SYNTHESIS AND REACTIONS OF

HETEROSUBSTITUTED N-HETEROCYCLIC CARBENE-BORANES

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SYNTHESIS AND REACTIONS OF

HETEROSUBSTITUTED N-HETEROCYCLIC CARBENE-BORANES

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Carbene-boranes 1,3-bis-(2,6-diisopropylphenyl)imidazol-2-ylidene borane (dipp-Imd-BH_3) and 1,3-dimethylimidazol-2-ylidene borane (diMe-Imd-BH_3) were treated with various electrophiles to compare reactivity of carbene-borane with nucleophilicity values of carbene-borane (dipp-Imd-BH_3 = 9.55 *N*, diMe-Imd-BH_3 = 11.88 *N*). Compounds with electrophilicity values greater –15 *E* reacted rapidly with carbene-borane, but compounds with electrophilicity values less than –15 *E* reacted slowly or not at all with carbene-borane. Hydroboration complexes were isolated from the reactions of diMe-Imd-BH_3 with benzylidenemalononitrile and 2-ethylidenemalononitrile. Overall the reactivity of carbene-borane matched predictions based on nucleophilicity and electrophilicity values.

Carbene-boranes were also treated with acid halides and halogens to form halogenated carbene-boranes. Iodination occurs most rapidly followed by bromination and then chlorination. Dipp-Imd-BH_3 can only be iodinated once likely due to the steric bulk around the boron atom while diMe-Imd-BH_3 can be iodinated once (0.5 equiv of I_2 added) or twice (1.0 equiv of I_2 added). Tribromination and trichlorination was possible for both carbene-boranes. Disproportionation of the halides bonded to the boron atoms occurred rapidly with iodide and slowly with bromide. These halogenated carbene-boranes also were reduced by lithium aluminum deuteride to give selectively deuterated carbene-borane species, and also underwent nucleophilic substitutions to give carbene-boryl-azide.

[3+2]-Dipolar cycloaddition reactions were performed on carbene-boryl-azide with electron deficient alkynes, alkenes, and nitriles to give new carbene-boryl-triazoles, -triazolidines, and -tetrazoles. Electron deficient alkynes and alkenes such as propiolate and acrylate were reactive with carbene-boryl-azide even at room temperature, but less electron deficient alkynes, nitriles, and alkenes required heating or microwave radiation to form cycloaddition borane products.

Carbene-boryl-triazoles are very robust and can withstand reductive and acidic conditions. The triazole can even be methylated by methyl iodide or methyl triflate to give a carbene-boryl-triazole salt. The triazole could be detached from the boron atom by reacting the boron atom with halogen, and decomplexing the carbene-borane in methanol.

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LIST OF ABBREVIATIONS

AIBN	azobisisobutyronitrile
arom.	aromatic
br s	broad singlet
d	doublet
DBAD	dibenzyl azodicarboxylate
DCM	dichloromethane
DEAD	diethyl azodicarboxylate
DIEA	N, N-diisopropylethylamine
diMe	dimethyl
DMS	dimethylsulfide
DMSO	dimethylsulfoxide
dipp	diisopropylphenyl
E	electrophilicity
ESI	electrospray ionization
Et	ethyl
eq	equation
equiv	equivalent(s)
h	hour
HRMS	high resolution mass spectrometry
Hz	hertz
IR	infrared
LAD	lithium aluminum deuteride
Me	methyl
MeCN	acetonitrile
mg	milligram(s)
MHz	megahertz
min	minute
mmol	millimole(s)
mp	melting point
N	nucleophilicity
NBS	N-bromosuccinimide
NMR	nuclear magnetic resonance
PhH	benzene
pin	pinacolato
PhMe	toluene
ppm	part per million

q	quartet
quant	quantitative (yield)
RAFT	Reversible Addition-Fragmentation chain Transfer
rt	room temperature
t	triplet
Tf	triflate
THF	tetrahydrofuran
TLC	thin layer chromoatography
TMS	tetramethyl sulfide
Tos	tosyl
UV	ultraviolet

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1.0 INTRODUCTION

1.1 BORANES

Boranes have a wide variety of uses in organic synthesis as catalysts and as reducing agents. The simplest borane, diborane (B_2H_6), has been used in hydroborations[1,2] and reductions,[3-5] but diborane is a pyrophoric gas that is difficult to handle. Dimethylsulfide-borane complex (DMS-BH_3) and tetrahydrofuran-borane complex (THF-BH_3) are today's preferred sources of borane (**Figure 1**). These borane complexes are commercially available in solution and are easier to handle than diborane. DMS-BH_3 and THF-BH_3 are also used for hydroboration reactions[6] and reductions[7,8] by acting as the equivalent of free borane. Even though borane is easily accessible from these complexes, the release of malodorous dimethyl sulfide from DMS-BH_3 and the instability of THF-BH_3 are disadvantageous for some applications.

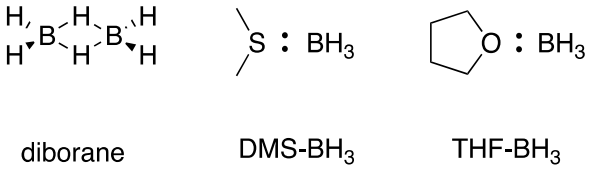


Figure 1. Common borane sources

Amine-boranes (**Figure 2**) are a class of borane complexes that are more stable than DMS-BH_3 or THF-BH_3, but amine-boranes can still serve as a source of free borane or perform other borane chemistry. Free borane can be released from amine-boranes by decomplexation

through amine exchange, acid addition, or heating.[9] Amine-boranes are often synthesized by Lewis base exchange with DMS-BH_3 or THF-BH_3,[9] but amine-boranes have also been made by treating an amine with sodium borohydride and iodine.[10] Amine-boranes have been used for hydroborations by acting as the source of borane instead of DMS-BH_3 or THF-BH_3.[11] Amine-boranes have also been used for reductive aminations[12] and reduction of ketones.[13] The borane can also sometimes function as a protecting group on an amine by masking the nucleophilicity of the amine.[14]

Similar to amines, phosphines complex with boranes to form phosphine-boranes, but unlike amine-boranes, phosphine-boranes do not act as a source of free borane (**Figure 2**). Work with phosphine-boranes, however, is often focused on phosphine rather than borane. As with amine-boranes, phosphine-boranes can be made by phosphine exchange with DMS-BH_3 or THF-BH_3[9] or by reaction of phosphines with sodium borohydride and a proton source.[10,15] Borane complexation can protect the phosphine from oxidation[16] and activate the phosphine P–H bond for hydrophosphination,[17] but the borane of phosphine-borane complexes is rarely used in reductions.[18] Decomplexation of phosphine-boranes is more difficult than amine-boranes, possibly due to greater basicity of the alkylated phosphorus center that leads to a stronger boron-phosphorus bond.[9] Decomplexation can be achieved, however, by secondary amine exchange, addition of strong acids, or by halogen exchange with the borane followed by hydrolysis.[9]

Figure 2. Amine-boranes and phosphine-boranes

The newest class of borane-complex is carbene-boranes, which are formed by complexing borane with another Lewis base: N-heterocyclic carbene. The unusual electronics of carbenes influences the unique chemistry of carbene-boranes.

Carbenes are neutral, divalent carbon compounds with only six valence electrons on an sp^2 hybridized carbon atom. The sp^2 orbital involved with carbene chemistry is referred to as the σ orbital, and the p orbital is referred to as the p_π orbital. Carbenes can exist in triplet or singlet ground states. In the triplet state, the σ and p_π orbitals are close in energy so one of the two non-bonded electrons is located in each orbital. A carbene in the singlet state, however, has a larger energy gap between the σ and p_π orbitals, and therefore the carbene has two electrons in the σ orbital and no electrons in the p_π orbital. N-heterocyclic carbenes have a singlet ground state because the lone pairs of electrons on the adjacent nitrogen atoms in the heterocyclic ring donate electron density to the empty p_π orbital of the carbene carbon, increasing the σ–p_π energy gap. This π electron density donation results in the stabilization of N-heterocyclic carbenes (**Figure 3**).[19]

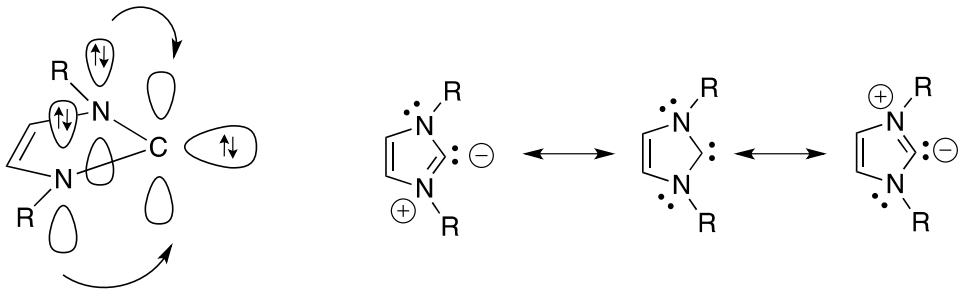


Figure 3. Structures and resonance of N-heterocyclic carbenes by donation of free electrons on nitrogen

Although most classes of carbenes are short lived, N-heterocyclic carbenes are often stable enough to be isolated and crystallized. Arduengo and coworkers isolated and characterized by X-ray crystallographic analysis the first stable N-heterocyclic carbene, 1,3-bis(adamantyl)-

imidazol-2-ylidene **1**, in 1991 (**Figure 4**).[20] Arduengo also reported synthesis and characterization of less sterically hindered stable carbenes including 1,3-dimethylimidazol-2-ylidene (hereafter diMe-Imd or **2**),[21] and the remarkably stable 1,3-bis-(2,6-diisopropylphenyl) imidizol-2-ylidene (hereafter, dipp-Imd or **3**).[22]

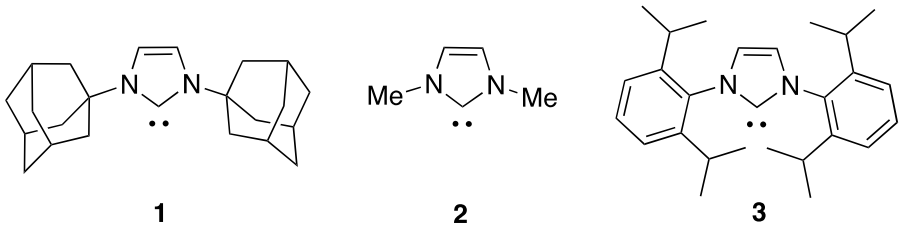


Figure 4. Select stable N-heterocyclic carbenes

Soon after their discovery, stable N-heterocyclic carbenes were complexed with boranes.[23] However, very little work on carbene-boranes appeared between 1993 and 2007. Since then, interest in the chemistry of carbene-boranes has grown quickly. In 2007 Robinson and coworkers described 1,3-bis-(2,6-diisopropylphenyl)imidazol-2-ylidene borane (dipp-Imd-BH_3, **4**) (**Figure 5**).[24,25] The lighter and less bulky 1,3-dimethylimidazol-2-ylidene borane (diMe-Imd-BH_3, **5**) was synthesized and its reactivity studied in 2010.[26,27]

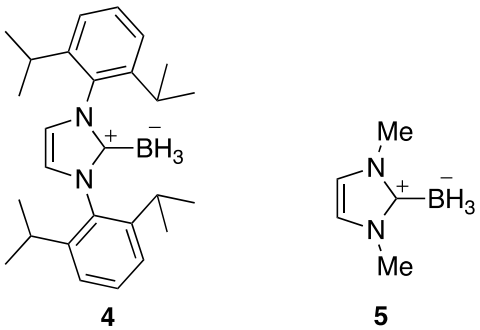


Figure 5. Select carbene-borane complexes

Carbene-boranes have a formal positive charge on the carbene carbon atom and a formal negative charge on boron, resulting in a net zero charge. To simplify structures going forward, formal charges on the carbene-carbon and on boron will be dropped. Also the 2,6-diisopropylphenyl groups will be represented by dipp (**Figure 6**).

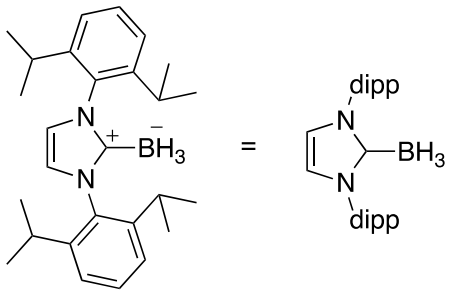
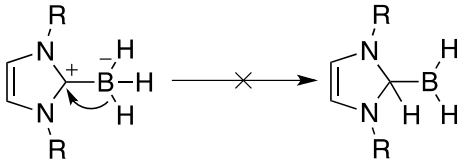


Figure 6. Abbreviation of 2,6-diisopropylphenyl on N-heterocyclic carbene and dropping of formal charges.

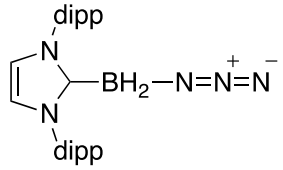
Many carbene-boranes, including **4** and **5**, are stable in ambient air at room temperature. They are also not sensitive to water. Similar to phosphine-boranes, carbene-boranes have unique chemistry and are not a source of free borane.[28] Although the partially positive carbene-carbon seems to be in position to be reduced by a 1,2-hydride shift from the negative boron, this reduction is not observed because the empty p_π of the carbene is a poor π-acceptor due in part to stabilization from the adjacent nitrogen in the imidazole ring (**Scheme 1**).[28]



Scheme 1. Hypothetical self-reduction of carbene-borane

A recent study of reactions of dipp-Imd-BH_3 **4** involved substitutions on the boron atom bearing halide and sulfonate ions.[29] A boryl-azide was synthesized by substitution reactions of

dipp-NHC-BH_2X (where X is triflate, iodide, or mesylate) with sodium azide. The resulting compound, dipp-NHC-BH_2N_3 **6** (**Figure 7**), was easily purified by flash chromatography and very stable toward hydrolysis and thermal conditions. Carbene-boryl-azide **6** is the first stable boryl-azide known. Its stability came as a surprise because azides are often reduced by boranes.[30] The chemistry of borane-azides like **6** is mostly unknown, and our goal is to begin to understand its reactivity in cycloadditions.



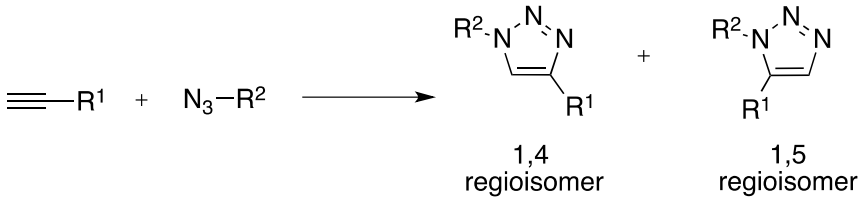
6

Figure 7. Carbene-boryl-azide

1.2 [3 + 2] CYCLOADDITIONS OF AZIDES AND ALKYNES

Azide-alkyne cycloadditions are efficient reactions that have become popular in the last decade especially in medicinal chemistry, biochemistry, and polymer science.[31-33] Huisgen and coworkers were first to demonstrate 1,3-dipolar cycloadditions in 1967 by heating organo-azides with dipolarophiles such as alkynes and alkenes,[34] therefore this type of reaction is known as a Huisgen cycloaddition. Selectivity is often poor with azide/alkyne cycloadditions under thermal conditions, yielding both 1,4- and 1,5-regioisomers of 1,2,3-triazoles (**Scheme 2**). In 2002, Meldal and Sharpless discovered that the use of copper (I) salts greatly increased the reaction rate and directed the 1,4 selectivity of the triazole.[35,36]

Some Huisgen cycloadditions fit in the selective group of reactions known as "click chemistry."[33] According to Sharpless and coworkers a click reaction must give very high yields, produce only byproducts that can be removed by non-chromatographic methods, be stereospecific, use readily available starting materials, give products that are isolated simply, and use no solvent or only solvents that can be easily removed.[37] These criteria are met by many Huisgen cycloaddition reactions, and also by other reactions such as Diels-Alder and ring-opening reactions by nucleophilic substitution.

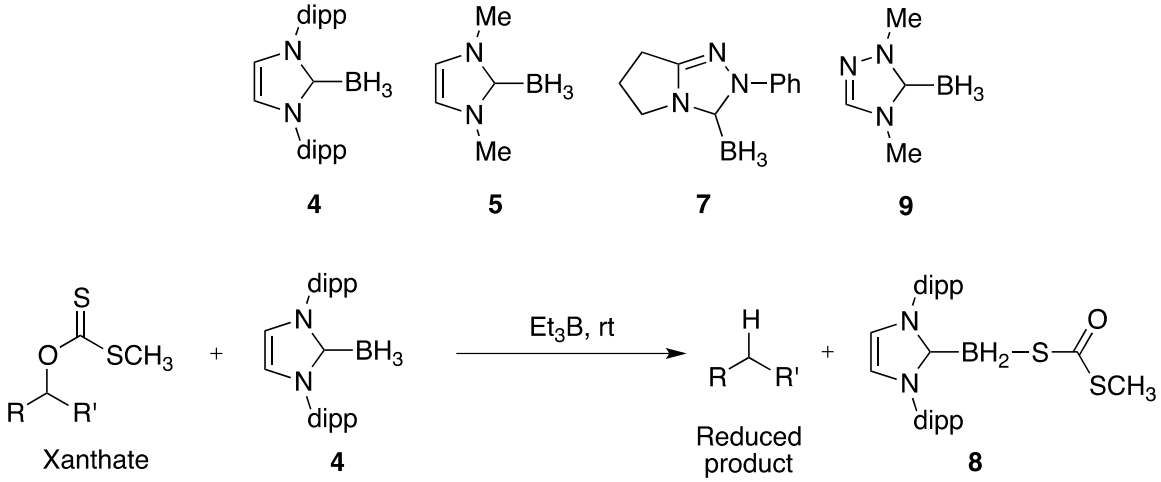


Scheme 2. Huisgen cycloadditions of azides with alkynes give a mixture of 1,4- and 1,5-regioisomers under thermal conditions, and favor the 1,4-regioisomer under copper-catalyzed conditions

Even though not all Huisgen cycloadditions between azides and alkynes meet the high standards of click chemistry, they still are useful in synthesis. Cycloadditions between organo-azides (R^2 = carbon group) and alkynes are well documented, as are Huisgen cycloadditions of metal-azides (R^2 = metallic group),[38,39] but very few Huisgen cycloadditions of borane-azides (R^2 = boron group) are known.

1.3 NUCLEOPHILICITY (*N*) SCALE APPLIED TO CARBENE-BORANES

Carbene-boranes were first used as reagents for radical reactions. Reactions of carbene-boranes **4** and **7** with xanthates were initiated by AIBN or triethylborane.[27,40] The reduced product and a new carbene borane derivative, xanthate carbene-borane **8**, were recovered after purification (**Scheme 3**). Carbene-boranes **5** and **9** proved to be even more effective than **4** and **7** at reducing xanthates and related functional groups.[27]



Scheme 3. Carbene-boranes studied in reduction of xanthates (top) and reduction of secondary xanthates with carbene-borane 4 with Et_3B/air as an initiator

Ionic reductions have also been accomplished with carbene boranes **4** and **7** as demonstrated by Chu and coworkers.[41] Reduction of dodecyl iodide with **4** under thermal conditions gave the reduced product dodecane and the substituted borane product **10** in high yield (**Figure 8**). Ionic reduction of halides, tosylates, mesylates, and triflates under thermal conditions with both **4** and **7** also gave reasonable yields of the reduced product and the correspondingly substituted carbene-borane. This study suggested that carbene-boranes could be hydride donors in ionic reactions in addition to being hydrogen atom donors under radical

conditions. Many types of ionic and neutral hydride donors are already known, so we looked for a way to quickly assess the reactivity of carbene-boranes.

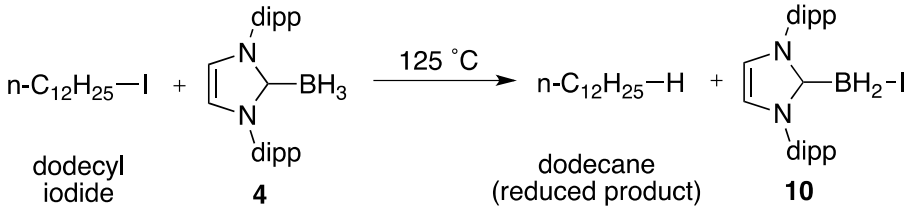


Figure 8. Ionic reduction of dodecyl iodide under thermal conditions with carbene-borane **4**

A method of quantitatively defining nucleophilicity or electrophilicity has been developed by Dr. H. Mayr and coworkers.[42] They created a scale that indicates the relative strength of nucleophiles to react with electrophiles and vice-versa.[43,44]

Electrophilic or nucleophilic reactivities are assigned for new compounds by measuring the reaction rate of the new compound with standards. Rates of nucleophile-electrophile combinations can be described by

$$\log k = s_N(N + E) \quad (1)$$

where k is the reaction rate of the nucleophile and electrophile at 20 ˚C, s_N is the nucleophile-specific parameter, N is the nucleophilicity parameter of the nucleophile, and E is an electrophilicity parameter of the electrophile. The nucleophile-specific parameter is empirical and describes the nucleophile's sensitivity to changes in the electrophile. It is needed along with N to fully quantify the strength of a nucleophile. Nucleophiles with similar structures often have comparable s_N values, and these values are typically in the range of 0.7 to 1.2.[43]

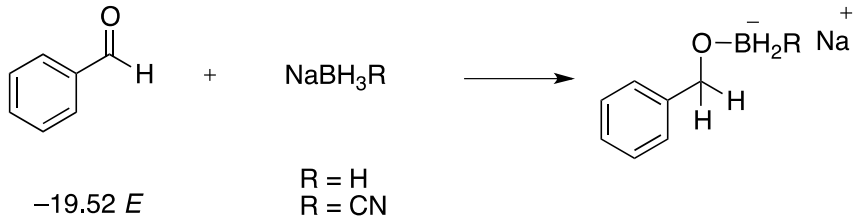
Using eq 1, Mayr and coworkers derived an equation to quickly determine whether a nucleophile and electrophile will react by considering a good reaction to have a half-life of less

than 3 h at a concentration of 1 M.[45] If $E + N$ exceeds –5 (eq 2), then a reaction should occur at room temperature.

$$E + N > -5 \quad (2)$$

For example, benzaldehyde has an E of –19.52, and sodium borohydride has an N value of 14.74. The value of $E + N$ in this case is –4.78 which is greater than –5. The equation predicts that a reaction will occur, and sodium borohydride does indeed react with benzaldehyde at room temperature (**Table 1**, entry 1). In contrast, sodium cyanoborohydride has and N value of 11.52, and a combination with benzaldehyde gives an $E + N$ of –8.00. This does not satisfy eq 2, and experimentally sodium cyanoborohydride does not react with benzaldehyde at room temperature (**Table 1**, entry 2).

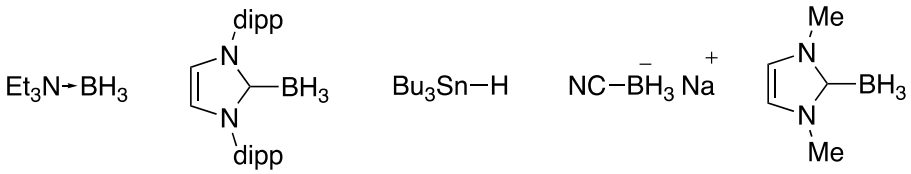
Table 1. Reaction predictions of sodium borohydride and sodium cyanoborohydride with benzaldehyde



Entry	R	*N* value	*E* + *N*	Results
1	H	14.74	–4.78	*E* + *N* is greater than –5 so reaction occurs
2	CN	11.52	–8.00	*E* + *N* is less than –5 so no reaction occurs

Mayr continues to broaden the number of compounds that have been assigned N or E values, so the value of the scale continues to increase.[44] Recently, the N values of carbene-boranes **4** and **5** were determined to be 9.55 and 11.88 respectively.[46] Compared to organic reagents like triethylamine-borane (8.90 N) and tributylstannane (9.96 N), **4** and **5** have some of

the highest nucleophilicity values for neutral hydride donors (**Figure 9**). Carbene-borane **5** even has a higher nucleophilicity value than ionic reagent sodium cyanoborohydride (11.52 *N*). The high values suggest that these carbene-boranes could be useful as organic soluble reagents to perform reductions in mild conditions without the toxicity associated with tributylstannane or sodium cyanoborohydride. We propose to use Mayr's *N* and *E* values as a guideline to discover new reductions with carbene-boranes.



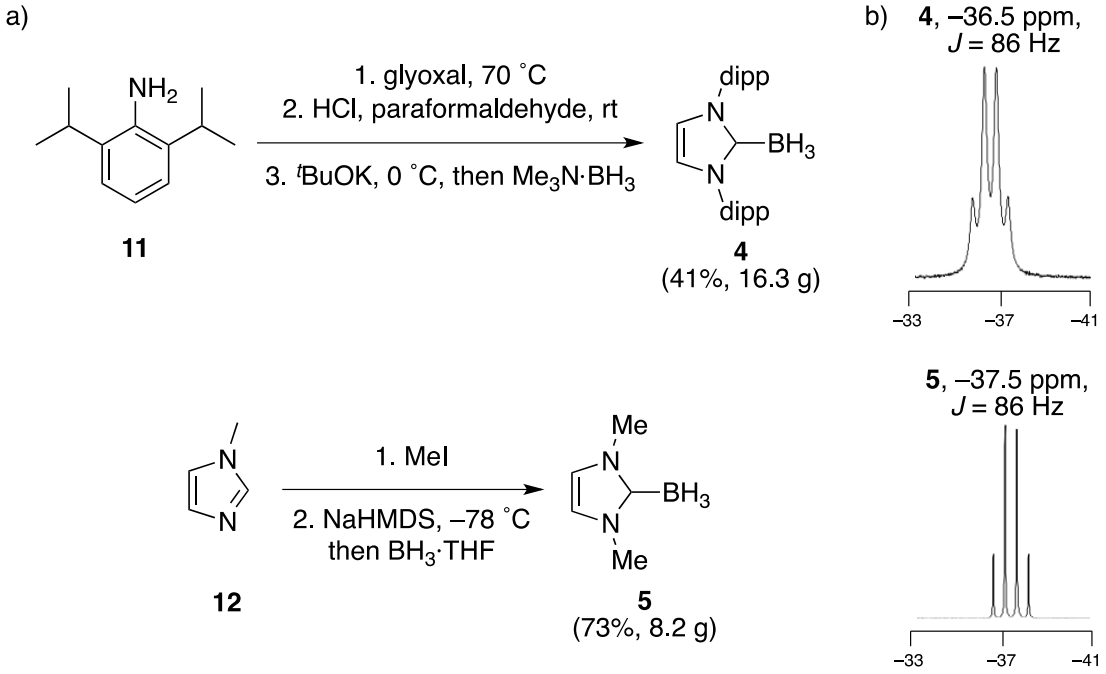
(8.90) **4** (9.55) (9.96) (11.52) **5** (11.88)

Figure 9. Nucleophilicity values *N* of selected hydride donors

2.0 RESULTS AND DISCUSSION

2.1 SYNTHESIS OF CARBENE-BORANES

Carbene-boranes 1,3-bis-(2,6-diisopropylphenyl)imidizol-2-ylidene-borane (**4**) and 1,3-dimethylimidizol-2-ylidene-borane (**5**) are key precursors that were used to make many different substituted carbene-boranes during this work (**Scheme 4**). Carbene-borane **4** was synthesized in three steps[47] from 2,6-isopropylaniline (**11**) to give 16.3 g of white solid in 41% overall yield. Carbene-borane **5** was synthesized in two steps[48] from methyl imidazole (**12**) to give 8.2 g of white solid in 73% overall yield.



Scheme 4. a) Synthesis of carbene-borane **4** and **5** b) ^{11}B NMR spectra of **4** and **5**

In **Scheme 4b**, the ^{11}B NMR signals for **4** (top) and **5** (bottom) are shown. Unlike proton NMR spectroscopy, ^{11}B NMR spectroscopy does not require deuterated solvents so spectra are often taken of crude reaction mixtures to determine how much of the starting material converted to other boron containing products. We will refer to yields obtained from crude NMR spectra as "NMR yields" where the percent yield of a product is calculated by dividing the integration of the ^{11}B NMR product peak by the integration of all the ^{11}B NMR product peaks. Error in these calculations can come from inaccurate integrations of very broad ^{11}B NMR signals and from absence of NMR signals from boron products that evolved as gas or precipitated, and these observations will be noted in the discussion. Reaction progress was also often monitored by TLC using UV visualization and staining with vanillin stain (carbene-borane compounds usually stain dark purple upon heating).

2.2 NUCLEOPHILICITY OF CARBENE-BORANES

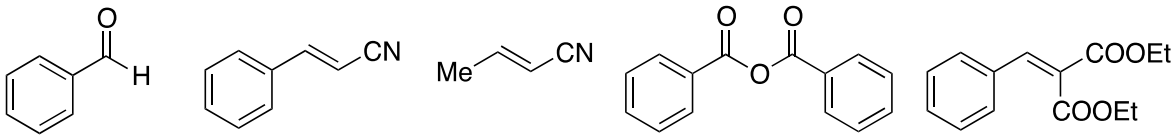
We used recently gained knowledge about the ionic reactivity of dipp-Imd-BH_3 **4** (9.55 *N*) and diMe-Imd-BH_3 **5** (11.88 *N*) to test the reduction of electrophiles by carbene-borane. Using Mayr's database of reactivity parameters,[44] electrophiles with an assigned electrophilicity parameter (*E*) that would satisfy eq 2 ($E + N > -5$) were selected to react with **4** and **5**. Ideal electrophiles have an *E* greater than –15 for **4** and an *E* greater than –17 for **5**, and are either commercially available or easy to synthesize. Some electrophiles tested did not have an assigned *E*, but these electrophiles were often related to other electrophiles we tested.

As a general procedure to probe reactivity of **4** or **5** with a given electrophile, the electrophile (1 equiv) was dissolved in DCM in an NMR tube followed by the addition of the

carbene-borane to the solution. The reaction progress was then monitored by ^{11}B NMR spectroscopy by looking for new boron signals in the crude mixture and a decrease in the intensity of the characteristic quartet at –36 ppm for Imd-BH_3. The electrophiles tested fell into four groups: 1) electrophiles unreactive with either **4** or **5**; 2) electrophiles reactive only with **5**; 3) electrophiles reactive with both **4** and **5**; and 4) electrophiles that form isolable hydroboration products with **5**.

2.2.1 Electrophiles Unreactive with Carbene-boranes 4 or 5

The electrophiles shown in **Figure 10** all were unreactive with diMe-Imd-BH_3 **5** at rt. *E* values are listed when available. Temperatures were elevated to 70 ˚C for the reaction with benzaldehyde **13** (–19.52 *E*) and to 40 ˚C for the reactions with nitriles **14** and **15**, yet still no reaction occurred with **5** after 18 h. Electrophiles **16** and **17** (–20.55 *E*) were mixed with **5** at room temperature, but no reaction was observed after 48 h. Since no reaction occurred with **5**, we did not to attempt reactions with the less nucleophilic dipp-Imd-BH_3 **4**.



13 (–19.52 *E*) **14** **15** **16** **17** (–20.55 *E*)

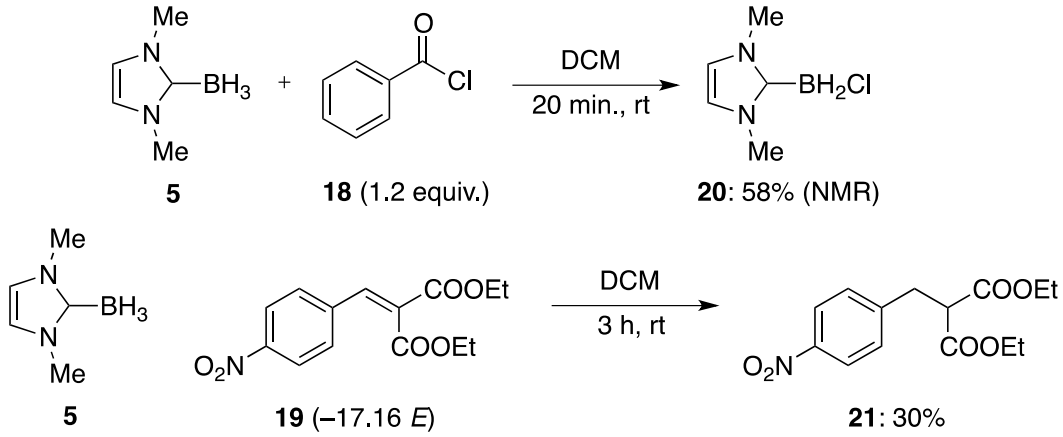
Figure 10. Electrophiles that are unreactive with carbene-boranes **4** and **5**

2.2.2 Electrophiles reactive only with carbene-borane 5

Two stronger electrophiles, benzoylchloride (**18**) and diethyl 2-(4-nitrobenzylidene)malonate (**19**), were treated with carbene-boranes **4** and **5** under the general reaction procedures.

Benzoylchloride (**18**) formed multiple products when treated with **5** in DCM after 15 min including one with an ^{11}B NMR triplet peak at –19 ppm (J = 111 Hz) in 58% NMR yield along with other decomposition products. The new boron peak matched the signal for known carbene-borane diMe-Imd-BH_2Cl **20** (**Scheme 5**).[49] The ^{1}H NMR spectrum of the crude mixture gave multiple peaks including signals for **20**.

Carbene-borane **5** was treated with diethyl 2-(4-nitrobenzylidene)malonate **19** (–17.16 *E*) at rt for 3 h in DCM. A triplet was observed in the ^{11}B NMR spectrum of the crude reaction mixture at –24 ppm, which is in the range of an alkyl or aryl substituted carbene-borane compound,[50] along with some minor peaks at –2 and 0 ppm. The mixture was purified by flash chromatography. Diethyl 2-(4-nitrobenzyl)malonate **21** was isolated in 30% yield, but no boron-containing products were recovered (**Scheme 5**). Apparently **19** is reduced by **5**, but the primary boron-carbanion product is readily protonated to give **21**. This reaction resembles 1,4 reductions by $NaBH_4$.

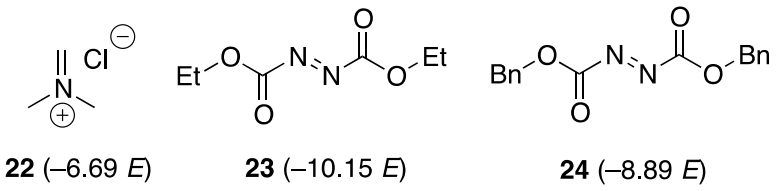


Scheme 5. Electrophiles that are only reactive with **5**

Dipp-Imd-BH_3 **4** was also treated with electrophiles **18** and **19**, but no new ^{11}B NMR signals were observed after 18 h at rt in DCM. Performing the reaction of **4** with **19** in toluene at 110 ˚C generated no new ^{11}B NMR signals even after 3 d.

2.2.3 Electrophiles reactive with both carbene-borane 4 and 5

Electrophiles with *E*'s much greater than –15 reacted with both **4** and **5**, but multiple new boron products were sometimes produced. Reaction of **4** and **5** with compounds **22** (–6.69 *E*), **23** (–10.15 *E*), and **24** (–8.89 *E*) produced many new boron signals in the ^{11}B NMR spectra, and clean products were not obtained (**Figure 11**). Dimethyl(methylene)ammonium chloride **22** reacted to completion within minutes for both carbene-boranes. Diethyl azodicarboxylate **23** was quick to react with carbene-borane **5**, but only slowly reacted with carbene-borane **4** over several hours even with heating to 40 ˚C. Dibenzyl azodicarboxylate **24** was found to slowly react with both **4** and **5** over the course of 2 d at 40 ˚C.



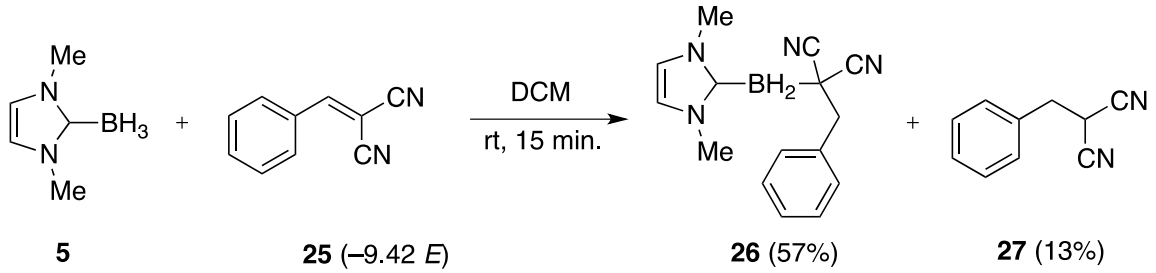
22 (–6.69 *E*) **23** (–10.15 *E*) **24** (–8.89 *E*)

Figure 11. Electrophiles that are reactive with both **4** and **5**

2.2.4 Electrophiles reactive with carbene-borane 5 that form hydroboration products

Benzylidenemalononitrile **25** has a favorable *E* of –9.42, and it was treated with **5**. The reaction progressed quickly, and the boron signal for **5** was completely gone after 15 min at rt. The ^{11}B

NMR spectrum showed that one major product was formed and it had a triplet at –23 ppm, which is similar to the signal observed with the reaction of **5** and **19** (**Scheme 5**). Purification by flash chromatography provided a new borane product in 57% yield (**Scheme 6**). The proton spectrum of the new product contained a new signal at 3.13 (s, 2 H) and new aromatic signals that integrated to 5 protons. These signals along with the triplet at –23.0 ppm in the ^{11}B NMR spectrum indicated that the hydroboration product **26** had formed. This is the first known hydroboration of alkene by carbene-borane. The reduced, protonated product, benzylmalononitrile (**27**),[51] was also recovered in 13% yield.



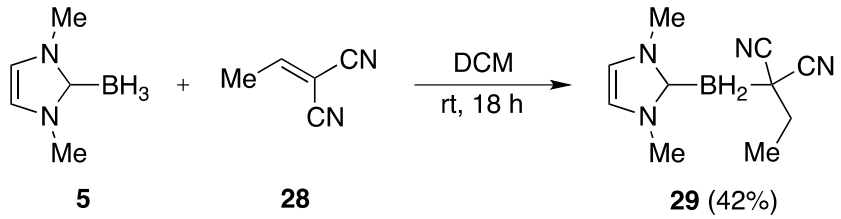
5 **25** (–9.42 *E*) **26** (57%) **27** (13%)

Scheme 6. Reaction of **5** with benzylidenemalononitrile **25**

Reaction of carbene-borane **4** with **25** was attempted at rt, but no new boron signals were observed by ^{11}B NMR spectroscopy after 18 h. The reaction was repeated in DMSO at 100 ˚C, and after 48 h, no new products were observed.

A similar malononitrile, 2-ethylidenemalonitrile **28**, was also treated with **5**, but the reaction was considerably slower than the reaction with benzylidenemalononitrile, taking 18 h to reach completion. The ^{11}B NMR spectrum showed that one major boron product had formed with a triplet peak at –23.0 ppm. Only the hydroboration product **29** was recovered by purification with flash chromatography in 42% yield (**Scheme 7**). The proton spectrum of **29**

contained a quartet at 1.92 ppm and a triplet at 1.23 ppm indicating that an ethyl group was present and accordingly that the boron was attached to the dinitrile carbon.



Scheme 7. Reaction of **5** with 2-ethylidenemalononitrile **28**

2.2.5 Conclusions and future work of carbene-borane nucleophilicity

Overall reactions with carbene-boranes **4** and **5** with various electrophiles matched eq 2 where a reaction occurs at rt if $E + N > -5$. When compared to **5**, benzaldehyde **13** and diethyl 2-benzylidenemalonate **17** have $E + N$ value of –7.75 and –8.78 which is less than –5, and they did not react with **5**. Diethyl 2-(4-nitrobenzylidene)malonate **19** has an E value of –17.16 which correlates to an $E + N$ value of –5.39 for **5**, and –7.61 for **6**. According to the rule of thumb, **25** should react slowly at rt with **5** and not at all with **4**, and indeed this is what is observed. Compounds **22**, **23**, and **24** all have $E + N$ values much greater than –5 for both **4** and **5**, and they reacted readily with the carbene-boranes.

The most interesting results of this nucleophilicity study are the boron-containing products that were isolated with the reaction of the malononitriles **25** and **28**. Intermediates of hydroboration reductions are rarely isolated, but remarkably these reductions with carbene-borane yielded hydroboration intermediates that were stable even to flash chromatography. The reaction of **25** and **5** also yielded the completely reduced product benzomalononitrile **27**.

In contrast, dipp-Imd-BH_3 (**4**) was relatively unreactive, even less reactive than Dr. Mayr's nucleophilicity values predicted. This decreased reactivity may be accounted for by steric hindrance issues created by the bulkiness of the diisopropylphenyl groups attached to the imidazole ring.

Future work may include studying other nucleophilic possibilities of carbene boranes, especially of **5**. DiMe-Imd-BH_3 (**5**) is particularly appealing because it is very stable and easy to handle. Also the lower molecular weight and decreased steric hindrance of the methyl groups are advantageous. DiMe-Imd-BH_3 (**5**) could be used as an organic hydride donor that is weaker than sodium borohydride, but as strong as cyanoborohydride without the toxicity issues of cyanide. By using Dr. Mayr's nucleophilicity and electrophilicity scale as a guide, prospects look good at discovering more noteworthy applications of carbene-borane.

2.3 HALOGEN EXCHANGES WITH CARBENE-BORANE

Halogenation of dipp-Imd-BH_3 (**4**) has been accomplished by reduction of alkyl halides,[41] acid-base reaction with hydrogen halides, or electrophilic reaction with diatomic halogen molecules.[29] In contrast, halogenation of diMe-Imd-BH_3 (**5**) is not as well studied. We therefore wanted to study the reactivity of diMe-Imd-BH_3 (**5**) towards halogenation in comparison to dipp-Imd-BH_3 (**4**). We expected **5** to be even more reactive to halogenating agents compared to **4** based on the larger nucleophilicity value of **5**. Additionally, synthesizing a variety of substituted carbene-bornes with different leaving groups could be useful in synthesizing even more new carbene-borane products.

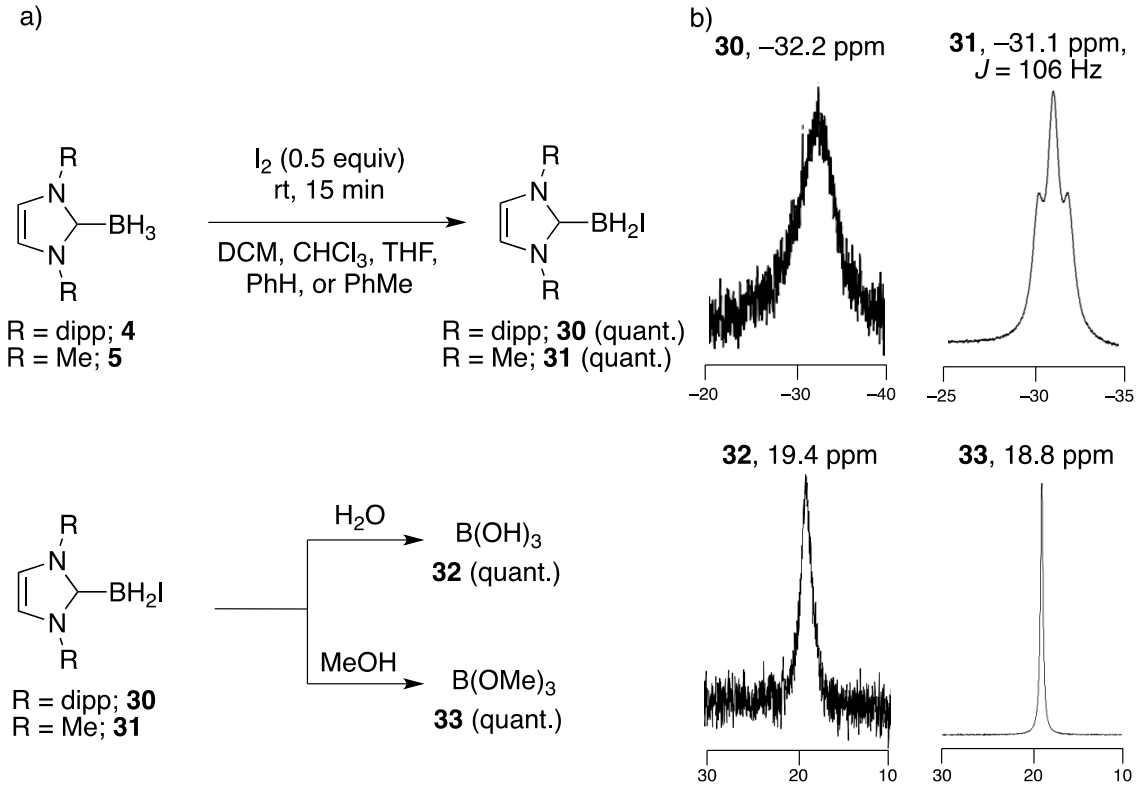
Most of the boryl-halides made from **5** were not stable to chromatography. Instead, we characterized them in situ by NMR spectroscopy. The schemes in this section will show the chemical structures for a given reaction in part "a)" and the observed ^{11}B NMR signals in part "b)." Unless otherwise noted, the percent yields in this section are "NMR yields."

2.3.1 Iodination of carbene-borane

Dipp-Imd-BH_3 reacts with 0.5 equiv iodine to give dipp-Imd-BH_2I (**30**) cleanly in DCM solution.[29] This is observed by ^{11}B NMR spectroscopy as a broad peak at –32.2 ppm (**Scheme 8**). The monoiodide **30** is formed by one molecule of carbene-borane reacting with an iodine molecule to form one molecule of **30** and one molecule of hydroiodic acid. Hydroiodic acid then reacts with another molecule of carbene-borane to give another molecule of **30** and hydrogen gas. Since the only byproduct is hydrogen gas, **30** is generally synthesized with no need of workup or purification. This ease of synthesis is fortunate because **30** is unstable on silica gel and decomposes slowly from the moisture in air.

Using a similar procedure as the synthesis of **30**, we synthesized diMe-Imd-BH_2I (**31**) from carbene-borane **5** (**Scheme 8**). DiMe-Imd-BH_3 (**5**) was dissolved in DCM, and a separately prepared solution of iodine (0.5 equiv) in DCM was added. Rapid bubbling and release of hydrogen gas occurred, and the color of the iodine solution immediately disappeared. The ^{11}B NMR spectrum showed only a broad triplet (J_{BH} = 106 Hz) at –31.2 ppm which we assigned to iodide **31**. This signal persisted in solution over 24 h and matches the range for the signal of dipp-Imd-BH_2I (**30**) at –32.2 ppm. Iodination of **5** in other solvents (chloroform, benzene, toluene) did not appear to affect the conversion to monoiodide **31**.

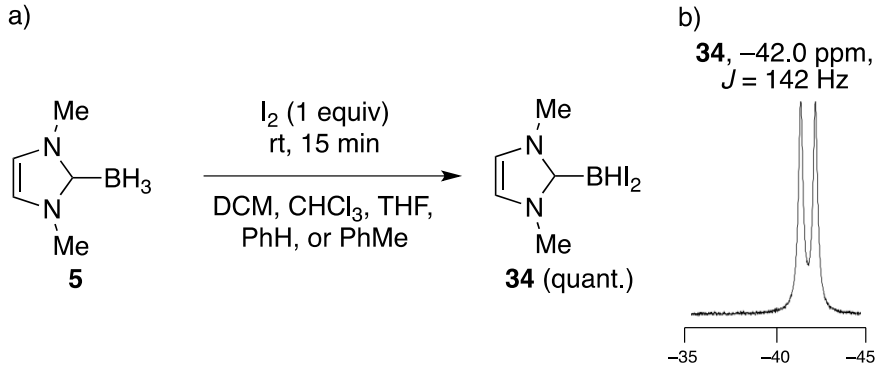
Compound **31** was exposed to air for 18 h, and the ^{11}B NMR spectrum of the resulting solution had no signal at –31.2 ppm and a new broad singlet at 19.4 ppm. Similarly, water was added to a solution of iodide **31**, which also only gave a new broad singlet at 19.4 ppm. The boron signal at 19.4 ppm matches the signal for boric acid (**32**), which is not surprising because **30** also decomposes to boric acid upon addition of water. Addition of methanol to a mixture of **31** results the formation of a broad singlet in the ^{11}B NMR spectrum at 18.8 ppm, which matches the signal for trimethyl borate (**33**), also similar to the results of adding methanol to dipp-Imd-BH_2I (**30**). Because of the instability of **30** and **31** to moisture, subsequent reactions with carbene-borane-iodides were kept in solution under argon to minimize contact with water.



Scheme 8. a) Synthesis and decomposition of carbene-borane iodide b) ^{11}B NMR spectra of **30**-**33**

Reaction of dipp-Imd-BH_3 (**4**) with iodine stops after addition of 0.5 equiv; the product **30** is not further converted to a carbene-borane di- or tri-iodide. In contrast, reaction of diMe-Imd-BH_3 with 1 equiv of iodine in DCM did give a new product signal in the ^{11}B NMR spectrum as a doublet (J_{BH} = 142 Hz) at –42.0 ppm. This boron signal was assigned to the disubstituted product diMe-Imd-BHI_2 (**34**). Diiodination of **5** in other solvents (chloroform, THF, benzene, toluene) were also successful. Like the monoiodide **31**, diiodide **34** is moisture sensitive and decomposes to boric acid with prolonged exposer to air.

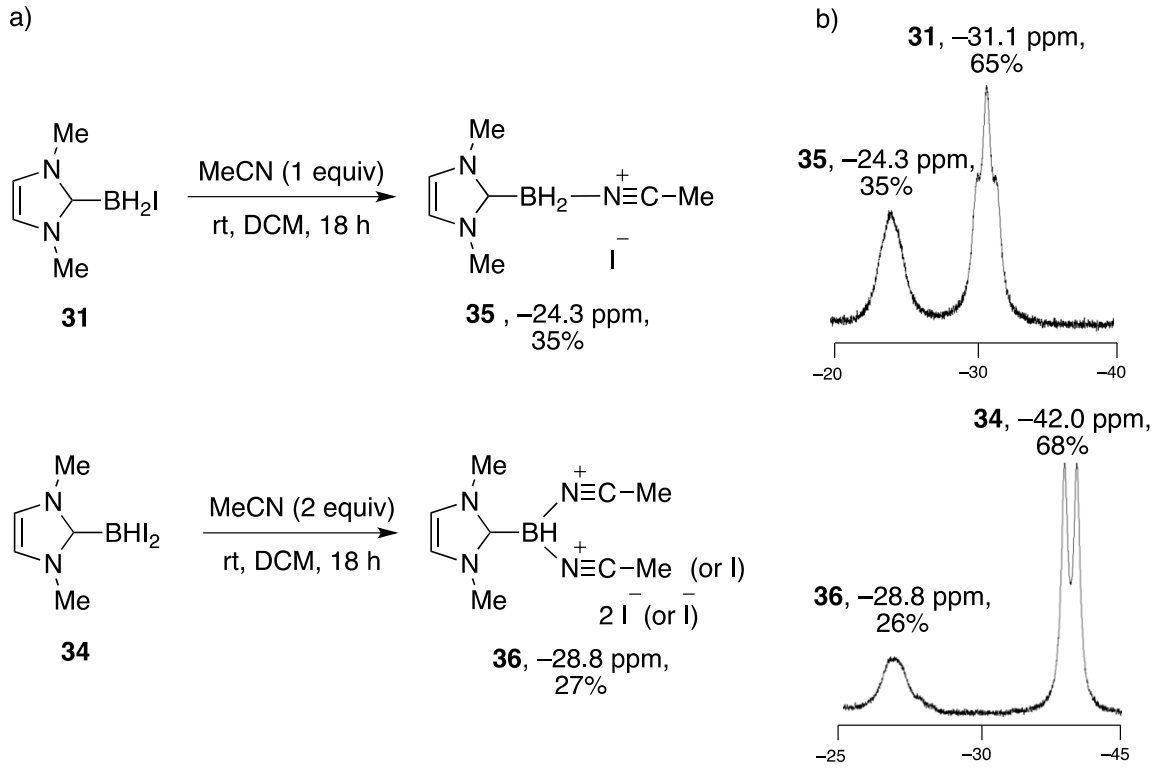
Reaction with excess iodine (>2 equiv) and diMe-Imd-BH_3 did not give any new ^{11}B NMR signals. A dark precipitate began to form as additional iodine solution was added. The intensity of the ^{11}B NMR signal for diiodide-borane decreased, indicating that the precipitate probably contained an insoluble boron product.



Scheme 9. a) Synthesis of carbene-borane diiodide **34** b) ^{11}B NMR spectrum of **34**

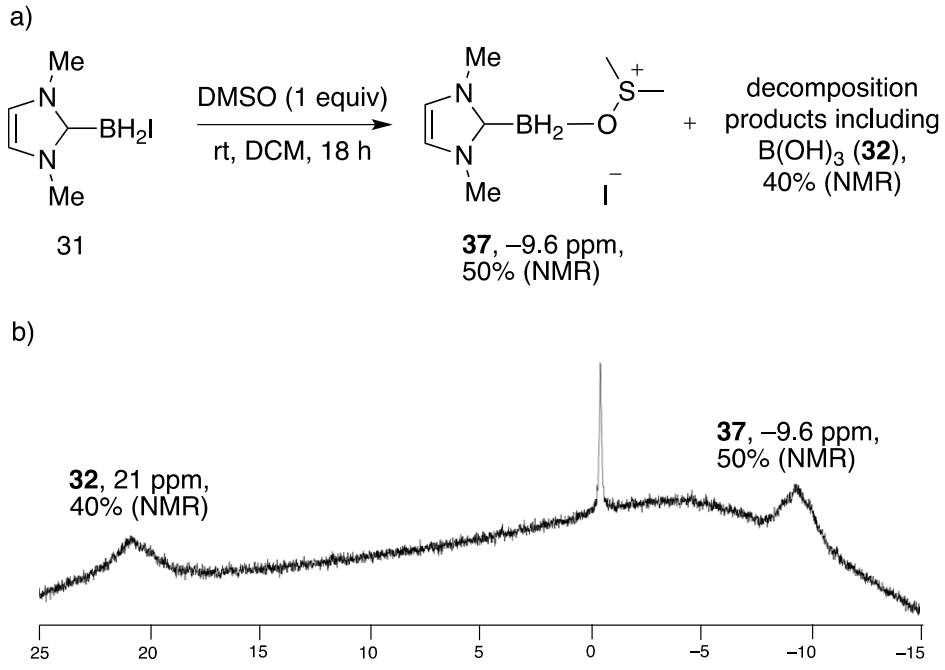
Iodination of diMe-Imd-BH_3 (**5**) occurred smoothly in non-nucleophilic solvents including DCM, chloroform, benzene, and toluene with the same or similar ^{11}B NMR resonances for **31** and **34** at –31.1 ppm and –42.0 ppm respectively. We attempted to iodinate **5** in two polar nucleophilic solvents, acetonitrile and DMSO, but the iodinated borane **31** or **34** was not detected. Addition of DMSO (2 equiv) or acetonitrile (2 or 4 equiv) to premade **31** and **34** (in

DCM), however, gave new product signals in the ^{11}B NMR spectrum of the crude mixture. Reaction of **31** with acetonitrile (2 equiv) resulted in a new ^{11}B NMR peak as a broad singlet at –24.3 ppm at 35% conversion with 65% of starting material **31** remaining. This new peak is similar to the one observed for the well characterized isocyanide of dipp-carbene-borane (–23.0 ppm), and a acetonitrile substituted dipp-carbene-borane was reported to have a broad ^{11}B NMR singlet at –24.0 ppm.[29] Therefore the new product is likely boronium ion **35**. Similarly, the reaction of **34** with acetonitrile (4 equiv) gave a new ^{11}B NMR peak at –28.8 as a broad singlet at 26% conversion along with some decomposition boron signals (~6%). Presumably this new product is an acetonitrile disubstituted carbene-borane **36** or possibly a carbene-borane with both an iodide and acetonitrile substitution (**Scheme 10**). Both boronium ion **35** and **36** are air and moisture sensitive, and neither was isolated after removing the solvent from the reaction.



Scheme 10. a) Reaction of acetonitrile with iodinated carbene-borane **31** and **34** b) ^{11}B NMR spectrum of acetonitrile reaction

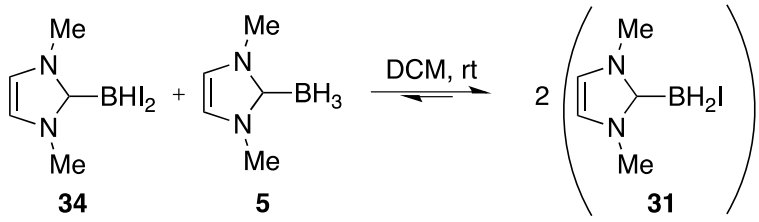
Reaction of a solution of **31** in DCM with DMSO (2 equiv) resulted in the formation of an ^{11}B NMR peak at –9.4 ppm, which is in the range of an NHC-BH_2-O compound (**Scheme 11**). We think that this product is compound **37**. We also observed decomposition product of $B(OH)_3$ (**32**) at 21 ppm (40% NMR yield) an unknown decomposition product sharp singlet at –0.86 ppm (10% NMR yield). Again the compound was not isolated after removal of the reaction solvent, but the odor of DMS was present indicating that some DMSO had been reduced. The presence of DMS suggests a Swern-like mechanism may be occurring with the boryl-iodide. These reactions of acetonitrile and DMSO with carbene-borane iodides show that iodide acts as both a good nucleophile and good leaving group, and iodide is labile enough to enter into equilibrium with polar nucleophilic solvents on the boron center.



Scheme 11. a) Reaction of **31** with DMSO b) ^{11}B NMR spectrum of DMSO reaction

2.3.1.1 Disproportionation of diiodide 34 with carbene-borane 5

Next we tested if the iodide on **34** could disproportionate with other boranes. A solution of **34** was prepared in DCM, and diMe-Imd-BH_3 **5** (1 equiv) was added to the mixture. An ^{11}B NMR spectrum taken immediately after addition showed only the signal for **31** (**Scheme 12**). The formation of only **31** indicates that halogen exchange between **34** and diMe-Imd-BH_3 occurs extremely quickly. This reaction is probably an equilibrium, and product **31** is highly favored. This also may explain why no diiodide is observed with the addition of 0.5 equiv of I_2 to **5** because if any diiodide formed, it would immediately equilibrate with unreacted starting material to the monoiodide.

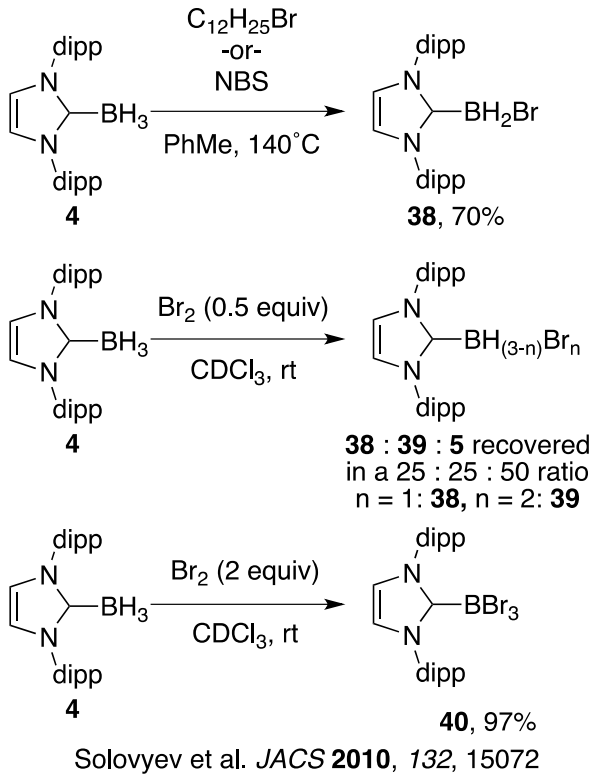


Scheme 12. Iodide disproportionation between **34** and **5**

2.3.2 Bromination of carbene-borane

Bromination of dipp-Imd-BH_3 has been studied[29] under general reaction conditions (**Scheme 13**). The monobrominated borane **38** can be obtained through reduction of dodecyl bromide with **4** at 140 ˚C or more easily by reaction with N-bromosuccinimide (NBS) in 70% yield without purification by column chromatography.[29] However, direct reaction between **4** and limiting amounts elemental bromine gives a mixture of monobrominated carbene-borane **38** (br s, –23.0 ppm) and dibrominated carbene-borane **39** (br s, –16.0 ppm) along with starting material in a 25 : 25 : 50 ratio. Reaction of excess bromine (1.5 or 2 equiv) with **4** gives the tribrominated

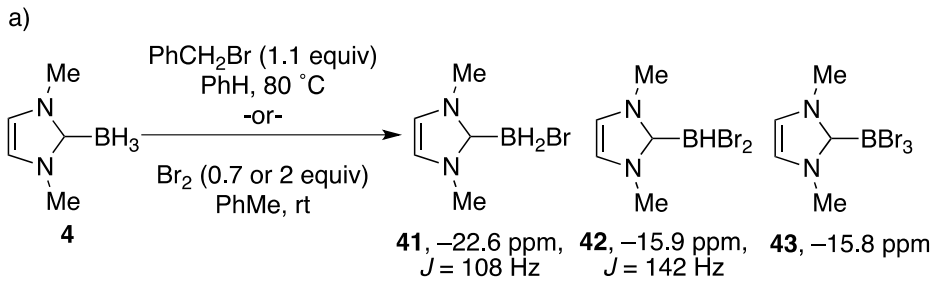
borane **40** (br s, –15.9 ppm) in 97% yield.[29] Like the reaction of carbene-borane with iodine, clearly both Br_2 and the product HBr brominate the borane.



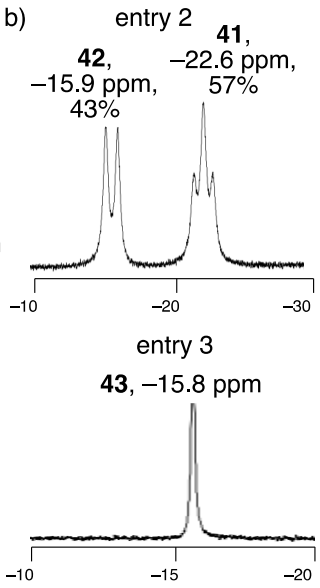
Scheme 13. Reported bromination of dipp-Imd-BH_3[29]

We treated diMe-Imd-BH_3 (**5**) with benzyl bromide (1.1 equiv) in benzene at 80 ˚C. An ^{11}B NMR spectrum of the crude product mixture showed full conversion of **5** into compounds with broad ^{11}B NMR peaks at –23.4 ppm (t, J = 98 Hz) and –16.6 ppm (d, J = 136 Hz) in 75 : 25 ratio (**Scheme 14**). The triplet at –23.4 ppm is similar to the shift for monobromide **38** and therefore was assigned to be diMe-Imd-BH_2Br (**41**). The doublet at –16.6 ppm has a similar shift to dibromide **39** and is suspected to belong to diMe-Imd-$BHBr_2$ (**42**). These results demonstrate that **41** may reduce a further molecule of benzyl bromide to give the dibrominated borane **42**, or the monobromide **41** could also be generated by disproportionation equilibrium of **5** with **42**.

The reaction of diMe-Imd-BH_3 with Br_2 (0.7 equiv) in toluene completely converted to the mono- (**41**) and dibrominated (**42**) carbene-boranes in a 57 : 43 ratio. Similar to the bromination of dipp-Imd-BH_3 (**4**), the monobromide (**41**) readily reacts with bromine or HBr to form the dibromide (**42**), which makes synthesis of the pure monobromide difficult. Reaction with an excess of Br_2 (2 equiv) gave a sharp ^{11}B NMR singlet at –15.8 ppm, which was assigned to be the tribrominated species **43** (**Scheme 14**). Although **43** formed in quantitative yield as an orange solid after evaporation of toluene, the compound decomposed in air slowly and is unstable to moisture, much like the iodinated boranes.



Entry	Conditions	Products, **41** : **42** : **43**
1	$PhCH_2Br$ (1.1 equiv) PhH, 80 ˚C	75 : 25 : 0
2	Br_2 (0.7 equiv) PhMe, rt	57 : 43 : 0
3	Br_2 (2 equiv) PhMe, rt	0 : 0 : 100

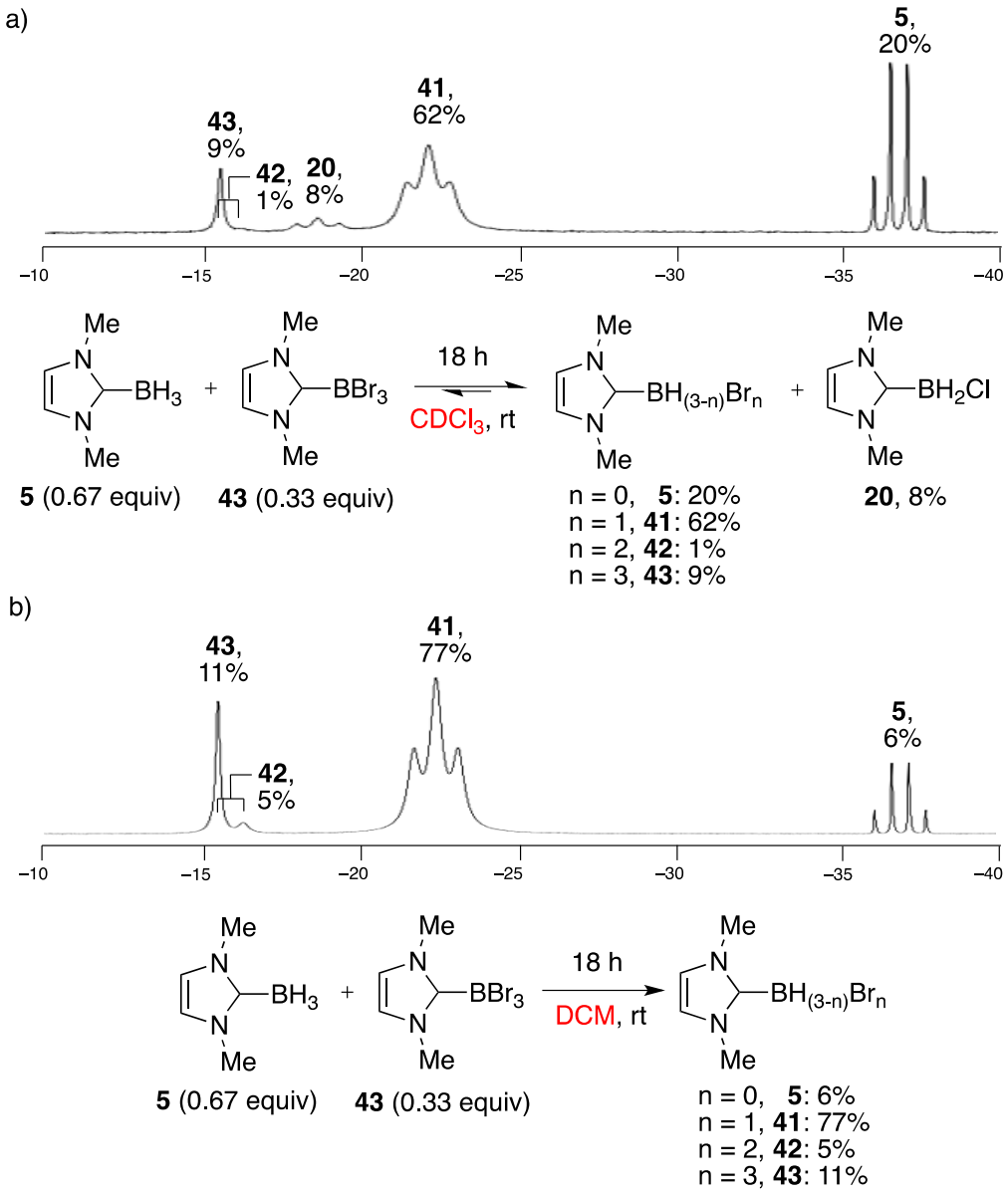


Scheme 14. a) Bromination of diMe-Imd-BH_3 **5** b) ^{11}B NMR spectra of the bromination of **5**

2.3.2.1 Disproportionation equilibrium of carbene-borane bromide

The ability of brominated borane **43** to exchange halogens with diMe-Imd-BH_3 (**5**) was also tested (**Scheme 15**). A solution of **43** (0.33 equiv) was prepared in $CDCl_3$ and added to **5** (0.67 equiv). The ^{11}B NMR spectrum of the reaction mixture after 18 h showed that 20% of **5**

and 9% of **43** remained. Monobromide **41** had formed in 62% yield along with about 1% of the dibromide **42**. Interestingly an addition triplet at –18.8 ppm (J_{BH} = 110 Hz) in the ^{11}B NMR was observed, and this signal was assigned to diMe-Imd-BH_2Cl (**20**) in 8% yield presumably from the reduction of chloroform by **5**. To avoid the chlorinated side product, the exchange reaction was repeated in dichloromethane with 0.67 equiv of diMe-Imd-BH_3 (**5**) and 0.33 equiv of **43**. After 18 h, the monobromide **41** had formed in a 77% yield along with a 5% yield of the dibromide **42**. About 6% of starting material diMe-Imd-BH_3 (**5**) and 11% of **43** remained. The discrepancy of additional tribromide **43** with respect to **5** may be explained by experimental error (too much of **43** was added, or not enough of **5** was added to balance out the amount of bromide present). Indeed, after an additional 24 h at rt, an ^{11}B NMR of the reaction mixture revealed that only 71% of the monobromide **41** and 29% of the dibromide **42** remained.

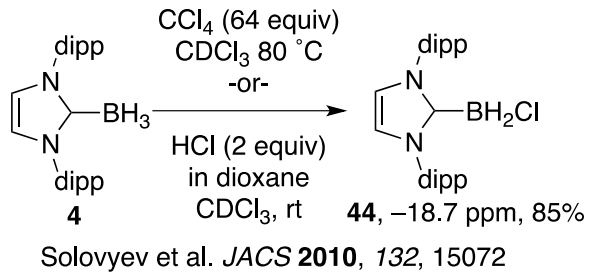


Scheme 15. Halogen exchange between diMe-Imd-BH_3 (**5**) and diMe-Imd-BBr_3 (**43**) in a) $CDCl_3$ and b) DCM

Although slower than iodide exchange between boranes, diMe-Imd-BBr_3 (**43**) does exchange bromine with diMe-Imd-BH_3 (**5**). Similar to the iodide disproportionation, the presumed equilibrium of bromo-substituted carbene-borane highly favors the monobromide followed by the dibromide. The equilibrium, however, is slow, which makes obtaining the mono- or dibrominated carbene-borane **41** or **42** in pure form very difficult.

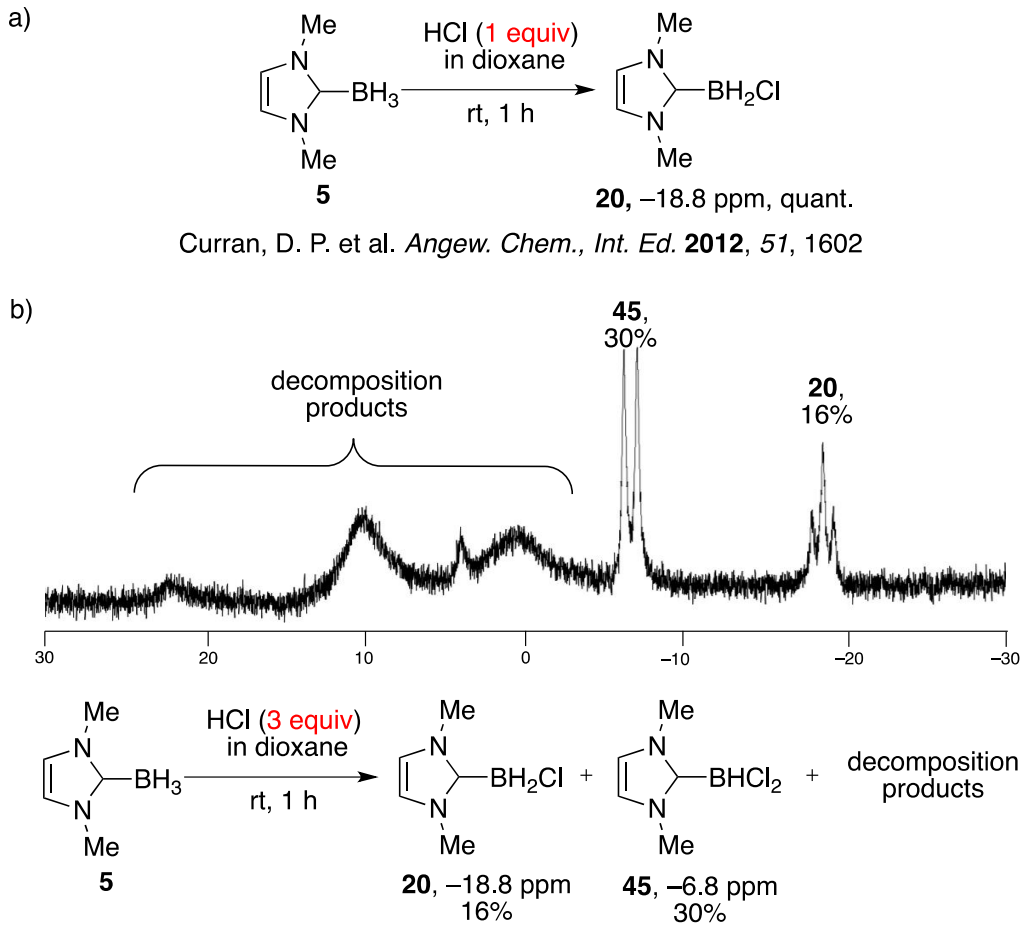
2.3.3 Chlorination of carbene-borane

The chlorination of carbene-borane was also tested by a variety of methods. Monochlorination of dipp-Imd-BH_3 was cleanly achieved by reaction with HCl (2 equiv) in organic solvent or by refluxing for 72 h in CCl_4 to give an 84% isolated yield of dipp-Imd-BH_2Cl (**44**, br s, –18.7 ppm).[29] The monochloride of dipp-carbene-borane is much more stable than the bromide and iodide and can be isolated by column chromatography. Also carbene-borane **4** can be treated with excess chlorinating reagents and only monosubstitution of **4** occurs.



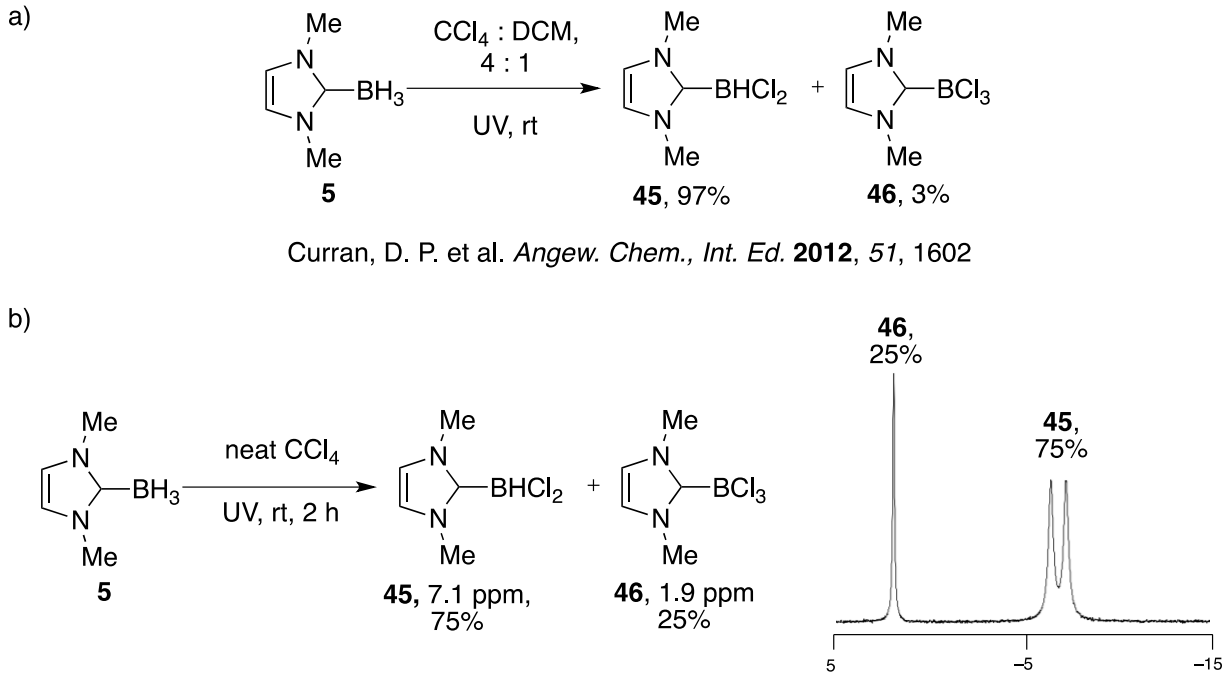
Scheme 16. Reported chlorination of dipp-Imd-BH_3 **4**

We used the same methods to chlorinate dipp-Imd-BH_3 with diMe-Imd-BH_3 (**5**). Addition of 1 equiv of anhydrous HCl in dioxane to a solution of **5** in DCM causes rapid bubbling of H_2 gas and results in the quantitative formation of an ^{11}B NMR triplet signal at –18.8 ppm (J = 110 Hz). This signal was attributed to diMe-Imd-BH_2Cl (**20**).[49] Excess anhydrous HCl (3 equiv) was next added to **5** to test for further chlorination, and a doublet at –6.8 ppm (J = 133 Hz) was observed (30%) along with the triplet for **20** (16%) and decomposition boron product peaks. The doublet matches the reported ^{11}B NMR shift for diMe-Imd-$BHCl_2$ (**45**).[49]



Scheme 17. a) Reported monochlorination **5** of by anhydrous HCl b) 11B NMR spectrum and scheme of reaction of **5** with excess anhydrous HCl

Radical reaction under UV light of diMe-Imd-BH_3 (**5**) with a 4 : 1 solvent mixture of CCl_4 : DCM was reported by our group to give 97% dichloride **45** with some trichloride impurities.[49] To try to force the carbene-borane completely to the trichloride, diMe-Imd-BH_3 was treated with neat CCl_4 in a quartz NMR tube under a UV light source (λ = 254 nm) to give 75% yield of dichloride **45** (7.1 ppm, 130 Hz) along with a 25% yield of a sharp ^{11}B NMR singlet at 1.9 ppm (**Scheme 18**). The singlet was identified as diMe-Imd-BCl_3 (**46**). Additional exposer to UV light did not significantly change the ratio of the ^{11}B NMR peak integrations of **45** and **46**.



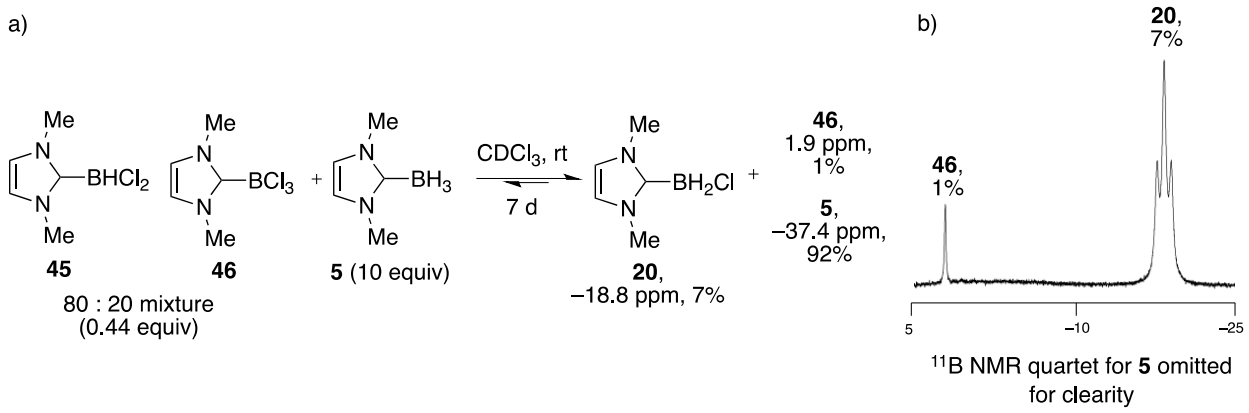
Scheme 18. a) Reported dichlorination of **5** b) ^{11}B NMR spectrum of reaction of **5** with neat CCl_4

Monochlorides **20** and **44**, and dichloride **45** are easy to obtain pure and at good yield, but the trichloride **46** is more difficult to synthesize from carbene-borane **5**. Direct complexation of BCl_3 with N-heterocyclic-carbene remains the best way to synthesize **46** in high purity and good yield.[52]

2.3.3.1 Disproportionation equilibrium of carbene-borane chloride

We tested the ability of **45** and **46** to disproportionate chloride. We anticipated slow exchange rates so an excess of **5** was added. Carbene-borane **5** (10 equiv) was added to an 75 : 25 mixture of **45** and **46** (0.44 equiv) in $CDCl_3$ at rt. ^{11}B NMR spectroscopy showed a very small triplet signal for the monochloride **20** after 18 h. The reaction was monitored over several days by ^{11}B NMR spectroscopy. After 7 d, the ^{11}B NMR signal for dichloride **45** had completely disappeared and the signal for the monochloride **20** had increased is intensity (7% yield). The

signal for the trichloride, however, was still present along with carbene-borane **5**. Chloride from **45** and **46** exchanges with **5**, but the equilibrium and exchange rate is much slower (even with 10 equiv of **5**) than the carbene-borane bromide and especially the carbene-borane iodides.



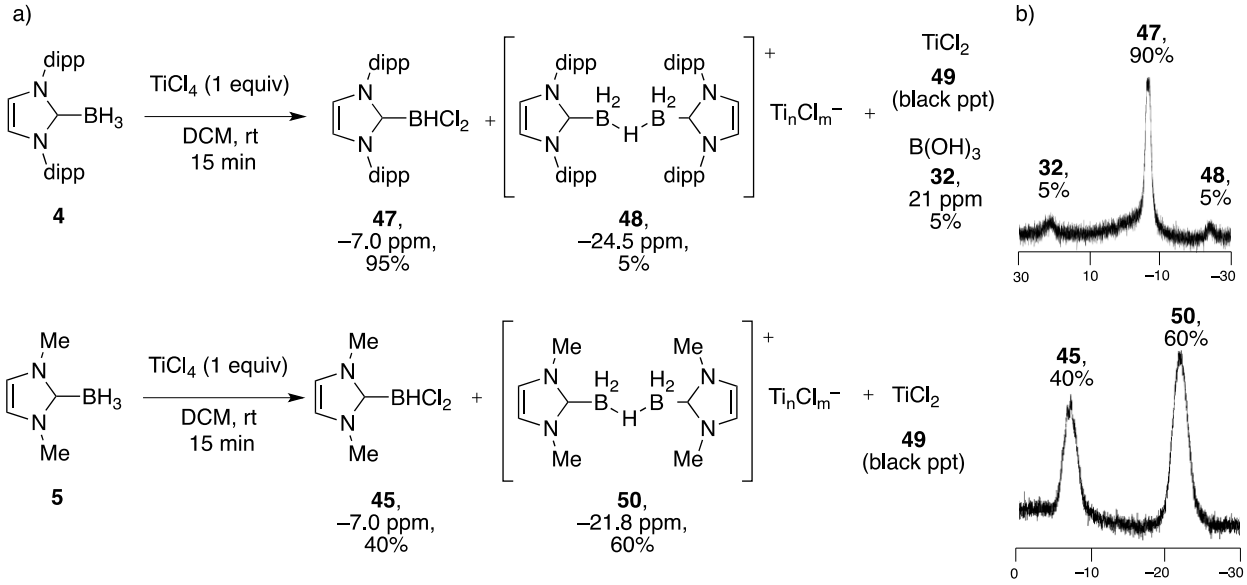
Scheme 19. a) Chloride disproportionation between **45**, **46**, and **5** b) ^{11}B NMR spectrum of chloride disproportionation

2.3.3.2 Chlorine exchange and reduction of Lewis acidic metals

We tested the reactivity of carbene-boranes **4** and **5** with heavy metal Lewis acids. Titanium (IV) chloride (1 equiv) was added to a solution of dipp-Imd-BH_3 **4** in $CDCl_3$. Rapid bubbling and black precipitate formation occurred immediately. An ^{11}B NMR spectrum of the dark green crude reaction mixture showed the formation of the dipp-carbene-borane dichloride **47** in 90% NMR yield (–7.0 ppm, br s) along with 5% NMR yield of boric acid **32** (21 ppm, br s) and 5% NMR yield for a new broad singlet at –24.5 ppm. The peak at –24.5 ppm matches the ^{11}B NMR shift reported for the boryl dimer isolated by Prokofjevs and coworkers in 2013 from the reaction between dipp-Imd-BH_3 and aluminum (III) chloride.[53] Therefore the new boron product was assigned to carbene-borane dimer **48**. The black precipitate is probably the reduced titanium product $TiCl_2$ (**49**), which is known to be black. Addition of methanol to the reaction

mixture caused rapid bubbling and the disappearance of the precipitate. The ^{11}B NMR spectrum of the methanol quenched mixture only showed trimethyl borate **33**.

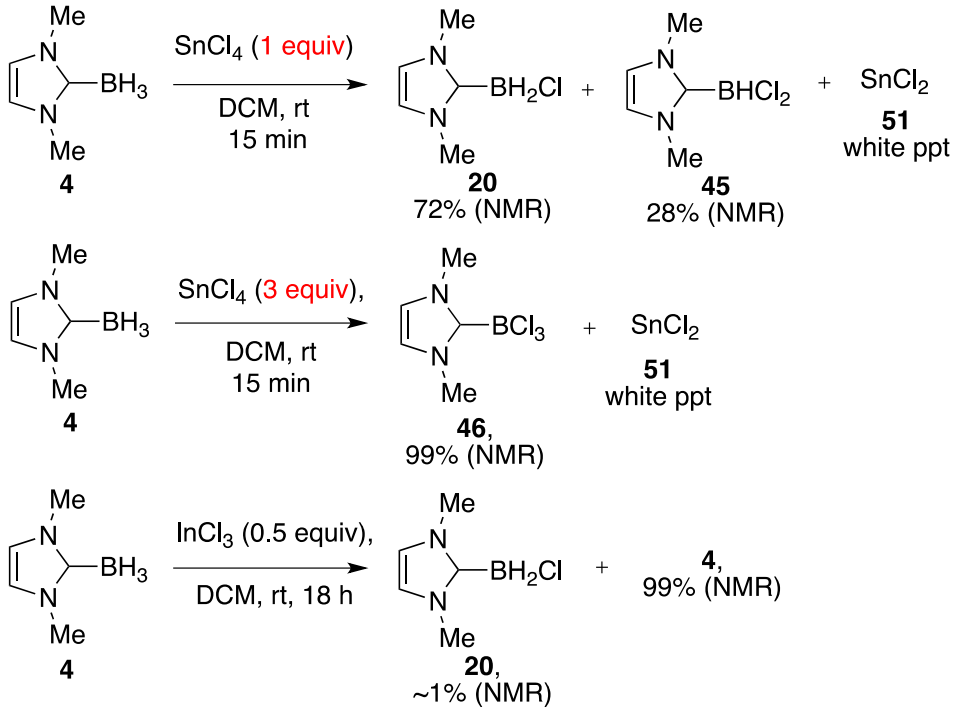
The reaction conditions with titanium (IV) chloride were repeated with diMe-Imd-BH_3 (**5**) in $CDCl_3$. Again rapid bubbling and black precipitate formed, and the ^{11}B NMR spectrum of the green crude mixture showed a 40% NMR yield of dichloride **45** (–7.0 ppm, br s) and 60% NMR yield of a new boron product (–22.2 ppm, br s). The signal for the new boron product matched the reported ^{11}B NMR shift for the diMe-carbene-borane dimer[53] so the –22.2 ppm shift was assigned to dimer **50**. Addition of methanol also caused rapid bubbling, the disappearance of the black precipitate, and only trimethyl borate **33**.



Scheme 20. a) Reactions of carbene-borane with $TiCl_4$ b) ^{11}B NMR spectra of crude reaction mixtures

Reactions of other Lewis acids with diMe-Imd-BH_3 **5** were performed under the similar reaction conditions (**Scheme 21**). Reaction of Tin (IV) chloride (1 M solution in DCM) with diMe-Imd-BH_3 resulted in rapid bubbling from hydrogen gas formation and immediate formation of a white precipitate. The ^{11}B NMR spectrum of the crude reaction mixture revealed

the formation of the monochloride **20** (–19.0 ppm, t, J = 105 Hz) in 72% NMR yield and the dichloride **45** (–6.9 ppm, d, J = 182 Hz) in 28% NMR yield. Addition of methanol to the reaction mixture resulted in rapid bubbling and the disappearance of the white precipitate. The white precipitate is likely tin (II) chloride (**51**) based on its reactivity, solubility, and color. Addition of methanol also decomposed the chlorinated boranes to trimethyl borate **33**. Addition of 3 equivalents of tin (IV) chloride to diMe-Imd-BH_3 **5** also caused rapid formation of hydrogen gas and white precipitate. The ^{11}B NMR spectrum of the reaction mixture, however, showed only the formation of trichlorinated borane **46** (1.9 ppm, s). Conversely, reaction of diMe-Imd-BH_3 with Indium (III) chloride (0.5 equiv) caused little to no hydrogen formation and only a small amount (~1%) of **20** was observed by ^{11}B NMR spectroscopy.



Scheme 21. Reaction of diMe-Imd-BH_3 with $SnCl_4$ and $InCl_3$

2.3.4 Conclusions on halogenation of carbene-borane

This study showed that diMe-Imd-BH_3 **5** reacts with halogens and halogenating reagents to give single, double and triple substituted carbene-boranes. To prepare carbene-borane in pure form for substitution reactions, we have found that dipp-Imd-BH_2I (**30**) and diMe-Imd-BH_2I (**31**) are the most accessible for single substitution, dipp-Imd-$BH(OTf)_2$ and diMe-Imd-BHI_2 are the most easily prepared for disubstituted carbene-boranes, and dipp-Imd-BBr_3 and diMe-Imd-BBr_3 are the easiest prepared trisubstituted carbene-boranes.

We also observed that the halide bonded to the boron center is in equilibrium with other boron centers present in solution. The exchange rate of the halides between boron centers increases as the halide size, leaving group capability, and nucleophilicity increase. Iodide disproportionates nearly instantly with the diiodo-carbene-borane **34** converting to the mono-iodo-carbene-borane **31** in the presence of **5**. Carbene-borane bromide disproportionates more slowly than iodide, followed by even slower carbene-borane chlorides. Except for carbene-borane-iodide, disproportionation is not a good way to obtain pure samples of mono- or disubstituted carbene-borane halides.

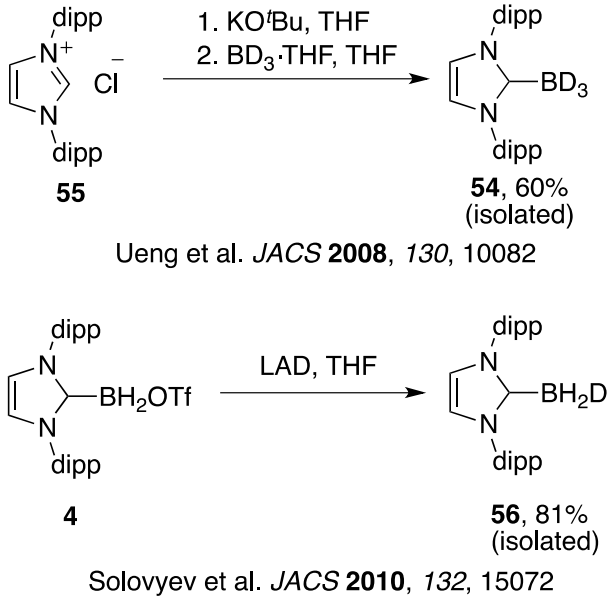
Carbene-borane may also be chlorinated by heavy metal Lewis acids $TiCl_4$ and $SnCl_4$. Interestingly carbene-borane appears to reduce titanium or tin to give highly reactive reduced species $TiCl_2$ (**49**) and $SnCl_2$ (**51**). These results suggest that reduction of other metals by carbene-borane could occur.

2.4 SUBSTITUTIONS OF CARBENE-BORANE-HALIDES

Although substitutions with dipp-Imd-BH_2OTf (**52**) and dipp-Imd-$BH(OTf)_2$ (**53**) are successful, triflic acid is required to make them and is expensive and corrosive. Triflate is a good leaving group for substitution reactions, but halides can also make good leaving groups. Carbene-borane halides were therefore studied as candidates for substitution reactions. We expected substitutions with carbene-boryl-iodides or carbene-boryl-bromides to go smoothly because iodide and bromide are very good leaving groups. Carbene-boryl-chlorides were not expected to substitute as easily due to chloride not being as good as a leaving group as triflate, iodide, or bromide.

2.4.1 Selective deuteration reactions of carbene-borane

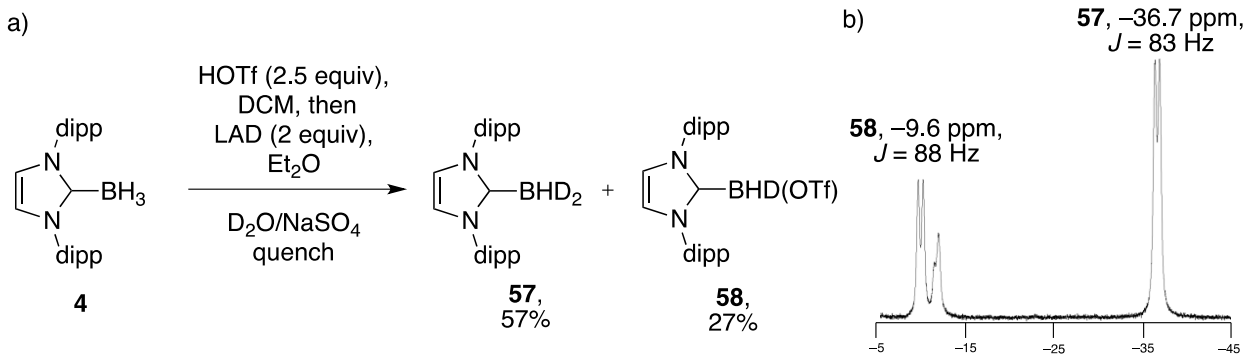
A deuterated carbene-borane is a useful reagent for mechanistic and kinetic isotope effect studies. Carbene-borane with a fixed percentage of deuterium to hydrogen on the boron atom could be useful for these types of experiments. Deuterated carbene-borane **54** has been made in 60% yield by reacting dipp-imidazolium salt **55** with base and BD_3·THF (**Scheme 22**),[48] but BD_3·THF is expensive and not readily available thus making it impractical to use in the synthesis of deuterated carbene-borane. Lithium aluminum deuteride (LAD) is a cheaper source of deuterium, and dipp-Imd-BH_2OTf (**52**) is known to react with LAD to give dipp-Imd-BH_2D (**56**) in 81% yield.[29] We wanted to extend this reaction with other halogenated dipp- and diMe-carbene-borane to make various mono-, di-, and trideuterated carbene-boranes. We targeted the reduction of dipp-Imd-$BH(OTf)_2$ (**53**), diMe-Imd-BH_2I (**31**), diMe-Imd-BHI_2 (**34**), dipp-Imd-BBr_3 (**40**), and diMe-Imd-BBr_3 (**43**) due to the ease of synthesizing these compounds in good purity in situ.



Scheme 22. Previous methods for deuteration of dipp-carbene-borane

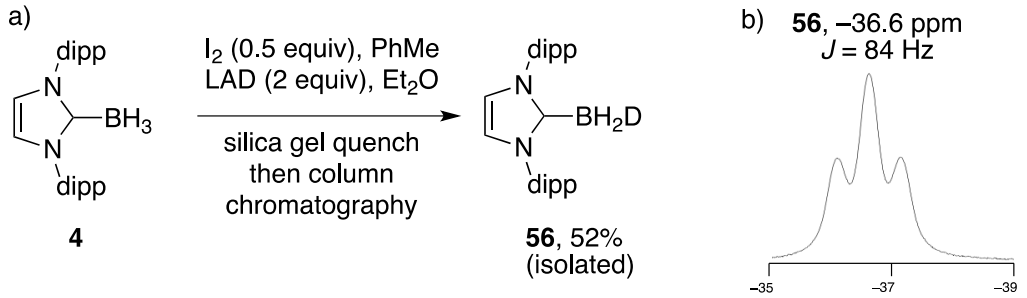
LAD reduction of dipp-Imd-BH(OTf)$_2$ (**53**) was expected to give the dideuterated borane. Dipp-Imd-BH(OTf)$_2$ (**53**) was prepared in dry DCM under argon atmosphere and its formation was verified by ^{11}B NMR spectroscopy as a broad singlet at –2.6 ppm.[29] A mixture of LAD was prepared by adding solid LAD (2 equiv) to a flask of dry diethylether. Some gray precipitate from impurities in the LAD (possibly lithium metal, lithium deuteride, and lithium hydroxide) remained in the mixture, but presumably most of the LAD had dissolved in the diethylether. The solution of the ditriflate-borane (**53**) was then slowly added by syringe to the LAD solution. Rapid bubbling occurred and a gray precipitate formed. ^{11}B NMR spectroscopy of the crude reaction mixture revealed a doublet signal at –36.7 ppm (J = 83 Hz), corresponding to dipp-Imd-BHD$_2$ (**57**), but other broad boron signals were present from –1.5 to –12.0 ppm. After quenching by saturated sodium sulfate in water, the ^{11}B NMR spectrum showed a 57% yield of dideuteride **57**, 27% yield of dipp-Imd-BHD(OTf) (**58**) (d, –9.6 ppm, J_{BH} = 88 Hz), and 16% NMR yield of

unknown product –11.7 ppm. Carbene-borane **57** was not isolated cleanly after purification by column chromatography.



Scheme 23. a) Dideuteration of dipp-Imd-BH_3 by HOTf and LAD b) ^{11}B NMR spectrum of **57** and **58**

We next reduced dipp-Imd-BH_2I (**30**) with LAD to compare with the reported reduction of dipp-Imd-BH_2OTf (**52**) by LAD to give dipp-Imd-BH_2D (**56**). The monoiodide **30** was prepared in toluene, and this solution was added to a solution of LAD (2 equiv) in diethyl ether. Bubbling and gray precipitate formation occurred, and ^{11}B NMR spectroscopy showed a triplet signal at –36.5 ppm (J_{BH} = 84 Hz), which nearly matches the reported chemical shift for dipp-Imd-BH_2D (–36.7 ppm).[29] A small, complex signal at –40.5 was also observed, which matches the chemical shift for $LiBD_4$. The reaction mixture was then quenched by water saturated with sodium sulfate, worked up in DCM, and purified by column chromatography to give a 52% isolated yield of dipp-Imd-BH_2D (**Scheme 24**). This is lower than the yield reported for the LAD reduction of **52** (81% yield). Still, the pure product was isolated.

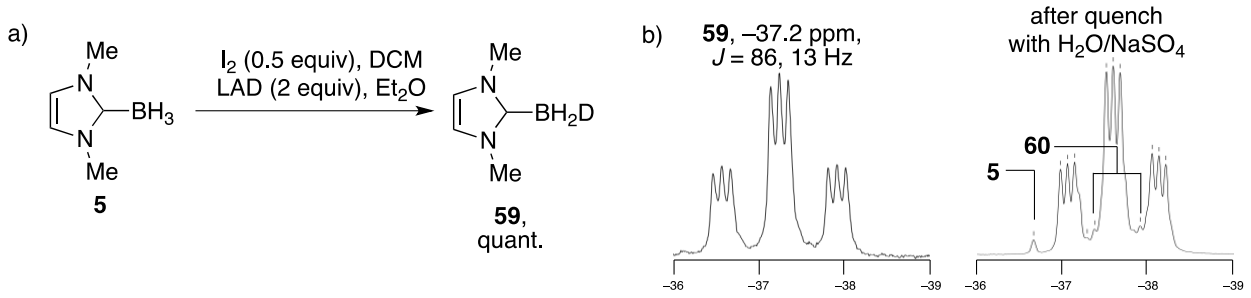


Scheme 24. a) Deuteration of dipp-Imd-BH_3 (**4**) by I_2 and LAD b) ^{11}B NMR spectrum of dipp-Imd-BH_2D (**56**)

We also tried to form dipp-carbene-borane trideuteride from the tribromide **40** using a similar procedure. The boryl-tribromide **40** was prepared in DCM, and the LAD mixture in diethylether was added. Lots of precipitation occurred, and ^{11}B NMR spectroscopy of the crude showed no boron signals. The tribromide probably precipitated upon diethylether addition, and it likely did not react with LAD.

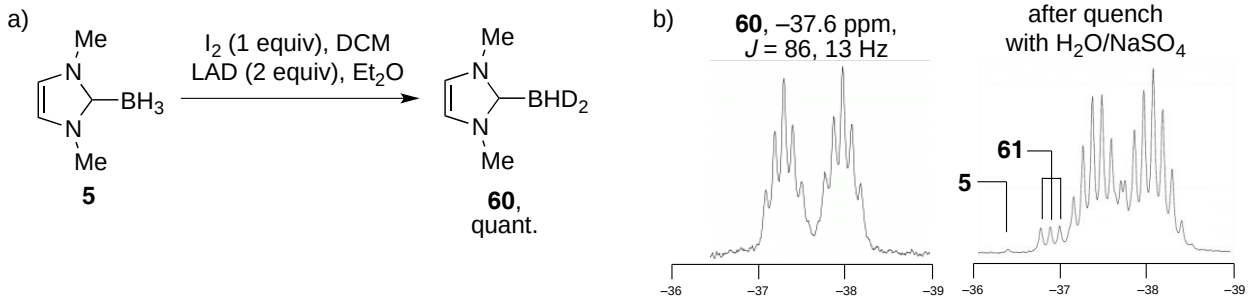
We next turned our attention towards the deuteration of halogenated diMe-carbene-borane. A solution of diMe-Imd-BH_2I (**31**) was prepared in DCM and added to a solution of LAD (2 equiv) in diethyl ether. Bubbling and gray precipitate formation occurred immediately upon addition. The ^{11}B NMR spectrum of the crude mixture showed a triplet (1:2:1 ratio, J_{BH} = 86 Hz) of triplets (1:1:1 ratio, J_{BD} = 13 Hz) at –37.2 ppm, which indicated that diMe-Imd-BH_2D (**59**). The reaction mixture was quenched with $H_2O/NaSO_4$ solution, resulting in vigorous bubbling and gray precipitate formation. An ^{11}B NMR spectrum of the crude borane compound after quenching (**Scheme 25b**) showed that the hydrogen and deuterium on the boron had scrambled to give boron atoms with monodeuteration (~90%), dideuteration (~5%), and no deuteration (~5%). The experiment was repeated with different LAD quenching methods including $D_2O/NaSO_4$, solid $NaHCO_3$ addition, ethyl acetate, dry silica gel addition, and dry basic alumina addition (**Scheme 25**), but proton/deuterium scrambling was still observed by ^{11}B

NMR spectroscopy. We could therefore observe the pure monodeuterated borane **59** by ^{11}B NMR spectroscopy, but we could not isolate it.



Scheme 25. a) Synthesis of diMe-Imd-BH_2D (**59**) b) ^{11}B NMR spectrum of **59** before quenching (left) and after $H_2O/NaSO_4$ quench (right)

We repeated the LAD reduction procedure on diMe-Imd-BHI_2 (**34**) to get the dideuterated borane. LAD (2 equiv) was dissolved in dry diethyl ether and a freshly prepared solution of diiodide **34** in DCM was added. Some bubbling and gray precipitate formation immediately occurred. An ^{11}B NMR spectrum of the crude mixture showed a doublet (J_{BH} = 86 Hz) of pentets (1:2:3:2:1 ratio, J_{BD} = 13 Hz) at –37.6 ppm, which indicated that diMe-Imd-BHD_2 (**60**) had formed (**Scheme 26**). Again quenching the LAD of this reaction mixture also resulted in proton/deuterium scrambling on the boron center, and **60** was not isolated.



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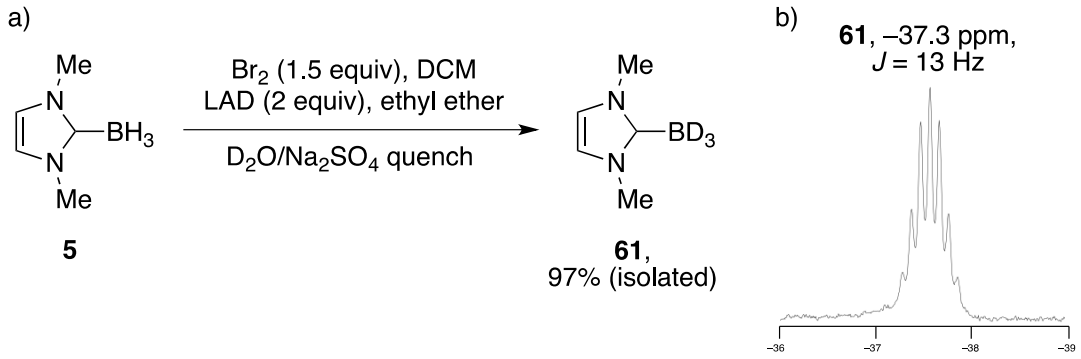
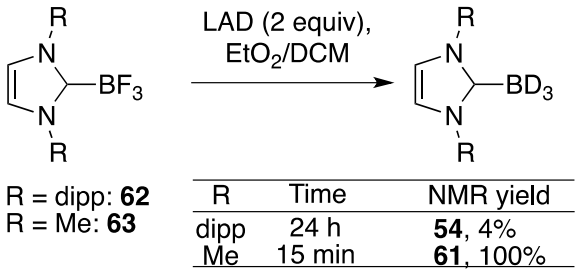
Scheme 26. a) Synthesis of diMe-Imd-BHD_2 (**60**) b) ^{11}B NMR spectrum of **60**

Next diMe-Imd-BBr_3 (**43**) was reduced by LAD to obtain the trideuterated carbene-borane. LAD (2 equiv) was dissolved in dry ethyl ether, and separately prepared solution of tribromide **43** in DCM was added. ^{11}B NMR spectroscopy showed the formation of a septet (1:3:6:7:6:3:1 ratio, J_{BD} = 13 Hz) at –37.3 ppm that corresponds to diMe-Imd-BD_3 (**61**). Quenching with $D_2O/NaSO_4$ solution and removal of the precipitate by filtration gave **61** with very little proton incorporation because only deuterium was present during the quench. The ^{1}H NMR spectrum of the worked up material also looked pure so no additional purification was needed to give **61** in 97% yield as a white solid.



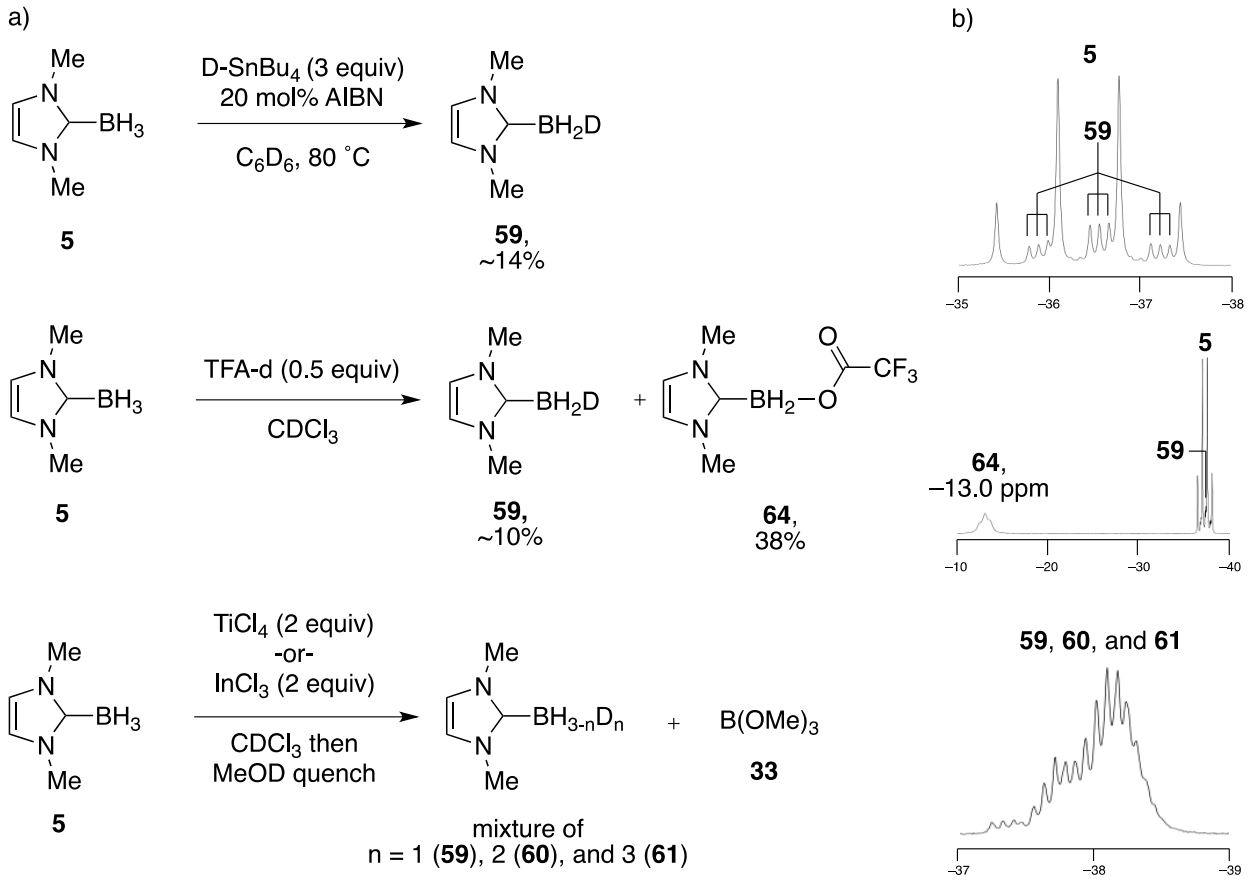
Scheme 27. a) Synthesis of diMe-Imd-BD_3 (**61**) b) ^{11}B NMR spectrum of **61**

Next, we wanted to see if LAD could also reduce the robust carbene-borane trifluorides **62** and **63**. A solution of LAD (2 equiv) in ethyl ether was prepared, and a solution of either **62** or **63** in DCM was added to the mixture. ^{11}B NMR spectra of the reaction with **62** showed that only 4% (determined by ^{11}B NMR peak integration) of the starting borane had converted to **54**. The reaction with **63**, however, showed that all of the starting borane had converted to **61** after 15 min. Some residual boron trifluoride etherate ($BF_3{\cdot}OEt_2$) was present in the starting material for these reactions, and this borane was converted to $LiBD_4$ as seen by a complex peak at –41.6 ppm in the ^{11}B NMR spectra.



Scheme 28. Reduction of trifluoro-carbene-boranes **62** and **63** by LAD

Other deuteration reactions of carbene-borane were less successful (**Scheme 29**). Radical deuteration was attempted by reacting diMe-Imd-BH_3 (**5**) with tributyltin deuteride in the presence of AIBN and heat. Only slight deuteration was observed by ^{11}B NMR spectroscopy (~10% **59**). Direct reaction with TFA-d (0.5 equiv) with diMe-Imd-BH_3 in $CDCl_3$ gave some deuterated carbene-borane (~10% **59**) in addition to TFA-substituted carbene-borane **64**. Finally, reaction of diMe-Imd-BH_3 (**5**) with Lewis acids $TiCl_4$ or $InCl_3$ (2 equiv) in $CDCl_3$ followed by quenching in deuterated methanol gave deuterated borane with various amounts of deuteration as well as decomposition of carbene-borane to trimethyl borate **33**.



Scheme 29. Other less successful methods to deuterate **5**

2.4.1.1 ^{11}B NMR splitting patterns of deuterated carbene-borane

^{11}B NMR signals are split by both deuterium and hydrogen, but deuterium has a spin of 1 whereas protium has a spin of ½, so combinations of these splitting patterns were observed. The ^{11}B NMR signals for deuterated dipp-carbene-boranes were too broad to observe the finer splitting patterns of deuterium. However, deuterium-boron coupling was observed on ^{11}B NMR spectra of deuterated diMe-carbene-boranes.

Deuterium has a nuclear spin of 1 and gives 1:1:1 triplets for each subsequent coupled deuterium. This means a splitting pattern of 1:1:1 triplet occurs for one deuterium coupling, a

1:2:3:2:1 pentet for two deuterium couplings, and 1:3:6:7:6:3:1 septet for three deuterium couplings.

The deuterated carbene-boranes **59** and **60** have both B-D and B-H splitting, and **61** only has B-D splitting (**Figure 12**). Compound **59** has a splitting pattern of a 1:2:1 triplet (J_{BH} = 86 Hz) of 1:1:1 triplets (J_{BD} = 13 Hz), whereas **60** has a splitting pattern of a 1:1 doublet (J_{BH} = 86 Hz) of 1:2:3:2:1 pentets (J_{BD} = 13 Hz). Compound **61** has a splitting pattern of a 1:3:6:7:6:3:1 septet (J_{BD} = 13 Hz).

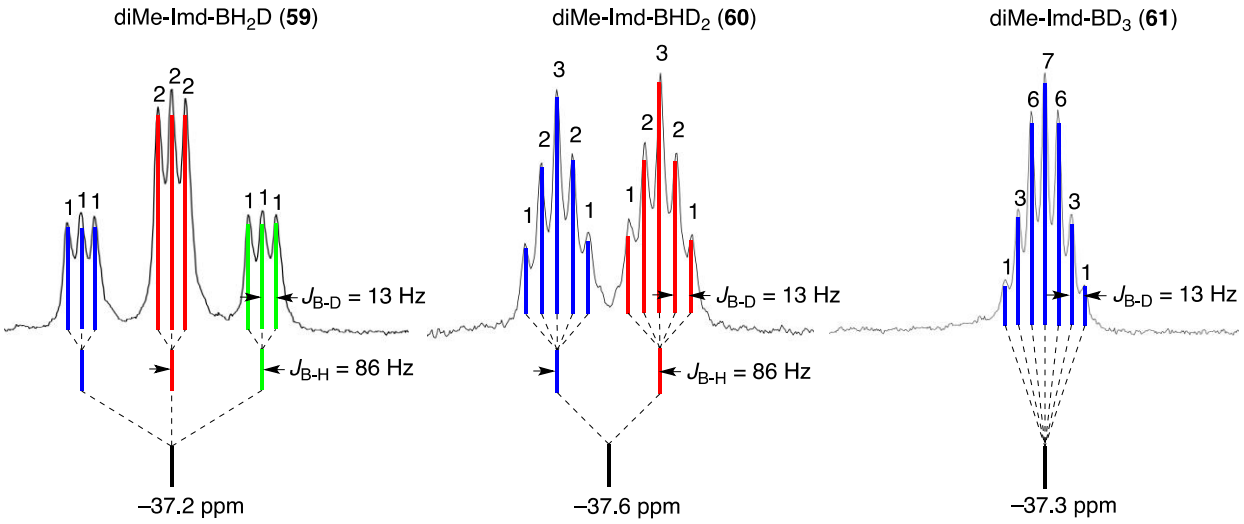


Figure 12. Splitting patterns of **59**, **60**, and **61**

2.4.1.2 Conclusions on deuteration of carbene-boranes

Selective deuteration of carbene-borane was successful by reduction of various halogenated carbene-boranes with LAD. Although radical and acidic deuteration of diMe-Imd-BH_3 occurred, the amount of deuteration of the boron center was either low, or nonselective. Complicated splitting patterns were observed for deuterated diMe-carbene-borane, but deuterium splitting for the ^{11}B NMR signals of deuterated dipp-carbene-borane were not observed because

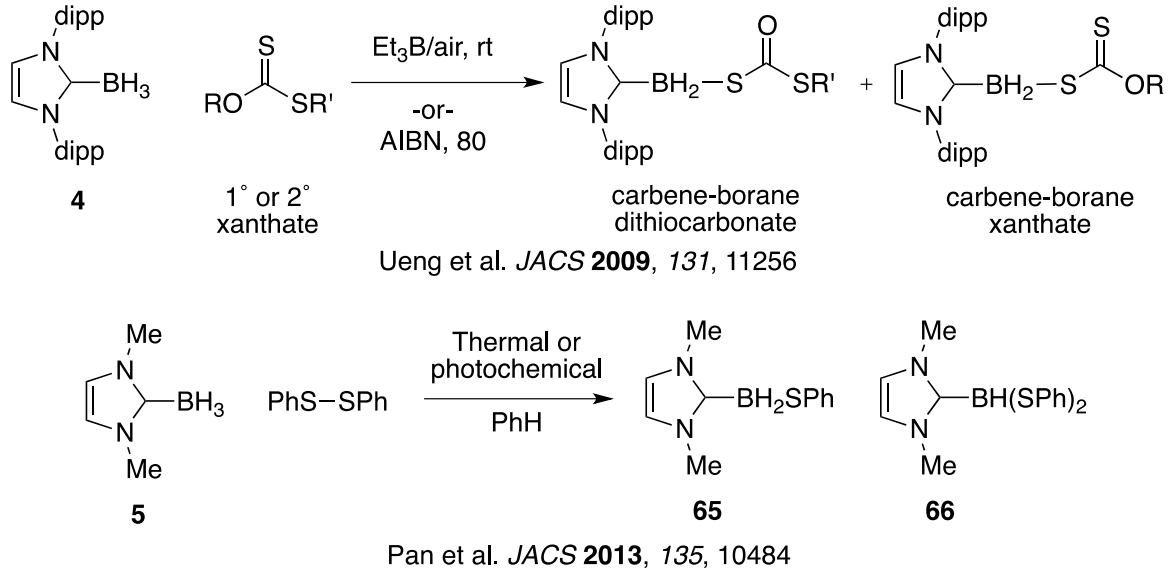
of the broadness of the ^{11}B NMR signals of dipp-carbene-borane overcame the relatively small J_{BD} (~13 Hz).

Deuterated dipp-carbene-borane appears to be stable to the quenching of excess LAD in the reaction mixture and to column chromatography. Deuterated diMe-carbene-boranes, however, appear to exchange hydrogen and deuterium during the quenching process of LAD, and therefore could not be isolated with purely single or double deuteration. DiMe-Imd-BD_3 (**61**), however, was isolated after quenching with saturated sodium sulfate in D_2O, which removed the possibility of proton contamination.

Future work would include finding a way to quench or remove unreacted LAD without disrupting the amount of deuteration on the boron atom of diMe-carbene-borane in order to isolate **59** and **60**. Once selectively deuterated diMe-carbene-boranes are isolated, new isotopic studies could be performed with advantage of having the proton-to-deuterium ratio built onto the boron atom.

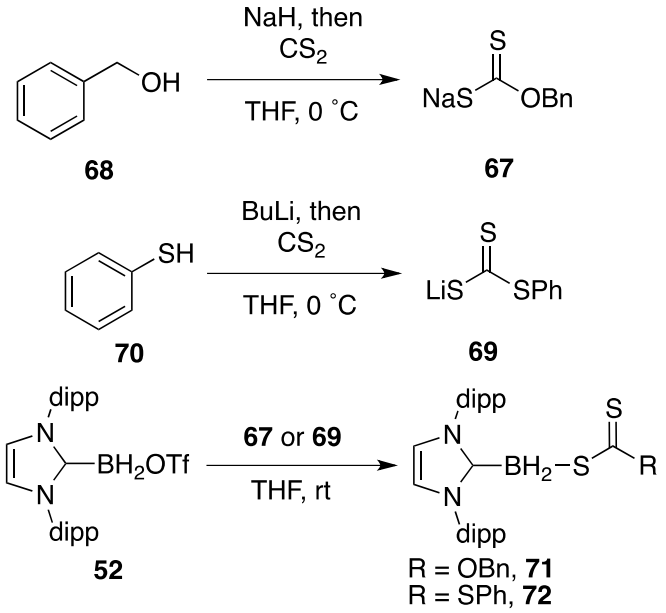
2.4.2 Synthesis of carbene-borane sulfur compounds

Sulfur substituted carbene-boranes were first observed as byproducts of the radical deoxygenation of xanthates by carbene-boranes (**Scheme 3**). Both carbene-borane dithiocarbonates and carbene-borane xanthates were isolated under radical conditions (**Scheme 30**). Carbene-borane thiols **65** and **66** were isolated from thermal or photochemical reactions of **5** with phenyl dithiol. Carbene-borane thiols were useful as initiators and precatalysts for radical reductions[54] so we wanted to synthesize carbene-borane xanthates or carbene-borane di- or trithiocarbonates as possible radical addition-fragmentation chain transfer (RAFT) polymerization reagents.



Scheme 30. Previous work on the synthesis of carbene-borane dithiocarbonates, xanthates, and thiols

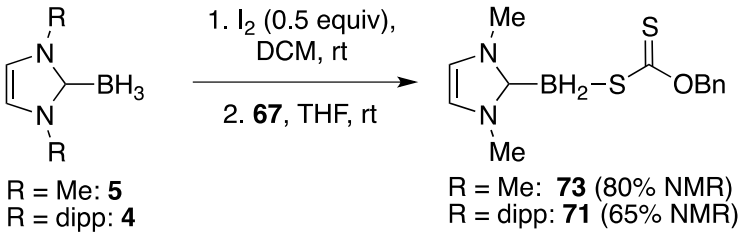
Synthesis of trithiocarbonate-substituted and xanthate-substituted dipp-NHC-borane by substitution of xanthate nucleophiles was reported by Dr. Andrey Sololyev in 2010 (**Scheme 31**).[29] Xanthate nucleophile **67** was synthesized by adding benzyl alcohol (**68**) to sodium hydride at 0 ˚C in THF, then adding carbon disulfide to the reaction mixture. Similarly, the trithiocarbonate **69** was synthesized by adding n-butyllithium to thiophenol (**70**), then adding carbon disulfide. The dipp-NHC-borane-triflate (**52**) was treated with **67** or **69** at rt to give xanthate-substituted borane **71** or trithiocarbonate-substituted borane **72**.



Scheme 31. Synthesis of thiocarbonate-carbene-borane by Dr. Andrey Solovyev

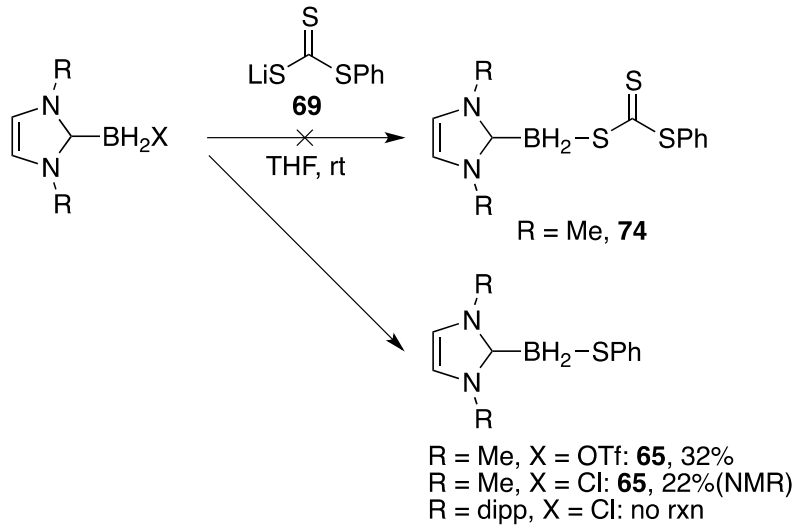
Given the success of these substitution reactions with dipp-NHC-BH_3, synthesis of similarly substituted diMe-NHC-borane was attempted. Also substitutions with diMe-Imd-BH_2I were successful with selective deuterium substitution, so the boryl-iodide **31** instead of a boryl-triflate was reacted under Solovyev's conditions. DiMe-NHC-BH_2I (**31**) was synthesized in DCM, and a solution of xanthate **67** in THF was added to the mixture at rt and stirred for 1 h (**Scheme 32**). ^{11}B NMR spectroscopy showed the formation of a broad singlet at –25.0 ppm, which is similar to the ^{11}B NMR signal of **71** (–24.4 ppm).[29] ^{13}C NMR spectroscopy of the crude sample showed the characteristic C=S carbon peak at 222.5 ppm[29] providing further support for the formation of xanthate-borane **73**. Purification by column chromatography was attempted, but the desired substituted-borane product (**73**) was not isolated. Dipp-Imd-BH_2I was also treated with **67** using the same procedure, which gave ^{11}B NMR peaks for **71** at –25 ppm (~65% of ^{11}B NMR peak integration) and for an unknown product at –24 ppm (~30% of borane peak

integration). Compound **71** nor any other byproduct were isolated by column chromatography. Iodine may be interfering with the formation of the xanthate-borane.



Scheme 32. Boryl-iodide reaction with xanthate **67**

The synthesis of trithiocarbonate-borane **74** was attempted by following Solovyev's procedures on diMe-Imd-BH_2OTf (**75**). The boryl-triflate **75** was prepared in DCM and trithiocarbonate **69** was added to the reaction mixture at rt. ^{11}B NMR spectroscopy showed the formation of a new broad triplet at –24.4 ppm (J_{BH} = 102 Hz). ^{13}C NMR spectroscopy, however, did not show the characteristic C=S peak. The product was isolated in 32% yield, and its spectra matched diMe-Imd-BH_2SPh (**65**, reported by Dr. Xiangcheng Pan in 2013[55]). Alternatively, substitution with diMe-Imd-BH_2Cl (**20**) was also tried using the same reaction conditions, but only 22% of **20** was converted and the product was again **65** instead of **74**. Dipp-NHC-BH_2Cl **44** did not react with trithiocarbonate **69**.



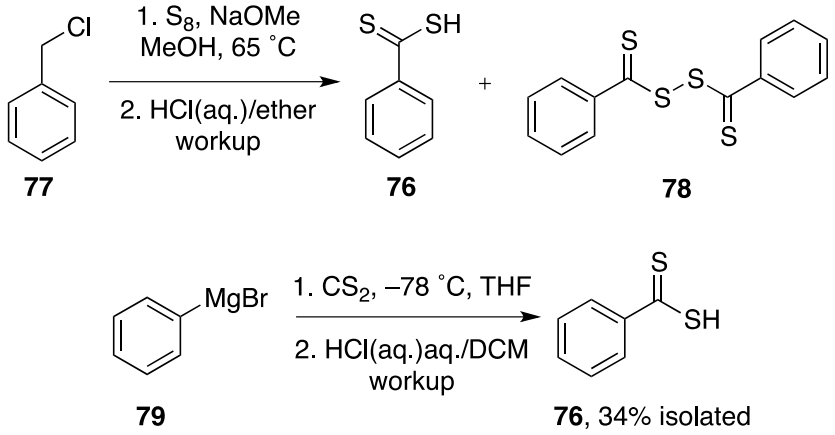
Scheme 33. Formation of carbene-borane thiol **65** from trithiocarbonate **69**

2.4.2.1 Synthesis of carbene-borane-dithiobenzoate

Next we wanted to try an acid-base reaction rather than a substitution reaction to form new carbene-borane sulfur compounds. Dithiobenzoic acid (**76**) was synthesized from a benzyl chloride (**77**) reaction with elemental sulfur and sodium methoxide in methanol at 65 ˚C.[56] Acidic workup (aq. HCl) gave a bright magenta solution in the organic layer. After rotary evaporation, a dark purple oil was obtained, and the ^{13}C NMR spectrum showed that both dithiobenzoic acid (**76**, thiocarbonyl peak at 225.4 ppm),[56] and the disulfide (**78**, thiocarbonyl peak at 219.6 ppm)[57] were present (**Scheme 34**).[58] Apparently, either the acid or its salt was partially oxidized during the reaction.

A procedure by Nuhn et al.[59] succeeded in synthesizing dithiobenzoic acid (**76**) without the disulfide impurity. Carbon disulfide was added to a solution of phenylmagnesium bromide (**79**) at 0 ˚C in THF. After acid workup and rotary evaporation of the organic layers, good quality crude dithiobenzoic acid (**76**) was obtained in 34% yield as a dark purple oil as determined by ^{1}H

and ^{13}C NMR spectroscopy (**Scheme 34**). The characteristic dithiocarbonic acid proton peak was observed in ^{1}H NMR at 6.39 ppm, and the thiocarbonyl peak was observed by ^{13}C NMR spectroscopy at 225.4 ppm, which matched the signals reported in literature.[56]

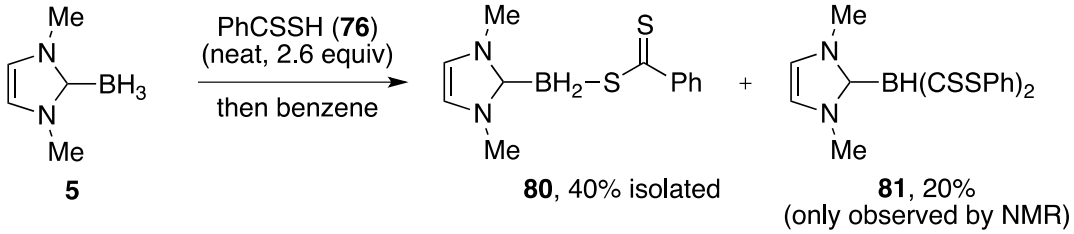


Scheme 34. Syntheses of impure (top) and pure (bottom) dithiobenzoic acid (**76)**

A substitution route to obtain a new sulfur-substituted carbene-borane product was then attempted by reacting diMe-Imd-BH_2OTf (**75**) in $CDCl_3$ with 1.1 equiv of dithiobenzoic acid (**76**) with and without potassium carbonate as a base to deprotonate the acid. Both reactions resulted in the formation of a new broad singlet in the ^{11}B NMR spectrum at –1.4 ppm, which is not a reasonable resonance for a sulfur-substituted carbene-borane. A TLC of the reaction mixture only streaked so the unknown product appeared to be unstable to silica gel.

We next performed acid-base reactions between **5** and **76**. DiMe-Imd-BH_3 (**5**) was treated with freshly synthesized dithiobenzoic acid (**76**). The carbene-borane was dissolved in $CDCl_3$ and 2 equiv of **76** was added to the solution. After 4 h about 11% of **5** had converted to a new compound with a broad triplet at –24.0 ppm as observed by ^{11}B NMR spectroscopy. In order to increase the conversion rate, the reaction was conducted at 60 ˚C in $CDCl_3$, but many new ^{11}B NMR peaks were observed after 4 h.

A direct reaction between neat dithiobenzoic acid (**76**) and diMe-Imd-BH_3 was then performed at rt to increase the conversion to new product. Dithiobenzoic acid (2.6 equiv) was added directly to solid carbene-borane **5** to form a dark purple slurry. After 30 min at rt, a small amount of benzene was added to dissolve all the solids, and the mixture was stirred for an additional 4 h. The desired broad singlet peak at –24.0 ppm was observed by ^{11}B NMR spectroscopy of the crude mixture in addition to smaller peaks at –15.7 ppm for a di-sulfur-substituted carbene-borane and at –13.2 ppm for an unknown boron compound. During column chromatography, the ruby red product band was collected, and after rotary evaporation a waxy ruby red solid was obtained. ^{11}B NMR spectroscopy of the ruby red compound showed that the product was the mono-sulfur-substituted carbene-borane **80**, isolated in 40% yield (**Scheme 35**). Additionally, the ^{13}C NMR of the ruby red compound showed a C=S signal at 239.5 ppm, which confirmed that the carbene-borane-dithiobenzoate **80** formed rather than the carbene-borane-sulfide **65**. The disubstituted carbene-borane product **81** (compound with a –15.7 ppm peak) was unfortunately not isolated and may be unstable to chromatography. Direct reaction of dithiobenzoic acid **76** with dipp-NHC-BH_3 was also attempted by using the same procedure as for **80**, but little to no reaction occurred.



Scheme 35. Carbene-borane **5** reaction with dithiobenzoic acid **76**

2.4.2.2 Conclusions on synthesis of carbene-borane-sulfur compounds

Substitution of diMe-carbene-borane to make carbene-borane xanthates or carbene-borane trithiocarbonates seems to occur similar to reactions with dipp-carbene-borane. Unlike reactions with dipp-carbene-borane, however, the resulting diMe-carbene-borane products are unstable to chromatography or may undergo side reactions. For example, formation of carbene-borane xanthate **73** was observed by ^{11}B and ^{13}C NMR, but the product was not stable to purification by column chromatography. Likewise, synthesis of trithiocarbonate **74** was not successful, and only the carbene-borane-thiol **65** was formed through loss of carbon disulfide.

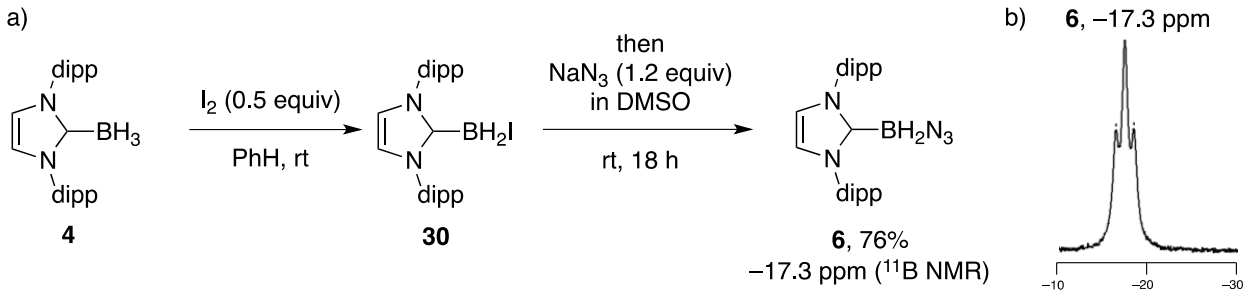
Direct acid-base reaction of dithiobenzoic acid (**76**) with carbene-borane **5** was successful, and the new carbene-borane-dithiocarbonate **80** was isolated. Acid-base reaction with carbene-borane **4**, however, did not occur. We anticipate that if acidic enough, other carbodithioic acids would react with carbene-boranes **4** and **5** to form new carbene-borane-dithiocarbonates.

2.4.3 Synthesis of carbene-boryl-azide

Substitution of halogenated carbene-borane with azide was our next goal; however, additional safety precautions were needed because explosive decomposition is a concern when working with low molecular weight azides. According to a rule of thumb, an organic azide will be non-explosive if the total number of nitrogen atoms in the compound does not exceed the total number of carbon atoms in the compound, and if $(N_O + N_C)/N_N \geq 3$ (N_O = number of oxygen atoms, N_C = number of carbon atoms, and N_N = number of nitrogen atoms in the compound).[60] This formula does not include boron atoms, which should be counted with carbon and oxygen atoms. However, since our compounds only have one boron atom, boron was omitted from the

calculations. In this study, dipp-Imd-BH_2N_3 **6** should be stable according to the rule above because the carbon-to-nitrogen ratio is 5.4. DiMe-Imd-BH_2N_3 (**82**) has a carbon-to-nitrogen ratio of 1.0, and therefore is potentially unstable and explosive. As a safety precaution, blast shields were used, and small-scale test reactions were performed whenever azide compounds were present. Halogenated solvents were also avoided to prevent the unintentional formation of highly explosive alkyl azides such as diazidomethane from dichloromethane.[61]

The mono-substituted boryl-azides were synthesized from **30** or **31**. Dipp-Imd-BH_2N_3 **6** was synthesized according to the method developed by Dr. A. Solovyev.[29] Dipp-Imd-BH_3 (6.2 mmol) was treated with iodine (0.5 equiv) to form dipp-Imd-BH_2I (**30**). The purity of **30** was checked by a crude ^{11}B NMR of the reaction mixture. The iodide was then treated with sodium azide (1.1 equiv) to give the carbene-boryl-azide **6** as determined by ^{1}H and ^{11}B NMR (t, –17.1 ppm, J_{BH} = 99 Hz) spectroscopy. The isolated yield of **6** was 76% after purification by flash chromatography (**Scheme 36**).



Scheme 36. Synthesis of dipp-Imd-BH_2N_3 (**6**)

Carbene-boryl-azide **6** melts at 180-182 ˚C, and bubbling presumably from nitrogen gas release occurs at 270 ˚C. The stability in polar solvents of boryl-azide **6** was tested by heating **6** to 80 ˚C as a 0.05 M solution in both DMSO and DMF. No changes to the ^{11}B or ^{1}H NMR spectrum were observed after 5 h. This suggested that small-scale thermal reactions with this

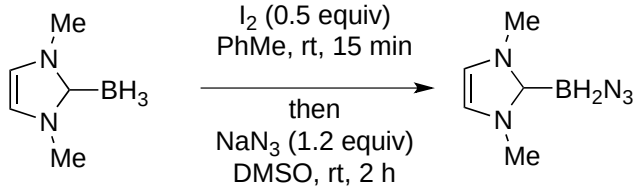
azide should be safe, but we still routinely use a shield in all thermal azide reactions as a precaution.

Encouraged by the stability of **6**, we next synthesized boryl-azides from diMe-Imd-BH_3 using similar reaction conditions as the synthesis of **6**. We started at a very small scale (~10 mg, 0.09 mmol) as a safety precaution. The monoiodide borane **31** was prepared in benzene, and a solution of sodium azide (1.2 equiv) in DMSO was added to the mixture. A crude ^{11}B NMR spectrum showed that **82** formed with a similar ^{11}B NMR signal (t, –17.9 ppm, J_{BH} = 99 Hz) as **6** (t, –17.1 ppm, J_{BH} = 99 Hz). A small amount of diazide **83** was observed as a doublet signal in the ^{11}B NMR spectrum at –7.0 ppm (J_{BH} = 112 Hz). This is similar to the reported signal reported for dipp-Imd-$BH(N_3)_2$ (d, –6.9 ppm, J_{BH} = 114 Hz).[29] Diethyl ether and water were added to the crude mixture to form a partition between the water and organic layer. The water layer was removed and the organic layer was washed three times with water and once with brine to remove the DMSO. Rotary evaporation of the organic solvents gave **82** as a colorless oil. The oil was dissolved in deuterated toluene, and ^{11}B NMR spectroscopy confirmed that the carbene-boryl-azide was present. This solution was then heated to 80 ˚C behind a blast shield for 5 h. Both ^{1}H and ^{11}B NMR spectroscopy showed little to no change after heating, indicating that **82** is somewhat thermally stable in solution.

Next we gradually increased the scale of the synthesis of **82**. Toluene was used instead of benzene in these scale up reactions to avoid the undesirable health effects of benzene. At 0.45 mmol scale, **82** was obtained after workup as a colorless oil with impurities **83** and **5**. Purification by column chromatography did not completely remove these impurities, giving a colorless oil at 40% yield with a 97% purity. The purity of **82** was calculated from the integration of the imidazolium methyl singlet in the ^{1}H NMR spectrum of **82** (3.84 ppm), **83** (3.89 ppm), and

5 (3.72 ppm). At 0.9 mmol scale, **82** was obtained in a 30% yield with 91% purity after column chromatography. Increasing the scale even more gave better yields with 84% yield and 99% purity at 1.8 mmol scale, and 90% yield and 97% purity at 2.7 mmol scale. The 2.7 mmol reaction was the maximum scale that **82** was synthesized (300 mg of **5**, 350 mg of iodine, and 198 mg of sodium azide to give 400 mg of **82**). Azide **82** was stored as a 0.066 M solution (10 g/L) in toluene in the freezer.

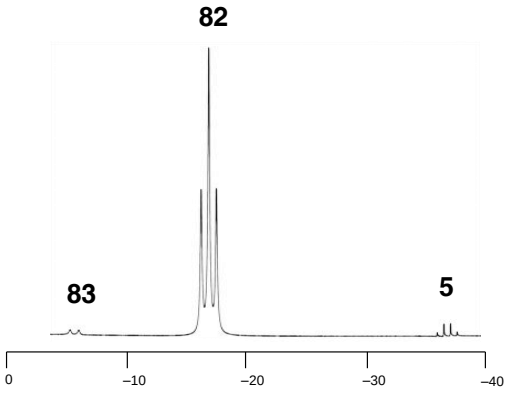
a)



5 **82**

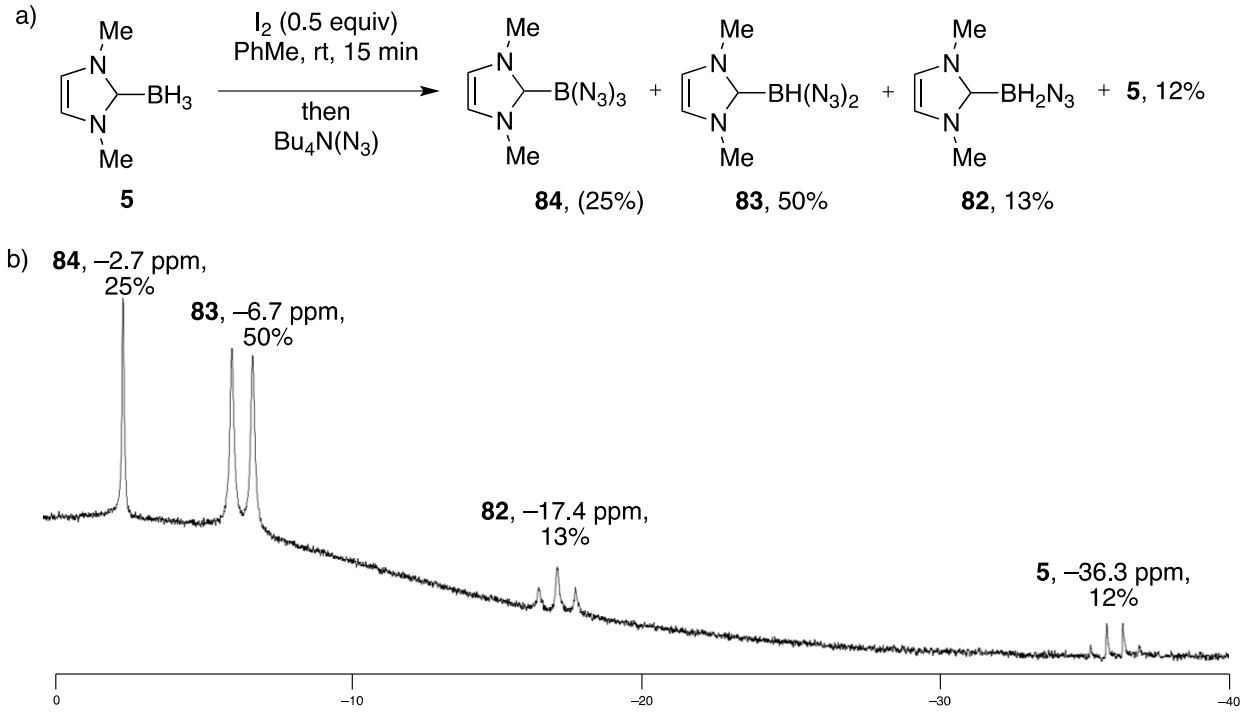
Entry	Scale (mmol)	Purity	Yield
1	0.45	97%	42%
2	0.9	91%	30%
3	1.8	99%	84%
4	2.7	97%	96%

b)



Scheme 37. a) Synthesis of **82** b) ^{11}B NMR of **82**

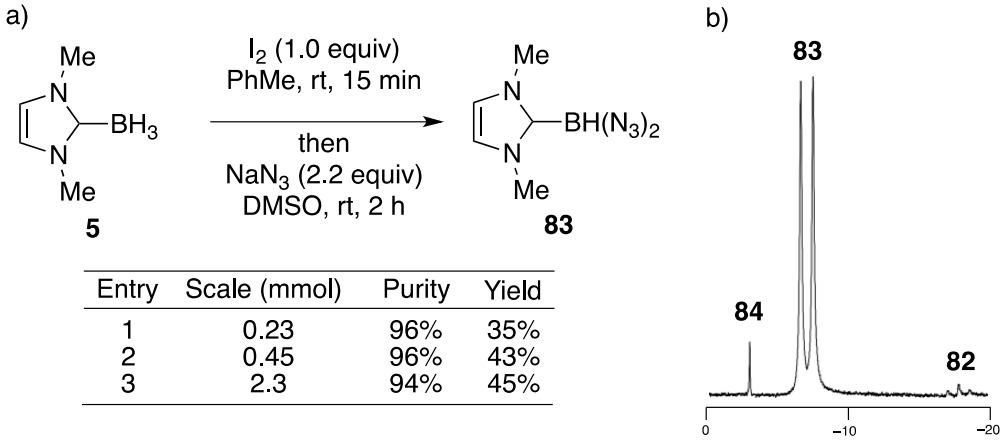
We also tried synthesizing **82** using tetrabutylammonium azide, $Bu_4N(N_3)$, instead of sodium azide in DMSO solution. DiMe-Imd-BH_2I was prepared in benzene, and tetrabutylammonium azide (1 equiv) was added as a solid to this solution. An ^{11}B NMR spectrum of the crude mixture was taken after 10 min, and four signals were observed. The starting carbene-borane **5**, the monoazide **82**, and the diazide **83** were present in the addition to the appearance of a new singlet at –2.7 ppm, which we suspect is the triazide **84**. The triazide **84** has an extremely low carbon-to-nitrogen ratio of 0.45, so we did not pursue isolation of this compound.



Scheme 38. a) Reaction of **5** with $Bu_4N(N_3)$ b) ^{11}B NMR spectrum of reaction mixture

Next we synthesized the diazide **83** from the diiodide **34**. The diazide **83** is also potentially explosive (0.63 carbon-to-nitrogen ratio) so blast shields were used during these reactions and workups. DiMe-Imd-BHI_2 (0.9 mmol) was prepared in toluene, and a solution of NaN_3 (2.2 equiv) in DMSO was added. The mixture was stirred for 2 h, and an ^{11}B NMR spectrum of the crude mixture showed that the main product formed was the diazide **83** (98%, d, –7.0 ppm, J_{BH} = 114 Hz) along with the suspected triazide **84** (2%, s, –2.9 ppm) and monoazide **82** (2%, t, –18.0 ppm) as minor byproducts. The crude mixture was worked up using water and diethyl ether to give a colorless oil. The oil was dissolved in toluene and heated to 80 ˚C for 5 h, and the ^{11}B NMR spectrum did not change, indicating some thermal stability in solution. The synthesis of the diazide-carbene-borane was repeated at 0.23 mmol scale to give a 35% yield of **83** in 96% purity after column chromatography. Similar to the synthesis of **82**, purity of **83** was

calculated from the integration of the imidazolium methyl ^{1}H NMR signals of **83** (3.89 ppm), **84** (4.00 ppm), and **82** (3.84 ppm). Scaling up to 0.45 mmol gave 43% yield in 96% purity of **83**, and a 2.3 mmol scale yielded 45% of **83** in 94% purity.



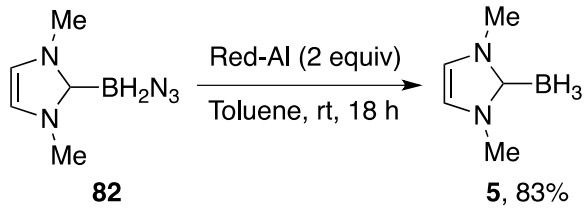
Entry	Scale (mmol)	Purity	Yield
1	0.23	96%	35%
2	0.45	96%	43%
3	2.3	94%	45%

Scheme 39. a) Synthesis of **83** b) ^{11}B NMR of **83**

In summary, carbene-boryl-azides **6**, **82**, and **83** were successfully synthesized from the corresponding carbene-borane in one pot by iodination followed by nucleophilic substitution. Although the dipp-Imd-BH$(N_3)_2$ has been synthesized from the ditriflate **53**,[29] synthesis through iodination was not possible since dipp-carbene-borane (**4**) only forms the mono-iodide **30** upon reaction with iodine. Azide **6** is easily handled as a bench-stable white solid, but **82** and **83** are oils that were stored in the freezer as a toluene solution. Syntheses of **82** and **83** generally gave better yields at larger scales, but purity seemed to be independent of scale. Checking that the formation of the carbene-borane-mono- or diiodide was complete by crude ^{11}B NMR spectroscopy was very important for obtaining good yields of the corresponding carbene-boryl-azides in high purity.

2.4.3.1 Attempted azide-like reactions of boryl-azide

There are standard conditions for reducing alkyl or aryl azides to amines.[30] We tried several of these reductive conditions to try to reduce the azide into an amine on the boron center. First we treated **82** with triphenylphosphine (6 equiv) using an established procedure[62] by dissolving both in THF/water solution and stirring for 18 h. A small amount of boric acid (~1%) was observed as a broad singlet at 24 ppm by ^{11}B NMR spectroscopy, but the signal for **82** was unchanged. Carbene-boryl-azide **82** was also treated with triphenylphosphine (5 equiv) in toluene at 110 ˚C for 48 h, but little to no change of the boron signal for **82** was observed in the ^{11}B NMR spectrum. Another azide reduction method was tried using sodium borohydride (1.05 equiv), triethylamine (2.0 equiv) and 10 mol% of 1,3-propanedithiol,[63] but no change of the ^{11}B NMR signal for **82** was observed. Finally, we treated **82** with a very strong reducing agent, Red-Al (sodium bis(2-methoxyethoxy)aluminumhydride), in toluene. Some gas evolution was observed, and ^{11}B NMR spectroscopy showed that 83% of **82** had been reduced to **5**. Boryl-azide is apparently very stable to reductive conditions.



82 **5**, 83%

Scheme 40. Reduction of **82** by Red-Al

The thermal experiments already showed that **82** does not decompose to a nitrene at 80 ˚C. We instead tried using UV light to make the boryl-nitrene from the carbene-boryl-azide. Using *Z*-stilbene (5 equiv) as a nitrene trap, we irradiated a 0.26 M solution in benzene of either

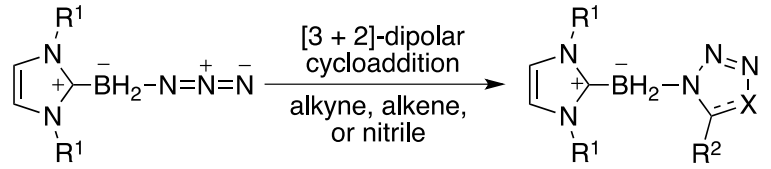
6 or **82** in a quartz NMR tube with UV light from a sun lamp for 1 h. No reaction occurred based on observations from ^{1}H and ^{11}B NMR spectroscopy.

Carbene-boryl-azides **6** and **82** are robust and tolerate some reductive reaction conditions. Red-Al, however, is a powerful reducing agent that over-reduced **82** to **5**. The quintessential reaction of azides is [3+2]-cycloadditions, so we decided to perform [3+2]-cycloadditions to further test the reactivity of carbene-boryl-azides since carbene-boryl-azides are also stable in solution at elevated temperatures.

2.5 CYCLOADDITIONS WITH CARBENE-BORYL-AZIDE

2.5.1 Cycloaddition reactions with dipp-Imd-BH_2N_3

Carbene-boryl-azide reacts with alkynes, alkenes, and nitriles by [3 + 2]-dipolar cycloaddition to give carbene-boryl-triazoles, -triazolidines, and –tetrazoles (**Scheme 41**). Carbene-boryl-azide and carbene-boryl-azide cycloaddition products all have a boron atom bonded to a carbene, two hydrogen atoms, and a nitrogen atom. This means that carbene-boryl-azide and carbene-borane-triazoles cannot easily be distinguished by ^{11}B NMR spectroscopy.



R^1 = dipp, **6**
R^1 = Me, **82**
EWG = electron withdrawling group

R^2 = H, alkyl, EWG
X = N, C–EWG, CH–EWG

Scheme 41. [3 + 2]-dipolar cycloaddition of carbene-boryl-azide

In order to monitor reaction completion trial reactions were conducted in deuterated solvents, and progress of cycloaddition reactions with **6** was followed by ^{1}H NMR spectroscopy. The proton signal of the hydrogen on the imidazole ring proved to be useful for following reaction progress (**Figure 13**). The starting material dipp-Imd-BH_2N_3 has an imidazole proton peak at 7.07 ppm in chloroform, and 6.33 ppm in benzene. The imidazole protons are sensitive to boron substituents, and the appearance of new singlets around 6.1 to 7.2 ppm indicated the formation of new products. NMR yields were calculated by integrating these ^{1}H NMR signals. In these calculations, we assumed that compound **6** only converted to the new cycloaddition products, and we will refer to these calculations as "NMR yields" in this section. When deuterated solvents were not used as a reaction solvent, progress was monitored by TLC using UV visualization and staining with vanillin stain. Carbene-borane compounds stain dark purple upon heating. Unless indicated otherwise, percent yields in this section are isolated yields after column chromatography.

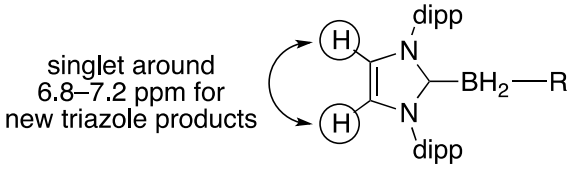


Figure 13. Imidazole protons used to monitor reactions by ^{1}H NMR spectroscopy

We expected carbene-boryl-azide to be more reactive with electron-deficient dipolarophiles because the boron donates electron density into the azide group making it more electron-rich. The unusual electronics of the carbene-boryl-azide and its high thermal stability could contribute to the synthesis of new or unusual triazoles.

2.5.2 Cycloadditions with terminal alkynes

Initially we studied cycloadditions of **6** with monosubstituted alkynes under thermal conditions. Dipp-Imd-BH_2N_3 **6** (1 equiv) was dissolved in deuterated benzene. Monosubstituted alkyne ethyl propiolate **85** (1 equiv) was added, and the mixture was heated for 21 h at 80 ˚C in an NMR tube. ^{1}H NMR spectroscopy revealed a new imidazole proton signal, and the absence of proton peaks from **6** indicated that it had been completely consumed. Purification by flash chromatography using ethyl acetate and hexanes gave triazole **86** in 78% yield (**Table 2**, entry 1).

Crystals were grown of triazole **86** for X-Ray crystallography by slow evaporation of a solution of the product in ethyl acetate and hexanes. The X-Ray crystal structure that was solved by Dr. S. Geib revealed that the triazole had formed as a 1,4-regioisomer (**Figure 14a**). The length of the boron-nitrogen bond of **86** is 1.567(5) Å, and this is similar to the boron-nitrogen bond length of the azide **6** (1.573(2) Å).[29] The boron-nitrogen bond of the borane-triazole is about 7% longer than the length of the carbon-nitrogen bond of a comparable triazole methyl 1-benzyl-1*H*-1,2,3-triazole-4-carboxylate **87** (1.4713(17) Å) (**Figure 14b**).[64]

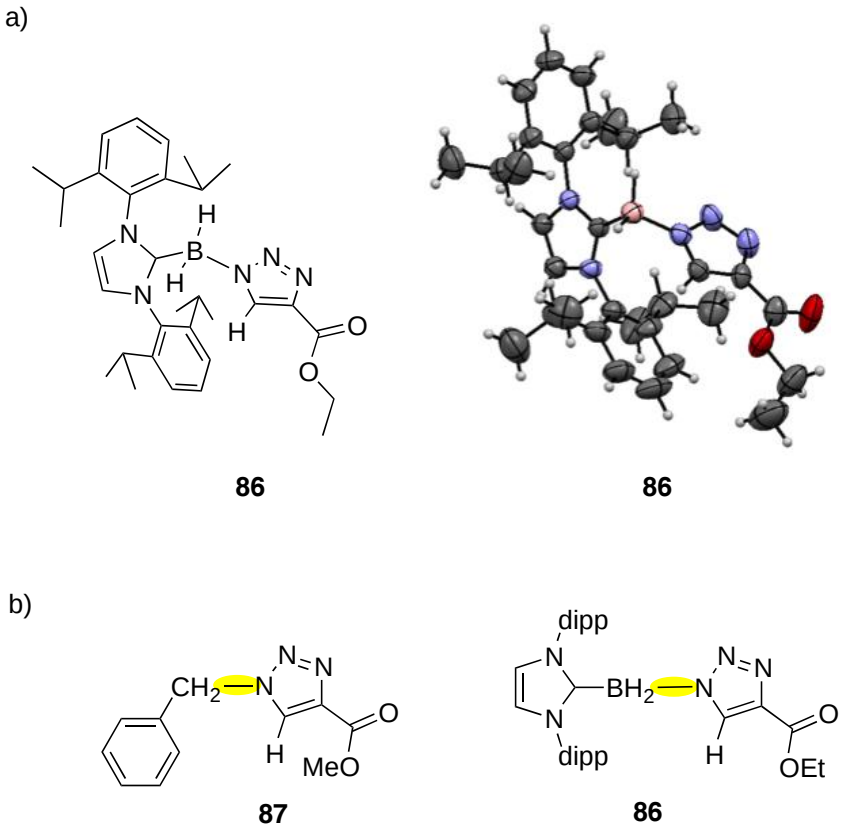


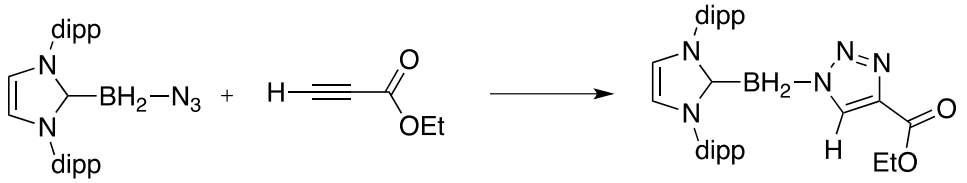
Figure 14. a) Crystal structure of carbene-borane-triazole **86**

b) Comparison of C–N bond length of triazole **87** and B–N bond length of **86**

Other reaction conditions were tried with ethyl propiolate **85** to increase the yield and decrease reaction time (**Table 2**). Excess of ethyl propiolate **85** (2 equiv) was treated with **6** in deuterated benzene at rt or at 80 ˚C. The reaction proceeded slowly at rt with only a 50% NMR yield after 1.5 d. The reaction at 80 ˚C was complete after 4 h, and purification by flash chromatography provided a 93% yield of **86**. An excess of **85** (2 equiv) was also treated with **6** in toluene, and the reaction mixture was heated to 110 ˚C. Progress was monitored by TLC, and the reaction was complete after 3.5 h. Purification by flash chromatography gave a 94% yield of

86. The reaction in toluene was repeated with 1.5 equiv of **85**, but only an 82% yield was obtained after 18 h at 110 ˚C.

Table 2. Thermal cycloaddition reactions of ethyl propiolate 12 and **6**



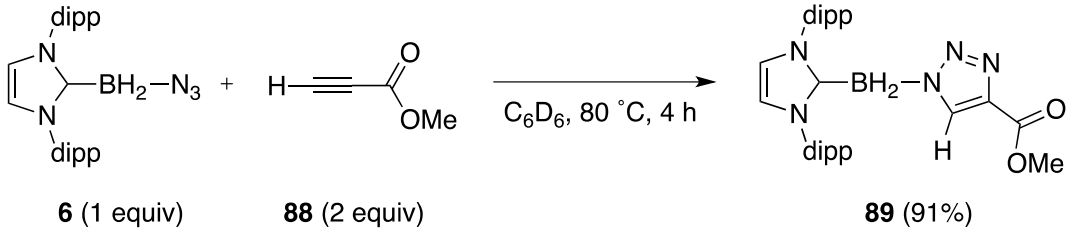
6 (1 equiv) **85** **86**

Entry	Equiv ethyl propiolate **85**	Temperature	Time	Yield of **86**
1	1	80 ˚C	21 h	78%[a]
2	2	rt	1.5 d	52%[b]
3	2	80 ˚C	4 h	93%[a]
4	2	110 ˚C (toluene)	3.5 h	94%[a]
5	1.5	110 ˚C (toluene)	18 h	82%[a]

a) Isolated yield after flash chromatography b) NMR yield

Although the best yield and reaction time came from using 2 equiv of **85** and refluxing the solution in toluene, the procedure using 2 equiv of alkyne and refluxing the solution in benzene was chosen for trial reactions. Toluene was a less desirable solvent for reactions in NMR tubes because deuterated toluene is more expensive than deuterated benzene. A typical reaction procedure for trial reactions was devised using benzene. One equiv of **6** (30 mg, 0.068 mmol) and 2 equiv of the alkyne (0.14 mmol) were dissolved in deuterated benzene (0.7 mL) in an NMR tube, and the reaction mixture was heated in an oil bath to 80 ˚C. Reaction progress was determined by ^{1}H NMR by observing changes in resonance intensity of the imidazole proton signals of **6** and the new product. The crude product was then purified by flash chromatography using a hexanes/ethyl acetate gradient.

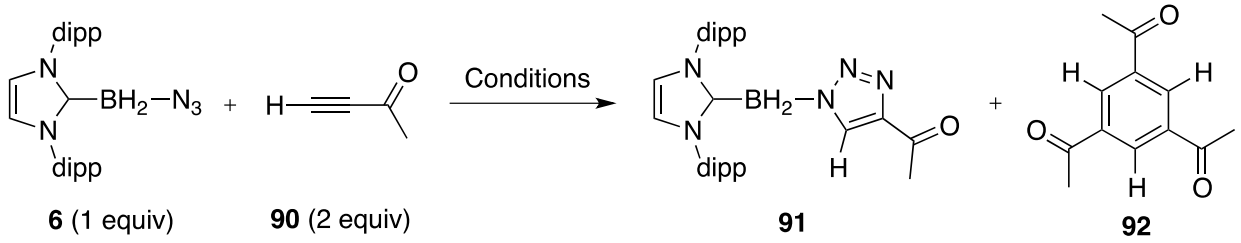
A very similar alkyne to **85**, methyl propiolate **88**, was treated with **6** using the typical reaction procedure. The reaction was complete after 4 h. Purification by flash chromatography gave a 91% yield of triazole **89** (**Scheme 42**).



Scheme 42. Thermal cycloaddition of **6** with methyl propiolate **89** under typical reaction conditions

Another terminal alkyne, 3-butyn-2-one **90**, was treated with **6** using typical reaction conditions. After the reaction mixture was heated for 4 h, purification by flash chromatography gave the triazole **91** in greater than 100% yield (**Table 3**, entry 1). Inspection of the ^{1}H NMR spectrum revealed an impurity identified by two singlets at 2.71 ppm and 8.70 ppm. Alkyne **90** is known to trimerize under thermal and catalytic conditions, and the ^{1}H NMR shifts match the values for the trimerized product 1,3,5-triacetylbenzene **92**.[65,66] The mole percentage of **19** present in the purified product was determined to be 5% by comparing the integration of the proton signals of **91** and **92**. In order to minimize the thermal cyclization of **90**, the reaction of **90** and **6** was performed at room temperature in benzene. The reaction was complete after 5 d, and purification by flash chromatography gave a 94% yield of triazole **91** (**Table 3**, entry 2). The final product still contained about 3 mol % of the impurity **92**. Although reduced temperatures appeared to prevent some formation of **92**, a ^{1}H NMR of the starting material **90** showed that it did contain a trace of trimer **92**.

Table 3. Cycloadditions of 3-butyn-2-one (**90**) and **6**

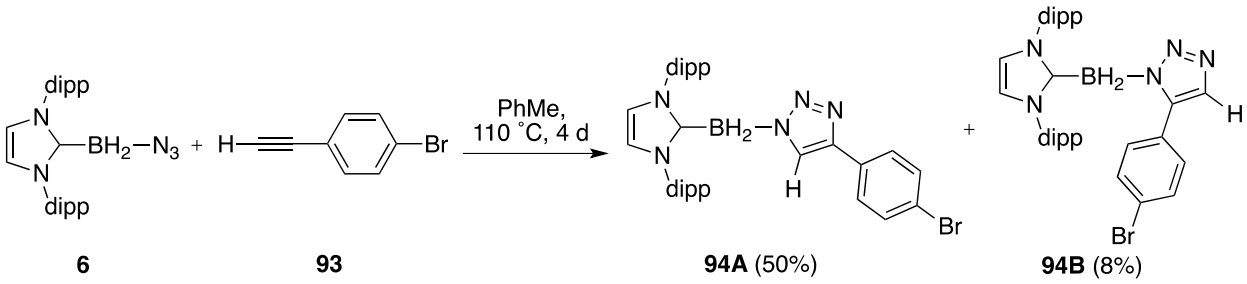


6 (1 equiv) **90** (2 equiv) **91** **92**

Entry	Conditions	Yield **91**[a]	Purity of **92**[b]
1	C_6D_6, 80 ˚C, 4 h	100%	95%
2	C_6D_6, rt, 5 d	94%	97%

*a) Yield after flash chromatography b) Percent of **18** in inseparable mixture of **18** and **19***

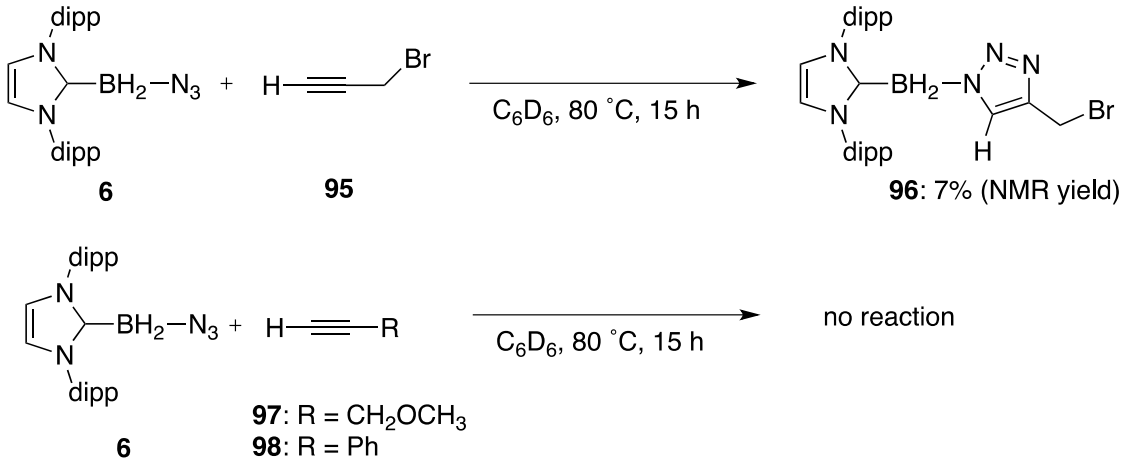
A terminal alkyne with an electron withdrawing aromatic group, 4-bromophenylacetylene **93**, was treated with **6**. After heating the mixture for 18 h under typical reaction conditions, an NMR yield of 1% was obtained. To achieve a higher yield of the triazole product, a mixture of **20** and **6** in toluene was heated to 110 ˚C. Reaction progress was monitored by TLC, and after 4 d the reaction was stopped. Flash chromatography gave an 8% yield of triazole regioisomer **94A** and a 50% of triazole regioisomer **94B** (**Scheme 43**). When two triazole products are formed that contain an aromatic group, the triazole with an aromatic group in the 1,5 position is designated **A**, and the triazole with an aromatic group in the 1,4 position is designated **B.** The method for identification of these regioisomers by ^{1}H NMR spectroscopy is discussed in section 2.1.2.



6 **93** **94A** (50%) **94B** (8%)

Scheme 43. Cycloaddition of **6** with 4-bormophenylacetylene 20

Propargyl bromide **95** was treated with **6** under typical reaction conditions, but the triazole product formed slowly. Proton NMR spectroscopy showed a 21% NMR yield after 40 h of a new product with an imidazole signal at 6.50 ppm. Presumably this was triazole **96**, but the resonance intensity for the new product decreased upon additional heating (**Scheme 44**). Methyl propargyl ether **97** and phenyl acetylene **98** did not react with **6** under typical reaction conditions. Apparently only terminal alkynes with an electron-withdrawing group readily perform thermal cycloadditions.

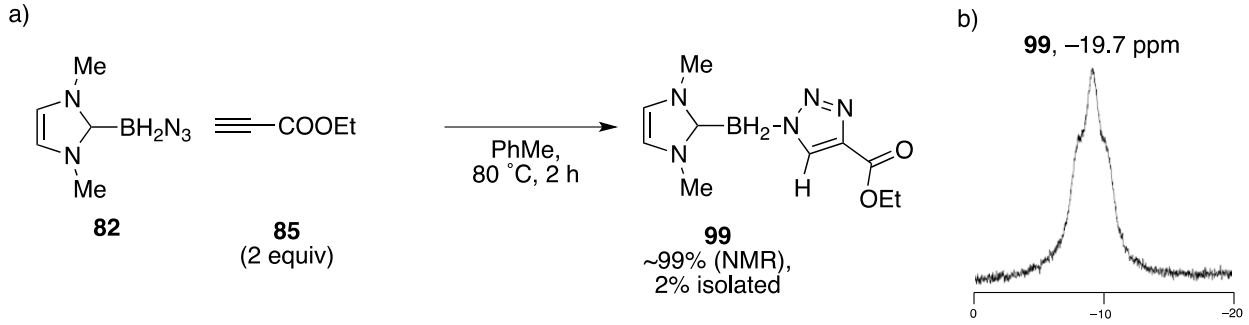


Scheme 44. Reaction of propargyl bromide **95**, methylpropargyl ether **97**, and phenylacetylene **98** with carbene-boryl-azide **6**

2.5.3 Cycloaddition of diMe-carbene-boryl-azides with alkynes

We treated monoazide **82** with electron-deficient alkynes to give new carbene-borane-triazole products. We expected increased reactivity of **82** with electron-deficient alkynes because of decreased sterics around the boron atom and azide. Also azide **82** is even more electron-rich than azide **6**, and therefore should be even more reactive with electron-deficient dipolarophiles.

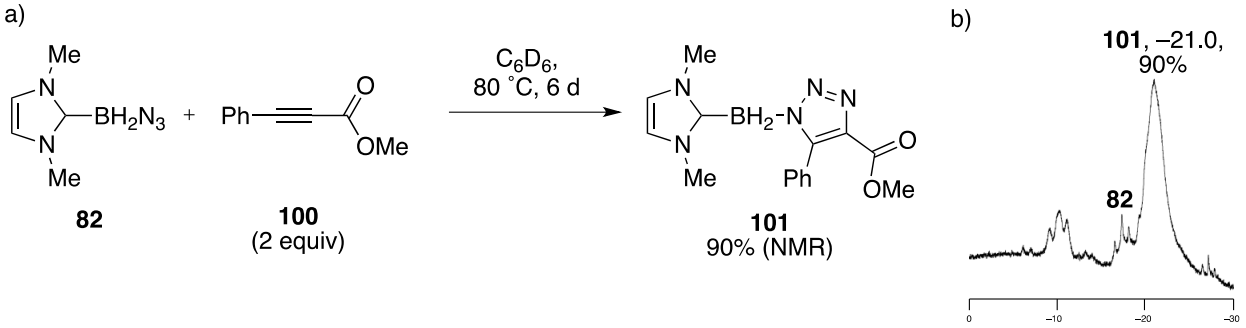
First we dissolved 0.11 mmol of **82** in C_6D_6. Ethyl propiolate (**85**) was then added to the solution. The color of the solution began to turn pink after 30 min, so ^{1}H and ^{11}B NMR spectra were taken. Small new imidazolium and ethyl ester ^{1}H NMR peaks were observed, and a new broad singlet ^{11}B NMR peak had formed at –19.5 ppm (**Scheme 45**). The mixture was stirred for 18 h at room temperature. Based on ^{1}H and ^{11}B NMR peak integration calculations, about 50% of **82** had converted to the new triazole product. To speed the conversion, the mixture was heated at 80 ˚C for 2 h. The reaction was deemed complete because the ^{11}B NMR signal for **82** had disappeared. Column chromatography (ethyl acetate/hexanes) was performed on the crude mixture, but the boryl-triazole **99** was not isolated. The reaction was scaled up to 0.9 mmol in toluene, and after 2 h heating at 80 ˚C the reaction was complete as determined by ^{11}B NMR spectroscopy. After purification by column chromatography, the very polar triazole product **99** was isolated in only 2% yield. Apparently the new product **99** is formed but is not stable to column chromatography.



Scheme 45. a) Reaction of azide **82** with ethyl propiolate (**85**) b) Crude ^{11}B NMR of triazole **99**

We next treated **82** with methyl phenylpropiolate (**100**). Methyl phenylpropiolate (2 equiv) was added to a solution of carbene-boryl-azide **82** (0.11 mmol) in C_6D_6, and the reaction mixture was heated to 80 ˚C. After 23 h about 62% of **82** had converted to a new triazole product, presumably compound **101**. The mixture was heated for a further 5 d, and the reaction

was 90% complete based on ^{11}B NMR peak integration (**Scheme 46**). Minor triplet peaks at –10.3 ppm and –27.0 ppm were present in addition to the main peak at –20.0 ppm in the ^{11}B NMR spectrum. Purification by column chromatography, again, did not yield any of the target triazole product.



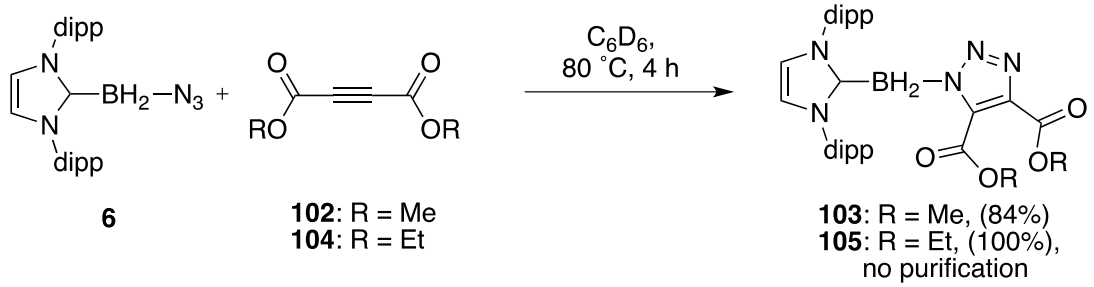
Scheme 46. a) Reaction of azide **82** with methyl phenylpropiolate **100** b) Crude ^{11}B NMR spectrum of triazole **101**

Based on these initial reactions with **82**, synthesis of diMe-imidazolium-carbene-borane-triazoles is possible, but the triazole products are very polar and are not stable to column chromatography. The reactivity of **82** with electron-deficient dipolarophiles also seemed to be about the same as the reactivity of **6**. We therefore focused our attention to cycloaddition reactions of dipp-carbene-boryl-azide **6** because dipp-imidazolium-carbene-boranes tend to be more stable and better amenable to column chromatography.[29] Dipp-Imd-BH_2N_3 (**6**) is easily handled as a solid and is safer than diMe-Imd-BH_2N_3 (**82**).

2.5.4 Cycloaddition with non-terminal alkynes

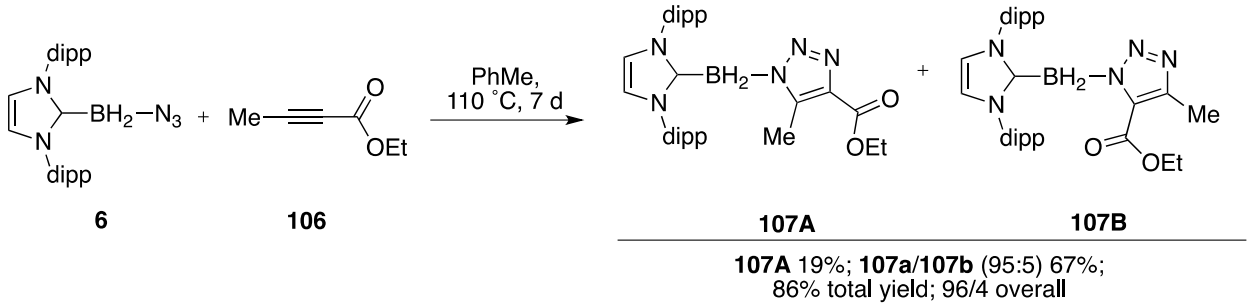
Based on the studies with terminal alkynes, only non-terminal alkynes containing at least one electron-withdrawing group were treated with **6**. An alkyne with two electron-withdrawing

carboxylate groups, dimethyl acetylenedicarboxylate (**102**), was treated with **6** using typical reaction conditions. After heating for 4 h, the reaction was complete, and purification by flash chromatography gave the triazole **103** in 84% yield (**Scheme 47**). Similarly, diethyl acetylenedicarboxylate (**104**) was treated with **6** under typical reaction conditions, and the reaction was complete after 4 h. Residual alkyne was removed by high vacuum to directly provide a relatively pure sample of **105** in 100% yield.



Scheme 47. Cycloadditions of **6** with acetylenedicarboxylates **102** and **104**

Ethyl 2-butynoate (**106**) was also submitted to typical reaction conditions with **6**, but very little formation of a new triazole product was observed after heating the mixture for 24 h. Compounds **106** and **6** were then dissolved in toluene, and the mixture was heated to 110 ˚C. Reaction progress was monitored by TLC, and all of **6** was consumed after 6 d. Proton NMR spectroscopy of the crude product showed a ratio of two triazole products in an 92 : 8 ratio. The crude product was purified by flash chromatography to give a 67% yield of a mixture of regioisomers **107A** : **107B** in an 95 : 5 ratio, and a 19% yield of pure **107A** (**Scheme 48**). The total recovered yield was 86%.



Scheme 48. Thermal cycloaddition of **6** with ethyl 2-butynoate (**106**) to give 86% total yield of **107**

Crystals of pure **107A** (major product) were grown by slow vapor diffusion of pentanes into dichloromethane. X-Ray crystallography performed by Dr. S. Geib showed that this was the 1,4-regioisomer (**Figure 15**). The boron-nitrogen bond of **107A**, 1.564(5) Å, was nearly identical to the boron-nitrogen bond length of **86**, 1.567(5) Å.

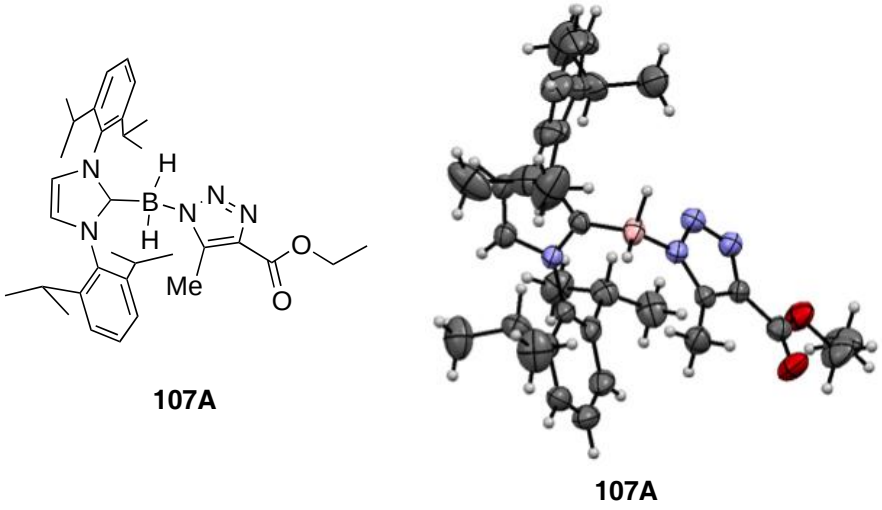
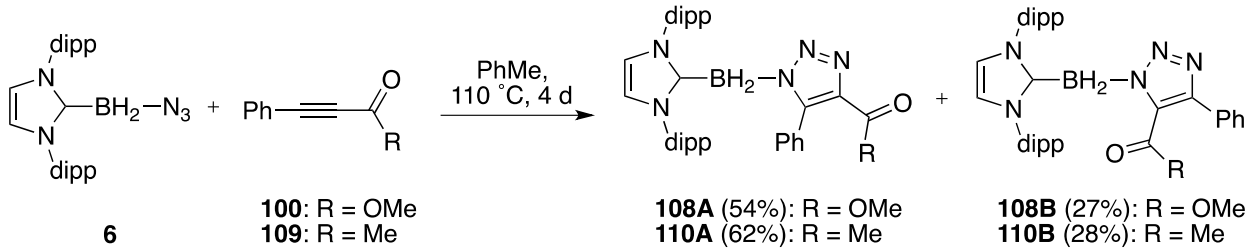


Figure 15. Crystal structure of **107A**

Methyl phenylpropiolate (**100**) was treated with **6** under typical reaction conditions. Only a 34% NMR yield was obtained after 2.5 d of heating. The reaction was repeated by refluxing a solution of **32** and **6** in toluene, and after 4 d the reaction was deemed complete by TLC analysis. The ^{1}H NMR spectrum of the crude product showed a 58 : 42 ratio of triazole regioisomers **108A**

to **108B**. Flash chromatography was performed to yield 54% of triazole regioisomer **108A** and 27% of the triazole regioisomer **108B** (**Scheme 49**). Characterization of the regioisomers is discussed below.

An alkyne with an acyl group and a phenyl group, 4-phenyl-3-butyn-2-one **109**, was also treated with **6** by refluxing the mixture in toluene. After 4 d, the reaction was complete, and a crude ^{1}H NMR spectrum showed a 67 : 33 ratio of triazole regioisomers **110A** to **110B**. Purification by flash chromatography gave 62% of regioisomer **110A** and 28% of triazole regioisomer **110B** (**Scheme 49**).



6

100: R = OMe
109: R = Me

108A (54%): R = OMe
110A (62%): R = Me

108B (27%): R = OMe
110B (28%): R = Me

Scheme 49. Thermal cycloaddition of **6** with methyl phenylpropiolate (**100**) and 4-phenyl-3-butyn-2-one (**109**)

In reactions with alkynes containing an aromatic group, the product triazoles showed a trend in the ^{1}H NMR spectra. A characteristic doublet was observed at 6.46 ppm for triazole **108A**, 6.47 for triazole **110A**, and 6.52 ppm for triazole **94A** (**Figure 16**). These signals are relatively shielded for aromatic protons. The corresponding doublets for the other regioisomer were observed at 7.57 ppm for **108B**, 7.53 ppm for **110B**, and 7.42 ppm for **94B**. We hypothesized that the protons in the 2 and 6 positions of the aromatic group attached to the triazole are shielded by the pi electron clouds on the dipp groups of the carbene-borane.[67]

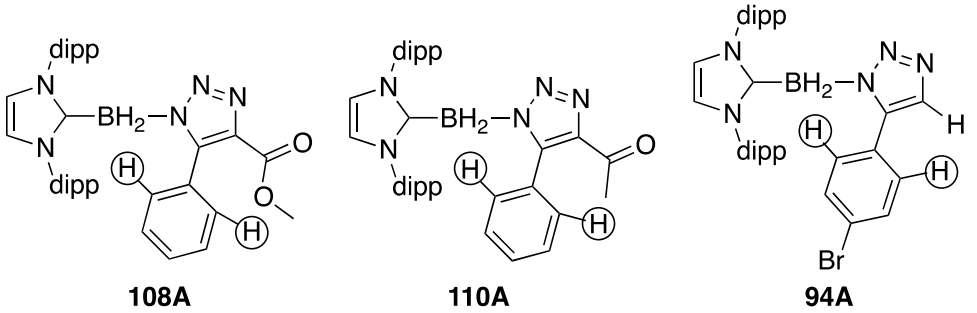


Figure 16. The circled hydrogen of triazole products **108A**, **110A**, and **94A** give upfield ^{1}H NMR spectroscopy signals

Crystals of **110A** were grown by slow vapor diffusion of pentanes into dichloromethane, and the crystal structure was solved by Dr. S. Geib. Indeed, one of the hydrogens on the phenyl ring of the triazole was too close to an aromatic ring of a dipp group (**Figure 17**). Based on these results, we assigned the phenyl group to be in the 5 position for structures that contained the upfield doublet in proton NMR spectra.

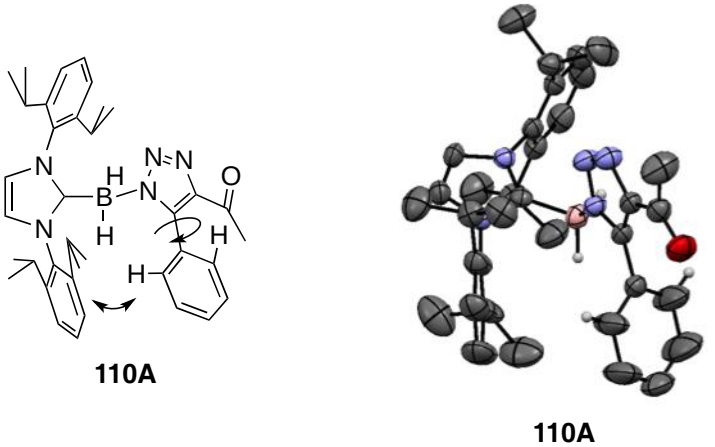


Figure 17. Crystal structure of **110A** (some hydrogens omitted for clarity). Arrows highlight shielded protons.

2.5.5 Microwave reactions

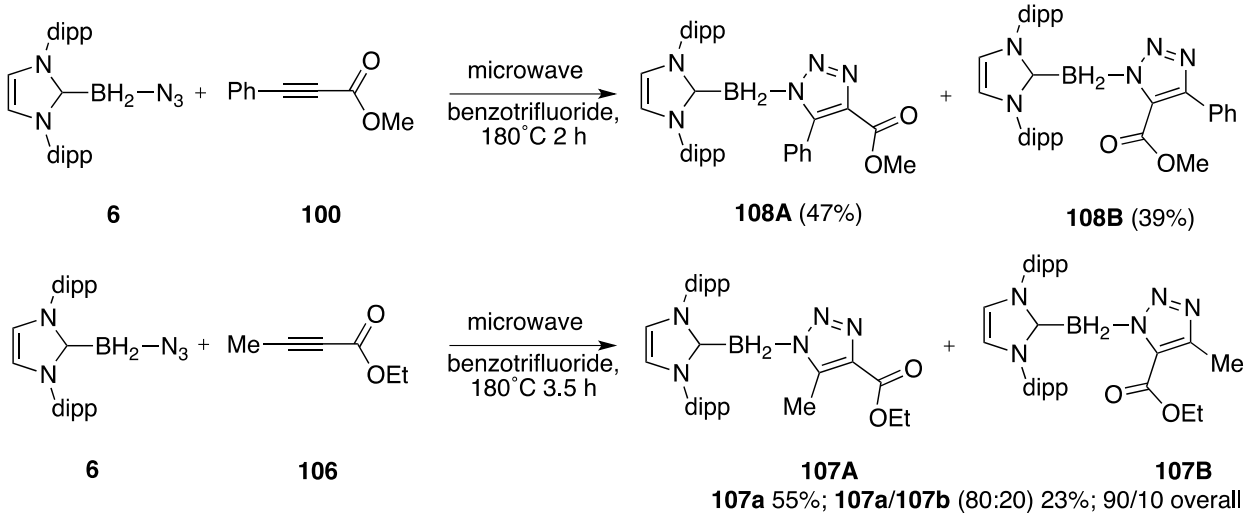
Although complete conversion to triazole products in reactions with non-terminal alkynes was possible, the reaction times were long and product yields were moderate. Microwave chemistry has been shown to decrease reaction times drastically by heating the reaction solvent uniformly, whereas oil baths only heat the reaction indirectly by conduction.[68] Microwave chemistry also allows the reaction solvent to be heated rapidly above its boiling point in an increased pressure environment.

The stability of dipp-Imd-BH_2N_3 in a microwave environment was first tested. A small amount of **6** (10 mg) was dissolved in toluene, and the solution was heated in the microwave. The reaction mixture, however, only reached 120 ˚C so benzotrifluoride (BTF) was used. Benzotrifluoride easily dissolved **6**, and the solution was heated to 180 ˚C in the microwave for 1 h. After evaporation of the BTF, the ^{1}H NMR spectrum showed that the azide remained intact.

Next 2 equiv of alkyne **100** was treated with 30 mg of azide **6** in benzotrifluoride at 180 ˚C. After 2 h, TLC showed a faint spot of the starting material **6** and two new spots. The crude product was purified by flash chromatography to give 47% of **108A**, 39% of **108B**, and 8% of starting material **6** (**Scheme 50**). The ratio of regioisomers of the microwave reactions (55 : 45) was lower than the ratio from the thermal reaction (69 : 31).

Alkyne **106** was also treated with 30 mg azide **6** in benzotrifluoride. A TLC of the crude reaction mixture after 2.5 h under microwave conditions showed that azide **6** was still present. The mixture was heated for an additional 1 h, and TLC showed that all of **6** had been consumed. The solvent and excess alkyne were evaporated and a ^{1}H NMR spectrum of the crude showed an 90 : 10 regioisomer ratio of **107A** to **107B** which is about the same as the 92 : 8 crude product

ratio of the thermal reaction. After column chromatography, a 55% yield of pure **107A** and a 23% yield of a 80 : 20 mixture of **107A**/**107B** was obtained (**Scheme 50**).



Scheme 50. Microwave reactions of **6** with non-terminal alkynes **100** and **106**

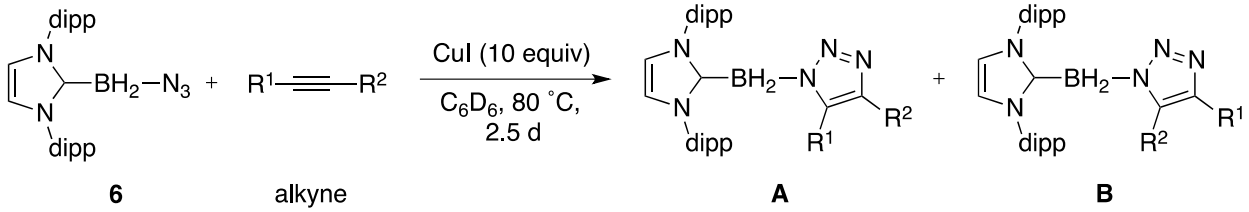
Although reaction times were reduced from 4 d to 2 h for **100**, and 6 d to 3.5 h for **106**, the 1,4 regioisomer was less favored in the formation of triazole products **108A** and **108B**. The microwave reaction with **106** gave similar ratios of regioisomers **107A** and **107B** as the thermal reaction.

2.5.6 Cycloadditions with copper catalysis

In search for better selectivity and shorter reaction times with non-terminal alkynes, copper salts were used in some cycloaddition reactions. Sharpless and coworkers found that copper (I) sources direct the formation of triazole to the 1,4 regioisomer.[36] Copper (I) sources can come from copper (I) salts directly, or copper (II) salts can be reduced in situ to give copper (I).[37]

Copper (I) iodide was used as a source of copper (I) for the cycloadditions of **93**, **98**, **106**, and **100**.[69] Ten equivalents of copper (I) iodide were added to a solution of **6** and 2 equiv of alkyne in deuterated benzene. After 2.5 d of heating at 80 ˚C, a 15% NMR yield was calculated for the reaction with 4-bromophenylacetylene **93** (**Table 4**, entry 1), but no new proton signals were observed for phenylacetylene **98** (**Table 4**, entry 2). Cycloaddition of ethyl 2-butynoate **106** gave a 26% NMR yield of **107** in an 86 : 14 ratio of regioisomers (**Table 4**, entry 3). Selectivity of regioisomers was still poor with the cycloaddition of methyl phenylpropiolate **100**, and a 44% NMR yield of **106** in a 61 : 39 ratio was obtained (**Table 4**, entry 4).

Table 4. Cycloaddition reactions with addition of copper (I) iodide



6 alkyne **A** **B**

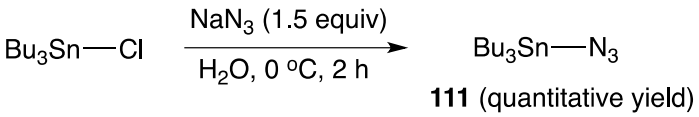
Entry	Alkyne	R^1	R^2	Yield (NMR)	Triazole Ratio (A : B)
1	**93**	*p*-BrPh	H	15%	0 : 100
2	**98**	Ph	H	0%	-
3	**106**	Me	COOEt	26%	86 : 14
4	**100**	Ph	COOMe	44%	61 : 39

Other experiments with combinations of copper salts and bases to generate copper (I) were tried. The copper salts CuI, $CuCl_2$, $CuSO_4$, and CuBr were used with bases diisopropylethylamine (DIEA), potassium carbonate, and sodium ascorbate for cycloaddition reactions.[36,69-71] None were successful at producing triazole products. Copper (I) iodide with no base was the only copper salt that gave any triazole products although the reaction time or selectivity remained nearly the same as the thermal cycloadditions at 80˚C without any salt.

2.5.7 Competition with tin-azide

We then turned our attention to comparing reactivity of a known metal-azide with boron-azide **6**. Tributyltin-azide **111** was selected because it is well known and easy to prepare.[72] We predicted that the carbene-boryl-azide would be more reactive than the tributyltin-azide because the electron-rich boron donates more electron density to the azide group than the tin metal center donates to the azide group.

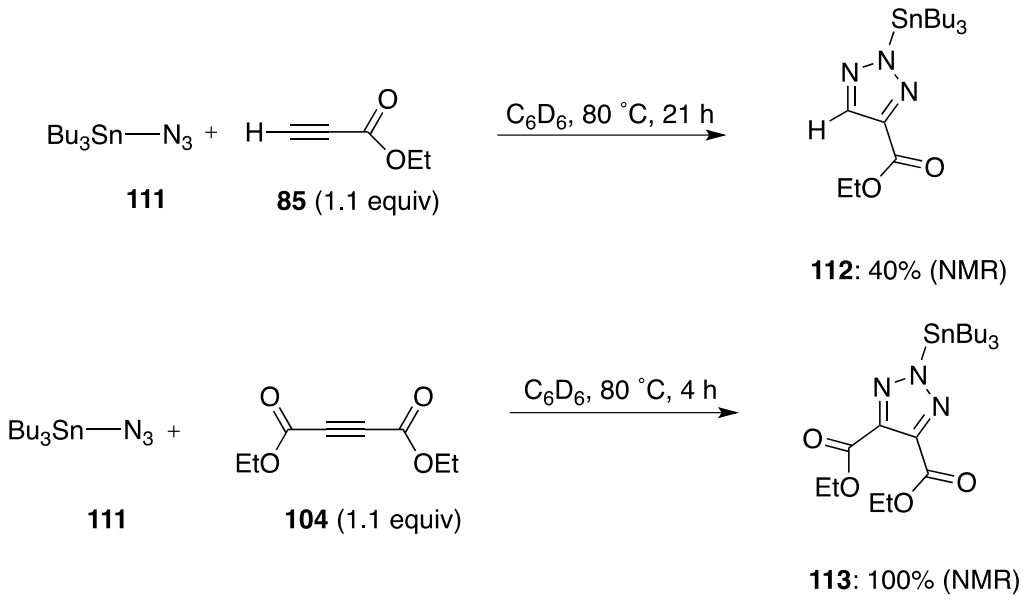
Tributyltin-azide **111** was prepared in quantitative yield according to literature procedures by a substitution reaction of tributyltin chloride and sodium azide (**Scheme 51**).[73] Proton and ^{119}Sn NMR spectroscopy showed that tributyltin-azide had been made in pure form.



Scheme 51. Synthesis of tributyltin-azide **111**

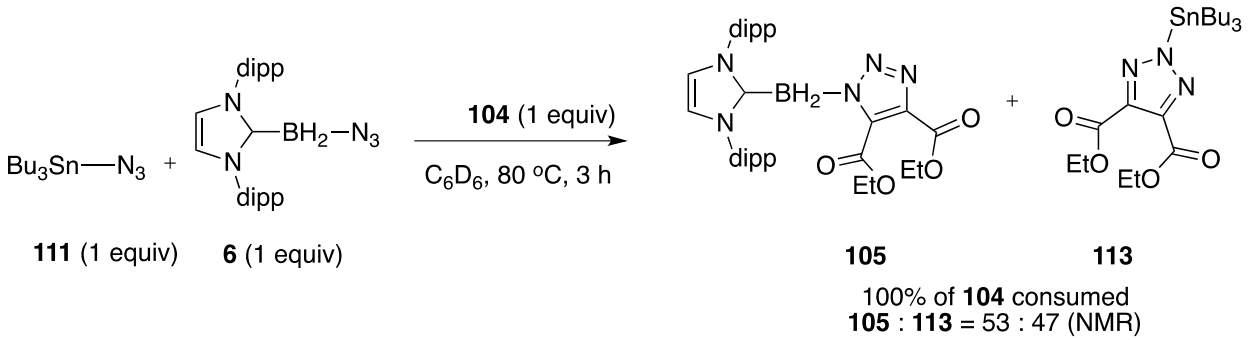
The reactivity of tributyltin-azide (**111**) was compared to the borane-azide **6** by reacting the tin-azide with ethyl propiolate (**85**) and diethyl acetylenedicarboxylate (**104**) at a concentration of 0.12 M for each reactant. The tin-azide **111** was dissolved in deuterated benzene with **85**. After the solution had been heated at 80 ˚C for 12 h, only 40% NMR yield was calculated of the tin-triazole **112**. This was longer than the 4 h required to completely react the carbene-boryl-azide **6** with **85** under the same conditions. A solution of diethyl acetylenedicarboxylate **104** and tributyltin-azide **111** was also heated to 80 ˚C. After 4 h, the reaction was complete to give tin-triazole **113** (**Scheme 52**). This was the same amount of time the carbene-boryl-azide **6** required to react with **104**. The ^{1}H NMR spectrum of **112** and **113** matched literature values, and the literature suggests that the tin is bonded to the middle nitrogen

on the triazole ring, and it is supported by the equivalence of the ethyl proton signals of the ethyl ester groups.[74,75]



Scheme 52. Cycloadditions of tributyltin-azide (**111**) and alkynes **85** and **104**

A competition reaction between the two azides was performed using 1 equiv each of tributyltin-azide **111**, dipp-Imd-BH_2N_3 **6**, and **104**, again at a concentration of 0.12 M. All of **104** was consumed after 3 h of heating the solution to 80 ˚C. The ratio of triazole products **105** : **113** was determined to be 53 : 47 by comparing the integrals of the quartet proton signals from the ethyl CH_2 of each product (**Scheme 53**). These experiments show that the rate of cycloaddition of azides **111** and **6** with alkyne **104** are comparable, but carbene-boryl-azide reacts faster than tributyltin-azide with the terminal alkyne **85**.

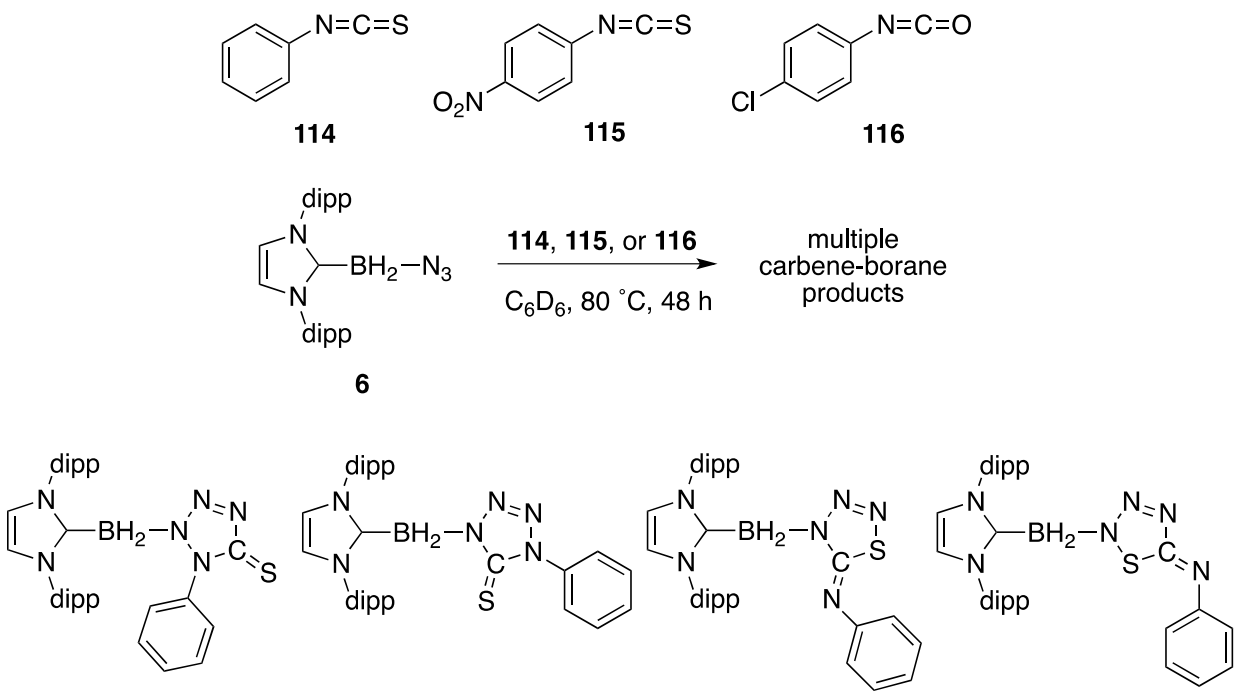


Scheme 53. Carbene-boryl-azide **6** competition reaction with tributyltin-azide **111**

2.5.8 Cycloadditions with Cumulenes

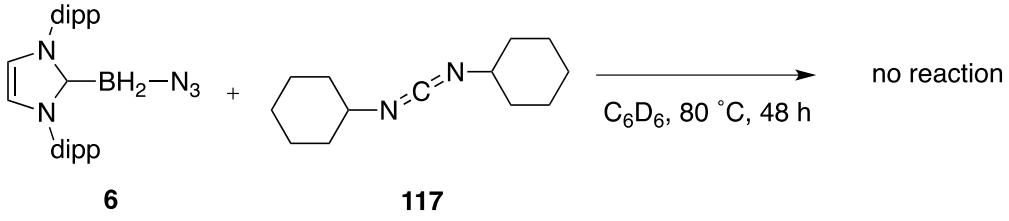
Having explored the reactivity dipp-Imd-BH_2N_3 **6** with a variety of alkynes, our interest moved towards cycloadditions of other functional groups. Based on the results from alkyne cycloadditions, thermal reaction conditions were applied to other dipolarophiles.

Isocyanates and isothiocyanates are known to react with organic azides so they were chosen for study with the carbene-boryl-azide **6**.[76] Isothiocyanatobenzene (**114**) was treated with **6** under typical reaction conditions, and after 48 h all of **6** had been consumed. At least four new products were observed by ^{1}H NMR spectroscopy, and attempts to purify by flash chromatography were unsuccessful. A similar reaction of 1-isothiocyanato-4-nitrobenzene (**115**) and 1-chloro-4-isocyanatobenzene (**116**) with **6** gave multiple products. These multiple products may be due to cyanates having two bonding sites for cycloaddition with the azide. For example, isothiocyanatobenzene **38** has two possible sites for cycloaddition, and two orientations for each site, resulting in four possible cycloaddition products (**Scheme 54**). We were unable to confirm these cycloaddition products because isolation of the products was not successful.



Scheme 54. Thermal cyanate reactions with **6** (top) and four possible cycloaddition products of the reaction of **114** and **6** (bottom)

To limit the number of possible cycloaddition products, the diimine N,N'-dicyclohexylcarbodiimine **117** was treated with azide **6** under typical reaction procedures; however, no reaction was observed after 48 h of heating (**Scheme 55**). Due to the low selectivity of the reactions with cumulenes was not performed.

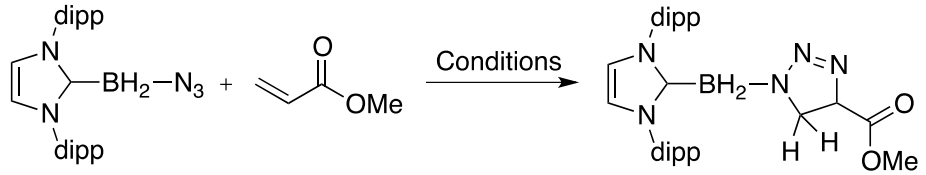


Scheme 55. Cycloaddition reaction of diimine **117** and azide **6**

2.5.9 Cycloadditions with alkenes

Next alkene reactions were tested under thermal conditions with azide **6**. Since methyl propiolate (**88**) reacted quickly with **6**, its alkene analog, methyl acrylate (**118**), was selected to react with **6**. Methyl acrylate **118** was submitted to typical reaction conditions for 7 h. Proton NMR spectroscopy showed that the symmetry of the isopropyl groups on the carbene-borane was broken, and new doublet of doublet signals at 4.11, 2.77, and 2.26 ppm. Purification by flash chromatography gave a 49% isolated yield of triazole **119** (**Table 5**, entry 1). A solution of **118** and **6** was then refluxed in deuterated toluene. After 5 h, we concluded that the product had begun to decompose because the ratio of the product to starting material had decreased as indicated by ^{1}H NMR spectrum (**Table 5**, entry 2). To avoid decomposition, a reaction of 3 equiv of **118** with **6** was performed in deuterated benzene at 70 ˚C, and it reached completion after 30 h. Purification by flash chromatography gave an 80% yield of triazole **119** (**Table 5**, entry 3).

Table 5. Reaction of methyl acrylate (**118**) with azide **6**



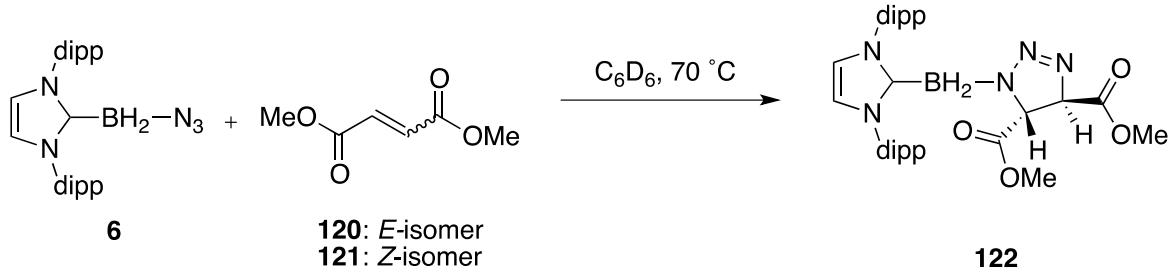
6 **118** **119**

Entry	Conditions	Isolated Yield of **119**
1	2 equiv **118**, PhH, 80 ˚C, 7 h	49%
2	2 equiv **118**, PhMe, 110 ˚C, 5 h	partial decomposition
3	3 equiv **118**, PhH, 70 ˚C, 30 h	80%

The reactivity of the stereoisomers dimethyl fumarate **120** and dimethyl maleate **121** with **6** were also tested. Dimethyl fumarate **120** (2 equiv) was dissolved with **6** in deuterated benzene, and the solution was heated to 70 ˚C. After 36 h, product formation appeared to have stopped even though about 28% of the azide remained unreacted. The mixture was purified by flash chromatography to give 64% of triazole **122** (**Table 6**, entry 1). This reaction was repeated in deuterated toluene at reflux, but like the methyl acrylate reaction, the triazole and alkene began to decompose at higher temperatures.

Dimethyl maleate **121** was treated with **6** in deuterated benzene at 70 ˚C, but after 3 d only a 40% NMR yield was obtained. The ^{1}H NMR spectrum of the crude product showed that triazole **122** had again formed. The spectrum also revealed that small amounts of dimethyl fumarate were present. Cycloadditions with dimethyl maleate have been known to form both cis and trans products because any base or acid in the reaction mixture can promote isomerization to the fumarate.[77] Dimethyl maleate has also been known to react more slowly than dimethyl fumarate in cycloaddition reactions.[78,79] Presumably, dimethyl maleate isomerized to dimethyl fumarate, and the fumarate then treated with **6** to give **122**. On the other hand, isomerization may have occurred after the heterocyclic ring of **122** had already formed because the protons in the heterocyclic ring of **122** are very acidic (**Table 6**, entry 2).

Table 6. Cycloaddition of azide **6** with dimethyl fumarate (**120**) and dimethyl maleate (**121**)

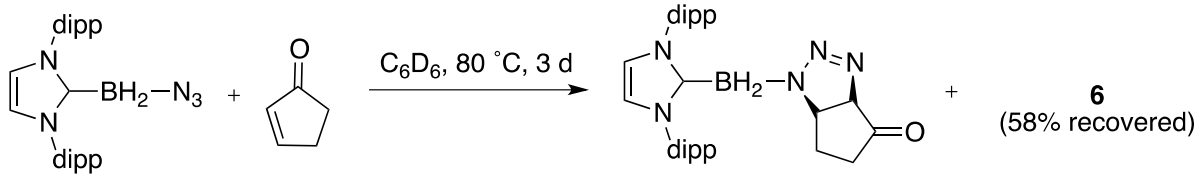


6 **120**: *E*-isomer **121**: *Z*-isomer **122**

Entry	Alkene	Time	Yield of **122**
1	dimethyl fumarate **120**	36 h	64%[a]
2	dimethyl maleate **121**	3 d	40%[b]

a) Isolated yield b) NMR yield

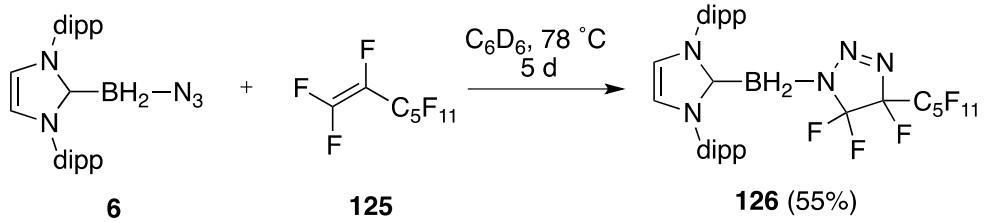
The cyclic alkene 2-cyclopentenone **123** was treated with **6**. This *Z*-alkene cannot be isomerized to an *E*-alkene configuration due to ring strain. The alkene **123** and azide **6** were dissolved in deuterated benzene, and the solution was refluxed for 3 d. Proton NMR spectroscopy showed a 35% NMR yield of triazole **124**. Flash chromatography gave 32% of the bicyclic triazole **124** and 58% of the starting azide **6** (**Scheme 56**). 2-Cyclopentenone **123** reacted more slowly than either methyl acrylate **118** or dimethyl fumarate **120**. Because **123** is not as electron-deficient as **118** or **120**, it may be slower to react with **6**. Also *cis* alkenes appear to be less reactive based on the results of the dimethyl maleate reaction.



6 **123** **124** (32%)

Scheme 56. Cycloaddition of 2-cyclopentenone **123** and azide **6**

Carbene-boryl-azide **6** was also treated with perfluoro-1-heptene (**125**) in deuterated benzene at 78 ˚C. The cycloaddition was somewhat sluggish, and it took 5 d for all of **6** to be consumed (determined by ^{1}H NMR spectrum of the crude). Purification by column chromatography gave the fluorinated-borane-triazole **126** in 55% yield.

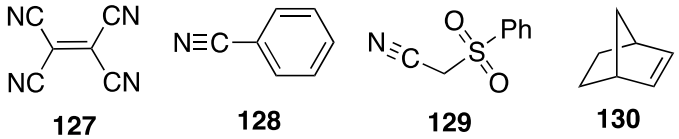


6 **125** **126** (55%)

Scheme 57. Cycloaddition of perfluoroheptene-1 (**125**) with azide **6**

2.5.10 Cycloadditions with nitriles

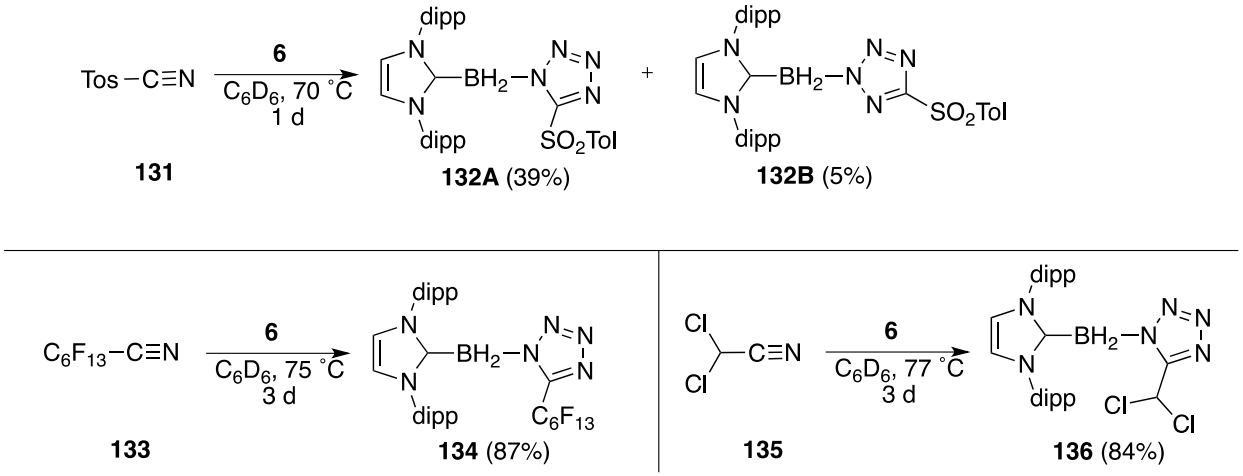
Cycloadditions of nitriles and select alkenes were tested with the help of an undergraduate worker Mr. V. Lamm by heating solutions of the nitrile or alkene with **6** in benzene. Reaction with tetracyanoethylene **127** gave a complicated mixture (likely cycloaddition with both the alkene and nitriles), but no products were recovered. Only starting materials were recovered upon reactions of **6** with benzonitrile **128**, (phenylsulfonyl)acetonitrile **129**, and norbornene **130** (**Figure 18**).



127 **128** **129** **130**

Figure 18. Alkenes and nitriles that are unreactive towards carbene-boryl-azide **6** except for **127** which gave a complex mixture of products

Carbene-boryl-azide **6** did react with electronically deficient nitrile *p*-toluenesulphonyl cyanide **131**. After heating at 70 ˚C in deuterated benzene and purification by flash chromatography, both the 1,5-tetrazole (**132A**, 39% yield) and 1,4-tetrazole (**132B**, 5%) were obtained (**Scheme 58**). The 1,4-tetrazole **132B** was identified on the shielding of the aryl protons on the tosyl group, similar to the observation on compounds **108B**, **110B**, and **94B** (**Figure 16**). Reaction of perfluoroheptane nitrile **133** with **6** at 75 ˚C for 3 d gave tetrazole **134** in 87% isolated yield after column chromatography. Reaction of **6** with dichloroacetonitrile (**135**) at 77 ˚C for 3 d in deuterated benzene gave tetrazole **136** in 84% isolated yield after column chromatography (**Scheme 58**).

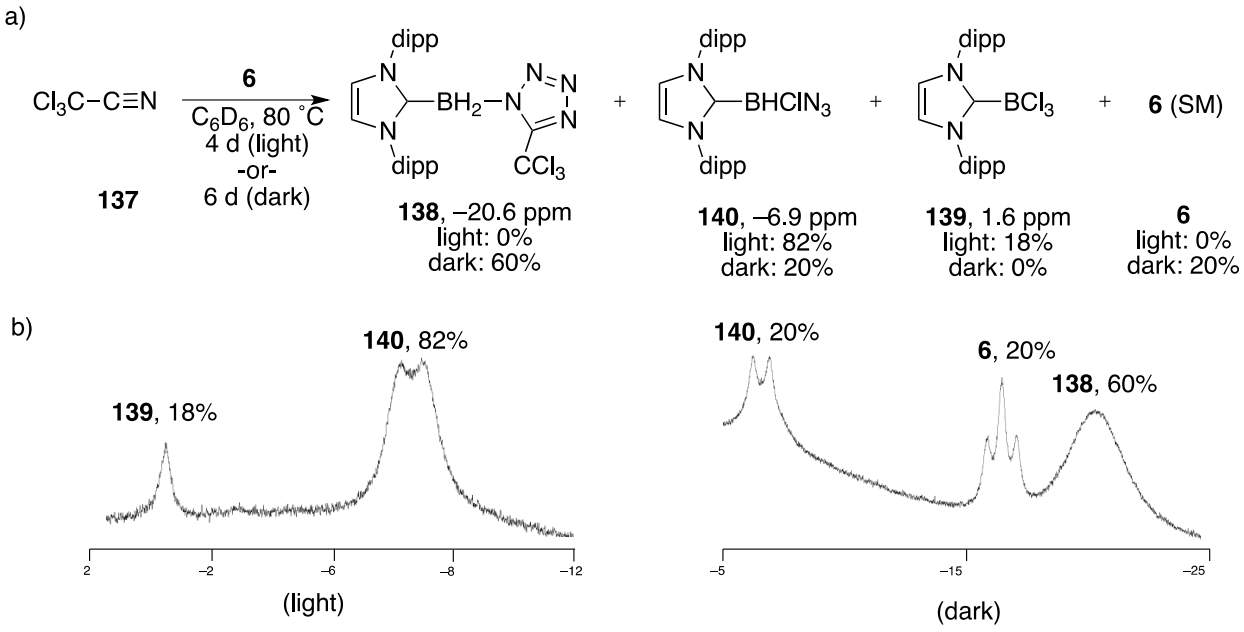


Scheme 58. Reaction of azide **6** with *p*-toluenesulphonyl cyanide (**131**), perfluoroheptane nitrile (**133**) and dichloroacetonitrile (**135**)

However, reaction with trichloroacetonitrile (**137**) did not give tetrazole **138** smoothly. After heating a solution of nitrile **137** with azide **6** t 80 ˚C for 4 d, the ^{11}B NMR spectrum of the crude mixture showed a broad doublet at –6.9 ppm (J_{BH} = 99 Hz) and a broad singlet at 1.6 ppm that matches the report shift for dipp-Imd-BCl_3 (**139**).[50] The doublet at –6.9 ppm is thought to be the chlorinated carbene-boryl-azide **140**. The doublet could also possibly be the chlorinated

carbene-borane tetrazole, but the signal for this double does not appear to be as broad as the signals of other carbene-borane tetrazoles and triazoles.

To try to reduce the light-initiated chlorination of the borane (similar to chlorination by CCl_4, **Scheme 18**), the reaction was performed in the dark by adding the reagents to a foil wrapped an NMR tube to keep out the light. After heating at 80 ˚C for 6 d, the ^{11}B NMR spectrum of the crude revealed a broad singlet at –20.6 ppm (~60% NMR yield). This signal is believed to be the target tetrazole **138** based on the ^{11}B NMR shift. About 20% of the chlorinated azide **140** and 20% of the starting azide **6** were also observed in the ^{11}B NMR spectrum. Column chromatography of the crude mixture did not yield any of the tetrazole **138**, so **138** appears to not be stable to column chromatography.



Scheme 59. a) Reaction of azide **6** with trichlroacetonitrile (**137**) under light and dark contions b) ^{11}B NMR spectra of crude reaction mixture under light (left) and dark (right) conditions

2.5.11 Removing the triazole from the carbene-borane

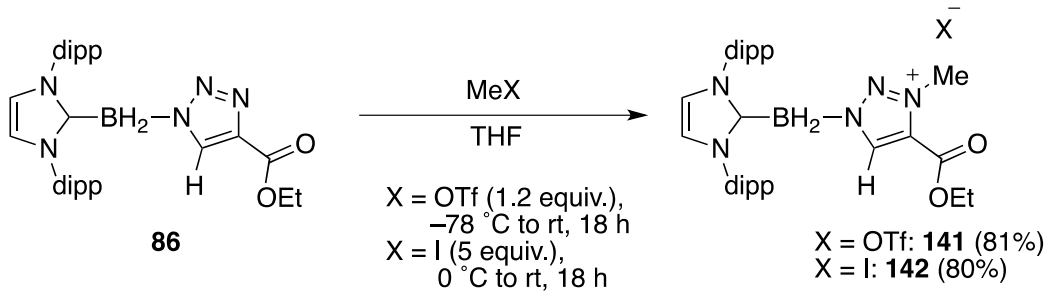
If these triazoles are to be used further in other reactions or syntheses, then easy removal of the carbene-borane from the triazole is needed. The stability of carbene-borane-triazole was tested using triazole **86** because of the ease of its synthesis and purification.

Reactions of **86** with different acids were first tried as a way to remove the triazole from the carbene-borane. First 4 M hydrochloric acid was added to a solution of triazole **86** in dichloromethane. After 2 d, the organic layer was extracted with dichloromethane, and no changes in the signals of **86** were observed by ^{1}H and ^{11}B NMR spectroscopy. Next 2 equiv of triflic acid were added to a solution of triazole **86** in dichloromethane, but again only triazole **86** was recovered.

We halogenated carbene-boryl-triazole to then decompose it in protic solvent. First iodine (0.5 equiv in $CDCl_3$) was added to triazole **86**, and after 5 d a small peak at –5.3 ppm was observed by ^{11}B NMR spectroscopy. This new peak likely is an iodinated carbene-boryl-triazole, but no decomposition product peaks for boric acid or borates was observed. Triazole **86** was then dissolved in THF, and iodine (0.1 equiv in THF) was added. After 18 h a small peak (~5%) for boric acid at 19 ppm in the ^{11}B NMR spectrum was observed. To increase the rate of decomposition, the reaction was repeated with bromine (0.2 equiv in THF) instead of iodine. After 18 h, all of **86** had converted to either boric acid (25%) or a new boron product with ^{11}B NMR peak at –11.8 ppm. Purification by column chromatography did not yield the free triazole.

To convert the triazole to a better leaving group, we decided to methylate it. First 1.2 equiv of methyl triflate were treated with triazole **86** in THF at –78 ˚C. After warming the mixture to room temperature and stirring for 18 h, the THF was removed under high vacuum, and a transparent oil was obtained. Addition of diethyl ether gave a white precipitate that was

collected by gravity filtration to yield 75% of the methylated triflate salt **141** (**Scheme 60**). The corresponding iodide salt was synthesized by dissolving triazole **86** in THF at 0 ˚C and adding 5 equiv of methyl iodide. The resulting mixture was allowed to warm to room temperature and was stirred for 18 h. Removal of the solvent by high vacuum gave a yellow oil. Addition of diethylether to the oil resulted in the formation of white precipitate that was isolated in 80% yield by gravity filtration to give methylated triazole **142** (**Scheme 60**).



Scheme 60. Methylation of triazole 13 with methyl triflate or methyl iodide

Crystals of the triflate salt **141** were grown by slow evaporation in ethyl acetate, and X-ray crystallography by Dr. S. Geib indicated that the triazole ring had been methylated on the nitrogen in the 3 position (**Figure 2.8**). The boron-nitrogen bond length was 1.590(5) Å which is about 1.5% longer than the boron-nitrogen bond length of 1.567(5) Å of the non-methylated triazole **86**.

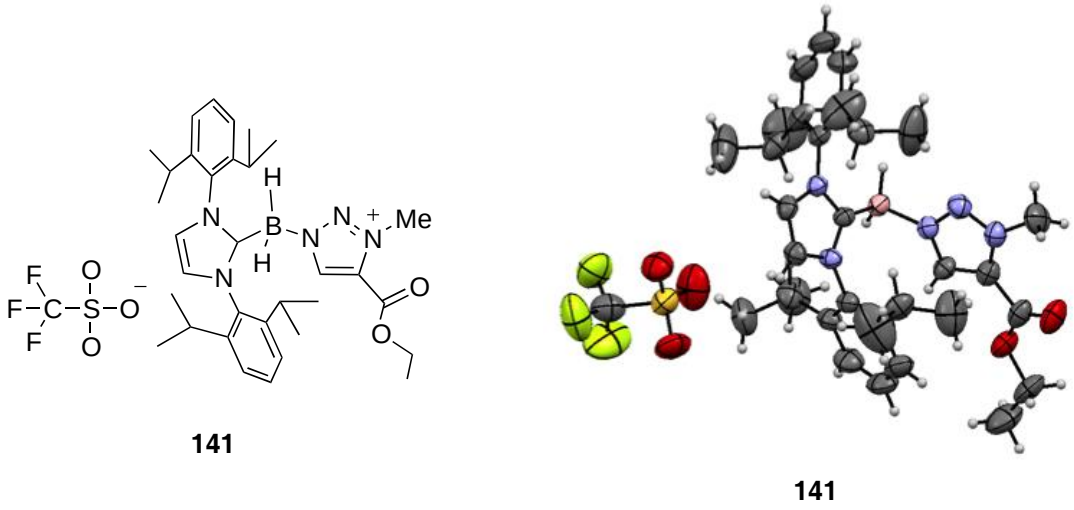
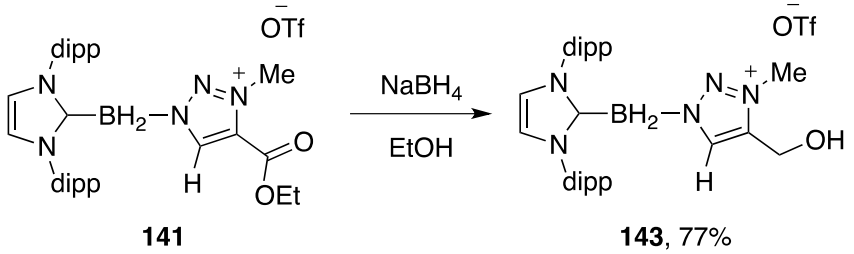


Figure 19. Crystal structure of methylated triazole **141**

Attempts to remove the methylated triazole from the carbene-borane **141** were performed first by testing its stability in DMSO or D_2O. No changes were observed in proton NMR spectroscopy even with heating to 40 ˚C. The methylated triazole **141** was submitted to harsh conditions including addition of triflic acid (2 equiv), oxidation with oxone (3 equiv), and nucleophilic substitution with sodium azide. No changes to the triazole were observed in ^{1}H NMR spectroscopy for any of these conditions.

We tried to reduce the borane of **141** with $NaBH_4$ to release the triazole. After stirring a mixture of **141** with $NaBH_4$ (6 equiv) in ethanol for 18 h, the ^{11}B NMR spectrum of the crude showed a peak at 2.9 ppm, –41.6 ppm ($NaBH_4$ signal), and –16.0 ppm. After workup with water to remove remaining $NaBH_4$ and DCM to extract the organics, ^{1}H NMR showed that the ester group of **141** had been reduced to an alcohol. The methyl group on the triazole was still present, and the ^{11}B NMR spectrum showed that carbene-borane-triazole was still present. Therefore, we determined that the new compound **143** had been synthesized in 77% yield (**Scheme 61**).

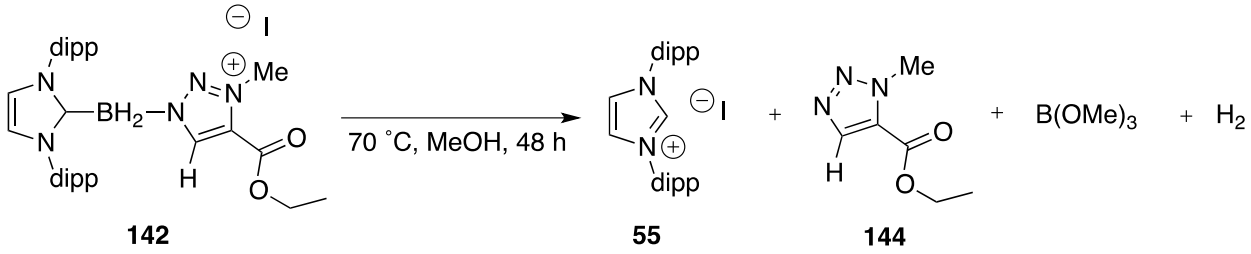


141 **143**, 77%

Scheme 61. Reduction of triflate salt **141** by $NaBH_4$

We tried another route to remove the triazole by using the nucleophilic iodide anion already present in **142** to perform a substitution. The iodide anion could attack the boron to release the triazole bonded to the borane. The resulting product of this substitution would be carbene-borane-iodide **30** which is known to decompose by methanolysis to trimethyl borate and imidazolium salt and release hydrogen gas.[29]

The methylated triazole **142** was dissolved in deuterated methanol and heated at reflux temperatures. The reaction was monitored periodically by both ^{1}H and ^{11}B spectroscopy. After 18 h of heating, a sharp singlet was observed in the ^{11}B NMR spectrum at +18 ppm, which corresponds to trimethyl borate.[80] The ^{1}H NMR spectrum also showed new signals. The signals at 8.17 (s, 1H), 4.31 (s, 3H), and 3.61 (q, 2H) indicated that ethyl 1-methyl-1*H*-1,2,3-triazole-5-carboxylate **144** was present in the deuterated methanol. The formation of imidazole salt **55** was also identified by the singlet observed at 8.28 ppm. Little additional change to the spectra was observed after 48 h so the mixture was purified by flash chromatography; however, neither the free triazole nor any other identifiable products were recovered (Figure 20). Unfortunately we were unable to match ^{1}H NMR spectra of **55** with the literature values because the crude NMR was performed in deuterated methanol, and we did not recover **55** to take the spectrum in deuterated chloroform.[81]

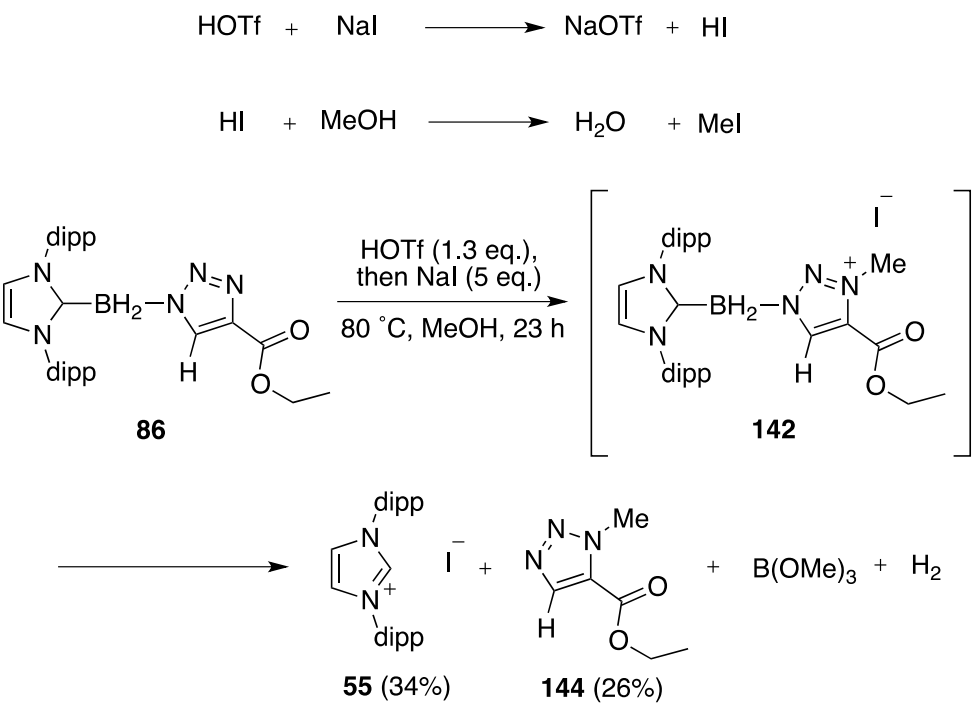


142 55 144

Figure 20. Decomposition of methylated triazole 62 by methanolysis to give free triazole 64

Although the free methylated triazole **144** was not recovered, we were encouraged that the carbene-borane had decomposed in methanol in the presence of iodide. Triazole **86** was dissolved in methanol, and 5 equiv of sodium iodide were added to the solution. The mixture was heated to 80 ˚C for 18 h, but no new boron shifts were observed by NMR spectroscopy. Five equivalents of 15-crown-5 ether were added to try to trap the sodium cation and make the iodide anion more nucleophilic, but this also proved unsuccessful.

Triflic acid (1.3 equiv) was next added to a solution of **86** in methanol to protonate the triazole before iodide substituted it. Then sodium iodide (5 equiv) was added, and this mixture was heated to 80 ˚C for 23 h. ^{11}B NMR spectroscopy revealed the formation of trimethyl borate with a boron singlet at +18 ppm. The reaction was quenched with sodium bicarbonate, and the organic layer extracted with dichloromethane. Purification by flash chromatography yielded 26% of the methylated triazole **144** and 34% of the imidazolium salt **55** (**Scheme 2.18**). Presumably the triflic acid formed HI in the presence of NaI, and this formed methyl iodide *in situ*. The methyl iodide then methylated **86**, which was then followed by methanolysis to give **144**.



Scheme 62. Formation of methyl iodide *in situ* (top), and decomposition of carbene-boryl-triazole **86** to free triazole **144** after methylation and methanolysis

Carbene-boryl-triazole **86** is stable to acid conditions, but it can be methylated with either methyl triflate or methyl iodide to form the corresponding triflate salt **141** or iodide salt **142**. Carbene-boryl-triazoles are succeptible to halogenation followed by decomposition in protic solvents like methanol or water to break the boron-nitrogen bond and release the free triazole.

2.5.12 Conclusions and future work of cycloaddition reactions with carbene-boryl-azide

The results show that only electron-deficient alkynes react efficiently with **6**. The propiolates and acetylenedicarboxylates both reacted quickly with **6** even though the acetylenedicarboxylates are non-terminal alkynes. Reaction rates were slower when an alkyl or phenyl group was paired with an electron-withdrawing group on the alkyne. In general, terminal

alkynes that reacted with **6** only formed the 1,4 regioisomer while non-terminal alkynes containing an aryl or alkyl group formed both the 1,4 and 1,5 regioisomers.

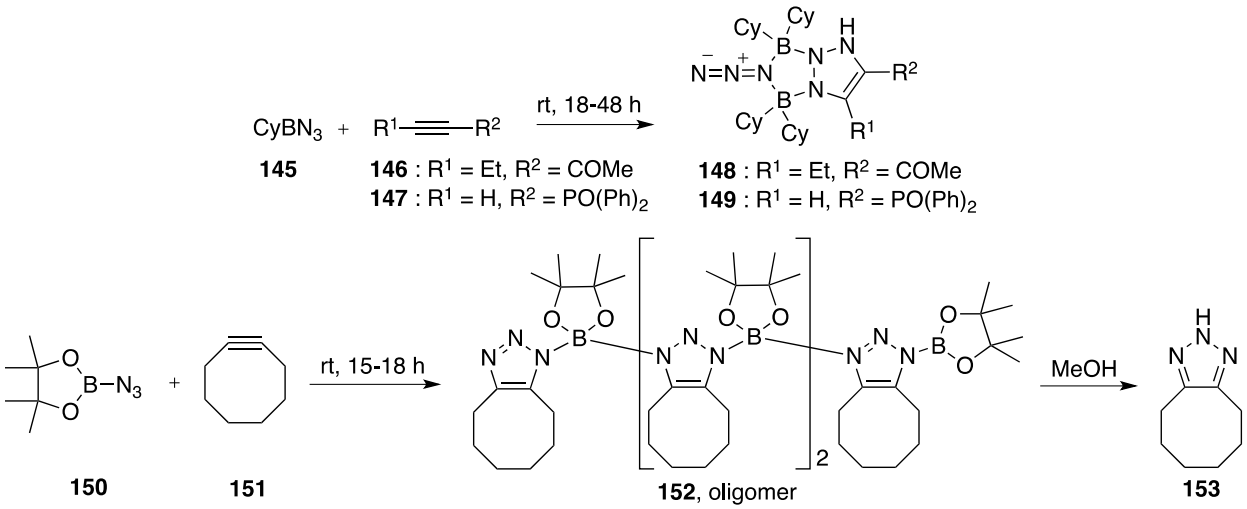
Microwave cycloadditions of alkynes **100** and **106** with **6** reached completion in hours instead of the days required by thermal conditions. Some regioselectivity was lost with the microwave reactions, but the regioselectivity of the thermal cycloadditions were modest anyway.

Addition of copper salts to cycloadditions between alkynes and azide **6** generally did not increase the reaction rate or selectivity significantly. Copper (I) iodide was the exception. It increased the rate of the cycloaddition at 80 ˚C, but running the reaction thermally at 110 ˚C or by microwave at 180 ˚C proved to be more effective at producing the product triazoles. Other procedures involving copper catalyst appeared to only produce very small amounts if any of the triazole product. This is in contrast to carbon-azide reactions whose reaction rates and regioselectivity are significantly increased in the presence of copper catalyst.[32]

Similar to the alkynes, electron-deficient alkenes and nitriles react with **6** to give triazole and tetrazole products. Perfluoroheptene-1 also reacted with **6** to give a fluorinated triazole. The borane-triazoles formed from alkenes are less stable to thermal conditions than boron-triazoles from alkynes. Triazoles formed from methyl acrylate **118** and dimethyl fumarate **120** started to decompose at temperatures higher than 70 ˚C.

Following our initial report,[82] recently Melen and coworkers successfully cyclized trivalent boryl azide **145** with electron deficient alkynes **146** or **147** to give cyclized products **148** and **149** containing two boron atoms.[83] Müller and coworkers also successfully cyclized $pinBN_3$ **150** with strained cyclooctyne (**151**) to give oligomer **152**.[84] Addition of methanol to **152** gave the triazole **153**. The trivalent boryl-azides used in these cycloadditions were not very thermally stable unlike carbene-borane azide **6**. Müller and coworkers also compared our carbene-boryl-

azide **6** with their trivalent boryl-azides. They concluded that σ donation from the carbene makes the boryl azide very electron rich, thus carbene-boryl-azide acts as Type I dipole.[83]



Scheme 63. Recently reported cycloaddition of boryl azides **145** and **150**

The triazole-borane **86** formed from ethyl propiolate proved to be rather robust. It was stable to a variety of conditions including oxidation, reduction, acidic conditions, and in some cases nucleophilic substitution. Indeed, it proved surprisingly difficult to separate the carbene-borane from the triazole. Nucleophilic substitution with iodide was successful at removing the triazole, but only after the triazole ring had been methylated.

Future work could include synthesizing other new triazoles by utilizing the unique reactive properties of azide **6**. Finding milder methods to isolate the triazole from the carbene-borane would increase the appeal of making new borane triazoles.

3.0 EXPERIMENTAL

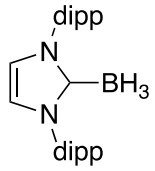
General Remarks: Chemicals were purchased from suppliers and used as received unless otherwise noted. Toluene, Et_2O, CH_2Cl_2, and THF were dried by passing through an activated alumina column. Reactions were monitored by TLC analysis or ^{11}B NMR spectroscopy. Visualization was accomplished with a 254 nm UV lamp, or by staining with vanillin solution. Separations were performed by using a Combiflash Rf automated flash chromatography apparatus from Teledyne ISCO with normal phase RediSep Rf columns containing 230-400 mesh silica gel. All microwave-mediated reactions were carried out with a Biotage Initiator Exp microwave synthesizer. The microwave parameters were set to variable power, constant temperature, with the fixed hold time set to on. The microwave reactions were carried out in 0.5-2 mL Biotage microwave vials.

Melting points (mp) were determined with a Mel-Temp II apparatus and are uncorrected. Infrared (IR) spectra were recorded on a Nicolet Avatar 360 FT-IR spectrometer as thin films (CH_2Cl_2) on NaCl plates. Proton (^1H), carbon (^{13}C), boron (^{11}B), and fluorine (^{19}F) nuclear magnetic resonance spectra (NMR) were performed on either a Bruker Avance III 300, 400, or 500 spectrometers. Unless otherwise noted, NMR spectra were run in $CDCl_3$. Chloroform (δ 7.26 ppm) or TMS (δ 0.00 ppm) was used as an internal standard for ^1H NMR spectra and $CDCl_3$ (δ 77.00 ppm) was used as an internal standard for ^{13}C NMR spectra. ^{11}B chemical shifts are relative to $Et_2O{\bullet}BF_3$ and ^{19}F chemical shifts are relative to $CFCl_3$. The following abbreviations

are used to describe coupling: s, d, t, q, quint., sept., m, and br represent singlet, doublet, triplet, quartet, quintet, septet, multiplet, and broad signal respectively. The resonances of hydrogen atoms connected to boron were often difficult to observe in ^{1}H NMR spectra due to quadrupole broadening. For the same reason, no resonances of carbon atoms bonded to the boron atom could be observed by ^{13}C NMR.

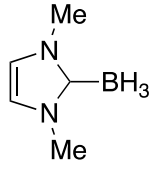
Low resolution mass spectra (LRMS) were measured by a Shimadzu LCMS and high resolution mass spectra (HRMS) were measured on a Micromass Inc. Autospec instrument with E-B-E geometry. X-ray diffractions were recorded by the Chemistry Department X-ray Diffraction Facility of the University of Pittsburgh (Dr. Steven J. Geib).

For safety recommendations on handling azides, see section **2.4.3** (page 53).



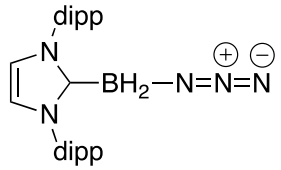
4

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene borane (4) Carbene-borane **4** was synthesized in 3 steps from literature procedures.[48]



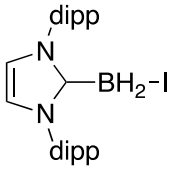
5

1,3-dimethylimidazol-2-ylidene borane (5) Carbene-borane **5** was synthesized in 2 steps from literature procedures.[47]



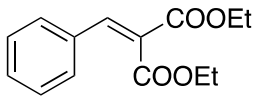
6

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene azidoborane (6) The borane (2.5 g, 6.2 mmol) was dissolved in benzene (50 mL). A solution of iodine (0.8 g, 3.1 mmol) in benzene (2 mL) was added dropwise to the solution. The mixture was stirred for 15 min, and the benzene was then evaporated. The remaining dark solid was dissolved in DMSO (50 mL) to form an amber solution. Sodium azide (0.44 g, 6.8 mmol) was dissolved in DMSO (3 mL) separately and added slowly to the main reaction mixture. The mixture was stirred for 18 h, and the product was extracted using diethyl ether (3 × 20 mL) and dried over $NaSO_4$. The ether was evaporated and the light yellow solid was purified by column chromatography (SiO_2, hexanes : ethyl acetate, 5 : 2) yielding a white solid (2.1 g, 76%). The product's spectra matched literature values.[29] ^{1}H NMR (300 MHz, $CDCl_3$): δ 7.50 (t, *J* = 6 Hz, 2 H, H arom.), 7.31 (d, *J* = 6 Hz, 4 H, H arom.), 7.07 (s, 2 H, =C*H*(N)), 2.51 (sept., *J* = 5.1 Hz, 4 H, C*H*Me$_2$), 1.31 (d, *J* = 5.1 Hz, 12 H, (C*H*$_3$)$_2$CH), 1.17 (d, *J* = 5.1 Hz, 12 H, (C*H*$_3$)$_2$CH).



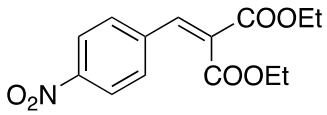
10

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene iodoborane (30): Dipp-Imd-BH_2I was synthesized from carbene-borane **4** in one step according to literature procedures.[29]



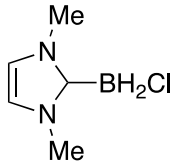
17

Diethyl 2-benzylidenemalonate (17): Diethyl 2-benzylidenemalonate **17** was synthesized in one step according to literature procedures.[85]



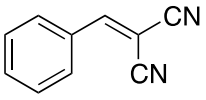
19

Diethyl 2-(4-nitrobenzylidene)malonate (19): Diethyl 2-(4-nitrobenzylidene)malonate **19** was synthesized in one step according to literature procedures.[85]



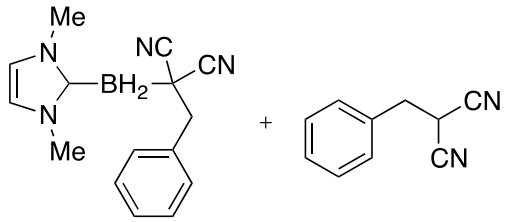
20

1,3-Dimethylimidazol-2-ylidene chloroborane (20): DiMe-Imd-BH_2Cl was synthesized from carbene-borane **5** in one step from literature procedures.[49]



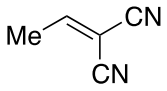
25

Benzylidene malononitrile (25): Benzylidene malononitrile **25** was synthesized in one step according to literature procedures.[86]



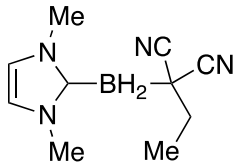
26 **27**

1,3-Dimethylimidazol-2-ylidene (1,1-dicyano-2-phenylethyl)borane (26): A solution of benzylidenemalonitrile **25** (250 mg, 1.62 mmol, 1.16 equiv) and diMe-Imd-BH_3 **5** (154 mg, 1.40 mmol) in CH_2Cl_2 (25 mL) was stirred at room temperature for 15 min. The solvent and volatiles were removed under vacuum and the residue was loaded onto silica gel. The product was purified by flash chromatography (elution with hexane:EtOAc = 25:75) to yield benzylmalononitrile **27**[51] (29 mg, 13%) and **26** as a white solid (210 mg, 57%): mp 140–145 ˚C; IR (thin film, cm^{-1}) ν_{max} 3150, 2960, 2393, 2253, 2229, 1820, 1795, 1483, 1381, 1232, 1096, 910, 732; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.42 (d, *J* = 7.0 Hz, 2H), 7.36 (t, *J* = 7.0 Hz, 2H), 7.31 (t, *J* = 7.0 Hz, 1H), 6.97 (s, 2H), 4.00 (s, 6H), 3.13 (s, 2H), 1.99 (br q, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 137.2, 129.6, 128.4, 127.4, 121.9, 121.5, 43.7, 37.2; ^{11}B NMR (BF_3•Et_2O, 96 MHz, $CDCl_3$) δ –23.7 (t, *J* = 95 Hz); HRMS (ESI) calcd. for $C_{15}H_{17}{}^{11}BN_4Na$ ([M + Na]$^+$) 287.1444, found 287.1449.



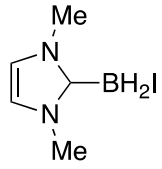
28

2-Ethylidene malononitrile (28): 2-Ethylidene malononitrile **28** was synthesized in one step from literature procedures.[87]



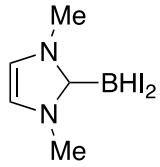
29

1,3-dimethylimidazol-2-ylidene (1,1-dicyanopropyl)borane (29): A solution of 2-ethylidenemalonitrile **28** (280 mg, 3.0 mmol, 2 equiv) and diMe-Imd-BH_3 **5** (167 mg, 1.52 mmol) in CH_2Cl_2 (25 mL) was stirred at room temperature for 18 h. The solvent and volatiles were removed under vacuum and the residue was loaded onto silica gel. The product was purified by flash chromatography (elution with hexane:EtOAc = 25:75) to yield diMe-Imd-$BH_2C(CN)_2Et$ **29** as a white solid (129 mg, 42%): mp 141–142 ˚C; IR (thin film, cm^{-1}) ν_{max} 3152, 2973, 2254, 1789, 1470, 1382, 1096, 909, 734; ^1H NMR (500 MHz, $CDCl_3$) δ 7.02 (s, 2H), 3.96 (s, 6H), 1.92 (q, *J* = 7.5 Hz, 2H), 1.23 (t, *J* = 7.5 Hz, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 121.8, 121.7, 36.9, 31.5, 11.4; ^{11}B NMR (BF_3•Et_2O, 96 MHz, $CDCl_3$) δ –25.4 (t, *J* = 96 Hz); HRMS (ESI) calcd. for $C_{10}H_{14}{}^{11}BN_4$ $[M - H]^+$) 201.1312, found 201.1329.



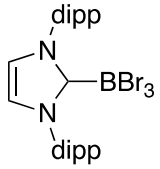
31

1,3-Dimethylimidazol-2-ylidene iodoborane (31): DiMe-Imd-BH_2I was synthesized from carbene-borane **5** in one step according to literature procedures.[88]



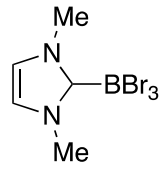
34

1,3-Dimethylimidazol-2-ylidene diiodoborane (34): 1,3-Dimethylimidazol-2-ylidene borane (50 mg, 0.455 mmol) was dissolved in toluene (3 mL) in a flame-dried flask under argon. In a separate vial, iodine (127 mg, 0.5 mmol) was dissolved in toluene (1 mL) and this solution was dripped into the borane solution via syringe. Initially the color of the iodine vanished, but after half of the iodine was added, the color persisted. The reaction mixture bubbled from the evolution of hydrogen gas. The mixture was stirred for 30 min and the reaction was deemed complete by ^{11}B NMR spectroscopy. The product is not moisture or air stable so quantitative yield was assumed according to ^{11}B NMR spectroscopy: ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.93 (s, 2H), 3.94 (s, 6H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 122.1, 37.4; ^{11}B NMR (BF_3•Et_2O, 160 MHz, $CDCl_3$) δ –42.1 (d, J = 141 Hz).



40

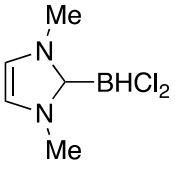
1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene tribromoborane (40): dipp-Imd-BBr_3 was prepared from carbene-borane **4** in one step according to literature procedures.[29]



43

1,3-Dimethylimidazol-2-ylidene tribromoborane (43): Carbene-borane **5** (100 mg, 0.91 mmol) was dissolved in dry DCM (2 mL) in a dry flask. A 1 M stock solution of bromine in DCM was prepared, and bromine (1.45 mL, 1.45 mmol) was added slowly to the carbene-borane solution. Rapid bubbling from hydrogen gas release occurred. The bromine color color disappeared until all the bromine was added, resulting in a light transparent red solution.

An ^{11}B NMR spectrum of the crude mixture was taken to confirm the presence of diMe-Imd-BBr_3. The solvent was removed to give a light yellow crystalline solid (248 mg, 79%). The solid decomposes slowly in air to a brown sticky solid. The solid can be stored as a solution in chloroform in the freezer, although reactions in situ with **43** are recommended: ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.98 (s, 2H), 4.26 (s, 6H); ^{11}B NMR (160 MHz, $CDCl_3$) δ 15.7 (s).



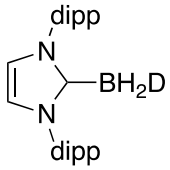
45

1,3-Dimethylimidazol-2-ylidene dichloroborane (45): DiMe-Imd-$BHCl_2$ was synthesized from carbene-borane **5** in one step according to literature procedures.[49]

General procedure 1 (GP1) (Reduction of carbene-borane by LAD)

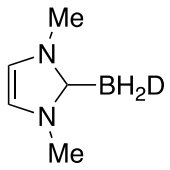
Similar to the reported procedure,[29] dry diethylether was added to a dry round bottom flask. Lithium aluminum deuteride (2 equiv) was added as one portion to the ether and stirred for

10 minutes. Some gray solid remained suspended in the ether. A solution in DCM of the carbene-borane halide was prepared in a separate flask, and this solution was dripped into the LAD/diethylether mixture. Some gas evolution and gray precipitate formation immediately occurred. The reaction mixture was stirred for 15 min, and then an ^{11}B NMR spectrum of the crude mixture was taken. Unreacted LAD was quenched by a saturated solution of $NaSO_4$ in water or D_2O. The solids were removed by gravity filtration, and the organic solvent was removed by vacuum to give the product as a white, powdery solid.



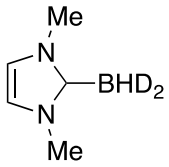
56

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene borane-*d*$_1$ (56): Compound **56** was prepared by GP1 by reacting carbene-borane **4** (90 mg, 0.22 mmol) with iodine (34 mg, 0.13 mmol) to give monoiodide **30** in 4 mL of DCM. This solution was added to a solution of LAD (19 mg, 0.45 mmol) in 4 mL of diethylether. The reaction was quenched with saturated $NaSO_4$ in H_2O, and the solids were removed by gravity filtration. The crude white solid was purified by column chromatography (SiO_2, DCM) to give a powdery white solid in 52% yield. ^{11}B NMR and ^1H NMR spectra matched the reported signals (see **Scheme 24**).[29]



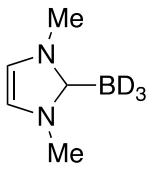
59

1,3-Dimethylimidazol-2-ylidene borane-d_1 (59): Compound **59** was prepared by GP1 by reacting carbene-borane **5** (50 mg, 0.45 mmol) with iodine (57 mg, 0.23 mmol) to give monoiodide **30** in 4 mL of DCM. This solution was added to a solution of LAD (38 mg, 0.91 mmol) in 4 mL of diethylether. The ^{11}B NMR spectrum showed a 1:2:1 triplet (J_{BH} = 86 Hz) of 1:1:1 triplets (J_{BD} = 13 Hz) at –37.2 ppm. Quenching of the reaction mixture with a saturated solution of $NaSO_4$ in H_2O or D_2O, however, scrambled the hydrogen and deuterium bonded to the boron atom (see **Scheme 25**).



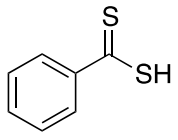
60

1,3-Dimethylimidazol-2-ylidene borane-d_2 (60): Compound **60** was prepared by GP1 by reacting carbene-borane **5** (50 mg, 0.45 mmol) with iodine (115 mg, 0.45 mmol) to give diiodide **34** in 4 mL of DCM. This solution was added to a solution of LAD (38 mg, 0.91 mmol) in 4 mL of diethylether. The ^{11}B NMR spectrum showed a doublet (J_{BH} = 86 Hz) of 1:2:3:2:1 pentets (J_{BD} = 13 Hz) at –37.6 ppm. Quenching of the reaction mixture with a saturated solution of $NaSO_4$ in H_2O or D_2O, however, scrambled the hydrogen and deuterium bonded to the boron atom (see **Scheme 26**).



61

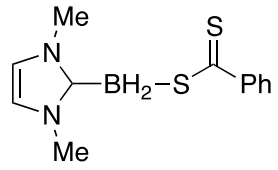
1,3-Dimethylimidazol-2-ylidene borane-d_3 (61): Compound **61** was prepared by GP1 by reacting carbene-borane **5** (100 mg, 0.91 mmol) with bromine (57 mg, 1.46 mmol) to give tribromide **40** in 4 mL of DCM. This solution was added to a solution of LAD (76 mg, 1.82 mmol) in 4 mL of diethylether. The reaction mixture was quenched with a saturated solution of $NaSO_4$ in D_2O, and the solids were removed by gravity filtration. Evaporation of the solvent under vacuum gave **61** as a white solid (99 mg, 97% yield). Inspection of the ^{11}B and ^{1}H NMR spectra revealed that no further purification was required (see **Scheme 27**). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.84 (s, 2H), 3.73 (s, 6H); ^{11}B NMR (128.4 MHz, $CDCl_3$) δ –37.8 (J_{BD} = 13 Hz).



76

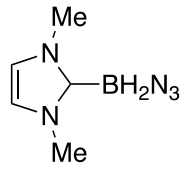
Dithiobenzoic acid (76): Synthesis of dithiobenzoic acid was based on literature procedures.[56,57] Phenyl magnesium bromide 3 M solution in diethyl ether (5.44 g, 30 mmol) was added to a dry flask and cooled to 0 ˚C in an ice water bath. Carbon disulfide (2.51 g, 33 mmol) was added dropwise to the solution and the solution was stirred for 30 min. Water (5 mL) was slowly added to quench the reaction and the mixture was rotary evaporated to give a reddish brown slurry. More water (20 mL) was added to the mixture and the precipitate was filtered off to give a burgundy colored solution. The solution was added to a separation funnel and 5% aqueous HCl was added until the color changed and precipitate began to form. The aqueous layer was washed with dichloromethane multiple times until no color remained in the aqueous layer. Additional HCl was added to ensure that all the dithiobenzoic salt had been converted to the acid. The organic layers were combined and dried over $NaSO_4$. The purple solution was then

rotary evaporated to give dithiobenzoic acid (1.56 g, 34%), a dark purple viscous oil which was stored in the freezer due to stability concerns. ^{1}H and ^{13}C NMR spectra of this oil matched the reported values in literature.[56,57] Key NMR peaks: ^{1}H NMR: 6.39 (bs, SH peak), ^{13}C NMR: 225.4 (C=S).



80

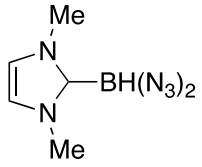
1,3-Dimethylimidazol-2-ylidene dithiobenzoic borane (80): 1,3-dimethylimidazol-2-ylidene borane (214 mg, 1.95 mmol) was added to a dry flask and dithiobenzoic acid (600 mg, 3.9 mmol) was added directly to the borane. Dry dichloromethane (1 mL) was used to fully dissolve the borane and dithiobenzoic acid and ensure homogeneous mixing. The dichloromethane was removed at room temperature by rotary evaporation and the resulting mixture was stirred overnight under argon. Dichloromethane (5 mL) was added to the mixture and adsorbed to silica gel. Column chromatography was performed by combiflash using a hexane : ethyl acetate gradient. 1,3-dimethylimidazol-2-ylidene dithiobenzoic borane eluted at 30% ethyl acetate. Evaporation of the solvent gave a waxy ruby red solid (124 mg, 24%): ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.08 (d, J = 6.0 Hz, 2H), 7.40 (t, J = 6.0 Hz, 1H), 7.28 (t, J = 6.0 Hz, 2H), 6.81 (s, 2H), 3.90 (s, 6H), 3.20– 2.20 (bq, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 239.5 (C=S), 148.4, 130.7, 127.5, 126.8, 120.8, 36.7; ^{11}B NMR (BF_3•Et_2O, 96 MHz, $CDCl_3$) δ –24, (t, *J* = 54 Hz); HRMS (ESI) calcd. for $C_{12}H_{14}BN_2S_2$ [M – H–] 261.0691, found 261.0703.



82

1,3-Dimethylimidazol-2-ylidene azidoborane (82): Carbene-borane **5** (302 mg, 2.75 mmol) was dissolved in 12 mL of toluene. In a glass vial, iodine (352 mg, 1.37 mmol) was dissolved in 2 mL of toluene and added slowly to the carbene-borane solution. Hydrogen gas was released, and the color of the reaction mixture became a brownish yellow. The reaction is complete when the brownish-yellow color remains. An ^{11}B NMR spectrum of the crude was taken to ensure that only diMe-Imd-BH_2I (**31**, –31.1ppm) was present. In another glass vial, sodium azide was dissolved in DMSO (5 mL). This solution was added to the mixture, which caused the solution to become white and cloudy immediately. The reaction mixture was stirred for 30 min.

Diethylether and water were added to the reaction mixture, and the water/DMSO layer was removed. The organic layer was then washed three times with water and once with brine to remove any residual salts or DMSO. The organic solvent was evaporated under vacuum to give a colorless oil. The oil was dissolved in some ethyl ether, and adsorbed to silica gel. Column chromatography was performed (hexanes/ethyl acetate), and the product eluted at 100% ethyl acetate to give a colorless oil (400 mg, 96%). ^{11}B NMR spectroscopy showed that the product was 97% pure with carbene-boryl-diazide (**83**) and carbene-borane (**5**) as minor impurities. The product was stored as a solution in 10 mL of dry toluene in the freezer. ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.91 (s, 2H), 3.84 (6H, s), 2.68 (1:1:1:1 q, J = 100 Hz, 2H); ^{11}B NMR (BF_3•Et_2O, 128.4 MHz, $CDCl_3$) δ –18.0 (t, J = 100 Hz).



83

1,3-Dimethylimidazol-2-ylidene diazidoborane (83): Carbene-borane **5** (250 mg, 2.27 mmol) was dissolved in 3 mL of toluene. In a glass vial, iodine (63 mg, 2.50 mmol) was dissolved in 2 mL of toluene and added slowly to the carbene-borane solution. The mixture was stirred for 15 min. Hydrogen gas was released, and the color of the reaction mixture became a dark purple. In another glass vial, sodium azide (325 mg, 5.00 mmol) was dissolved in DMSO (5 mL). A small amount of solid did not completely dissolve. This mixture was added to the borane mixture (some additional DMSO was used to rinse any remaining solid NaN_3 in the glass vial into the reaction mixture). The mixture was stirred for 30 min, and ^{11}B NMR spectroscopy of the crude reaction mixture showed that the diazide (–6.7 ppm) was the major product with minor amounts of the monoazide (–17.4 ppm) and triazide (–2.7 ppm).

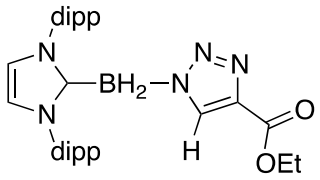
Diethylether and water were added to the reaction mixture, and the water/DMSO layer was removed. The organic layer was then washed three times with water and once with brine to remove any residual salts or DMSO. The organic solvent was evaporated under vacuum to give a colorless oil (210 mg, 45%). ^{11}B NMR spectroscopy showed that the product was 96% pure with carbene-boryl-azide and carbene-boryl-triazide as minor impurities. The product was stored as a solution in 5 mL of dry toluene in the freezer. ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.90 (s, 2H), 3.89 (s, 6H); ^{11}B NMR (96 MHz, $CDCl_3$) δ –7.0 (d, J = 114 Hz).

General Procedure 2 (GP2) (Carbene borane triazole synthesis via conventional heating)

A solution of dipp-Imd-BH_2N_3 (**6**) was made in an NMR tube or a pressure tube. Gentle heating was needed to completely dissolve the azide in some nonpolar solvents. The alkyne was then added to the tube, and the solution was heated in an oil bath until the reaction was deemed complete either by TLC analysis or NMR spectroscopy. The product was then purified by column chromatography (SiO_2, hexanes : ethyl acetate, 5 : 1 to 5 : 2).

General Procedure 3 (GP3) (Carbene borane triazole synthesis via microwave heating)

A solution of dipp-Imd-BH_2N_3 was made in a microwave vial with benzotrifluoride (1 mL). The alkyne was added to the vial, and the mixture was heated by microwave to 180˚C. The reaction progress was monitored by TLC. The solvent was evaporated, and the product was purified by column chromatography (SiO_2, hexanes : ethyl acetate, 5 : 1 to 5 : 2).

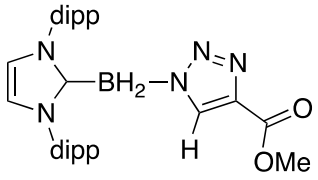


86

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(ethyl-1*H*-1,2,3-triazole-4-carboxylate)borane (86)

a) *Thermal Method 80 ˚C*: Compound **86** was prepared by GP2 by heating a solution of dipp-Imd-BH_2N_3 (30 mg, 0.068 mmol) and ethyl propiolate (0.014 mL, 0.14 mmol) in C_6D_6 at 80˚C for 12 h in an NMR tube. The reaction was monitored by ^{1}H NMR spectroscopy. The solvent was evaporated, and purification by flash chromatography gave a light pink solid (34 mg, 93%).

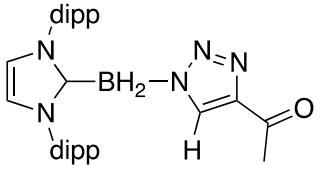
b) *Thermal Method 110 ˚C*: Compound **86** was prepared by GP1 by heating a solution of dipp-Imd-BH_2N_3 (100 mg, 0.23 mmol) and ethyl propiolate (0.034 mL, 0.34 mmol) in toluene at 110˚C for 6 h in a seal tube. The reaction was monitored by TLC. The solvent was evaporated, and purification by flash chromatography gave a light pink solid (115 mg, 94%): mp 183-185 ˚C; IR (thin film, cm^{-1}) ν_{max} 3943, 3689, 3054, 2984, 2929, 2685, 2410, 2305, 1725, 1535, 1422, 1328, 1265, 1207, 1048, 896, 740, 706; 1H NMR (400 MHz, $CDCl_3$) δ 7.45 (t, *J* = 7.6 Hz, 2 H, H arom.), 7.24 (d, *J* = 8 Hz, 4 H, H arom.), 7.18 (s, 2 H, =C*H*(N)), 4.26 (q, *J* = 7.2 Hz, 2 H, C$H_2$$CH_3$), 4.11 (q, *J* = 7.2 Hz, 2 H, C$H_2$$CH_3$), 2.59 (sept., *J* = 6.8 Hz, 4 H, C*H*Me_2), 1.28 (t, 3 H, *J* = 7.2 Hz, CH_2CH_3), 1.18 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH), 1.15 (t, 3 H, *J* = 7.2 Hz, CH_2CH_3), 1.12 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH); ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.8, 161.0, 145.5, 137.1, 135.8, 133.0, 130.4, 124.0, 123.4, 61.3, 60.4, 29.7, 28.5, 25.7, 22.4, 14.2, 13.9; ^{11}B NMR (BF_3•Et_2O, 133 MHz, C_6D_6) δ –18.9 (bs); HRMS (ESI) calcd. for $C_{32}H_{44}{}^{11}BN_5O_2Na$ ([M + Na]$^+$) 564.3486, found 564.3464.



89

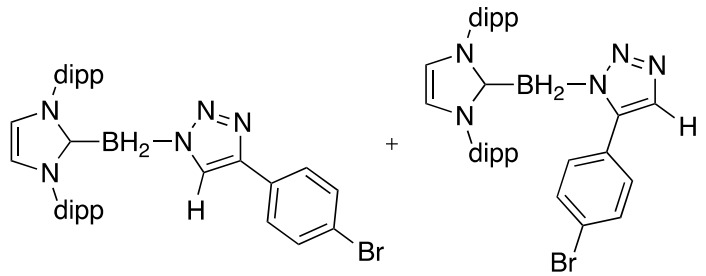
1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(methyl-1*H*-1,2,3-triazole-4-carboxylate)borane (89) Compound **89** was prepared by GP2 by heating a solution of dipp-Imd-BH_2N_3 (42 mg, 0.095 mmol) and methyl propiolate (0.013 mL, 0.14 mmol) in toluene at 110 ˚C for 6 h in a seal tube. Progress was monitored by TLC. The solvent was evaporated, and the product was purified by flash chromatography to yield a white solid (48 mg, 95%): mp 185–187 ˚C; IR (thin film, cm^{-1}) ν_{max} 3943, 3054, 2968, 2684, 2411, 2306, 1728, 1536, 1423, 1265,

1211, 1048, 896, 739, 706; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.49 (t, *J* = 7.6 Hz, 2 H, H arom.), 7.26 (d, *J* = 7.6 Hz, 4 H, H arom.), 7.15 (s, 2 H, =C*H*(N)), 7.01 (s, 1 H, H triazole), 4.29 (q, *J* = 7.2 Hz, 2 H, C*H*$_2$CH$_3$), 2.53 (sept., *J* = 6.8 Hz, 4 H, C*H*Me$_2$), 1.32 (t, 3 H, *J* = 7.2 Hz, CH$_2$C*H*$_3$), 1.23 (d, *J* = 6.8 Hz, 12 H, (C*H*$_3$)$_2$CH), 1.30 (d, *J* = 6.8 Hz, 12 H, (C*H*$_3$)$_2$CH); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.1, 145.4, 137.9, 133.0, 133.0, 130.6, 124.0, 123.2, 59.9, 28.7, 25.5, 22.4, 14.4; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –18.5 (br). HRMS (ESI) calcd. for $C_{31}H_{42}{}^{11}BN_5O_2Na$ ([M + Na]$^+$) 550.3329, found 550.3381.



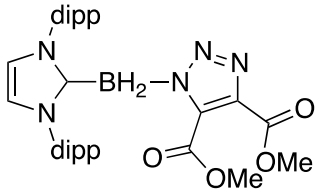
91

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(1*H*-1,2,3-triazole-4-acetate)-borane (91) Compound **91** was prepared by GP2 by heating a solution of dipp-Imd-BH_2N_3 (40 mg, 0.090 mmol) and 3-butyn-2-one (0.015 mL, 0.19 mmol) in C_6D_6 (0.6 mL) at 80 ˚C for 3.5 h in an NMR tube. The reaction was monitored by ^{1}H NMR spectroscopy. The solvent was evaporated, and the product was purified by flash chromatography to yield a white solid (44 mg, 94%): mp 201–203 ˚C; IR (thin film, cm^{-1}) ν_{max} 3944, 2681, 3054, 2986, 2688, 2306, 1422, 1265, 896, 739, 706; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (t, *J* = 7.6 Hz, 2 H, H arom.), 7.25 (d, *J* = 7.6 Hz, 4 H, H arom.), 7.17 (s, 2 H, =C*H*(N)), 3.81 (s, 3 H, COOC*H*$_3$), 3.61 (s, 3 H, COOC*H*$_3$), 2.57 (sept., *J* = 6.8 Hz, 4 H, C*H*Me$_2$), 1.19 (d, *J* = 6.8 Hz, 12 H, (C*H*$_3$)$_2$CH), 1.13 (d, *J* = 6.8 Hz, 12 H, (C*H*$_3$)$_2$CH); ^{13}C NMR (100 MHz, CDCl3) δ 162.3, 161.5, 145.5, 137.2, 135.6, 133.0, 130.5, 124.0, 123.4, 52.4, 51.7, 29.7, 28.6, 25.7, 22.5; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –20 (bs). HRMS (ESI) calcd. for $C_{31}H_{43}{}^{11}BN_5O$ ([M + H]$^+$) 512.3561, found 512.3591.



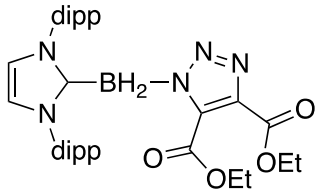
94A **94B**

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(4-(4-bromophenyl)-1*H*-1,2,3-triazole)borane (94A) and 1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(5-(4-bromophenyl)-1*H*-1,2,3-triazole)borane (94B) Compound **94** was prepared by GP2 by heating a solution of dipp-Imd-BH_2N_3 (40 mg, 0.090 mmol) and 1-bromo-4-ethynylbenzene (0.034 mg, 0.18 mmol) in toluene (0.7 mL) at 110˚C for 3 d in a seal tube. The reaction was monitored by TLC. The solvent was evaporated, and the isomers were isolated by column chromatography to yield compound **94A** (28 mg, 50%) and **94B** (5 mg, 8%) as light yellow solids. mp 230–236 ˚C; IR (thin film, cm^{-1}) ν_{max} 3936, 3053, 2965, 2927, 2869, 2404, 2302, 1732, 1466, 1265, 1100, 1009, 805, 738, 702; (**94A**) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 (t, *J* = 8.0 Hz, 2 H, H arom.), 7.32 (s, 1H, H triazole), 7.25 (d, *J* = 8.0 Hz, 4 H, H arom.), 7.22 (d, *J* = 8.4 Hz, 2 H, H arom.), 7.16 (s, 2H, =C*H*(N)), 6.52 (d, *J* = 8.4 Hz, 2 H, H arom.), 2.64 (sept., *J* = 6.8 Hz, 4 H, C*H*Me_2), 1.12 (d, *J* = 6.8 Hz, 24 H); (**94B**) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35–7.48 (m, 6 H, H arom.), 7.24 (d, *J* = 8.0 Hz, 4 H, H arom.), 7.14 (s, 2H, =C*H*(N)), 6.58 (s, 1 H, H triazole), 2.55 (sept., *J* = 6.8 Hz, 4 H, C*H*Me_2), 1.23 (d, *J* = 6.8 Hz, 12 H), 1.13 (d, *J* = 6.8 Hz, 12 H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 145.6, 143.9, 133.2, 131.8, 131.4, 130.5, 126.8, 125.7, 124.0, 123.1, 119.8, 28.7, 25.5, 22.4; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –18.8; HRMS (ESI) calcd. for $C_{35}H_{44}{}^{11}BN_5Br$ ($[M + H]^+$) 624.2873, found 624.2934.



103

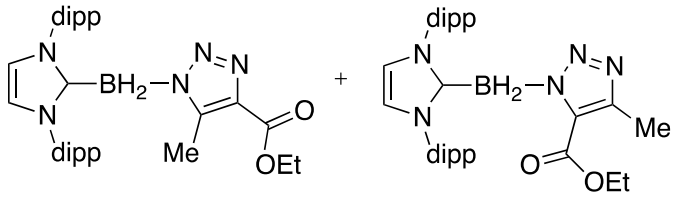
1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(dimethyl-1*H*-1,2,3-triazole-4,5 dicarboxylate) borane (103) Compound **103** was prepared by GP2 by heating a solution of dipp-Imd-BH_2N_3 (100 mg, 0.23 mmol) and dimethyl acetylene dicarboxylate (0.028 mL, 0.23 mmol) in toluene (1.5 mL) at 110˚C for 4 h in a seal tube. The reaction was monitored by TLC. The solvent was evaporated, and the product was purified by column chromatography (SiO_2, hexane : ethyl acetate, 2 : 1) to yield a light yellow solid (111 mg, 84%): mp 200-205 ˚C; IR (thin film, cm^{-1}) ν_{max} 3944, 3054, 2986, 2688, 2411, 2306, 1740, 1423, 1265, 1057, 896, 740, 706; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (t, *J* = 8 Hz, 2 H, H arom.), 7.24 (d, *J* = 8 Hz, 4 H, H arom.), 7.15 (s, 2 H, =C*H*(N)), 6.97 (s, 1 H, H triazole), 2.52 (sept., *J* = 6.8 Hz, 4 H, C*H*Me_2), 2.50 (s, 3 H, COCH_3), 1.23 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH), 1.13 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH); ^{13}C NMR (100 MHz, $CDCl_3$) δ ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –18.6 (bs). HRMS (ESI) calcd. for $C_{33}H_{44}{}^{11}BN_5O_4Na$ ([M + Na]$^+$) 608.3384, found 608.3360.



105

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(diethyl-1*H*-1,2,3-triazole-4,5 dicarboxylate) borane (105) Compound **105** was prepared by GP2 by heating a solution of dipp-Imd-BH_2N_3 (30 mg, 0.068 mmol) and diethyl acetylene dicarboxylate (0.022 mL, 0.14

mmol) in C_6D_6 (0.7 mL) at 80 ˚C for 4 h in an NMR tube. The reaction was monitored by ^{1}H NMR spectroscopy. The solvent was evaporated to yield a light yellow solid (41 mg, 99%): mp 211-215 ˚C; IR (thin film, cm^{-1}) ν_{max} 3944, 3054, 2986, 2685, 2411, 2305, 1731, 1422, 1265, 896, 747, 706; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 (t, *J* = 8 Hz, 2 H, H arom.), 7.24 (d, *J* = 8 Hz, 4 H, H arom.), 7.17 (s, 2 H, =C*H*(N)), 4.62 (q, *J* = 7.2 Hz, 2H, COOCH_2CH$_3$), 4.11 (q, *J* = 7.2 Hz, 2H, COOCH_2CH$_3$), 2.59 (sept., *J* = 6.8 Hz, 4 H, C*H*Me$_2$), 1.28 (t, *J* = 7.2 Hz, 3H, COOCH$_2$CH_3), 1.18 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH), 1.15 (t, *J* = 7.2 Hz, 3H, COOCH$_2$CH_3), 1.12 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH); ^{13}C NMR (100 MHz, $CDCl_3$) δ 161.8, 161.0, 145.5, 137.1, 135.8, 133.0, 130.4, 124.0, 123.4, 61.3, 60.4, 29.7, 28.5, 25.7, 22.4, 14.2, 13.9; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$): δ –19.4 (bs). HRMS (ESI) calcd. for $C_{35}H_{48}{}^{11}BN_5O_4Na$ ([M + Na]$^+$) 636.3697, found 636.3723.



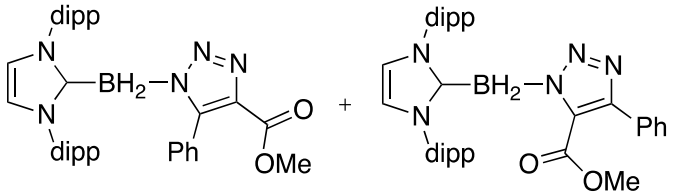
107A **107B**

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(ethyl 5-methyl-1*H*-1,2,3-triazole-4-carboxylate)borane (107A) and 1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(ethyl 4-methyl-1*H*-1,2,3-triazole-5-carboxylate)borane (107B)

a) *Thermal Method 110 ˚C*: Compounds **107A** and **107B** were prepared by GP2 by heating a solution of dipp-Imd-BH_2N_3 (100 mg, 0.23 mmol) and ethyl 2-butynoate (0.053 mL, 0.45 mmol) in toluene (1.5 mL) at 110˚C for 7 d in a seal tube. Progress was monitored by TLC. The solvent was evaporated, and the product was purified by column chromatography to yield

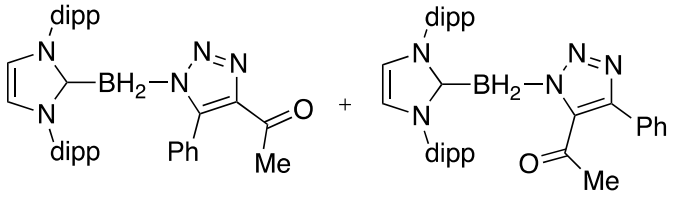
two inseparable isomers (1:12) as a light yellow solid (108 mg, 86%). A crystal structure of **107A** was obtained by slow vapor diffusion of pentanes into dichloromethane.

b) *Microwave Method 180 ˚C*: Compounds **107A** and **107B** were prepared by GP3 by microwaving a solution of dipp-Imd-BH_2N_3 (30 mg, 0.068 mmol) and ethyl 2-butynoate (0.016 mL, 0.14 mmol) in benzotrifluoride (1 mL) at 180˚C for 3.5 h in a microwave tube. The reaction was monitored by TLC. The solvent was evaporated and ^{1}H NMR showed a 1:6 mixture of two isomers. The compound was obtained in a quantitative crude yield (37 mg): mp 250-254; IR (thin film, cm^{-1}) ν_{max} 3054, 2986, 2680, 2410, 2306, 1704, 1423, 1265, 896, 740, 706; (**107A**) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 (t, *J* = 7.6 Hz, 2 H, H arom.), 7.25 (d, *J* = 8.0 Hz, 4 H, H arom.), 7.15 (s, 2 H, =C*H*(N)), 4.28 (q, *J* = 7.2 Hz, 2 H, COOCH_2CH$_3$), 2.56 (sept., *J* = 6.8 Hz, 4 H, C*H*Me$_2$), 1.77 (s, 3 H, triazole-CH_3), 1.31 (t, 3 H, *J* = 6.8 Hz, COOCH$_2$CH_3), 1.19 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH), 1.11 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.2, 145.7, 142.3, 134.3, 133.3, 130.5, 124.0 123.2, 59.7, 28.6, 25.6, 22.4, 14.4, 9.3; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –21.1 (bs); (**107B** in mixture with **107A**) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.39 (t, *J* = 7.6 Hz, 2 H, H arom.), 7.20 (d, *J* = 8.0 Hz, 4 H, H arom.), 7.12 (s, 2 H 1.19, =C*H*(N)), 4.11 (q, *J* = 7.2 Hz, 2 H, COOCH_2CH$_3$), 2.73 (sept., *J* = 6.8 Hz, 4 H, C*H*Me$_2$), 1.25 (t, *J* = 6.8 Hz, COOCH$_2$CH_3), 1.19 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH), 1.11 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH). HRMS (ESI) calcd. for $C_{33}H_{46}{}^{11}BN_5O_2Na$ ([M + Na]$^+$) 578.3642, found 578.3647.



108A **108B**

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(methyl-5-phenyl-1*H*-1,2,3-triazole-4-carboxylate)borane (108A) and 1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(methyl-4-phenyl-1*H*-1,2,3-triazole-5-carboxylate)borane (108B) Compounds **108A** and **108B** were prepared by GP2 by heating a solution of dipp-Imd-BH_2N_3 (100 mg, 0.23 mmol) and 4-phenyl-3-butyn-2-one (0.068 mL, 0.45 mmol) in toluene (1.5 mL) at 110˚C for 7 d in a seal tube. Progress was monitored by TLC. The solvent was evaporated, and the isomers were separated by column chromatography to yield **108B** (37 mg, 27%), which eluted first and **108A** (74 mg, 54%), which eluted second. A crystal structure of **108A** was obtained by slow vapor diffusion of pentanes into dichloromethane: mp >250 ˚C; IR (thin film, cm^{-1}) ν_{max} 4952, 3054, 2969, 2688, 2411, 2306, 1718, 1422, 1265, 1178, 1047, 896, 738, 705; (**108A**) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.48 (t, *J* = 7.6 Hz, 2 H, H arom.), 7.26 (d, *J* = 8.0 Hz, 4 H, H arom.), 7.18 (t, *J* = 6 Hz, 1H, H arom.), 7.16 (s, 2 H, =C*H*(N)), 7.11 (t, *J* = 6.8 Hz, 2 H, H arom.), 6.46 (d, *J* = 6.8 Hz, 2 H Hz, H arom.), 3.71 (s, 3 H, COOCH_3), 2.59 (sept., *J* = 6.8 Hz, 4 H, C*H*Me_2), 1.11 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH), 1.09 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH); ^{13}C NMR (100 mHz, CDCl3) δ 162.7, 145.7, 145.2, 134.5, 133.3, 130.4, 130.1, 129.4, 127.6, 126.7, 124.0, 123.2, 51.1, 29.6, 28.5, 25.6, 22.4; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –20.2 (bs); (**108B**) ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 (d, *J* = 7.2 Hz, 2 H Hz, H arom.), 7.44 (t, *J* = 8 Hz, 2 H, H arom.), 7.32 (t, *J* = 7.2 Hz, 2 H, H arom.), 7.27 (t, *J* = 8.8 Hz, 2 H, H arom.), 7.25 (d, *J* = 8 Hz, 4 H, H arom.), 7.17 (s, 2 H, =C*H*(N)), 3.56 (s, 3 H, COOCH_3), 2.73 (sept., *J* = 6.8 Hz, 4 H, C*H*Me_2), 1.25 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH), 1.15 (d, *J* = 6.8 Hz, 12 H, (CH_3)$_2$CH); ^{13}C NMR (100 MHz, $CDCl_3$) δ 162.7, 145.9, 145.6, 133.2, 131.9, 130.3, 129.4, 128.0, 127.9, 127.3, 124.0, 123.2, 51.5, 29.7, 28.5, 25.7, 22.5; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –19.0 (bs); HRMS (ESI) calcd. for $C_{39}H_{45}{}^{11}BN_5O_2$ ($[M + Na]^+$) 626.3642, found 626.3675.



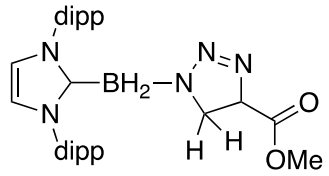
110A **110B**

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(5-phenyl-1*H*-1,2,3-triazole-4-acetate)borane (110A) and 1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(4-phenyl-1*H*-1,2,3-triazole-5-acetate)borane (110B)

a) *Thermal Method 110 ˚C*: Compounds **110A** and **110B** were prepared by GP2 by heating a solution of dipp-Imd-BH_2N_3 (100 mg, 0.23 mmol) and 4-phenyl-3-butyn-2-one (0.068 mL, 0.45 mmol) in toluene (1.5 mL) at 110˚C for 7 d in a seal tube. The reaction was monitored by TLC. The solvent was evaporated, and the isomers were separated by column chromatography to yield **110B** (37 mg, 28%), which eluted first and **110A** (82 mg, 61%), which eluted second. A crystal structure of **110A** was obtained by slow vapor diffusion of pentanes into dichloromethane.

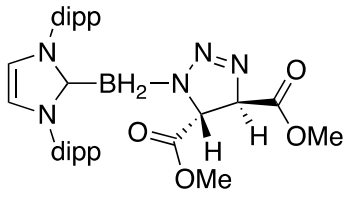
b) *Microwave Method 180 ˚C*: Compounds **110A** and **110B** were prepared by GP3 by microwaving a solution of dipp-Imd-BH_2N_3 (30 mg, 0.068 mmol) and 4-phenyl-3-butyn-2-one (0.021 mL, 0.14 mmol) in benzotrifluoride (1 mL) at 180˚C for 2 h in a microwave tube. The reaction was monitored by TLC. The solvent was evaporated, and the isomers were separated by column chromatography to yield **110A** (19 mg, 47%), which eluted second and **110B** (15 mg, 39%), which eluted first: mp 257-259; IR (thin film, cm^{-1}) ν_{max} 3054, 2984, 2921, 2868, 2676, 2410, 2306, 1676, 1422, 1265, 1177, 947, 896, 740, 706; (**110A**) ^{1}H NMR (400 MHz, $CDCl_3$): δ; ^{13}C NMR (100 mHz, CDCl3): δ 196.1, 145.7, 144.3, 137.5, 133.3, 132.0, 130.4, 128.1, 127.9,

127.4, 124.0, 123.3, 31.3, 29.7, 28.5, 25.7, 22.6; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$): δ –19.1 (bs); (**110B**) ^{1}H NMR (400 MHz, $CDCl_3$): δ ; ^{13}C NMR (100 mHz, CDCl3): δ 193.1, 145.6, 143.4, 142.4, 133.3, 130.4, 130.2, 129.6, 127.6, 126.7, 124.0, 123.2, 29.6, 28.5, 28.1, 25.6, 22.4; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$): δ –20.5 (bs); HRMS (ESI) calcd. for $C_{37}H_{46}{}^{11}BN_5ONa$ ($[M + Na]^+$) 610.3693, found 610.3678.



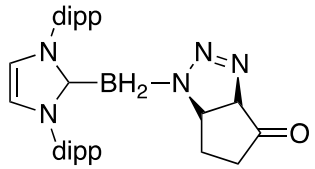
119

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(dimethyl-4,5-dihydro-1*H*-1,2,3-triazole-4,5-dicarboxylate)borane (119) Compound **119** was prepared using GP2 by dissolving the dipp-Imd-BH_2N_3 (30 mg, 0.068 mmol) in 0.6 mL of C_7D_8 in an NMR tube. Dimethyl fumarate (0.020 mg, 0.14 mmol) was added to the solution, and the NMR tube was heated at 80˚C for 7 h. The reaction progress was monitored by NMR. The compound was purified by column chromatography and recovered as a light gray solid (25 mg, 64%): mp 140-145; IR (thin film, cm^{-1}) ν_{max} 3054, 2968 2306, 1740, 1424, 1265, 1209, 1078, 896, 740, 706; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 (t, *J* = 8.0 Hz, 2 H, H arom.), 7.28 (d, *J* = 8.8 Hz, 2 H, H arom.), 7.26 (d, *J* = 7.6 Hz 2 H, H arom.), 7.09 (s, 2 H, =C*H*(N)), 4.11 (dd, *J* = 13.2, 14.0 Hz, 1 H, CH_2=C*H*COOCH3), 3.63 (s, 3 H, COOCH_3), 2.77 (dd, *J* = 11.2, 13.2 Hz, 1 H, CH_2CHCOOCH$_3$), 2.59 (m, 4H, C*H*Me_2), 2.26 (dd, *J* = 13.2, 14.0 Hz, 1 H, CH_2CHCOOCH$_3$), 1.28 (dd, *J* = 6.8, 17.2 Hz, 12 H, (CH_3)$_2$CH), 1.14 (dd, *J* = 4.0, 6.8 Hz, 12 H, (CH_3)$_2$CH); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.4, 145.5, 145.3, 133.5, 130.3, 124.0, 123.9, 122.7, 74.6, 51.9, 50.6, 28.7, 25.4, 25.2, 22.6, 22.5; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –19.0.



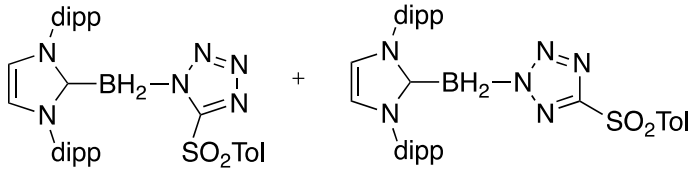
122

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(methyl-4,5-dihydro-1*H*-1,2,3-triazole-4-carboxylate)borane (122) Compound **122** was prepared using GP2 by dissolving the dipp-Imd-BH_2N_3 (30 mg, 0.068 mmol) in 0.6 mL of C_6D_6 in an NMR tube. Methyl acrylate (0.019 mL, 0.20 mmol) was added to the solution, and the NMR tube was heated at 70˚C for 22 h. The reaction progress was monitored by NMR. The compound was purified by column chromatography and recovered as a clear oil (29 mg, 80%): mp 150-154; IR (thin film, cm^{-1}) ν_{max} 3944, 3054, 2986, 2685, 2406, 2306, 1734, 1422, 1265, 1154, 896, 740, 706; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 (t, *J* = 7.6 Hz, 2 H, H arom.), 7.29 (d, *J* = 7.6 Hz, 2 H, H arom.), 7.25 (d, *J* = 7.6 Hz, 2 H, H arom.), 7.10 (s, 2 H, =C*H*(N)), 4.78 (d, *J* = 11.6, 1 H, NC*H*$COOCH_3$), 3.68 (s, 3 H, $COOCH_3$), 3.52 (d, *J* = 11.6, 1 H, NC*H*$COOCH_3$), 3.35 (s, 3 H, $COOCH_3$), 2.61 (sept., *J* = 6.8 Hz, 4 H, C*H*Me_2), 1.24 (dd, *J* = 6.8, 19.6 Hz, 12 H, $(CH_3)_2CH$), 1.12 (dd, *J* = 2.4, 6.8 Hz, $(CH_3)_2CH$); ^{13}C NMR (100 MHz, $CDCl_3$) δ 171.7, 169.5, 145.5, 145.4, 133.5, 130.2, 124.0, 123.9, 122.9, 80.4, 64.2, 52.2, 51.8, 28.6, 28.5, 25.5, 25.4, 22.5, 22.4; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –20.1 (bs); HRMS (ESI) calcd. for $C_{33}H_{47}{}^{11}BN_5O_4$ $[M + H]^+$ 588.3721, found 588.3726.



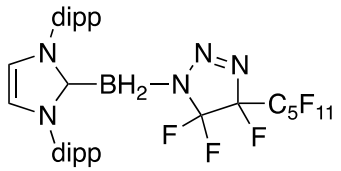
124

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(1,5,6,6a-tetrahydrocyclopenta-[*d*][1,2,3]triazol-4(3a*H*)-one)borane (124) Compound **124** was prepared using GP2 by dissolving the dipp-Imd-BH_2N_3 (30 mg, 0.068 mmol) in 0.6 mL of C_6D_6 in an NMR tube. 2-Cyclopenten-1-one (0.017 mL, 0.20 mmol) was added to the solution, and the NMR tube was heated at 80˚C for 48 h. The reaction progress was monitored by NMR. The compound was purified by column chromatography and recovered as a white solid (11 mg, 32%): mp 230-236 ˚C; IR (thin film, cm^{-1}) ν_{max} 3154, 2967, 2929, 2872, 2254, 1739, 1467, 1386, 1164, 1098, 907, 733; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47 (t, *J* = 8 Hz, 2 H, H arom.), 7.30 (d, *J* = 7.0 Hz, 2 H, H arom.), 7.27 (d, *J* = 5.5 Hz, 2 H, H arom.), 7.12 (s, 2 H, =C*H*(N)), 3.99 (d, *J* = 11.0 Hz, 1 H, H triazole), 2.99 (dd, *J* = 6.0, 11.0 Hz, 1 H, H triazole), 2.70–2.55 (m, 4 H, C*H*Me_2), 1.50–1.80 (m, 4H, H pentane ring), 1.29 (dd, *J* = 7.0, 21.5 Hz, 12 H, (C*H*$_3$)$_2$CH), 1.16 (dd, *J* = 5.0, 7.0 Hz, 12 H, (C*H*$_3$)$_2$CH); ^{13}C NMR (100 MHz, $CDCl_3$) δ 212.9, 145.7, 145.4, 133.6, 130.3, 124.0, 123.9, 122.8, 82.5, 61.2, 34.6, 29.6, 28.7, 25.4, 25.3, 22.7, 22.4; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –20.3; HRMS (ESI) calcd. for $C_{32}H_{45}{}^{11}BN_5O$ [M + H] 526.3730, found 588.3717.



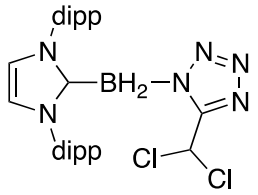
132A **132B**

1,3-Bis (2,6-diisopropyl(phenyl)imidazole-2-ylidene[5-(4- methylphenylsulfonyltetrazol-1-yl)]borane (132A) and 1,3-Bis(2,6-diisopropyl(phenyl)imidazole-2-ylidene[4-(4-methylphenyl-sulfonyltetrazol-1-yl)]borane (132B): Compound **132** was prepared according to GP2 by heating a solution of dipp-Imd-BH_2N_3 (42 mg, 0.095 mmol) and *p*-toluenesulphonyl cyanide (54 mg, 0.54 mmol) in C_6D_6 (0.7 mL) at 80 °C for 24 h. The solvent was evaporated, and the isomers were separated by column chromatography to yield the 1,4 regioisomer **132B** (3 mg, 5%) followed by **132A** (23 mg, 39%) as white solids: (**132A**) mp 214-216 ˚C; IR (thin film, cm_{-1}) ν_{max} 3169, 2966, 2928, 2870, 2450, 2116, 1596, 1469, 1345, 1167, 805, 759, 705; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64 (d, *J* = 8.0 Hz, 2H, H arom.), 7.44 (t, *J* = 7.8 Hz, 2H, H arom.), 7.21 (d, *J* = 8.0 Hz, 4H, H arom.), 7.19 (s, 2H, =C*H*(N)), 7.12 (d, *J* = 8.4 Hz, 2H, H arom.), 2.56 (septet, *J* = 6.8 Hz, 4H, C*H*Me_2), 2.37 (s, 3H, $C_6H_5CH_3$), 1.12 (d, *J* = 6.4 Hz, 24H, $(CH_3)_2CH$); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.2, 145.5, 144.8, 136.1, 132.9, 130.6, 129.5, 128.8, 124.2, 123.6, 28.6, 25.8, 22.5, 21.7; ^{11}B NMR (128 MHz, $CDCl_3$) δ –20.0 (bs); HRMS (ESI) calcd. for $C_{35}H_{45}{}^{11}BN_6O_2SNa$ ($[M + Na]^+$) 647.3315, found 647.3315; (**132B**) ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.85 (d, *J* = 8.5 Hz, 2H, H arom.), 7.51 (t, *J* = 8.0 Hz, 2H, H arom.), 7.43 (d, *J* = 8.5 Hz, 2H, H arom.), 7.29 (d, *J* = 8.0 Hz, 4H, H arom.), 7.22 (s, 2H, =C*H*(N)), 2.51 (s, 3H, $C_6H_5CH_3$), 2.47 (sept., *J* = 7.0 Hz, 4H, C*H*Me_2), 1.25 (d, *J* = 7.0 Hz, 12H, $CH(CH_3)_2$), 1.15 (d, *J* = 7.0 Hz, 12H, $CH(CH_3)_2$); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.2, 145.2, 132.4, 131.5, 131.1, 130.4, 124.4, 123.6, 108.3, 28.8, 25.7, 22.3, 22.2; ^{11}B NMR (BF_3•Et_2O, 128 MHz, $CDCl_3$) δ –19.9 (bs); HRMS (ESI) calcd. for $C_{35}H_{46}{}^{11}BN_6O_2S$ ($[M + H]^+$) 625.3496, found 625.3503.



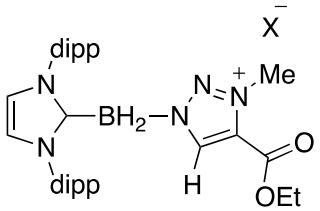
134

1,3-Bis(2,6-diisopropyl(phenyl)imidazole-2-ylidene [5-(perfluorohexyl)-1H-tetrazol-1-yl)]-borane (134): Compound **134** was prepared according to GP2 by heating a solution of dipp-Imd-BH_2N_3 (42 mg, 0.10 mmol) and perfluoroheptanenitrile (.060 mL, 0.29 mmol) in C_6D_6 (0.5 mL) at 75 °C for 72 h. Chromatographic separation (elution with hexane : EtOAc = 1 : 2) gave compound **134** as a white solid (66 mg, 87%): mp 180-182 ˚C; IR (thin film, cm^{-1}) ν_{max} 3165, 3122, 3088, 2968, 2929, 2873, 2478, 2433, 2344, 2119, 1741, 1595, 1560, 1477, 1460, 1432, 1386, 1366, 1352, 1331, 1299, 1239, 1134, 1108, 1074, 1040, 991, 949, 936, 891, 810, 774, 768, 760, 747, 732, 720, 708; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44 (t, *J* = 7.8 Hz, 2H, H arom.), 7.24 (d, *J* = 8.4 Hz, 4H, H arom.), 7.23 (s, 2H, =C*H*(N)), 2.57 (sept., *J* = 6.8 Hz, 4H, C*H*Me_2), 1.14 (d, *J* = 1.6 Hz, 12H, CH(C*H*$_3$)$_2$), 1.13 (d, *J* = 1.6 Hz, 12H, CH(C*H*$_3$)$_2$); ^{1}H NMR (400 MHz, C_6D_6) δ 7.16 (t, *J* = 8.4 Hz, 2 H, H arom.), 7.00 (d, *J* = 8.0 Hz, 4 H, H arom.), 6.52 (s, 2 H, =C*H*(N)), 2.66 (sept., *J* = 6.8 Hz, 4 H, C*H*Me_2), 1.17 (d, *J* = 6.8 Hz, 12 H, CH(C*H*$_3$)$_2$), 0.95 (d, *J* = 6.8 Hz, 12 H, CH(C*H*$_3$)$_2$); ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.6 (t), 145.5, 132.9, 130.7, 124.1, 123.7, 28.6, 25.8, 22.3; ^{11}B NMR (BF_3•Et_2O, 128 MHz, $CDCl_3$) δ –20.1 (bs); ^{19}F NMR (376 MHz, $CDCl_3$) δ –80.8 (3F), –108.1 (2F), –121.1 (2F), –121.8 (2F), –122.9 (2F), –126.2 (2F); HRMS (ESI) calcd. for $C_{34}H_{38}{}^{11}BF_{13}N_6Na$ ([M + Na]$^+$) 811.2952, found 811.2941. Crystals of **134** were grown for X-Ray analysis by slow vapor diffusion of hexanes into dichloromethane.



136

1,3-Bis(2,6-diisopropyl(phenyl)imidazole-2-ylidene [5-(dichloromethyl)-1H-tetrazol-1-yl)]-borane (136): Compound **136** was prepared according to GP2 by heating of solution of dipp-Imd-BH_2N_3 (42 mg, 0.10 mmol) and dichloroacetonitrile (0.080 mL, 0.96 mmol) in C_6D_6 (0.5 mL) at 77 °C for 72 h. Chromatographic separation (elution with hexane : EtOAc = 1 : 1) gave the product as a white solid (20 mg, 38%): mp 234-236 ˚C; IR (thin film, cm^{-1}) ν_{max} 3165, 3122, 3088, 2968, 2929, 2873, 2478, 2433, 2344, 2119, 1741, 1595, 1560, 1477, 1460, 1432, 1386, 1366, 1352, 1331, 1299, 1239, 1148, 1134, 1108, 1074, 1060, 1040, 1030, 991, 949, 936, 891, 810, 774, 768, 760, 747, 732, 720, 708; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.48 (t, *J* = 7.5 Hz, 2H, H arom.), 7.26 (d, *J* = 8.0 Hz, 4H, H arom.), 7.23 (s, 2H, =C*H*(N)), 6.13 (s, 1H, C*H*Cl_2), 2.52 (sept., *J* = 7.0 Hz, 4H, C*H*Me_2), 1.18 (d, *J* = 6.5 Hz, 12H, CH(C*H*$_3$)$_2$), 1.14 (d, *J* = 7.0 Hz, 12H, CH(C*H*$_3$)$_2$); ^{13}C NMR (100 MHz, $CDCl_3$) δ 156.4, 145.5, 132.8, 131.0, 124.3, 123.7, 58.9, 28.7, 25.8, 22.4; ^{11}B NMR (BF_3•Et_2O, 128 MHz, $CDCl_3$) δ –21.1 (bs); HRMS (ESI) calcd. for $C_{29}H_{39}{}^{11}BCl_2N_6Na$ ([M + Na]$^+$) 575.2599, found 575.2604.



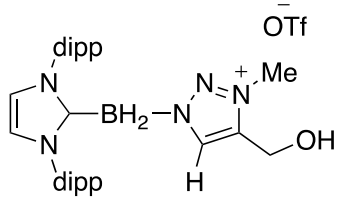
X = OTf: **141**
X = I: **142**

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(ethyl-3-methyl-1*H*-1,2,3-triazol-3-ium-4-carboxylate)borane triflate (141) or iodide (142)

a) *Reaction with methyl triflate*: Compound **141** was prepared by dissolving a solution of compound **86** (40 mg, 0.074 mmol) in dry THF (2 mL), and cooling the solution to –78˚C. Methyl triflate (0.017 mL, 0.15 mmol) was then added, and the mixture was stallowed to warm to rt over 18 h while stirring. The solvent was evaporated to give a colorless oil. Diethyl ether (2 mL) was added to the oil, and the oil was stirred by a spatula to give a white precipitate. The precipitate was collected by gravity filtration to give compound **141** as a light gray crystalline solid (42 mg, 81%). mp 165-167 ˚C; IR (thin film, cm^{-1}) ν_{max} 3944, 3701, 3055, 2985, 2685, 2412, 2306, 1746, 1423, 1265, 1153, 1031, 896, 739, 706; ^{1}H NMR (400 MHz, $CDCl_3$) δ ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.53 (t, *J* = 7.5 Hz, 2 H, H arom.), 7.49 (s, 2 H, 7.56, =C*H*(N)), 7.29 (d, *J* = 8.0 Hz, 4 H, H arom.), 7.16 (s, 1H, H triazole), 4.44 (q, *J* = 8.0 Hz, 2 H, CH_2CH$_3$), 4.25 (s, 3 H, CH_3 triazole), 2.39 (sept, 4 H, *J* = 7.0 Hz, C*H*Me$_2$), 1.39 (t, 3H, *J* = 7.0 Hz, CH$_2$CH_3), 1.18 (d, 12 H, *J* = 2.0 Hz, (CH_3)$_2$CH), 1.17 (d, 12 H, *J* = 2.0 Hz, (CH_3)$_2$CH); ^{13}C NMR (125 MHz, $CDCl_3$) δ 155.1, 145.2, 136.3, 132.1, 131.2, 121, 125.0, 124.3, 63.7, 39.9, 28.8, 25.3, 22.2, 13.9; ^{11}B NMR (BF_3•Et_2O, 133 MHz, $CDCl_3$) δ –16.8; ^{19}F NMR (376 MHz, $CDCl_3$) δ –78.3; HRMS (ESI) calcd. for $C_{33}H_{47}{}^{10}BN_5O_2$ $[M]^+$ 555.3859, found 555.3832.

b) *Reaction with methyl iodide*: Compound **142** was prepared by making a solution of compound **86** (51 mg, 0.094 mmol) in THF (1 mL), and the solution was cooled to 0 ˚C, and adding methyl iodide (0.029 mL, 0.47 mmol). Compound **142** was collected as a light orange crystalline solid (52 mg, 80%). ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.57 (s, 2 H, 7.56, =C*H*(N)), 7.56 (t, *J* = 8.1 Hz, 2 H, H arom.), 7.31 (d, *J* = 7.8 Hz, 4 H, H arom.), 7.19 (s, 1H, H triazole), 4.48 (q, *J* = 7.2 Hz, 2 H, CH_2CH$_3$), 4.34 (s, 3 H, CH_3 triazole), 2.40 (sept, 4 H, *J* = 6.9 Hz, C*H*Me$_2$), 1.42

(t, 3H, J = 7.2 Hz, CH_2CH_3), 1.21 (d, 12 H, J = 1.8 Hz, $(CH_3)_2CH$), 1.19 (d, 12 H, J = 1.8 Hz, $(CH_3)_2CH$).



143

1,3-Bis-(2,6-diisopropylphenyl)imidazol-2-ylidene 1-(ethyl-3-methyl-1*H*-1,2,3-triazol-3-ium-4-hydroxymethyl)borane triflate (143): Boryl-triazole **141** (30 mg, 0.43 mmol) was dissolved in 1.5 mL of ethanol. Sodium borohydride (10 mg, 0.26 mmol) was added in one portion to the mixture. The sodium borohydride did not completely dissolve, and no bubbling or temperature change was observed. The mixture was allowed to stir overnight. A TLC (10% MeOH and CH_2Cl_2) of the crude reaction mixture showed no new spots. An ^{11}B NMR spectrum of the crude mixture showed peaks at 2.9 ppm, –16 ppm, and –41.6 ppm. The ethanol was removed, and the resulting solid was dissolved in DCM, washed three times with water and once with brine, and dried over $NaSO_4$ to remove remaining sodium borohydride. The DCM was removed by vacuum to give a white solid (17 mg, 77%) ^1H NMR spectroscopy confirmed that **143** had formed. ^1H NMR (500 MHz, $CDCl_3$) δ 7.56 (t, J = 7.8 Hz, 2H), 7.31 (d, J = 7.6 Hz, 4H), 7.29 (s, 2H), 5.05 (bs, CH_2OH), 4.60 (s, 2H), 3.99 (s, 3H), 2.41 (sept, J = 6.8 Hz, 4H), 1.20 (d, J = 6.8 Hz, 12H), 1.17 (d, J = 7.2 Hz, 12H); ^{11}B NMR (128.4 MHz, $CDCl_3$) δ –17.0 (bs); ^{19}F NMR (376 MHz, $CDCl_3$) δ –78.26 (s).

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