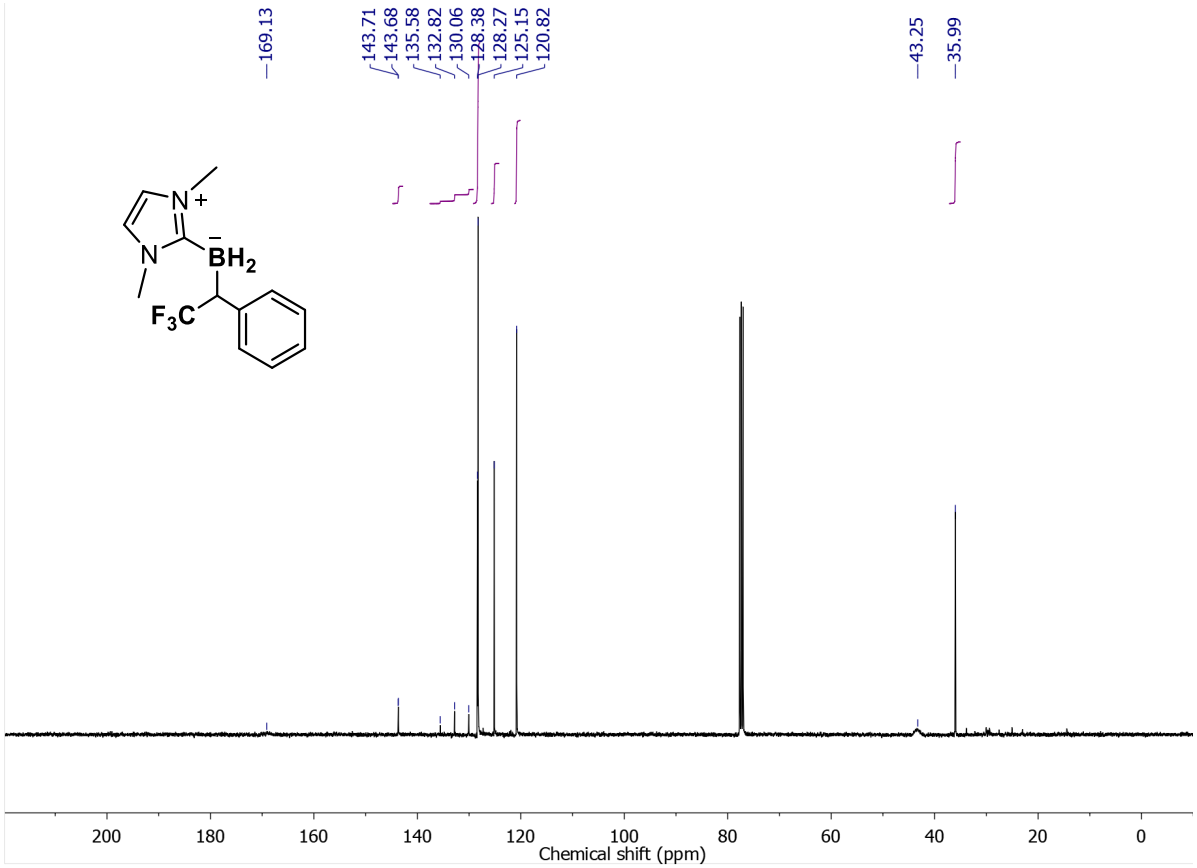

6.89 6.89 6.88 4.11 4.09 4.09 4.08 4.07 4.07 4.06 4.05 4.05 4.05 4.04 4.03 4.03 4.02 4.01 3.99 3.79 3.78 3.78 3.78 3.77 3.76 3.75 2.65 2.03 2.00 1.77 1.66 1.54 1.42 1.36 1.34 1.34 1.32 1.32 1.31 1.31 1.30 1.30 1.29 1.28 1.28 1.27 1.27 1.26 1.21 1.21 1.20 1.19 1.18 1.18 1.17 1.16
BH2
OEt
F3C
O
2.00
2.05
6.21
1.00
2.32
3.07
8 7 6 5 4 3 2 1 0
Chemical shift (ppm)

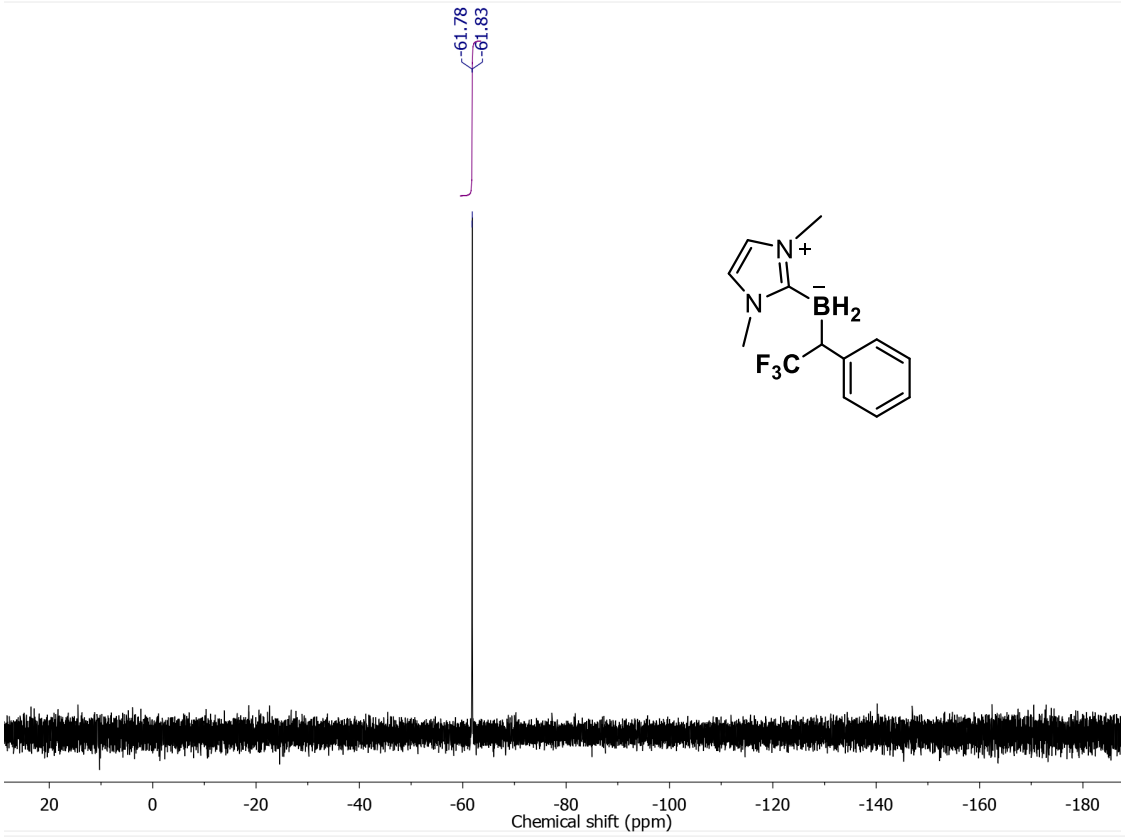

174.18
174.12
132.85
130.11
127.36
124.62
121.18
60.04
42.64
36.32
14.55
BH2
OEt
F3C
O
200 180 160 140 120 100 80 60 40 20 0
Chemical shift (ppm)

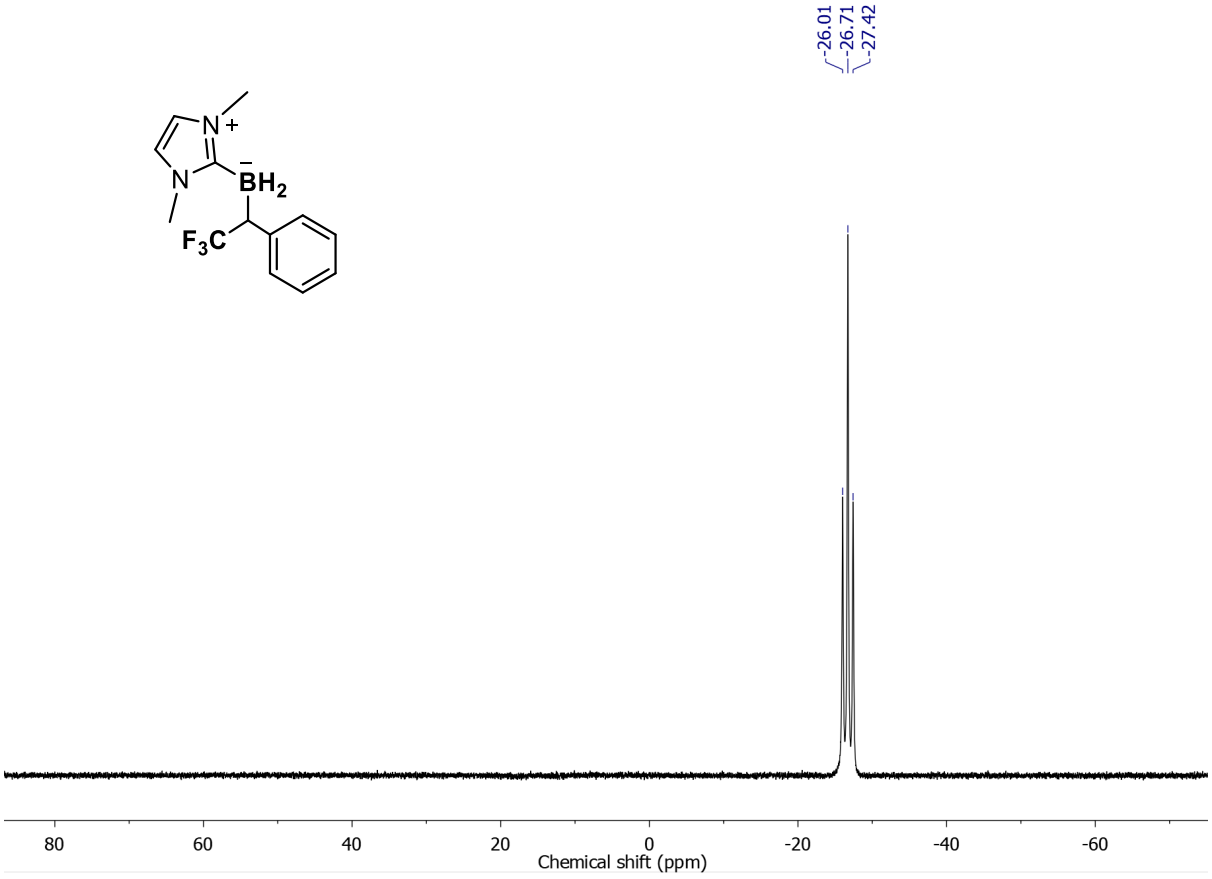

-27.85
-28.57
-29.30
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

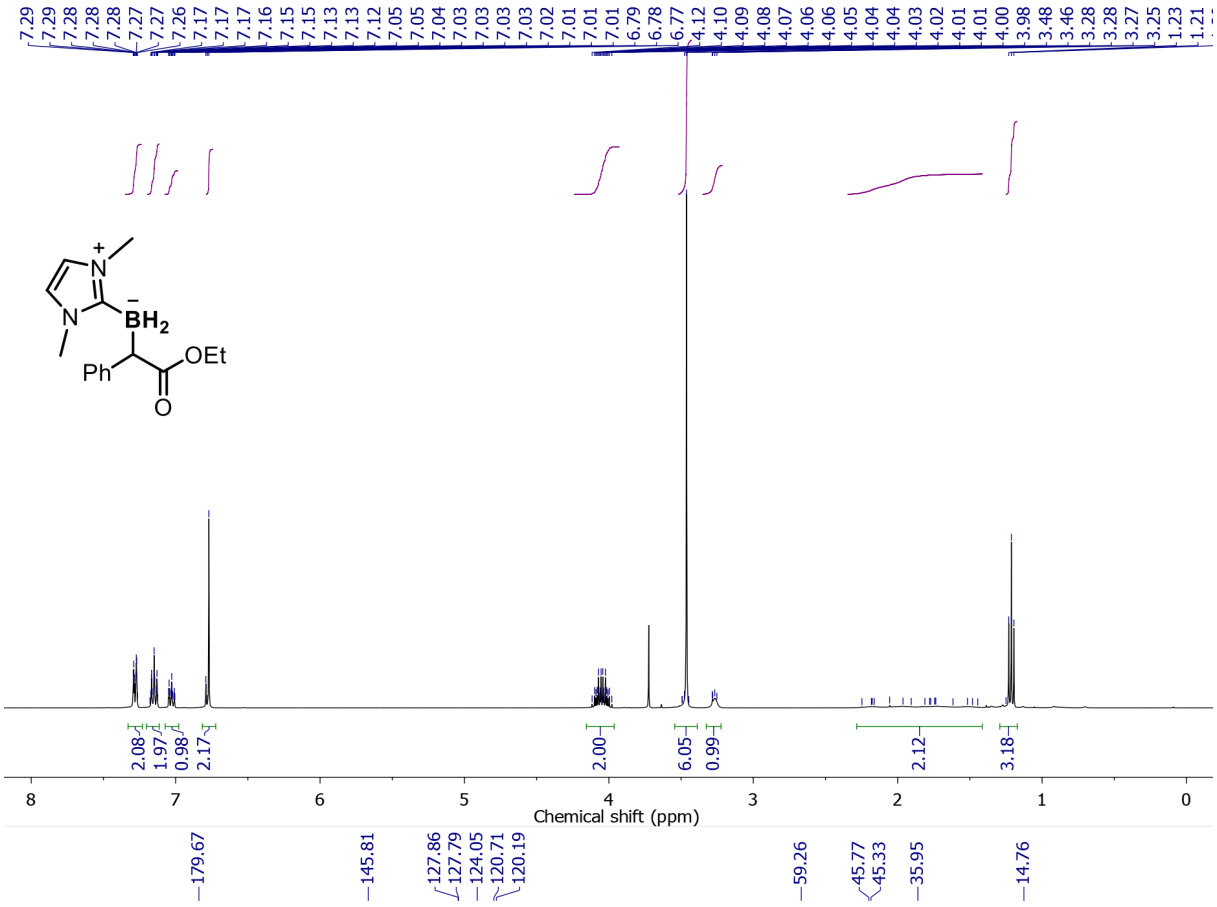

-62.45
-62.49
20
0
-20
-40
-60
-80
-100
-120
-140
-160
Chemical shift (ppm)


7.21 7.21 7.20 7.20 7.19 7.19 7.19 7.19 7.18 7.18 7.17 7.17 7.17 7.16 7.16 7.14 7.14 7.14 7.12 7.11 7.11 7.11 7.11 7.10 7.10 7.09 7.09 7.08 7.08 7.07 6.78 6.77 6.76 6.75 6.75 3.56 3.55 3.54 3.54 3.54 3.53 3.53 3.52 3.51 3.49 3.49 2.74 2.70 2.00 2.00 1.99 1.78 1.69 1.64 1.55
N+
N
BH2
F3C
5.00
1.93
6.07
0.99
2.09
8 7 6 5 4 3 2 1 0
Chemical shift (ppm)


169.13
143.71 143.68 135.58 132.82 130.06 128.38 128.27 125.15 120.82
43.25 35.99
N+
N
BH2
F3C
200 180 160 140 120 100 80 60 40 20 0
Chemical shift (ppm)


-61.78
-61.83
N+
N
BH2
F3C
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
Chemical shift (ppm)


-26.01
-26.71
-27.42
N+
N
BH2
F3C
80
60
40
20
0
-20
-40
-60
Chemical shift (ppm)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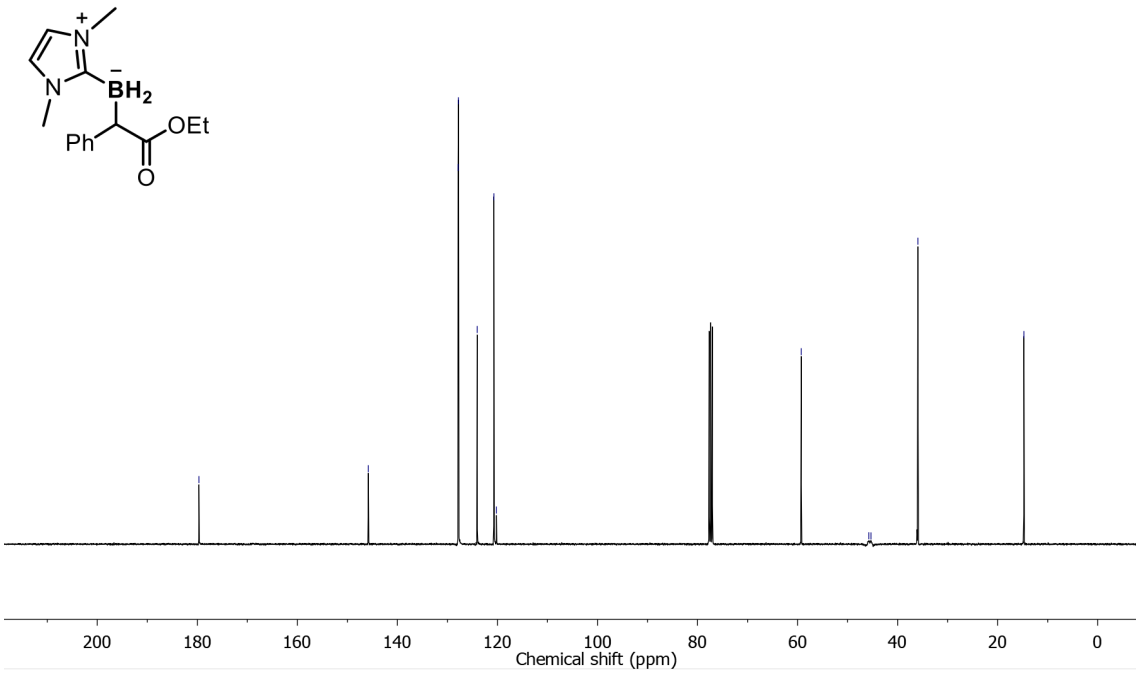
N
BH2
OEt
Ph
O
2.08 1.97 0.98 2.17 2.00 6.05 0.99 2.12 3.18
8 7 6 5 4 3 2 1 0
Chemical shift (ppm)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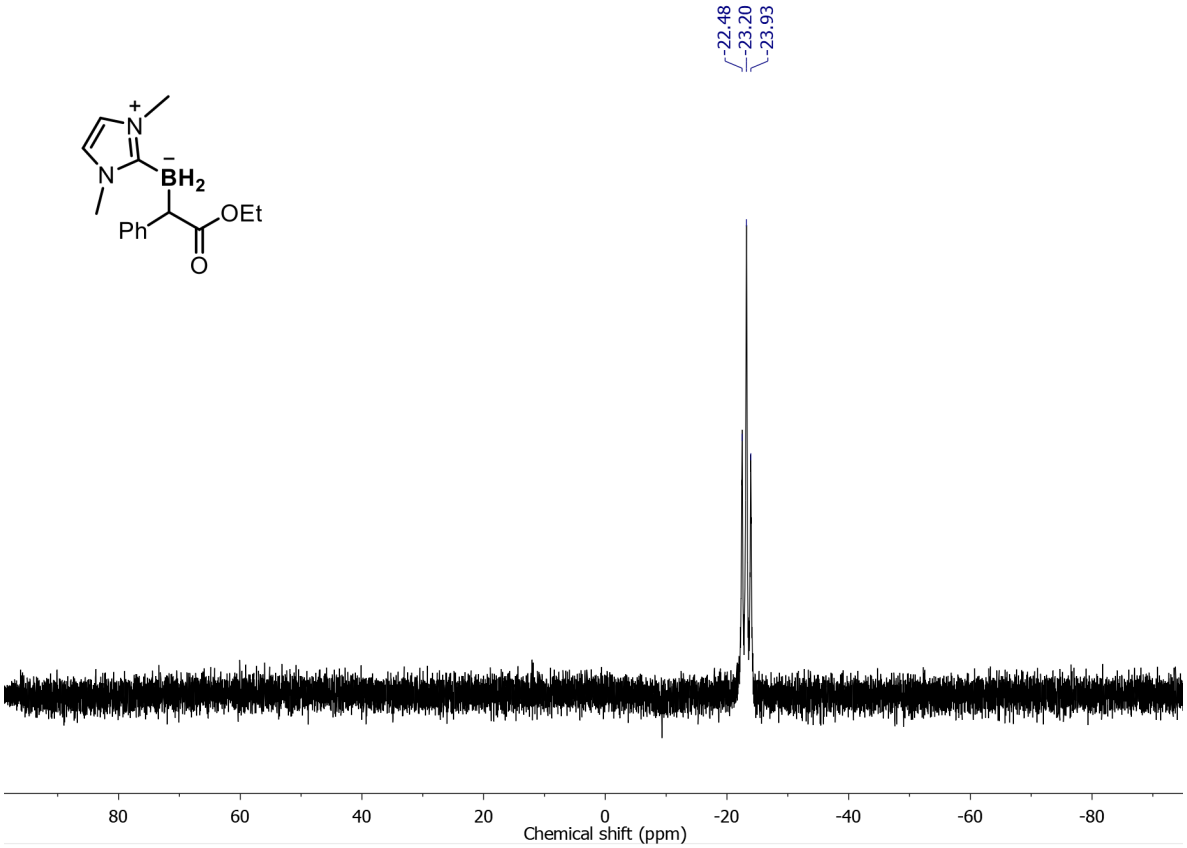
BH2
OEt
Ph
O
200 180 160 140 120 100 80 60 40 20 0
Chemical shift (ppm)

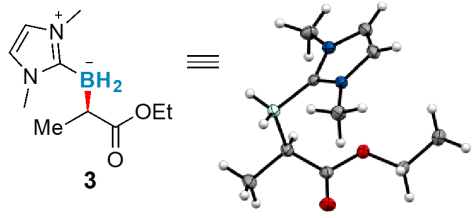

-22.48
-23.20
-23.93
Ph
OEt
O
80
60
40
20
0
-20
-40
-60
-80
Chemical shift (ppm)

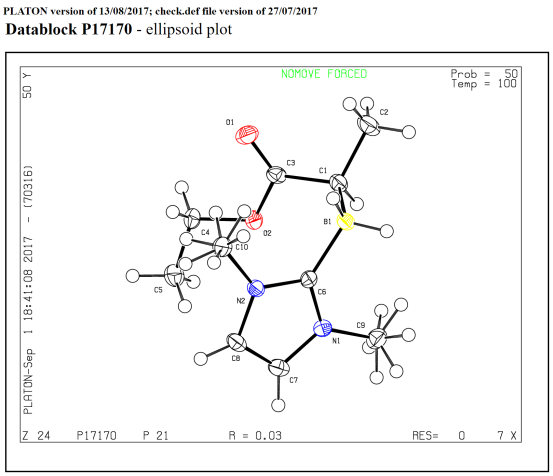
XI. X-ray Crystallography and the Assignments of Absolute Configuration

For products **3** and **18**, 10 mg of pure compound was dissolved in 0.5 mL ethylacetate and added to a 4 mL vial, which was then placed in a 20 mL vial containing 10 mL *n*-pentane. The 20 mL vial was capped, sealed with parafilm, and left undisturbed for three days at 4 ^{o}C. A suitable crystal was selected and mounted in a nylon loop in immersion oil. All measurements were made on a Bruker photon diffractometer with filtered Cu-Kα radiation. Crystals of compound **12** were obtained via slow evaporation of an ethylacetate solution of **12** at room temperature.

Low-temperature diffraction data (ϕ- and ω-scans) were collected on a Bruker AXS D8 VENTURE KAPPA diffractometer coupled to a PHOTON 100 CMOS detector with Cu K_α radiation (λ = 1.54178 Å) from an IμS micro-source. The structure was solved by direct methods using SHELXS[15] and refined against F^2 on all data by full-matrix least squares with SHELXL-2016[16] using established refinement techniques[17]. All non-hydrogen atoms were refined anisotropically. Unless otherwise noted, all hydrogen atoms were included into the model at geometrically calculated positions and refined using a riding model. The isotropic displacement parameters of all hydrogen atoms were fixed to 1.2 times the *U* value of the atoms they are linked to (1.5 times for methyl groups). Compound **18** (sample No. P17253) crystallizes in the monoclinic space group $P2_1$ with two molecules in the asymmetric unit. The coordinates for the hydrogen atoms bound to B1 and B2 were located in the difference Fourier synthesis and refined semi-freely with the help of a restraint on the B–H distance (1.12(4) Å). The crystal was refined as a two-component twin.

The absolute configurations of compounds **3**, **12** and **18** were established by anomalous-dispersion effects using Cu K_α radiation (λ = 1.54178 Å). For P17170 (compound **3**), the Flack *x* parameter of 0.02(7) was determined using 1062 quotients $[(I^+)-(I^-)]/[(I^+)+(I^-)]$. For P17207 (compound **18**), the Flack *x* parameter of 0.08(3) was determined using 2543 quotients $[(I^+)-(I^-)]/[(I^+)+(I^-)]$ and the Hooft *y* is 0.06(2). For P17253 (a two component twin, compound **12**), the Flack *x* parameter of 0.07(10) was determined using 2069 quotients $[(I^+)-(I^-)]/[(I^+)+(I^-)]$, the Hooft *y* is 0.16(9), and the PLATON P3 is 0.997. The Flack and van Hooft parameters are measures of the confidence of the absolute structure determination (zero (within several estimated standard deviation) for correct enantiomer, one for incorrect, intermediate for racemic twinning)[18,19].





Crystal data and structure refinement for organoborane **3**:

Identification code	P17170	
Empirical formula	C10 H19 B N2 O2	
Formula weight	210.08	
Temperature	100(2) K	
Wavelength	1.54178 Å	
Crystal system	Monoclinic	
Space group	$P2_1$	
Unit cell dimensions	a = 7.5635(4) Å	a= 90°.
	b = 9.4499(5) Å	b= 98.612(2)°.
	c = 8.3935(4) Å	g = 90°.
Volume	593.16(5) $Å^3$	
Z	2	
Density (calculated)	1.176 Mg/m^3	
Absorption coefficient	0.643 mm^{-1}	
F(000)	228	
Crystal size	0.150 x 0.150 x 0.050 mm^3	
Theta range for data collection	5.330 to 74.490°.	
Index ranges	-9<=h<=9, -11<=k<=11, -10<=l<=9	
Reflections collected	11161	
Independent reflections	2410 [R(int) = 0.0311]	
Completeness to theta = 67.679°	100.0 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	1.000 and 0.9210	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	2410 / 1 / 138	
Goodness-of-fit on F^2	1.075	
Final R indices [I>2sigma(I)]	R1 = 0.0285, wR2 = 0.0703	
R indices (all data)	R1 = 0.0297, wR2 = 0.0711	
Absolute structure parameter	0.02(7)	
Extinction coefficient	n/a	
Largest diff. peak and hole	0.150 and -0.204 e.$Å^{-3}$	

Datablock: P17170

Bond precision: C-C = 0.0020 A Wavelength=1.54178

Cell: a=7.5635(4) b=9.4499(5) c=8.3935(4)
alpha=90 beta=98.612(2) gamma=90

Temperature: 100 K

	Calculated	Reported
Volume	593.16(5)	593.16(5)
Space group	P 21	P 21
Hall group	P 2yb	P 2yb
Moiety formula	C10 H19 B N2 O2	?
Sum formula	C10 H19 B N2 O2	C10 H19 B N2 O2
Mr	210.08	210.08
Dx,g cm-3	1.176	1.176
Z	2	2
Mu (mm-1)	0.643	0.643
F000	228.0	228.0
F000'	228.66	
h,k,lmax	9,11,10	9,11,10
Nref	2425[1290]	2410
Tmin,Tmax	0.908,0.968	0.921,1.000
Tmin'	0.908	

Correction method= # Reported T Limits: Tmin=0.921 Tmax=1.000
AbsCorr = MULTI-SCAN

Data completeness= 1.87/0.99 Theta(max)= 74.490

R(reflections)= 0.0285(2341) wR2(reflections)= 0.0711(2410)

S = 1.075 Npar= 138

The following ALERTS were generated. Each ALERT has the format
test-name_ALERT_alert-type_alert-level.
Click on the hyperlinks for more details of the test.

Alert level C

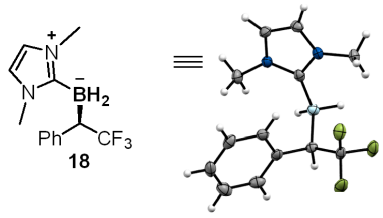
PLAT413_ALERT_2_C Short Inter XH3 .. XHn H2A .. H9F .. 2.09 Ang.
PLAT978_ALERT_2_C Number C-C Bonds with Positive Residual Density. 0 Info

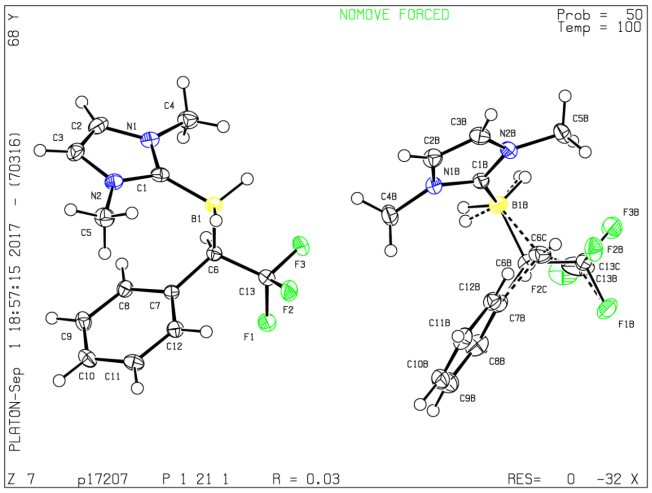
Alert level G

PLAT300_ALERT_4_G Atom Site Occupancy of H9A is Constrained at 0.5 Check
And 11 other PLAT300 Alerts

PLAT300_ALERT_4_G Atom Site Occupancy of H9B is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H9C is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H9D is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H9E is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H9F is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H10A is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H10B is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H10C is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H10D is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H10E is Constrained at 0.5 Check
PLAT300_ALERT_4_G Atom Site Occupancy of H10F is Constrained at 0.5 Check

PLAT791_ALERT_4_G The Model has Chirality at C1 (Chiral SPGR) R Verify
PLAT912_ALERT_4_G Missing # of FCF Reflections Above STh/L= 0.600 2 Note





Crystal data and structure refinement for organoborane **18**:

Identification code	p17207	
Empirical formula	C13 H16 B F3 N2	
Formula weight	268.09	
Temperature	100 K	
Wavelength	1.54178 Å	
Crystal system	Monoclinic	
Space group	P 1 21 1	
Unit cell dimensions	a = 5.6677(7) Å	a= 90°
	b = 15.3928(16) Å	b= 98.957(6)°
	c = 15.4429(18) Å	g = 90°
Volume	1330.8(3) $Å^3$	
Z	4	
Density (calculated)	1.338 Mg/m^3	
Absorption coefficient	0.920 mm^{-1}	
F(000)	560	
Crystal size	0.21 x 0.18 x 0.05 mm^3	
Theta range for data collection	2.897 to 78.467°.	
Index ranges	-7<=h<=7, -19<=k<=19, -19<=l<=19	
Reflections collected	53323	
Independent reflections	5657 [R(int) = 0.0403]	
Completeness to theta = 67.000°	100.0 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	1.0000 and 0.8917	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	5657 / 1 / 375	
Goodness-of-fit on F^2	1.058	
Final R indices [I>2sigma(I)]	R1 = 0.0307, wR2 = 0.0757	
R indices (all data)	R1 = 0.0318, wR2 = 0.0763	
Absolute structure parameter	0.08(3)	
Extinction coefficient	n/a	
Largest diff. peak and hole	0.150 and -0.236 e.$Å^{-3}$	

Datablock: p17207

```
Bond precision:        C-C = 0.0031 A                Wavelength=1.54178
Cell:        a=5.6677(7)       b=15.3928(16)     c=15.4429(18)
             alpha=90          beta=98.957(6)    gamma=90
Temperature: 100 K
                     Calculated                          Reported
Volume               1330.8(3)                           1330.8(3)
Space group          P 21                                P 1 21 1
Hall group           P 2yb                               P 2yb
Moiety formula       C13 H16 B F3 N2                     C13 H16 B F3 N2
Sum formula          C13 H16 B F3 N2                     C13 H16 B F3 N2
Mr                   268.09                              268.09
Dx,g cm-3            1.338                               1.338
Z                    4                                   4
Mu (mm-1)            0.920                               0.920
F000                 560.0                               560.0
F000'                562.00
h,k,lmax             7,19,19                             7,19,19
Nref                 5722[ 2971]                         5657
Tmin,Tmax            0.824,0.955                         0.892,1.000
Tmin'                0.824
Correction method= # Reported T Limits: Tmin=0.892 Tmax=1.000
AbsCorr = MULTI-SCAN
Data completeness= 1.90/0.99       Theta(max)= 78.467
R(reflections)= 0.0307( 5508)         wR2(reflections)= 0.0763( 5657)
S = 1.058               Npar= 375
```

The following ALERTS were generated. Each ALERT has the format
test-name_ALERT_alert-type_alert-level.
Click on the hyperlinks for more details of the test.

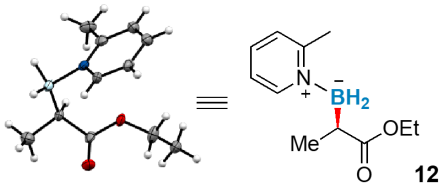
Alert level B

PLAT410 ALERT 2 B Short Intra H...H Contact H12B .. H6C . 1.84 Ang.

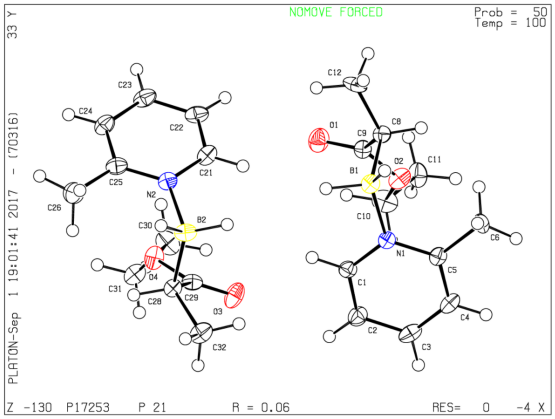
Author Response: H6C is a 15% occupied disordered site. There is presumably some accomodation by the phenyl ring part of the time.

Alert level G

PLAT301 ALERT 3 G	Main Residue Disorder .....(Resd 1)..	16%	Note
PLAT720 ALERT 4 G	Number of Unusual/Non-Standard Labels	10	Note
PLAT791 ALERT 4 G	The Model has Chirality at C6 (Chiral SPGR)	R	Verify
PLAT791 ALERT 4 G	The Model has Chirality at C6B (Chiral SPGR)	R	Verify
PLAT912 ALERT 4 G	Missing # of FCF Reflections Above STh/L= 0.600	5	Note
PLAT978 ALERT 2 G	Number C-C Bonds with Positive Residual Density.	2	Info



12



Crystal data and structure refinement for organoborane **12**:

Identification code	P17253	
Empirical formula	C11 H18 B N O2	
Formula weight	207.07	
Temperature	100(2) K	
Wavelength	1.54178 Å	
Crystal system	Monoclinic	
Space group	$P2_1$	
Unit cell dimensions	a = 8.0292(3) Å	a= 90°.
	b = 19.3346(8) Å	b= 106.631(2)°.
	c = 8.0293(3) Å	g = 90°.
Volume	1194.34(8) $Å^3$	
Z	4	
Density (calculated)	1.152 Mg/m^3	
Absorption coefficient	0.611 mm^{-1}	
F(000)	448	
Crystal size	0.250 x 0.200 x 0.100 mm^3	
Theta range for data collection	2.285 to 74.659°.	
Index ranges	-9<=h<=10, -24<=k<=24, -10<=l<=10	
Reflections collected	15764	
Independent reflections	4783 [R(int) = 0.0592]	
Completeness to theta = 67.679°	100.0 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.7538 and 0.6598	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	4783 / 5 / 290	
Goodness-of-fit on F^2	1.109	
Final R indices [I>2sigma(I)]	R1 = 0.0592, wR2 = 0.1453	
R indices (all data)	R1 = 0.0624, wR2 = 0.1496	
Absolute structure parameter	0.07(10)	
Extinction coefficient	n/a	
Largest diff. peak and hole	0.624 and -0.287 e.$Å^{-3}$	

Datablock: P17253

Bond precision: C-C = 0.0083 A Wavelength=1.54178

Cell: a=8.0292(3) b=19.3346(8) c=8.0293(3)
alpha=90 beta=106.631(2) gamma=90

Temperature: 100 K

	Calculated	Reported
Volume	1194.34(8)	1194.34(8)
Space group	P 21	P 21
Hall group	P 2yb	P 2yb
Moiety formula	C11 H18 B N O2	?
Sum formula	C11 H18 B N O2	C11 H18 B N O2
Mr	207.07	207.07
Dx,g cm-3	1.152	1.152
Z	4	4
Mu (mm-1)	0.611	0.611
F000	448.0	448.0
F000'	449.28	
h,k,lmax	10,24,10	10,24,10
Nref	4856[2503]	4783
Tmin,Tmax	0.864,0.941	0.660,0.754
Tmin'	0.858	

Correction method= # Reported T Limits: Tmin=0.660 Tmax=0.754
AbsCorr = MULTI-SCAN

Data completeness= 1.91/0.98 Theta(max)= 74.659

R(reflections)= 0.0592(4582) wR2(reflections)= 0.1496(4783)

S = 1.109 Npar= 290

The following ALERTS were generated. Each ALERT has the format
test-name_ALERT_alert-type_alert-level.
Click on the hyperlinks for more details of the test.

Alert level C

DIFMX02 ALERT 1 C The maximum difference density is > 0.1*ZMAX*0.75
The relevant atom site should be identified.

PLAT094 ALERT 2 C	Ratio of Maximum / Minimum Residual Density	2.17	Report
PLAT097 ALERT 2 C	Large Reported Max. (Positive) Residual Density	0.62	eA-3
PLAT340 ALERT 3 C	Low Bond Precision on C-C Bonds	0.00831	Ang.
PLAT480 ALERT 4 C	Long H...A H-Bond Reported H1 .. O3 ..	2.61	Ang.
PLAT480 ALERT 4 C	Long H...A H-Bond Reported H2 .. O3 ..	2.62	Ang.
PLAT911 ALERT 3 C	Missing # FCF Refl Between THmin & STh/L= 0.600	4	Report

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Alert level G

PLAT002 ALERT 2 G	Number of Distance or Angle Restraints on AtSite	6	Note
PLAT172 ALERT 4 G	The CIF-Embedded .res File Contains DFIX Records	1	Report
PLAT720 ALERT 4 G	Number of Unusual/Non-Standard Labels	4	Note
PLAT791 ALERT 4 G	The Model has Chirality at C8 (Chiral SPGR)	R	Verify
PLAT791 ALERT 4 G	The Model has Chirality at C28 (Chiral SPGR)	R	Verify
PLAT860 ALERT 3 G	Number of Least-Squares Restraints	5	Note
PLAT870 ALERT 4 G	ALERTS Related to Twinning Effects Suppressed ..	!	Info
PLAT912 ALERT 4 G	Missing # of FCF Reflections Above STh/L= 0.600	9	Note
PLAT931 ALERT 5 G	Found Twin Law (1 0 -1)[ ] Estimated BASF	0.49	Check

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XII. Supplemental References

1 L. Gao, B. C. Kang, D. H. Ryu, Catalytic asymmetric insertion of diazoesters into aryl–CHO bonds: highly enantioselective construction of chiral all-carbon quaternary centers. *J. Am. Chem. Soc.* **135**, 14556–14559 (2013).

2 C. Peng, Y. Wang, J. Wang, Palladium-catalyzed cross-coupling of *α*-diazocarbonyl compounds with arylboronic acids. *J. Am. Chem. Soc.* **130**, 1566–1567 (2008).

3 X. Gao, B. Wu, W.-X. Huang, M-W. Chen, Y-G. Zhou, Enantioselective palladium-catalyzed C–H functionalization of indoles using an axially chiral 2,2'-bipyridine ligand. *Angew. Chem. Int. Ed.* **54**, 11956–11960 (2015).

4 Y. Tang, Q. Chen, X. Liu, G. Wang, L. Lin, X. Feng, Direct synthesis of chiral allenoates from the asymmetric C–H insertion of *α*-diazoesters into terminal alkynes. *Angew. Chem. Int. Ed.* **54**, 9512–9516 (2015).

5 G. Shi, Y. Xu, Trifluoromethyl-substituted carbethoxy carbene as a novel CF_3-containing a^2 synthon equivalent for the preparation of 2-(trifluoromethyl)-4-oxo carboxylic ester derivatives: highly functionalized synthetic building blocks bearing a CF_3 group. *J. Org. Chem.* **55**, 3383–3386 (1990).

6 E. Emer, J. Twilton, M. Tredwell, S. Calderwood, T. L. Collier, B. Liégault, M. Taillefer, V. Gouverneur, Diversity-oriented approach to CF_3CHF-, CF_3CFBr-, CF_3CF_2-, $(CF_3)_2CH$-, and $CF_3(SCF_3)CH$-substituted arenes from 1-(diazo-2,2,2-trifluoroethyl)arenes. *Org. Lett.* **16**, 6004–6007 (2014).

7 A. Solovyev, S.-H. Ueng, J. Monot, L. Fensterbank, M. Malacria, E. Lacôte, D. P. Curran, Estimated rate constants for hydrogen abstraction from *N*-heterocyclic carbene−borane complexes by an alkyl radical. *Org. Lett.* **12**, 2998–3001 (2010).

8 X. Li, D. P. Curran, Insertion of reactive rhodium carbenes into boron−hydrogen bonds of stable *N*–heterocyclic carbene boranes. *J. Am. Chem. Soc.* **135**, 12076−12081 (2013).

9 S. Huang, X. Qi, T. Liu, K. Wang, W. Zhang, J. Li, Q. Zhang, Towards safer rocket fuels: hypergolic imidazolylidene-borane compounds as replacements for hydrazine derivatives. *Chem. Eur. J.* **22**, 10187–10193 (2016).

10 M.-H. Wang, L.-Y. Chen, An efficient $FeCl_3$-mediated approach for reduction of ketones through *N*-heterocyclic carbene boranes. *Tetrahedron Lett.* **58**, 732–735 (2017).

11 S.-C. Ren, F.-L. Zhang, J. Qi, Y.-S. Huang, A.-Q. Xu, H.-Y. Yan, Y-F. Wang, Radical borylation/cyclization cascade of 1,6-enynes for the synthesis of boron-handled hetero- and carbocycles. *J. Am. Chem. Soc.* **139**, 6050–6053 (2017).

12 J.-M. Yang, Z.-Q. Li, M.-L. Li, Q. He, S.-F. Zhu, Q.-L. Zhou, Catalytic B−H bond insertion reactions using alkynes as carbene precursors. *J. Am. Chem. Soc.* **139**, 3784−3789 (2017).

13 D. Sterk, M. Stephan, B. Mohar, Highly enantioselective transfer hydrogenation of fluoroalkyl ketones. *Org. Lett.* **8**, 5935–5938 (2006).

14 J. Y. Hamilton, B. Morandi, E. M. Carreira, Homologative trifluoromethylation of acetals. *Synthesis* **45**, 1857–1862 (2013).

15 G. M. Sheldrick, Phase annealing in SHELX-90: Direct methods for larger structures. *Acta Cryst.* **A46**, 467–473 (1990).

16 G. M. Sheldrick, Crystal structure refinement with SHELXL. *Acta Cryst.* **C71**, 3–8 (2015).

17 P. Müller, Practical suggestions for better crystal structures. *Crystallogr. Rev.* **15**, 57–83 (2009).
18 S. Parsons, H. D. Flack, T. Wagner, Use of intensity quotients and differences in absolute structure refinement. *Acta Cryst.* **B69**, 249–259 (2013).
19 R. W. W. Hooft, L. H. Straver, A. L. Spek, Using the *t*-distribution to improve the absolute structure assignment with likelihood calculations. *J. Appl. Cryst.* **43**, 665–668 (2010).