SUPPORTING INFORMATION

Diboration of 3-Substituted Propargylic Alcohols using a Bimetallic Catalyst System: Access to (*Z*)-Allyl, Vinyldiboronates

Cheryl L. Peck, Jan Nekvinda and Webster L. Santos*

Department of Chemistry, Virginia Tech, Blacksburg, Virginia 24061, United States. Email: santosw@vt.edu

Table of Contents

1. Materials and Methods

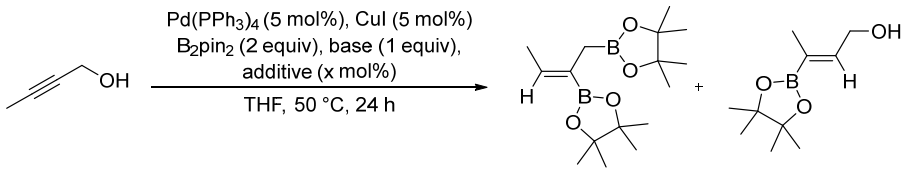
Unless otherwise noted, all reactions were conducted under a nitrogen or argon atmosphere using oven-dried glassware. Deionized water (DI) was used from the house DI water system without degassing or further purification. Tetrahydrofuran, dichloromethane, acetonitrile, toluene, and *N,N*-dimethylformamide were obtained from an Innovative Technology Pure Solv-MD solvent purification system and further degassed by bubbling N_2 for at least 10 minutes. Additional solvents were purchased with sure-seal tops and used as received. Symmetrical diboron reagent bis(pinacolato)diboron (B_2pin_2) was donated from AllylChem or purchased from Boron Molecular and used as received while unsymmetrical diboron reagent 2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2,3-dihydro-1H-naphtho[1,8-de][1,3,2]diazaborinine (pinB–Bdan) was synthesized according to the literature.[1] All other commercially available catalysts, substrates, and reagents were purchased and used as received. TLC analyses were performed using EMD silica gel 60 F254 plates, Agela Technologies silica gel MF254 plates, or Silicycle Aluminium backed silica gel F-254 plates. Visualization of developed plates were observed under UV light (254 nm) and with permanganate or phosphomolybdic acid stains. Gas chromatography (GC) yields were determined by constructing calibration curves with benzophenone as an internal standard.

2. Instrumentation

^{1}H NMR spectra were recorded on a Bruker Avance II 500 MHz, Bruker Avance 600 MHz, Agilent MR 400 MHz, or Agilent DD2 400 MHz spectrometer. Chemical shifts are reported in ppm with the solvent resonance as the internal standard ($CDCl_3$: 7.26 ppm, $(CD_2)_3CO$: 2.05 ppm, $(CD_3)_2SO$: 2.50 ppm). Data is reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, dd = doublet of doublets, dt = doublet of triplets, qt = quartet of triplets, tt = triplet of triplets, br = broad), coupling constants (Hz), and integration. ^{13}C NMR spectra were recorded on a Bruker Avance II 500 MHz, Bruker Avance III 600 MHz, Agilent MR 400 MHz or Agilent D2 400 MHz spectrometer. Chemical shifts are reported in ppm with the solvent resonance as the internal standard ($CDCl_3$: 77.16 ppm, $(CD_3)_2SO$: 39.52 ppm, $(CD_3)_2CO$: 29.84 ppm). The carbon directly attached to the boron may not be observed due to quadrupolar relaxation. In the diborated products, the primary carbon on both boron atoms may overlap and be observed as a single signal. ^{11}B NMR spectra were recorded on an Agilent DD2 400 MHz or Varian Inova 400 MHz spectrometer. Chemical shifts are reported in ppm using boron trifluoride diethyl etherate as an external standard (BF_3•Et_2O: 0 ppm). High resolution mass spectra (HRMS) were performed on an Agilent LC-ESI-TOF. Ionization techniques implemented are reported as electron spray ionization (ESI+) or mixed extraction ion chromatrography (+mixed EIC), a mixture of ESI and atmospheric pressure chemical ionization (APCI). GC analyses were performed on an Agilent 789B Series system coupled to an Agilent 5977A Mass Selective Detector and an Agilent 7693 autosampler.

3. Optimization studies

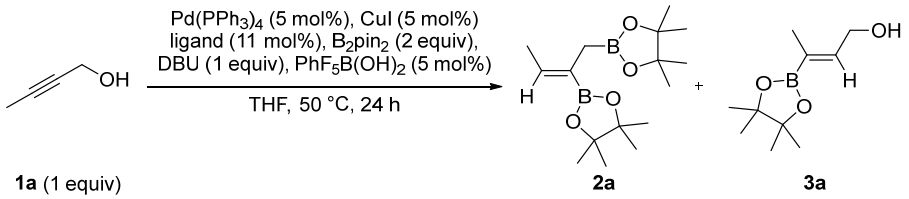
Table 1 Base and additive screenings for the borylation of propargylic alcohol species.[a]



Entry	Base	Additive (x mol %)	Ratio **2a**:**3a**[b]	Yield **2a** (%)[c]
1	pyridine	-	85:15	(4)
2	Et_3N	-	>1:99	(>1)
3	NaOH	-	75:25	(15)
4	NaO^tBu	-	18:82	(7)
5	DBU	-	28:72	(8)
6	DBU	$PhF_5B(OH)_2$ (100)	65:35	(7)
7	DBU	$PhF_5B(OH)_2$ (20)	89:11	(14)
8	DBU	$PhF_5B(OH)_2$ (10)	86:14	20
9	**DBU**	**$PhF_5B(OH)_2$ (5)**	**90:10**	**22**
10	DBU	$Ti(O^iPr)_4$ (5)	88:12	11
11	DBU	$FeCl_3$ (5)	90:10	17
12	DBU	$AlCl_3$ (5)	76:24	7
13	DBU	TMSCl (5)	71:29	14

[a] Reaction conditions: In an Ar purged flask, $Pd(PPh_3)_4$ (0.024 mmol) and CuI (0.024 mmol) were premixed in THF (1.5 mL) for 30 min. **2a** (0.484 mmol) and base (0.484 mmol) were added before cannulating in a solution of B_2pin_2 (0.968 mmol) and additive (0.024 mmol) in THF (0.5 mL). [b] Ratios determined by GC analysis of crude mixture and stereochemistry was confirmed by NOE experiments. [c] GC yields determined using benzophenone as an internal standard, isolated yields shown in parenthesis.

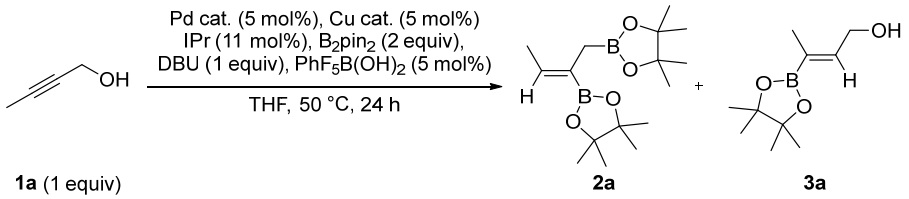
Table 2 Screening of ligands for the borylation of propargylic alcohol species.[a]



Entry	Ligand	Ratio **2a**:**3a**[b]	Yield **2a** (%)[c]
	Xantphos	100:0	29
2	DPEPhos	100:0	7
3	dppf	>99:1	15
4	(*R*,*R*)-QuinoxP*	61:39	2
5	dppp	100:0	2
6	bpy	>99:1	32
7	4,4'-di-tert-butyl-2,2'-bpy	94:6	32
8	4,4'-di-methoxy-2,2'-bpy	90:10	21
9	1,10-phenanthroline	70:30	3
10	3,4,7,8-tetramethyl-1,10-phenanthroline	84:16	7
11	hexafluoroacetylacetone	73:27	11
12	tridentate ligand	61:39	2
13	SPhos	100:0	4
14	RuPhos	>99:0	12
15	^{t}BuDavePhos	85:15	19
16	PCy_3	80:20	16
17	$P(Net_2)_3$	94:6	21
18	$P(OPh)_3$	97:3	10
19[d]	ICy•BF_4	64:36	2
20[d]	IMes•Cl	83:17	9
21	**IPr**	**98:2**	**37**

[a] Reaction conditions: In an Ar purged flask, $Pd(PPh_3)_4$ (0.024 mmol), CuI (0.024 mmol) and ligand (0.053 mmol) were premixed in THF (1.5 mL) for 30 min. **2a** (0.484 mmol) and DBU (0.484 mmol) were added before cannulating in a solution of B_2pin_2 (0.968 mmol) and $PhF_5B(OH)_2$ (0.024 mmol) in THF (0.5 mL). [b] Ratios determined by GC analysis of crude mixture and stereochemistry was confirmed by NOE experiments. [c] GC yields determined using benzophenone as an internal standard, isolated yields shown in parenthesis. [d] Ligand deprotonated with NaO^{t}Bu (1 equiv).

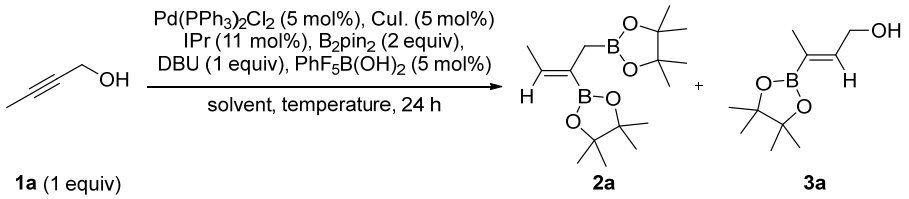
Table 3 Screening catalysts for the borylation of propargylic alcohol species.[a]



Entry	Palladium Catalyst	Copper Catalyst	Ratio **2a**:**3a**[b]	Yield **2a** (%)[c]
1	$Pd(PPh_3)_4$	CuI	98:2	37
2	**$Pd(PPh_3)_2Cl_2$**	**CuI**	**98:2**	**37**
3	$Pd(OAc)_2$	CuI	70:30	trace
4	$Pd(TFA)_2$	CuI	100:0	trace
5	$Pd(MeCN)_2(BF_4)_2$	CuI	97:3	trace
6	$Pd(dppf)_2Cl_2$	CuI	68:31	6
7	$Pd_2(dba)_3$	CuI	100:0	trace
8	$Pd(PPh_3)_2Cl_2$	CuCl	100:0	trace
9	$Pd(PPh_3)_2Cl_2$	CuBr	100:0	26
10	$Pd(PPh_3)_2Cl_2$	CuCN	100:0	32
11	$Pd(PPh_3)_2Cl_2$	$Cu(OAc)_2$	100:0	trace
12	$Pd(PPh_3)_2Cl_2$	$Cu(acac)_2$	100:0	trace

[a] Reaction conditions: In an Ar purged flask, Pd catalyst (0.024 mmol), Cu catalyst (0.024 mmol) and IPr (0.053 mmol) were premixed in THF (1.5 mL) for 30 min. **2a** (0.484 mmol) and DBU (0.484 mmol) were added before cannulating in a solution of B_2pin_2 (0.968 mmol) and $PhF_5B(OH)_2$ (0.024 mmol) in THF (0.5 mL). [b] Ratios determined by GC analysis of crude mixture and stereochemistry was confirmed by NOE experiments. [c] GC yields determined using benzophenone as an internal standard, isolated yields shown in parenthesis.

Table 4 Screening solvents and temperatures for the borylation of propargylic alcohol species.[a]



Entry	Solvent	Temperature (°C)	Ratio **2a**:**3a**[b]	Yield **2a** (%)[c]
1	THF	50	98:2	37
2	DCM	50	94:6	44
3	DMF	50	71:29	11
4	MeCN	50	93:7	49
5	DMA	50	86:14	19
6	DCM:MeCN[d]	50	83:17	21
7	toluene	50	98:2	16
8	1,4-dioxane	50	67:36	14
9	benzene	50	71:29	17
10	MTBE	50	99:1	trace
11	cyclohexane	50	31:68	15
12	**MeCN**	**rt**	**96:4**	**68 (36)**
13	MeCN	reflux	89:11	53
14[e]	MeCN	rt	n.r.	n.r.
15[f]	MeCN	rt	0:100	0
16[g]	MeCN	rt	n.r.	n.r.
17[h]	MeCN	rt	n.r.	n.r.

[a] Reaction conditions: In an Ar purged flask, $Pd(PPh_3)_2Cl_2$ (0.024 mmol), CuI (0.024 mmol) and IPr (0.053 mmol) were premixed in THF (1.5 mL) for 30 min. **2a** (0.484 mmol) and DBU (0.484 mmol) were added before cannulating in a solution of B_2pin_2 (0.968 mmol) and $PhF_5B(OH)_2$ (0.024 mmol) in THF (0.5 mL). [b] Ratios determined by GC analysis of crude mixture and stereochemistry was confirmed by NOE experiments. [c] GC yields determined using benzophenone as an internal standard, isolated yields shown in parenthesis. [d] 1:1 mixture. [e] pinB-Bdan used as the diboron reagent. [f] Reaction run in the absence of Pd. [g] Reaction run in the absence of copper. [h] Reaction run in the absence of DBU. n.r. = no reaction.

4. Stability studies

In an effort to understand why the isolated yields were significantly lower than the GC yields, two stability studies were conducted. Over the period of 3 days, compound **2a** was analyzed by ^{1}H NMR to determine potential decomposition (Figure 1). Results indicated that regardless of whether the compound was stored under argon or left open-to-air, no decomposition was observed. Alternatively, we looked into the possibility of the product decomposing during purification (Figure 2). When isolated compound **2a** was combined with silica for 1 hour, the product had decomposed significantly (Figure 3). Unfortunately, deactivated silica and alumina provided similar results. Despite minimal product decomposition being observed when using florisil, we were unable to use it for purification. The allyl and vinyl boronate products are not UV active and must be observed using $KMnO_4$ stain; unfortunately, florisil TLC plates do not stain effectively, making it difficult to find an ideal solvent system for purification. Regardless of this, it was noticed that purifying the product in less than 15 minutes was crucial to limiting decomposition.

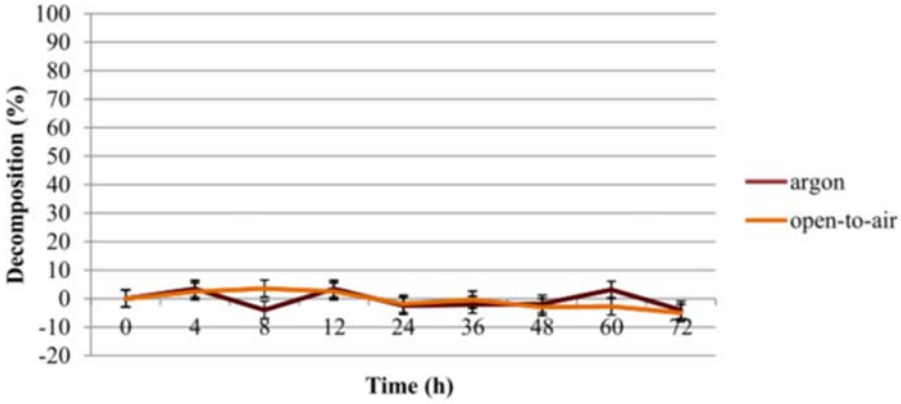


Figure 1. Stability of **2a** in solution over time.

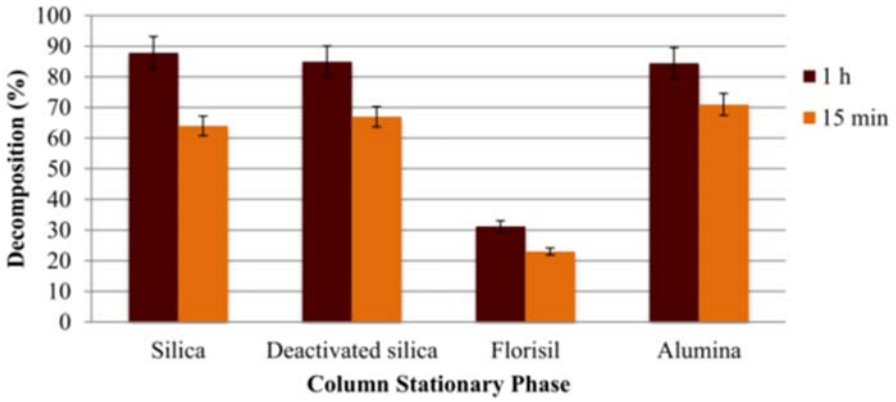


Figure 2 Decomposition of **2a** on column stationary phases.

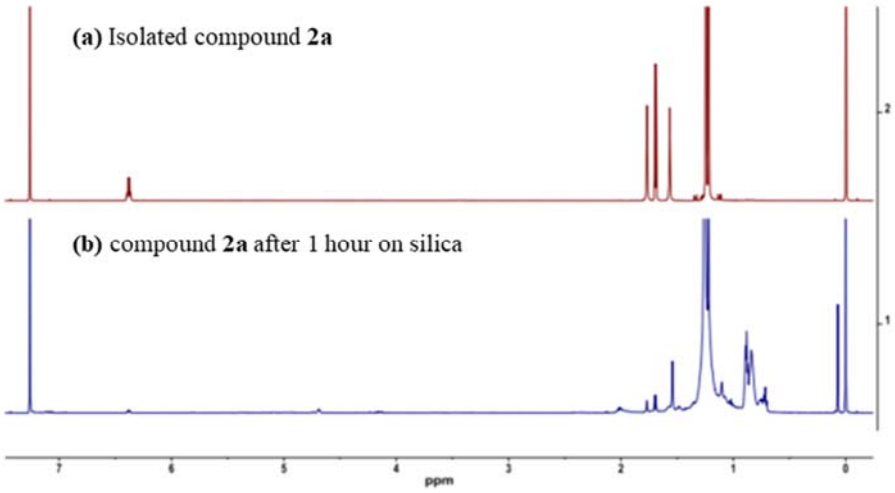


Figure 3 ^{1}H NMR illustrating the decomposition of **2a** on silica.

General procedure to determine the stability of vinyl and allyl boronate products on column stationary phases:

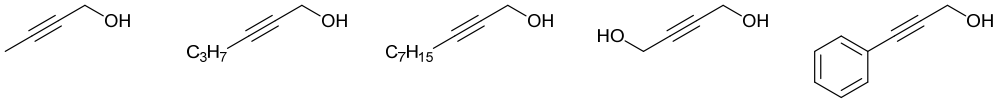
Approximately 5.0-7.0 mg of compound **2a** was weighed out into a 1-dram vial and dissolved in 1.0 mL of $CDCl_3$. The designated stationary phase was added to the vial that was then purged with argon and wrapped in parafilm. The solution was mixed every few minutes. Afterwards, the solution was filtered and concentrated in vacuo before obtaining an NMR yield using 750 µL of $CDCl_3$ with 0.05% v/v TMSCl as the internal standard. A Bruker Avance III 600 MHz equipped with a BBO probe was used to obtain the NMR spectra. The amount of decomposition was determined by the amount of product lost compared to the pure product. The ^{1}H NMR yield from each test are shown in Table 5.

Table 5 Stability study and subsequent NMR yields of the product **2a**.

Entry	Stationary Phase	Time (min)	^{1}H NMR yield (%)
1	Silica	15	36
2	Silica	60	12
3	Deactivated Silica	15	33
4	Deactivated Silica	60	15
5	Florisil	15	77
6	Florisil	60	69
7	Alumina	15	29
8	Alumina	60	16

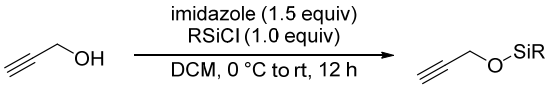
5. Substrate synthesis

Commercially available substrates **1a-c,h,i**.



1a **1b** **1c** **1h** **1i**

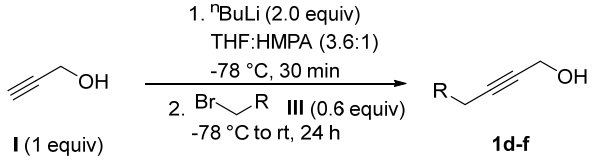
General procedure **A** for the synthesis of alcohol protected intermediate **I**:



I (1 equiv) **II**

Dry DCM (7.92 mL, 0.705 M total) was added to a nitrogen purged flask containing alcohol **I** (0.8 g, 1.0 equiv). The flask was cooled to 0 °C before the addition of imidazole (570 mg, 1.5 equiv) which was dissolved in dry DCM (6 mL). After 10 minutes, tert-butyldiphenylsilane chloride (1.45 mL, 1.0 equiv.) or tert-butyldimethylsilyl chloride (1.56 g dissolved in 1.92 mL DCM, 1.0 equiv) was added to the reaction dropwise. The mixture was allowed to warm up to room temperature. The progress of the reaction was followed by TLC. The aqueous phase was extracted with DCM (3 x 25 mL). The combined organic phases were washed with DI water (1 x 25 mL), brine, dried over Na_2SO_4, filtered, and concentrated in vacuo. Column chromatography was used to purify the product, eluting with hexanes and EtOAc to yield the desired compound. Note: Compound **II** is volatile under reduced pressure.

General procedure **B** for the synthesis of propargylic alcohol species **1d-f**:

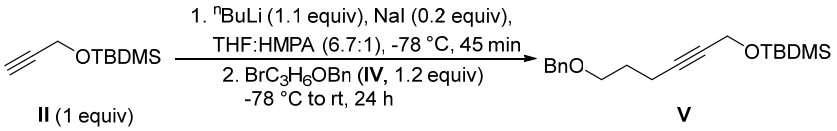


I (1 equiv) **1d-f**

Prop-2-yn-1-ol **I** (0.5 mL, 1.0 equiv) was added to a nitrogen purged flask followed by dry THF:HMPA (3.6:1 ratio, 17.3 mL, 0.5 M). The flask was cooled to -78 °C before the dropwise addition of n-butyllithium (6.93 mL of 2.5 M in hexanes, 2.0 equiv) over a period of 10 minutes. The reaction was stirred at -78 °C for 45 minutes before alkyl bromide **III** (0.581 mL, 0.6 equiv) was added dropwise. The solution was allowed to slowly warm up to room temperature overnight. The reaction was quenched by adding sat. NH_4Cl. The aqueous layer was washed with Et_2O (3 x 10 mL), brine, dried over Na_2SO_4, filtered, and concentrated in vacuo. Column

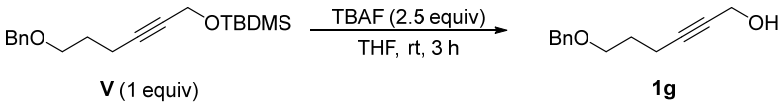
chromatography was used to purify the product, eluting with hexanes and EtOAc to yield the desired compounds.

General procedure **C** for the synthesis of TBS protected propargylic alcohol species **V**:



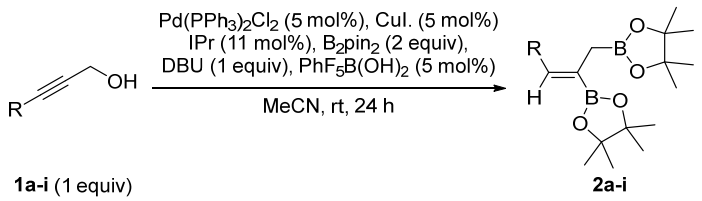
Tert-butyldimethyl(prop-2-yn-1-yloxy)silane **II** (0.5 g, 1.0 equiv) was added to a nitrogen purged flask followed by dry THF:HMPA (6.67:1 ratio, 8.2 mL, 0.306 M total). The flask was cooled to -78 °C before the dropwise addition of n-butyllithium (1.29 mL of 2.5 M in hexanes, 1.1 equiv) over a period of 10 minutes. The reaction was stirred at -78 °C for 45 minutes. Afterwards, NaI (88 mg, 0.2 equiv.) dissolved in dry THF:HMPA (6.67:1 ratio, 1.4 mL) and ((3-bromopropoxy)methyl)benzene **IV** (0.65 mL, 1.2 equiv) were added dropwise. The solution was allowed to slowly warm up to room temperature overnight. After 24 hours, the reaction was quenched by adding sat. aq. NH_4Cl. The aqueous layer was washed with Et_2O (3 x 20 mL), brine and dried over Na_2SO_4, filtered, and concentrated in vacuo. Column chromatography was used to purify the product, eluting with hexanes and Et_2O to yield the title compound.

General procedure **D** for the deprotection of **V** to synthesize propargylic alcohol species **1g**:



In an oven dried flask, ((6-(benzyloxy)hex-2-yn-1-yl)oxy)(tert-butyl)dimethylsilane **V** (205 mg, 1.0 equiv) was dissolved in dry THF (2.14 mL, 0.3 M) followed by the addition of tetrabutylammonium fluoride (1.6 mL of 1 M in THF, 2.5 equiv). The reaction was stirred at ambient temperature for 3 hours. Once the reaction is complete, the crude mixture was dried with Na_2SO_4, filtered, and concentrated in vacuo. Column chromatography was used to purify the product, eluting with hexanes and EtOAc to yield the title compound.

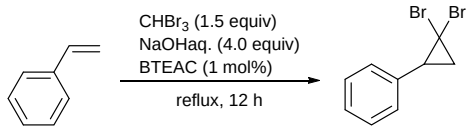
General procedure **E** for the diboration of propargylic alcohol species **2a-i**:



1a-i (1 equiv) **2a-i**

To an argon purged oven dried flask, bis(triphenylphosphine)palladium(II) chloride (17.0 mg, 0.05 equiv), IPr (1,3-bis(2,6-diisopropylphenyl)-1H-imidazol-3-ium-2-ide) (21.0 mg, 0.11 equiv), and copper(I) iodide (4.6 mg, 0.05 equiv) were quickly added followed by MeCN (1.45 mL of 1.95 mL, 0.25 M total). The catalysts and ligand were premixed under argon at room temperature for 30 minutes. Afterwards, propargylic alcohol species **1a-i** (37 µL, 1.0 equiv, 0.484 mmol) and DBU (2,3,4,6,7,8,9,10-octahydropyrimido[1,2-a]azeprine) (74 µL, 1.0 equiv) were added. In a separate flask, $PhF_5B(OH)_2$ ((perfluorophenyl)boronic acid) (5.1 mg, 0.05 equiv) and B_2pin_2 (4,4,4',4',5,5,5',5'-octamethyl-2,2'-bi(1,3,2-dioxaborolane)) (246 mg, 2.0 equiv) were dissolved in MeCN (0.5 mL) and added to the original flask *via* cannulate. The reaction was stirred at ambient temperature for 24 hours. Afterwards, EtOAc was added to the reaction, filtered through a celite pad, and concentrated in vacuo. The residue was purified by column chromatography eluting with hexanes and EtOAc to yield the desired compound. Note: Elution of the product in ≤ 15 minutes is important due to the product degrading on silica.

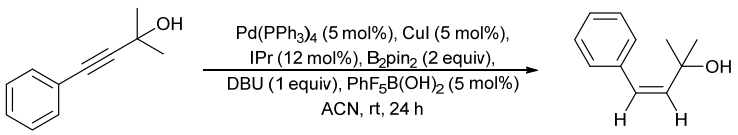
General procedure **F** for dibromocyclopropyl **VII**:



VI (1.0 equiv) **VII**

Styrene **VI** (0.220 mL, 1.0 equiv), bromoform (0.252 mL, 1.5 equiv), and BTEAC (benzyltriethylammonium chloride) (4.37 mg, 0.01 equiv) were added to an argon purged oven dried flask equipped with a reflux condenser. After the reaction was heated to 60 °C, aqueous sodium hydroxide (307 mg, 25 M in DI H_2O, 4.0 equiv) was added dropwise. The reaction as allowed to stir overnight. The crude reaction mixture was extracted with $CDCl_3$ (3 x 15 mL). The combined organic layers were washed with brine, dried over Na_2SO_4, filtered, and concentrated in vacuo. The resulting product was purified using Kugelrohr distillation to furnish the desired product.

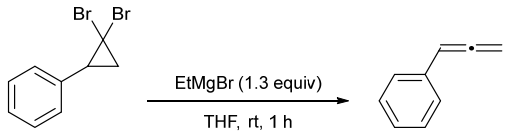
General procedure **G** for propargylic boronate **4**:



1j **4**

To an argon purged oven dried flask, bis(triphenylphosphine)palladium(II) chloride (17.0 mg, 0.05 equiv), 1,3-bis(2,6-diisopropylphenyl)-1H-imidazol-3-ium-2-ide (21.0 mg, 0.11 equiv), and copper(I) iodide (4.6 mg, 0.05 equiv) were quickly added followed by MeCN (1.45 mL of 1.95 mL, 0.25 M total). The catalysts and ligand were premixed under argon at room temperature for 30 minutes. Afterwards, propargylic alcohol species **1j** (37 µL, 1.0 equiv, 0.484 mmol) and 2,3,4,6,7,8,9,10-octahydropyrimido[1,2-a]azeprine (74 µL, 1.0 equiv.) were added. In a separate flask, (perfluorophenyl)boronic acid (5.1 mg, 0.05 equiv.) and 4,4,4',4',5,5,5',5'-octamethyl-2,2'-bi(1,3,2-dioxaborolane) (246 mg, 2.0 equiv) were dissolved in MeCN (0.5 mL) and added to the original flask *via* cannulate. The reaction was stirred at ambient temperature for 24 hours. Afterwards, EtOAc was added to the reaction, filtered through a pad of celite, and concentrated in vacuo. The residue was purified by column chromatography eluting with hexanes and EtOAc to yield the desired compound. Note: Elution of the product in ≤15 minutes is important due to the product degrading on silica.

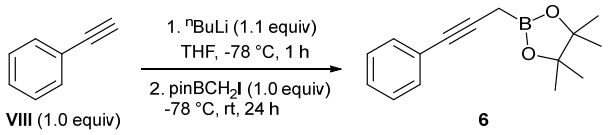
General procedure **H** for the synthesis of phenyl allene **5**:



VII (1.0 equiv) **5**

(2,2-Diboromocyclopropyl)benzene **VII** (0.4 g, 1.0 equiv) was added to an argon purged flask followed by addition of THF (2.9 mL, 0.5 M). Ethylmagnesium bromide solution (0.63 mL of 3M in Et_2O, 1.3 equiv) was added dropwise and the reaction was stirred at ambient temperature for 1 hour. The reaction was quenched with DI water. After separating the organic and aqueous layers, the aqueous layer was extracted with PET Et_2O (3 x 10 mL). The organic layers were combined, dried over Na_2SO_4, filtered, and concentrated in vacuo. The crude product was purified through a silica plug, eluting with PET Et_2O to furnish the desired product. Note: the allene **5** is volatile under reduced pressure.

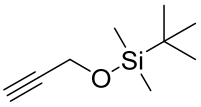
General procedure **I** for propargylic boronate **6**:



Dry THF (1.9 mL, 0.5 M) and ethynylbenzene **VIII** (108 µL, 1.0 equiv) were added to a nitorgen purged round bottom flask. The reaction was cooled to -78 °C before the dropwise addition of n-butyllithium (422 µL, 1.1 equiv) over a period of 5 minutes. After stirring for 1 hour, 2-(iodomethyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (257 mg, 1.0 equiv) was added dropwise. The reaction was kept cold for 6 hours before warming up to room temperature overnight. Once complete, the reaction was quenched with DI water and EtOAc. After separating the layers, the aqueous layer was washed with EtOAc (3 x 15 mL) collecting the organic layer each time. The organic layer was then washed with brine, dried over Na_2SO_4, filtered, and concentrated in vacuo. The resulting yellow oil was then carried forward crude in the borylation reaction.

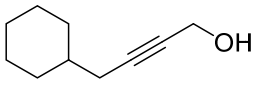
6. Characterization data

tert-Butyldimethyl(prop-2-yn-1-yloxy)silane (**II**):



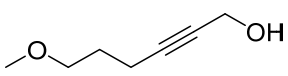
Compound **II** was synthesized according to General Procedure **A** and isolated in a 87% yield as a colorless liquid. TLC R_f = 0.35 (95:5 Hex:EtOAc). ^{1}H and ^{13}C NMR spectra are consistent with the literature.[2]

4-Cyclohexylbut-2-yn-1-ol (**1d**):



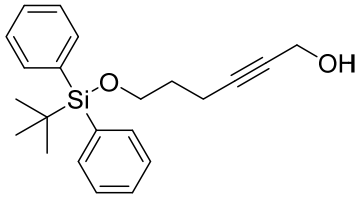
Compound **1d** was synthesized according to General Procedure **B** and isolated in a 15% yield as a light-yellow oil. TLC R_f = 0.29 (80:20 Hex:EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.26 (t, *J* = 2.2 Hz, 2H), 2.10 (dt, *J* = 6.7, 2.2 Hz, 2H), 1.83 – 1.61 (m, 5H), 1.50 (br s, 1H), 1.50 – 1.39 (m, 1H), 1.30 – 1.07 (m, 3H), 0.97 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 85.6, 79.3, 51.6, 37.4, 32.8, 26.7, 26.4, 26.2; GCMS (+EI): calcd for $C_{10}H_{16}O$ $[M]^+$: 152.2370, Found: 152.2.

6-Methoxyhex-2-yn-1-ol (**1e**):



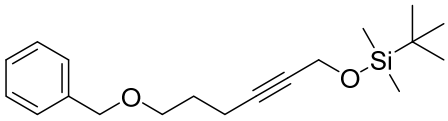
Compound **1e** was synthesized according to General Procedure **B** and isolated in a 21% yield as a light-yellow liquid. TLC R_f = 0.22 (75:25 Hex:EtOAc). ^{1}H and ^{13}C NMR spectra are consistent with the literature.[3]

6-((tert-Butyldiphenylsilyl)oxy)hex-2-yn-1-ol (**1f**):



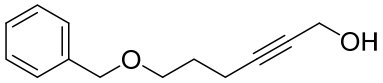
Compound **1f** was synthesized according to General Procedure **B** and isolated in a 32% yield as a yellow oil. TLC R_f = 0.31 (85:15 Hex:EtOAc). ^{1}H and ^{13}C NMR spectra are consistent with the literature.[4]

((6-(Benzyloxy)hex-2-yn-1-yl)oxy)(tert-butyl)dimethylsilane (**V**):



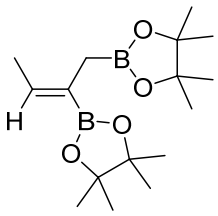
Compound **V** was synthesized according to General Procedure **C** and isolated in a 30% yield as a colorless oil. TLC R_f = 0.32 (97:3 Hex:Et_2O); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 – 7.27 (m, 5H), 4.51 (s, 2H), 4.29 (t, *J* = 2.2 Hz, 2H), 3.56 (t, *J* = 6.2 Hz, 2H), 2.33 (tt, *J* = 7.1, 2.2 Hz, 2H), 1.85 – 1.77 (m, 2H), 0.91 (s, 9H), 0.11 (s, 6H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.6, 128.5, 127.8, 127.7, 84.8, 79.1, 73.1, 69.0, 52.1, 28.9, 26.0, 18.5, 15.8, -4.9; HRMS (+Mixed EIC): calcd for $C_{19}H_{31}O_2Si$ $[M+H]^+$: 319.2086, Found: 319.2088.

6-(Benzyloxy)hex-2-yn-1-ol (**1g**):



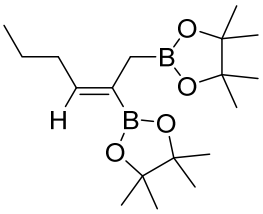
Compound **1g** was synthesized according to General Procedure **D** and isolated in a 94% yield as a colorless oil. TLC R_f = 0.24 (80:20 Hex:EtOAc). ^{1}H and ^{13}C NMR spectra are consistent with the literature.[5]

(*E*)-2,2'-(But-2-ene-1,3-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane)enoate (**2a**):



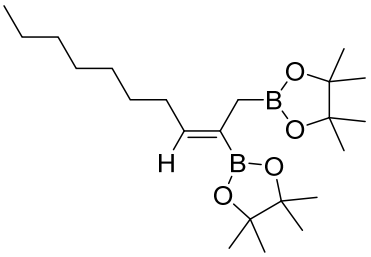
Compound **2a** was synthesized according to General Procedure **E** and isolated in a 36% yield when using but-2-yn-1-ol (**1a**) and a 5% yield when using but-2-yne-1,4-diol (**1h**) as a yellow oil. TLC R_f = 0.40 (90:10 Hex:EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.35 (qt, *J* = 6.8, 1.4 Hz, 1H), 1.77 (br s, 2H), 1.68 (d, *J* = 6.8 Hz, 3H), 1.24 (s, 12H), 1.22 (s, 12H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.7, 83.2, 83.1, 24.9, 14.5; ^{11}B NMR (128 MHz, $CDCl_3$): δ 33.04, 30.32; HRMS (ESI+): calcd for $C_{16}H_{31}B_2O_4$ $[M+H]^+$: 309.2403, Found: 309.2398.

(*Z*)-2,2'-(Hex-2-ene-1,3-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**2b**):



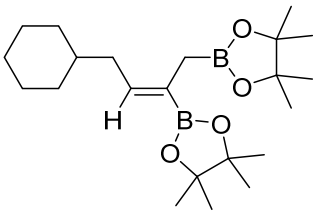
Compound **2b** was synthesized according to General Procedure **E** and isolated in a 19% yield as a yellow oil. R_f = 0.28 (95:5 Hex:EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.26 (tt, *J* = 7.0, 1.4 Hz, 1H), 2.08 (q, *J* = 7.3 Hz, 2H), 1.76 (br.s, 2H), 1.47 – 1.36 (m, 2H), 1.25 (s, 12H), 1.21 (s, 12H), 0.90 (t, *J* = 7.3 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.2, 83.2, 83.0, 31.0, 24.91, 24.90, 22.3, 14.3; ^{11}B NMR (128 MHz, $CDCl_3$) δ 33.10, 30.83; HRMS (ESI+): calcd for $C_{18}H_{35}B_2O_4$ $[M+H]^+$: 337.2716, Found: 337.2732.

(*Z*)-2,2'-(Dec-2-ene-1,2-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**2c**):



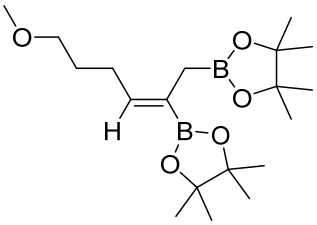
Compound **2c** was synthesized according to General Procedure **E** and isolated in a 35% yield as a yellow oil. TLC R_f = 0.26 (95:5 Hex:EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.26 (tt, *J* = 7.0, 1.3 Hz, 1H), 2.09 (q, *J* = 7.2 Hz, 2H), 1.76 (br s, 2H), 1.42 – 1.34 (m, 2H), 1.33 – 1.23 (m, 20H), 1.21 (s, 12H), 0.87 (t, *J* = 7.0 Hz, 3H); 13C NMR (101 MHz, $CDCl_3$) δ 144.5, 83.1, 83.0, 32.0, 29.7, 29.4, 29.1, 28.9, 24.91, 24.90, 22.8, 14.3; 11B NMR (128 MHz, $CDCl_3$) δ 33.08, 30.99; HRMS (ESI+): calcd for $C_{22}H_{43}B_2O_4$ $[M+H]^+$: 393.3342, Found: 393.3357.

(*Z*)-2,2'-(4-Cyclohexylbut-2-ene-1,2-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**2d**):



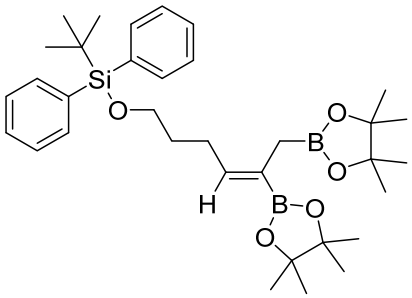
Compound **2d** was synthesized according to according to General Procedure **E** and isolated in a 14% yield as a yellow oil. TLC R_f = 0.30 (95:5 Hex:EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.26 (tt, *J* = 7.0, 1.3 Hz, 1H), 1.99 (t, *J* = 7.0 Hz, 2H), 1.78-1.52 (m, 10H), 1.42 – 1.06 (m, 25H), 0.97 – 0.82 (m, 2H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.9, 83.1, 83.0, 38.0, 36.7, 33.5, 26.7, 26.6, 24.93, 24.92; ^{11}B NMR (128 MHz, $CDCl_3$) δ 32.99, 31.37; HRMS (+Mixed EIC): calcd for $C_{22}H_{41}B_2O_4$ $[M+H]^+$: 391.3185, Found: 391.3157.

(*Z*)-2,2'-(6-Methoxyhex-2-ene-1,2-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**2e**):



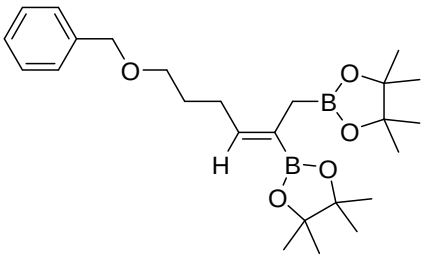
Compound **2e** was synthesized according General Procedure **E** isolated in a 14% yield as an orange oil. TLC R_f = 0.29 (85:15 Hex:EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.24 (tt, *J* = 7.0, 1.4 Hz, 1H), 3.37 (t, *J* = 6.7 Hz, 2H), 3.32 (s, 3H), 2.16 (q, *J* = 7.5 Hz, 2H), 1.76 (s, 2H), 1.72 – 1.64 (m, 2H), 1.25 (s, 12H), 1.21 (s, 12H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.3, 83.2, 83.1, 72.6, 58.6, 29.0, 25.3, 24.9; ^{11}B NMR (128 MHz, $CDCl_3$): δ 33.14, 30.57; HRMS (ESI+): Calcd for $C_{19}H_{37}B_2O_5$ $[M+H]^+$: 367.2822, Found: 367.2838.

(*Z*)-((5,6-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hex-4-en-1-yl)oxy)(tertbutyl)-diphenylsilane (**2f**):



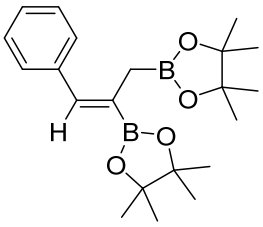
Compound **2f** was synthesized according to General Procedure **E** and isolated in a 28% yield as a viscious yellow oil. TLC R_f = 0.34 (90:10 Hex:EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.68 -7.64 (m, 4H), 7.43 – 7.34 (m, 6H), 6.26 (tt, *J* = 6.9, 1.4 Hz, 1H), 3.67 (t, *J* = 6.4 Hz, 2H), 2.22 – 2.14 (m, 2H), 1.77 (br s, 1H), 1.71 – 1.62 (m, 2H), 1.25 (s, 12H), 1.20 (s, 12H), 1.03 (s, 9H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.8, 135.7, 134.3, 129.6, 127.7, 83.2, 83.0, 63.9, 32.2, 27.0, 25.3, 24.92, 24.89, 19.4; ^{11}B NMR (128 MHz, $(CD_3)_2CO$): δ 33.79, 31.14; HRMS (ESI+): calcd for $C_{34}H_{53}B_2O_5Si$ $[M+H]^+$: 591.3843, Found: 591.3848.

(*Z*)-2,2'-(6-(Benzyloxy)hex-2-ene-1,2-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**2g**):



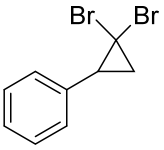
Compound **2g** was synthesized according to General Procedure **E** and isolated in a 23% yield as a yellow oil. TLC R_f = 0.28 (80:20 Hex:EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 – 7.23 (m, 5H), 6.25 (tt, *J* = 7.0, 1.4 Hz, 1H), 4.49 (s, 2H), 3.48 (t, *J* = 6.7 Hz, 2H), 2.20 (q, *J* = 7.4 Hz, 2H), 1.78 – 1.69 (m, 4H), 1.25 (s, 12H), 1.21 (s, 12H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.4, 138.9, 128.5, 127.7, 127.5, 83.2, 83.1, 72.9, 70.3, 29.1, 25.4, 24.9; ^{11}B NMR (128 MHz, $CDCl_3$) δ 33.19, 31.59; HRMS (+Mixed EIC): Calcd for $C_{25}H_{41}B_2O_5$ $[M+H]^+$: 443.3143, Found: 443.3118.

(*Z*)-2,2'-(3-Phenylprop-2-ene-1,2-diyl)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (**2h**):



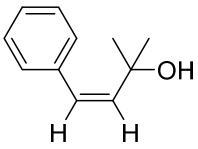
Compound **2h** was synthesized according to General Procedure **E** and isolated in a 7% yield as a yellow oil. TLC R_f = 0.34 (90:10 Hex:EtOAc). ^{1}H and ^{13}C NMR spectra are consistent with the literature.[6]

(2,2-Dibromocyclopropyl)benzene (**VII**):



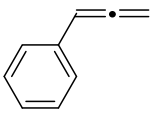
Compound **VII** was synthesized according to General Procedure **F** and isolated in a 44% yield as a colorless oil. TLC R_f = 0.5 (100% Hex). ^{1}H and ^{13}C NMR spectra are consistent with the literature.[7]

(*Z*)-2-Methyl-4-phenylbut-3-en-2-ol (**4**):



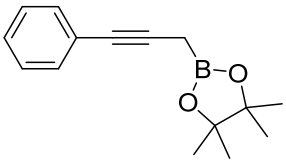
Compound **4** was synthesized according to General Procedure **G** and isolated in a 41% yield as a colorless oil. TLC R_f = 0.34 (85:15 Hex:EtOAc). ^{1}H and ^{13}C NMR spectra are consistent with the literature.[8]

Propa-1,2-dien-1-ylbenzene (**5**):



Compound **5** was synthesized according to General Procedure **H** and isolated in a 37% yield as a colorless oil. TLC R_f = 0.76 (100% Hex). ^{1}H and ^{13}C NMR spectra are consistent with the literature.[7]

4,4,5,5-Tetramethyl-2-(3-phenylprop-2-yn-1-yl)-1,3,2-dioxaborolane (**6**):



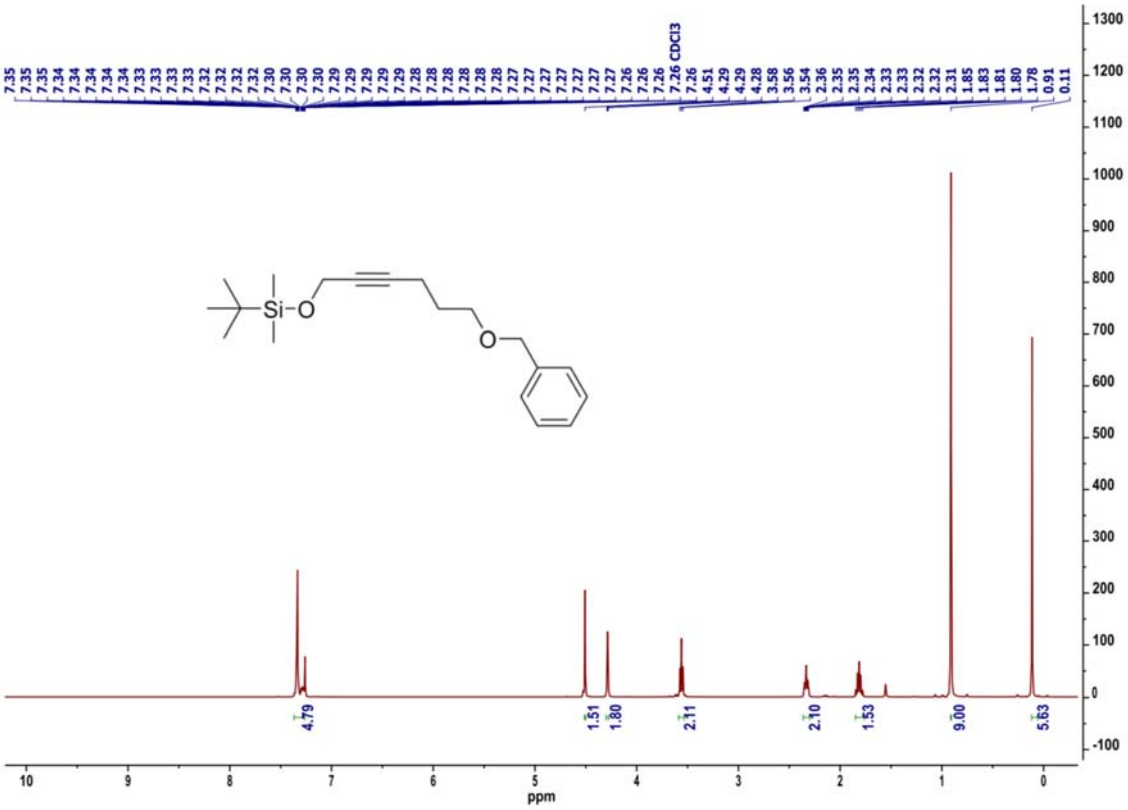
Compound **6** was synthesized according to General Procedure **I** and obtained in a 40% yield (NMR) as a yellow oil. TLC R_f = 0.29 (80:20 Hexanes:EtOAc); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 – 7.26 (m, 3H), 7.25 – 7.22 (m, 2H), 2.04 (s, 2H), 1.30 (s, 12H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 131.8, 128.2, 127.3, 124.7, 86.4, 84.2, 79.5, 77.2, 24.9; ^{11}B NMR (128 MHz, $CDCl_3$): δ 22.84; HRMS (ESI+): calcd for $C_{30}H_{42}B_2NO_4$ $[2M+NH_4]^+$: 503.3310., Found: 503.3305.

7. References

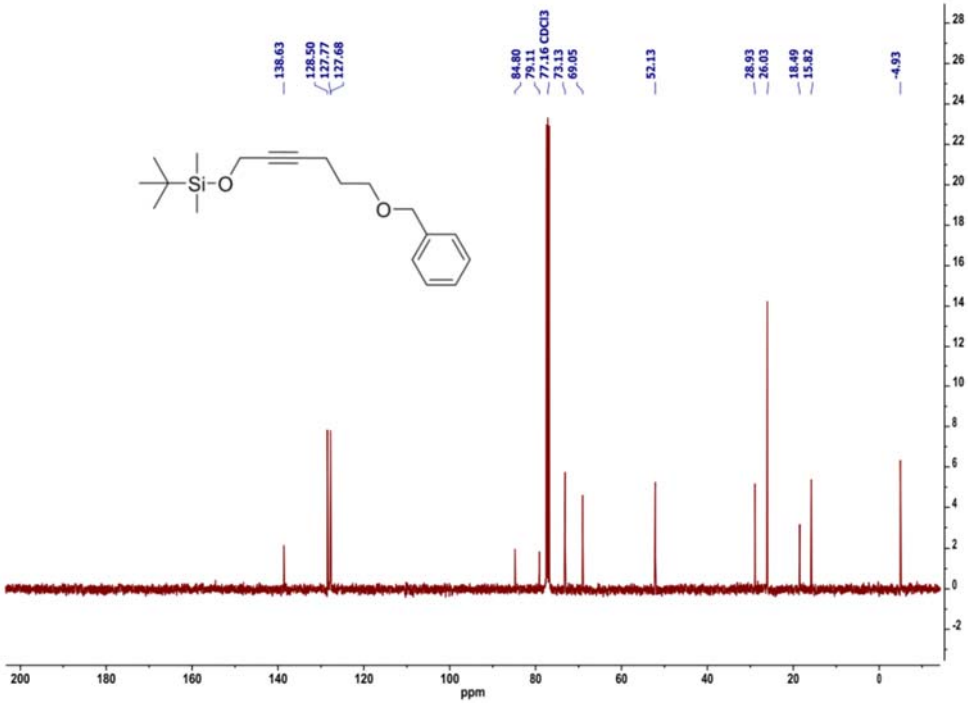
1. V. M. Dembitsky, H. A. Ali and M. Srebnik, *ChemInform*, 2004, **35**.
2. M. Koura, Y. Yamaguchi, S. Kurobuchi, H. Sumida, Y. Watanabe, T. Enomoto, T. Matsuda, A. Okuda, T. Koshizawa, Y. Matsumoto and K. Shibuya, *Biorg. Med. Chem.*, 2016, **24**, 3436-3446.
3. T. Debnar, S. Dreisigacker and D. Menche, *Chem. Commun.*, 2013, **49**, 725-727.
4. K. Nacro, M. Baltas and L. Gorrichon, *Tetrahedron*, 1999, **55**, 14013-14030.
5. J. M. Schomaker, V. R. Pulgam and B. Borhan, *J. Am. Chem. Soc*, 2004, **126**, 13600-13601.
6. F.-Y. Yang and C.-H. Cheng, *J. Am. Chem. Soc*, 2001, **123**, 761-762.
7. T. Matsubara, K. Takahashi, J. Ishihara and S. Hatakeyama, *Angew. Chem. Int. Ed.*, 2014, **53**, 757-760.
8. S. Fu, N.-Y. Chen, X. Liu, Z. Shao, S.-P. Luo and Q. Liu, *J. Am. Chem. Soc*, 2016, **138**, 8588-8594.

8. NMR Spectra

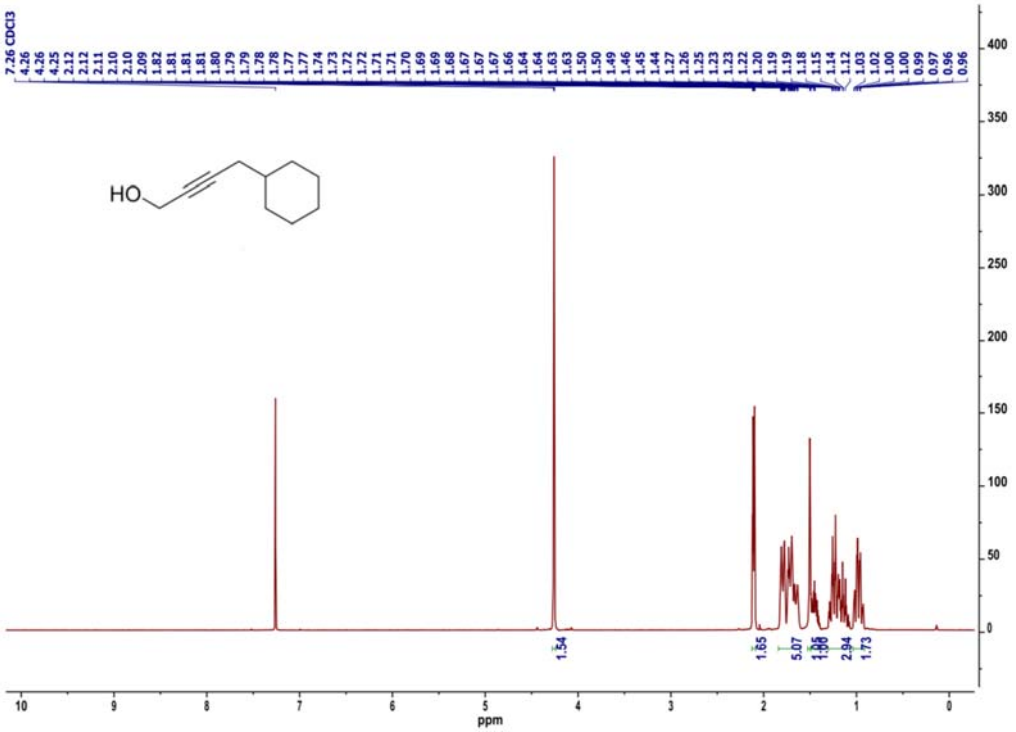
^{1}H NMR of compound **V**.



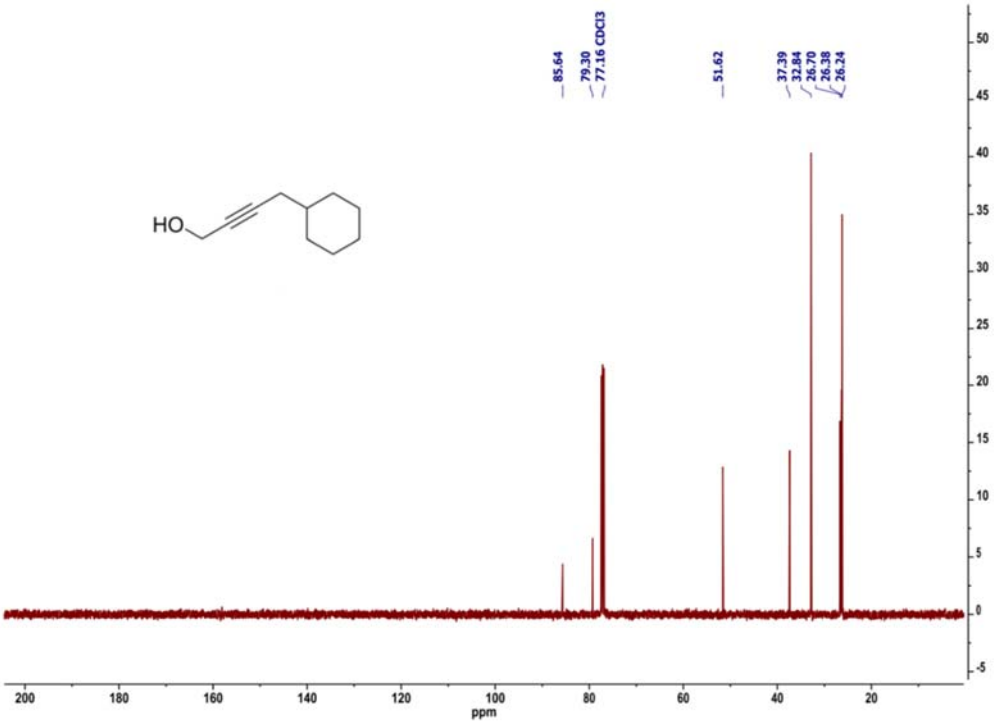
^{13}C NMR of compound **V**.



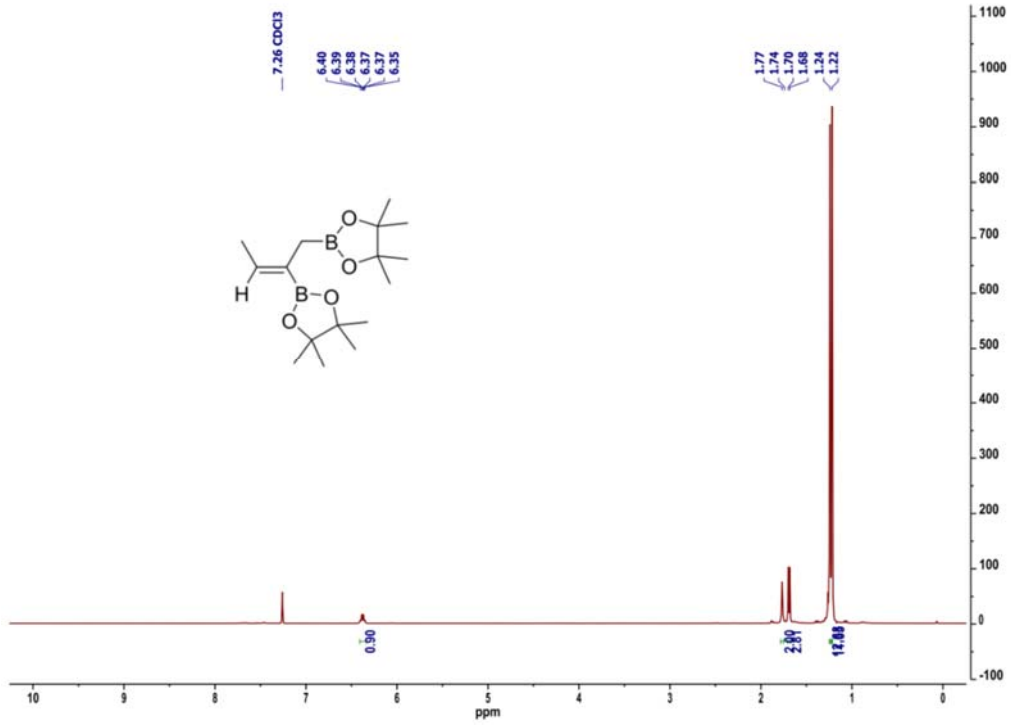
^{1}H NMR of compound **1d**.



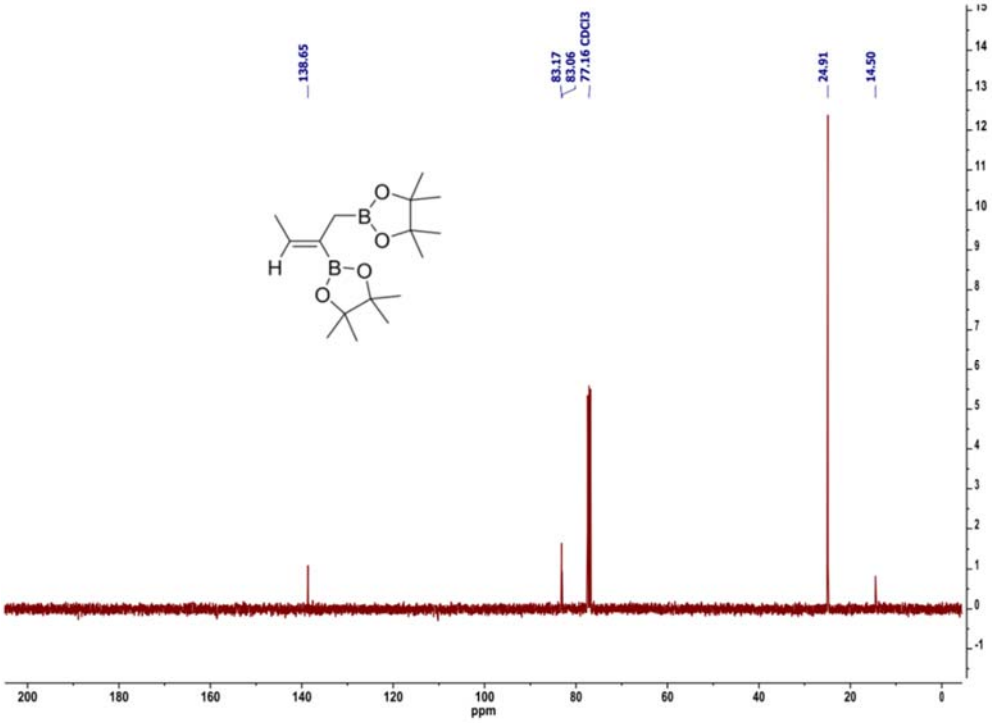
^{13}C NMR of compound **1d**.



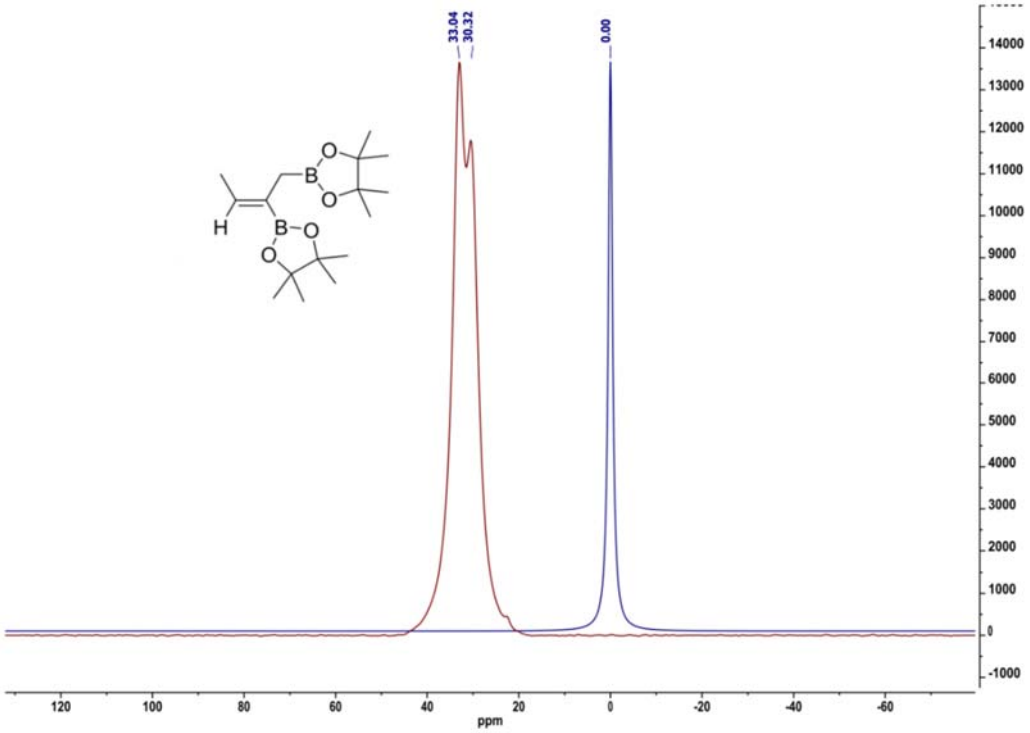
^{1}H NMR of compound **2a**.



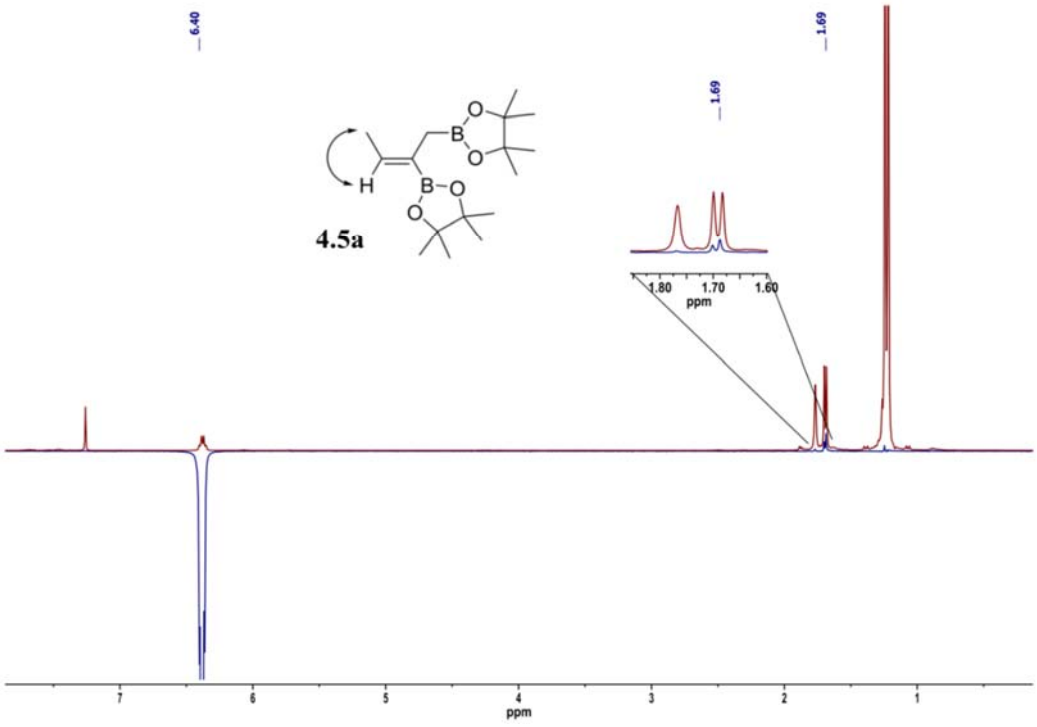
^{13}C NMR of compound **2a**.



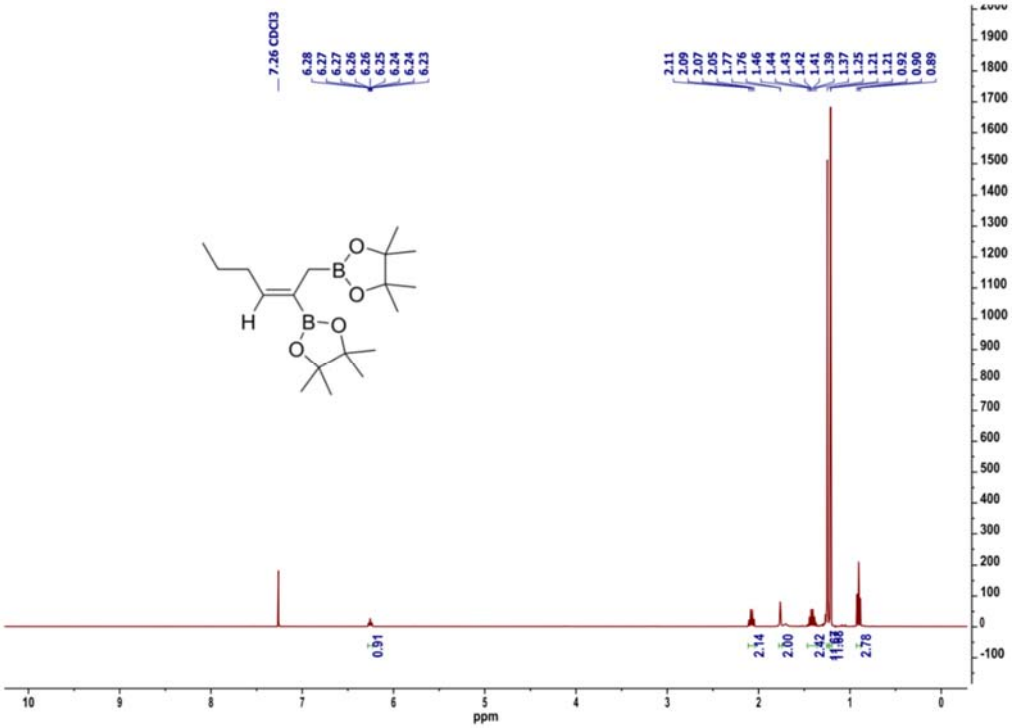
^{11}B NMR of compound **2a**.



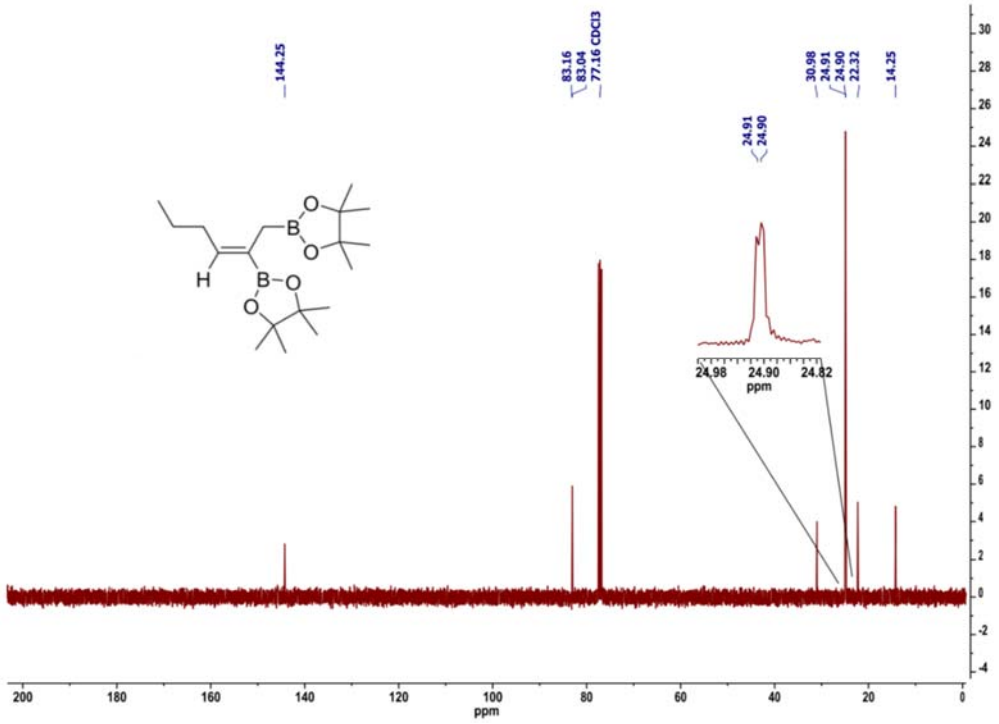
NOESY ^{1}H NMR of compound **2a**.



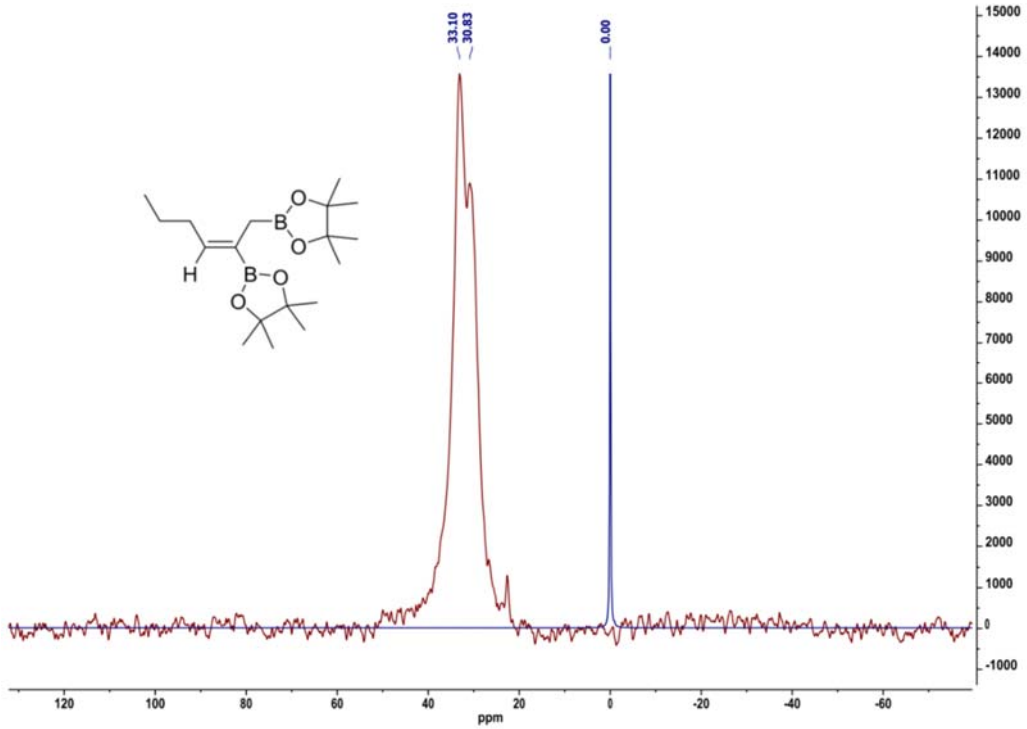
^{1}H NMR of compound **2b**.



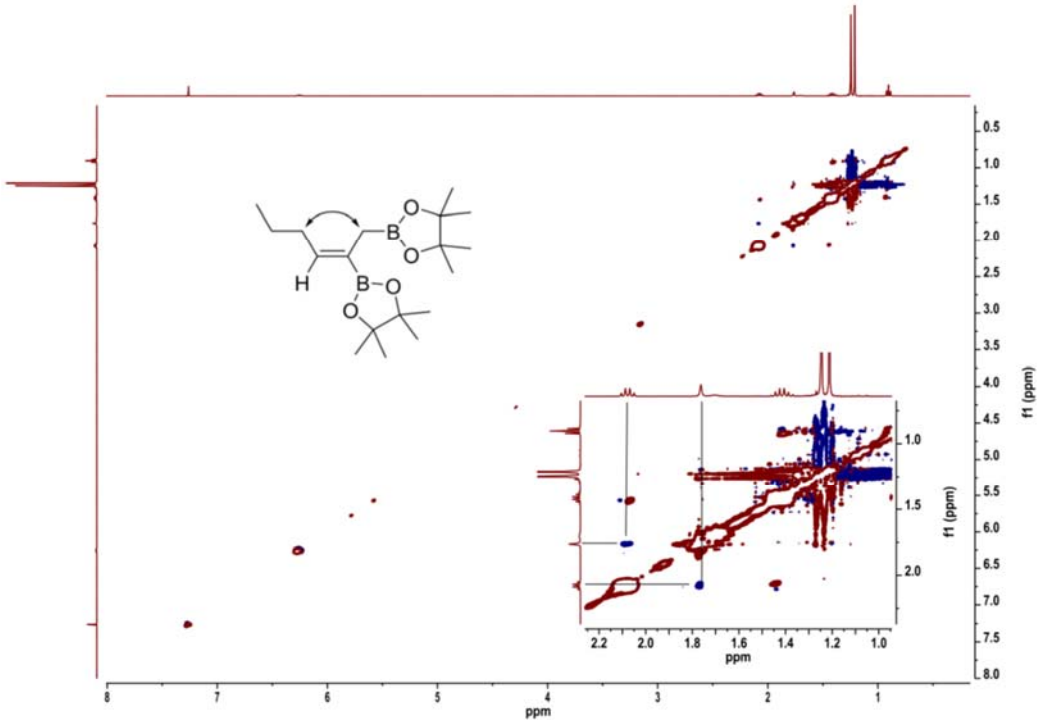
^{13}C NMR of compound **2b**.



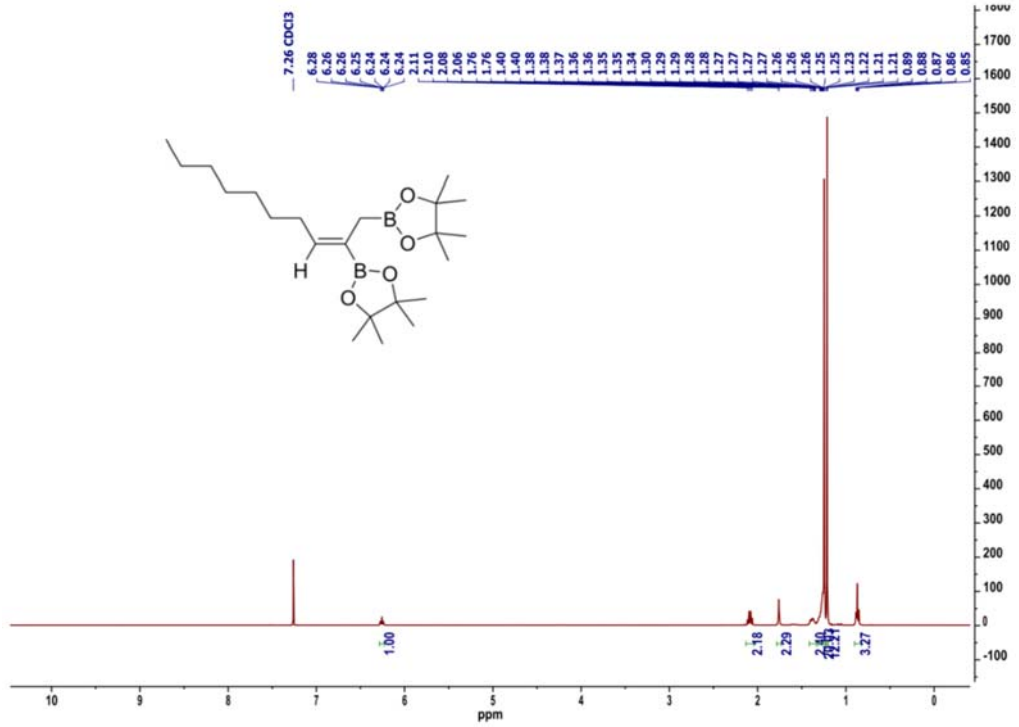
^{11}B NMR of compound **2b**.



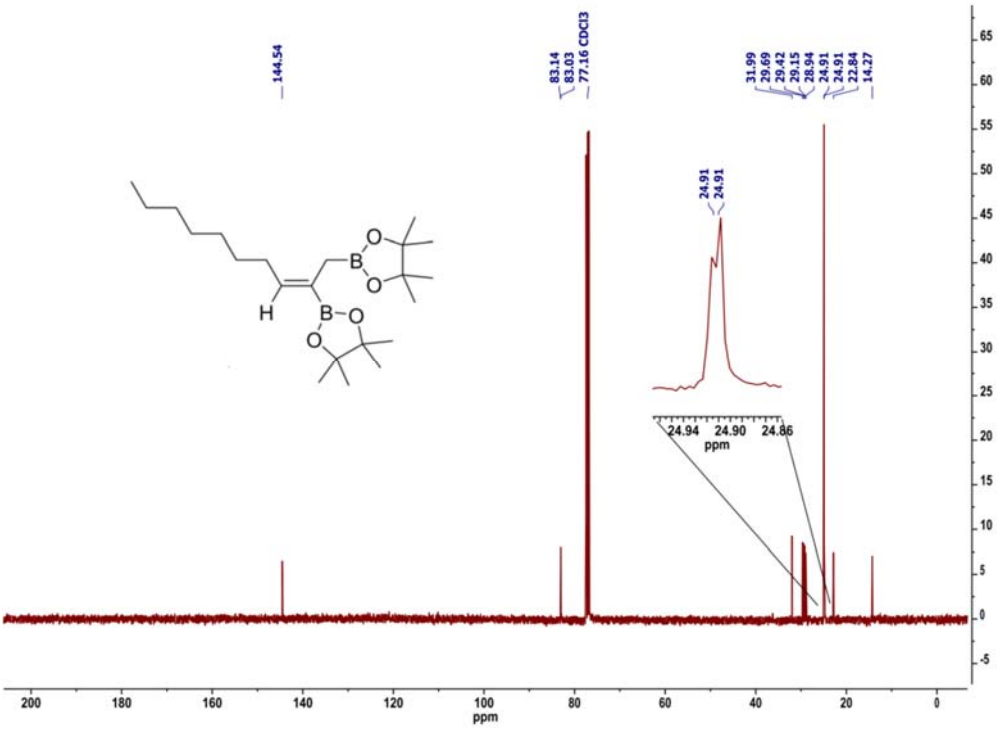
2D ^{1}H NOESY NMR of compound **2b**.



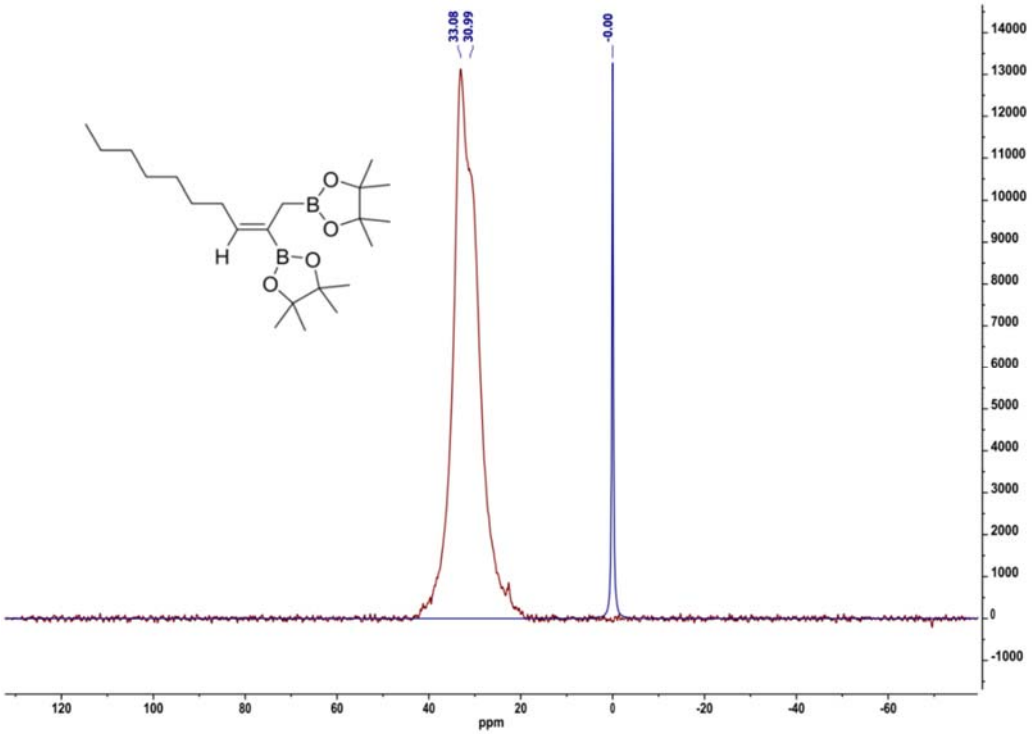
^{1}H NMR of compound **2c**.



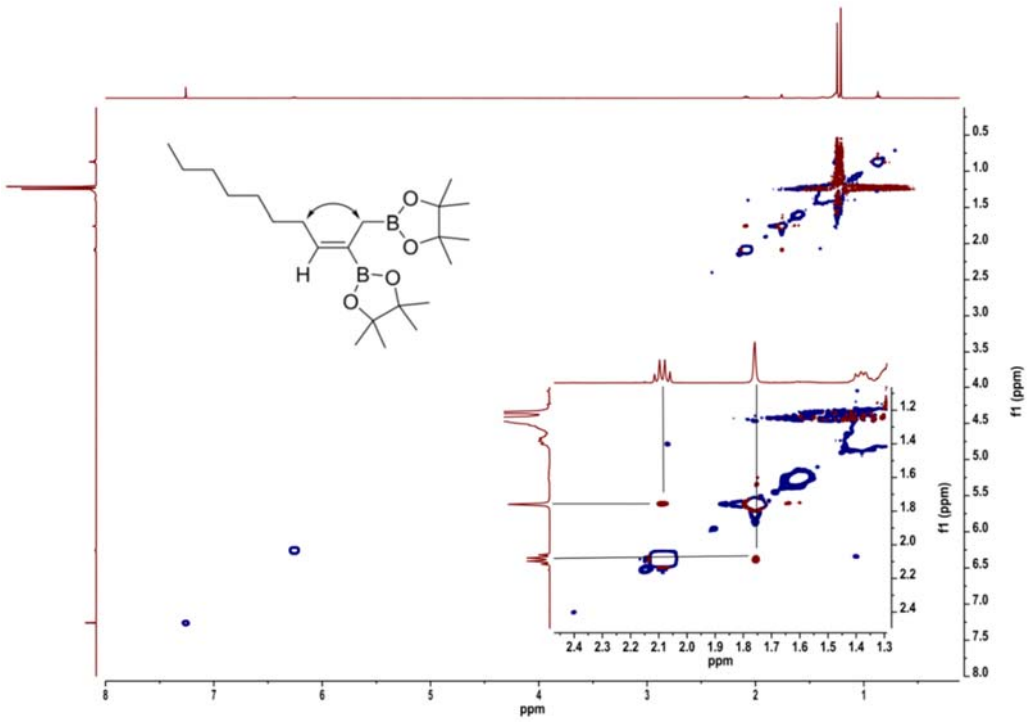
^{13}C NMR of compound **2c**.



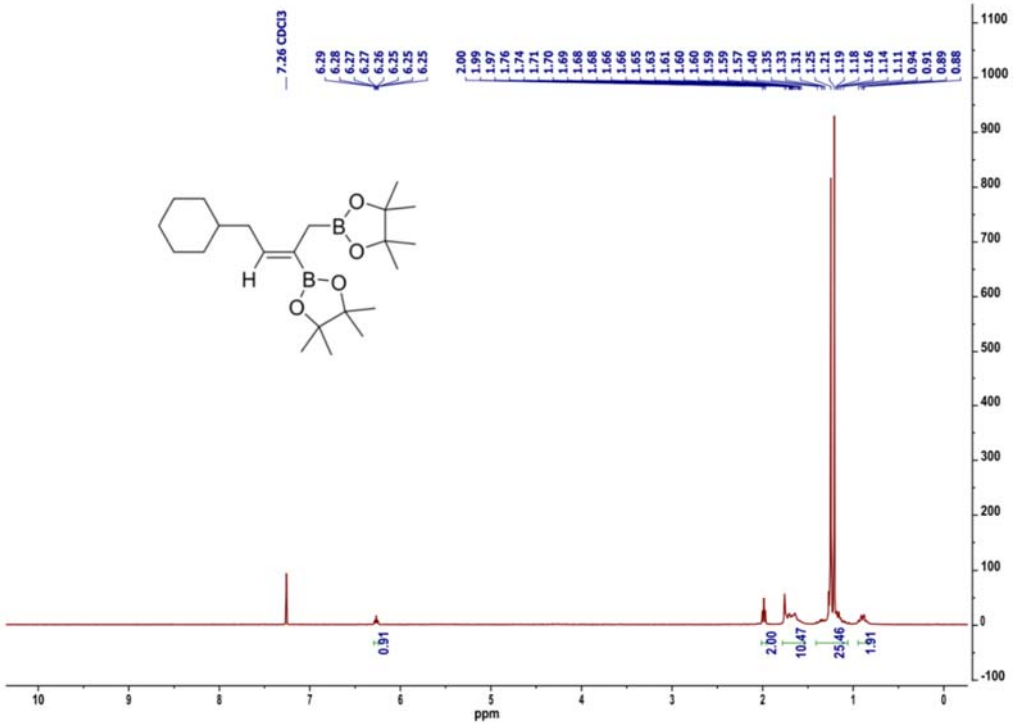
^{11}B NMR of compound **2c**.



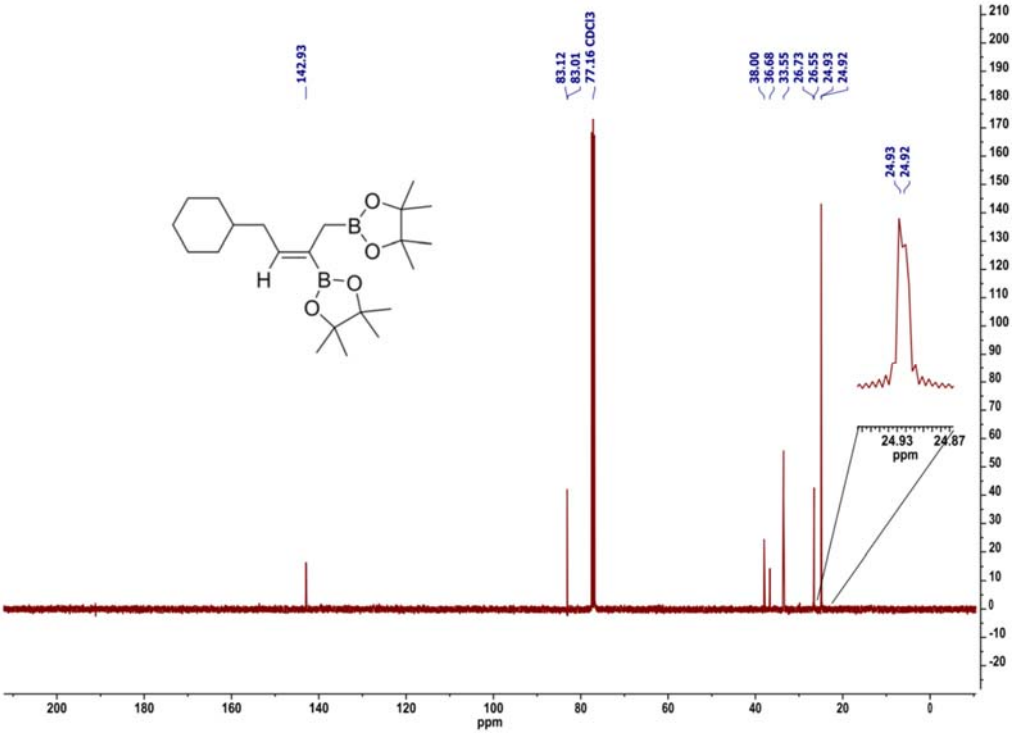
2D NOESY ^{1}H NMR of compound **2c**.



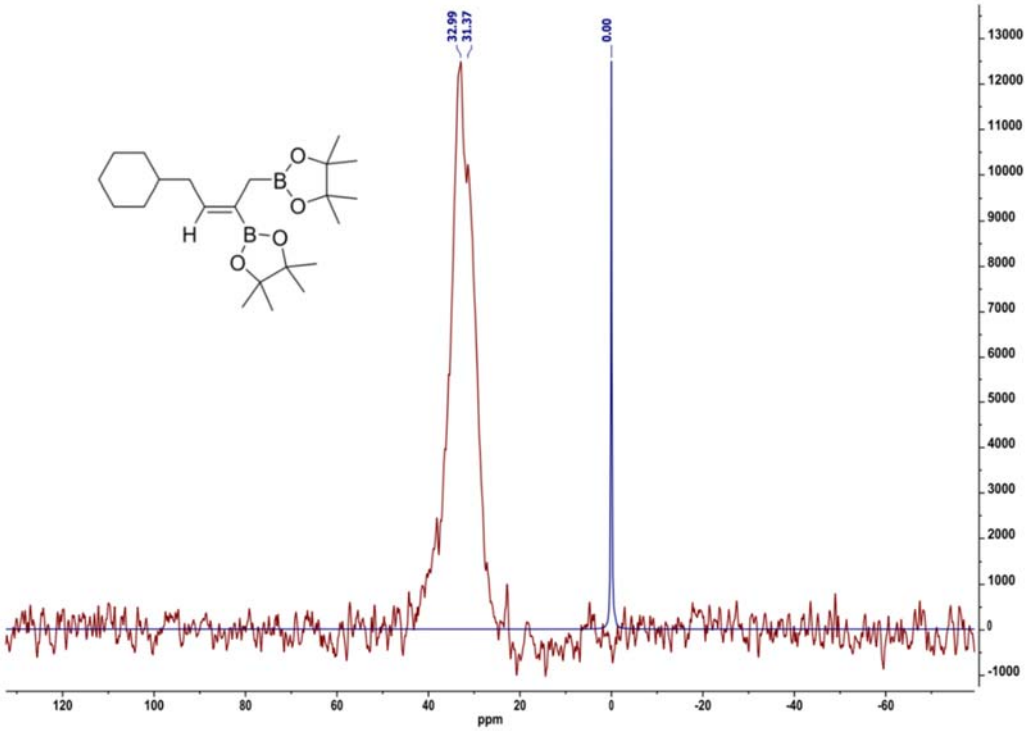
^{1}H NMR of compound **2d**.



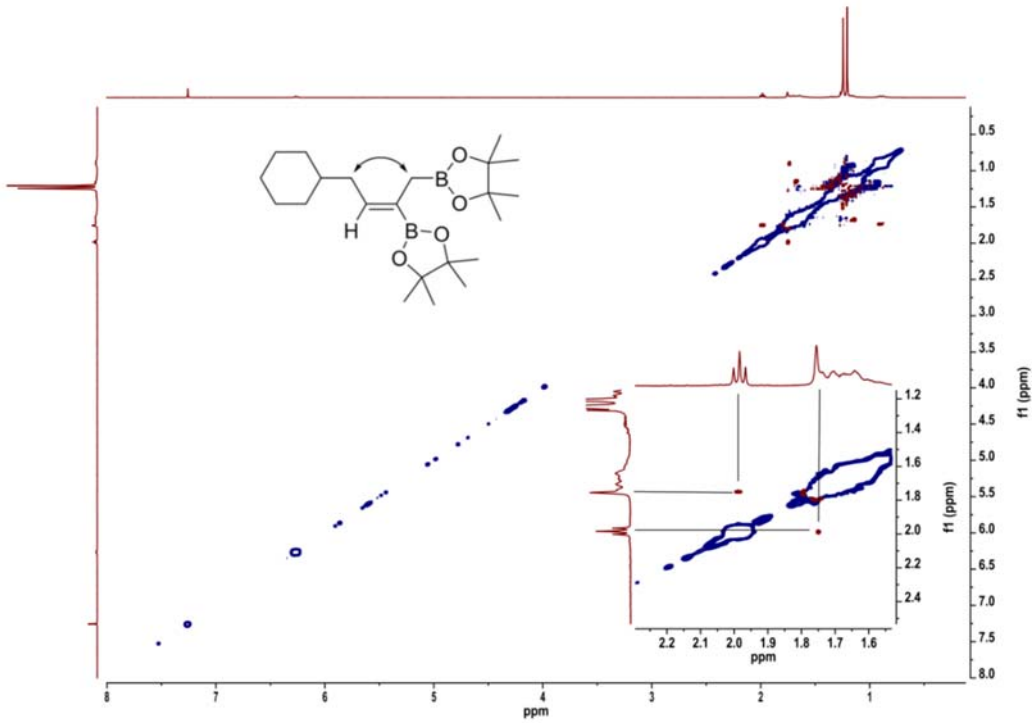
^{13}C NMR of compound **2d**.



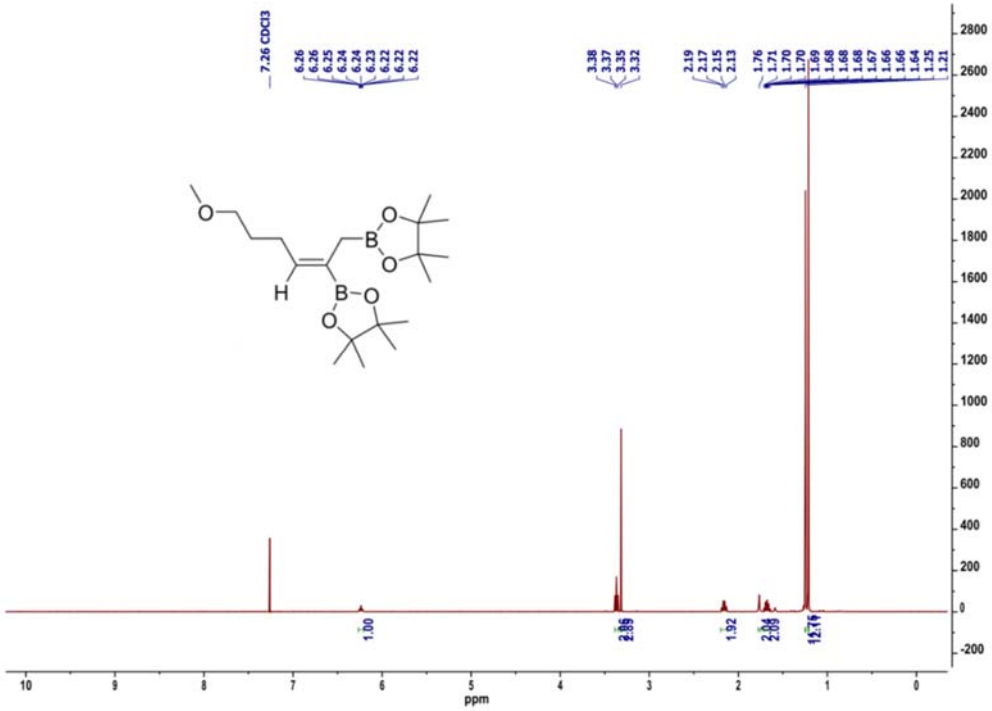
^{11}B NMR of compound **2d**.



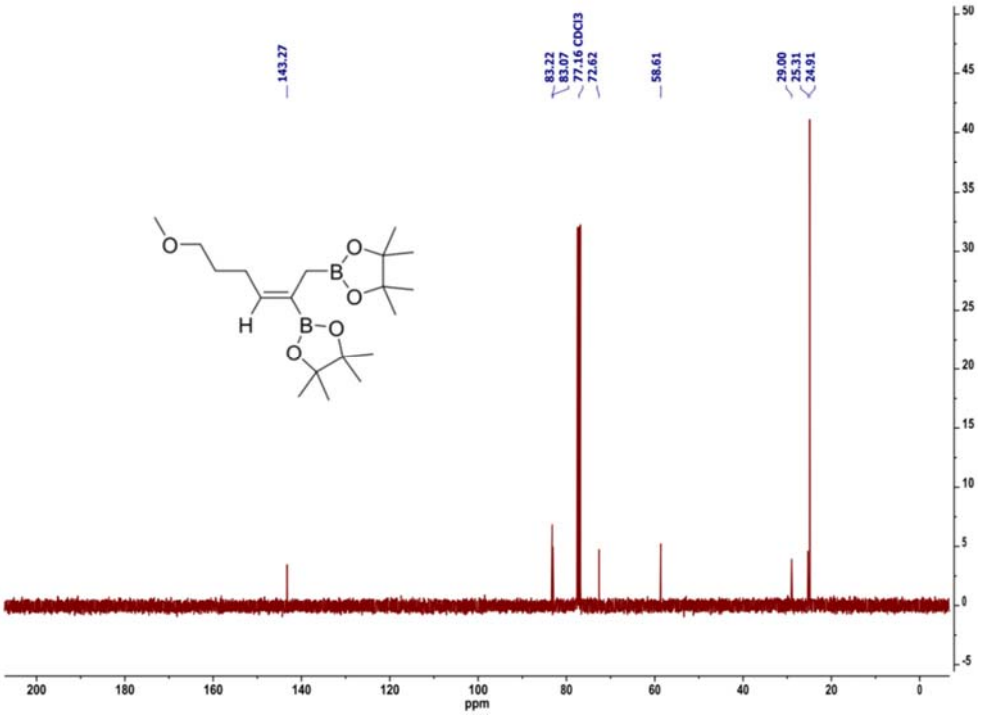
2D NOESY ^{1}H NMR of compound **2d**.



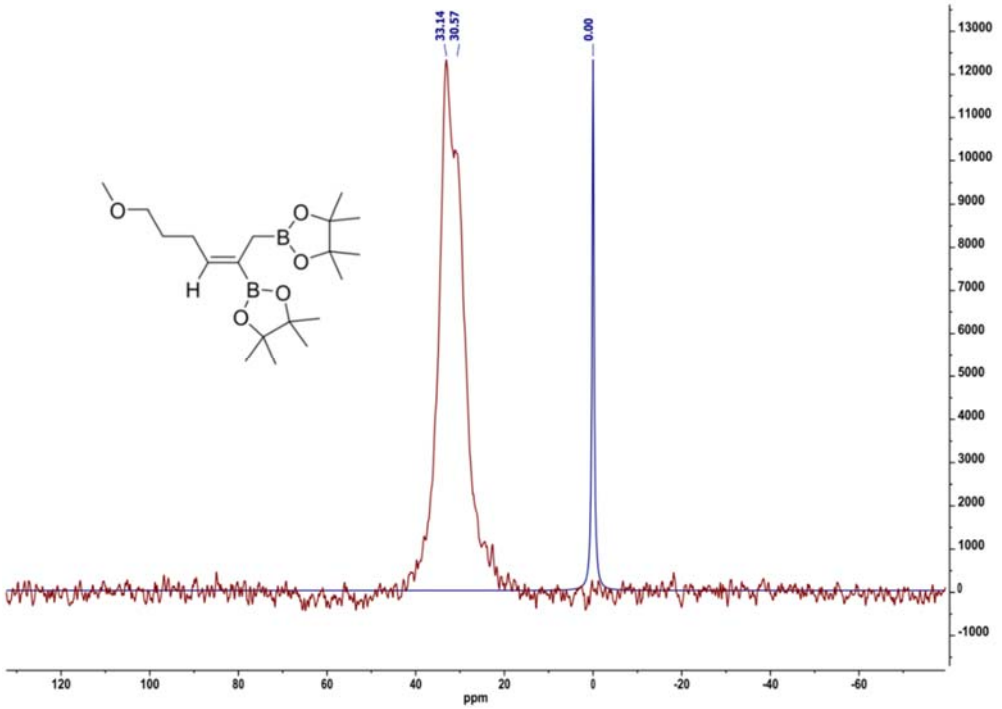
^{1}H NMR of compound **2e**.



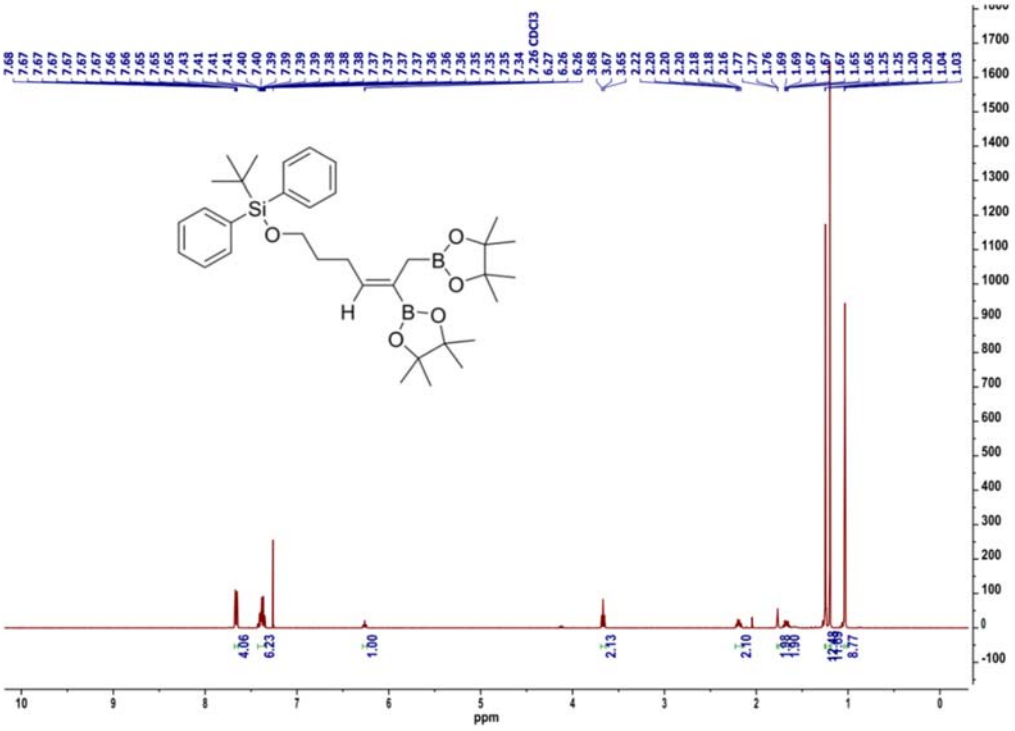
^{13}C NMR of compound **2e**.



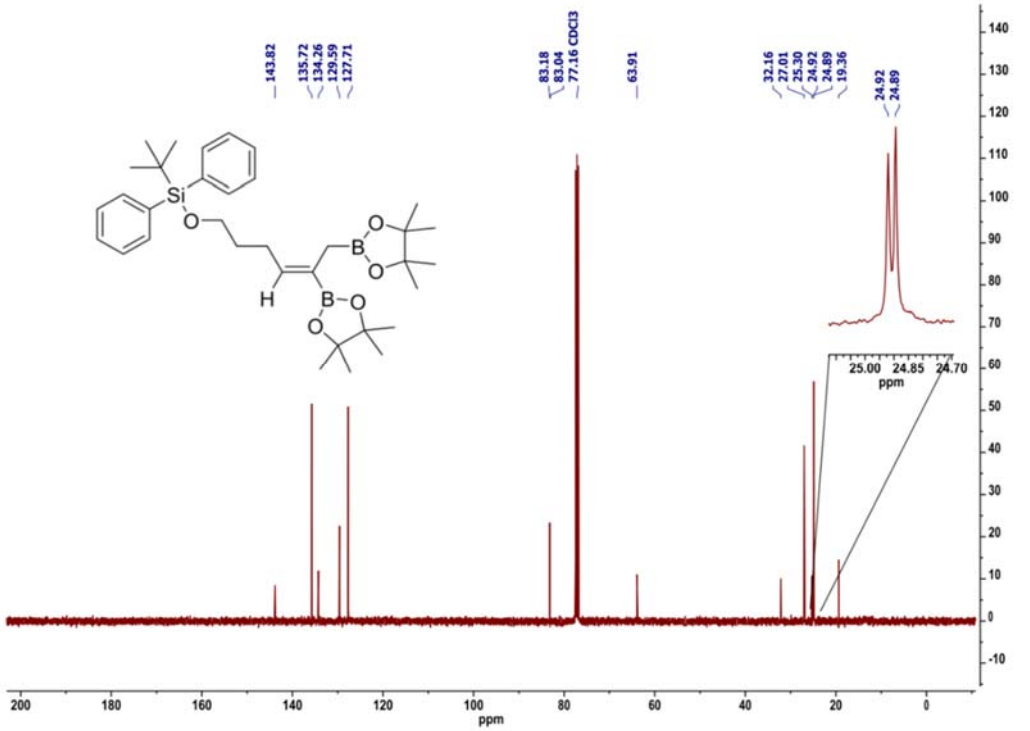
^{11}B NMR of compound **2e**.



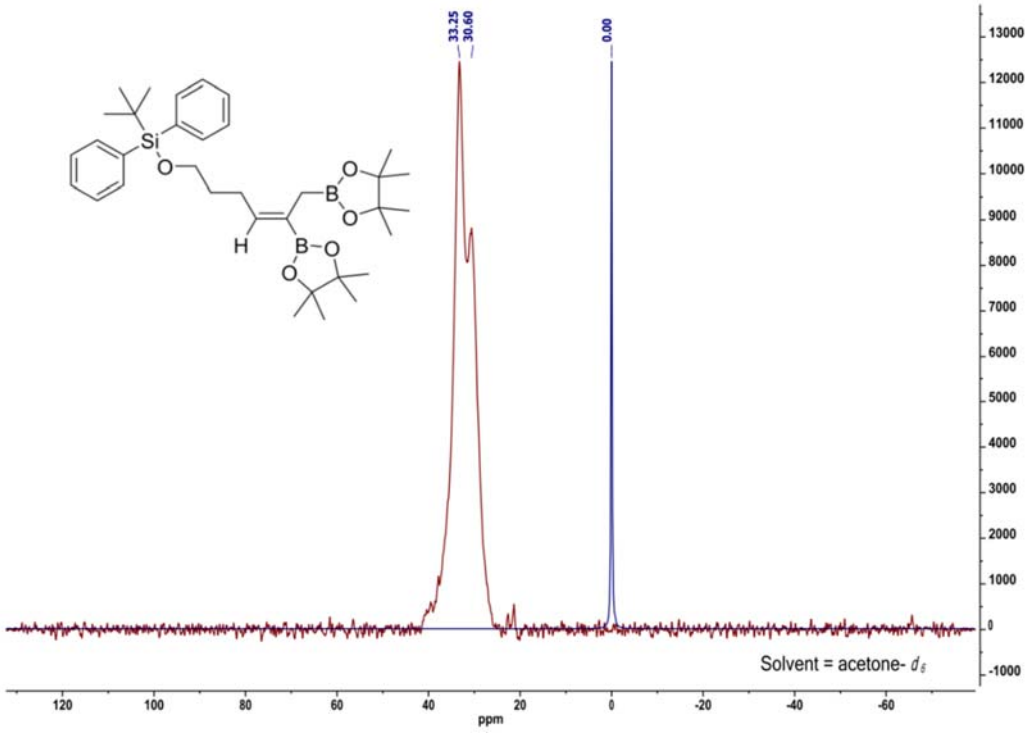
^{1}H NMR of compound **2f**.



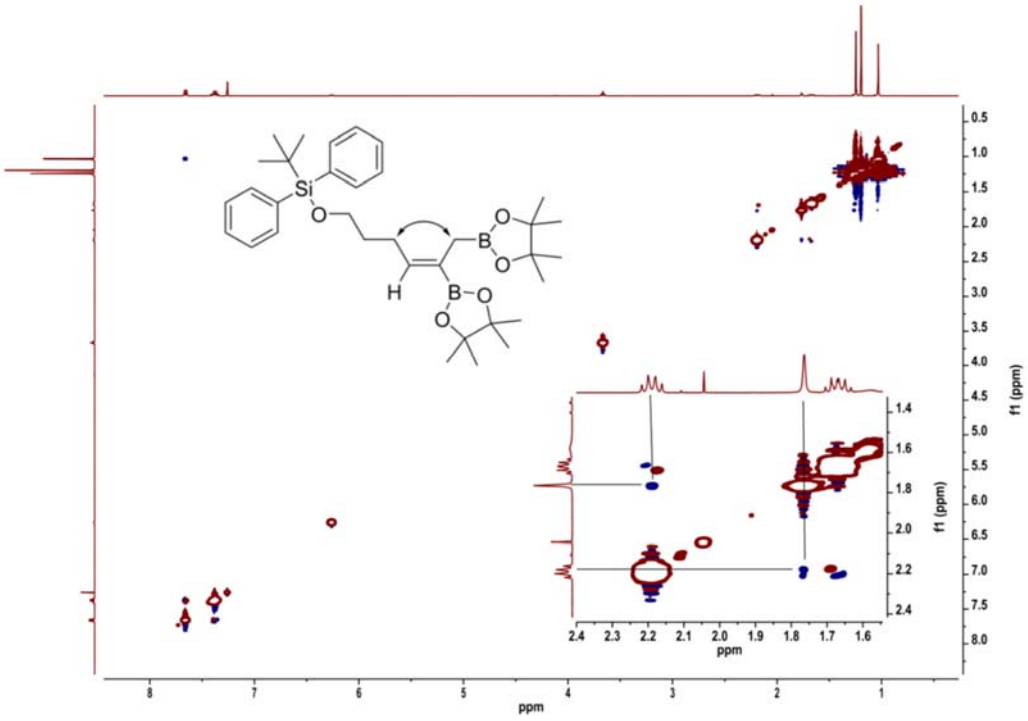
^{13}C NMR of compound **2f**.



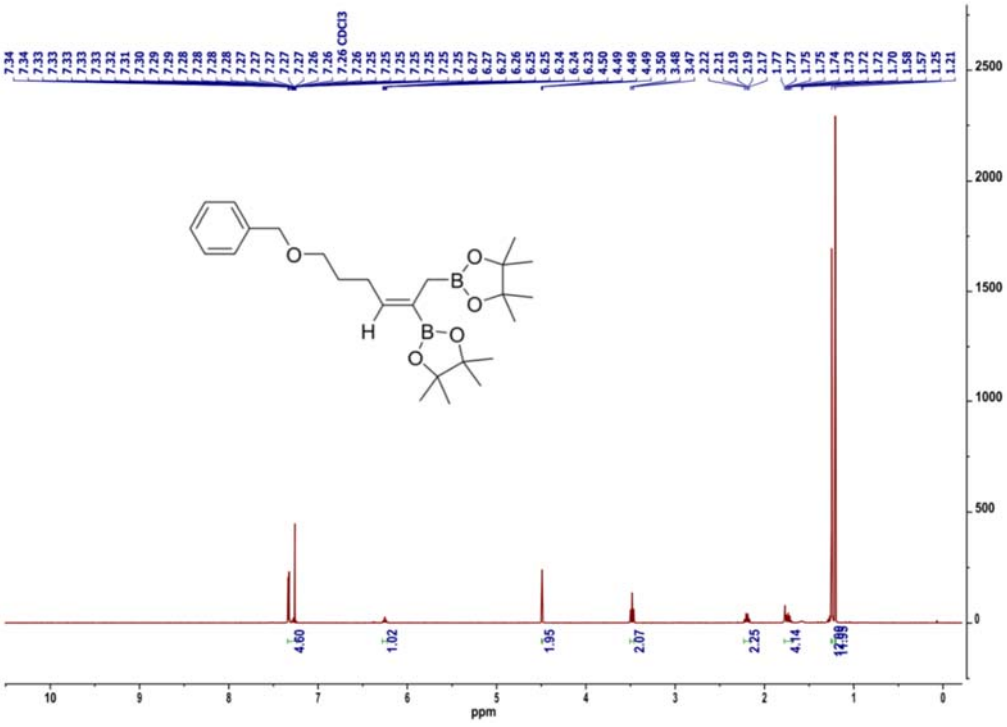
^{11}B NMR of compound **2f**.



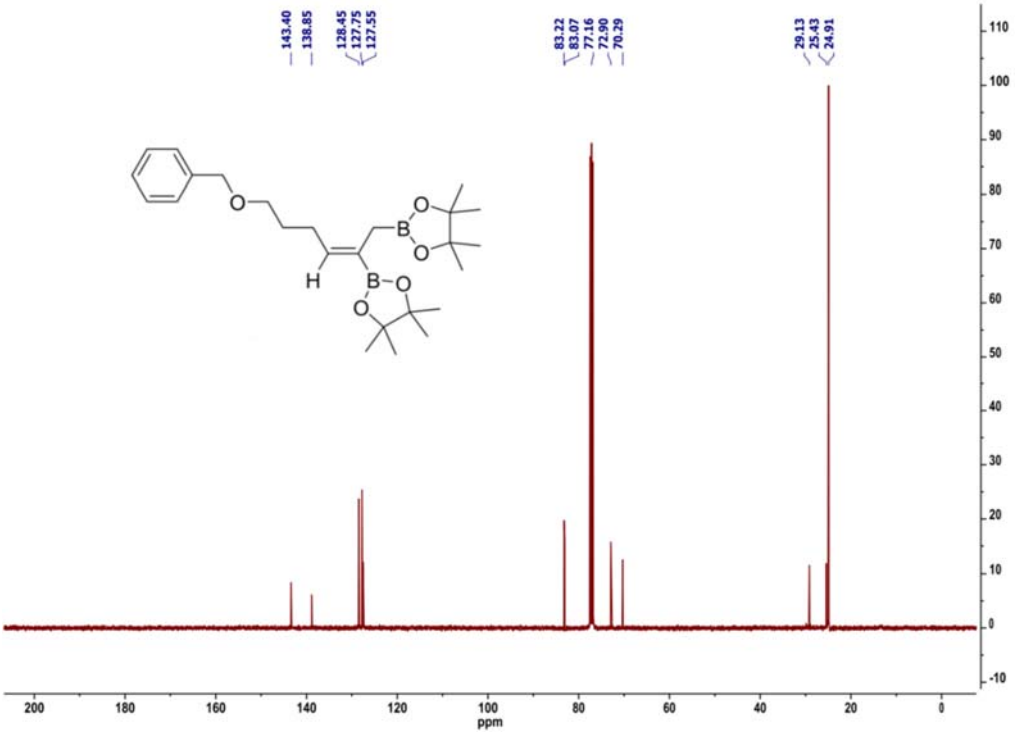
2D NOESY ^{1}H NMR of compound **2f**.



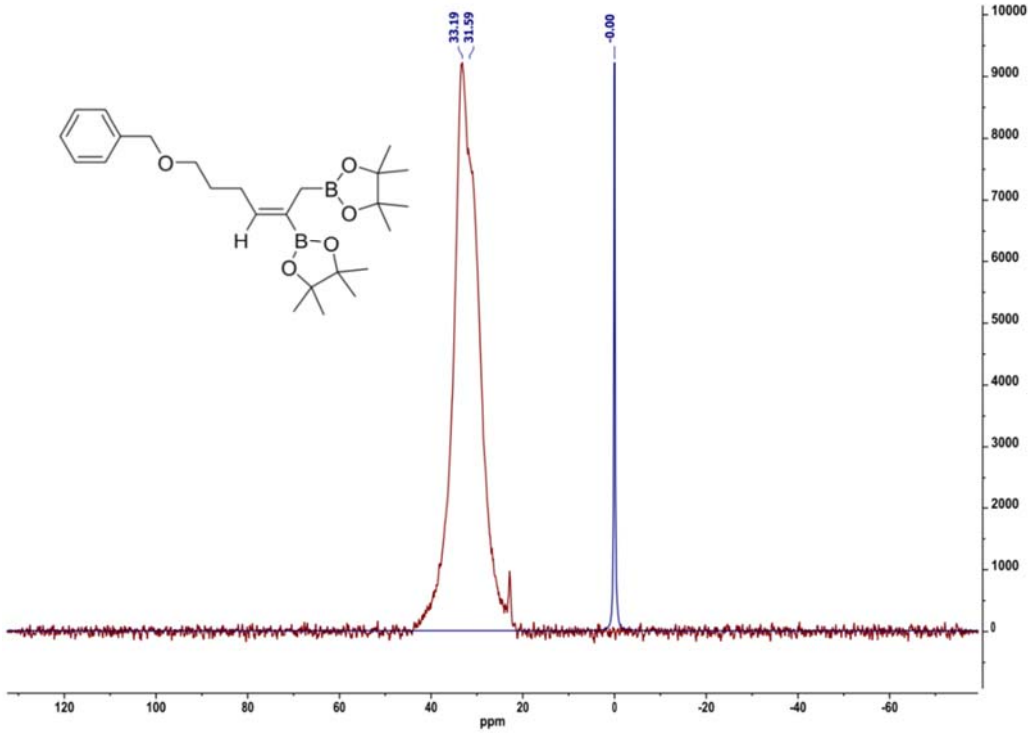
^{1}H NMR of compound **2g**.



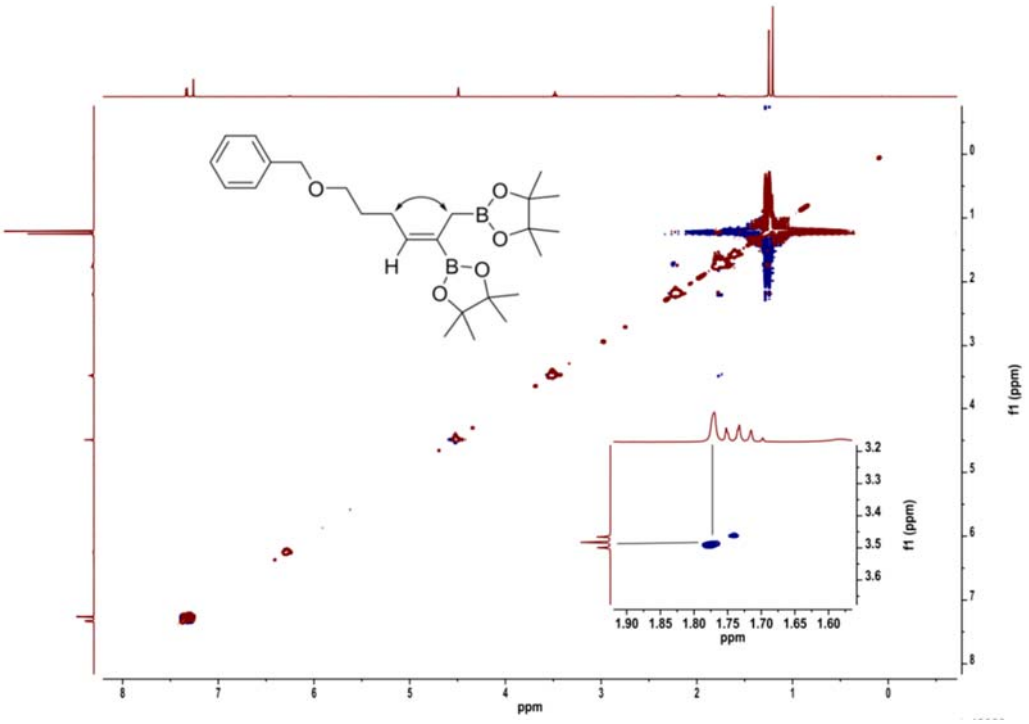
^{13}C NMR of compound **2g**.



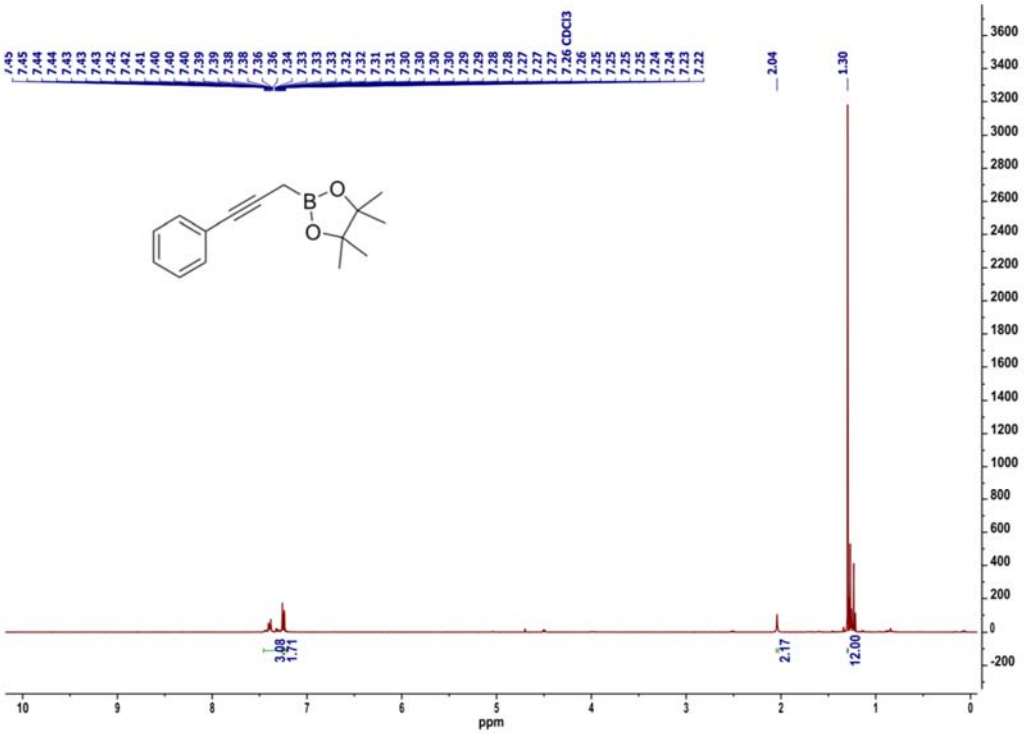
^{11}B NMR of compound **2g**.



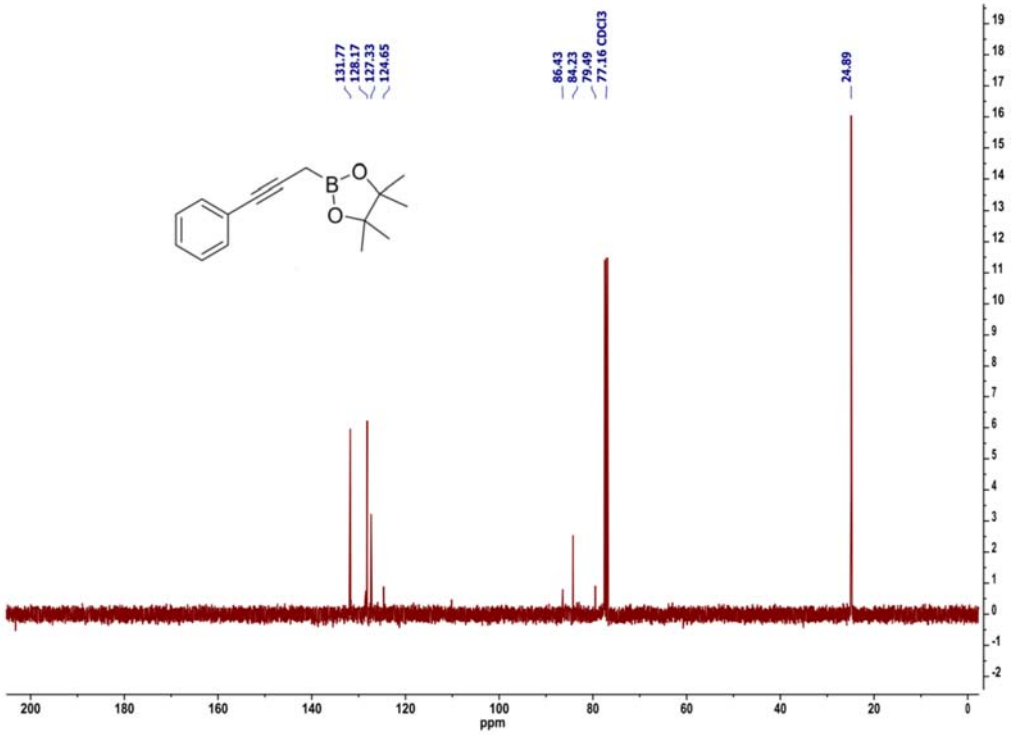
2D NOESY ^{1}H NMR of compound **2g**.



^{1}H NMR of compound **6**.



^{13}C NMR of compound **6**.



^{11}B NMR of compound **6**.