Title
OBSERVATIONS IN REACTIVITY BETWEEN BH CONTAINING COMPOUNDS AND ORGANOMETALLIC REAGENTS: SYNTHESIS OF BORONIC ACIDS, BORONIC ESTERS, AND MAGNESIUM HYDRIDES

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OBSERVATIONS IN REACTIVITY BETWEEN BH CONTAINING COMPOUNDS AND ORGANOMETALLIC REAGENTS: SYNTHESIS OF BORONIC ACIDS, BORONIC ESTERS, AND MAGNESIUM HYDRIDES

A dissertation submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

CHEMISTRY AND BIOCHEMISTRY

by

Jacob William Clary
March 2012

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Abstract

OBSERVATIONS IN REACTIVITY BETWEEN BH CONTAINING COMPOUNDS AND ORGANOMETALLIC REAGENTS: SYNTHESIS OF BORONIC ACIDS, BORONIC ESTERS, AND MAGNESIUM HYDRIDES

Jacob W. Clary

Diisopropylaminoborane (BH$_2$-N(iPr)$_2$) is prepared by reacting lithium diisopropylaminoborohydride (iPr-LAB) with trimethylsilyl chloride (TMSCl). Aliphatic, aromatic, and heteroaromatic (diisopropylamino)boranes are readily synthesized at ambient temperature (0 °C) in 1h by the reaction of Grignard reagents with (BH$_2$-N(iPr)$_2$). Two contending reaction pathways have tentatively been identified. In one pathway, bromomagnesium hydride (HMgBr) acts as the leaving group from the initially formed bromomagnesium organo(diisopropylamino)borohydride, affording the product organodiisopropylaminoborane (RBH-N(iPr)$_2$). The increased stersics and the diminished Lewis acidity of (RBH-N(iPr)$_2$) prevents it from further reacting with Grignard reagents. In the second pathway, the product may be formed by a hydride transfer from bromomagnesium organo(diisopropylamino)borohydride to the starting material (BH$_2$-N(iPr)$_2$). It was found that only 1.2 equivalents of (BH$_2$-N(iPr)$_2$) was required for greater than 95% conversion to the organo(diisopropylamino)borane. During the mechanistic investigation, bromomagnesium diisopropylaminoborohydride was identified as a byproduct and was subsequently synthesized from diisopropylamine borane and methylmagnesium chloride. This
borylation reaction can be carried out under Barbier conditions, where \((\text{BH}_2-\text{N}(i\text{Pr})_2)\) traps the in situ formed Grignard reagent from the corresponding organic halide and magnesium metal. Simple acid hydrolysis of the product organo(diisopropylamino)borane leads to the corresponding boronic acid in good to excellent yield.

Grignard reagents (aliphatic, aromatic, heteroaromatic, vinyl or allylic) react with one equivalent of 4,4,5,5-tetramethyl-1,3,2-dioxaborolane, \((\text{pinacolborane}, \text{PinBH})\) at ambient temperature in tetrahydrofuran (THF) to afford the corresponding pinacol boronates. Initially formed dialkoxy alkylborohydride intermediate quickly eliminates hydridomagnesium bromide \((\text{HMgBr})\) and affords the product boronic ester in very good yield. Hydridomagnesium bromide \((\text{HMgBr})\), in turn disproportionates to a 1:1 mixture of magnesium hydride \((\text{MgH}_2)\) and magnesium bromide \((\text{MgBr}_2)\) on addition of pentane to the reaction mixture. DFT calculations (Gaussian09) at the B3LYP/6-31G(d) level of theory show that disproportionation of \(\text{HMgBr}\) to \(\text{MgH}_2\) and \(\text{MgBr}_2\) is viable in the coordinating ethereal solvents. This reaction also can be carried out under Barbier conditions where the neat PinBH is added to the flask prior to the in situ formation of Grignard reagent from the corresponding organic halide and magnesium metal. Pinacol boronic ester synthesis under Barbier conditions does not give Wurtz coupling side products from reactive halides, such as benzylic and allylic halides. The reaction between PinBH and various Grignard reagents is an efficient, mild and general method for the synthesis of pinacol boronates.
This Thesis is dedicated to my God, family and many friends.

Thank you for believing in me.

He gives power to the weak and strength to the powerless.

Even youths will become weak and tired, and young men will fall in exhaustion.

But those who trust in the Lord will find new strength.

They will soar high on wings like eagles.

They will run and not grow weary.

They will walk and not faint. Isaiah 40:29-31
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To my friends: Shane, you are my brother and the way you and Hannah live has inspired me in many ways. Its not the fishing and drinking that I will miss most,
but the way we could hang, words not needed. Hannah, your hospitality and joy for life is contagious, thank you. Chris, we have been friends a long time and shared a lot of life together, I’m grateful. Jensen, I look forward to kick fighting you in tall grass one of these days.

To my parents: Dad, thank you for the many sacrifices you have made. I cannot imagine a better upbringing. The way you always believe in me gives me strength and I cannot say enough about how much I love you. Your character is highlighted through the success of your family. Mom, the way you love and depend on Jesus has influenced me profoundly. Some of my earliest memories are of us memorizing Bible verses together.

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CHAPTER 1

Boronic Acid Derivatives in Modern Organic Chemistry
1.1 Introduction

Organoboronic acids have profoundly affected the exploratory and industrial synthesis of materials and medicines. The study of organoboronic acid chemical properties has grown into one of the major branches of organic chemistry. Fundamental to organic synthesis is the ability to construct carbon-carbon bonds. Of even higher significance is the stereocontrolled construction of carbon-carbon bonds. Boronic acids have been integral in achieving both of these synthetic challenges. In 1979, metal-catalyzed C-C bond forming reactions were discovered by Suzuki and Miyaura utilizing boronic acids and aryl halides.\(^1\) Also in 1979, it was observed by Hoffmann and Zeiss that allylboronic esters stereoselectively added to aldehydes.\(^2\)

Additionally, boronic acids have found applications as components of chiral auxillaries,\(^3\) as protecting groups,\(^3\) as catalysts in Diels-Alder reactions,\(^4\) as precurseors to boron enolates\(^5\) and in the separation of cyclic cis-and trans-1,2-diols.\(^6\) The contribution of organoboron chemistry to organic chemistry was recognized with the 1979 Nobel Prize awarded to Professor Herbert C. Brown, the pioneer of organoboron chemistry. Recently, Akira Suzuki was awarded the 2010 Nobel Prize in chemistry for his work on palladium catalyzed cross-coupling between aryl halides and boronic acids. These awards demonstrate the importance boronic acids have played in organic chemistry.
1.1.1 Nomenclature of boronic acids

Boranes consists of a boron atom covalently bonded to three hydrogen or three carbon atoms. Borane in its pure form exists as a dimer, \( \text{B}_2\text{H}_6 \), because the monomer of borane (\( \text{BH}_3 \)) is unstable due to the boron atom only being surrounded by six valence electrons. In order to form a stable octet, \( \text{BH}_3 \) shares the electrons of a B-H bond on another boron atom. This type of bonding is known as a 3-center-2-electron bond; that is three atoms share two electrons (Figure 1.1).\(^7\,^8\)

![Figure 1.1. Borane dimer, diborane (\( \text{B}_2\text{H}_6 \))](image)

Trisubstituted, particularly oxygenated boron species are generally considered derivates of borane, all of which are trigonal planar compounds (Figure 1.2). A borinic acid is comprised of a boron atom bonded to two carbon atoms and one hydroxyl group. Relative to borinic acids, boronic acids are further oxygenated, containing one C-B bond and two B-OH bonds. Like boronic acids, boronic esters have one C-B bond and two B-O bonds, however, the hydroxyl groups are replaced with alkoxy groups (\( \text{OR} \)). Boronic esters can be further derivatized, with the carbon atoms of the alkoxy groups tethered together to form a cyclic boronic ester. The final oxidative degradation product of boranes, boronic acids and boronic esters is boric acid, which has three B-OH bonds.
Figure 1.2. Organic and oxygenated boron compounds

Boronic acids readily react with alcohols, eliminating a water molecule to give cyclic and acyclic boronic esters, also known as boronates. This reaction is more generally known as an esterification (Figure 1.3). Esterification of boronic acids with 1,2-diols form five-member cyclic dioxaborolanes, while esterification of boronic acids with 1,3-diols form six-member cyclic dioxaborinanes.

Figure 1.3. Boronic acid esterification

The methylene groups of the diol may be substituted for steric or asymmetric induction purposes. Common optically active 1,2-diols include those derived from tartrate esters, pinanediol and camphor derived 1,2-diols (Figure 1.4). 9,10,11
1.1.2 Properties of Boronic Acids and Boronic Esters

Boronic acids are $sp^2$ hybridized with trigonal planar geometry. This is because boron only has six electrons in its valence shell, making it electron deficient with one empty p-orbital. The empty p-orbital readily accepts an electron pair from a Lewis base, making boronic acids Lewis acidic. The addition of a Lewis base to a boronic acid results in the formation of an anionic tetrahedral boronate (eq 1).

$$\text{PhB(OH)}_2 + \text{H}_2\text{O} \rightarrow \text{PhB(OH)}_2^+ \text{OH}^-$$

Unlike Brønsted acids, the p$K_a$ of a boronic acid does not refer to its deprotonation. Instead, it is a measure of the proton released from a water molecule once it has added to the trigonal boron to form the boronate (eq 1). Thus boronic acids are Lewis acids and not Bronsted acids. As a reference point, the p$K_a$ of phenylboronic acid is 8.8.$^{12,13}$

Under dehydration conditions, boronic acids can form six-membered cyclotrimeric anhydrides of organoboronic acids known as boroxines ($1,3,5,2,4,6$-trioxatriborinanes, $R_3B_3O_3$).$^{14}$ The formation of boroxines is accomplished by the
simple dehydration of boronic acids, either through thermal azeotropic removal of water or by exhaustive drying over sulfuric acid or phosphorus pentoxide (eq 2). In some cases the boroxine ring system will form by simply heating the corresponding boronic acid in an anhydrous solvent.

$$\begin{align*}
3 \quad \text{R-BOH} & \quad \xrightarrow{-3 \text{H}_2\text{O}} \quad \text{R-B-BO-B-R} \\
\text{R} & \quad \text{alkyl, alkoxy or aryl}
\end{align*}$$

Boroxine anhydrides are more reactive to oxidation than boronic acids and are generally avoided to increase the shelf life of boronic acids. Avoiding boroxine formation is accomplished by avoiding the dehydrative conditions.$^{15,16}$

Aside from low molecular weight compounds, boronic acids are generally thermally stable and inert to water and oxygen, making them convenient reagents. Additionally, boron based byproducts are easy to remove from reaction mixtures, making them highly practical for industrial purposes. The low toxicity of the boronic acid byproducts also makes them highly desirable reagents, especially for large scale processes.$^{17,18}$
1.1.3 Analysis of Boronic Acids

The determination of a free boronic acid’s melting point is difficult and the results are unreliable. It was observed in 1930 at Cornell University that phenylboronic acid gave inconsistent melting point results. It was later confirmed that the observed melting points were actually the dehydration (boroxine formation) or decomposition points arising from heating the boronic acid. The amount of water content in samples has also been brought into question regarding the inconsistent melting points due to the effect that water has on boroxine formation. However, there are a number of characterization methods available for the analysis of boronic acids.

Boronic acids have been used to derivatize bifunctional compounds, namely 1,2- and 1,3-diols, for analysis by gas chromatography (GC). However, GC analysis of free boronic acids suffers from dehydration in the high temperature GC injector. The boroxine formed in the injection port is chromatographically stable, which makes the characterization of boronic acids very difficult due to the unavoidable mixture of the acid and anhydride in variable composition. Conversion of the free boronic acid to a cyclic boronate by reaction with a 1,2- or 1,3-diol yields a thermally and hydrolytically stable compound compatible with GC analysis.

The isotopic pattern of boron, 20% $^{10}$B and 80% $^{11}$B, is a theoretically useful fingerprint to identify boronic acids using mass spectrometry (MS). However, it is difficult to obtain intense signals with most ionization methods due to the low volatility of these compounds. This problem is amplified by the gas phase
dehydration reaction forming boroxine derivatives, as in high temperature GC injectors. The derivitization of boronic acids with diols to form cyclic boronic esters has reliably eliminated boroxine formation. Nevertheless, soft ionization techniques such as electrospray ionization (ESI) and atmospheric pressure chemical ionization (APCI) are not able to reliably produce molecular ions of boronic esters. Electron ionization or electron impact mass spectrometry (EI-MS) uses a higher energy to ionize compounds, and is therefore known as a “hard ionization” technique. EI-MS has been used to analyze various boronic esters.\textsuperscript{24,25}

The most important analytical tool for organoboron compounds is NMR spectroscopy. Of the two boron isotopes, \textsuperscript{10}B (20%, I = 3) and \textsuperscript{11}B (80%, I = 3/2), the latter possesses superior NMR properties. \textsuperscript{11}B NMR spectra have two characteristics that give information about the chemical environment of boron. \textsuperscript{11}B NMR chemical shifts are identified in units of parts per million (ppm), most commonly relative to an external BF\textsubscript{3}:OEt\textsubscript{2} standard (0 ppm). The \textsuperscript{11}B NMR chemical shifts cover a broad range of about 250 ppm and are dependent on the charge, the coordination number, and the substituents bonded to boron.\textsuperscript{26} The second piece of information gained from a \textsuperscript{11}B NMR spectra is the coupling constants \(J(\textsuperscript{11}B-\textsuperscript{1}H)\) in units of Hz. The B-H coupling values have the following trend: BH 120-190 Hz, BH\textsubscript{2} 110-130 Hz, BH\textsubscript{3} 90-110 Hz, BH\textsubscript{4} 70-80 Hz.\textsuperscript{27} Some of the NMR properties of the \textsuperscript{11}B nucleus which make it so useful as an analytical tool are the strong NMR signal and 80.4% natural abundance, resonance at high frequency, and relative sensitivity of the \textsuperscript{11}B nucleus to different perturbations including bonding strain, substituents, etc.
1.2 Boronic Acids in Organic Chemistry

Fundamental to organic synthesis is the ability to construct carbon-carbon bonds. Also of high significance is stereocontrol in the construction of carbon-carbon bonds. Boronic acids are integral in achieving both of these synthetic challenges. Carbon-carbon (C-C) bonds are formed through the Suzuki cross-coupling reaction and through the allylboration of aldehydes and ketones. Both methods have been developed into highly stereoselective methods for C-C bond construction.

1.2.1 Suzuki-Miyaura C-C Cross-coupling

Substituted biphenyl compounds have become a central component to many fine chemical industries, with a wide range of applications. The synthesis of unsymmetrical biaryls is widely utilized in the pharmaceutical and agrochemical industry. Unsymmetrical biaryls are present in natural products such as: alkaloids, lignans, terpenes, flavonoids, tannins, polyketides, coumarins, peptides, and glycopeptides. Biphenyls have also been widely incorporated into herbicides, chiral ligands in various catalyst, and as liquid crystals in organic conductors. The most common method for constructing aryl-aryl bonds is the palladium catalyzed coupling of aryl halides or triflates with arylboronic acids. This reaction is known as the Suzuki-Miyaura cross-coupling reaction, which is often truncated to the “Suzuki reaction” or “Suzuki coupling” (Scheme 1.1).
According to Carey,\textsuperscript{32} the Suzuki reaction is now the most commonly employed reaction in the pharmaceutical industry for the synthesis of carbon-carbon bonds. Another application of the Suzuki reaction is in the synthesis of pi conjugated materials, such as conductive polymers like polyphenylene liquid crystal and organic emitting displays such as organic light emitting diodes (OLEDs).\textsuperscript{32} The Suzuki coupling reaction has been expanded upon and optimized numerous times. The reaction can be performed under mild conditions in aqueous solutions with the tolerance of a wide range of functional groups. Under varying conditions, this reaction now encompasses the coupling of aryl, heteroaryl, vinyl, and alkyl halides or triflates with aryl, heteroaryl, vinyl and alkyl boronic acids, esters and trifluorborates. Because the Suzuki coupling reaction has found such wide application, Professor Akira Suzuki shared the 2010 Nobel Prize in Chemistry with Professor Richard Heck and Professor Ei-ichi Negishi for their distinctive contributions to palladium catalyzed cross-coupling reactions.

1.2.1.1 Applications of the Suzuki-Miyaura C-C Cross-coupling Reaction

Boscalid\textsuperscript{®} is an important fungicide belonging to the class of succinate dehydrogenase inhibitors, which protects fruit and vegetable crops from ascomycetes
(kingdom fungi). Boscalid® is produced by BASF and has been on the market since 2003. In 2009 the current total production volume was more than 1000 tons/year. The synthesis of 2-amino-4´-chlorobiphenyl, the key intermediate in the synthesis of Boscalid®, illustrates the impact that the Suzuki-Miyaura cross-coupling has had on the industrial synthesis of unsymmetrical biaryl systems. The patent literature does not give the full synthetic details, but it does rely on the Pd(0)-catalyzed Suzuki-Miyaura cross-coupling of 1-chloro-2-nitrobenzene 1 with 4-chlorophenylboronic acid 2 (Scheme 1.2).

Scheme 1.2. Industrial synthesis of Boscalid®

Many research groups, including that of Akira Suzuki, have highlighted the value and efficiency of the palladium catalyzed cross-coupling method through the synthesis of Boscalid®. Prior to Suzuki cross-coupling, five synthetic steps were required from comparable materials to obtain the key intermediate 3. Today the palladium catalyzed cross-coupling reaction has been conducted under flow reactor conditions, whereby the core intermediate 3 is produced in a single step in 92% isolated yield.
Though Suzuki coupling has revolutionized C-C bond formation, some limitations remain, specifically for reactions run on large scale such as those used by the pharmaceutical industry. The main issue arises from the palladium catalyst, which is toxic and expensive, even in catalytic amounts. Spent palladium is usually recovered and sent to its manufacturer for salvage, and new catalyst needs to be purchased for each batch.\textsuperscript{38} With regards to chemical synthesis, residual palladium can have adverse effects on downstream chemical process. Additionally, the presence of heavy metal impurities in pharmaceutical products are closely regulated because of their inherent toxicity to human beings. Great effort has been directed towards reducing the cost and minimizing environmental impact by the immobilization and reuse of the palladium catalyst. Many approaches toward this goal have revolved around the coordination of palladium to a polymer through a covalently tethered phosphine ligand.\textsuperscript{38} Homogeneous palladium catalysts are sequestered from the reaction mixture through a phosphine-polymer covalent linkage, allowing catalyst retrieval by filtration.\textsuperscript{39} Palladium catalysts have also been incorporated into hetergenous systems where the palladium is bound to carbon,\textsuperscript{40} tethered to a hetergenous polymer,\textsuperscript{41,42} or tethered to solid mesoporous material like silica\textsuperscript{43} (Scheme 1.3). These heterogeneous systems have greatly improved the Suzuki reaction to give comparable catalytic activity to that of other homogeneous palladium catalyzed systems.
Scheme 1.3. Solid support-bound palladium catalyzed cross-coupling reaction of organoboranes and aryl and alkenyl halides and triflates

Highlighting the many advances that the Suzuki reaction has undergone, Ranu synthesized the key intermediate of Boscalide® in 90% yield using heterogeneous mesoporous-bound palladium under ligand free conditions (eq 3). Examples of biaryl systems in medicine and natural products are shown in Table 1.

Table 1.1. Compounds synthesized by Suzuki-Miyaura cross-coupling
Furoylpyrroloquinolones, potent and selective PDE3 inhibitor\textsuperscript{45}

Treatment of Erectile Dysfunction

p38 MAP Kinase Inhibitor\textsuperscript{46}

Losartan\textsuperscript{47}
Angiotensin II Receptor Antagonist
Antihypertensive

Valsartan\textsuperscript{48}
Angiotensin II Receptor Antagonist
Antihypertensive

22 million users worldwide
1.2.1.2 Mechanism of the Suzuki-Miyaura Cross-Coupling

As in other cross-coupling mechanisms, the catalytic cycle of the Suzuki-Miyaura reaction includes oxidative addition, transmetallation and reductive elimination (Scheme 1.4). The efficiency of palladium(0) originates from its ability to activate C-X bonds in the oxidative addition of organic halides or triflates to form a palladium complex, R-Pd-X. A very wide range of palladium(0) catalysts or Pd(II) precursors can be used for the cross-coupling reaction. Pd(PPh$_3$)$_4$ is most commonly used, but PdCl$_2$(PPh$_3$)$_2$ and Pd(OAc)$_2$ plus other phosphine ligands are also efficient. Often the rate determining step is the oxidative addition, but this has been shown to be dependent on the identity of the aryl halide. With aryl bromide the rate determining step is the oxidative addition and with iodides it is the transmetallation. The reactivity decreases in the order of I > OTf > Br >> Cl. The second step is the transmetallation between the organopalladium(II) complex (R-Pd-X) and the organoboron compound (R'-B). This step will not proceed in the absence of base, however, the exact role of the base is unknown. It has been proposed that the base either replaces the halide in the palladium complex or binds to the organoborane species depending on the base affinity for the organoborane. The reductive elimination step produces the carbon-carbon bond and regenerates the palladium(0) catalyst.
Scheme 1.4. Catalytic cycle for Suzuki-Miyaura cross-coupling

1.2.2 Stereoselective Suzuki Cross-coupling

The three dimensional shape of molecules has intrigued scientist and philosophers for generations. In 1848 Louis Pasteur discovered that a racemic mixture of tartaric acid crystallized from water produced two sets of crystals which were mirror images of each other (Figure 1). He then separated (resolved) the crystals by hand, dissolved them separately in water and observed that they rotated plane polarized light in opposite and equal directions. The correlation between crystal morphology and optical rotation was known at that time. It had been shown by Herschel in 1822 that right-handed quartz crystals, as judged by their morphology, are dextrorotatory and left-handed quartz crystals are levorotatory. The new
observation was that composition alone did not completely describe the compound under analysis and that there was an underlying property to the molecules. This property came to be known as chirality.

![Figure 1.5](image)

**Figure 1.5.** A. tartaric acid crystals\(^{56}\) B. (S,S) and (R,R) tartaric acid

This phenomenon of chirality was explored exhaustively over the next several decades, and by the 1950s was common knowledge amongst chemists and physicists. The impact of this finding finally affected the common citizen when a drug, thalidomide, was prescribed to mothers experiencing morning sickness.

Babies born in Europe between the years of 1957 and 1961 were severely deformed and it is estimated that between 10,000 and 20,000 people were affected. Notably, the newly formed United States Federal Drug Administration (FDA) rejected approval of thalidomide because of a lack of testing. Thalidomide was quickly linked to the unprecedented phenomenon and it was pulled from most world markets by 1961. Thalidomide has one stereocenter and the “drug” was administered as a racemic mixture. Further testing determined that only one enantiomer was
responsible for the analgesic properties associated with morning sickness, while the other was found out to be a teratogen. Furthermore the administration of one enantiomer would be futile because the compound racemizes under physiological conditions.

This incident was known as “one of the biggest medical tragedies of modern times”\textsuperscript{57} and it changed how chemists and the general public thought about drugs, how the government regulated the sales of drugs, and how biologists thought about the human body. Since the thalidomide incident, the FDA requires that drugs containing stereocenters must have both enantiomers or all diastereomers tested independently. The need for synthetic methods to produce isomerically pure compounds was born out of this tragedy and continues to have lasting effects upon the pharmaceutical industry.

Atropisomers are stereoisomers resulting from restricted rotation around a single bond, which allows for isolation of the two isomers. With regard to biaryl systems, this is known as axial chirality. The restricted rotation around the biaryl bond is due to the presence of at least two bulky substituents in the \textit{ortho} position to this bond. The restricted rotation around the biaryl bond makes atropisomers conformational isomers and they are often referred to as rotamers.

Axially chiral biaryls are structural motifs present in many natural products. Michellamine B is an anti-HIV napthylisoquinoline alkaloid which contains axial chirality (Figure 1.6).\textsuperscript{58}
Figure 1.6 Michellamine B

The synthesis of axial chiral biaryls can be classified into two types: diastereoselective and enantioselective.\textsuperscript{59} Diastereoselective methods consist either of a chirality transfer from planar to axial (path a) or central to axial (path b) (Figure 1.7). Enantioselective methods (path c) involve a chiral palladium ligand as the source of chirality.
Figure 1.7. Diastereoselective (path a and b) vs. enantioselective (path c) Suzuki coupling

Uemura subjected chiral tricarbonyl(arene)chromium complexes to the Suzuki coupling reaction. He found that the chromium complex blocked one face of the aryl halide (planar chirality), this induced axial chirality in the Suzuki coupling. Planar chirality describes a molecule which lacks an asymmetric carbon atom but posesses two non-coplanar rings that are each dissymmetric and which cannot easily rotate around the biaryl bond. Uemura found that the kinetically favored cis product was formed exclusively, but upon heating could be converted to the thermodynamically more stable syn product (eq 4).
Axial chirality can be induced in the Suzuki reaction by a stereogenic center which is a short distance from the biaryl axis. Nicolaou applied a chiral cyclic boronic acid in the synthesis of the key intermediate in vancomycin 9 (eq 5). The reaction produced a 2:1 dr, favoring the desired diastereomer.
One year after Nicolaou reported the asymmetric synthesis of the key intermediate for vancomycin, he applied the use of a chiral catalyst in the Suzuki coupling reaction. This was the first example of a chiral ligand used for biaryl Suzuki coupling.\textsuperscript{62} However, the development of an asymmetric Suzuki coupling reaction using chiral ligands was previously investigated by many others including Hayashi,\textsuperscript{63} Uemura,\textsuperscript{64} and Shibasaki.\textsuperscript{65} Using the achiral cyclic boronic acid 11 and the same chiral iodo compound 7 as in his previous studies, Nicolaou applied the common chiral catalyst 2,2’-bis(diphenylphosphino)-1,1’-binapthyl (BINAP)\textsuperscript{66} to the Suzuki coupling and observed a diastereomeric ratio of 3.5:1 (12:13) (eq 6).

![Chemical reaction image]

\textsuperscript{(S)-L: } dr = 3.5:1 (12:13)  
\textsuperscript{(R)-L: } dr = 1:3.5 (12:13) 

(6)

Applying both \textit{R} and \textit{S} enantiomers of the catalyst to produce both diasteromers of the biaryl product 12 and 13 confirmed that the diastereoselectivity is controlled by the chirality of the ligand used.
The first chiral biaryl system synthesized using Suzuki coupling where chirality was solely obtained through a catalyst was reported by Buchwald. The catalytic system was comprised of a binaphthyl-based phosphine ligand and tris(dibenzylideneacetone)dipalladium(0) (Pd₂(dba)₃). He synthesized various axially chiral phenynaphthyls and binaphthyls in 57-92% ee with excellent yields. The 2-ethylphenylboronic acid was coupled with phosphonate 14 by reaction with 0.2 mol % Pd(0) and 0.24 mol % ligand (eq 7).

\[
\begin{align*}
\text{Br} & \quad \text{P(O)(OEt)₂} \\
\text{14} & \\
\text{B(OH)₂} & \quad \text{Et} \quad \text{P(O)(OEt)₂} \\
\text{15} & \quad \text{NMe₂} \quad \text{PCy₂} \\
& \quad \text{94% yield} \quad \text{92% ee}
\end{align*}
\]

Diastereoselective and enantioselective Suzuki coupling is now an available method for the synthesis of axial chiral biaryl systems. The diastereoselective methods are the most selective and versatile while the enantiomeric route is the most direct.

### 1.2.3 C-N and C-O Cross-coupling Reactions With Boronic Acids

Beyond Suzuki coupling, boronic acids have found additional utility as cross-coupling reagents for the formation of heteroatom-carbon bonds. It was observed by Chan that cupric acetate in the presence of a tertiary amine facilitated cross-coupling of boronic acids with N-H and O-H containing aryl compounds. This finding was an
extension of his previous work on the cross-coupling of N-H bonds with triarylbumuth catalyzed by cupric acetate and tertiary amines (eq 8).\textsuperscript{69}

\[ \begin{align*}
X & \quad \begin{array}{c}
\text{Ar}_3\text{Bi/Cu(OAc)}_2 \\
\text{CH}_2\text{C}l_2, \text{Et}_3\text{N or Py, 25 }^\circ\text{C}
\end{array} \\
\text{N-H} & \rightarrow \\
\text{Y} & \quad \begin{array}{c}
\text{Ar} \\
\text{N} - \text{Ar} \\
\text{Y}
\end{array}
\end{align*} \]

\( X, Y = \text{COR, COR}_2, \text{CONR}_2, \text{SO}_2\text{R}, \text{R, H} (\text{R} = \text{alkyl and aryl}) \) \hspace{1cm} (8)

Using the same reaction conditions as in the triarylbumuth arylation, boronic acids were able to replace the bismuth reagent. His findings were very broad; compatible substrates included phenols, amines, anilines, amides, imides, ureas, carbamates, and sulfonamides (eq 9).

\[ \begin{align*}
\text{R-X-H} & \quad \begin{array}{c}
\text{(HO)}_2\text{B} \\
\text{Cu(OAc)}_2, \text{Et}_3\text{N or Py} \\
\text{CH}_2\text{C}l_2, 25 ^\circ\text{C}
\end{array} \\
\text{X} = \text{N, O} & \quad \begin{array}{c}
\text{R} - \text{X} - \text{R}' \\
\text{R}'
\end{array}
\end{align*} \]

\( (\text{HO})_2\text{B} \) \( \text{Cu(OAc)}_2, \text{Et}_3\text{N or Py} \) \( \text{CH}_2\text{C}l_2, 25 ^\circ\text{C} \) \hspace{1cm} (9)

The general reaction stoichiometry is arylboronic acid (2-3 equiv.), anhydrous Cu(OAc)\(_2\) (1-2 equiv.), a tertiary amine such as triethylamine or pyridine (2-3 equiv.) in methylene chloride stirred at room temperature for 24-72 hours. This method is superior to the triarylbumuth reaction because many boronic acids are commercially available or easily prepared.

Evans expanded the copper (II) promoted cross-coupling reaction, focusing solely on the synthesis of biaryl ethers from various substituted phenols.\textsuperscript{70} It was found that 5 equivalents of base increased reaction yields and that the addition of molecular sieves reduced the formation of phenol and diphenyl ether as unwanted side products. Evans reasoned that even though the reaction was conducted under
anhydrous conditions, the formation of boroxine concomitantly formed water. Water was then competitively arylated by the aryl-copper species. In applying this methodology to the 4-hydroxyphenylglycine derivative, no competitive N-arylation was observed (eq 10).

\[
\text{EtO}C\text{NHAc}+\text{(HO)}_2\text{B}+\text{Cu(OAc)}_2\rightarrow \text{EtO}C\text{NHAc}^{81}\%
\]

Chan and Lam then expanded the substrate scope, focusing primarily on aryl/heteroaryl C-N bond cross-coupling (eq 11).\(^{71}\) A variety of N-H containing heteroarenes were cross coupled with arylboronic acids under equivalent conditions put forth in Chan’s seminal work.

\[
\begin{align*}
\text{R} = \text{CF}_3 & \quad \text{X} = \text{N}, \text{CH} \\
\text{CH}_3 & \quad \text{R} = \text{substituents or benzofused} \\
\text{CH}_3\text{O} & \quad \text{CH}_2\text{Cl}_2
\end{align*}
\]

Based on this early work, the use of copper(II) and amines for the synthesis of carbon-heteroatom cross-coupling has been optimized and applied in the synthesis of many biologically and industrially important molecules. The work of Chan, Lam, and Evans has provided a mild alternative to classical Ullmann-type chemistry, normally carried out at elevated temperatures.\(^{72}\)

The numerous advantages that pertain to using boronic acids in cross-coupling reactions has prompted researchers to exhaustively extend the limits of their use.
Today boronic acids cross-couple with many functional groups beyond aryl groups including: alkenes, alkynes, carbonyl compounds and imines. Cross-coupling reactions utilizing boronic acids are catalyzed by various metals including palladium, rhodium, ruthenium, copper, nickel, and mixed iron-zinc catalysts.

1.2.4 Biological and Medicinal Applications

The development of boron-mediated reactions and processes for synthetic chemistry has dramatically impacted the ability to design and synthesize many new and important types of drug leads as well as chemical probes and other chemical tools for biological research and drug discovery. However, the contributions of organoboron compounds exceed their value as synthetic intermediates.

Despite the rarity of boron containing natural products, a number of synthetic compounds containing boron have shown strong bioactivity and are even suitable as pharmaceuticals agents for clinical use. The mild Lewis acidic nature of the boronic acid moiety has led to the use of boron at the active site of enzyme inhibitors. The motif which has received the most attention is that of α-aminoboronic acid derivatives which serve as mimics of amino acids and allow their incorporation into designed and optimized enzyme inhibitors. The enzyme inhibiting activity of boronic acid derivatives was first observed by Matteson in 1981. Using the novel homologation methodology that he developed, he produced both the R and S enantiomers of 1-acetamido-2-phenylethaneboronic acid. Optically pure (+)-
pinanediol benzylboronate 17 reacts rapidly with (dichloromethyl)lithium at -100 °C to form 18, which rearranges at 20 °C or above to the α-chloro boronic ester 19. In situ treatment of 19 with lithiumhexamethyldisilazane yields the silylated amino boronic ester 20. (+)-Pinanediol (R)-1-acetamido-2-phenylethaneboronate 21 is formed following the addition of acetic anhydride and acetic acid. After isolation by chromatography and recrystallization from dichloromethane, the pinanediol ester was cleaved with boron trichloride to yield (R)-1-acetamido-2-phenylethaneboronic acid 22 (Scheme 1.5).

Scheme 1.5. Synthesis of (R)-1-acetamido-2-phenylethaneboronic Acid

Over the past 30 years, the only reported synthesis of enantioenriched α-amino boronic acids have relied on Matteson’s protocol. One of these substrates is bortezomib (Velcade®), an α-amino boronic acid which was recently approved for clinical use as an anticancer agent for the treatment of myeloma (Figure 1.8).86
The first alternative to Matteson’s homologation procedure was recently published by Ellman.\textsuperscript{87} He reported a highly diastereoselective copper-catalyzed addition of bis(pinacolato)diboron to \textit{N}-\textit{tert}-butanesulfinylaldimines (eq 12).

\begin{center}
\begin{tikzpicture}
\node at (0,0) {\includegraphics[width=0.5\textwidth]{figure1.png}};
\end{tikzpicture}
\end{center}

Based on the findings of Sadighi,\textsuperscript{88} that a copper(I) boryl complex is generated when B\textsubscript{2}Pin\textsubscript{2} is mixed with a copper NHC, Ellman mixed (1,3-dicyclohexylimidazol-2-ylidene)copper(I) \textit{tert}-butoxide ((ICy)CuOt-Bu) with B\textsubscript{2}Pin\textsubscript{2}. Two pathways were conceived to explain the observed steroselectivity. In the first pathway, the copper(I) boryl complex interacts with the sulfinylaldimine such that a boron-carbon bond is formed directly (Scheme 1.6). In the second pathway, an organocopper intermediate is first formed, which is expected to undergo transmetallation with retention of configuration (Scheme 1.6) In both cases the stereochemistry is accounted for by the borylated reagent attacking from the least hindered face in an open transition state.
Scheme 1.6 Proposed rational for observed diastereoselectivity

This transformation uses an inexpensive Cu/lignad catalyst system and readily accessible N-sulfinyl aldimine starting compounds. The reaction affords good yields and very high diastereoselectivities. This method was also used in the synthesis of bortezomib.\(^3\) \(\alpha\)-Amino boronic acids have become important pharmacophores for serine protease inhibition and have been incorporated into inhibitors of numerous therapeutically important proteases, including thrombin, elastase, and dipeptidyl peptidase IV.\(^8\)

Other boron-containing compounds which have shown strong bioactivity include the antifungal benzoaborolidines,\(^9\) a number of antibacterial oxazaborolidines,\(^1\) the antibacterial and antimalarial agent diazaborine,\(^2\) and other boron analogues of biomolecules\(^3,4\) (Figure 1.9).

29
Boron containing pharmacophores

Boronic acids have long been investigated for the treatment of cancer through boron neutron capture therapy (BNCT). Boron naturally exists as a mixture of the $^{11}\text{B}$ and $^{10}\text{B}$ isotopes, occurring in an 81.17 to 18.83 ratio, with the latter having a cross-section of 3850 barns. Barns is a non SI unit describing the cross sectional area of an atom, with 1 Barn equal to $10^{-24}$ square centimeters. The cross section of the $^{10}\text{B}$ isotope efficiently captures low energy neutrons to give the following nuclear reaction:

$$^{10}\text{B} + ^1\text{n} \rightarrow ^7\text{Li} + ^4\text{He} + \gamma (2.4\text{MeV})$$

The high kinetic energy released in this transmutation (over 2.40 Mev) enables the resulting fragments to be destructive. The path length of the emitted particles are equivalent to cell diameters (ca. 10 μm). If boron could be introduced preferentially into malignant cells, selective destruction of unhealthy tissues could result, and the destruction would be confined to the immediate vicinity of the boron atom. This is the basic principal of BNCT.\textsuperscript{95}
1.3 Synthesis of Boronic Acids

The vast number of applications of boronic acids to organic synthesis have led to an increasing amount of research into efficient methods of their synthesis. The Lewis acidic properties of boron make the formation of C-B bonds limited only by the number of methods available for producing synthons of Lewis basic carbon. The most common methods utilized to date and those highlighted herein for the synthesis of aryl boronic acids include: transmetallation of organometallic reagents with various trialkyl borates, and transition metal catalyzed cross-coupling and borylation through transition metal catalyzed C-H activation. This review is focused on the current methods for the synthesis of aryl boronic acids, and therefore the pericyclic reaction between boranes and unsaturated hydrocarbons, the hydroboration reaction, will not be discussed in great detail.

The hydroboration reaction was the first method to make organoboranes readily available. Brown observed that B-H containing compounds regioselectively added across alkenes with the boron bonding to the least hindered carbon atom (eq 14).96

\[
\begin{align*}
\text{R-} & \quad \text{H-B} \\
\text{R} & \quad \text{H-B} \\
\text{R} & \quad \text{H-B}
\end{align*}
\]

(14)
Of particular significance is the fact that the hydroboration reaction holds a very important position in the history of asymmetric synthesis. The first highly successful non-enzymatic asymmetric synthesis involved the hydroboration of cis-2-butene with diisopinocamphenylborane, Ipc₂BH, prepared from α-pinene and borane in diglyme (DG) (eq 15). ⁹⁷

\[ \text{Me} + \text{BH}_3 \xrightarrow{\text{DG} \ \ 0 \ ^\circ \text{C}} \text{MeBH} \xrightarrow{\text{B-H}} \text{MeBH}_2 \xrightarrow{[\text{O}]} \text{HO-Me} \]

\[(R)-(-), \ 87\% \ \text{ee} \quad (15)\]

The resulting optical induction of 87% was essentially stereospecific due to the fact that the commercially available α-pinene at the time was at best 92% ee. The hydroboration reaction has been extended to include many different chiral borane reagents as well as various transition metal catalyzed variations; many prochiral alkenes have been hydroborated with 100% ee. ⁹⁸ Many excellent reviews have been compiled regarding the broad field of hydroboration. ⁹⁸,⁹⁹,¹⁰⁰,¹⁰¹

1.3.1 Transmetallation of Grignard and Organolithium Reagents

It was observed and recorded in 1909 that a methylborate solution added to an ethereal solution of phenylmagnesium bromide produced phenyboronic acid. ¹⁰² It was determined later that this reaction was very low yielding, and the major component was diphenylborinic acid (eq 16).
In 1931, Johnson found that reversing the order of addition and running the reaction at low temperature (-12 °C) produced phenylboronic acid in approximately 30% yield. Finally a systematic study between phenylmagnesium bromide and trimethylborate in diethyl ether confirmed the low temperature requirement (generally below -50 °C) for increased yields of boronic acid (eq 17).

As reaction conditions approach ambient temperatures, increasing amounts of diphenylborinic ester are formed by the second addition of Grignard reagent to the intermediate dimethylbenzene boronate. Utilization of this method for large scale industrial production is limited due to the low temperature requirements. This problem has been reduced by using excess amounts of trialkylborate. Also the use of cyclic dioxaborolanes such as isopropoxypinacolborane have reduced the formation of borinic acid side products. With increased reaction temperatures, organomagnesium halide reagents react readily with most electrophilic functional groups. The incompatability of Grignard reagents with many functional groups is the major limitation of this methodology.
A highly improved method for producing arylboronic acids was put forth by Brown and Cole. The method utilized the transmetallation of aryllithium reagents with an excess of trialkylborate such as; trimethyl-, triethyl-, or triisopropylborate, followed by acid hydrolysis. Due to the high reactivity of lithium reagents, the reaction must be carried out at -78 °C to avoid multiple additions (eq 18).

\[
\begin{align*}
\text{X} = \text{Cl, Br} & \quad 1. \text{tBuLi} \\
& \quad 2. \text{B(OiPr)}_3 \\
& \quad -78 \degree \text{C} \\
& \quad \text{HCl} \\
\end{align*}
\]

(18)

1.3.2 Cross-coupling Reaction of Bis(pinacolato)diboron and Pinacolborane

The classical methods for producing boronic acids rely on transmetallation between organomagnesium or lithium derivatives and boron compounds. These organometallic intermediates are highly reactive toward electrophiles, which extremely limits the scope of functional groups tolerated by this method. Additionally, rigorous anhydrous conditions are required in order to maintain the fidelity of the organometallic species.

As the Suzuki cross-coupling reaction was developed through the 1980s and 90s, the need for additional methods of synthesizing boronic acids expanded. Because the Suzuki cross-coupling reaction is very tolerant of functionality, a convergent synthesis of highly functionalized biaryls was envisioned.
In 1995 Miyaura and coworkers observed that the palladium catalyzed cross-coupling between the pinacol ester of diboron (bis(pinacolato)diboron, B$_2$Pin$_2$) with aryl bromides, iodides and triflates, directly provides arylpinacolboronates.$^{108}$ The reaction conditions were mild enough to tolerate a variety of functional groups including nitriles, esters, and ketones. The incorporation of these functionalities would be impossible using organolithium reagents under the Brown-Cole method$^{107}$ or by the use of Grignard reagents and trialkylborate. The simple synthetic sequence consists of heating the aryl halide and B$_2$Pin$_2$ to 80 °C in DMSO with a palladium catalyst and a mild base (potassium acetate). The palladium catalyst used was PdCl$_2$(dppf) (dppf = 1,1'-bis(diphenylphosphino)ferrocene) (Figure 1.10).

Figure 1.10. PdCl$_2$(dppf) (dppf = 1,1'-bis(diphenylphosphino)ferrocene)

The reaction is complete in 1-24 hours, depending on the substrate. The cross-coupling reaction of haloarenes having electron donating groups, such as NMe$_2$ or OMe, is slow and requires up to 24 hours. Substrates with electron withdrawing properties accelerate the reaction, requiring between 1 to 2 hours. For example, methyl 4-bromoanisole requires 24 hours to provide the arylboronate in 69% yield (eq 19). Under the same conditions, 4-bromobenzonitrile requires only 1 hour to yield the
corresponding boronic ester in 76% yield (eq 20). This valuable alternative to the use of highly reactive organometallics is known as Miyaura coupling.

\[
\text{MeO-}\text{CBr} + \text{B}_2\text{Pin}_2 \xrightarrow{3 \text{ mol}\% \text{PdCl}_2 \text{(dppf)}} \text{MeO-}\text{CBOH} \quad \text{DMSO, 80 °C, 24h} \quad 69\% \quad (19)
\]

\[
\text{NC-}\text{CBr} + \text{B}_2\text{Pin}_2 \xrightarrow{3 \text{ mol}\% \text{PdCl}_2 \text{(dppf)}} \text{NC-}\text{CBOH} \quad \text{KOAc / DMSO, 80 °C, 1h} \quad 76\% \quad (20)
\]

Under similar conditions as the palladium catalyzed Miyaura reaction, Murata reported the synthesis of boronic esters using the dialkoxhydroborane pinacolborane as a boron source.\(^{109,110}\) This was the first example of a catalytic system utilizing a hydroborane as a boron source other than for hydroboration.\(^{111}\) The main advantage of this method is the atom economy gained by avoiding the diboron reagent B\(_2\)Pin\(_2\). Bis(pinacolato)diboron is expensive, and therefore prohibitive for large scale use. The catalyst Murata used was PdCl\(_2\)(dppf), and the amount required was equivalent to the Miyaura reaction at 3 mol %. The base and solvent used in this reaction are triethylamine and dioxane, respectively. This method produces arylpinacol boronic esters in high yields and tolerates a wide range of functional groups. For example, 4-iodoethylbenzoate and 4-bromobenzonitrile were converted to their corresponding boronic esters in 79% and 73% yield, respectively (eq 21 and eq 22).

\[
\text{EtO}\text{C-}\text{I} + \text{HBO}_2\text{O} \xrightarrow{3 \text{ mol}\% \text{PdCl}_2 \text{(dppf)}} \text{EtO}\text{C-}\text{BOH} \quad \text{dioxane/Et}_3\text{N, 80 °C, 2h} \quad 79\% \quad (21)
\]
Unlike the Miyaura reaction, this coupling methodology is not greatly affected by the presence of electron withdrawing or donating groups. Murata highlighted the limited effect that sterics has on the reaction by the conversion of orthotolyl iodide to the corresponding boronic ester in 78% yield.\textsuperscript{110}

Since the seminal discovery of palladium catalyzed borylation, boron donors have now been expanded to include aminoboranes. It was recently shown that the monomeric dialkylaminoborane, diisopropylaminoborane (BH\textsubscript{2}-N(iPr)\textsubscript{2}), can be used as an inexpensive boron source in palladium catalyzed Alcaraz-Vaultier borylation of aryl halides (eq 23).\textsuperscript{112}

Due to the high cost of palladium, other catalytic systems have been investigated including copper and nickel. In 2006, after demonstrating that CuI/L-proline is a powerful catalytic system for coupling reactions of aryl halides with nucleophiles such as azides,\textsuperscript{113} Ma applied the CuI catalyst to the Miyaura reaction. He successfully coupled pinacolborane with various aryl iodides (eq 24).\textsuperscript{114}
Though this reaction requires the strong base sodium hydride, and is not suitable with aryl bromides, the catalyst is inexpensive and the reaction proceeds at room temperature, making this a very practical reaction.

Marder has long been interested in the insertion of substrates into the Cu-B bond in (NHC)Cu(boryl) complexes (NHC = N-heterocyclic carbene), in particular alkenes.\textsuperscript{115} During the course of his investigations, he became interested in the reaction of a copper(I) boryl complex with aryl halides. It was found that treatment of the boryl complex [(iPrNHC)CuBPin] (iPrNHC = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene) with p-iodotoluene led to the formation of p-tolylinacolborane (eq 25).\textsuperscript{116} The borylcomplex was prepared in situ from [(iPrNHC)CuOtBu] and B\textsubscript{2}Pin\textsubscript{2}.

\[\text{R} = \text{2,6-iPr_2C_6H_3}\]

The aryl halide was treated with B\textsubscript{2}Pin\textsubscript{2} (1.5 equiv.) in the presence of KOTBu (1.5 equiv.) as the base, CuI (0.1 equiv.), and nBu\textsubscript{3}P (0.13 equiv.) as the ligand in THF at room temperature. Though the requirements of this borylation methodology are greater than that for the Ma procedure,\textsuperscript{113} this method highlights greater versatility and the growing interest in alternative borylation catalysts.
In 2000, the nickel catalyst (1,3-bis-(diphenylphosphino)propane)nickel(II) chloride, Ni(dppp)Cl₂ was observed to effectively facilitate cross-coupling between pinacolborane and di- and tribromo arenes.¹¹⁷ This methodology was then expanded on by Percec to include not only a much less expensive boron source, 5,5-dimethyl-1,3,2-dioxaborinane (neopentylglycolborane), but an expanded set of aryl halides. He employed a mixed ligand catalyst NiCl₂(dppp)/dpf system, and found that the addition of zinc metal significantly accelerated the reaction. The neopentylglycolborylation of aryl iodides, bromides, and chlorides proceeds to completion generally within 1 hour or less (eq 26).¹¹⁸,¹¹⁹

\[
\begin{align*}
\text{R} \quad \text{X} + \quad \text{H-B} \quad \text{O} \quad \text{O} & \quad \xrightarrow{\text{5\% NiCl}_2(dppp)} \quad \text{R} \quad \text{B} \quad \text{O} \quad \text{O} \\
\text{x} = \text{Cl}, \text{Br}, \text{I} & \\
\text{R} = \text{OMe}, \text{Me}, \text{COMe}, \text{CO}_2\text{Me}, \text{X}, \text{CN}, \text{CF}_3
\end{align*}
\]

Cross-coupling reactions utilizing transition metal catalysts have found significant application in the synthesis of boronic acids and boronic esters. The most attractive characteristic of transition metal catalyzed borylation is the high functional group tolerance. A negative aspect of this reaction is in the high cost of the catalyst, the required elevated reaction temperatures and the subsequent removal and purification of product from the metal catalyst.
1.3.3 C-H Bond Activation

Most recently, arylboronic esters have been prepared through transition metal catalyzed C-H activation. This method does not require halogenated arenes and supplements the use of Grignard or organolithium reagents for rhodium or iridium complexes. The direct borylation of aromatic rings was first accomplished by Smith using pinacolborane and Hartwig’s rhodium precatalyst, Cp*Rh(η⁴-C₆Me₆) (eq 27). Hartwig’s seminal work in the catalyzed borylation of non-activated alkanes paved the way for Smith to apply the catalytic system to arenes.¹²³

\[ \text{MeO} + \text{H-B} \xrightarrow{\text{Cp*Rh(η⁴-C₆Me₆)}} \text{MeO} \]

(27)

Ishiyama, Miyaura and Hartwig were able to borylate arenes using bis(pinacolato)diboron with an iridium(I) complex (eq 28).¹²⁴,¹²⁵,¹²⁶

\[ \text{MeO} \xrightarrow{[(COD)IrCl]₂, bipy, 80 °C, 16h} \text{MeO} \]

(28)

These catalytic systems are highly dependent on reaction conditions and generally require elevated temperatures, however some examples have demonstrated reaction at room temperature.¹²⁷,¹²⁸ The challenges associated with these methods are the high cost of the catalytic components, catalyst decomposition, regioselectivity, and non-trivial isolation of products free of heavy metal impurities. These methodologies tolerate functionality quite well but the poor regioselectivity of the
borylation limits this methodology to symmetrical substrates or requires separation of the regioisomers, which will be produced in less than quantitative yields. To date, this methodology has not been scaled up for industrial use.

1.4 Conclusion

In summary, the use of boronic acids in synthetic organic chemistry is becoming more ubiquitous. Aryl boronic acids are thermally stable and inert to water and oxygen, making them convienient reagents. Boron based byproducts have extremely low toxicity and are easy to remove from reaction mixtures, making them highly useful for large scale industrial purposes.

Boronic acids selectively react with 1,2- and 1,3-diols, and this is of significant importance for separating carbohydrates as well as a method used for alcohol derivitization and protection. The largest impact boronic acids have had in organic chemistry comes from their ability to react with organopalladium species to form C-C bonds through the Suzuki reaction. The Suzuki reaction has made the synthesis of unsymmetrical biaryl and alkenyl systems convienent, practical, and cost effective. Asymmetric versions of the Suzuki reaction have allowed for the synthesis of axially chiral unsymmetrical biaryl systems. Boronic acids have also found an important role as bioactive compounds. α-Amino boronic acids have become important pharmacophores for serine protease inhibition, and have been incorporated into inhibitors of numerous therapeutically important proteases.
1.5. Thesis Outline

The second chapter discusses the synthesis of aminoboranes and their application as borylating reagents. A wide variety of aryl(diisopropylamino)boranes are formed by the reaction of Grignard reagents and diisopropylaminoborane (eq 29). The synthesis of various aryl(diisopropylamino)boranes is also achieved under modified Barbier conditions. Alkyl, aryl, heteroaryl and allyl boronic acids are produced by the hydrolysis of the corresponding aryl(diisopropylamino)boranes.

The third chapter discusses the synthesis of magnesium diisopropylaminoborohydride and its subsequent use as a reducing agent. When the phenyl Weinreb amide was subjected to reduction by magnesium dimethylaminoborohydride, partial reduction to benzaldehyde was observed (eq 32). It was also observed that magnesium hydride can partially reduce phenyl Weinreb amide to benzaldehyde (eq 30). The development of both of these selective reducing agents is discussed.
The fourth and final chapter discusses the use of B-H containing dioxaborilanes as boron sources compatible with organometallic reagents. Grignard reagents react with 4,4,5,5-tetramethyl-1,3,2-dioxaborolane (pinacolborane) at ambient temperature in THF to afford the corresponding pinacol boronates (eq 31).

\[
\begin{align*}
\text{R-MgBr} + \text{HB} & \xrightarrow{1. \text{THF, } 25^\circ\text{C, } 1\text{h}} \text{R-B} + \text{H-MgBr} \\
\end{align*}
\]

(31)

Interestingly, the initially formed dialkoxy alkylborohydride intermediate eliminates hydridomagnesium bromide (HMgBr) as a side product. The reaction pathway of this process is investigated and discussed.
1.6. References


15 Chan, D. M. T.; Monaco, K. L.; Li, R.; Bonne, D.; Clark, C. G.; Lam, P. Y. S. 


17 Matteson, D. S.; Soloway, A. H.; Tomlinson, D. W.; Campbell, J. D.; Nixon, G. A. 


*79*, 2898-2901.


4194-4200.


39 He, H. S.; Yan, J. J.; Shen, R. X. *Synlett* 2006, 4, 563-566.


118 Rosen, B. M; Huang, C.; Percec, V. *Org. Lett.* **2008**, *10*, 2597-2600.


127 Mkhalid, I. A.; Barnard, J. H.; Marder, T. B.; Murphy, J. M.; Hartwig, J. F. Chem. Rev. 2010, 110, 890-931.

CHAPTER 2

Reaction of Grignard Reagents with Diisopropylaminoborane. Synthesis of Alkyl, Aryl, Heteroaryl and Allyl Boronic Acids From Organodiisopropylaminoborane by a Simple Hydrolysis
2.1 Introduction

Aminoboranes, $H_2BNRR'$, are the subject of significant interest not only for hydrogen storage purposes, but also more recently as monomer units for inorganic polymeric materials. For example, Manners has shown the metal catalyzed polymerization of methylamineborane, $H_3B:NH_2Me$, by ruthenium, rhodium, and palladium complexes to give high molecular weight polyaminoboranes, $[H_2BNMeH]_n$ (eq 1).\textsuperscript{129}

\[
\text{MeNH}_2\text{BH}_2 \xrightarrow{\text{THF, 10 M, 0-20 °C, 20min}} [\begin{array}{c} H \\ N \\ Me \end{array} \begin{array}{c} H \\ H \\ H \end{array} \begin{array}{c} H \\ Me \end{array}]_n + H_2
\]

The mechanism is believed to consist of two stages: first the Ir catalyst dehydrogenates the amine borane complex to form the aminoborane monomer. Second, the catalyst effects the subsequent polymerization of the aminoborane species. The nature of the polyaminoborane formed is of considerable interest from the perspective of hydrogen storage, but also because these inorganic polymers can be thought of as BN analogues of polypropylene. Polyolefins are one of the most important modern synthetic polymers which makes a BN analogue very interesting. The isoelectronic relationship between C-C and B-N bonds has led to a variety of new molecules and materials, including BN analogs of pyrene,\textsuperscript{130} carbon nanotubes\textsuperscript{131} and BN hollow spheres.\textsuperscript{132}
Aminoboranes have also been used as a boron source for C-B bond forming reactions. This can be traced back to the pioneering work of Hoffmann toward stereoselective allylboration reactions. At that time, a stereoselective method for synthesizing β-methyl alcohols did not exist. β-Methyl alcohols are a structural motif important to natural product synthesis (Figure 2.1).

Figure 2.1. (+)-Discodermolide, an example of a natural product synthesis using the aldol reaction as a key step

This can be further traced back to the highly successful synthesis of β-methyl alcohols via the Aldol addition reaction. It was observed that mixing two prochiral components, the aldehydes and the enolate, resulted in a diastereomeric mixture of both erythro and threo β-methyl alcohols (eq 2).
A large effort was put forth to develop pairs of stereoisomeric reagents capable of converting aldehydes stereoselectively to either the *syn* or *anti* β-methyl alcohol adducts. To this end, Hoffmann observed that *E* and *Z* crotylboronates diastereoselectively added to aldehydes (eq 3).\(^{137}\)

\[
\begin{align*}
\text{PhCHO} & \xrightleftharpoons[1\text{]}{-78{^\circ}\text{C}} \text{PhHO} \\
\text{PhCHO} & \xrightleftharpoons[2\text{]}{-78{^\circ}\text{C}} \text{PhHO}
\end{align*}
\]

Furthermore, compared to lithium enolates, crotylboronates showed increased reactivity toward aldehydes and proceeded at or below ambient temperature. Hoffman used the analysis put forth by Evans describing the stereochemical outcomes of the Aldol reaction: the transformation proceeds by a pericyclic process via a cyclic six membered transition state having a chair-like conformation (eq 4).\(^{138}\)
Using the Evans model, the enolate or allylboronate geometry determines the stereochemistry of the product if the R group of the aldehyde occupies exclusively an equatorial position.

In order for the crotylboronates to be of synthetic use, it was required that they not equilibrate under the reaction conditions of the C-C bond forming step. It was observed that the E and Z dialkycrotylboron compounds did, however, equilibrate via borotropic rearrangement through the 1-methylallyl compound 4 (Scheme 2.1).
Scheme 2.1. Borotropic rearrangement of crotylboron compounds

Dialkycrotylboron compounds are fluxional molecules at room temperature, the rate of rearrangement decreasing with increasing \( \pi \)-donor property of the substituents on boron.\(^{139} \) It was observed that the substitution of one alkyl group to a hydroxyl group on the boron is not sufficient to suppress the borotropic shift at -20 °C (Scheme 2.1),\(^{137,140} \) but that one amino substituent in 5b renders this compound stable up to 150 °C.\(^{137,141} \) Thus, it was concluded that with two amino substituents, 3c would not equilibrate to 5c at ambient temperature. Unfortunately, the allyldiaminoboranes 3c and 5c did not react with aldehydes. This can be rationalized by the severely decreased Lewis acidity of boron due to the back-bonding of nitrogen nonbonding electrons into the empty \( p \)-orbital of boron.\(^{142} \) Consequently, allylpinacol boronates of type 3d and 5d were used in the early studies of asymmetric allylboration. To synthesize the allylboronates, butenyl potassium was reacted with chorobis(dimethylamino)borane followed by transesterification with pinacol (eq 5).\(^{143} \)
Crotylboronates such as $5d$ are less configurationally stable than the diamino analog, however they are still easily handled at room temperature and sufficiently reactive toward aldehydes. This is one of the first examples of an organometallic reagent reacting with an aminoborane for the purposes of forming a C-B bond.

In 1993, Vaultier reported that Grignard reagents react with chlorobis(diethylamino)boranes to afford a mixture of monoalkylbis(dialkylamino)boranes and dialkyl(diethylamino)boranes (Table 2.1.).

![Chemical reaction](image)
Table 2.1. Borylation of organomagnesium derivatives with chlorobis(diethylamino)borane

<table>
<thead>
<tr>
<th>Entry</th>
<th>R-MgBr</th>
<th>Overall yield</th>
<th>Mol Ratio (8:9:10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EtMgBr</td>
<td>73</td>
<td>81:14:5</td>
</tr>
<tr>
<td>2</td>
<td>nBuMgBr</td>
<td>70</td>
<td>80:20:0</td>
</tr>
<tr>
<td>3</td>
<td>nHeptMgBr</td>
<td>77</td>
<td>78:22:0</td>
</tr>
<tr>
<td>4</td>
<td>PhMgBr</td>
<td>95</td>
<td>79:12:9</td>
</tr>
</tbody>
</table>

* A mixture of 8+9+10 was obtained from distillation. The values of the overall yield were calculated from the mass of the mixture and the ratio of products determined by $^1$H NMR spectra.

It was found that there was always an appreciable amount of dialkyl(diethylamino)borane 9 formed (Table 2.1, entries 1-4). The formation of trialkylborane was also observed (Table 2.1, entries 1 and 4). The use of more polar solvents, including THF and dioxane, increased the formation of dialkyl(diethylamino)borane. Mixing of the reagents at -30 °C and slowly raising the temperature did not alter the results. Vaultier also employed the more sterically

X = Br, Cl
demanding chloro(diisopropylamino)borane, and found similar amounts of dialkyl(diethylamino)borane formation.

This chapter will discuss the novel observation that $\text{H}_2\text{BN}(i-\text{Pr})_2$ selectively reacts with Grignard reagents to form a variety of mono-addition products.

2.2 Properties and Structural Considerations of Aminoboranes

Compounds containing a dative bond between boron and nitrogen have been known since the early 19th century. The first such compound was ammonia-trifluoroborane, $\text{H}_3\text{N}:\text{BF}_3$, prepared by Gay-Lussac. The first amineborane containing all hydride substituents on boron was $\text{Me}_3\text{N}:\text{BH}_3$, prepared in 1937. The most straightforward method for preparing compounds of this type is the reaction between amines and the labile borane Lewis base adducts borane-tetrahydrofuran ($\text{BH}_3$:THF) or borane-dimethylsulfide ($\text{BH}_3$:SMe$_2$, BMS). An amineborane is characterized as a Lewis acid/Lewis base adduct, where the nitrogen species is a two electron donor. The boron coordinates with the nitrogen’s lone pair electrons through an empty $p$-orbital. The boron atom in the resulting adduct takes on approximate tetrahedral geometry, with a change in hybridization at boron from approximately $sp^2$ to $sp^3$ (eq 6).
With aminoboranes (R$_2$BNR’$_2$), the bond between boron and nitrogen is no longer a coordination bond, but rather a covalent bond. However, the nitrogen still has a lone pair of electrons and the boron still has an empty $p$-orbital. For this reason, the BN bond in aminoboranes has been postulated to exist as a double bond (eq 7).$^{146,148}$

![Diagram of aminoboranes](image)

(eq 7)

The quasi double bond nature of aminoboranes requires boron take on sp$^2$ geometry. This requirement has been demonstrated many times over with compounds such as borazine, and various other B-N containing species.$^{149}$ The double bond nature of these compounds should also restrict rotation around the B-N bond. This has been confirmed through NMR investigations based on the following observation: a non-symmetrical aminoborane, (methylphenylamino)-dimethylborane (MePhNBMe$_2$), should display non-equivalent methyl groups in the $^1$H NMR spectrum if rotation is restricted about the B-N bond (eq 7). $^1$H NMR analysis of MePhNBMe$_2$ does in fact show that each methyl group is in a different chemical environment, i.e. they have different chemical shifts. Additionally, upon warming the reaction mixture, the required activation energy for rotation is surpassed, and the two
separate NMR signals merge into one as the rotation rate is now faster than the NMR time scale.\textsuperscript{150,151}

2.3 Current Methods of Aminoborane Synthesis

In recent times, interest in aminoboranes has increased dramatically, mostly due to their potential applications in hydrogen storage.\textsuperscript{152,153,154} Aminoboranes (R\textsubscript{1}R\textsubscript{2}N–BH\textsubscript{2}) are well-known in material science as precursors of BN-based ceramics.\textsuperscript{155,156,157} Unfortunately, many methods available for the synthesis of aminoboranes are known to form mixtures of dimers and oligomers, which prevents purification.\textsuperscript{158} Consequently, they have been scarcely studied as useful tools in synthetic organic chemistry. However, it was recently shown that the monomeric dialkylaminoborane, diisopropylaminoborane [BH\textsubscript{2}–N(iPr)\textsubscript{2}], can be used as an inexpensive boron source in palladium catalyzed borylation of aryl halides.\textsuperscript{159}

2.3.1 Thermal Dehydrogenation

Methods to synthesize aminoboranes include thermally induced dehydrogenation of secondary amine-borane adducts (R\textsubscript{1}R\textsubscript{2}HN:BH\textsubscript{3}).\textsuperscript{148,160} Amineborane compounds undergo thermally induced dehydrogenation at elevated temperatures, affording mixtures of small rings such as cyclic aminoboranes and
borazines. For instance, dimethylamineborane eliminates hydrogen at 130 °C to quantitatively yield a cyclic dimer (eq 8).

\[
\begin{align*}
\text{Me}_2N\cdot\text{BH}_3 & \xrightarrow{130 \degree C} \text{Me}_2\text{N-BH}_2 \\
\text{Me} & \text{Me} \\
\text{Me} & \text{Me}
\end{align*}
\]

Provided the nitrogen atom is hindered enough, monomeric aminoboranes can be easily isolated in more than 80% yield on the multigram scale as distillable and non-pyrophoric liquids. For example, diisopropylamineborane was converted to the corresponding aminoborane in 85% isolated yield (eq 9).

\[
\begin{align*}
\text{H}_2\text{N-BH}_3 & \xrightarrow{130 \degree C} \text{H}_2\text{N-BH}_2 \\
\text{Me} & \text{Me} \\
\text{Me} & \text{Me}
\end{align*}
\]

It was also discovered that this synthetic route was amenable to the synthesis of a chiral version of a dialkylaminoborane (eq 10).

\[
\begin{align*}
\text{Me} & \text{Me} \\
\text{Me} & \text{Me} \\
\text{Me} & \text{Me}
\end{align*}
\]

\[\alpha_{D}^{22} = -20.7 \text{ (c 2.07, THF)}\]

All the aminoboranes synthesized with nitrogens bearing large substituents display deshielded triplets in the range of 35-36 ppm in their $^{11}$B NMR spectra, confirming the formation of monomeric dialkylaminoboranes.
2.3.2 Reduction of Aminodihaloboranes

Dialkylaminoboranes can be synthesized from the corresponding aminodihaloboranes by reduction with lithium aluminum hydride (LiAlH\(_4\), LAH) in toluene (eq 11).\(^1\) Aminodihaloboranes are synthesized from the corresponding amine and BCl\(_3\).\(^2\) The products of this reduction are strongly dependent on the substituents of the amine in the aminodihaloborane species. When secondary aminodihaloboranes RR’NBX\(_2\), with very bulky amino substituents are reduced by LAH, the corresponding monomeric aminoboranes are formed as the sole products. Conversely, when the amino substituents of the aminodihaloboranes are small, several other byproducts are formed along with the desired monomeric aminoborane. There have been no further reports on this synthetic route to aminoboranes, presumably because other methods are more practical.

\[
\text{N-BCl}_2 + \text{LiAlH}_4 \xrightarrow{\text{Toluene}} \text{N-BH}_2
\]

(11)

2.3.3 Metal Catalyzed Dehydrogenation

Amineborane complexes undergo dehydrogenation at elevated temperatures, producing mixtures of monomeric and dimeric aminoboranes.\(^3\) However, the same amineboranes can produce the same products at significantly lower temperatures in the presence of a transition metal catalyst.\(^4\) For example, a solution of
dimethylamineborane in the presence of 0.5 mol% of \([\text{Rh}(1,5\text{-cod})(\mu\text{-Cl})]_2\) (1,5-cod = 1,5-cyclooctadiene) or \(\text{RhCl}_3\cdot3\text{H}_2\text{O}\) provides the cyclic dimethylaminoboranes in 40-60 hours at room temperature (eq 12).

\[
\begin{align*}
\text{Me}_2\text{NH}_3\text{BH}_3 & \xrightarrow{\text{0.5 mol\%, 25-45 °C.}} \text{H}_2\text{B} \text{NMe}_2\text{BH}_2 \\
\text{Me} & \text{Me} \\
\text{Me} & \text{Me} \nonumber
\end{align*}
\]

(eq 12)

This transformation has also been achieved using the iridium complex \([\text{Ir}(1,5\text{-cod})(\mu\text{-Cl})]_2\), which is less effective, requiring 72 hours at 45 °C for complete dehydrogenation to occur.\(^{158}\) When neat dimethylamineborane is heated to 45 °C for 7 days in the absence of a catalyst, the starting amineborane is recovered quantitatively. This clearly demonstrates the catalytic effect of the Rh and Ir complexes in the dehydrogenation of amineborane complexes.

This catalytic dehydrogenation strategy can also be applied to heterocyclic amineboranes such as pyrrolidinoborane.\(^{165,166}\) This procedure can also be utilized for the formation of monomeric dialkylaminoboranes with product distribution relative to the steric requirements of the amine substituents. For instance, when diisopropylamineborane is treated with a Rh catalyst, the corresponding monomeric dialkylaminoborane is produced with the evolution of hydrogen gas (eq 13).

\[
\begin{align*}
\text{H}_2\text{B} \text{NMe}_2\text{BH}_3 & \xrightarrow{\text{0.5 mol\%, 25-45 °C.}} \text{N-BH}_2 \\
\text{Me} & \\
\text{Me} & \nonumber
\end{align*}
\]

(eq 13)
Primary amineborane complexes such as H₃B:NH₃ can also undergo catalytic dehydrogenation. However, the product that was isolated from this reaction was not an aminoborane species, but rather a borazine derivative (eq 14).

\[
\text{H}_3\text{B}:\text{NH}_3 \xrightarrow{\text{Rh(I) or Rh(III) catalyst}} \text{HN} = \text{B} = \text{NH} + 6\text{H}_2
\]

Borazine is an interesting molecule. It is isoelectronic with benzene, and has substantial aromatic character. Borazine and its derivatives are potential precursors to boron nitride ceramics.

2.4 Results and Discussion

2.4.1 New Methods of Aminoborane Synthesis

During previous work on the hydroboration of \( \beta,\beta \)-disubstituted enamines, Singaram observed the unexpected formation of aminoboranes as one of the reaction products (Scheme 2.2).

\[
\text{\text{O}} \xrightarrow{\text{H}_3\text{B-SMe}_2} \text{H}_3\text{B-SMe}_2 + \text{HN} = \text{B} = \text{NH} \quad \text{11B-NMR: } \delta+42 (d) \quad \delta+3(t)
\]

Scheme 2.2 Hydroboration of a \( \beta,\beta \)-disubstituted enamine
In order to verify this result, an authentic sample of the aminoborane was required. During studies on lithium aminoborohydrides (LABs), it was observed that aminoboranes can be synthesized readily in situ by the reduction of methyl iodide using LAB reagents.\textsuperscript{172} Reaction of morpholino-LAB 11 with methyl iodide at 0 °C gave morpholinoborane in high purity, as determined by \textsuperscript{11}B-NMR spectroscopy (Scheme 2.3). This procedure has now been extended to synthesize representative aminoboranes (Table 2.2).

Scheme 2.3. Preparation of morpholinoborane from LAB and methyl iodide
Table 2.2. $^{11}$B-NMR spectroscopy of aminoboranes ($H_2BNR_2$) prepared in hexanes from LAB and methyl iodide

<table>
<thead>
<tr>
<th>Entry</th>
<th>Relative ratio&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Monomer</th>
<th>Relative ratio&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Dimer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40</td>
<td>$\delta$ +36.6, ($J$=127 Hz)</td>
<td>60</td>
<td>$\delta$ +2.5, ($J$=112 Hz)</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>$\delta$ +37.3 ($J$=126 Hz)</td>
<td>80</td>
<td>$\delta$ +2.8 (t, unresolved)</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>$\delta$ +35.1 ($J$=127 Hz)</td>
<td>0</td>
<td>None formed</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>None formed</td>
<td>100</td>
<td>$\delta$ +3.1, ($J$=112 Hz)</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>None formed</td>
<td>100</td>
<td>$\delta$ +2.0 ($J$=111 Hz)</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>None formed</td>
<td>100</td>
<td>$\delta$ +1.9 (t, unresolved)</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>$\delta$ +38.0 ($J$=126 Hz)</td>
<td>95</td>
<td>$\delta$ +3.2 ($J$=111 Hz)</td>
</tr>
</tbody>
</table>

<sup>a</sup> The yield of aminoboranes were not determined, but the ratio was determined by $^{11}$B-NMR spectroscopy (80.25 MHz, hexanes).

Several of the aminoboranes presented in this table exist as mixtures of dimers and monomers (Table 2.1, entries 1, 2, 7). However, some of the aminoboranes can form pure dimers, and others exist as pure monomers. For example,
diisopropylaminoborane exists as a pure monomer while diethylaminoborane is a 40:60 mixture of monomer and dimer (Figure 2.2).

![Figure 2.2 Aminoboranes: monomers and monomer/dimer mixtures](image)

The sterics around the nitrogen of the aminoborane is believed to be a key factor in the ratio of formation of monomer, dimer or monomer/dimer mixtures. The most sterically hindered aminoborane, diisopropylaminoborane, exists as a monomer (Table 2.2, entry 2). The least sterically demanding aminoboranes such as piperidino-, pyrrolidino-, and morpholinoboranes form pure dimers (Table 2.2, entries 4-6). Therefore, by changing the sterics of the amine of the LAB reagent, one can control the formation of monomer or dimer aminoborane.

Unfortunately, the reaction of methyl iodide with LABs is sensitive to temperature (Scheme 2.3). At 0 °C, this reaction produces a mixture of amineborane ($\text{BH}_3:\text{NMeR}_2$) along with the desired aminoboranes. However, the reaction of LABs with methyl iodide in the presence of a catalytic amount of triethylborane produces aminoboranes exclusively (eq 15).
It has been shown that addition of a catalytic amount of triethylborane to LABs generates LiEt$_3$BH (Super-Hydride$^\text{®}$) and aminoborane.$^{175,176}$ Super-Hydride$^\text{®}$ is known to reduce methyl iodide, regenerating triethylborane, which in turn reacts with more LAB, generating Super-Hydride$^\text{®}$ and aminoborane (Figure 2.3). While this method of generating aminoborane is interesting, it requires the use of pyrophoric triethylborane.

![Catalytic cycle in the reaction of Et$_3$B with LAB and methyl iodide](image)

**Figure 2.3.** Catalytic cycle in the reaction of Et$_3$B with LAB and methyl iodide

To explore formation of aminoboranes further, various aminoboranes were synthesized from different LABs and other alkyl halides. Gratifyingly, the reactions
of LAB reagents were found to produce exclusively the corresponding aminoboranes (BH$_2$-NR$_2$) when treated with TMS-Cl at 25 °C (Scheme 2.4). These aminoboranes were characterized in solution by $^{11}$B-NMR spectroscopy, which displayed only the signal attributable to aminoboranes, indicating essentially quantitative formation of the products. These results are summarized in Table 2.3.

Scheme 2.4. General synthesis of aminoborane from LAB and TMS-Cl
Table 2.3 Aminoboranes synthesized from LAB and TMS-Cl

<table>
<thead>
<tr>
<th>Entry</th>
<th>R₂N-BH₂</th>
<th>Relative ratioᵃ</th>
<th>Monomer</th>
<th>Relative ratioᵃ</th>
<th>Dimer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>![Structural formula]</td>
<td>10ᵇ</td>
<td>δ +36.9 (t, J=125 Hz)</td>
<td>90ᵇ</td>
<td>δ +2.2 (t, J=110 Hz)</td>
</tr>
<tr>
<td>2</td>
<td>![Structural formula]</td>
<td>100</td>
<td>δ +35.2, t, J=125 Hz</td>
<td>0</td>
<td>None formed</td>
</tr>
<tr>
<td>3</td>
<td>![Structural formula]</td>
<td>100</td>
<td>δ +35.4 (t, J=113 Hz)</td>
<td>0</td>
<td>None formed</td>
</tr>
<tr>
<td>4ᶜ</td>
<td>![Structural formula]</td>
<td>1</td>
<td>δ +35.9 (t, J=113 Hz)</td>
<td>99</td>
<td>δ +1.9 (t, J=113 Hz)</td>
</tr>
<tr>
<td>5ᶜ</td>
<td>![Structural formula]</td>
<td>0</td>
<td>None formed</td>
<td>100</td>
<td>δ +3.1 (t, J=113 Hz)</td>
</tr>
<tr>
<td>6ᶜ</td>
<td>![Structural formula]</td>
<td>0</td>
<td>None formed</td>
<td>100</td>
<td>δ +1.8 (t, J=107 Hz)</td>
</tr>
</tbody>
</table>

ᵃ The ratios of aminoboranes were determined by ¹¹B-NMR spectroscopy (80.25 MHz, hexanes). The spectra displayed only the signal attributable to aminoboranes indicating essentially quantitative formation of the product.ᵇ See Ref 15.ᶜ Minor amounts of N-TMS amineborane was formed as byproduct.

The same trend of monomer/dimer formations of aminoboranes is observed during these syntheses, except for diethylaminoborane.¹⁷⁷ Sterically hindered aminoboranes exist exclusively as monomers (Table 2.3, entries 2 and 3), whereas less sterically demanding aminoboranes either form pure dimers (Table 2.3, entries 5 and 6) or monomer-dimer mixtures in different ratios (Table 2.3, entries 1 and 4).
Hence, monomer/dimer formation is only dependent on the steric environment of aminoborane, regardless of preparation method.

In contrast to LAB reagents containing secondary amines, heterocyclic LAB reagents, such as pyrazolyl-LAB and imidazolyl-LAB,\textsuperscript{178} did not afford the corresponding aminoboranes when reacted with TMS-Cl. Unfortunately, it is difficult to synthesize pyrrolyl-LAB from pyrrole, BH\textsubscript{3}:THF and n-butyllithium (n-BuLi). This is due to the fact that pyrrole does not form a pyrrole-borane complex.\textsuperscript{179} Consequently, pyrrolylborane was synthesized by the direct reaction of pyrrole with BH\textsubscript{3}:THF (Scheme 2.5, Table 2.4, Entry 2).

![Scheme 2.5. Synthesis of pyrrolylborane.](image)

Pyrazole, and imidazole also produced the corresponding aminoboranes with BH\textsubscript{3}:THF at 65 °C (Table 2.4, entries 1 and 3).

**Table 2.4.** Aminoboranes synthesized from heterocyclic amines and BH\textsubscript{3}:THF.

<table>
<thead>
<tr>
<th>Entry</th>
<th>( \text{N-BH}_2 )</th>
<th>Relative ratio\textsuperscript{a}</th>
<th>Monomer</th>
<th>Relative\textsuperscript{a} ratio</th>
<th>Dimer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image" alt="image" /></td>
<td>0</td>
<td>None formed</td>
<td>100 ( \delta -8.5 ) (t, ( J=107 ) Hz)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td><img src="image" alt="image" /></td>
<td>0</td>
<td>None formed</td>
<td>100 ( \delta +4.7 ) (t, ( J=113 ) Hz)</td>
<td></td>
</tr>
<tr>
<td>3\textsuperscript{b}</td>
<td><img src="image" alt="image" /></td>
<td>0</td>
<td>None formed</td>
<td>100 ( \delta -9.1 ) (broad singlet)</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{a}As determined by \( ^{11}\text{B}-\text{NMR} \) spectroscopy (80.25 MHz, THF). \textsuperscript{b}Less than 10\% formed.
It has been reported that pyrrole and pyrazole form dimeric aminoboranes\textsuperscript{180}, whereas imidazole generates polymeric aminoboranes.\textsuperscript{181} Pyrazole-derived aminoborane has been reported to form a six-membered dimer through boron-nitrogen coordination (Figure 2.4 a).\textsuperscript{182,183,184} In contrast, pyrrole forms a four-membered dimer through boron-hydrogen coordination (Figure 2.4 b).\textsuperscript{180} Although the multiplicity of the $^{11}$B NMR signal shows a BH$_2$ moiety, it is difficult to assign the degree of aggregation from the $^{11}$B NMR chemical shifts alone.

![Figure 2.4](image)

**Figure 2.4.** Dimers of (a) pyrazolylborane\textsuperscript{182,183} and (b) pyrrolylborane\textsuperscript{180}

Thus far, several mild and convenient methods have been described to synthesize a variety of aminoboranes in situ. Different alkyl halides have been shown to react with LABs to produce aminoboranes. Both heterocyclic and secondary amines can be used for the synthesis of aminoboranes. Depending on the steric hindrance around the amine, aminoboranes exist as monomers, dimers or monomer/dimer mixtures. The reactivity of these aminoboranes was then studied.
2.4.2 Reactivity of Aminoboranes

2.4.2.1 Vaultier Borylation

During the investigation into the properties of aminoboranes, it was found that aminoborane dimers are inert as hydride donors both in hydroboration and reduction reactions. Consequently, the focus of this study was on the reactions of monomeric aminoboranes, such as diisopropylaminoborane (BH$_2$-N(iPr)$_2$) 12. First, this aminoborane prepared in situ was examined as a potential boron source for the synthesis of boronic acids. Thus, the palladium catalyzed borylation of aryl bromides with BH$_2$-N(iPr)$_2$, synthesized in situ from iPr-LAB, was attempted under Vaultier conditions.$^{159}$ Utilizing the reported reaction conditions, phenylboronic acid and 4-methoxyphenylboronic acid were successfully synthesized from the corresponding aryl bromides (Scheme 2.6).

Scheme 2.6. Palladium catalyzed synthesis of boronic acids from aryl bromides and BH$_2$-N(iPr)$_2$

This reaction is compatible with various functionalities, such as esters, fluorides, methoxy groups, and amines.$^{159}$ However, nitrile containing aryl bromides behaved differently, and led to the discovery that BH$_2$-N(iPr)$_2$ can reduce nitriles in the presence of a catalytic amount of LiBH$_4$.$^{185}$

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2.4.2.2 Hydroboration of Alkenes and Alkynes

To explore the properties of aminoboranes even further, aminoboranes were investigated as possible hydroborating agents for alkenes and alkynes. A series of hydroboration reactions were attempted utilizing different aminoboranes and either 1-hexene or 1-hexyne. Disappointingly, with the exception of pyrrolylborane, none of the aminoboranes exhibited hydroboration properties. However, this reveals the potential of aminoboranes as selective reducing agents for various functional groups in the presence of multiple bonds.

As reported previously\textsuperscript{180}, pyrrolylborane successfully hydroborates both alkenes and alkynes. Additionally, in the earlier study 1-pyrrolylborane-tetrahydrofuran complex behaves as a monoalkylborane and reacts with two equivalents of alkene to afford $B$-pyrrolyldialkylborane. Similarly, 1-pyrrolylborane was reported to hydroborate two equivalents of an alkyne to give $B$-pyrrolyldialkenylborane. In this thesis study, alkenes and alkynes were found to undergo stepwise hydroboration; the reaction can be stopped at the monohydroboration stage. For example, hydroboration of one equivalent of styrene \textbf{15} with pyrrolylborane at 25 \textdegree C gives 2-phenylethylboronic acid \textbf{16} as the major product after basic hydrolysis (Scheme 2.7). Similarly, hydroboration of one equivalent of phenylacetylene \textbf{17} at 25 \textdegree C gives $E$-2-phenylethenylboronic acid \textbf{18} as the major product after basic hydrolysis (Scheme 2.8).
Scheme 2.7. Hydroboration of styrene with pyrrolylborane

Scheme 2.8 Hydroboration of phenylacetylene with pyrrolylborane

The success of this hydroboration reaction can be attributed to the aromaticity of pyrrolylborane. Because the nitrogen lone pair is participating in aromatic bonding, it is not available for back-bonding into the empty $p$-orbital of boron, therefore the Lewis acidity of boron and reactivity toward hydroboration is maintained. Subsequently, imidazolylborane and pyrazolylborane were tested in the hydroboration of both 1-hexene and 1-hexyne. Unfortunately, neither imidazolylborane nor pyrazolylborane showed any hydroborating properties. This could be due to the dimeric and oligomeric/polymeric boron-nitrogen bonds in pyrazolylborane and imidazolylborane respectively (Figure 2.3).$^{186,187,188}$

In previous studies, it was observed that arylaminoborane compounds can be converted to the corresponding boronic acid via an aqueous quench.$^{189}$ $^{11}$B NMR analysis of the reaction mixture quenched with water showed the aryl aminoborane adduct and aminoborohydride peaks replaced by a singlet (δ +30) and a quartet (δ -
corresponding to the boronic acid and amineborane complex, respectively. Although both the magnesium aminoborohydride and the corresponding amineborane reagents appear as sharp quartets with virtually identical chemical shifts in their respective $^{11}$B NMR spectra, the coupling constants are significantly different. The aminoborohydride reagent exhibits $^{11}$B NMR $J$ values between 82-87 Hz. In contrast, the amineboranes have coupling constants ranging from 95-98 Hz. The boronic acid was then separated from the amineborane by an acidic liquid-liquid extraction. It has been shown previously that aryldiisopropylaminoborane compounds can be directly converted to the corresponding pinacol and neopentylglycol boronic ester by quenching with the corresponding alcohol (Scheme 2.9).

**Scheme 2.9** Conversion of arylaminoborane to boronic acid by the addition of water

Investigation of the compatibility of BH$_2$-N(iPr)$_2$ with Grignard reagents for the synthesis of aryldiisopropylaminoborane adducts was then pursued, because these compounds are known to hydrolyze to the corresponding boronic acids.
2.4.2.3 Synthesis of Boronic Acids via Grignard Reagents

Diisopropylaminoborane (BH$_2$-N(iPr)$_2$) 12 was mixed with one equivalent of $p$-tolylmagnesium bromide 19 at 25 °C in THF, and the reaction progress was followed by $^{11}$B NMR spectroscopy. After 30 minutes, $^{11}$B NMR analysis revealed the absence of 12 (δ $+35$, t, $J = 125$ Hz) and the appearance of the single addition product aryl isopropylaminoborane 21 (δ $+38$, d, $J = 112$ Hz) and what appeared to be the magnesium version of LAB, bromomagnesium aminoborohydride 22 (BrMg$^+$ - BH$_3$-NiPr$_2$, δ $-22$, q, $J = 88$ Hz).$^{21,191}$ The $^{11}$B NMR spectrum also showed small amounts of the initially formed BH$_2$-arylaminoborohydride adduct 3 (δ $-12$, t, $J = 75$ Hz) (Figure 2.5).
Reaction conditions: *p*-tolylmagnesiuim bromide (1M/THF, 2.0 mmol) added to BH$_2$-Ni(Pr)$_2$ (1M, 2.0 mmol) under argon at 0 °C, 30 min.

Figure 2.5. A. Proposed reaction pathways. B. $^{11}$B NMR spectrum of reaction mixture$^a$

The mechanism of borylation involves an initial nucleophilic attack by 19 at the boron atom of 12, forming the BH$_2$-arylaminoborohydride adduct 20. Once 20 is formed, the next step in the reaction pathway is either a hydride transfer to magnesium forming 21 and hydridomagnesium bromide (HMgBr, path a), or a hydride transfer to starting material 12 forming 21 and 22 (path b). Consequently, magnesium borohydride 22 could be the product of hydride transfer from either adduct 20 or HMgBr.
HMgBr is a known compound, which does not undergo reductive elimination but rather disproportionates to MgBr$_2$ and MgH$_2$ in THF.$^{192,193}$ Compared to HMgBr, HMgCl also does not undergo reductive elimination but also does not disproportionate to MgCl$_2$ and MgH$_2$.\textsuperscript{193} MgH$_2$ and HMgCl are both mild reducing agents soluble in THF.\textsuperscript{194,193} HMgCl is prepared quantitatively by reacting isopropylmagnesium halide with pinacolborane in THF.\textsuperscript{193} HMgCl was generated in situ and reacted with 12 to determine if HMgCl was capable of transferring a hydride to BH$_2$-N(iPr)$_2$ forming chloromagnesium diisopropylaminoborohydride (Scheme 2.10).

\begin{center}
\begin{tikzpicture}
\node[style=None] (A) at (0,0) {MgCl};
\node[style=None] (B) at (1.5,0) {BH$_2$-N(iPr)$_2$};
\node[style=None] (C) at (3.5,0) {HMgCl};
\node[style=None] (D) at (5,0) {H$_2$B=N(iPr)$_2$ unreacted via $^{11}$B NMR};
\draw[->] (A) -- (B);
\draw[->] (B) -- (C);
\draw[->] (C) -- (D);
\end{tikzpicture}
\end{center}

**Scheme 2.10** Testing the ability of hydridomagnesium chloride to transfer hydride to BH$_2$-N(iPr)$_2$

Analysis of the reaction mixture by $^{11}$B NMR spectroscopy showed the absence of a signal due to chloromagnesium diisopropylaminoborohydride. Because there is an expected difference in reactivity between HMgCl and HMgBr this experiment does not conclusively rule out pathway (a). It does however provide strong evidence that the observed bromomagnesium diisopropylaminoborohydride 22 is the result of hydride transfer from intermediate 20 to 12 (pathway b).

Interestingly, it was found that only 1.2 equivalents of 18 were required for greater than 95% conversion to the boronic acid. This result indicates that the reaction
pathway does not exclusively proceed through route (b), as two equivalents of BH$_2$-N(iPr)$_2$ would be required to account for the quantitative conversion. This data suggests that the product distribution between HMgCl and BrMg$^+$ BH$_3$-NiPr$_2$ is approximately (80:20). Although the reaction mechanism is not fully understood, it is clear that the reaction proceeds concomitantly through both paths a and b.

In a separate experiment, to characterize 22 (chemical shift and coupling constant), synthesis of authentic halo-magnesium aminoborohydride was attempted from diisopropylamineborane and methylmagnesium chloride in THF. $^{11}$B NMR analysis of the reaction mixture showed a small amount of the chloromagnesium diisopropylaminoborohydride ($\delta$ -17, $J = 83$Hz) and a number of disproportionation products. When the less sterically encumbered dimethylamineborane was deprotonated with methylmagnesium chloride, chloromagnesium dimethylaminoborohydride ($\delta$ -20, $J = 83$ Hz) was produced quantitatively (Eq 16).

![Chemical Reaction](image)

The generality of reaction of Grignard reagents with BH$_2$-N(iPr)$_2$ was investigated by using commercially available Grignard reagents, which were titrated to accurately determine their concentration. The boronic acids were isolated from the magnesium hydride and aminoborohydride by quenching the reaction mixture with hydrochloric acid (3M) followed by diethyl ether extraction. This methodology
was applied to a variety of aryl and alkyl Grignard reagents affording the corresponding boronic acids in often quantitative yields (Table 2.4). With preformed Grignard reagents the reaction was carried out at 0 °C for 1 hour (entry 1-7). Both organomagnesium bromide and organomagnesium chloride (entry 2 and 5) are compatible Grignard reagents with BH$_2$-N(iPr)$_2$. It was interesting to find that phenylmagnesium bromide smoothly converted to the boronic acid in less than 30 minutes at -45 °C. This result implied that 1 hour of reaction time was not required at the reaction temperature of 0 °C. However, when the reaction was carried out at -78 °C the reaction mixture would freeze and magnetic stirring would stop. In this case, the reaction flask was removed from the cryogenic conditions, allowed to warm until the magnetic stir bar was free flowing and returned to the -78 °C conditions. Though the isotherm was not maintained at a constant temperature the isolated yield of boronic acid was greater than 90%. Unfortunately, the solution of phenylmagnesium bromide was old and $^1$H NMR showed signs of degradation. Therefore, these results are not reported in Table 2.4 though $^{11}$B NMR analysis showed only monoaddition product.
Table 2.5. Synthesis of Boronic Acids using Commercial Grignard Reagents\(^d\)

![Chemical Reaction Diagram]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate (R)</th>
<th>Product</th>
<th>Yield(^b)(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\text{PhMgBr})</td>
<td>(\text{PhB(OH)}_2)</td>
<td>95</td>
</tr>
<tr>
<td>2</td>
<td>(\text{PhMgCl})</td>
<td>(\text{PhB(OH)}_2)</td>
<td>88</td>
</tr>
<tr>
<td>3</td>
<td>(\text{PhMgBr})</td>
<td>(\text{PhB(OH)}_2)</td>
<td>95</td>
</tr>
<tr>
<td>4</td>
<td>(\text{3-PhMgBr})</td>
<td>(\text{3-PhB(OH)}_2)</td>
<td>94</td>
</tr>
<tr>
<td>5</td>
<td>(\text{CyclopentylMgCl})</td>
<td>(\text{CyclopentylB(OH)}_2)</td>
<td>97</td>
</tr>
<tr>
<td>6</td>
<td>(\text{HexylMgBr})</td>
<td>(\text{HexylB(OH)}_2)</td>
<td>78</td>
</tr>
<tr>
<td>7</td>
<td>(\text{5-MethylhexylMgBr})</td>
<td>(\text{5-MethylhexylB(OH)}_2)</td>
<td>95</td>
</tr>
</tbody>
</table>
Reagents and conditions: BH$_2$-N(iPr)$_2$ (1M, 2.4 mmol), Grignard reagent (1M, 2.0 mmol), argon, 0 °C, 1 h. Isolated yield of boronic acid after aqueous workup.

2.4.2.4 Synthesis of Boronic Acids under Barbier Conditions

The reaction of Grignard reagents with trimethylborate is always the first method considered for the synthesis of simple boronic acids.$^{196}$ This reaction is generally a good method for effecting this transformation. The formation of Grignard reagents is always theoretically accompanied by competing Wurtz coupling of the halide. The competitive Wurtz coupling however is only an issue when dealing with reactive halides toward substitution such as allyl, benzyl, and primary halides (eq 17). Therefore, for compounds such as aryl halides or alkenyl halides, Wurtz coupling is not an issue.

\[
\text{Br} \quad \overset{\text{Mg}}{\text{Et}_2\text{O}} \quad \rightarrow \quad \text{Br}
\]

The synthesis of highly reactive species such as allylmagnesium bromide is performed at low temperature and under conditions of low concentration to avoid the formation of 1,5-hexadiene as the major, or even sole product of the reaction.$^{197,198}$ The Barbier reaction was developed for the synthesis of alcohols from carbonyl compounds and organomagnesium reagents. The method entails heating a mixture of the alkyl halide and carbonyl compound together with magnesium under an inert atmosphere. It was found that with reactive halides, Wurtz coupling was greatly reduced. The reasoning was that by having the carbonyl compound (the electrophile)
present during the formation of allylmagnesium bromide (the nucleophile), the organometallic nucleophile would attack the harder of the two electrophiles, giving the alcohol rather than the 1,5-hexadiene.

In addition to allowing for the synthesis of Grignard reagents from highly reactive halides, the experimental set-up for Barbier reaction is much simpler than the classic Grignard reaction. Under Barbier conditions, essentially all of the reagents are added at one time avoiding the more labor intensive stepwise addition of reagents. After the compatibility of BH$_2$-N(iPr)$_2$ with Grignard reagents was established, simplification of the procedure was examined by employing a modified Barbier system. In this case, the organic halide is added to a mixture of magnesium turnings and BH$_2$-N(iPr)$_2$ (1M/THF) at 65 °C. Under Barbier-type conditions, a number of aryl halides underwent smooth conversion to the corresponding boronic acids with good isolated yields (Table 2.6).
The synthesis of boronic acids under the modified Barbier conditions was amenable to a number of arylbromides, including 1-bromonaphthalene (entry 1), 4-bromoanisole (entry 2) and the heteroaromatic substrate 2-bromothiophene (entry 3).
Non-aryl substrates, including α-bromostyrene and 9-bromoanthracene, were not compatible with the Barbier conditions. When allyl and benzyl halides were subjected to the Barbier conditions, rapid consumption of the magnesium metal was observed. Subsequent $^{11}$B NMR analysis showed approximately a 1:1 mixture of the corresponding allylaminoborane and unreacted BH$_2$-N(iPr)$_2$ (entry 4 and 5). This observation is explained by the high reactivity of allyl and benzylbromide reagents towards homocoupling and reduction.

2.5 Conclusion

In conclusion, several mild and convenient methods for the in situ synthesis of aminoboranes in solution have been developed. Diisopropylaminoborane can be synthesized from iPr-LAB and methyl iodide in the presence of 5 mol% triethylborane. Aminoboranes can also be prepared from LAB reagents by reaction with either TMS-Cl or methyl iodide. Both heterocyclic and secondary amines can be used for the synthesis of aminoboranes. Depending on the steric hindrance around the amine, aminoboranes exist as monomers, dimers or monomer/dimer mixtures. Aminoboranes derived from heterocyclic amines, such as pyrrole, pyrazole, and imidazole, can be prepared by direct reaction with borane-tetrahydrofuran (BH$_3$:THF). Pyrrole and pyrazole form dimeric aminoboranes, whereas imidazole forms polymeric aminoboranes. Pyrazole-derived aminoborane forms a six-membered dimer through boron-nitrogen coordination. It was found that
pyrrolylborane mono-hydroborates both styrene and alkynes at ambient temperatures. Diisopropylaminoborane is inexpensively synthesized and stable in THF for long periods of time (upwards of one year). A simple and mild borylation of aryl and alkyl halides with BH$_2$-N(iPr)$_2$ has been described, under mild Grignard and Barbier conditions. Performing the borylation reaction under Barbier conditions allows the use of a simple one pot procedure, and avoids the use of low temperatures and expensive transition metal catalysts. The reaction boasts excellent yields of the easily purified single addition product under mild conditions and does not require the use of a molar excess of the boron source. Although the borylation mechanism is not fully understood, evidence is provided that the reaction mechanism is distributed between two reaction pathways.

2.6 Experimental

General Methods. All reactions were performed in oven-dried, argon-cooled glassware. The BH$_2$-N(iPr)$_2$ was used as synthesized; it was stored under Ar at room temperature. All Grignard reagents were used as received from Aldrich, they were stored in the bottle received and kept in the refrigerator held at 15 °C. Magnesium metal was used as received from Aldrich. All air- and moisture-sensitive compounds were introduced via syringe or cannula through a rubber septum. Tetrahydrofuran (THF) was freshly obtained from a solvent purification system (Pure Solv MD, Innovative Technology inc.). NMR spectra were recorded in CDCl$_3$. Chemical shifts
are reported relative to TMS (δ = 0) for 1H NMR (500 MHz) and are referenced against the CDCl₃ resonance (δ = 77) for 13C NMR (125 MHz) spectra. Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, br = broad, m = multiplet, app = apparent), coupling constant and integration. Boron NMR samples were recorded at 160.4 MHz and are reported relative to the external standard BF₃:Et₂O (δ = 0).

**General Procedure for the Preparation of LAB Reagent 1 M Solution in THF.**

The following procedure for the preparation of LiH₃BN(iPr)₂ is representative. Diisopropylamine (5.00 g, 7 mL, 50 mmol, 1 eq) was mixed with anhydrous THF (18 mL) in a 100-mL round bottom flask. The solution was cooled to 0°C (ice bath) and borane dimethylsulfide (5 mL, 10 M, 50 mmol, 1 eq.) was added dropwise via syringe, stirred for 1 hour at 0°C and analyzed by 11B NMR. The analysis showed the solution to be diisopropylamine borane complex (δ -21.1, q, J = 95.3 Hz). Then, n-butyl lithium in hexanes (20 mL, 2.5 M, 50 mmol, 1 eq.) was measured in oven dried graduated cylinder and added dropwise via cannula needle to the solution of amine borane at 0°C (CAUTION: Hydrogen evolution). After stirring at 0°C for 1 hour, an aliquot was taken and analyzed by 11B NMR (160.4 MHz, THF) which showed the solution to be lithium diisopropilaminoborohydride (δ -23.6, q, J = 83.4 Hz). LAB reagent was transferred to an oven-dried, nitrogen cooled ampoule via a cannula needle.
Note that, although the chemical shift of the corresponding amine borane complex is virtually identical to that of the LAB, the $J$-values of the amine borane complex is different and range from 95-98 Hz. LAB reagents can be stored in an ampoule under nitrogen without decomposition for at least six months.

**Synthesis of Aminoborane from LAB and methyl Iodide.**

The following procedure for the preparation of diisopropyl aminoborane is representative. To a 50-mL round bottom flask with side arm was added lithium diisopropyl aminoborohydrides (prepared from 1.1 eq $n$-BuLi) (5.0 mL, 1M in THF, 5.0 mmol) and 3 mL of anhydrous THF. The reaction was cooled to 0 °C (ice bath) and methyl iodide (0.31 mL, 5.0 mmol) was added dropwise (**CAUTION**: very exothermic reaction). After all methyl iodide was added, the ice bath was removed and reaction was stirred at room temperature for one hour. After 1 hour, the $^{11}$B NMR spectrum showed formation of diisopropyl aminoborane complex ($t, \delta = +35, J = 125$ Hz). For other aminoboranes prepared by this method see Table 2.1.

**Synthesis of Diisopropyl Aminoborane from LAB and TMS-Cl.**

Diisopropylamine (3.51 mL, 25 mmol) was mixed with anhydrous THF (20.8 mL) in a 100-mL round bottom flask. The solution was cooled to 0 °C (ice bath) and borane dimethylsulfide (2.5 mL, 10M solution in THF, 25 mmol) was added dropwise over 3 min via syringe. After stirring for 1 h at 0 °C $n$-BuLi (10 mL, 2.5 M solution in toluene, 25 mmol) was added dropwise over 5 min via syringe. After 1 hour of stirring at 0 °C, a 0.5 mL aliquot was analyzed via $^{11}$B NMR, which showed
the solution to be lithium diisopropylaminoborohydride ($\delta$ -23.8, q, $J = 84$ Hz). The solution was then allowed to warm to 25 °C and subsequently TMS-Cl (3.20 mL, 25 mmol) was added dropwise over 5 min via syringe while stirring at room temp. After 1 h of stirring at room temperature a 0.5 mL aliquot was taken and analyzed via $^{11}$B NMR, which showed the solution to be monomeric diisopropylaminoborane ($\delta$ +35.1, t, $J = 125$ Hz).

**Synthesis of Diisopropyl Aminoborane from LAB in THF, Methyl Iodide and Catalytic Amount of Et$_3$B.**

To a 50-mL round-bottom flask with side arm was added lithium diisopropyl aminoborohydride (5 mL, 1M in THF, 5 mmol), 3 mL of anhydrous THF, Et$_3$B (0.25 mL, 1M, 10 mol %). The reaction was cooled to 0 °C (ice bath) and methyl iodide (0.31 mL, 5.0 mmol) was added slowly dropwise (*CAUTION very exothermic reaction*). After all methyl iodide was added, the ice bath was removed and reaction was stirred at room temperature for 1 h. After 1 h, the $^{11}$B NMR spectrum showed formation of diisopropyl aminoborane complex (t, $\delta$ +35, $J = 125$ Hz).

**General Synthesis of Aminoborane from the Direct Reaction of Heterocyclic Amines with BH$_3$:THF.**

To a 50-mL round bottom flask BH$_3$:THF (30 mL, 30 mmol) was added. To this, pyrrole (2.1 mL, 30 mmol) was added dropwise over 3 min. After stirring at 25 °C for 1 h an aliquot was withdrawn for $^{11}$B-NMR analysis, the spectra showed significant amounts of unreacted BH$_3$:THF ($\delta$ -1.5, t, $J = 104$ Hz). After 4 h $^{11}$B NMR spectroscopy analysis showed the completion of the reaction and exclusive
formation of pyrrolylborane ($\delta +4.0$, t, $J=113$ Hz). For other heterocyclic aminoboranes prepared by this method see Table 2.4.

**Palladium Catalyzed Synthesis of Aryl Boronic Acids.**

A 100-mL round bottom flask with side arm was charged with triethylamine (3.47 mL, 25 mmol, 5 equiv), 4-bromoanisole (0.61 mL, 5 mmol, 1 equiv) and THF (3 mL). The septum was replaced with a reflux condenser while adding palladium (0.175 g, 0.5 mmol, 5 mol%). Finally, diisopropylaminoborane (15 mL, 1M solution in THF, 15 mmol, 3 equiv) was added to the reaction mixture via syringe. The reaction mixture was subsequently heated to reflux at 65 °C. After 19 hours of refluxing the reaction was cooled to 25 °C and methanol (8 mL) was added slowly (**CAUTION**: exothermic reaction). The solvent was evaporated in vacuo (25 Torr) and the residue was dissolved with sodium hydroxide (3M, 8 mL). The aqueous layer was washed with hexanes (3x10 mL) and then acidified with 3M HCl (pH=1). In most cases, the boronic acid precipitated out of the solution. The slurry was extracted with diethyl ether (4x15 mL). The organic portions were combined, dried with anhydrous MgSO$_4$, and filtered. Solvents were evaporated in vacuo to produce 4-methoxyphenylboronic acid as a white solid.

![4-Methoxyphenylboronic Acid](image)

**4-Methoxyphenylboronic Acid:** White solid 78 % yield (0.598 g); $^{199}$ MP = 203-207 °C (Lit. mp 209-210); $^1$H NMR (500 MHz, NaOD): $\delta$ 3.74 (s, 3H), 6.85 (d, $J = 8$ Hz).
Hz, 2H), 7.55 (s, 2H), 7.7 (d, J=8 Hz, 2H); $^{13}$C NMR (125 MHz, NaOD): $\delta$ 55.5, 114.1, 136.7, 163.9; $^{11}$B NMR (80.25 MHz, NaOD): $\delta$ +1 (s).

Phenylboronic Acid: White solid 82 % yield (0.501 g); $^{189}$ $^1$H NMR (500 MHz, MeOH): $\delta$ 7.31 (m, 3H), 7.56 (d, J = 6.5 Hz, 1H), 7.71 (d, J = 7 Hz, 1H); $^{13}$C NMR (125 MHz, MeOH): $\delta$ 128.6, 128.7, 130.8, 131.3, 134.6, 135.0; $^{11}$B NMR (80.25 MHz, MeOH): $\delta$ +18 (s).

**General Procedure for Hydroboration and Boronic Acid Synthesis.**

To a 50-mL round bottom flask equipped with magnetic stir bar and fitted with a rubber septum was added pyrrolylborane (5.3 mL, 5 mmol). The reaction flask was cooled to 0 °C (ice bath), followed by the addition of styrene (0.573 mL, 5 mmol). With the addition of styrene the reaction was allowed to warm to room temperature and stirred for 19 h. After 19 h THF was removed in vacuo and vented to argon. To the remaining oil excess anhydrous methanol (10mL, 0.25 mol) was added and allowed to stir for 2 h where it was then transferred to a separatory funnel. Pentane (10mL) was added followed by conc. HCl (1.5mL), and the two layers immediately separated and the methanol layer was extracted with pentane (5 × 15mL). The combined organic layers were dried with anhydrous MgSO$_4$, and evaporated in vacuo. The boronic acids can be isolated by water quench and a basic extraction with ether.
2-Phenylethylboronic acid ester: White solid 51 % yield (0.388 g), \(^{1}\)H NMR (600 MHz, CDCl\(_3\)) \(\delta\) 1.14 (t, J=8.25 Hz, 2H), 2.72 (t, J=8.25 Hz, 2H), 3.56 (s, 6H), 7.18-7.31 (m, 5H); \(^{13}\)C NMR (600 MHz, CDCl\(_3\)) \(\delta\) 30.0, 30.1, 38.2, 51.3, 76.8, 77.0, 77.3, 125.5, 125.6, 125.7, 126.2, 128.0, 128.2, 128.3, 128.5, 129.1, 145.20; \(^{11}\)B-NMR (160.4 MHz, THF) \(\delta\) +29.3 (s).

E-Phenylethenylboronic acid ester: Yellowish solid, 42 % yield (0.61 g), \(^{1}\)H NMR (600 MHz, CDCl\(_3\)) \(\delta\) 3.56 (s, 3H), 6.34 (d, J=18 Hz, 1H), 7.54-7.27 (m, 6H); \(^{13}\)C NMR (600 MHz, CDCl\(_3\)) \(\delta\) 30.1, 51.3, 51.6, 125.6, 127.1, 127.2, 127.3, 128.0, 128.2, 128.4, 128.5, 128.6, 128.7, 128.8, 129.0, 138.0, 148.4; \(^{11}\)B-NMR (160.4 MHz, THF): \(\delta\) +28.2 (s).

\[\text{MgCl} \quad \Theta \quad \Theta \]
\[\begin{array}{c}
\text{H} \\
\text{H} \quad \text{Me} \\
\text{H} \quad \text{B} \quad \text{N} \\
\text{H} \quad \text{Me}
\end{array}\]

Synthesis of Chloromagnesium dimethylaminoborohydride
Methylmagnesium chloride (0.83 mL, 2.4 M solution in THF, 2.0 mmol) was cooled to 0 °C (ice bath). In a separate flask diisopropylamineborane (0.118 g, 2.0 mmol) was dissolved in anhydrous THF (2.0 mL) in a 25-mL round bottom flask. The diisopropylamineborane/THF solution was added dropwise over 10 min via syringe at 0 °C to the methylmagnesium bromide/THF solution. After 0.5 h of stirring at 0 °C a 0.5 mL aliquot was analyzed via $^{11}$B NMR, which showed the solution to be bromomagnesium diisopropylaminoborohydride ($\delta$ -15.6, q, $J = 83$ Hz).

**General Procedure for the Preparation of Aryl Boronic Acids from Grignard Reagents.**

The following procedure for the preparation of $p$-tolyl boronic acid is representative. A 50-mL round-bottom flask equipped with a magnetic stir bar and fitted with rubber septum was charged with BH$_2$-N(iPr)$_2$ (2.4 mL, 2.4 mmol, 1.2 eq.). $p$-Tolylmagnesium bromide (2 mL, 2 mmol, 1 eq.) was added dropwise over 5 min via syringe while stirring at 0 °C (ice bath). After 1 h, with the reaction still on ice, 3M HCl (5 mL) was added dropwise over 5 min and allowed to stir for 30 min. The reaction mixture was then refluxed for 15 min. Following reflux, the solution was transferred to a separatory funnel and extracted with diethyl ether (2 x 15 mL). The organic layers were combined and extracted with 1M HCl (4 x 15mL), dried over anhydrous MgSO$_4$, and concentrated in vacuo (25 °C, 1 Torr) to afford $p$-tolylphenyl boronic acid as a white powder. For other boronic acids prepared by this method see Table 2.5.
Phenylboronic acid (Table 2.5, entry 1, 8, 9);\textsuperscript{189} White powder; (0.234 g, 95%). \textsuperscript{1}H NMR (500 MHz, CDCl\textsubscript{3}): \(\delta\) 7.52 (t, \(J = 6\) Hz, 2H), 7.61 (t, \(J = 7\) Hz, 1H), 8.26 (d, \(J = 5.5\) Hz, 2H); \textsuperscript{13}C NMR (125.7 MHz, CDCl\textsubscript{3}): \(\delta\) 128.0, 132.7, 135.7; \textsuperscript{11}B NMR (160.4 MHz, CDCl\textsubscript{3}): \(\delta\) +30.7.

\[ \begin{array}{c} \text{Ph} \text{-} \text{B(OH)}_2 \\ \text{Ph} \end{array} \]

\(\text{o-}\text{-Tolylboronic acid (Table 2.5, entry 2);}\textsuperscript{189} \) White powder; (0.226 g, 88%). \textsuperscript{1}H NMR (500 MHz, CDCl\textsubscript{3}): \(\delta\) 2.82, 7.27 (m, 2H), 7.459 (dt, \(J = 1.5, 7\) Hz, 1H), 8.22 (dd, \(J = 7\) Hz, 1H); \textsuperscript{13}C NMR (125.7 MHz, CDCl\textsubscript{3}): \(\delta\) 23.1, 125.3, 130.7, 132.3, 137.4, 146.4; \textsuperscript{11}B NMR (160.4 MHz, CDCl\textsubscript{3}): \(\delta\) +31.9.

\[ \begin{array}{c} \text{Ph} \text{-} \text{B(OH)}_2 \\ \text{Ph} \end{array} \]

\(\text{p-}\text{-Tolylboronic acid (Table 2.5, entry 3);}\textsuperscript{189} \) White powder; (0.345 g, 95%). \textsuperscript{1}H NMR (500 MHz, CDCl\textsubscript{3}): \(\delta\) 2.44 (s, 3H), 7.32 (d, \(J = 7.5\) Hz, 1H), 8.13 (d, \(J = 7.5\) Hz, 1H); \textsuperscript{13}C NMR (125.7 MHz, CDCl\textsubscript{3}): \(\delta\) 21.9, 128.9, 133.7, 135.9, 143.1; \textsuperscript{11}B NMR (160.4 MHz, CDCl\textsubscript{3}): \(\delta\) +30.4.

\[ \begin{array}{c} \text{Ph} \text{-} \text{B(OH)}_2 \\ \text{Ph} \end{array} \]

\(\text{t-Butylboronic acid (Table 2.5, entry 4);}\textsuperscript{200} \) White powder; (0.481 g, 94%). \textsuperscript{13}C NMR (125.7 MHz, CDCl\textsubscript{3}): \(\delta\) 27.8; \textsuperscript{11}B NMR (160.4 MHz, CDCl\textsubscript{3}): \(\delta\) +32.7.
Cyclohexylboronic acid (Table 2.5, entry 5); White powder; (0.497g, 97%). $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 27.3, 27.5, 28.3; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +33.5.

\[ \text{B(OH)}_2 \]

$n$-Hexylboronic acid (Table 2.5, entry 6); $^{201}$ White powder; (0.404g, 95%). $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 14.7, 23.4, 24.2, 25.0, 32.5, 32.8; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +34.4.

\[ \text{B(OH)}_2 \]

$n$-Decylboronic acid (Table 2.5, entry 7); $^{202}$ White powder; (0.888g, 95%). $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 14.1, 22.7, 23.4, 24.4, 29.4, 29.5, 29.7, 31.9, 32.4; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +33.9.

**General Procedure for the Preparation of Aryl Boronic Acids Under Barbier-type Conditions.**

The following procedure for the preparation of 1-naphthylboronic acid is representative. A 25-mL round-bottom flask with equipped with a condenser and magnetic stir bar was charged with magnesium turnings (0.058 g, 2.4 mmol) and was activated by addition of iodine crystals and warming until the iodine sublimed. The flask was cooled to 25 °C and was purged with Ar. BH$_2$-N(iPr)$_2$ (2.4 mL, 2.4 mmol)
was added to the flask and brought to reflux. 1-bromonaphthalene (1.5M, 2.0 mmol) was then added dropwise over five minutes with constant stirring at 65 °C. The reaction was complete after 4 h as evidenced by the disappearance of BH$_2$-N(iPr)$_2$ starting material ($\delta$ +35, t, $J = 125$ Hz), and the appearance of a doublet at ($\delta$ +38, d, $J=112$ Hz) with the corresponding bromomagnesium aminoborohydride signal (MgBr$^+$ BH$_3$-NiPr$_2$, $\delta$ -28, q, $J = 88$ Hz). The reaction was then cooled to 25 °C and acidified with 3M aqueous HCl (3mL) (CAUTION: hydrogen evolution). After 10 min of stirring the reaction mixture was warmed to 65 °C and stirred for an additional 15 min. The reaction mixture was then transferred to a separatory funnel and extracted with diethyl ether (3 x 15 mL). The combined organic layers were dried over anhydrous MgSO$_4$, filtered, and concentrated in vacuo (25 °C, 1 Torr) to afford 1-napthylboronic acid as a white solid. The results for the other boronic acids prepared by this method are summarized in Table 2.6. For copies of the $^1$H, $^{13}$C and $^{11}$B NMR spectrum see Appendix A.

Because of their facile dehydration, boronic acids tend to provide inconsistent melting points. Therefore, the melting points for boronic acids were not taken.$^{203}$

![1-napthylboronic acid (Table 2.6, entry 1)]$^{189}$ White powder; (0.253 g, 79%). $^1$H NMR (500 MHz, DMSO-d$_6$): $\delta$ 3.44 (brs, 1H), 7.50 (m, 3H), 7.78 (d, $J = 5$ Hz, 1H), 7.91 (t, $J = 9.5$ Hz, 2H), 8.36 (brs, OH), 8.42 (dd, $J = 8$ Hz, 1 Hz, 1H); $^{13}$C NMR
(125.7 MHz, DMSO-d6): δ 128.2, 128.8, 129.1, 132.0, 132.9, 135.7; \(^{11}\)B NMR (160.4 MHz, DMSO-d6): δ +30.2.

4-methoxyphenylboronic acid (Table 2.6, entry 2);\(^{189}\) White powder; (0.196 g, 67%). \(^1\)H NMR (500 MHz, CDCl\(_3\)): δ 3.89 (s, 3H), 7.03 (d, \(J = 8.5\) Hz, 2H), 8.17 (d, \(J = 8.5\) Hz, 2H); \(^{13}\)C NMR (125.7 MHz, CDCl\(_3\)): δ 55.3, 113.7, 137.7, 163.4; \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): δ +29.1.

2-Thiopheneboronic acid (Table 2.6, entry 3);\(^{189}\) White powder; (0.221 g, 74%). \(^1\)H NMR (500 MHz, CDCl\(_3\)): δ 7.33 (dd, \(J = 3.5, 4.5\) Hz, 1H), 7.83 (d, \(J = 4.5\) Hz, 1H), 8.06 (d, \(J = 4\) Hz, 1H); \(^{13}\)C NMR (125.7 MHz, CDCl\(_3\)): δ 128.9, 135.1, 139.8; \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): δ +27.0.

Allylboronic acid (Table 2.6, entry 4);\(^{204}\) \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): δ +42.1 (d, \(J = 147\) Hz), +36.6 (t, \(J = 129\) Hz).

1-Boronic acid ethylbenzene (Table 2.6, entry 5);\(^{205}\) \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): δ +42.1 (d, \(J = 147\) Hz, 1H), +36.6 (t, \(J = 123\) Hz, 2H).
2.6 References


130 Liu, Z.; Marder, T. B. *Angew. Chem. Int. Ed.* **2008**, *47*, 242-244.


Dimethylaminoborane was synthesized from the corresponding LAB, methyl iodide and 1 equiv. of triethylborane. This showed the dimethylaminoborane to be 100% dimer by $^{11}$B-NMR (80.25 MHz, THF). ($\delta = +3.3$, $J = 98$ Hz).

At present it is not apparent why different ratios of monomer/dimer are obtained for diethylaminoborane synthesized from methyl iodide or TMS-Cl and LAB.

These LAB reagents were prepared from the corresponding heterocyclic borane complex and $n$-BuLi.


205 Chen, A.; Ren, Li; Crudden, C. M. *J. Org. Chem.* **1999**, 64, 9704-9710.
CHAPTER 3

Synthesis of Hydridomagnesium Halide and Bromomagnesium Dimethylaminoborohydride, and Reduction of Weinreb Amides
3.1 Introduction

Metal hydrides have received attention as reducing agents capable of both reduction and hydrometalation.\textsuperscript{206,207} Metal hydrides have also been extensively investigated for hydrogen storage purposes.\textsuperscript{208} These reagents can be formed by the addition of hydrogen to a metal (eq 1).

\[
\begin{align*}
M + \frac{n}{2} H_2 & \rightleftharpoons MH_n + \text{heat} \\
M = \text{metal, metal alloy, intermetallic compound}
\end{align*}
\]

These reactions are exothermic and reversible, therefore if metal hydrides are heated, they can release hydrogen (H\textsubscript{2}). In theory this process can be repeated indefinitely. This forms the basis for the use of metal-metal/hydride hydrogen storage systems.

It has been speculated that H\textsubscript{2} is an ideal secondary energy source with great potential to solve present and future energy problems.\textsuperscript{209,210} A major advantage of hydrogen as an energy source is the fact that H\textsubscript{2} exhibits the highest energy content per unit weight of all chemical fuels. At 120 MJ/kg it has approximately three times the energy density of petroleum (40 MJ/kg).\textsuperscript{208} In addition, hydrogen can be simply and economically transported as a gas and has been used extensively in electricity generation by fuel cells.\textsuperscript{211} Widespread use of hydrogen as an energy source is mainly dependent on finding simple, economical, and safe ways to store large quantities in a small volume and with an acceptable weight. Hydrogen can be stored in its elemental form as a gas or a liquid, or in a chemical form. As a chemical form of hydrogen
storage, metal hydrides have received an enormous amount of attention, especially MgH\textsubscript{2} since it has the highest energy density per unit weight (9 MJ/kg) of all metal hydrides studied.\textsuperscript{212}

3.2 Magnesium Hydride

In an effort to identify new hydride reducing agents, Ashby became interested in the synthesis and reactivity of magnesium hydride (MgH\textsubscript{2}).\textsuperscript{213} Through this study, three general methods for preparing MgH\textsubscript{2} were identified: pyrolysis of diethylmagnesium (A),\textsuperscript{214} reaction of lithium aluminum hydride (LiAlH\textsubscript{4}, or LAH) with diethylmagnesium (B),\textsuperscript{215} and from the respective elements via hydrogenation (C) (Scheme 3.1).

\begin{align*}
\text{A} & \quad \text{MgEt}_2 \quad \text{175 °C} \quad \text{MgH}_2 + 2\text{C}_2\text{H}_4 \\
\text{B} & \quad \text{LiAlH}_4 + 2\text{MgEt}_2 \quad \rightarrow \quad 2\text{MgH}_2 + \text{LiAl(C}_2\text{H}_5)_4 \\
\text{C} & \quad \text{Mg} + \text{H}_2 \quad \text{570 °C} \quad \text{200 bar} \quad \rightarrow \quad \text{MgH}_2
\end{align*}

Scheme 3.1 Methods of MgH\textsubscript{2} synthesis

It was determined that the reactivity of MgH\textsubscript{2} largely depends upon the method of preparation in addition to the presence of transition metal impurities. For example, MgH\textsubscript{2} produced by diethylmagnesium pyrolysis is highly reactive (Scheme 3.1 A), being pyrophoric and reacting violently with water.\textsuperscript{214} MgH\textsubscript{2} prepared via the
reaction of dialkylmagnesium compounds with LAH (Scheme 3.1 B) also produces a highly reactive form of MgH₂. In contrast, MgH₂ prepared by hydrogenation of elemental magnesium, is air-stable and only reacts slowly with water (Scheme 3.1 C).

Although the preparation of MgH₂ from the elements requires drastic conditions and long reaction times, it has sparked further investigation due to the potential utility of the resulting MgH₂ as a reductant and in reversible hydrogen storage systems. Attempts have been made to increase the rate of hydrogenation by adding other metals to the system, including In, Al, Ce, Fe, Mg₂Ni, and Mg₂Cu. Bogdanovic observed that the addition of anthracene, CrCl₃, and TiCl₄ in substoichiometric amounts activated magnesium toward hydrogenation. Magnesium is known to react with anthracene to form a more reactive, highly soluble form of Mg, Mg-anthracene 2 (Scheme 3.2). The ¹H and ¹³C NMR spectra of 2 show magnesium bonded to carbon atoms 9 and 10 of the anthracene ring. When 2 is hydrogenated with 2 moles of H₂, MgH₂ is produced along with 9,10-dihydroanthracene. At 58 °C and 75 bar, the reaction requires 35 hours to go to completion (Scheme 3.2). This demonstrates a significant improvement from the pure Mg and H₂ system, which requires temperatures greater than 500 °C and pressure greater than 200 bar. This reaction was further improved by the use of 2 mol% of TiCl₄ per mole of 2, which produced MgH₂ at a tenfold faster rate. This methodology
has been used to synthesize MgH\(_2\) on up to a 15-kg scale for hydrogen storage purposes.\(^{212}\)

\[ \text{Scheme 3.2 Mg-Anthracene catalyzed MgH}_2 \text{ generation} \]

Ashby investigated the application of MgH\(_2\) prepared from LiAl\(_4\) and Et\(_2\)Mg as a reducing agent.\(^{218}\) He found this form of MgH\(_2\) to be insoluble in organic solvents, and speculated that this was due to a highly polymeric structure bonded via double-hydrogen bridging bonds (Figure 3.1).\(^{219}\)

Figure 3.1. Proposed liner polymer of MgH\(_2\)

Ashby found that a MgH\(_2\)/tetrahydrofuran (THF) slurry reduces benzaldehyde in 1 hour at -40 °C (eq 2),\(^{218}\) camphor in 24 hour at 25 °C (eq 3),\(^{220}\) and 4-tert-butylcyclohexanone in 1 hour at 25 °C (eq 4),\(^{218}\) with quantitative conversion to the corresponding alcohol products. Under these conditions, the cis to trans ratio of 4-
tert-butylcyclohexanol was 24:76 (eq 4). In the reduction of camphor, hydride attack predominated from the endo side, giving the exo alcohol isoborneol in 92% ee (eq 3). The observed stereoselectivity for 4-tert-butylcyclohexanone and endo camphor reduction suggests that MgH$_2$ has a low steric requirement.

\[ \text{MgH}_2 \xrightarrow{\text{THF, 1h, -40 °C}} \text{PhOH} \quad 100\% \] (2)

\[ \text{MgH}_2 \xrightarrow{\text{THF, 24h, 25 °C}} \begin{align*} \text{endo OH} & + \text{endo H} \\ 92\% & \quad 8\% \end{align*} \] (3)

\[ \text{MgH}_2 \xrightarrow{\text{THF, 1h, 25 °C}} \begin{align*} \text{exo OH} & + \text{exo H} \\ 24\% & \quad 76\% \end{align*} \] (4)

MgH$_2$ has also been prepared from LAH and Et$_2$Mg, and used to transfer hydride to magnesium chloride in the formation of hydromagnesium chloride (HMgCl), which will be discussed in the following section.
3.3 Hydridomagnesium Halides

Hydridomagnesium halides (HMgX, where X = halogen) have been investigated since the late 1950s.\textsuperscript{221} The literature on this subject contains a number of discrepancies regarding the different methods and conditions used for HMgX synthesis. Eugene Ashby has pioneered the majority of the work reported in this field. In 1977 Ashby and Goel published a paper in \textit{Inorganic Chemistry} titled “Concerning the Existence of HMgX Compounds.”\textsuperscript{222} However, Ashby later reported that essentially all previous accounts on this topic were flawed, and where not reproducible following detailed investigation.\textsuperscript{215,223} Specifically, Ashby focused on three methods of HMgX synthesis. Wiber and Strebel reported the synthesis of HMgCl and HMgBr \textit{via} the reaction of Grignard reagents with diborane (Scheme 3.3).\textsuperscript{221} When the exact reaction conditions were repeated by Ashby, chloromagnesium borohydride was the sole product, isolated as a white crystalline solid (Scheme 3.3).\textsuperscript{224} To ensure that the crystalline product was not a mixture of MgCl\textsubscript{2} and Mg(BH\textsubscript{4})\textsubscript{2}, Ashby compared the solubility of MgCl\textsubscript{2} and ClMgBH\textsubscript{4} in benzene. The material ClMgBH\textsubscript{4} is freely soluble in benzene, while MgCl\textsubscript{2} was determined to have a solubility of 0.02 g/100g benzene.
Scheme 3.3 Reactions of Grignard with diborane

In a separate investigation, Ashby evaluated the work reported by Dymova and Eliseeva, whereby soluble HMgX was synthesized by hydrogenolysis of ethylmagnesium halides in diethyl ether. Ashby used X-ray powder-diffraction analysis to demonstrate that under the reported conditions, the solid recovered was a mixture of MgX$_2$ and MgH$_2$. In addition, it was shown by X-ray powder-diffraction analysis that pyrolysis of ethylmagnesium bromide does not produce HMgBr as reported by Rice, but rather a mixture of MgBr$_2$ and MgH$_2$.

Previously, Ashby reported the preparation of hydridomagnesium halides by the reaction of magnesium halides (MgX$_2$) with an active form of MgH$_2$ (eq 5). Preparation of the active form of MgH$_2$ was achieved using Ph$_2$Mg or Et$_2$Mg and equimolar amounts of LAH in diethyl ether. The resulting MgH$_2$ was insoluble in ether and was isolated from the soluble LiAlH$_2$Et$_2$ by filtration. The solid MgH$_2$ was slurried in THF and mixed with MgX$_2$ (X = Cl and Br) at 25 °C (eq 5).
This reaction was exothermic and resulted in a clear solution within 15 minutes. This result indicated that reaction between MgH₂ and MgX₂ had occurred since MgH₂ is insoluble. According to the earlier reports evaluated by Ashby, HMgX compounds are insoluble in diethyl ether. However, Ashby reported that both HMgBr and HMgCl are soluble in THF. The infrared spectra of both HMgCl and HMgBr in THF showed a medium to strong absorption band in the region of 1280 cm⁻¹, which is not present in the spectrum of MgCl₂ or MgBr₂ in THF. The Mg-H stretching band in HMgBr and HMgCl was determined by preparing DMgBr and DMgCl by the method above using LiAlD₄, and comparing the IR spectra of the HMgX and DMgX compounds. Bands at 1260 and 1290 cm⁻¹ correspond to HMgBr and HMgCl in THF, respectively. Molecular weight studies on HMgBr and HMgCl in THF showed the compounds to be dimeric in dilute solution with the following molecular structure (Figure 3.2).

![Figure 3.2 Proposed molecular structure of dimeric HMgX](image)

MgH₂, prepared from LAH and Et₂Mg, can also be used for the synthesis of alkoxy and dialkylaminomagnesium hydrides. In a similar fashion to the reaction of MgH₂ with MgX₂ to form HMgX, MgH₂ reacts with Mg(OR)₂ and Mg(NR₂)₂ to...
form the corresponding THF soluble alkoxy and dialkylaminomagnesium hydrides (Scheme 3.4).

\[
\text{Mg} \left( \text{NR}_2 \right)_2 + \text{MgH}_2 \xrightarrow{\text{THF}} \text{2H} \text{MgNR}_2 \\
\text{Mg} \left( \text{OR} \right)_2 + \text{MgH}_2 \xrightarrow{\text{THF}} \text{2H} \text{MgOR}
\]

**Scheme 3.4** Synthesis of alkoxy and dialkylaminomagnesium hydrides

The dialkoxy magnesium compounds were prepared by reacting the corresponding alcohol with dimethylmagnesium in refluxing THF/Et\(_2\)O (eq 6). Similarly, the bis(dialkylamino)magnesium compounds were prepared by mixing the corresponding dialkylamine with dimethylmagnesium in refluxing THF/Et\(_2\)O (eq 7).

\[
2 \text{ROH} + \text{Me}_2\text{Mg} \xrightarrow{\text{THF/Et}_2\text{O}} \text{reflux 24 h} \quad \text{Mg(OR)}_2 + 2 \text{CH}_4 \uparrow
\]

\[
2 \text{R}_2\text{NH} + \text{Me}_2\text{Mg} \xrightarrow{\text{THF/Et}_2\text{O}} \text{reflux 24 h} \quad (\text{R}_2\text{N})_2\text{Mg} + 2 \text{CH}_4 \uparrow
\]

The alkoxy magnesium and dialkylaminomagnesium hydrides are soluble in THF and exhibit reductive properties toward ketones. For example the alkoxy magnesium hydride \(\text{HMgO}(2,6-\text{t-Bu}_2-4-\text{MeC}_6\text{H}_2)\) reduced 2-methylcyclohexanone, 3,3,5-trimethylcyclohexanone, and camphor in quantitative yields and gave selective formation of the less stable exo alcohol in 99% yield (eq 8).
Unfortunately, dialkylaminomagnesium hydrides showed essentially non-selective reduction. For example, the reduction of 4-tert-butylcyclohexanone with 2,6-dimethylpiperidinomagnesium hydride gave a 45:55 mixture of axial to equatorial 4-tert-butylcyclohexanol (eq 9).\(^{220}\)

\[
\text{HMgO-} \quad \text{t-Bu} \quad \xrightarrow{\text{O}} \quad \text{HMgO} \quad \text{t-Bu} \quad 99\%
\]

\[
\text{t-Bu} \quad \xrightarrow{\text{OH}} \quad \text{t-Bu} \quad \text{OH} \quad \xrightarrow{\text{99\%}}
\]

In summary, the reactivity of MgH\(_2\) is dependent on the method used for its synthesis. When prepared from LAH and Et\(_2\)Mg, MgH\(_2\) reduces cyclic ketones and benzaldehyde. Hydridomagnesium halide (HMgX) is formed by the reaction of MgH\(_2\) with MgX\(_2\). Similarly, alkoxy and dialkylaminomagnesium hydrides are formed by the reaction of MgH\(_2\) with Mg(OR)\(_2\) and Mg(NR\(_2\))\(_2\). These compounds also reduce cyclic ketones and benzaldehyde to the corresponding alcohols. However, these reagents have not been applied to amide reduction.
3.4 Properties and Synthesis of N-Methoxy-N-methylamides (Weinreb Amides)

3.4.1 Properties of Weinreb Amides

In 1981 Nahm and Weinreb discovered that N-methoxy-N-methylamides (Weinreb amides) cleanly react with Grignard reagents and organolithium species to produce ketones (eq 10).\(^\text{230}\)

![Chemical structure of Weinreb amides](image)

(10)

The use of various organometallics lead to the formation of a new C-C bonds, and functional conversion from amide to ketone. This was a significant finding at the time because there were few reliable methods for synthesizing ketones from carboxylic acid derivatives. The organometallic reagents used are either Grignard or organolithium compounds (M = MgX or Li) with the following substituents (R\(^\prime\)): alkyl, alkenyl, alkynyl, aryl, and heteroaryl. Another important finding was that the metal hydrides LAH and diisobutylaluminum hydride (DIBAL) react with Weinreb amides to produce aldehydes. The formation of primary alcohols is completely avoided, even if a large excess of the reducing agent is used.\(^\text{230}\) Additionally, the reaction conditions are reasonably mild, usually run between -78 and 0 °C in solvents such as THF or dimethylamine (DME), and few side reactions occur.
These results are due to the stable metal chelated intermediate 4 which forms after the first equivalent of organometallic species or reducing agent is added. The stability of the metal chelated intermediate does not allow for collapse of the tetrahedral intermediate to the ketone or aldehyde, thus preventing further attack by the nucleophile. The tetrahedral intermediate 4 smoothly decomposes in dilute hydrochloric acid to yield the corresponding ketone or aldehyde. Simultaneously, the aqueous acidic quenches excess equivalents of organometallic species, thus preventing over addition product from being formed, even with large excess of reagent.

The seminal report by Nahm and Weinreb showed stoichiometric conversion of cyclohexyl and N-methoxy-N-methylbenzamide to the corresponding ketones when reacted with various Grignard and organolithium reagents (Table 3.1). The tetrahedral metal-chelated intermediate was stable even in the presence of excess organometallic reagent. In three separate experiments, 1.1, 3, and 75 equivalents of MeMgBr were added to N-methoxy-N-methylbenzamide to yield acetophenone in 93 to 96% yield (Table 3.1, entries 1, 2, 3 respectively). Phenylmagnesium bromide and phenyl lithium reacted with N-methoxy-N-methylbenzamide to form benzophenone in 93 and 96% yield respectively (Table 3.1, entries 4 and 5). Also reported but not highlighted, was the use of aliphatic and alkenyl N-methoxy-N-methylamides.
Table 3.1 Addition of organometallics to N-methoxy-N-methylamides in THF

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>R’M (equiv.)</th>
<th>Yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ph</td>
<td>MeMgBr (1.1)</td>
<td>93</td>
</tr>
<tr>
<td>2</td>
<td>Ph</td>
<td>MeMgBr (3)</td>
<td>95</td>
</tr>
<tr>
<td>3</td>
<td>Ph</td>
<td>MeMgBr (75)</td>
<td>96</td>
</tr>
<tr>
<td>4</td>
<td>Ph</td>
<td>PhMgBr</td>
<td>93</td>
</tr>
<tr>
<td>5</td>
<td>Ph</td>
<td>PhLi</td>
<td>95</td>
</tr>
<tr>
<td>6</td>
<td>Cyclohexyl</td>
<td>Ph</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>Cyclohexyl</td>
<td>n-butyl</td>
<td>97</td>
</tr>
</tbody>
</table>

One of the main applications of Weinreb’s amide has been in the synthesis of ketones.\textsuperscript{231,232} In the formal synthesis of (+)-brefeldin A, the Weinreb amide 6 derived from (S)-lactate was reacted with the anion of silyloxyheptyne 7 to afford the conjugated alkynyl ketone 8 in good yield (eq 11).\textsuperscript{233} For the formation of ketones, the nucleophilic species is invariably either an organolithium or organomagnesium reagent.
3.4.2 Synthesis of Weinreb Amides

Weinreb amides are easily prepared from \( N,O \)-dimethylhydroxylamine (DMHA) and an acid chloride or other activated acid derivatives (see Figure 3.3 below). The stability of Weinreb amides are equivalent to tertiary amides and therefore require no special handling or storage and are easily purified by column chromatography or distillation.\(^{234}\) DMHA is commercially available as the hydrochloride salt (DMHA•HCl). DMHA is generated in situ by the addition of one equivalent of base, freeing the amine to attack the highly electrophilic acyl chloride (eq 12).\(^{235}\)

\[
\text{AcCl} + \text{DMHA•HCl} \xrightarrow{\text{pyridine, } \text{CH}_2\text{Cl}_2, 0 - 25^\circ \text{C}, 2h} \text{NOMe}
\]

While acid chlorides react smoothly with DMHA, it can be difficult to selectively convert acids into acid chlorides in multifunctional compounds. Hence, it is highly desirable to synthesize Weinreb amides from the corresponding carboxylic acids in a one-pot system. The conversion of carboxylic acids to Weinreb amides has
been achieved using various peptide coupling reagents. For example, benzotriazol-1-yloxy-tris(dimethylamino)phosphonium hexafluorophosphate (BOP) has been used to activate the N-protected alpha amino acid to achieve Weinreb amide synthesis by converting the acid into a good leaving group (Scheme 3.5).\textsuperscript{236,237}

![Scheme 3.5 Synthesis of Weinreb amide using BOP activation](image)

In general, carboxylate activation consists of the replacement of the hydroxyl group of the carboxylic acid with a leaving group followed by reaction with DMHA, which can be done in situ.\textsuperscript{238,239} Several coupling reagents have been employed in the synthesis of Weinreb amides including 4-(4,6-dimethoxy-1,3,5-triazin-2-yl)-methylmorpholinium chloride (DMT-MM),\textsuperscript{240} 2-chloro-4,6-dimethoxy-[1,3,5]triazine (CDMT),\textsuperscript{241} S-(1-oxido-2-pyridinyl) 1,1,3,3-tetramethylthiouuronium hexafluorophosphate (HOTT),\textsuperscript{242} dicyclohexylcarbodiimide (DCC),\textsuperscript{243} and 1-(methanesulfonyl)benzotriazol (BtMs)\textsuperscript{244} (Figure 3.3).
3.5 DIBAL and LAH Reduction of Weinreb Amides

The initial investigation of various substrates as Weinreb amides included two hydride reducing agents: LAH and Dibal as compatible organometallics (eq13).

Reduction of various Weinreb amides 9 with DIBAL and LAH produced the corresponding aldehydes 10 in good yield. Only a small fraction of the corresponding
alcohol 11 was observed (Table 3.2). Weinreb showed that the use of DIBAL is superior to LAH for the clean reduction of Weinreb amides to aldehydes, since LAH induces over reduction.

**Table 3.2 Reduction of Weinreb amides to aldehydes with DIBAL and LAH**

<table>
<thead>
<tr>
<th>Entry</th>
<th>R</th>
<th>R’M (equiv.)</th>
<th>1. DIBAL or LAH</th>
<th>2. H₂O⁺</th>
<th>Yield(%) (8:9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ph-</td>
<td>DIBAL</td>
<td>THF 0 °C</td>
<td></td>
<td>71</td>
</tr>
<tr>
<td>2</td>
<td>Ph-</td>
<td>LAH</td>
<td></td>
<td></td>
<td>67:5</td>
</tr>
<tr>
<td>3</td>
<td>n-C₁₇H₃₅⁻</td>
<td>DIBAL</td>
<td></td>
<td></td>
<td>71</td>
</tr>
<tr>
<td>4</td>
<td>n-C₁₇H₃₅⁻</td>
<td>LAH</td>
<td></td>
<td></td>
<td>50:25</td>
</tr>
<tr>
<td>5</td>
<td>PhC₃H₂⁻</td>
<td>DIBAL</td>
<td></td>
<td></td>
<td>76:3</td>
</tr>
<tr>
<td>6</td>
<td>PhC₃H₂⁻</td>
<td>LAH</td>
<td></td>
<td></td>
<td>70:14</td>
</tr>
</tbody>
</table>

Weinreb amides have been extensively utilized in the synthesis of natural products and various other synthetic intermediates. γ-Bicyclohomofarnesal (Ambral® 12), is produced by the reduction of the corresponding Weinreb amide. Ambral is a useful synthetic intermediate that has been employed as a starting point for the synthesis of a number of terpene derivatives such as (+)-galanolactone²⁴⁵ 13 and (-)-Ambrox®²⁴⁶ 14 (eq 14).
De La Torre utilized Weinreb amide chemistry to synthesize 12 and its internal olefin isomer 15. 247 The commercially available lactone (R)-(+) sclareolide was opened with DMHA in the presence of trimethylaluminum at room temperature, producing the Weinreb amide in 88% yield (Scheme 3.6). The tertiary alcohol was dehydrated with thionyl chloride and pyridine to yield the two separable isomers in 50 and 32% yield, respectively. Each isomer was reduced with LAH to yield 12 and 15 in 89 and 91% yield, respectively (Scheme 3.6).
Scheme 3.6 Synthesis of γ-bicyclohomofarnesal 12 and its internal olefin isomer 15

As can be seen by this example, Weinreb amides are useful intermediates for the synthesis of natural products. They serve as acylating agents for organolithium and organomagnesium reagents and are excellent and robust precursor to aldehydes.

3.6 Results and Discussion

3.6.1 Vinylmagnesium Bromide Addition to Phenyl Weinreb Amide

Braslau and Tansakul observed that when commercially prepared vinylmagnesium bromide was added to tetrahydropyranyl (THP)-protected Weinreb amide 16, a mixture of the desired product 17 and an aldehyde 18 were produced (eq 15).
It was further observed that when freshly prepared vinylmagnesium bromide was used, only the desired $\alpha,\beta$-unsaturated ketone 17 was formed. This result indicates that the commercially sourced vinylmagnesium bromide contained a hydride reducing agent. In order to confirm this hypothesis, the commercially obtained vinylmagnesium bromide was reacted with benzaldehyde. $^1$H NMR analysis of the product mixture revealed a 2:1 mixture of allylic alcohol and benzyl alcohol (eq 16).

This result confirmed the presence of a hydride reducing agent in this commercially obtained reagent. A literature search on the topic of hydrides and Grignard reagents revealed a paper by Ashby titled “Concerning the Formation of Magnesium Hydride in the Preparation of Grignard Reagents.” Ashby attempted to explain the observation that the addition of methylmagnesium bromide to benzophenone produced both the methyl addition product as well as benzhydrol (eq 17). This was unexpected, since methylmagnesium bromide does not possess $\beta$-
hydrogens, and consequently cannot participate in β-hydrogen reduction. In addition, diarylketones are not enolizable, because they lack α-hydrogen atoms. Therefore only the addition product of methylmagnesium bromide to benzophenone was expected.

![Chemical diagram](image)

(17)

Ashby questioned the grade of magnesium used for Grignard synthesis. He employed magnesium from two different commercial sources for the synthesis of methylmagnesium bromide. He used magnesium from Dow Chemical Company, which is purified by double sublimation. The second source of magnesium was from Research Organic/Inorganic Chemical Corp. (ROC/RIC): the method of magnesium purification was not disclosed. The addition of MeMgBr prepared from Dow doubly sublimed magnesium to 2-methylbenzophenone (2-MBP) yielded the 1,2-addition product along with 25% of 2-methylbenzhydrol. The same reaction was performed using MeMgBr synthesized from magnesium supplied by ROC/RIC; no reduction product was observed. In a third experiment, MeMgBr (400 equiv), prepared from magnesium supplied by ROC/RIC, which gave no reduction of 2-MBP, was mixed with MgH₂ (0.6 equiv) and added to 2-MBP (1.0 equiv). The product mixture was analyzed; equivalent results to the study using MeMgBr formed from Dow magnesium were obtained: 75% 1,2-addition product and 25% 2-methylbenzhydrol.
were formed (eq 18). The fact that 25% of reduction product was observed when the alkylating agent was in such large excess (400:1) indicates that MgH₂ is an unusually powerful reducing agent toward ketones. Hence, it was concluded that the observations by Braslau and Tansakul were the result of magnesium hydride present in the vinyl Grignard solution.

\[
\begin{align*}
\text{MgH}_2 + \text{MeMgBr} + \text{MeMgBr} & \rightarrow \text{MgH}_2 + \text{HOCH}_2 + \text{HOCH}_2 \\
\text{0.6 equiv} & \text{ 400 equiv} & \text{1.0 equiv} \quad \text{75\%} \quad \text{25\%}
\end{align*}
\]

The Singaram group here at UCSC has investigated the reactivity of Grignard reagents with pinacolborane, and observed the formation of HMgX as a byproduct (see Chapter 4). Using this novel method for HMgX production, its utility for Weinreb amide reduction was investigated.

### 3.6.2 Synthesis of Hydridomagnesium Halide from Grignard and Pinacolborane

\( p \)-Tolylmagnesium bromide was reacted with a PinBH in a THF solution at 25 °C. After 1 hour of stirring at 25 °C an aliquot of the reaction mixture was analyzed by \(^{11}\text{B} \) NMR spectroscopy. The \(^{11}\text{B} \) NMR spectrum showed essentially quantitative formation of the \( p \)-tolylpinacolboronate (Scheme 3.7). Usually, dialkoxy-alkylborohydride species display a broad singlet in the region of 0 to +10 ppm in the \(^{11}\text{B} \) NMR spectrum. However, \(^{11}\text{B} \) NMR analysis of the reaction product mixture
showed no evidence of the initial borohydride adduct. Based on the reaction stoichiometry, it was concluded that 1 equivalent of H\text{MgBr} was formed along with the arylboronic ester.

Scheme 3.7 Formation of arylboronic ester and H\text{MgBr}

Encouraged by the initial \textsuperscript{11}B NMR results, the arylboronic ester was isolated by the addition of pentanes and characterized. The product was isolated by the addition of pentanes. Upon the addition of pentanes, a solid precipitate was formed, which was separated from the supernatant through a Schlenk filter system. After the supernatant was dried over MgSO\textsubscript{4} and evaporated in \textit{vacuo}, the resulting oil was analyzed by \textsuperscript{11}B, \textsuperscript{1}H and \textsuperscript{13}C NMR spectroscopy. The spectra confirmed formation of \textit{p}-tolylboronic acid in 90% yield.
3.6.3 Analysis of Hydridomagnesium Halide

The sealed NMR tube containing \( p \)-tolyboronic acid in chloroform formed crystals after sitting undisturbed for one week. This was an unexpected event, because the reaction mixture had already been subjected to the addition of pentanes, which produced copious amounts of precipitate. To determine the identity of the crystals produced upon pentane addition, various crystallization techniques to isolate samples suitable for X-ray analysis were attempted. The crystallization method of vapor diffusion provided the desired block crystals. To produce the crystals, crystallization was conducted in a 20-mL scintillation flask placed in a larger argon charged flask containing a shallow layer of pentane (about 1 cm in height). Crystals formed upon standing overnight in the refrigerator held at 15 °C. The resultant crystals, characterized by single crystal X-ray diffraction, were identified as the known compound MgBr\(_2\)(THF)\(_4\) (Appendix B). It should be pointed out that there was no gas evolution during the reaction of Grignard reagent and PinBH. It is speculated that the reaction proceeds through a distinctive pathway where hydridomagnesium bromide (HMgBr) acts as the leaving group; under the non-polar conditions it disproportionates to form MgBr\(_2\) and MgH\(_2\). Using the reaction stoichiometry, the following reaction scheme is proposed (Scheme 3.8).
To investigate the solubility of the magnesium hydride in THF/pentane, the reaction was repeated with the initial pentane workup procedure. Instead of removing the solvent under reduced pressure, water (1mL) was added to the reaction. Upon the addition of water, hydrogen gas evolution was observed. This supports the hypothesis that the missing hydrogen was in fact tied up as a metal-hydride complex which was soluble in the THF/pentane mixture. In an attempt to chelate MgH$_2$, tetramethylethylenediamine (TMEDA) was added to the mixture. TMEDA is known to chelate various magnesium based crystals, which might then be characterized by X-ray diffraction analysis.$^{251}$

To produce MgH$_2$, $n$-hexylmagnesium bromide was reacted with an equimolar amount of PinBH in THF. The MgBr$_2$ precipitate was separated from the supernatant via Schlenk line filtration. The resulting supernatant was cooled to 0 °C followed by the addition of 0.25 equivalents of TMEDA. After two days of standing in the 15 °C in the refrigerator, no crystals formed. Therefore, an additional 0.25 equivalents of TMEDA were added: crystals formed overnight. The resulting TMEDA complex

![Scheme 3.8 Proposed stoichiometry of MgH$_2$ formation](image)
crystallized from the THF solution. X-ray analysis showed the complex consisted of two five-coordinate magnesium centers. Each magnesium was chelated by the nitrogen atoms of a TMEDA ligand, a bromine and two bridging oxygens from the boronate ligands (Figure 3.4). The coordination geometry about each Mg is a highly distorted hybrid of trigonal bipyramidal and square pyramidal. Unfortunately, the resulting crystal data revealed that there was no hydride present in the structure. Due to the three day production of these crystals, it is probable that this structure arises from a source of water contamination with concomitant evolution of hydrogen gas. Alternatively, TMEDA could simply contain a small amount of water.

**Figure 3.4** X-ray structure of Mg-TMEDA complex. Crystal data for $\text{C}_{24}\text{H}_{56}\text{B}_{2}\text{Br}_{2}\text{Mg}_{2}\text{N}_{4}\text{O}_{6}$; $M_r = 726.79$; monoclinic; space group $\text{P2}_1/c$; $a = 14.572(2)$ Å; $b = 10.5623(15)$ Å; $c = 24.687(4)$ Å; $\alpha = 90^\circ$; $\beta = 102.502(2)^\circ$; $\gamma = 90^\circ$; $V = 3709.7(9)$ Å$^3$; $Z = 4$; $T = 150(2)$ K; $\lambda$(Mo-Kα) = 0.71073 Å; $\mu$(Mo-Kα) = 2.257 mm$^{-1}$; $d_{\text{calc}} = 1.301\text{g.cm}^{-3}$; 40826 reflections collected; 9208 unique ($R_{\text{int}} = 0.0246$); giving $R_1 = 0.0262$, $wR_2 = 0.0621$ for 7455 data with $|I|>2\sigma(I)$ and $R_1 = 0.0379$, $wR_2 = 0.0668$ for all data.
A slow pentane vapor diffusion technique provided crystals suitable for single crystal X-ray analysis from the product mixture of \( p \)-tolylmagnesium bromide and PinBH. However, single crystal X-ray diffraction showed this material to be \( \text{MgBr}_2(\text{THF})_4 \), a known compound which is sparingly soluble in THF at about 5g/100g (see Appendix B).\textsuperscript{252,253,254}\ These results are best explained by a facile disproportionation of \( \text{HMgBr} \) to \( \text{MgH}_2 \) and \( \text{MgBr}_2 \).\textsuperscript{222} The absence of any hydride containing species in the isolated crystals suggested two conclusions. First, the \( \text{MgH}_2 \) species is soluble in THF/pentane mixture and did not precipitate upon the addition of pentanes. Second, during the crystallization process, moisture from the atmosphere was introduced into the system and hydrogen was slowly liberated. The hypothesis that \( \text{MgH}_2 \) remained solvated in the THF/pentane mixture was verified by adding an aliquot of the supernatant (1 mmol) to a \( \text{BH}_3:\text{THF} \) solution (1 mmol) at 25 °C. \textsuperscript{11}\text{B} NMR analysis of the reaction showed quantitative formation of a borohydride species as a quintet at -40 ppm and the complete absence of a signal corresponding to \( \text{BH}_3:\text{THF} \) at 0 ppm (Figure 3.5).
To further quantify the now corroborated hydride species, the volume of hydrogen gas evolved after quenching known amounts of the supernatant solution with water/methanol was measured. Based on the ideal gas law, the volume of hydrogen gas evolved is directly proportional to the concentration of hydride in solution. Therefore, $p$-tolylmagnesium bromide (3.45 mL, 1M/THF) was reacted with PinBH (0.5 mL, 3.45 mmol) in THF (1.75 mL) for 1 hour at room temperature. Following the addition of pentanes (1.75 mL) and the precipitation of MgBr₂, stirring was stopped to allow the precipitate to settle down. The 0.46 M supernatant solution was analyzed for its hydride content by injecting 1 mL aliquots into a gas measuring device with a quenching solution of H₂O/MeOH (1:1) (Table 3.3). Metal hydrides react rapidly and quantitatively with protic solvents, including water, to produce hydrogen gas (eq 19).
Measuring the volume of hydrogen gas produced provides a highly accurate method for determining the concentration of metal hydrides. An illustration of the gas burette system used for measuring the volume of hydrogen gas is shown if Figure 3.6.

**Figure 3.6.** Gas burette for measuring the volume of gas evolved

The quenching flask was filled with 25 mL of 1:1 H₂O/MeOH and the cold trap was cooled in a dry ice/acetone bath. With the stopcock open to atmosphere, the burette and glass tube were filled with 150 mL of water through the leveling bulb. Stopcock 2 was then closed and stopcock 1 was turned so that the quenching flask and the graduated burette form a closed system. The level of water in the glass tube was marked with a piece of tape and the volume of water in the burette was recorded. An accurately measured aliquot of the metal hydride solution was then added slowly through the inlet septum of the quenching flask to the stirred H₂O/MeOH solution
using a syringe. When the hydrolysis was complete, the water level in the glass tube was observed relative to its original position.

To obtain the volume of hydrogen gas produced the level of water in the glass tube must was raised to the initial position. This was accomplished by lowering the leveling bulb to a point below the outlet of the side tube in the burette and then raising the leveling bulb to its original position. The lowering and raising of the lowering bulb were repeated until the level of the water in glass tube reached its original position. The volume of water remaining in the burette was then measured. The analysis was repeated eight times. The molarity of the MgH$_2$ solution was calculated using the following equation$^{256}$ (eq 20):

$$
\text{MgH}_2 \text{ concentration} = \frac{(P1-P2) (273) (V1-V2)}{(760) (T) (22.4) (V2) (n)}
$$

Where:
- $P1$ = observed pressure (mm Hg)
- $P2$ = vapor pressure (mm Hg) of water at $T$
- $V1$ = volume (mL) of hydrogen gas evolved
- $V2$ = volume (mL) of MgH$_2$ solution injected into hydrolyzing solution
- $T$ = observed temperature (K)
- $n$ = number of moles of hydrogen produced per mole of MgH$_2$, $n = 2$ for MgH$_2$

(20)
Table 3.3. Analysis of magnesium hydride (MgH₂) concentration.\textsuperscript{a}

\begin{align*}
\text{MgBr} & + \text{HBpin} & \text{THF} & \text{1 equiv} & \text{1 equiv} & 1h, 25^\circ\text{C} & \text{BPin} & + \text{MgH}_2 & + \text{MgBr}_2(\text{THF})_4 & \text{H}_2 \text{gas} & \text{1 equiv} & [0.46\text{ M}] & [0.23\text{ M}] & [0.46\text{ M}] \\
\end{align*}

<table>
<thead>
<tr>
<th>Run</th>
<th>V(injected, mL)</th>
<th>V(displaced, mL)</th>
<th>mmol H\textsubscript{2}\textsuperscript{c}</th>
<th>mmol MgH\textsubscript{2}</th>
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</thead>
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<tr>
<td>1</td>
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<td>19.6</td>
<td>0.79</td>
<td>0.39</td>
</tr>
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</tr>
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</tr>
<tr>
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<tr>
<td>8</td>
<td>1.0</td>
<td>23.6</td>
<td>0.95</td>
<td>0.48</td>
</tr>
</tbody>
</table>

AVG= 0.458

STD DEV= 0.06

Theory M = 0.46

Exp. M = 0.458 (>99%)\textsuperscript{b}

\textsuperscript{a}Reagents and conditions: PinBH (0.5 mL, 3.45 mmol), anhydrous THF (1.75 mL), p-tolylmagnesium bromide (3.45 mmol, 1M/THF), argon, 25 °C, 1h. Pentanes added (1.75 mL), stirring stopped, supernatant analyzed for hydride content. \textsuperscript{b}Theoretical molarity of MgH\textsubscript{2} = 0.46. \textsuperscript{c}mmol H\textsubscript{2} = Volume displaced per 1mL injection calculated according to eq 20 with the following parameters: P\textsubscript{1}=756 mm Hg, P\textsubscript{2}=17.974 mm Hg, V\textsubscript{1}=22.75 mL, V\textsubscript{2}=1 mL, T=293.65 K, n=2.
The number of moles of hydrogen gas produced by quenching 1 mL of the solution was equivalent to the molarity of the arylboronate. This is explained by the stoichiometry of the borylation and subsequent disproportionation reaction. For each borylation event, one equivalent of HMgBr is formed, which disproportionates to 0.5 equivalents of both MgBr\(_2\) and MgH\(_2\). In turn, one equivalent of MgH\(_2\) contains two equivalents of hydride; upon quenching with water two equivalents of hydrogen gas are produced (eq 21). Simplification of the reaction provides the following stoichiometry: for every half equivalent of MgH\(_2\), one equivalent of hydrogen gas is produced when quenched with water. After data analysis, the experimental molarity of MgH\(_2\) concurred with the theoretical molarity with greater than 99% agreement.

\[
\begin{align*}
1 \text{MgH}_2 & \rightarrow \text{H}_2\text{O/MeOH} \\
& \rightarrow 2 \text{H}_2 \text{gas} \\
1:2 (\text{MgH}_2 / \text{H}_2) 
\end{align*}
\]  

(21)

In a second experiment, isopropylmagnesium chloride was reacted with PinBH in THF. As observed previously (See chapter 4), when alkylmagnesium chlorides react with PinBH, the resulting HMgCl does not disproportionate to MgH\(_2\) and MgCl\(_2\). The reaction solution was analyzed by injecting 1 mL aliquots into the gas measuring device with a quenching solution of H\(_2\)O/MeOH (1:1). The various data points corresponding to the volume of H\(_2\) gas produced are summarized below (Table 3.4).
Table 3.4 Analysis of hydridomagnesium chloride (HMgCl) concentration.\textsuperscript{a}

\begin{center}
\begin{tabular}{cccccc}
Run & V(injected, mL) & V(displaced, mL) & mmol H\textsubscript{2}\textsuperscript{c} & mmol HMgCl \\
1 & 1.0 & 12 & 0.48 & 0.48 \\
2 & 1.0 & 12.4 & 0.50 & 0.50 \\
3 & 1.0 & 11.2 & 0.45 & 0.45 \\
4 & 1.0 & 12.4 & 0.50 & 0.50 \\
5 & 1.0 & 12.6 & 0.51 & 0.51 \\
6 & 1.0 & 12.6 & 0.51 & 0.51 \\
7 & 1.0 & 12.4 & 0.50 & 0.50 \\
\hline
Avg. = & & & 0.49 & \\
STD DEV = & & & 0.02 & \\
Theory M & & & 0.50 & \\
Exp. M = & & & 0.49 (98\%) & \\
\end{tabular}
\end{center}

\textsuperscript{a}Reagents and conditions: PinBH (0.58 mL, 4 mmol), anhydrous THF (5.4 mL), isopropylmagnesium chloride (4 mmol, 2M/THF), argon, 25 °C, 1h. \textsuperscript{b}Theoretical molarity of HMgCl= 0.50. \textsuperscript{c}mmol H\textsubscript{2} = Volume displaced per 1mL injection calculated according to eq 20 with the following parameters: P\textsubscript{1}=756 mm Hg, P\textsubscript{2}=17.974 mm Hg, V\textsubscript{1}=12.23 mL, V\textsubscript{2}=1 mL, T=293.65 K, n=1.

The data demonstrate that the measured moles of hydrogen gas evolved per one milliliter of quenched supernatant are equivalent to the alkylboronate molarity.
Without the formation of precipitate, the reaction shows 1:1 stoichiometry between alkylboronate and HMgCl. The fact that the moles of hydrogen gas produced are equivalent to the moles of substrate indicates that the identity of the hydride species is a monohydridomagnesium halide (eq 22).

\[
\text{1 HMgCl} \xrightarrow{\text{H}_2\text{O/MeOH}} \text{1 H}_2 \text{gas} \quad 1:1 (\text{HMgCl} / \text{H}_2) \quad (22)
\]

Finally, HMgCl formation was confirmed unambiguously through IR analysis. The observed medium to strong absorption band at 1292 cm\(^{-1}\) corresponds to the H-MgCl stretching.\(^{215}\) Ashby identified the HMgCl IR absorption band by comparing the IR spectrum of DMgCl, prepared from LiAlD\(_4\) and MgEt\(_2\), and HMgCl.

The data from both of these experiments clearly shows that the hydride gets transferred to magnesiumbromide in the reaction of Grignard reagents with PinBH in THF. Additionally, it was shown that the magnesium hydride species resulting from HMgBr disproportionation produces a dihydride species. From the stoichiometry of the reaction and the identification of the precipitate by crystallography, the dihydride species appears to be MgH\(_2\). Furthermore, this is a novel route for the production of THF soluble HMgCl, HMgBr, and THF/pentane soluble MgH\(_2\).

**3.6.4 Computation Analysis of HMgBr Disproportionation**

The disproportionation of 2HMgBr to MgBr\(_2\) and MgH\(_2\) was studied by Professor Todd Wipke at UCSC by DFT calculations (Gaussian09) at the B3LYP/6-
31G(d) level of theory with the polarized continuum solvent model (PCM) (solvent = THF) for geometry optimization and final energy. The analysis showed that the reaction is endothermic by 0.56 kcal/mol. Formation of the bridged complex BrMg(µH,Br)MgH from 2HMgBr (Figure 3.7) is exothermic by −21.0 kcal/mol. The µ(H,H) bridged dimer is more stable at −21.4 kcal/mol and the µ(Br,Br) bridged dimer is less stable at −18.9 kcal/mol, however the µ(H,Br) bridged dimer enables the disproportionation by breaking opposite bonds of the bridge (Figure 3.7). As a model for THF, dimethyl ether was chosen for explicit coordination together with PCM (solvent = THF). The reaction in Scheme 3.8 was shown experimentally to occur also in diethyl ether, making dimethyl ether (DME) a good computational model. The disproportionation of two octahedral HMgBr-DME₄ to octahedral MgBr₂-DME₄ + MgH₂-DME₄ was found to be slightly exothermic by −0.51 kcal/mol. Formation of the bisoctahedral DME₃HMg(µH,Br)MgBrDME₃ intermediate from HMgBr-DME₄ is endothermic by +0.45 kcal/mol, thus explicit solvation favors product formation. The transition states for interconversion of the µ-bridged dimers, potential energy surfaces, and solvation studies are presented in Appendix B. These calculations support the observed disproportionation reaction in THF.
**Figure 3.7** A. The μHBr-bridged HMgBr dimer is the key intermediate in the Schlenk equilibrium. B. Schematic reaction coordinate state diagram for the Schlenk equilibrium, energies are in kcal/mol relative to 2HMgBr

### 3.6.5 Reduction of a Weinreb Amide Using Magnesium Hydride

MgH$_2$ and HMgCl, produced by the reaction of Grignards with PinBH, were investigated as viable reducing agents. MgH$_2$, produced by the reaction of LAH with MgBr$_2$, was found by Ashby to be insoluble in THF. He reported that insoluble MgH$_2$ could be slurried with THF to reduce both ketones and aldehydes as well as to
transfer hydride to MgBr₂, Mg(NR₂)₂, and Mg(OR)₂. The Singaram group reported that when MgH₂ is produced from Grignards and PinBH, it is indeed soluble in THF as well as in a THF/pentane mixture.²⁵⁸

It was determined that the observations made by Braslau and Tansakul regarding competitive reduction of N-methoxy-N-methylbenzamide in the presence of vinyl Grignard was the result of MgH₂ present in the Grignard solution. Because of this, the first experiment to probe MgH₂ reduction on a Weinreb amide was on N-methoxy-N-methylbenzamide. The investigation began with a one hour reaction between equimolar amounts of methylmagnesium bromide and PinBH to make a 0.34 M THF solution of MgH₂. Following the addition of pentanes and the precipitation of MgBr₂, stirring was stopped and the precipitate was allowed to settle. The separation of supernatant from precipitate by syringe was attempted. However, the removal of supernatant free of precipitate was not successful. Regardless, this solution was added to a THF solution of N-methoxy-N-methylbenzamide (1 equiv). The reaction was stirred at 25 °C for 3 hours. TLC analysis showed the disappearance of the amide coinciding with the formation of benzaldehyde. Unfortunately, a TLC spot corresponding to benzyl alcohol also appeared, providing evidence for over-reduction (eq 23).
It was speculated that the order of reagent addition was contributing to the observed mixture of products. In the next experiment, a 0.34 M solution of MgH₂ was produced under the same conditions. After one hour of stirring, N-methoxy-N-methylbenzamide was added to the heterogeneous solution of MeBPin, MgBr₂, and MgH₂. The reaction stirred at 25 °C for 3 hours; TLC analysis showed benzaldehyde to be the main product along with a small amount of unreacted N-methoxy-N-methylbenzamide. Unfortunately, after an acidic work up, ¹H NMR analysis showed benzyl alcohol as one of the reaction products as well as amide starting material (eq 24).

In an attempt to limit benzaldehyde reduction, a non-aqueous quench was employed by adding acetaldehyde (MeCHO) in hexanes to the reaction mixture. It was reasoned that a sacrificial electrophile, being more reactive than benzaldehyde, could scavenge any hydrides present. Following the MeCHO quench, ¹H NMR analysis showed less benzyl alcohol than previously observed. Controlled one-step
reduction of Weinreb amides remains a challenging transformation. As reviewed earlier, the only successful and widely applied reagents are DIBAL and LAH. Despite the challenges encountered thus far, the preliminary results generated in this study are compelling and have warranted further investigated from the Singaram lab. Christopher Bailey of the Singaram lab is currently exploring a collaboration with the Lokey group at UCSC to reduce resin bound Weinreb amides using this methodology.

In a subsequent experiment to investigate the convenience and utility of magnesium hydride formation from Grignard and PinBH, HMgCl was synthesized from iPrMgCl and PinBH. To the best of our knowledge, the reduction potential of HMgCl toward common functional groups has not previously been investigated. As outlined above, HMgCl is produced as a THF soluble magnesium hydride species, by the reaction of an organomagnesium chloride reagent with PinBH. A 0.37M THF solution of HMgCl was produce along with one equivalent of iPrBPIn. HMgCl was chosen as the reducing agent because it can be produced in a reliable concentration without the formation of MgBr₂ precipitate. The hydridomagnesium choride/iPrBPIn solution was added to both benzaldehyde and 4-bromoacetophenone in THF (eq 25 and 26 respectively). In both cases conversion to the corresponding alcohol was quantitative in two hours at 25 °C.

\[ \text{Benzaldehyde} + \text{HMgCl/iPrBPIn} \rightarrow \text{Benzyl alcohol} + \text{iPrBPIn} \]
3.6.6 Reduction of a Weinreb Amide Using Chloromagnesium Aminoborohydride

Grignard reagents have been widely applied to the synthesis of ketones by reaction with Weinreb amides. The success of these reactions is due to the strong tetrahedral magnesium-chelated intermediate. In previous work, a simple and efficient procedure for the synthesis of chloromagnesium dimethylaminoborohydride (MgAB, δ -15.6, q, J = 83 Hz) was developed. Chloromagnesium dimethylaminoborohydride was quantitatively formed by the deprotonation of dimethylamine and subsequent reaction with borane (eq 27).

\[
\begin{align*}
\text{H}_3\text{B}:\text{N} & \quad \text{Me} \quad \xrightarrow{\text{MeMgCl}} \quad \text{H} \quad \text{Me} \\
\text{H} \quad \text{Me} & \qquad \text{Me} \\
\text{H} \quad \text{B} & \quad \text{N} \quad \text{Me}
\end{align*}
\]

(δ -15.6, q, J = 83 Hz)

It was thought that the reaction of MgAB with a Weinreb amide would produce a stable tetrahedral magnesium-chelated intermediate, and in turn form the corresponding aldehyde upon quenching. A 0.7M THF solution of MgAB was synthesized from MeMgCl and dimethyamineborane in THF. In a separate flask N-methoxy-N-methylbenzamide (0.9 equiv) was diluted in Et₂O and cooled to 0 °C. The
MgAB solution was then added dropwise with stirring to $N$-methoxy-$N$-methylbenzamide. TLC analysis at 45 minutes showed a very large and intense spot corresponding to benzaldehyde and a very small faint spot corresponding to benzyl alcohol. At this point the reaction was quenched with saturated ammonium chloride (sat. NH$_4$Cl) and a white precipitate formed. The supernatant was removed by syringe and the precipitate was washed with hexanes. The organic layers were combined and analyzed by TLC. The TLC plates, pre- and post-quench were equivalent, showing predominantly benzaldehyde formation. Surprisingly, after the organic layer was dried over MgSO$_4$ and evaporated in vacuo, both TLC and $^1$H NMR analysis showed quantitative conversion to benzyl alcohol. From previous studies on the synthesis of aminoboranes from LAB reagents and TMSCl, it is expected that the byproduct from MgAB reduction is dimethylaminoborane. Dimethylaminoborane exists as a tightly bound dimer as evidenced by the chemical shift of the $^{11}$B NMR (see chapter 2).$^{258}$ At this point it is unclear how benzaldehyde is reduced to benzyl alcohol. This work was carried out in collaboration with Christopher Bailey in the Singaram lab. He is currently working on this problem as well developing MgAB as a general reducing agent.

3.7 Conclusions

It has been clearly shown that hydride is transferred to magnesiumbromide in the addition reaction of Grignard reagents and PinBH. The counter ion which facilitates hydride transfer is the corresponding magnesium halide from the parent
Grignard reagent. Both alkyl and arylmagnesium bromides or chlorides smoothly react with PinBH at 25 °C to form the corresponding organoboronic ester and HMgX. Further analysis on the reactivity of Grignard reagents with PinBH revealed that alkylmagnesium bromide reagents produce a precipitate within minutes at 25 °C, while alkylmagnesium chloride reagents do not produce any precipitate. Addition of pentanes or hexanes to the reaction mixture forms MgH₂ and MgCl₂ as a precipitate. In contrast, aryl Grignards do not readily form precipitates regardless of bromine or chlorine atoms present in the Grignard reagent. This data will be described in detail in Chapter 4. Single crystal X-ray analysis showed the precipitate to be MgBr₂. Based on the reaction stoichiometry, HMgBr disproportionates to form MgBr₂ and MgH₂. MgH₂ was found to be highly soluble in THF/pentane. The stoichiometric formation of MgH₂ was determined by measuring the volume of hydrogen gas released when quenched with water. Three distinctly different THF-soluble magnesium hydride reagents are formed: MgH₂, HMgBr, and HMgCl based on the reaction conditions.

Preliminary data on the reduction potential of these hydride species show smooth and quantitative conversion of benzaldehyde and p-bromoacetophenone to the corresponding alcohols. MgH₂ reduces N-methoxy-N-methylbenzamide to benzaldehyde, which is a particularly difficult transformation. HMgCl formation is a byproduct of pinacol organoboronic ester formation, therefore any reduction using this system will require the removal of the pinacol organoboronic ester from the product mixture. Currently, a method to remove the organoboronate by a simple
chemical transformation or through liquid-liquid extraction does not exist. However, the separation of alcohols and boronic esters is a routine operation using column chromatography.

A new reagent, halomagnesium dimethylaminoborohydride (MgAB) has been identified as a viable reducing agent capable of reducing Weinreb amides to the corresponding aldehydes. Investigation on the scope and selectivity of these reagents in currently underway in the Singaram lab. The utility of the reaction between Grignard reagents and PinBH for the synthesis of boronic esters is discussed extensively in chapter 4.

### 3.8 Experimental

**General Methods.** All reactions were performed in oven-dried, argon-cooled glassware. The pinacolborane was used as received from Aldrich, stored under Ar in a refrigerator held at 15 °C. All Grignard reagents were used as received from Aldrich, they were stored in the bottle received and kept in the refrigerator held at 15 °C. Magnesium metal was used as received from Aldrich. All air and moisture-sensitive compounds were introduced via syringes or cannula through a rubber septum. Pinacolborane was added via syringe, with the dispensed amounts measured by mass difference of the syringe before and after addition. Tetrahydrofuran (THF) was freshly obtained from a solvent purification system (Pure Solv MD, Innovative
Technology inc.). NMR spectra were recorded in CDCl$_3$. Chemical shifts are reported relative to TMS ($\delta = 0$) for $^1$H NMR (500 MHz) and are referred to the CDCl$_3$ resonance ($\delta = 77$) for $^{13}$C NMR (125 MHz) spectra. Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, br = broad, m = multiplet, app = apparent), coupling constant and integration. Boron NMR samples were recorded at 160.4 MHz and are reported relative to external standard BF$_3$:Et$_2$O ($\delta = 0$).

**Mg-TMEDA crystallization procedure**

A 50-mL round-bottom flask equipped with a magnetic stir bar and fitted with rubber septum was charged with anhydrous THF (3 mL) followed by pinacolborane (0.38 g, 0.42 mL, 3 mmol). $n$-Hexylmagnesium bromide (3 mmol, 2M/THF) was added dropwise over 5 min. at 25 °C with constant stirring. Precipitate formed within 10 min. with continued stirring for 30 min. At 30 min. pentanes (3 mL) was added and allowed to stir for 10 min. The supernatant was decanted with an Ar charged syringe and passed through a Schlenk filter into a dry Ar charged 50-mL round bottom flask fitted with a stir bar and septa. The MgH$_2$ solution was cooled to 0 °C. TMEDA (0.11 mL, 0.75 mmol) was added dropwise over 5 min. to the stirring solution of MgH$_2$. Stirring was stopped and the reaction vessel was placed in a refrigerator held at 15 °C. After sitting overnight at 15 °C, no precipitate was present so additional TMEDA was added (0.11 mL, 0.75 mmol). The reaction vessel was again placed in the refrigerator. After 48 h. large clear needles formed. A fragment of
a colorless block-like crystal having approximate dimensions of $0.43 \times 0.31 \times 0.18$ mm was mounted on a Kapton loop using Paratone N hydrocarbon oil. All measurements were made on a Bruker APEX-II$^1$ CCD area detector with graphite monochromated Mo-Kα radiation. Structure solution and refinement can be found in Apendix B.

**Vapor diffusion crystallization procedure using pentanes**

A 1 Dram clear glass vial dried in an oven was fitted with a septum and cooled under Ar. The vial was charged with pinacolborane (1.1 mL, 1M/THF) followed by dropwise addition of $p$-tolylmagnesium bromide (1 mL, 1M/THF) at 25 °C. After 30 minutes of reaction time, the septum was removed and the vial was placed inside of a 25-mL scintillation vial which contained 1 cm of pentanes. The larger scintillation flask was capped with a septum and flushed with Ar in a quick manner. The crystallization chamber was placed in a refrigerator held at 15 °C. After 24 h at 15 °C, crystals formed. A fragment of a colorless tablet-like crystal having approximate dimensions of $0.47 \times 0.47 \times 0.31$ mm was mounted on a Kapton loop using Paratone N hydrocarbon oil. All measurements were made on a Bruker APEX-II$^1$ CCD area detector with graphite monochromated Mo-Kα radiation. Structure solution and refinement can be found in Apendix B.
General Procedure for Analysis of Hydridomagnesium Chloride (HMgCl) and Magnesium Hydride (MgH₂) Concentration by Gas Evolution Analysis.

A 50-mL round-bottom flask equipped with a magnetic stir bar and fitted with rubber septum was charged with anhydrous THF (1.75 mL) followed by pinacolborane (0.441 g, 0.5 mL, 3.45 mmol). p-Tolylmagnesium bromide (3.45 mmol, 1 M/THF) was added dropwise over 5 min. at 25 °C with constant stirring. The reaction was complete after 1 h as evidenced by ¹¹B NMR analysis. Hexanes (1.75 mL) was added to induce precipitation of MgBr₂. Aliquots from the supernatant (0.5 mL) were injected into the gas measuring device with a 1:1 quenching solution of H₂O/MeOH with constant stirring. The volume displaced by hydrogen gas was measured and converted to moles of hydrogen gas according to the ideal gas law (PV = nRT) see equation 20. The process was repeated eight times (Table 3.3).

HMgCl was produced under the same anhydrous reaction conditions as above. Isopropylmagnesium chloride was used instead of p-tolylmagnesium bromide. The addition of pentanes was omitted, the precipitate free reaction mixture was analyzed as outlined above. See Table 3.4.
Procedure for the Preparation of HMgCl from Grignard Reagents and Pinacolborane

The following procedure for the preparation HMgCl from isopropylmagnesium chloride and 4,4,5,5-tetramethyl-1,3,2-dioxaborolane is representative. A 25-mL round-bottom flask equipped with a magnetic stir bar and fitted with rubber septum was charged with anhydrous THF (4.0 mL) followed by pinacolborane (0.57g, 4.5 mmol). Isopropylmagnesium chloride (4.5 mmol, 1 M/THF) was added dropwise over 5 min. at 25 °C with constant stirring. The reaction was complete after 1 h as evidenced by the disappearance of pinacolborane starting material (δ +27.7, d, J = 173.9 Hz), and the appearance of a singlet at +30.5 ppm via $^{11}$B-NMR. Note that no precipitate is formed in this reaction.

General Procedure for Reduction using HMgCl/iPrBPin

The following procedure for the preparation of benzyl alcohol is representative. HMgCl/iPrBPin is prepared as outlined above and added dropwise to a solution of benzaldehyde (1 equiv., 0.20 mL, 2 mmol) in THF (2 mL) with constant stirring over 20 min. at 25 °C . Reaction progress was monitored by thin layer chromatography. Disappearance of the benzaldehyde starting material was observed after 2 h. Reaction was quenched with HCl (3.5 mL, 1 M) and diluted with hexanes (10 mL). The reaction mixture was then transferred to a separatory funnel and extracted with hexanes (3 x 15 mL). The combined organic layers were dried over
anhydrous MgSO₄, filtered, and concentrated in vacuo (25 °C, 1 Torr) to afford a mixture of benzyl alcohol and iPrBPin.

Benzyl alcohol (eq. 23, 100% conversion). ¹H NMR (500 MHz, DMSO-d₆): δ 4.65 (s, 2H), 7.24 (s, 1H), 7.28 (m, 1H), 7.34 (d, J = 4.5 Hz, 2H); ¹³C NMR (125.7 MHz, DMSO-d₆): δ 65.4, 127.1, 127.8, 128.7, 141.0.

1-(4-Bromophenyl)ethanol (eq 24, 100% conversion). ²⁵⁹ ¹H NMR (500 MHz, DMSO-d₆): δ 1.39 (d, J = 6.5 Hz, 3H), 2.61 (brs, 1H), 4.76 (q, J = 6.5 Hz, 1H), 7.16 (d, J = 8.5, 2H), 7.40 (d, J = 8.5, 2H); ¹³C NMR (125.7 MHz, DMSO-d₆): δ 26.3, 69.7, 121.1, 127.3, 131.6, 144.9.

Procedure for MgH₂ reduction of N-methoxy-N-methylbenzamide

MgH₂/iPrBPin is prepared as outlined above and added dropwise to a solution of N-methoxy-N-methylbenzamide (1 equiv., 0.26 mL, 1.70 mmol) in THF (3.4 mL) with constant stirring over 20 min. at 25 °C. Reaction progress was monitored by thin layer chromatography. Disappearance of the N-methoxy-N-methylbenzamide starting material was observed after 3 h. Reaction was quenched with HCl (3.5 mL, 1 M) and diluted with hexanes (10 mL). The reaction mixture was then transferred to a
separatory funnel and extracted with hexanes (3 x 15 mL). The combined organic layers were dried over anhydrous MgSO₄, filtered, and concentrated in vacuo (25 °C, 1 Torr) to afford an off white oil with a distinct sweet smell. ¹H NMR analysis indicated a mixture of benzaldehyde and benzyl alcohol.

\[
\text{Benzaldehyde (eq 22). } ¹H \text{ NMR (500 MHz, CDCl}_3\text{): } \delta 7.56 \text{ (m, 1H), } 7.62 \text{ (m, 2H), } 7.83 \text{ (m, 2H), } 9.97 \text{ (s, 1H).}
\]

\[
\text{Benzyl alcohol (eq 22) } ¹H \text{ NMR (500 MHz, CDCl}_3\text{): } \delta 4.65 \text{ (s, 2H), } 7.24 \text{ (s, 1H), } 7.28 \text{ (m, 1H), } 7.34 \text{ (d, } J = 4.5 \text{ Hz, 2H).}
\]

![Benzaldehyde structure](image)

**Synthesis of Chloromagnesium dimethylaminoborohydride**

Methylmagnesium chloride (0.83 mL, 2.4 M solution in THF, 2.0 mmol) was cooled to 0 °C (ice bath). In a separate flask diisopropylamineborane (0.118 g, 2.0 mmol) was dissolved in anhydrous THF (2.0 mL) in a 25-mL round bottom flask. The diisopropylamineborane/THF solution was added dropwise over 10 min via syringe at 0 °C to the methylmagnesium bromide/THF solution. After 0.5 h of stirring at 0 °C a 0.5 mL aliquot was analyzed via ¹¹B NMR, which showed the solution to be bromomagnesium diisopropylaminoborohydride. ¹¹B NMR (160.4 MHz, CDCl₃): \( \delta -15.6, q, J = 83 \text{ Hz).} \)
3.9 References


256 Aldrich Technical Information Bulletin AL-123.

257 Clary, J. W.; Rettenmaier, T. J.; Eagon, S.; Murphy, C.; Bailey, C. L.; Singaram, B. *Manuscript in Preparation*


CHAPTER 4

Reaction of Pinacolborane with Halides Under Grignard and Barbier Conditions. One Pot Synthesis of Pinacol Alkyl, Aryl, Heteroaryl, Vinyl and Allylboronic Esters
4.1 Introduction

One of the most useful and versatile methods for synthesizing biaryls is the Suzuki-Miyaura reaction. In this reaction, an aryl boronic acid or boronic ester derivative is coupled with an aryl halide or triflate by a palladium catalyst. When simple aryl and alkenyl substrates are employed, this method is reliable and tolerated by a wide range of functional groups. However, when sterically hindered partners are employed, boronic acids instead undergo extensive deboronation, giving observable rise to arenes and olefins. To achieve quantitative conversion, excess boronic acid is commonly employed. This problem is not always explicitly mentioned in papers, but is implicit in the high boronic acid derivative/organic electrophile ratios used in the reactions (5:1 ratios are common in literature). Because boronic acids are stable to acidic conditions, it is concluded that deboronation occurs through the formation of a metalated species followed by reaction with water. It is also observed that the detrimental deboronation event is circumvented when sterically demanding boronic ester derivatives are used in the cross-coupling (eq 1). However, ethylene glycol boronic ester provided a better yield than the pinacol derivative.

\[
\begin{align*}
\text{Ar} \quad \text{Me} & + \quad \text{Ar} \quad \text{Me} \quad \text{B(O\text{R}')}_2 \\
& \xrightarrow{3 \text{ mol}\% \text{PdCl}_2/6 \text{ mol}\% \text{PPh}_3} \quad \text{CsF-DME} \\
& \quad \text{Me} \\
R' &= \text{H, H} \\
R' &= -\text{C(CH}_3)_2\text{C(CH}_3)_2^- \\
R' &= -\text{CH}_2\text{CH}_2^- \\
& \text{trace} \\
& 36\% \\
& 69\%
\end{align*}
\]

(1)
4.2 Stability of Pinacol Arylboronates (2-aryl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane)

In general, pinacol arylboronates (2-aryl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane) are known to be very stable under oxidative and hydrolytic conditions compared to arylboronic acids. The increased stability of this cyclic boronic ester allows for ease in handling and purification. The proposed rational for the observed increase in stability is that the rigid cyclic structure promotes a more coplanar orientation of the oxygen and boron atomic orbitals. This allows for more efficient back-bonding from the Lewis basic oxygen atoms to the vacant 2p-orbital of boron, which in turn decreases the Lewis acidity of the boron atom (Figure 4.1).265,266

![Figure 4.1](image.png)

**Figure 4.1.** Partial molecular orbital view of (2-aryl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane)

This argument that back-bonding from Lewis basic substituents into the empty p-orbital of boron reduces Lewis acidity was used by Brown in an investigation on the rate of allylboration of various representative allylboronates.267 It was found that among cyclic allylboronates, the five-membered heterocycles (1,3,2-dioxaborolane derivatives Table 4.1, entries 2-5), undergo allylboration more rapidly than the six-membered cyclic boronate B-allyl-1,3,2-dioxaborinane (Table 4.1, entry 1).
**Table 4.1.** A comparison of the rates of allylboration of benzaldehyde with representative cyclic and acyclic allylboronates

<table>
<thead>
<tr>
<th>Entry</th>
<th>Boronate</th>
<th>$T_{1/2}$ min, 25 °C$^{b}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="Boronate 1" /></td>
<td>40 (120 at 0 °C)</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2" alt="Boronate 2" /></td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td><img src="image3" alt="Boronate 3" /></td>
<td>10</td>
</tr>
<tr>
<td>4</td>
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<td>5</td>
</tr>
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<td><img src="image5" alt="Boronate 5" /></td>
<td>instantaneous</td>
</tr>
<tr>
<td>6</td>
<td><img src="image6" alt="Boronate 6" /></td>
<td>instantaneous at 0 °C</td>
</tr>
<tr>
<td>7</td>
<td><img src="image7" alt="Boronate 7" /></td>
<td>9 at 0 °C</td>
</tr>
</tbody>
</table>

$^{a}$Boronate = 0.5 M, benzaldehyde = 0.5 M in dichloromethane $^{b}$determined by $^{11}$B NMR spectroscopy$^{267}$

The increased rate of allylboration of five-membered cyclic boronate derivatives over the six-membered cyclic boronate derivative was rationalized with a
sterics argument. The argument was that the six-membered cyclic boronate is more sterically encumbered, which then increases the back donation of the lone pair electrons of oxygen to the boron atom. This in turn decreases the Lewis acidity and the rate of allylboration. An alternative analysis is that the geometry of the six membered cyclic boronate promotes increased back-bonding due to better alignment of the corresponding highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) of the boronic ester. Despite unclear rational, the decreased Lewis acidity of the five membered boronates are clearly demonstrated by a consistent $^{11}$B NMR downfield chemical shift of +3 to +4 ppm, compared to the six-membered cyclic boronate B-allyl-1,3,2-dioxaborinane (Table 4.1, entry 1).\textsuperscript{267} Additionally, allylboronic acid is shifted +2 ppm downfield relative to B-allyl-1,3,2-dioxaborinane and is exceedingly more reactive toward allylboration. Brown made the reasonable suggestion that the compounds stability is directly related to the Lewis acidity of boron,\textsuperscript{267} which can be comparatively measured using $^{11}$B NMR. Increased Lewis acidity corresponds to greater deshielding and a downfield chemical shift in $^{11}$B NMR.

It was observed that arylboronic esters, specifically cyclic arylboronic esters, are not only compatible coupling partners in the Suzuki-Miyaura reaction but also offer significant advantages over their free boronic acid counterparts. Their added stability and compatibility as coupling partners in the Suzuki-Miyaura cross-coupling
reaction makes pinacol boronates synthetically valuable targets, prompting researchers to explore efficient methods for their synthesis.\textsuperscript{268}

4.3. Properties of 4,4,5,5-Tetramethyl-1,3,2-dioxaborolane (pinacolborane)

4.3.1. Synthesis of Pinacolborane

Pinacolborane can be synthesized by the addition of pinacol to a solution of BH\textsubscript{3}:SMe\textsubscript{2} (BMS) or BH\textsubscript{3}:THF (1:1 stoichiometry) in dry dichloromethane. After rapid evolution of hydrogen gas followed by 1 hour of stirring at 0 °C, then followed by 1 hour at 25 °C, the reagent is ready to use (Scheme 4.1).\textsuperscript{269} Pinacolborane can be further purified by vacuum distillation (42-43 °C, 50 mmHg), but for most applications further purification is not necessary.

\begin{center}
\textbf{Scheme 4.1} Synthesis of pinacolborane
\end{center}

Unfortunately, there are significant challenges associated with the use of BH\textsubscript{3}:THF, as it is unstable and prone to disproportionation unless stored in low concentration and low temperature. THF is a weak Lewis base which coordinates to BH\textsubscript{3}, forming a complex which can equilibrate to dissociated products. One of these dissociated products is free diborane, which is a highly volatile and pyrophoric gas known to readily ignite when brought in contact with water or air.\textsuperscript{270} In a second
degradation pathway, borane facilitates hydride-mediated ring opening of THF to produce dibutoxyborane or tributoxyborane (eq 2).

\[
\begin{align*}
\text{O: BH}_3 & \xrightarrow{\text{THF}} \text{''BuOBH}_2 & \xrightarrow{\text{THF}} (\text{''BuO})_2\text{BH} & \xrightarrow{\text{THF}} (\text{''BuO})_3\text{B} \\
\end{align*}
\]

(2)

At or above room temperature, the degradation is facile, however the ring opening is absent or minimal below 5 °C. BMS does not have this problem because the neat complex in dimethyl sulfide is very stable. However, BMS liberates a stoichiometric amount of highly volatile and flammable dimethyl sulfide, which is insoluble in water and has a very pungent odor. These limitations inhibit the application of borane reactions in large scale processes, and create unique problems associated with their storage and large scale transportation. Safer and more stable borane carriers have been proposed including BH\(_3\):THF solutions containing Lewis base stabilizers that would scavenge free borane,\(^{271}\) polymer bound borane systems,\(^{272}\) and borane complexes with hindered tertiary amines.\(^{273,274}\) Though there have been many advances in the development of safer and more stable borane carriers, no one system has been able to match the vigorous reactivity of BH\(_3\):THF and BMS.

A recent study by Miyaura was focused on the synthesis of PinBH using amine-borane complexes as a borane source.\(^{275}\) This was an effort to take advantage of their ability to be used in large scale processes, as amine-borane complexes which have high thermal stability, low vapor pressure, and are much less flammable than BH\(_3\):THF or BMS.\(^{276,277}\) Miyaura synthesized various amine-borane complexes by reacting BMS with a selection of amines in THF. Borane coordinates to 2,6-
diethylaniline (BH$_3$:N(C$_6$H$_3$)Et$_2$) and smoothly reactes with pinacol in a 1:1 stoichiometry to afford PinBH. However, a 50% excess of BH$_3$:N(C$_6$H$_3$)Et$_2$ is required to minimize formation of the main disproportionation product 2,2’-(2,3-dimethyl-2,3-butanediyl-oxy)bis(4,4,5,5-tertramethyl-1,3,2-dioxaborolane) (B$_2$Pin$_3$) during distillation (eq 3).

\[
\text{BH}_3:\text{N(C}_6\text{H}_3\text{)Et}_2 \rightarrow \text{HO} \rightarrow \text{HO} \rightarrow \text{HBPin} + \text{B}_2\text{Pin}_2
\]

(3)

Herin is described an investigation into the reactions of Grignard reagents with boron species containing a B-H bond, such as PinBH. The direct reaction between PinBH and various Grignard reagents, both preformed and formed in situ, is reported as an efficient and mild method for the synthesis of alkyl, aryl, heteroaryl, vinyl, benzylic and allylic pinacol boronates.

4.4 Results and Discussion

4.4.1 Reactivity of Organometallic Reagents with Boron Species Containing a B-H Bond.

The reactions of Grignard reagents with boron species containing a B-H bond, such as PinBH, were investigated as a new approach toward boronic ester synthesis. A literature search revealed a previous study by Noth regarding arylborohydride
Tetrahydroborates and trialkylhydroborates of alkali metals had proven to be very versatile reducing agents, and a number of groups have explored methods for producing hydroborates and alkylhydroborates of alkali metals. In 1983, Noth synthesized lithium mono-organotrihydroborates by the reaction of organolithium reagents with borane complexes such as BH₃:THF, BMS, and BH₃:NMMe₃.²⁷⁸

In that same year, Kabalka investigated the preparation of arylmagnesium borohydride via the addition of an arylmagnesium bromide to a tetrahydrofuran solution of borane (BH₃:THF).²⁷⁹ Duplicate experiments were performed; in one experiment the Grignard reagent was prepared in the presence of the borane (eq 4), while in another experiment the Grignard was prepared in a separate pot. Analysis of the hydrolyzed product showed that the reaction with the Grignard prepared in situ was identical to the separately prepared Grignard reagent with respect to the yield and purity of the isolated boronic acid.

\[
\text{Ar} \equiv \text{Br} \xrightarrow{\text{Mg}} \text{BH}_3\text{MgBr} \xrightarrow{\text{H}_2\text{O}} \text{Ar} \equiv \text{B(OH)}_2
\]

(4)

¹¹B NMR analysis of the reaction mixture revealed a complex equilibrium where arylmagnesium borohydride readily transfers a hydride to the more Lewis acidic borane molecule. If less than 4 equivalents of BH₃ are used, the monoaryl borohydride is quickly converted to diaryl-, triaryl-, and tetraaryl-boron derivatives establishing a complex equilibrium (Scheme 4.2).
When arylmagnesium bromide was treated with one equivalent of borane, all of the equilibrium products were observed (Scheme 4.2). Kabalka found that an excess of borane was required in order to diminish side products. A four-fold excess of borane yielded arylboronic acid in 60% to 80%, depending on the arylbromide. Interest in the Singaram lab was directed toward the development of a reaction between Grignard reagents and B-H containing compounds which would be atom economical with respect to boron and avoid the complex equilibrium mixtures observed between Grignard reagents and BH₃:THF.

The investigation was begun by studying the reaction of dialkoxyboranes with p-tolylmagnesium bromide (p-tolylMgBr) or phenyllithium while monitoring the reactions by $^{11}$B NMR spectroscopy. Both Grignard reagents and phenyllithium reacted with acyclic dialkoxyboranes, such as diisopropoxyborane, at both 25 °C and
0 °C, to yield a mixture of products resulting from multiple addition of the organometallic reagent to diisopropoxyborane (eq 5).

\[
\begin{align*}
R-\text{MgBr} & \quad + \quad \text{H-B(O-i-Pr)}_2 \quad \xrightarrow{1. \text{ hr}, 25 ^\circ \text{C}, \text{THF}} \quad \text{Ar-B(OH)}_2 + \text{Ar-B(\text{OH})Ar} \\
R = \text{H, M = MgBr} & \quad R = \text{Me, M = Li}
\end{align*}
\]

(5)

It was a delight to find that \( p \)-tolylMgBr reacted readily with the cyclic dialkoxyborane, PinBH, to give exclusively the mono-addition product, as evidenced by TLC and \(^{11}\text{B} \) NMR analysis (eq 6).

\[
\begin{align*}
\text{Ph-MgBr} & \quad + \quad \text{HB(O-i-Pr)O} \quad \xrightarrow{1 \text{ hr}, 25 ^\circ \text{C}} \quad \text{Ph-B(OH)}_2 \\
27.7 \text{ ppm} & \quad (d, J = 173.9) \quad \text{observed by NMR} \\
30.5 \text{ ppm, s}
\end{align*}
\]

(6)

A literature search revealed two analogous reactions between PinBH and triorganylsllyllumolithium reagents (eq 7)\(^{280}\) as well as alkynyllithium reagents (eq 8).\(^{281}\)

\[
\begin{align*}
\text{PhMe}_2\text{SiLi} & \quad + \quad \text{H-B(O-i-Pr)O} \quad \xrightarrow{\text{THF/hexane (1/1), 0 °C-25 °C}} \quad \text{PhMe}_2\text{Si-B(OH)}_2 + \text{LiH} \\
\text{2 equiv.} & \quad 73\%
\end{align*}
\]

(7)

(8)
However, it was found that these reactions cannot be extended to alkyl and aryl lithium reagents. The compatibility of PinBH with phenyllithium in THF was tested in the Singaram lab. Phenyllithium was added to a THF solution of PinBH both at room temperature and at -78 °C, while in a third experiment, the order of addition was reversed in which a PinBH/THF solution was added to phenyllithium at -78 °C. In all cases, multiple addition products were observed including the formation of B₂Pin₂, even at low temperature and with 1.5 equivalents of PinBH (Scheme 4.3).

![Scheme 4.3 Reaction between phenyllithium and pinacolborane](image)

**Scheme 4.3** Reaction between phenyllithium and pinacolborane **A.** T = 25 °C, **B.** T = -78 °C, **C.** T = -78 °C, reverse addition

The arylmagnesium bromide reagents give exclusively a mono-addition product with PinBH, as pinacol arylboronates are sterically demanding enough to prevent multiple additions. Crystal data obtained by Todd Marder of Durham University supports this conclusion. The crystal structure of p-tolylinacolboronate shows the five-membered boron-pinacol ring adopting a twist conformation, and deviating from the CBO₂ plane by an average of 0.23 Å in opposite directions (Figure
It is possible that the chemical space occupied by the four methyl groups is sufficient to hinder the addition of a second Grignard reagent to the aryl-BPin adduct.

Figure 4.2 Crystal structure of \( p \)-tolylpinacolboronate\(^{282} \)

4.4.2 Stability of Pinacolborane

To determine the utility of PinBH as a reagent, a study to determine the stability of PinBH in various solvents was conducted. PinBH was purchased as a neat (97%) liquid from Aldrich. The neat PinBH was analyzed by \( ^{11} \)B NMR and was determined to be, approximately 97% pure with respect to boron as reported by the manufacturer. The reagent was used without further purification. Four oven-dried NMR tubes were flushed with argon and capped with septa. One tube was filled with neat PinBH (0.70 mL), the second tube with anhydrous THF (0.5 mL), the third tube with anhydrous pentane (0.5 mL), and the fourth with anhydrous dichloromethane (DCM) (0.5 mL). To each NMR tube containing solvent, PinBH was added (0.2 mL, 1.77 mmol) to make 2.5 M solutions. The NMR tubes were stored at 25 °C and analyzed daily for 35 days by \( ^{11} \)B NMR spectroscopy. Integration of the PinBH and
B$_2$Pin$_3$ peaks in the $^{11}$B NMR spectra gave an approximate ratio of reaction composition, which was plotted for comparison (Figure 4.3).

![Figure 4.3 Analysis of pinacolborane stability in various solvents, by $^{11}$B NMR spectroscopy](image)

PinBH dissolved in the coordinating solvent of THF degraded by more than 60% in 35 days. PinBH dissolved in pentane degraded 15% over 35 days, and PinBH stored in DCM degraded by 20%. In comparison, PinBH stored neat showed less than 5% degradation after the same period of time. Thus the best conditions for storing PinBH at 25 °C are in either a non-coordinating solvent or neat to avoid disproportionation. The main disproportionation product is 2,2’-(2,3-dimethyl-2,3-butanediyl-oxy)bis(4,4,5,5-trtramethyl-1,3,2-dioxaborolane), or B$_2$Pin$_3$, which reacts with multiple Grignard reagents (eq 9).$^{283,284}$
For the rest of the studies on the reactivity of Grignard reagents with PinBH, commercial pinacolborane (97%) was used. It was stored neat at 15 °C followed by dilution in THF as needed. When refrigerated and stored neat in an Ar-charged ampoule, PinBH was found to be stable for greater than 7 months, as confirmed by $^{11}$B NMR analysis (Figure 4.4).

Figure 4.4 $^{11}$B NMR spectrum of neat pinacolborane stored for 7.5 months
4.4.3 Reaction Characterization.

4.4.3.1 Examination of Reaction Products

*p*-Tolylmagnesium bromide was mixed with a PinBH/THF solution at 25 °C. After 1h of stirring an aliquot of the reaction mixture was analyzed by $^{11}$B NMR spectroscopy, showing essentially quantitative formation of the *p*-tolylpinacolboronate. Under these reaction conditions, the initially formed dialkoxyarylborohydride “ate” complex was not observed, but rapidly disproportionated to the product pinacol boronate and HMgBr (Scheme 4.4).

Scheme 4.4 Synthesis of *p*-tolyl pinacolboronate

Usually dialkoxyalkylborohydride species display a broad singlet in the region of 0 to +10 ppm in the $^{11}$B NMR spectrum. They are also known to transfer hydride to more Lewis acidic di- and trialkylborates. Brown showed that the addition of KHB(O-iPr)$_3$ to 1.0 equivalents of (i-Bu)$_3$B in THF at 25 °C resulted in rapid, quantitative hydride transfer to yield an equimolar mixture of KHB(i-Bu)$_3$ and B(O-iPr)$_3$ (eq 10).
B NMR analysis of the reaction between p-tolylmagnesium bromide and PinBH in an NMR tube or under non-stirred conditions shows that multiple additions afford byproducts such as trialkylborohydride (-9.7 ppm, d, $J = 78$ Hz) and tetraalkylborate (s, -15 ppm) (see Appendix C for $^{11}$B NMR spectroscopy). This is most likely due to localized “hot spots” leading to disproportionation of PinBH and eventually to multiple additions of the Grignard reagent. PinBH is known to disproportionate to bis(pinacolato)diboron ($\text{B}_2\text{Pin}_2$) (Scheme 4.5 A). It is highly probable that the reactivity of $\text{B}_2\text{Pin}_2$ toward Grignard reagents is equivalent to that of other trialkylborates, resulting in the formation of a mixture of products including trialkylborane (Scheme 4.5 B). It was demonstrated by Brown that alkoxyborohydrides transfer hydride to more Lewis acidic boranes. Therefore, the trialkylborane formed under non-stirred conditions could react with the initially formed dialkoxyorganoborohydride to give the corresponding borohydride observed by Dunach (see Appendix B for $^{11}$B NMR analysis) (Scheme 4.5 C).
Consequently, it is important to carry out the reaction of Grignard reagents with PinBH at ambient temperature (0 - 25 °C) with brisk stirring to ensure heat dissipation.

During our investigations of boronic ester synthesis from PinBH and Grignard reagents, Dunach reported a synthesis of benzyl boronates by catalytic reductive coupling between benzyl bromides and PinBH. She reported using 10 mol% of magnesium metal (Mg°) and stoichiometric amounts of triethylamine (Et$_3$N) under refluxing THF for 15 h (eq 11).

She also claimed to observe the initial adduct, dialkoxymonalkylborohydride, at $\delta$ -9.7 ppm (d, $J$ = 86 Hz). However, this chemical shift is very close to the chemical shift range for trialkylborohydride species ($\delta$ -10 to -14 ppm). Our experimental and spectroscopic results are substantially different from those reported.
by Dunach, and indicate a unique pathway for the reaction of Grignard reagents with PinBH in the absence of triethylamine. The reaction reported herein proceeds by a novel elimination of HMgBr from the initially formed borate complex, which disproportionates to MgBr₂ and MgH₂ upon the addition of pentanes. Based on the spectroscopic observations, it is suggested that the ¹¹B NMR data reported by Dunach corresponds to tribenzylborohydride rather than to benzylpinacolborohydride.

As discussed in detail in Chapter 3, two experiments were used to identify and quantify hydridomagnesium halide as a byproduct of the reaction between PinBH and p-tolylmagnesium bromide (eq 12).

\[
\text{HMgBr}$ quantitatively disproportionates to MgBr₂ and MgH₂ when hexanes or pentanes are added to the product mixture of pinacol arylboronate and HMgBr. In the first experiment, the product mixture containing p-tolylpinacolboronate and MgH₂ was added to 1 equivalent of BH₃:THF. The resulting ¹¹B NMR spectrum showed quantitative conversion to bromomagnesium borohydride (eq 13).
Grignard reagents generated from alkyl halides do not produce a precipitate when reacted with PinBH. Rather the HMgCl byproduct is stable and soluble in THF. The molarity of the HMgCl was determined by quenching the reaction with water and measuring the number of moles of hydrogen gas produced. The experimentally measured moles of HMgCl produced in THF/pentane was in 98% agreement with the theoretical value.

\[ \text{Grignard Reagents.} \]

The generality of this reaction was investigated by using commercially available Grignard reagents which have been titrated to confirm their concentration. The pinacolboronic ester, absent of magnesium hydride, was readily isolated by quenching the reaction mixture with hydrochloric acid (1M) followed by diethyl ether extraction. Alternatively, saturated aqueous ammonium chloride can be added followed by extraction with diethyl ether. A wide variety of Grignard reagents could be accommodated in this reaction, affording the expected pure products in high yields (Table 4.2). Aryl Grignard reagents react completely with PinBH within 1 hour at 25 °C (entries 1-6), whereas alkyl Grignard reagents only require 30 minutes (entries 7-10) These products were characterized by \(^{11}\text{B} \) NMR, \(^{1}\text{H} \) NMR and \(^{13}\text{C} \) NMR spectral analyses.
Table 4.2 Synthesis of aryl and alkyl boronates from Grignard reagents

![Reaction scheme]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Product</th>
<th>Yield (%)</th>
<th>Entry</th>
<th>Product</th>
<th>Yield (%)</th>
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<tr>
<td>1</td>
<td>![Bpin]</td>
<td>90</td>
<td>6</td>
<td>![Bpin]</td>
<td>85(^d)</td>
</tr>
<tr>
<td>2</td>
<td>![Bpin]</td>
<td>80(^c)</td>
<td>7</td>
<td>![Bpin]</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>![Bpin]</td>
<td>90</td>
<td>8</td>
<td>![Bpin]</td>
<td>82(^e)</td>
</tr>
<tr>
<td>4</td>
<td>![Bpin]</td>
<td>89</td>
<td>9</td>
<td>![Bpin]</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>![MeO Bpin]</td>
<td>70</td>
<td>10</td>
<td>![Bpin]</td>
<td>99</td>
</tr>
</tbody>
</table>

\(^{a}\)Reagents and conditions: PinBH (4.5 mmol), anhydrous THF (4.0 mL), Grignard reagent (4.5 mmol), argon, 25 °C, 1h. The reaction mixture was acidified with 3M HCl (3mL), then extracted with diethyl ether. The organic layer was dried and the solvent was evaporated under reduced pressure. \(^{b}\)Isolated yield of crude product. \(^{c}\)Ortho-tolylmagnesium chloride starting material. \(^{d}\)Isolated yield after flash column chromatography (hexane/ethyl acetate, 30:1). \(^{e}\)Cyclohexylmagnesium chloride starting material

It should be noted that functional groups cannot be incorporated in this boronic ester preparation, due to an inherent limitation of any synthesis involving Grignard reagents.
With the successful demonstration of compatibility between PinBH and Grignard reagents for boronic ester synthesis, a second cyclic dialkoxyborane, neopentylglycolborane was investigated for similar purposes. Neopentylglycolborane has precedence in the literature as a boron source in various methods of producing arylneopentylglycol boronates, including cross-coupling methods and C-H activation.\textsuperscript{289} Neopentylglycolboronic esters are also compatible with Ni-catalyzed cross-coupling and therefore are of high interest.\textsuperscript{289,290} Neopentylglycolborane is easily synthesized by reacting equal equivalents of neopentylglycol and BMS (Scheme 4.6).\textsuperscript{291} In fact, the neopentylglycolborane has a significant cost advantage over pinacolborane; the corresponding diol neopentylglycol costs $0.02/g compared to $0.60/g for pinacol, a 96% cost reduction.\textsuperscript{292} The neopentylglycolborane, as with pinacolborane synthesized by this method, can be further purified by vacuum distillation. For the synthesis of neopentylglycolborane, 1.1 equivalents of neopentylglycol was reacted with 1.0 equivalent of BMS at 0 °C for 30 minutes, followed by stirring at 25 °C for 90 minutes (Scheme 4.6). The reaction mixture was then characterized by $^{11}$B NMR spectroscopy, where a small amount of unreacted BMS was observed. Without purification of the neopentylglycolborane solution, \textit{m}-tolylmagnesium bromide was added at room temperature and stirred for 1 hour. After acidic quench (3M HCl) \textit{m}-tolyboronic acid neopentylglycol ester was isolated by liquid-liquid extraction in 60% yield (Scheme 4.6).
Scheme 4.6 One pot synthesis of 5,5-dimethyl-2-m-tolyl-1,3,2-dioxaborinane

These results indicate that other dialkoxyboranes may be compatible with this simple and efficient methodology, opening a new avenue towards the cost effective production of arylcyclicboronates.

4.4.5 Syntheses of Aryl and Alkyl Pinacol Boronates using Mg\(^0\) under Barbier-type Conditions.

Under Barbier-type conditions, an array of aryl halides underwent smooth conversion to the corresponding boronates in good to excellent isolated yields. The organic halides were added to a mixture of magnesium turnings and PinBH in THF at 25 °C with a 1.2:1.0:1.0 stoichiometry of reagents (Table 4.3). Entry 6 shows the compatibility of this methodology with the acetal group upon work-up, \(p\)-(4,4,5,5-tetramethyl-1,3,2-dioxaborolanyl)-benzaldehyde dimethyl acetal (entry 6) was isolated in 87% yield. This compound can be deprotected under acidic conditions to yield the \(p\)-(4,4,5,5-tetramethyl-1,3,2-dioxaborolanyl)-benzaldehyde. Also synthesized under these conditions was 4,4,5,5-tetramethyl-2-(1-phenylethyl)-1,3,2-dioxaborolane (entry 9). Entries 10 and 11 highlight the ability of this methodology to form heterocyclic boronates. Also under Barbier conditions, \(\alpha\)-bromostyrene was converted to the corresponding pinacol vinylboronic ester (entry 12).
**Table 4.3** Synthesis of boronates under Barbier conditions

\[ \text{R}−\text{Br} + \text{Mg}^0 + \text{HB}−\text{O} \rightarrow \text{R}−\text{B}−\text{O} \]

\[ \text{THF, } <3\text{ h, } 25^\circ\text{C} \]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Product</th>
<th>Isolated Yield (%)</th>
<th>Entry</th>
<th>Product</th>
<th>Isolated Yield (%)</th>
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<td>65&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>12</td>
<td><img src="image12" alt="Structure" /></td>
<td>80</td>
</tr>
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</table>

<sup>a</sup>Reagents and conditions: Mg° (2.4 mmol), PinBH (2.0 mmol), anhydrous THF (4.0 mL), organohalide (2.0 mmol), argon, 25 °C, 2-3 h. The reaction mixture was acidified with 3M HCl (3mL), and then extracted with diethyl ether. The organic layer was dried and the solvent was evaporated under reduced pressure.  
<sup>b</sup>Yield of crude product.  
<sup>c</sup>Mg° (2 equiv.), PinBH (2 equiv.).  
<sup>d</sup>2 equiv. (1-bromoethyl)benzene.
4.4.6 Synthesis of Allylboronates Under Barbier Conditions

When allylbromide was used under the Barbier conditions described above, \(^{11}\text{B}\) NMR analysis showed that approximately a 1:1 mixture of the corresponding allylboronate and unreacted PinBH was recovered. Additionally, approximately 50\% of the Mg\(^{0}\) remained unreacted, even after extended periods of reaction time. It was suspected that competitive Wurtz coupling was occurring, due to the high reactivity of allylbromide reagents towards homocoupling. However, \(^{1}\text{H}\) NMR analysis of the product mixture showed no Wurtz coupling products or allylbromide starting material. Thus it was speculated that the HMgBr byproduct was reducing the unreacted allylbromide, which would account for the 1:1 mixture of allylboronate and PinBH observed in the \(^{11}\text{B}\) NMR spectra. This problem was circumvented by the addition of a second equivalent of allylbromide. Thus, the synthesis of pinacol allylboronates (PinBAll) requires a stoichiometric amount of magnesium metal and portion-wise addition of two equivalents of allylbromide to achieve excellent yields (Table 4.4).
Table 4.4 Synthesis of allylboronates under Barbier conditions

![Chemical Structure]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Product</th>
<th>Isolated Yield (%)&lt;sup&gt;b&lt;/sup&gt;</th>
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<td>2</td>
<td><img src="structure.png" alt="Bpin" /></td>
<td>90&lt;sup&gt;d&lt;/sup&gt;</td>
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<tr>
<td>3</td>
<td><img src="structure.png" alt="Bpin" /></td>
<td>90&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>4</td>
<td><img src="structure.png" alt="Bpin" /></td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td><img src="structure.png" alt="Bpin" /></td>
<td>95&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Reagents and conditions: Mg° (2.4 mmol), PinBH (2.0 mmol) in anhydrous THF to make 0.5-1.0 M solution, allylhalide (4.0 mmol), argon, 25 °C, 3h. Reaction mixture was acidified with 3M HCl (3mL), then extracted with diethyl ether. The organic layer was dried and the solvent was evaporated under reduced pressure. <sup>b</sup>Yield of crude product. <sup>c</sup>Reaction quenched with benzaldehyde, isolated yield of 1-phenylbut-3-en-1-ol. <sup>d</sup>Used allylchloride as starting halide. <sup>e</sup>An Isomeric mixture of crotyl bromide was used (E/Z ratio = 90:10). <sup>f</sup>Prenylbromide starting material.
The result of entries 3 and 5 confirm the previously reported allyl inversion of substituted allylic substrates subjected to magnesation followed by subsequent reaction with electrophiles such as methylborate (eq 14).293,294,295

\[ \text{E/Z} \quad \begin{array}{c}
1. \text{Mg}^0, \text{Et}_2\text{O} \\
2. \text{B(OMe)}_3 \\
3. \text{HCl} \\
4. \text{nBuOH}
\end{array} \rightarrow \frac{23\%}{44\%} \text{B(OBu)}_2 + \frac{77\%}{\text{B(OBu)}_2} \]

Under the reported Barbier conditions, an isomeric mixture of E and Z crotlyl bromide (90:10) was borylated with PinBH, of which the sole isolated product was 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolane-2-yl)-but-1-ene in 90% yield (Table 4.4, entry 3). It was also observed that 3,3-dimethylallyl bromide (prenyl bromide) reacted under Barbier conditions with PinBH to form the rearranged product in 95% isolated yield (Table 4.4, entry 5). The method reported in this manuscript is one of the best ways to synthesize allyl, methallyl and substituted pinacol allylboronates from magnesium under Barbier conditions at room temperature.

**4.4.7 One Pot Synthesis of Haloarylboronic acids**

The preparation of bifunctionalized benzene is of great interest because this structural unit is found in various drugs and natural products, and is used extensively as building blocks in organic synthesis. A viable route towards bifunctional benzene and arene compounds is successive functionalization of the corresponding dihalo
compounds using metal-halogen exchange. Additionally, dimetalated organic compounds allow for the synthesis of bifunctional substrates efficiently through multiple bond formation in a single step, or stepwise transformation in one pot.\textsuperscript{296,297}

It was demonstrated by Gilman that lithium-bromine exchange of bromosubstituted arylboronic acids does not work, as evidenced by the mixture of products obtained.\textsuperscript{298} It was later shown by Brown that organolithium reagents directly react with boronic acids, forming the corresponding borinic acid.\textsuperscript{299} Later, Knochel observed that iPrMgCl reacted with $p$-iodopinacolboronate did not participate in metal-halogen exchange, but rather added directly to the boron atom of the boronic ester. However, with this new iPrMgCl:LiCl reagent, metal-halogen exchange was observed exclusively at -78 \degree C.\textsuperscript{300} This was the first successful metal-halogen exchange of a halogenated arylboronate. At low temperatures, the Grignard reagent did not react with the boronic ester. It did, however, add to more reactive electrophiles like acetyl chloride and allylbromide (eq 15).

\begin{equation}
\text{THF, -78 \degree C} \quad \text{iPrMgCl:LiCl} \quad \begin{array}{c}
\text{O} \\
\text{O}
\end{array} \\
\text{B} \\
\text{I} \\
\text{O} \\
\text{O}
\mapsto
\begin{array}{c}
\text{O} \\
\text{O}
\end{array} \\
\text{B} \\
\text{MgCl} \\
\text{R} \\
\text{Br}
\end{equation}

The reaction between commercially available aryl dihalides with PinBH and magnesium under Barbier conditions at room temperature was investigated for the synthesis of pinacol chloro-substituted arylboronates. Because of the inherent
difference in reactivity toward magnesium insertion between aryl bromides and chlorides, \(m\)-bromochlorobenzene was chosen for the initial study. The dihalide was added to a THF solution of magnesium turnings and PinBH at 25 °C with 1.0:1.2:1.0 stoichiometry (Table 4.5, entry 2). The reactions progress was monitored by both TLC and \(^{11}\)B NMR spectroscopy.
Table 4.5 Synthesis of arylhaloboronic esters

![Reaction scheme: Mg° + aryldihalide → arylhaloboronic ester](image)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate (R)</th>
<th>Product</th>
<th>Yield(^b)(%)</th>
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<td>Cl&lt;sub&gt;3&lt;/sub&gt;BPin</td>
<td>59</td>
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</table>

\(^a\)Reagents and conditions: Mg\(^\circ\) (2.4 mmol), PinBH (2.0 mmol) in anhydrous THF to make 0.5-1.0 M soln., aryldihalide (2.0 mmol), argon, 25 °C, 3h. The reaction mixture was acidified with 3M HCl (3mL) and extracted with diethyl ether. The organic layer was dried and the solvent was evaporated under reduced pressure. \(^b\)Isolated crude yield.
After isolating the product, TLC and NMR analysis confirmed that the boronic acid was the sole product in moderate to excellent yield. This was a pleasant surprise, and to the best of our knowledge, this constitutes the first example of chlorophenylboronic ester synthesis from Grignard reagents at room temperature. A series of bromochlorobenzene compounds were subjected to magnesation followed by borylation (Table 4.5). In future studies, it is expected that the synthesis of functionalized arylboronates will be realized through functionalization of the aryl halide.

4.5 Conclusion

In summary, a mild, simple, and highly efficient method for synthesizing pinacol boronates utilizing PinBH and commercially available Grignard reagents in THF at 25 °C has been developed. It has also been shown that under Barbier conditions, aryl, vinyl, benzyl, and allylic halides are converted to the corresponding boronic esters in good to excellent yields. Additionally, performing the borylation reaction under Barbier conditions avoids Wurtz coupling by-products as well as allowing the use of a simple one pot procedure for the synthesis of allylboronates from allyl bromides. Boronic ester synthesis by these methods avoids the use of low temperatures and expensive transition metal catalysts. Neopentylglycolborane, another B-H containing cyclic dialkoxylborane, was also a compatible boron source for reaction with Grignard reagents.
It appears that this reaction proceeds through a unique pathway, where hydridomagnesium bromide (HMgBr) is the byproduct. X-ray analysis revealed that the precipitate formed by the addition of hexanes is MgBr₂(THF)₄. DFT calculations indicated that disproportionation of HMgBr to MgH₂ and MgBr₂ is viable in coordinating ethereal solvents. MgH₂ was qualitatively and quantitatively identified as a disproportionation byproduct by trapping it with one equivalent BH₃:THF and by formation of H₂ upon reaction with water.

The method reported herein is one of the best procedures available to quantitatively synthesize allyl, methallyl and substituted pinacol allylboronates without any Wurtz coupling under Barbier condition at room temperature with a 1.2:1 stoichiometry between Mg and PinBH.

4.6 Experimental

General Methods. All reactions were performed in oven-dried, argon-cooled glassware. The pinacolborane was used as received from Aldrich, stored under Ar in a refrigerator held at 15 °C. All Grignard reagents were used as received from Aldrich, they were stored in the bottle received and kept in the refrigerator held at 15 °C. Magnesium metal was used as received from Aldrich. All air and moisture-sensitive compounds were introduced via syringes or cannula through a rubber septum. Pinacolborane was added via syringe, with the dispensed amounts measured by mass difference of the syringe before and after addition. Tetrahydrofuran (THF) was freshly obtained from a solvent purification system (Pure Solv MD, Innovative
Technology inc.). NMR spectra were recorded in CDCl$_3$. Chemical shifts are reported relative to TMS (δ = 0) for $^1$H NMR (500 MHz) and are referred to the CDCl$_3$ resonance (δ = 77) for $^{13}$C NMR (125 MHz) spectra. Data are reported as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, br = broad, m = multiplet, app = apparent), coupling constant and integration. Boron NMR samples were recorded at 160.4 MHz and are reported relative to external standard BF$_3$:Et$_2$O (δ = 0).

**General Procedure for the Preparation of B-aryl and B-alkyl-pinacol boronates from preformed Grignard reagents.**

The following procedure for the preparation of 4,4,5,5-tetramethyl-2-$m$-tolyl-1,3,2-dioxaborolane is representative. A 25-mL round-bottom flask equipped with a magnetic stir bar and fitted with rubber septum was charged with anhydrous THF (4.0 mL) followed by pinacolborane (0.57g, 4.5 mmol). $m$-Tolylmagnesium bromide (4.5 mmol, 1M/THF) was added dropwise over 5 min at 25 °C with constant stirring. The reaction was complete after 1 h as evidenced by the disappearance of pinacolborane starting material (δ $+27.7$, d, $J$=173.9 Hz), and the appearance of a singlet at $+30.5$ ppm via $^{11}$B NMR. The reaction was then cooled to 0 °C (ice bath) and acidified with 3M aqueous HCl (3mL) (CAUTION: hydrogen evolution). After 10 min of stirring the reaction mixture was warmed to 25 °C and stirred for an additional 30 min. The reaction mixture was then transferred to a separatory funnel and extracted with diethyl ether (3 x 15 mL). The combined organic layers were
dried over anhydrous MgSO₄, filtered, and dried under vacuo (25 °C, 1 Torr) to afford 4,4,5,5-tetramethyl-2-m-tolyl-1,3,2-dioxaborolane as a pale yellow oil. The results for the other pinacolborane esters prepared by this method are summarized in Table 1. For copies of the ¹H, ¹³C and ¹¹B NMR spectrum see Appendix B.

4,4,5,5-tetramethyl-2-phenyl-1,3,2-dioxaborolane (Table 1, entry 4.4);³⁰¹
Colorless oil; 96% yield (0.598 g). ¹H NMR (500 MHz, CDCl₃) δ 1.36 (s, 12H), 7.38 (m, 2H), 7.47 (m, 1H), 7.83 (d, J = 7.2 Hz, 2H); ¹³C NMR (125.7 MHz, CDCl₃): δ 25.0, 83.8, 127.9, 131.4, 134.9; ¹¹B NMR (160.4 MHz, CDCl₃): δ +30.8 (s).

4,4,5,5-tetramethyl-2-o-tolyl-1,3,2-dioxaborolane (Table 4.4, entry 2);²¹
Colorless oil; 80% yield (0.865 g). ¹H NMR (500 MHz, CDCl₃): δ 1.43 (s, 12H), 2.65 (s, 3H), 7.24-7.26 (m, 2H), 7.41 (t, J = 8, 1H), 7.89 (d, J = 7, 1H). ¹³C NMR (125.7 MHz, CDCl₃): δ 22.5, 25.1, 83.6, 125.1, 130.1, 131.1, 136.4, 145.1; ¹¹B NMR (160.4 MHz, CDCl₃): δ +32.0 (s).

4,4,5,5-tetramethyl-2-m-tolyl-1,3,2-dioxaborolane (Table 4.4, entry 3);²⁶
Colorless oil; 78% yield (0.855 g). ¹H NMR (500 MHz, CDCl₃): δ 1.36 (s, 12H), 2.37 (s, 3H), 7.28-7.29 (m, 2H), 7.62-7.63 (m, 1H), 7.65 (s, 1H). ¹³C NMR (125.7 MHz, CDCl₃): δ 25.0, 83.8, 127.9, 131.4, 134.9; ¹¹B NMR (160.4 MHz, CDCl₃): δ +30.8 (s).
MHz, CDCl$_3$): $\delta$ 21.3, 24.9, 83.8, 124.4, 127.8, 131.9, 132.2, 135.5, 137.3. $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +30.3 (s).

4,4,5,5-tetramethyl-2-p-tolyl-1,3,2-dioxaborolane (Table 4.4, entry 4);$^{21}$ Colorless/yellow oil; 89% yield (0.579 g). $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 1.46 (s, 12H), 2.48 (s, 3H), 7.32 (d, $J = 2.4$, 2H), 7.89 (d, $J = 2.6$ Hz, 2H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 21.8, 25.0, 83.7, 128.7, 128.8, 135.1, 141.5; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +31.6 (s).  

2-(4-methoxyphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.4, entry 5);$^{21}$ Colorless oil; 70% yield (0.804 g). $^1$H NMR (500 MHz, CDCl$_3$): 1.35 (s, 12H), 3.84 (s, 3H), 6.91 (d, $J = 8.5$ Hz, 2H), 7.77 (d, $J = 8.5$ Hz, 2H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 25.0, 55.2, 83.7, 113.5, 136.7, 160.2; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +29.6 (s).  

4,4,5,5-tetramethyl-2-(phenanthren-1-yl)-1,3,2-dioxaborolane (Table 4.4, entry 6);$^{302}$ Colorless oil; 85% isolated yield after flash column chromatography (hexane/ethyl acetate, 30:1) (1.16 g). $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 1.47 (s, 12H),
7.60 (app dt, $J = 1.5$, 8 Hz, 1H), 7.64-7.66 (m, 2H), 7.68-7.72 (m, 1H), 7.95 (d, $J = 8$
Hz, 1H), 8.40 (s, 1H), 8.59 (d, $J = 8$ Hz, 1H), 8.71-8.73 (m, 1H), 8.84-8.86 (m, 1H);
$^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 25.1, 84.0, 122.6, 122.7, 126.3, 126.6, 126.8, 127.9,
128.7, 129.3, 129.5, 130.0, 131.2, 132.0, 134.5, 138.3; $^{11}$B NMR (160.4 MHz,
CDCl$_3$): δ +32.5 (s).

2-hexyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.4, entry 7);\textsuperscript{41}
Colorless oil; 90% yield (0.941 g). $^1$H NMR (500 MHz, CDCl$_3$): δ 0.78 (t, $J = 6.5$
Hz, 2H), 0.89 (t, $J = 5.0$ Hz, 3H), 1.26 (s, 12H), 1.22-1.32 (m, 18H); $^{13}$C NMR (125.7
MHz, CDCl$_3$): δ 14.1, 22.6, 23.9, 24.8, 31.6, 32.1, 82.9; $^{11}$B NMR (160.4 MHz,
CDCl$_3$): δ +32.8 (s).

2-cyclohexyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.4, entry 8);\textsuperscript{303}
Colorless oil; 82% yield (0.856 g). $^1$H NMR (600 MHz, CDCl$_3$): δ 0.93-1.00(m, 1H),
1.23 (s, 12H), 1.26-1.40 (m, 4H), 1.54-1.70 (m, 6H); $^{13}$C NMR (125.7 MHz, CDCl$_3$):
δ 24.4, 26.5, 26.8, 27.7, 82.4; $^{11}$B NMR (160.4 MHz, CDCl$_3$): δ +33.8 (s).

2-tert-butyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.4, entry 9);\textsuperscript{27}
Colorless oil; 65% yield (0.598 g). $^1$H NMR (500 MHz, CDCl$_3$): δ 0.94 (s, 9H), 1.23
(s, 12H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 24.6, 26.9, 82.8; $^{11}$B NMR (160.4 MHz, CDCl$_3$): δ +34.6 (s).

$^{4,4,5,5}$-tetramethyl-2-(pentan-3-yl)-1,3,2-dioxaborolane (Table 4.4, entry 10); Colorless oil; 98% yield (0.991 g). $^1$H NMR (500 MHz, CDCl$_3$): δ 0.89 (t, $J$=7.8 Hz, 6H), 0.94 (t, $J$=7.2, 1H), 1.24 (s, 12H), 1.41 (m, 4H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 13.4, 23.8, 24.6, 82.6; $^{11}$B NMR (160.4 MHz, CDCl$_3$): δ +34.2 (s).

**Synthesis and Reaction of Neopentylglycolborane with $m$-Tolylmagnesium Bromide.**

A solution of neopentylglycol (17.8 mmol, 1.85g, 1.2 equiv) in dry THF (10 mL) was stirred and cooled to 0 °C. A solution of BH$_3$:SMe$_2$ (15 mmol, 10M in methyl sulfide) was added dropwise via syringe under argon. After 30 min of stirring at 0 °C, the reaction mixture was warmed to 25 °C and stirring was continued until no further evolution of hydrogen was observed (ca. 90 min). The solution was distilled under reduced pressure to isolate pure neopentylglycolborane as a clear oil.$^{23}$ $m$-tolylmagnesium bromide (10 mmol, 1M) was added dropwise at 25 °C with constant stirring. The reaction was complete after 1 h as evidenced by the disappearance of the neopentylglycolborane starting material (δ +26.9, d, $J$=176.0 Hz), and the appearance of a singlet at +28.0 ppm via $^{11}$B-NMR analysis. The reaction was then cooled to 0 °C (ice bath) and acidified with 3M aqueous HCl (3mL) (CAUTION: hydrogen evolution). After 10 min of stirring the reaction mixture was warmed to 25
°C and stirred for an additional 30 min. The reaction mixture was then transferred to a separatory funnel and extracted with diethyl ether (3 x 15 mL). The combined organic layers were dried over anhydrous MgSO₄, filtered, and dried under vacuo (25 °C, 1 Torr) to afford 5,5-dimethyl-2-m-tolyl-1,3,2-dioxaborinane as a pale yellow oil.

![Chemical Structure](image)

**5,5-dimethyl-2-m-tolyl-1,3,2-dioxaborinane**: Colorless oil; 60% yield based on m-tolylmagnesium bromide (0.612 g). ¹H NMR (500 MHz, CDCl₃): δ 1.03 (s, 6H), 2.37 (s, 3H), 3.78 (s, 4H), 7.277-7.289 (m, 2H), 7.616-7.630 (m, 1H), 7.649 (s, 1H).

¹³C NMR (125.7 MHz, CDCl₃): δ 21.9, 72.4, 127.7, 131.0, 131.6, 134.6, 137.3. ¹¹B NMR (160.4 MHz, CDCl₃): δ +28.0 (s).

**General Procedure for the Preparation of B-aryl and B-alkyl-pinacolboronic Esters Under Barbier-type Conditions.**

The following procedure for the preparation m-tolyl pinacolborane is representative. A 25-mL round-bottom flask equipped with a magnetic stir bar was charged with magnesium turnings (0.058 g, 2.4 mmol) and was activated by the addition of iodine crystals and warming until iodine sublimed. The flask was cooled to 25 °C and was purged with Ar. THF (3.5 mL) was added to the flask, followed by the addition of neat pinacolborane (0.29 mL, 2.0 mmol). m-tolyl bromide (0.243 mL, 2.0 mmol) was then added dropwise over five minutes with constant stirring at 25 °C.
The reaction was complete after 3 h as evidenced by the disappearance of pinacolborane starting material ($\delta +27.7$, d, $J=173.9$ Hz), and the appearance of a singlet at +30.6 ppm via $^{11}$B-NMR. The reaction was then cooled to 0 °C (ice bath) and acidified with 3M aqueous HCl (3mL) (CAUTION: hydrogen evolution). After 10 min of stirring the reaction mixture was warmed to 25 °C and stirred for an additional 30 min. Table entries 4, 6, 7, 8 were quenched with aqueous NH$_4$Cl (2.5mL, 0.16M). The reaction mixture was then transferred to a separatory funnel and extracted with diethyl ether (3 x 15 mL). The combined organic layers were dried over anhydrous MgSO$_4$, filtered, and dried under vacuo (25 °C, 1 Torr) to afford $m$-tolyl pinacolborane as a pale yellow oil. The results for the other pinacolborane esters prepared by this method are summarized in Table 2. For copies of the $^1$H, $^{13}$C and $^{11}$B NMR spectrum see Appendix B.

2-(4-ethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.5, entry 1)$^{304}$ Clear oil; 99% yield (0.483g). $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 1.24 (t, $J = 6$ Hz, 3H), 1.34 (s, 12H), 2.67 (q, $J = 7.5$ Hz, 2H) 7.23 (d, $J = 8$ Hz, 1H), 7.75 (d, $J = 8$ Hz, 1H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 15.4, 24.8, 29.1, 83.7, 127.4, 135.0; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta +30.8$ (s).
4,4,5,5-tetramethyl-2-\(m\)-tolyl-1,3,2-dioxaborolane (Table 4.5, entry 2);\(^{26}\) Clear oil; 99% yield (0.436 g). \(^1\)H NMR (500 MHz, CDCl\(_3\)): \(\delta\) 1.36 (s, 12H), 2.37 (s, 3H), 7.26-7.29 (m, 2H), 7.63 (t, 1H), 7.65 (s, 1H), 7.54 (m, 1H); \(^{13}\)C NMR (125.7 MHz, CDCl\(_3\)): \(\delta\) 21.3, 24.9, 83.7, 127.8, 131.9, 132.0, 132.2, 135.5, 137.2; \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): \(\delta\) +30.6 (s).

4,4,5,5-tetramethyl-2-(pyren-2-yl)-1,3,2-dioxaborolane (Table 4.5, entry 3);\(^{34}\) Deep red oil; 78% yield (0.511 g). \(^1\)H NMR (500 MHz, CDCl\(_3\)): \(\delta\) 1.51 (s, 12H), 8.12 (m, 7H), 8.57 (d, \(J = 7.5\) Hz, 1H), 9.11 (d, \(J = 9.5\) Hz, 1H); \(^{13}\)C NMR (125.7 MHz, CDCl\(_3\)): \(\delta\) 25.1, 84.0, 124.2, 125.0, 125.3, 125.4, 125.8, 125.9, 127.5, 127.6, 127.9, 128.2, 128.6, 130.9, 131.3, 133.6, 134.0, 136.6; \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): \(\delta\) +22.50 (s), +31.9 (s).

2-(biphenyl-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.5, entry 4);\(^{305}\) Clear oil; 88% yield (0.351 g). \(^1\)H NMR (500 MHz, CDCl\(_3\)): \(\delta\) 1.24 (s, 12H), 7.35-7.49 (m, 8H); 7.76 (d, \(J = 7.5\) Hz, 1H) \(^{13}\)C NMR (125.7 MHz, CDCl\(_3\)): \(\delta\) 24.6, 83.8, 126.4, 126.9, 127.9, 129.1, 129.3, 130.2, 134.6, 143.4, 147.7; \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): \(\delta\) +30.7 (s).
2-(4-methoxy-2-methylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.5, entry 5); Clear oil; 97% yield (0.483g). $^1$H NMR (500 MHz, CDCl$_3$): δ 1.29 (s, 12H), 2.56 (s, 3H), 3.82 (s, 3H), 6.74 (m, 2H), 7.77 (d, $J = 7$ Hz, 1H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 22.4, 24.9, 54.9, 83.1, 110.1, 115.5, 137.8; $^{11}$B NMR (160.4 MHz, CDCl$_3$): δ +30.7 (s).

2-(4-(dimethoxymethyl)phenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.5, entry 6). Clear oil; 81% yield (0.450g). $^1$H NMR (500 MHz, CDCl$_3$): δ 1.29 (s, 12H), 3.35 (s, 6H), 5.38 (s, 1H), 7.41 (d, $J = 7.5$ Hz, 2H), 7.78 (d, $J = 8.5$ Hz, 2H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 24.7, 24.8, 52.4, 52.6, 83.8, 102.8, 10.1, 126.1, 134.7, 141.0; $^{11}$B NMR (160.4 MHz, CDCl$_3$): δ +30.4 (s).

4,4,5,5-tetramethyl-2-octyl-1,3,2-dioxaborolane (Table 4.5, entry 7); Clear oil; 86% yield (0.411g). $^1$H NMR (500 MHz, CDCl$_3$): δ 0.76 (t, $J = 7.5$ Hz, 2H), 0.86 (t, $J = 7$ Hz, 3H), 1.23 (s, 12H), 1.25 (s, 8H), 1.38 (m, 4H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 14.1, 22.7, 24.0, 24.8, 29.2, 29.4, 31.9, 32.4, 82.5; $^{11}$B NMR (160.4 MHz, CDCl$_3$): δ +33.7(s).

1,4-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (Table 4.5, entry 8); 2.2 eq of Mg$^0$ and 2.5 eq PinBH were used. Clear oil; 61% yield (0.404g). $^1$H NMR (500 MHz, CDCl$_3$): δ 1.34 (s, 24H), 7.81 (s, 4H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 24.9, 134.0; $^{11}$B NMR (160.4 MHz, CDCl$_3$): δ +30.7(s).
4,4,5,5-tetramethyl-2-(1-phenylethyl)-1,3,2-dioxaborolane (Table 4.5, entry 9); Clear oil; 75% yield (0.351g). $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 1.25 (s, 6H), 1.275 (s, 6H), 1.40 (d, $J = 7.5$ Hz, 3H), 2.50 (q, $J = 7.5$ Hz, 1H), 7.30 (m, 5H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 17.1, 24.6, 47.5, 83.3, 125.1, 127.8, 128.3, 144.9; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +33.2 (s).

4,4,5,5-tetramethyl-2-(thiophen-2-yl)-1,3,2-dioxaborolane (Table 4.5, entry 10);$^{21}$ White solid; 92 % yield (0.193g). $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 1.36 (s, 12H), 7.21-7.19 (m, 1H), 7.27 (d, $J = 4.5$ Hz, 1H), 7.64-7.67 (m, 1H); $\delta$ $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 24.7, 84.1, 128.3, 132.5, 137.3; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +29.4 (s).

2-(5-chlorothiophen-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.5, entry 11);$^{308}$ Clear oil; 75% yield (0.360g). IR (Nujol) 1019, 1056, 1146, 1211, 1302, 1377, 1463, 1522 cm$^{-1}$; $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 1.34 (s, 12H), 6.98 (d, $J = 3.5$ Hz, 1H), 7.41 (d, $J = 4$ Hz, 1H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 24.7, 84.3, 127.7, 136.9; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +28.1(s).
4,4,5,5-tetramethyl-2-(1-phenylvinyl)-1,3,2-dioxaborolane (Table 4.5, entry 12); Clear oil; 75% yield (0.352 g). $^1$H NMR (500 MHz, CDCl$_3$): $\delta$ 1.35 (s, 12H), 6.0 (d, $J = 0.9$ Hz, 1H), 6.11 (d, $J = 0.8$ Hz, 1H), 7.27 (dt, $J = 1.5$, 5.5 Hz, 1H), 7.34 (dt, $J = 2$, 5.5 Hz, 1H), 7.516 (m, 1H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 24.8, 83.9, 127.1, 127.3, 128.3, 131.0, 141.5; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta +29.9$(s).

**General Procedure for the Preparation of B-allylpinacolboronate and Subsequent Reaction with Benzaldehyde.**

The following procedure for the preparation of B-allylpinacol boronate is representative. A 25-mL round-bottom flask equipped with a magnetic stir bar was charged with magnesium turnings (0.04 g, 1.65 mmol) and fitted with a rubber septum. The flask was purged with Ar and charged with dry THF (2.3 mL) followed by PinBH (0.199 mL, 1.37 mmol). To the reaction mixture allylbromide (0.116 mL, 1.37 mmol) was added dropwise with constant stirring over five minutes at 25 °C. After stirring for 30 min at 25 °C, a second equivalent of allylbromide (0.116 mL, 1.37 mmol) was added. After 90 min of stirring at 25 °C the magnesium turnings were fully consumed and $^{11}$B NMR analysis confirmed the complete formation of allylpinacolboronate. The reaction was then diluted with hexanes (5 mL) and quenched with aqueous 0.1M HCl (10 mL) (CAUTION: hydrogen evolution). After 10 min of stirring the reaction mixture was transferred to a separatory funnel and extracted with hexanes (3 x 15 mL). The combined organic layers were dried over anhydrous MgSO$_4$, filtered, and dried under vacuo (25 °C, 1 Torr) to afford 2-allyl-
4,4,5,5-tetramethyl-1,3,2-dioxaborolane as a clear oil. The results for the other substituted B-allylpinacolboronic esters prepared by this method are summarized in Table 3. For copies of the $^1$H, $^{13}$C and $^{11}$B NMR spectrum see Appendix B.

2-allyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.6, entry 1 & 2); $^{310}$

Clear oil; 90% yield (0.207 g). $^1$H NMR (500 MHz, CDCl$_3$): δ 1.25 (s, 12H), 1.72 (d, $J = 6.5$ Hz, 2H), 4.93 (d, $J = 10$ Hz, 1H), 5.0 (d, $J = 17$ Hz, 1H), 5.83-5.89 (m, 1H); $^{11}$B NMR (160.4 Hz, CDCl$_3$): δ +33.0(s).

3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolane-2-yl)-but-1-ene (Table 4.6, entry 3); $^{311,312}$ Isomeric mixture of crotyl bromide used was (E/Z ratio = 90:10). Clear oil; 90% yield (0.224 g). $^1$H NMR (500 MHz, CDCl$_3$): δ 1.09 (d, $J = 7.5$ Hz, 3H), 1.23 (s, 12H), 1.89 (quint, $J = 7.5$ Hz, 1H), 4.92 (app dt, $J = 10$ Hz, 2H), 4.97 (app dt, $J = 17.5$ Hz, 2H), 5.90-5.97 (m, 1H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): δ 14.1, 24.6, 25.5, 83.2, 112.0, 141.0; $^{11}$B NMR (160.4 MHz, CDCl$_3$): δ +33.1 (s).
4,4,5,5-tetramethyl-2-(2-methylallyl)-1,3,2-dioxaborolane (Table 4.6, entry 4);\textsuperscript{313} Clear/light yellow oil; 90% yield (0.222). \textsuperscript{1}H NMR (500 MHz, CDCl\textsubscript{3}): \(\delta\) 1.25 (s, 12H), 1.72 (s, 2H), 1.77 (s, 3H), 4.66-4.69 (m, 2H); \textsuperscript{13}C NMR (125.7 MHz, CDCl\textsubscript{3}): \(\delta\) 24.4, 24.7, 83.3, 110.2, 142.9; \textsuperscript{11}B NMR (160.4 MHz, CDCl\textsubscript{3}): \(\delta\) +33.1 (s).

\begin{center}
\begin{tikzpicture}
\draw[thick, color=black] (0,0) -- (0.5,0.5) -- (1,0) -- (0.5,-0.5) -- cycle;
\draw[thick, color=black] (0.5,0.5) -- (1,1.5) -- (1.5,1) -- (1,0) -- cycle;
\end{tikzpicture}
\end{center}

3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolane-2-yl)-3-methylbut-1-ene (Table 4.6, entry 5),\textsuperscript{60} starting halide: 1-bromo-3-methylbut-2-ene. Clear oil; 95% yield (0.242 g). \textsuperscript{1}H NMR (500 MHz, CDCl\textsubscript{3}): \(\delta\) 1.07 (s, 6H), 1.22 (s, 12H), 4.90 (dd, \(J = 0.5, 0.5\) Hz, 1H), 4.93 (dd, \(J = 0.3, 0.6\) Hz, 1H), 5.96 (dd, \(J = 5.7, 3.3\) Hz, 1H); \textsuperscript{13}C NMR (125.7 MHz, CDCl\textsubscript{3}): \(\delta\) 23.4, 24.5, 83.2, 110.0, 146.7; \textsuperscript{11}B NMR (160.4 MHz, CDCl\textsubscript{3}): \(\delta\) +33.9 (s).

\begin{center}
\begin{tikzpicture}
\draw[thick, color=black] (0,0) -- (0.5,0.5) -- (1,0) -- (0.5,-0.5) -- cycle;
\draw[thick, color=black] (0.5,0.5) -- (1,1.5) -- (1.5,1) -- (1,0) -- cycle;
\end{tikzpicture}
\end{center}

1-Phenyl-3-buten-1-ol (Table 3, entry 1);\textsuperscript{314} Alternative to the aqueous quench, benzaldehyde (0.138 mL, 1.37 mmol) was then added and the reaction mixture was stirred for an additional 12h at 25 °C. The reaction mixture was then diluted with hexane (5 mL), quenched with aqueous 1M HCl (5 mL), and transferred to a separatory funnel. The organic layer was washed with aqueous 1M NaOH (2 x 5 mL) and DI water (2 x 3 mL). The combined organic layers were dried over anhydrous
MgSO₄, filtered, and dried under vacuo (25 °C, 1 Torr) to afford 1-phenyl-3-butene-1-ol as a clear/light yellow oil; 94% yield (0.190 g). ¹H NMR (500 MHz, CDCl₃): δ 2.50-2.57 (m, 2H), 4.75 (dd, J = 5, 7.5 Hz, 1H), 5.15-5.20 (m, 2H), 5.79-5.87 (m, 1H), 7.28-7.38 (m, 5H); ¹³C NMR (125.7 MHz, CDCl₃): δ 43.9, 73.3, 118.5, 125.9, 127.6, 128.5, 134.6, 144.0.

General Procedure for the Preparation of Haloarylboronic Esters From Aryldihalides.

The following procedure for the preparation of m-chloropinacolborane is representative. A 10-mL round-bottom flask equipped with a magnetic stir bar and magnesium turnings (0.05g, 2.0 mmol) and fitted with a rubber septum. The flask was purged with argon and charged with dry THF (3.5 mL) followed by PinBH (0.295 mL, 2.0 mmol). To the reaction mixture m-Bromochloromagnesium bromide (0.38g, 2.0 mmol) was added dropwise with constant stirring over 15 minutes at 25 °C. Solid substrates were added to an oven dried and argon purged scintillation vial and diluted with anhydrous THF (3.5 mL). The reaction was complete after 2 h as evidenced by the disappearance of PinBH starting material (δ +27.7, d, J=173.9 Hz), and the appearance of a singlet at +30.5 ppm via ¹¹B-NMR. The reaction was then acidified with 1.0 M aqueous HCl (3 mL) and stirred for 10 min. (CAUTION: hydrogen evolution). The reaction mixture was then transferred to a separatory funnel and extracted with diethyl ether (3 × 15 mL). The combined organic layers were washed with NaOH (1×15 mL 0.1 M) followed by brine (1×15 mL), dried over
anhydrous MgSO$_4$, filtered, and dried under vacuo (25 °C, 1 Torr) to afford $m$-chloro pinacolborane as a colorless oil. The results for the other pinacolborane esters prepared by this method are summarized in Table 4.7. For copies of the $^1$H, $^{13}$C and $^{11}$B NMR spectrum see Appendix C.

\[ \text{Cl} \begin{array}{c} \text{B} \\ \text{O} \end{array} \]

$m$-Chlorobenzene pinacolester (Table 4.5, entry 1); Colorless oil; 73% yield (0.174 g). $^{315}$ $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 1.36 (s, 12H), 7.33 (t, $J$ = 7.5 Hz, 1H), 7.44 (d, $J$ = 8 Hz, 1H), 7.69 (d, $J$ = 7.5 Hz, 1H), 7.80 (s, 1H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 24.8, 84.1, 129.2, 131.3, 132.7, 134.6; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +31.4 (s).

\[ \text{Cl} \begin{array}{c} \text{B} \\ \text{O} \end{array} \]

$p$-Chlorobenzene pinacolester (Table 4.5, entry 2); Colorless oil; 87% yield (0.381 g). $^{315}$ $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 1.35 (s, 12H), 7.37 (t, $J$ = 8.5 Hz, 2H), 7.76 (d, $J$ = 8 Hz, 2H); $^{13}$C NMR (125.7 MHz, CDCl$_3$): $\delta$ 24.8, 84.0, 128.0, 128.3, 136.2, 137.6; $^{11}$B NMR (160.4 MHz, CDCl$_3$): $\delta$ +31.4 (s).

\[ \text{Cl} \begin{array}{c} \text{B} \\ \text{O} \end{array} \]

3,4-Dichlorobenzene pinacolester (Table 4.5, entry 3); Yellow oil; 89% yield (0.136 g). $^{315}$ $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 1.35 (s, 12H), 7.47 (d, $J$ = 8 Hz, 1H),
7.63 (dd, \( J = 1 \) Hz, 8 Hz 1H), 7.88 (d, \( J = 8 \) Hz, 1H); \(^{13}\)C NMR (125.7 MHz, CDCl\(_3\)): \( \delta \) 24.9, 84.5, 130.2, 130.3, 133.9, 136.7; \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): \( \delta \) +31.2 (s).

\begin{center}
\includegraphics[width=0.5\textwidth]{structure.png}
\end{center}

**3,5-Dichlorobenzene pinacolester (Table 4.5, entry 4);** Yellow oil; 94% yield (0.511 g).\(^{316}\) \(^1\)H NMR (500 MHz, CDCl\(_3\)) \( \delta \) 1.35 (s, 12H), 7.44 (t, 1H), 7.63 (d, \( J = 2 \) Hz, 2H); \(^{13}\)C NMR (125.7 MHz, CDCl\(_3\)): \( \delta \) 24.8, 84.6, 131.2, 132.8, 134.9; \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): \( \delta \) +30.8 (s).

\begin{center}
\includegraphics[width=0.5\textwidth]{structure.png}
\end{center}

**p-Bromobenzene pinacolester (Table 4.5, entry 5);** Colorless oil; 78% yield (0.224 g).\(^{315}\) \(^1\)H NMR (500 MHz, CDCl\(_3\)) \( \delta \) 1.36 (s, 12H), 7.51 (d, \( J = 8 \) Hz, 2H), 7.66 (d, \( J = 8 \) Hz, 2H); \(^{13}\)C NMR (125.7 MHz, CDCl\(_3\)): \( \delta \) 24.8, 84.1, 129.2, 131.3, 132.7, 134.5; \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): \( \delta \) +31.4 (s). \(^{11}\)B NMR (160.4 MHz, CDCl\(_3\)): \( \delta \) +31.4 (s).
4.7 References


270 Diborane, B₂H₆, MSDS reference: 040, chemical abstracts 19287-45-7, UN no. 1911.


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APPENDIX A

Spectra for compounds and reactions in chapter 2
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$J = 98$ Hz
Equation 16; $^{11}$B NMR of Chloromagnesium dimethylaminoborohydride
Table 2.3, entry 1
Table 2.3, entry 2

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Entry & Reaction & Yield & Notes \\
\hline
2 & 1 & 0.65 & Fresh \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{Diagram of reaction conditions.}
\end{figure}
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Table 2.3, entry 5
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Scheme 2.6, 13
Scheme 2.6, 13
Scheme 2.6, 14
Scheme 2.6, 14
Scheme 2.6, 14
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$^1$B NMR
Table 2.5, entry 1
Table 2.5, entry 1
Table 2.5, entry 1
Table 2.5, entry 2
Table 2.5, entry 2
Table 2.5, entry 3
Table 2.5, entry 3
Table 2.5, entry 3
Table 2.5, entry 4

\[ \text{B(OH)}_2 \]
Table 2.5, entry 4
Table 2.5, entry 5
Table 2.5, entry 5
Table 2.5, entry 6
Table 2.5, entry 6
Table 2.5, entry 7
Table 2.5, entry 7

Decaboronic acid
13C NMR 125.7 MHz CDCl3
Pulse Sequence: sput
Table 2.6, entry 1

\[
\text{HO-B} \quad \text{HO}
\]

30.718
Table 2.6, entry 1
Table 2.6, entry 1

B(OH)$_2$
Table 2.6, entry 2

Table 2.6, entry 2
Table 2.6, entry 2
Table 2.6, entry 3
Table 2.6, entry 3

Table 1, entry 12

S B
OH
OH
Table 2.6, entry 3

Table 1, entry 12
S B
OH OH
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APPENDIX B

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Computational Methods

All calculations were performed using DFT calculations (Gaussian09) at the B3LYP/6-31G(d) level of theory with the PCM polarized continuum solvent model (solvent=THF) for geometry optimization and final energy. Energies are not corrected for zero vibration point energy.

Figure 1. The μHBr bridged HMgBr dimer is the key intermediate in the Schlenk equilibrium.

Schlenk Equilibrium. The chemical species in the Schlenk equilibrium (Figure 2) were optimized to a stable point with tight optimization. The energies obtained are presented in Table 4 in Hartrees and relative to the sum of the component molecules (kcal/mol). Of the three μ-bridged dimers, the H-H dimer is lowest in energy (−21.44 kcal/mol), the Br-Br dimer has the highest energy (−18.92 kcal/mol), and the key H-Br dimer that leads to products has an intermediate energy.
We searched for transition states along each reaction pathway. Plausible reaction trajectories were generated by driving the length of a \( \mu \)-bridge bond and by increasing the Mg-Mg interatomic distance. The transition states were located using Gaussian's "opt=TS" search. Formation of each \( \mu \)-bridged dimer from two HMgBr monomers apparently occurs without a transition state, but interconversion between \( \mu \)-bridged dimers does exhibit a transition state. The reaction path involves breaking one bridge bond and pivoting around the remaining bridging atom to bridge to the previously non-bridging atom. These transition states are labeled TS1 and TS2 in Figure 3 showing a schematic reaction coordinate state diagram for the equilibrium, and their geometry is presented in Figure 4.

**Figure 2.** Schematic reaction coordinate state diagram for the Schlenk equilibrium. Energies are in kcal/mol relative to 2HMgBr.
Figure 3. Computed geometries of chemical species in Schlenk equilibrium. Distances along bonds are in Ångströms, angles in degrees. TS1 and TS2 are transition states.

Transition state TS1 has a single H-bridge, whereas TS2 has a single Br-bridge, with energies of $-11.40$ and $-7.72$ kcal/mol, respectively. We note that the trend observed with the μ-bridged dimers, namely that H-H is lower energy than Br-Br, is also observed for the transition states. The structure with an H-bridge is lower energy than that with a Br-bridge.

Table 1. Total Molecular Energies (a.u.) and Relative Energies (kcal/mol).

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Dimethyl ether (DME) -155.027340
HBrMgHgMgBr TS1 -5545.009713 -11.40
HBrMgHgMgBr TS2 -5545.003845 -7.72
μHH (HgMgBr)2 -5545.025703 -21.44
μHBr (HgMgBr)2 -5545.024975 -20.98
μBrBr (HgMgBr)2 -5545.021693 -18.92
Trig HgMgBr-DME -2927.547419 -15.25
Tet HgMgBr-DME2 -3082.596199 -28.71
Tbp HgMgBr-DME3 -3237.635000 -35.90
Oct HgMgBr-DME4 -3392.667714 -39.27
Oct MgBr2-DME4 -5963.899731 -51.80
Oct MgH2-DME4 -821.436515 -29.56
μHBr (HgMgBr-DME)2 -5855.131762 -53.68
μHBr (HgMgBr-DME2)2 -6165.202940 -64.03
μHH (HgMgBr-DME3)2 -6475.281648 -79.10
μHBr (HgMgBr-DME3)2 -6475.280028 -78.09
μBrBr (HgMgBr-DME3)2 -6475.275963 -75.54

*Relative to sum of components, e.g., TS1 is relative to 2HgMgBr.

Potential Energy Surfaces. An overview of the potential energy surface surrounding each transition state was obtained by fixing the single bridging atom (Y) and performing a rigid scan varying the Mg-Y-Mg angle (A2) from 90-150° and the Br-Mg-Y-Mg dihedral angle (D2) from 0-180°. The two surfaces shown in Figure 5 are quite different. When the bridging atom Y=H (TS1), the lowest energy region is where the Mg-H-Mg angle = 160°, but when Y=Br (TS2), the lowest energy region is where the Mg-Br-Mg angle A2 = 110°. TS1 is planar (D2 = 0), whereas TS2 is non-planar, with the Br-Mg-Br-Mg dihedral angle D2 = 91°. The rearrangement pathway
requires D2 to go from 0 to 180 or vice-versa, for that interchanges the bridging atoms and the products are planar.

**Figure 4.** (Left) Energy surface in kcal/mol for H-bridged TS1, D2 is the Br-Mg-Y-Mg dihedral angle, A2 is the Mg-Y-Mg angle. (Right) Energy surface in kcal/mol for
Br-bridged TS2. This is a rigid scan with no relaxation. The reaction path goes from D2=0 to D2=180°.

**Solvation Studies.** In order to simplify our computational studies of solvation effects, we chose to use dimethyl ether (DME) in place of tetrahydrofuran (THF). Since the reactions in this paper have also been observed in diethyl ether, DME seemed to be a good model. In addition to explicitly adding solvent molecules, we used the PCM polarized continuum solvent model (solvent=THF), i.e., every calculation with or without explicit DME involved PCM solvation(THF). Equations 1-4 show the effect of sequentially adding solvent molecules. The exothermicity declines with each addition until the fourth DME yields only $\delta E = -3.37 \text{ kcal/mol}$.

\[
\begin{align*}
\text{HMgBr} + \text{DME} & \rightarrow \text{HMgBr-DME} & \delta E = -15.25 \text{ kcal/mol} \\
\text{HMgBr-DME} + \text{DME} & \rightarrow \text{HMgBr-DME}_2 & -13.45 \text{ kcal/mol} \\
\text{HMgBr-DME}_2 + \text{DME} & \rightarrow \text{HMgBr-DME}_3 & -7.19 \text{ kcal/mol} \\
\text{HMgBr-DME}_3 + \text{DME} & \rightarrow \text{HMgBr-DME}_4 & -3.37 \text{ kcal/mol}
\end{align*}
\]

Equations 5-7 show the effect of ligands attached to Mg on solvation energies. Bromine increases the strength of the O-Mg coordination. We examined the Schlenk equilibrium (Equation 8) in which each reactant and product is coordinated to four DME molecules and found it to be exothermic by $\delta E = -0.51 \text{ kcal/mol}$, thus explicit solvation makes the reaction more favorable. Equation 8 presumably proceeds through the fully explicitly solvated $\mu$-HBr-bridged intermediate as in Equation 9, a process that is endothermic.
by 0.45 kcal/mol, in contrast to the formation of the μ-bridged intermediate μ-HBr (HMgBr)$_2$ which is exothermic by −20.98 kcal/mol. Equation 10 shows another of the many ways the fully explicitly solvated μ-HBr-bridged intermediate can be formed. The lowest energy arrangement of ligands for the product of Equation 9 is with the DME's axial and H opposite H, Br opposite Br equatorially:

\[
\text{HMgH} + 4 \text{DME} \rightarrow \text{MgH}_2\text{-DME}_4 \quad \delta E = -27.81 \text{ kcal/mol} \quad (5)
\]

\[
\text{HMgBr} + 4 \text{DME} \rightarrow \text{HMgBr}-\text{DME}_4 \quad -39.27 \text{ kcal/mol} \quad (6)
\]

\[
\text{BrMgBr} + 4 \text{DME} \rightarrow \text{MgBr}_2\text{-DME}_4 \quad -51.80 \text{ kcal/mol} \quad (7)
\]

\[
2 \text{HMgBr-DME}_4 \rightarrow \text{MgH}_2\text{-DME}_4 + \text{MgBr}_2\text{-DME}_4 \quad -0.51 \text{ kcal/mol} \quad (8)
\]

\[
2 \text{HMgBr-DME}_4 \rightarrow \mu\text{HBr (HMgBr-DME}_3)_2 + \text{DME}_2 \quad 0.45 \text{ kcal/mol} \quad (9)
\]

\[
2 \text{HMgBr-DME}_3 \rightarrow \mu\text{HBr (HMgBr-DME}_3)_2 \quad -6.29 \text{ kcal/mol} \quad (10)
\]

To conclude, the effect of explicit dimethyl ether solvation is to make the Schlenk equilibrium favor products, and it makes formation of the μ-HBr-bridged intermediate essentially an isoenergetic process instead of being highly exothermic. We have also studied intermediate levels of explicit solvation and found the same trends so they will not be reported here.
Atomic Coordinates of Key Structures

The following entries start with the number of atoms, the structure reference in Table 1, and Figure 3, followed by the atom symbol and the Cartesian x, y, z coordinates. Last is the energy reported by Gaussian09 matching that in Table 1.

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HF$=-5545.021692$

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12

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21

Tetrahed_MgHBr-DME2

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HF$=-3082.596199$

281
### 30

**TBP_{MgHBr-DME3} DME2ax**

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<td>-3.8149567785</td>
<td>0.7113295718</td>
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</tbody>
</table>

HF = -6475.275963
Sample: XSC08023

X-ray Structure Report, MgBr$_2$•4THF
Discussion

The complex crystallizes as colorless tablets from a THF solution. There are two molecules of the Mg complex in the unit cell of the primitive, acentric tetragonal space group P4\(_2\)2\(_1\)2. The correct enantiomorph of the space group was determined by comparison of known intensities of Friedel pairs of reflections. The Flack parameter derived from this comparison was refined to 0.34(2). This value indicates a significant amount of racemic twinning, which was accounted for with a simple racemic TWIN command and appropriate Batch Scale Factor (BASF refined to 0.34). The complex is identical to the previously reported MgBr\(_2\)(THF)\(_4\) complexes (*Naturwissenschaften*, (1966), 53, 360 and a *private communication* to the CSD, (1998)). The Mg is coordinated in an octahedral fashion by two bromine atoms and the oxygens of four THF molecules. The THF molecules are arranged about the equator of the complex (see Figures). However, the previous examples were refined against data recorded at room temperature. The data recorded for this experiment were obtained at 150 K.

As with the other examples, this complex exhibits positional disorder of the THF moiety. It has been modeled as two half occupancy THF molecules.

The bond distances and angles are as expected.

Data Collection

A fragment of a colorless tablet-like crystal of C\(_{16}\)H\(_{32}\)Br\(_2\)MgO\(_4\) having approximate dimensions of 0.47 × 0.47 × 0.31 mm was mounted on a Kapton loop using Paratone N hydrocarbon oil. All measurements were made on a Bruker APEX-II\(^1\) CCD area
detector with graphite monochromated Mo-Kα radiation.

Cell constants and an orientation matrix, obtained from a least-squares refinement using the measured positions of 5517 centered reflections with I > 10σ(I) in the range 5.25 < θ < 26.18° corresponded to a tetragonal cell with dimensions:

\[
\begin{align*}
    a &= 7.7653(5) \text{ Å} & \alpha &= 90° \\
    b &= 7.7653(5) \text{ Å} & \beta &= 90° \\
    c &= 17.0129(12) \text{ Å} & \gamma &= 90° \\
    V &= 1025.88(12) \text{ Å}^3
\end{align*}
\]

For Z = 2 and F.W. = 472.55, the calculated density is 1.530 g.cm\(^{-3}\).

Analysis of the systematic absences allowed the space group to be uniquely determined to be:

\[
P4_{21}2
\]

The data were collected at a temperature of 150(2) K. Frames corresponding to an arbitrary sphere of data were collected using ω-scans of 0.3° counted for a total of 10 seconds per frame.

**Data Reduction**

Data were integrated by the program SAINT\(^2\) to a maximum θ-value of 28.24°. The data were corrected for Lorentz and polarization effects. Data were analyzed for agreement and possible absorption using XPREP\(^3\). An empirical absorption correction
based on comparison of redundant and equivalent reflections was applied using SADABS\textsuperscript{4}. \((\text{Tmax} = 0.3705, \text{Tmin} = 0.2553)\). Of the 11447 reflections that were collected, 1275 were unique \((R_{\text{int}} = 0.0186)\); equivalent reflections were merged. No decay correction was applied.

**Structure Solution and Refinement**

The structure was solved by direct methods\textsuperscript{5} and expanded using Fourier techniques\textsuperscript{6}. Non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included in calculated positions but were not refined. The final cycle of full-matrix least-squares refinement\textsuperscript{7} was based on 1275 reflections (all data) and 91 variable parameters and converged (largest parameter shift was 0.018 times its esd) with conventional unweighted and weighted agreement factors of:

\[
R_1 = \frac{\sum |F_o| - |F_c|}{\sum |F_o|} = 0.0179 \text{ for 1191 data with } I > 2\sigma(I)
\]

\[
wR_2 = \left[ \frac{\sum w (|F_o|^2 - |F_c|^2)^2 / \sum w |F_o|^2) }{1/2} \right] = 0.0416
\]

The standard deviation of an observation of unit weight\textsuperscript{8} was 1.081. The weighting scheme was based on counting statistics and included a factor to downweight the intense reflections. The maximum and minimum peaks on the final difference Fourier map corresponded to 0.239 and -0.144 e\textsuperscript{-}Å\textsuperscript{3}, respectively.

Neutral atom scattering factors were taken from Cromer and Waber\textsuperscript{9}. Anomalous dispersion effects were included in Fcalc\textsuperscript{2}; the values for \(\Delta f'\) and \(\Delta f''\) were those of Creagh and McAuley\textsuperscript{10}. The values for the mass attenuation coefficients are those of Creagh and Hubbel\textsuperscript{11}. All calculations were performed using the SHELXTL\textsuperscript{1-6} crystallographic software package of Bruker Analytical X-ray Systems Inc.
References


(2) SAINT: SAX Area-Detector Integration Program, 7.34A; Siemens Industrial Automation, Inc.: Madison, WI, (2006)


(4) SADABS: Siemens Area Detector ABSorption correction program v.2.10, George Sheldrick, (2005).


(7) Least-Squares:

Function minimized: \( \Sigma w (|F_o|^2 - |F_c|^2)^2 \)

(8) Standard deviation of an observation of unit weight:

\[ [\Sigma w(|F_o|^2 - |F_c|^2)^2/(N_o - N_v)]^{1/2} \]

where: \( N_o = \) number of observations

\( N_v = \) number of variables

(9) Cromer, D. T. & Waber, J. T.; "International Tables for X-ray Crystallography", 294


Crystal data for C\textsubscript{16}H\textsubscript{32}Br\textsubscript{2}MgO\textsubscript{4}; M\textsubscript{r} = 472.55; Tetragonal; space group P4\textsubscript{2}2\textsubscript{1}2; \(a = 7.7653(5)\) Å; \(b = 7.7653(5)\) Å; \(c = 17.0129(12)\) Å; \(\alpha = 90^\circ\); \(\beta = 90^\circ\); \(\gamma = 90^\circ\); \(V = 1025.88(12)\) Å\textsuperscript{3}; \(Z = 2\); \(T = 150(2)\) K; \(\lambda(\text{Mo-K}\alpha) = 0.71073\) Å; \(\mu(\text{Mo-K}\alpha) = 3.996\) mm\textsuperscript{-1}; \(d_{\text{calc}} = 1.530\) g cm\textsuperscript{-3}; 11447 reflections collected; 1275 unique (\(R_{\text{int}} = 0.0186\)); giving \(R_1 = 0.0179\), \(wR_2 = 0.0416\) for 1191 data with \([I>2\sigma(I)]\) and \(R_1 = 0.0202\), \(wR_2 = 0.0424\) for all 1275 data. Residual electron density (e Å\textsuperscript{-3}) max/min: 0.239/-0.144.

An arbitrary sphere of data were collected on a colorless tablet-like crystal, having approximate dimensions of 0.47 × 0.47 × 0.31 mm, on a Bruker APEX-II diffractometer using a combination of \(\omega\)- and \(\varphi\)-scans of 0.3\(^\circ\). Data were corrected for absorption and polarization effects and analyzed for space group determination. The structure was solved by direct methods and expanded routinely. The model was refined by full-matrix least-squares analysis of \(F^2\) against all reflections. All non-hydrogen atoms were refined with anisotropic thermal displacement parameters. Unless otherwise noted, hydrogen atoms were included in calculated positions. Thermal parameters for the hydrogens were tied to the isotropic thermal parameter of the atom to which they are bonded (1.5 X for methyl, 1.2 for all others).

ACKNOWLEDGMENT

The single crystal X-ray diffraction data in this work were recorded on an instrument supported by the National Science Foundation, Major Research Instrumentation (MRI) Program under Grant No. CHE-0521569.
Table 2. Crystal data and structure refinement for xsc08023.

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<th>Property</th>
<th>Value</th>
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<tr>
<td>Identification code</td>
<td>xsc08023</td>
</tr>
<tr>
<td>Empirical formula</td>
<td>C\textsubscript{16}H\textsubscript{32}Br\textsubscript{2}MgO\textsubscript{4}</td>
</tr>
<tr>
<td>Formula weight</td>
<td>472.55</td>
</tr>
<tr>
<td>Temperature</td>
<td>150(2) K</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.71073 Å</td>
</tr>
<tr>
<td>Crystal system</td>
<td>Tetragonal</td>
</tr>
<tr>
<td>Space group</td>
<td>P4\textsubscript{2}2\textsubscript{1}2</td>
</tr>
<tr>
<td>Unit cell dimensions</td>
<td>\begin{align*}</td>
</tr>
<tr>
<td>(a)</td>
<td>7.7653(5) Å</td>
</tr>
<tr>
<td>(b)</td>
<td>7.7653(5) Å</td>
</tr>
<tr>
<td>(c)</td>
<td>17.0129(12) Å</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>90°</td>
</tr>
<tr>
<td>(\beta)</td>
<td>90°</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>90°</td>
</tr>
<tr>
<td>Volume</td>
<td>1025.88(12) Å</td>
</tr>
<tr>
<td>(Z)</td>
<td>2</td>
</tr>
<tr>
<td>Density (calculated)</td>
<td>1.530 g.cm(^{-3})</td>
</tr>
<tr>
<td>Absorption coefficient ((\mu))</td>
<td>3.996 mm(^{-1})</td>
</tr>
<tr>
<td>(F(000))</td>
<td>484</td>
</tr>
<tr>
<td>Crystal size</td>
<td>0.47 \times 0.47 \times 0.31 mm(^3)</td>
</tr>
<tr>
<td>(\omega) range for data collection</td>
<td>2.88 to 28.24°</td>
</tr>
<tr>
<td>Index ranges</td>
<td>(-10 \leq h \leq 0, -9 \leq k \leq 10, -22 \leq l \leq 22)</td>
</tr>
<tr>
<td>Reflections collected</td>
<td>11447</td>
</tr>
<tr>
<td>Independent reflections</td>
<td>1275 ([R_{int} = 0.0186])</td>
</tr>
<tr>
<td>Completeness to (\theta = 28.24°)</td>
<td>99.4 %</td>
</tr>
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<td>Description</td>
<td>Value</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Absorption correction</td>
<td>Numerical</td>
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<td>Max. and min. transmission</td>
<td>0.3705 and 0.2553</td>
</tr>
<tr>
<td>Refinement method</td>
<td>Full-matrix least-squares on $F^2$</td>
</tr>
<tr>
<td>Data / restraints / parameters</td>
<td>1275 / 0 / 91</td>
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<tr>
<td>Goodness-of-fit on $F^2$</td>
<td>1.081</td>
</tr>
<tr>
<td>Final R indices [I&gt;2σ(I)]</td>
<td>$R_1 = 0.0179$, wR$_2 = 0.0416$</td>
</tr>
<tr>
<td>R indices (all data)</td>
<td>$R_1 = 0.0202$, wR$_2 = 0.0424$</td>
</tr>
<tr>
<td>Absolute structure parameter</td>
<td>0.34(2)</td>
</tr>
<tr>
<td>Largest diff. peak and hole</td>
<td>0.239 and -0.144 e$^-1$.Å$^{-3}$</td>
</tr>
</tbody>
</table>
Table 3. Atomic coordinates and equivalent isotropic displacement parameters (Å\(^2\)) for xsc08023. \(U_{\text{eq}}\) is defined as one third of the trace of the orthogonalized \(U_{ij}\) tensor.

<table>
<thead>
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<th></th>
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<th>y</th>
<th>z</th>
<th>(U_{\text{eq}})</th>
</tr>
</thead>
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<td>0.75800(2)</td>
<td>0.24200(2)</td>
<td>0.0000</td>
<td>0.039(1)</td>
</tr>
<tr>
<td>Mg(1)</td>
<td>1.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.026(1)</td>
</tr>
<tr>
<td>O(1)</td>
<td>1.13694(18)</td>
<td>0.13627(16)</td>
<td>0.08647(6)</td>
<td>0.037(1)</td>
</tr>
<tr>
<td>C(1)</td>
<td>1.1780(13)</td>
<td>0.3215(13)</td>
<td>0.0786(5)</td>
<td>0.049(2)</td>
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<tr>
<td>C(2)</td>
<td>1.2548(9)</td>
<td>0.3752(8)</td>
<td>0.1523(4)</td>
<td>0.051(2)</td>
</tr>
<tr>
<td>C(3)</td>
<td>1.330(2)</td>
<td>0.2037(19)</td>
<td>0.1792(10)</td>
<td>0.083(5)</td>
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<tr>
<td>C(4)</td>
<td>1.2020(9)</td>
<td>0.0709(11)</td>
<td>0.1597(4)</td>
<td>0.047(2)</td>
</tr>
<tr>
<td>O(1A)</td>
<td>1.13694(18)</td>
<td>0.13627(16)</td>
<td>0.08647(6)</td>
<td>0.037(1)</td>
</tr>
<tr>
<td>C(1A)</td>
<td>1.1327(11)</td>
<td>0.3200(13)</td>
<td>0.0998(5)</td>
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<tr>
<td>C(2A)</td>
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<td>0.3501(9)</td>
<td>0.1328(4)</td>
<td>0.041(1)</td>
</tr>
<tr>
<td>C(3A)</td>
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<td>0.2082(13)</td>
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<td>0.047(2)</td>
</tr>
<tr>
<td>C(4A)</td>
<td>1.2673(9)</td>
<td>0.0605(10)</td>
<td>0.1397(4)</td>
<td>0.053(2)</td>
</tr>
<tr>
<td>H(1A)</td>
<td>1.2596</td>
<td>0.3400</td>
<td>0.0347</td>
<td>0.059</td>
</tr>
<tr>
<td>H(1B)</td>
<td>1.0720</td>
<td>0.3884</td>
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<tr>
<td>H(2A)</td>
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<td>0.4195</td>
<td>0.1896</td>
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<tr>
<td>H(2B)</td>
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<td>0.4631</td>
<td>0.1443</td>
<td>0.061</td>
</tr>
<tr>
<td></td>
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<td></td>
</tr>
<tr>
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<tr>
<td>H(3A)</td>
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<td>0.1804</td>
<td>0.1518</td>
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<tr>
<td>H(3B)</td>
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<td>0.2365</td>
<td>0.100</td>
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<td>H(2AA)</td>
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<td>0.3377</td>
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<tr>
<td>H(2AB)</td>
<td>1.3277</td>
<td>0.4654</td>
<td>0.1571</td>
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<td>H(3AA)</td>
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<tr>
<td>H(3AB)</td>
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<td>0.1904</td>
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<td>0.056</td>
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<tr>
<td>H(4AA)</td>
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<td>0.063</td>
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<tr>
<td>H(4AB)</td>
<td>1.2155</td>
<td>-0.0327</td>
<td>0.1716</td>
<td>0.063</td>
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Table 4. Anisotropic displacement parameters (Å$^2$) for xsc08023. The anisotropic displacement factor exponent takes the form: $-2\pi^2 \left[ a^2 U_{11} + ... + 2hk ab^* U_{12} \right]$

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<thead>
<tr>
<th></th>
<th>$U_{11}$</th>
<th>$U_{22}$</th>
<th>$U_{33}$</th>
<th>$U_{23}$</th>
<th>$U_{13}$</th>
<th>$U_{12}$</th>
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<tbody>
<tr>
<td>Br(1)</td>
<td>0.0292(1)</td>
<td>0.0292(1)</td>
<td>0.0592(1)</td>
<td>-0.0050(1)</td>
<td>-0.0050(1)</td>
<td>0.0049(1)</td>
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<tr>
<td>Mg(1)</td>
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<td>0.0237(2)</td>
<td>0.0304(4)</td>
<td>0.000</td>
<td>0.000</td>
<td>-0.0020(3)</td>
</tr>
<tr>
<td>O(1)</td>
<td>0.0476(8)</td>
<td>0.0226(6)</td>
<td>0.0399(5)</td>
<td>0.0029(5)</td>
<td>-0.0180(6)</td>
<td>-0.0012(4)</td>
</tr>
<tr>
<td>C(1)</td>
<td>0.073(7)</td>
<td>0.021(2)</td>
<td>0.054(5)</td>
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<td>-0.020(3)</td>
<td>-0.007(4)</td>
</tr>
<tr>
<td>C(2)</td>
<td>0.073(5)</td>
<td>0.035(3)</td>
<td>0.043(3)</td>
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<td>-0.014(3)</td>
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<tr>
<td>C(3)</td>
<td>0.082(6)</td>
<td>0.097(8)</td>
<td>0.070(9)</td>
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<td>-0.053(6)</td>
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<tr>
<td>C(4)</td>
<td>0.062(4)</td>
<td>0.040(2)</td>
<td>0.038(3)</td>
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<td>O(1A)</td>
<td>0.0476(8)</td>
<td>0.0226(6)</td>
<td>0.0399(5)</td>
<td>0.0029(5)</td>
<td>-0.0180(6)</td>
<td>-0.0012(4)</td>
</tr>
<tr>
<td>C(1A)</td>
<td>0.041(3)</td>
<td>0.024(2)</td>
<td>0.037(4)</td>
<td>0.000(2)</td>
<td>-0.007(2)</td>
<td>0.000(2)</td>
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<tr>
<td>C(2A)</td>
<td>0.034(3)</td>
<td>0.040(3)</td>
<td>0.050(3)</td>
<td>-0.019(2)</td>
<td>-0.004(2)</td>
<td>-0.005(2)</td>
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<tr>
<td>C(3A)</td>
<td>0.059(4)</td>
<td>0.039(3)</td>
<td>0.042(4)</td>
<td>-0.018(2)</td>
<td>-0.031(3)</td>
<td>0.012(3)</td>
</tr>
<tr>
<td>C(4A)</td>
<td>0.071(5)</td>
<td>0.035(2)</td>
<td>0.052(4)</td>
<td>0.000(3)</td>
<td>-0.038(3)</td>
<td>0.010(3)</td>
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</table>
Table 5. Bond lengths [Å] for xsc08023.

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<th>atom-atom</th>
<th>distance</th>
<th>atom-atom</th>
<th>distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Br(1)-Mg(1)</td>
<td>2.6576(2)</td>
<td>Mg(1)-O(1)</td>
<td>2.1011(9)</td>
</tr>
<tr>
<td></td>
<td>2.1011(9)</td>
<td>Mg(1)-O(1)#1</td>
<td>2.1011(9)</td>
</tr>
<tr>
<td>Mg(1)-O(1A)#2</td>
<td>2.1011(9)</td>
<td>Mg(1)-O(1)#2</td>
<td>2.1011(9)</td>
</tr>
<tr>
<td>Mg(1)-O(1)#3</td>
<td>2.1011(9)</td>
<td>Mg(1)-O(1A)#3</td>
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<tr>
<td>Mg(1)-Br(1)#3</td>
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<td>O(1)-C(4)</td>
<td>1.437(8)</td>
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<tr>
<td></td>
<td>1.479(10)</td>
<td>C(1)-C(2)</td>
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</tr>
<tr>
<td>C(3)-C(4)</td>
<td>1.469(18)</td>
<td>C(1A)-C(2A)</td>
<td>1.555(11)</td>
</tr>
<tr>
<td></td>
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<td>C(3A)-C(4A)</td>
<td>1.553(14)</td>
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</table>

Symmetry transformations used to generate equivalent atoms:

#1 -y+1,-x+1,-z    #2 y+1,x-1,-z    #3 -x+2,-y,z
Table 6. Bond angles [°] for xsc08023.

<table>
<thead>
<tr>
<th>atom-atom-atom</th>
<th>angle</th>
<th>atom-atom-atom</th>
<th>angle</th>
</tr>
</thead>
<tbody>
<tr>
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<td>O(1)-Mg(1)-O(1)#1</td>
<td>179.80(9)</td>
</tr>
<tr>
<td>O(1A)#1-Mg(1)-O(1)#1</td>
<td>0.00(7)</td>
<td>O(1)-Mg(1)-O(1A)#2</td>
<td>88.88(6)</td>
</tr>
<tr>
<td>O(1)-Mg(1)-O(1A)#2</td>
<td>88.88(6)</td>
<td>O(1A)#1-Mg(1)-O(1A)#2</td>
<td>91.12(6)</td>
</tr>
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<td>91.12(6)</td>
<td>O(1)#1-Mg(1)-O(1A)#2</td>
<td>91.12(6)</td>
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<tr>
<td>O(1)-Mg(1)-O(1A)#2</td>
<td>91.12(6)</td>
<td>O(1A)#1-Mg(1)-O(1)#2</td>
<td>0.00(7)</td>
</tr>
<tr>
<td>O(1A)#1-Mg(1)-O(1)#2</td>
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<td>O(1)-Mg(1)-O(1)#3</td>
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</tr>
<tr>
<td>O(1A)#1-Mg(1)-O(1)#3</td>
<td>88.88(6)</td>
<td>O(1A)#1-Mg(1)-O(1)#3</td>
<td>88.88(6)</td>
</tr>
<tr>
<td>O(1A)#2-Mg(1)-O(1)#3</td>
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<td>O(1A)#2-Mg(1)-O(1)#3</td>
<td>179.80(9)</td>
</tr>
<tr>
<td>O(1)#2-Mg(1)-O(1)#3</td>
<td>179.80(9)</td>
<td>O(1)-Mg(1)-O(1A)#3</td>
<td>91.12(6)</td>
</tr>
<tr>
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<td>O(1)-Mg(1)-O(1A)#3</td>
<td>91.12(6)</td>
</tr>
<tr>
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<td>91.12(6)</td>
<td>O(1A)#2-Mg(1)-O(1A)#3</td>
<td>179.80(9)</td>
</tr>
<tr>
<td>O(1)#2-Mg(1)-O(1A)#3</td>
<td>179.80(9)</td>
<td>O(1)#2-Mg(1)-O(1A)#3</td>
<td>179.80(9)</td>
</tr>
<tr>
<td>O(1)#3-Mg(1)-O(1A)#3</td>
<td>0.00(7)</td>
<td>O(1)-Mg(1)-Br(1)#3</td>
<td>89.90(4)</td>
</tr>
<tr>
<td>O(1)-Mg(1)-Br(1)#3</td>
<td>89.90(4)</td>
<td>O(1A)#1-Mg(1)-Br(1)#3</td>
<td>89.90(4)</td>
</tr>
<tr>
<td>O(1A)#1-Mg(1)-Br(1)#3</td>
<td>89.90(4)</td>
<td>O(1)#1-Mg(1)-Br(1)#3</td>
<td>89.90(4)</td>
</tr>
<tr>
<td>O(1A)#2-Mg(1)-Br(1)#3</td>
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<td>O(1)#2-Mg(1)-Br(1)#3</td>
<td>90.10(4)</td>
</tr>
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<td>O(1)#3-Mg(1)-Br(1)#3</td>
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<tr>
<td>Bond</td>
<td>Distance (Å)</td>
<td>Angle (°)</td>
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<tr>
<td>----------------------</td>
<td>--------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>O(1A)#3-Mg(1)-Br(1)#3</td>
<td>90.10(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O(1)-Mg(1)-Br(1)</td>
<td>90.10(4)</td>
<td>90.10(4)</td>
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</tr>
<tr>
<td>O(1)#1-Mg(1)-Br(1)</td>
<td>90.10(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O(1A)#2-Mg(1)-Br(1)</td>
<td>89.90(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O(1)#2-Mg(1)-Br(1)</td>
<td>89.90(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O(1)#3-Mg(1)-Br(1)</td>
<td>89.90(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O(1A)#3-Mg(1)-Br(1)</td>
<td>89.90(4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Br(1)#3-Mg(1)-Br(1)</td>
<td>180.000(4)</td>
<td></td>
<td></td>
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<tr>
<td>C(4)-O(1)-C(1)</td>
<td>110.3(6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(4)-O(1)-Mg(1)</td>
<td>127.4(4)</td>
<td>122.4(4)</td>
<td></td>
</tr>
<tr>
<td>C(2)-C(1)-O(1)</td>
<td>106.9(7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(1)-C(2)-C(3)</td>
<td>99.5(8)</td>
<td>106.7(11)</td>
<td></td>
</tr>
<tr>
<td>C(4)-C(3)-C(2)</td>
<td>100.7(8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C(3A)-C(2A)-C(1A)</td>
<td>102.1(7)</td>
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<td></td>
</tr>
</tbody>
</table>

Symmetry transformations used to generate equivalent atoms:

#1 -y+1,-x+1,-z  #2 y+1,x-1,-z  #3 -x+2,-y,z
Table 7. Torsion angles \([°\)] for xsc08023.

<table>
<thead>
<tr>
<th>atom-atom-atom-atom</th>
<th>angle</th>
<th>atom-atom-atom-atom</th>
</tr>
</thead>
<tbody>
<tr>
<td>O(1A)#1-Mg(1)-O(1)-C(4)</td>
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<td></td>
</tr>
<tr>
<td>O(1)#1-Mg(1)-O(1)-C(4)</td>
<td>-51.2(3)</td>
<td></td>
</tr>
<tr>
<td>O(1A)#2-Mg(1)-O(1)-C(4)</td>
<td>-141.3(3)</td>
<td></td>
</tr>
<tr>
<td>O(1)#2-Mg(1)-O(1)-C(4)</td>
<td>-141.3(3)</td>
<td></td>
</tr>
<tr>
<td>O(1)#3-Mg(1)-O(1)-C(4)</td>
<td>38.9(3)</td>
<td></td>
</tr>
<tr>
<td>O(1A)#3-Mg(1)-O(1)-C(4)</td>
<td>38.9(3)</td>
<td></td>
</tr>
<tr>
<td>Br(1)#3-Mg(1)-O(1)-C(4)</td>
<td>-51.2(3)</td>
<td></td>
</tr>
<tr>
<td>Br(1)-Mg(1)-O(1)-C(4)</td>
<td>128.8(3)</td>
<td></td>
</tr>
<tr>
<td>O(1A)#1-Mg(1)-O(1)-C(1)</td>
<td>129.4(4)</td>
<td></td>
</tr>
<tr>
<td>O(1)#1-Mg(1)-O(1)-C(1)</td>
<td>129.4(4)</td>
<td></td>
</tr>
<tr>
<td>O(1A)#2-Mg(1)-O(1)-C(1)</td>
<td>39.3(4)</td>
<td></td>
</tr>
<tr>
<td>O(1)#2-Mg(1)-O(1)-C(1)</td>
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<td>O(1)#3-Mg(1)-O(1)-C(1)</td>
<td>-140.5(4)</td>
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<tr>
<td>O(1A)#3-Mg(1)-O(1)-C(1)</td>
<td>-140.5(4)</td>
<td></td>
</tr>
<tr>
<td>Br(1)#3-Mg(1)-O(1)-C(1)</td>
<td>129.4(4)</td>
<td></td>
</tr>
<tr>
<td>Br(1)-Mg(1)-O(1)-C(1)</td>
<td>-50.6(4)</td>
<td></td>
</tr>
<tr>
<td>C(4)-O(1)-C(1)-C(2)</td>
<td>-5.8(7)</td>
<td></td>
</tr>
<tr>
<td>Mg(1)-O(1)-C(1)-C(2)</td>
<td>173.7(4)</td>
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</tr>
<tr>
<td>O(1)-C(1)-C(2)-C(3)</td>
<td>26.8(10)</td>
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</tr>
</tbody>
</table>
C(1)-C(2)-C(3)-C(4)  -40.1(12)
C(1)-O(1)-C(4)-C(3)  -19.0(8)
Mg(1)-O(1)-C(4)-C(3)  161.6(7)
C(2)-C(3)-C(4)-O(1)  36.5(11)
C(1A)-C(2A)-C(3A)-C(4A)  48.4(8)

Symmetry transformations used to generate equivalent atoms:
#1  -y+1,-x+1,-z  #2  y+1,x-1,-z  #3  -x+2,-y,z
Sample: xsc08048

X-ray Structure Report
Discussion

The complex crystallizes as colorless blocks from a THF solution. There are four molecules of the complex in the unit cell of the primitive monoclinic space group P2₁/c.

The complex consists of two five-coordinate magnesium centers. Each magnesium is chelated by the nitrogens of a TMEDA ligand, a bromine and two bridging oxygens from the boronate ligands (see Figures). The coordination geometry about each Mg is a highly distorted hybrid of trigonal bipyramidal and square pyramidal. The tau-5 value (a metric devised for representing the distortion, see additional tau-5.pdf for details) is: 0.24 and 0.11 for Mg1 and Mg2, respectively. A value of 0 (zero) indicates a true square pyramidal geometry; a value of 1 a trigonal bipyramidal configuration. The oxygen, O1, occupies the apical position of the square pyramid about Mg1 and Br2 the apical position for the geometry of Mg2.

There are close contacts from Mg1 to the boron centers and from each Mg to the other. These are simply artifacts of the software and do not represent real bonds. The bond distances and angles are otherwise representative of their type.

Data Collection

A fragment of a colorless block-like crystal of C_{24}H_{56}B_{2}Br_{2}Mg_{2}N_{4}O_{6} having approximate dimensions of 0.43 × 0.31 × 0.18 mm was mounted on a Kapton loop using Paratone N hydrocarbon oil. All measurements were made on a Bruker APEX-II¹ CCD area detector with graphite monochromated Mo-Kα radiation.

Cell constants and an orientation matrix, obtained from a least-squares refinement
using the measured positions of 9898 centered reflections with $I > 10\sigma(I)$ in the range $2.40 < \theta < 28.32^\circ$ corresponded to a monoclinic cell with dimensions:

\[
\begin{align*}
    a &= 14.572(2) \text{ Å} & \alpha &= 90^\circ \\
    b &= 10.5623(15) \text{ Å} & \beta &= 102.502(2)^\circ \\
    c &= 24.687(4) \text{ Å} & \gamma &= 90^\circ \\
    V &= 3709.7(9) \text{ Å}^3
\end{align*}
\]

For $Z = 4$ and F.W. = 726.79, the calculated density is 1.301 g.cm$^{-3}$.

Analysis of the systematic absences allowed the space group to be uniquely determined to be:

$$P2_1/c$$

The data were collected at a temperature of 150(2) K. Frames corresponding to an arbitrary sphere of data were collected using $\omega$-scans of 0.3° counted for a total of 10 seconds per frame.

Data Reduction

Data were integrated by the program SAINT$^2$ to a maximum $\theta$-value of 28.37°. The data were corrected for Lorentz and polarization effects. Data were analyzed for agreement and possible absorption using XPREP$^3$. An empirical absorption correction based on comparison of redundant and equivalent reflections was applied using SADABS$^4$. ($T_{\text{max}} = 0.6868$, $T_{\text{min}} = 0.4437$). Of the 40826 reflections that were collected, 9208 were unique ($R_{\text{int}} = 0.0246$); equivalent reflections were merged. No decay correction was applied.

Structure Solution and Refinement

The structure was solved by direct methods$^5$ and expanded using Fourier techniques$^6$. 
Non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included in calculated positions but were not refined. The final cycle of full-matrix least-squares refinement was based on 9208 reflections (all data) and 377 variable parameters and converged (largest parameter shift was 0.002 times its esd) with conventional unweighted and weighted agreement factors of:

\[ R_1 = \frac{\sum ||Fo| - |Fc||}{\sum |Fo|} = 0.0262 \text{ for 7455 data with } I > 2\sigma(I) \]
\[ wR_2 = \left[ \frac{\sum w (|Fo|^2 - |Fc|^2)^2}{\sum w |Fo|^2} \right]^{1/2} = 0.0621 \]

The standard deviation of an observation of unit weight was 1.018. The weighting scheme was based on counting statistics and included a factor to downweight the intense reflections. The maximum and minimum peaks on the final difference Fourier map corresponded to 0.563 and -0.485 e\(^{-}\)\(\text{Å}^3\), respectively.

Neutral atom scattering factors were taken from Cromer and Waber. Anomalous dispersion effects were included in \( F_{\text{calc}} \); the values for \( \Delta f' \) and \( \Delta f'' \) were those of Creagh and McAuley. The values for the mass attenuation coefficients are those of Creagh and Hubbel. All calculations were performed using the SHELXTL crystallographic software package of Bruker Analytical X-ray Systems Inc.

References


(2) SAINT: SAX Area-Dectector Integration Program, 7.34A; Siemens Industrial Automation, Inc.: Madison, WI, (2006)

(4) **SADABS**: Siemens Area Detector ABSorption correction program v.2.10, George Sheldrick, (2005).


(7) **Least-Squares**:

Function minimized: \( \Sigma w (|F_{o}|^2 - |F_{c}|^2)^2 \)

(8) Standard deviation of an observation of unit weight:

\[
[\Sigma w(|F_{o}|^2 -|F_{c}|^2)^2/(N_o-N_v)]^{1/2}
\]

where:

- \( N_o \) = number of observations
- \( N_v \) = number of variables


Crystal data for C$_{24}$H$_{56}$B$_2$Mg$_2$N$_4$O$_6$; M$_r$ = 726.79; monoclinic; space group P2$_1$/c; $a = 14.572(2)$ Å; $b = 10.5623(15)$ Å; $c = 24.687(4)$ Å; $\alpha = 90^\circ$; $\beta = 102.502(2)^\circ$; $\gamma = 90^\circ$; $V = 3709.7(9)$ Å$^3$; Z = 4; T = 150(2) K; $\lambda$(Mo-K$\alpha$) = 0.71073 Å; $\mu$(Mo-K$\alpha$) = 2.257 mm$^{-1}$; $d_{\text{calc}} = 1.301$ g.cm$^{-3}$; 40826 reflections collected; 9208 unique (R$_{\text{int}}$ = 0.0246); giving R$_1 = 0.0262$, wR$_2 = 0.0621$ for 7455 data with [I>2$\sigma$(I)] and R$_1 = 0.0379$, wR$_2 = 0.0668$ for all 9208 data. Residual electron density (e$^{-}\cdot$Å$^{-3}$) max/min: 0.563/-0.485. An arbitrary sphere of data were collected on a colorless block-like crystal, having approximate dimensions of 0.43 × 0.31 × 0.18 mm, on a Bruker APEX-II diffractometer using a combination of $\omega$- and $\varphi$-scans of 0.3$^\circ$. Data were corrected for absorption and polarization effects and analyzed for space group determination. The structure was solved by direct methods and expanded routinely. The model was refined by full-matrix least-squares analysis of F$^2$ against all reflections. All non-hydrogen atoms were refined with anisotropic thermal displacement parameters. Unless otherwise noted, hydrogen atoms were included in calculated positions. Thermal parameters for the hydrogens were tied to the isotropic thermal parameter of the atom to which they are bonded (1.5 X for methyl, 1.2 for all others).

ACKNOWLEDGMENT

The single crystal X-ray diffraction data in this work were recorded on an instrument supported by the National Science Foundation, Major Research Instrumentation (MRI) Program under Grant No. CHE-0521569.
Table 8. Crystal data and structure refinement for xsc08048.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td>Identification code</td>
<td>xsc08048</td>
</tr>
<tr>
<td>Empirical formula</td>
<td>C_{24}H_{56}B_{2}Br_{2}Mg_{2}N_{4}O_{6}</td>
</tr>
<tr>
<td>Formula weight</td>
<td>726.79</td>
</tr>
<tr>
<td>Temperature</td>
<td>150(2) K</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.71073 Å</td>
</tr>
<tr>
<td>Crystal system</td>
<td>Monoclinic</td>
</tr>
<tr>
<td>Space group</td>
<td>P2_1/c</td>
</tr>
<tr>
<td>Unit cell dimensions</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>14.572(2) Å</td>
</tr>
<tr>
<td>α</td>
<td>90°</td>
</tr>
<tr>
<td>b</td>
<td>10.5623(15) Å</td>
</tr>
<tr>
<td>β</td>
<td>102.502(2)°</td>
</tr>
<tr>
<td>c</td>
<td>24.687(4) Å</td>
</tr>
<tr>
<td>γ</td>
<td>90°</td>
</tr>
<tr>
<td>Volume</td>
<td>3709.7(9) Å^3</td>
</tr>
<tr>
<td>Z</td>
<td>4</td>
</tr>
<tr>
<td>Density (calculated)</td>
<td>1.301 g.cm(^{-3})</td>
</tr>
<tr>
<td>Absorption coefficient (μ)</td>
<td>2.257 mm(^{-1})</td>
</tr>
<tr>
<td>F(000)</td>
<td>1520</td>
</tr>
<tr>
<td>Crystal size</td>
<td>0.43 × 0.31 × 0.18 mm(^3)</td>
</tr>
<tr>
<td>ω range for data collection</td>
<td>1.96 to 28.37°</td>
</tr>
<tr>
<td>Index ranges</td>
<td>-19 ≤ h ≤ 9, -14 ≤ k ≤ 14, -32 ≤ l ≤ 32</td>
</tr>
<tr>
<td>Reflections collected</td>
<td>40826</td>
</tr>
<tr>
<td>Independent reflections</td>
<td>9208 [R(_{int}) = 0.0246]</td>
</tr>
<tr>
<td>Completeness to θ = 28.37°</td>
<td>99.3 %</td>
</tr>
<tr>
<td>Absorption correction</td>
<td>Numerical</td>
</tr>
<tr>
<td>Max. and min. transmission</td>
<td>0.6868 and 0.4437</td>
</tr>
<tr>
<td>Refinement method</td>
<td>Full-matrix least-squares on F(^2)</td>
</tr>
<tr>
<td>Data / restraints / parameters</td>
<td>9208 / 0 / 377</td>
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<tr>
<td>Goodness-of-fit on F(^2)</td>
<td>1.018</td>
</tr>
<tr>
<td>Final R indices [I&gt;2σ(I)]</td>
<td>R(_1) = 0.0262, wR(_2) = 0.0621</td>
</tr>
<tr>
<td>R indices (all data)</td>
<td>R(_1) = 0.0379, wR(_2) = 0.0668</td>
</tr>
<tr>
<td>Largest diff. peak and hole</td>
<td>0.563 and -0.485 e .Å(^{-3})</td>
</tr>
</tbody>
</table>
Table 9. Atomic coordinates and equivalent isotropic displacement parameters (Å²) for xsc08048. U(eq) is defined as one third of the trace of the orthogonalized U_{ij} tensor.

<table>
<thead>
<tr>
<th>Element</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>U(eq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg(1)</td>
<td>0.25736(3)</td>
<td>0.37959(4)</td>
<td>0.16536(2)</td>
<td>0.023(1)</td>
</tr>
<tr>
<td>Mg(2)</td>
<td>0.22400(3)</td>
<td>0.62856(4)</td>
<td>0.10764(2)</td>
<td>0.021(1)</td>
</tr>
<tr>
<td>Br(1)</td>
<td>0.09608(1)</td>
<td>0.30069(2)</td>
<td>0.10744(1)</td>
<td>0.035(1)</td>
</tr>
<tr>
<td>Br(2)</td>
<td>0.34975(1)</td>
<td>0.79307(2)</td>
<td>0.13480(1)</td>
<td>0.039(1)</td>
</tr>
<tr>
<td>O(1)</td>
<td>0.21390(7)</td>
<td>0.55131(9)</td>
<td>0.18092(4)</td>
<td>0.024(1)</td>
</tr>
<tr>
<td>O(2)</td>
<td>0.20087(8)</td>
<td>0.51703(10)</td>
<td>0.27471(4)</td>
<td>0.029(1)</td>
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<tr>
<td>O(3)</td>
<td>0.17696(8)</td>
<td>0.71804(10)</td>
<td>0.23970(4)</td>
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</tr>
<tr>
<td>O(4)</td>
<td>0.28752(7)</td>
<td>0.46467(9)</td>
<td>0.09831(4)</td>
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</tr>
<tr>
<td>O(5)</td>
<td>0.34104(9)</td>
<td>0.39074(11)</td>
<td>0.01704(5)</td>
<td>0.037(1)</td>
</tr>
<tr>
<td>O(6)</td>
<td>0.34923(8)</td>
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Table 10. Anisotropic displacement parameters (Å$^2$) for xsc08048. The anisotropic displacement factor exponent takes the form: $-2\pi^2 [h^2a^*^2U_{11} + \ldots + 2hkab^*c^*U_{12}]$

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Symmetry transformations used to generate equivalent atoms:
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Symmetry transformations used to generate equivalent atoms:
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324
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Symmetry transformations used to generate equivalent atoms:
Table 14. Planes for xsc08046.

Least-squares planes \((x,y,z)\) in crystal coordinates) and deviations from them (* indicates atom used to define plane)

\[
11.9479 (0.0047) x + 3.2764 (0.0029) y + 7.2158 (0.0114) z = 5.5897 (0.0018)
\]

* -0.0779 (0.0004) Mg1

* -0.0772 (0.0004) Mg2

* 0.0778 (0.0004) O1

* 0.0774 (0.0004) O4

Rms deviation of fitted atoms = 0.0776

\[
-5.7536 (0.0096) x + 6.8520 (0.0060) y + 17.7903 (0.0117) z = 4.0778 (0.0039)
\]

Angle to first plane (with approximate esd) = 79.01 (0.04)

* -0.0158 (0.0007) Mg1

* -0.1165 (0.0011) N1

* 0.1624 (0.0011) N2

* 0.2760 (0.0014) C1

* -0.3061 (0.0014) C2

Rms deviation of fitted atoms = 0.2050

\[
6.5699 (0.0075) x + 9.1087 (0.0030) y + 3.1413 (0.0142) z = 7.4880 (0.0014)
\]

Angle to first plane (with approximate esd) = 41.58 (0.05)

* 0.0472 (0.0006) Mg2

* 0.0764 (0.0009) N3
* -0.2067 (0.0009) N4
* -0.2463 (0.0011) C7
* 0.3294 (0.0011) C8

Rms deviation of fitted atoms = 0.2097

13.5401 (0.0051) x + 1.0419 (0.0077) y + 3.6210 (0.0210) z = 4.1314 (0.0071)

Angle to first plane (with approximate esd) = 15.45 (0.08)

* -0.0017 (0.0009) B1
* 0.1220 (0.0009) O2
* -0.1192 (0.0010) O3
* -0.1814 (0.0009) C13
* 0.1803 (0.0010) C14

Rms deviation of fitted atoms = 0.1375

12.4302 (0.0076) x + 2.7420 (0.0088) y + 6.3540 (0.0211) z = 5.5169 (0.0020)

Angle to first plane (with approximate esd) = 3.83 (0.10)

* -0.0134 (0.0010) B2
* -0.0981 (0.0011) O5
* 0.1195 (0.0010) O6
* 0.1584 (0.0011) C19
* -0.1664 (0.0011) C20

Rms deviation of fitted atoms = 0.1240
Appendix C

Spectra for compounds and reactions in chapter 4
1H, 13C, and 11B NMR spectrum of Boronic Esters (Table 4.2-4.4, Scheme 4.6)

Table 4.2

4,4,5,5-tetramethyl-2-phenyl-1,3,2-dioxaborolane (Table 4.2, entry 1) 233
4,4,5,5-tetramethyl-2-o-tolyl-1,3,2-dioxaborolane (Table 4.2, entry 2) 236
4,4,5,5-tetramethyl-2-m-tolyl-1,3,2-dioxaborolane (Table 4.2, entry 3) 239
4,4,5,5-tetramethyl-2-p-tolyl-1,3,2-dioxaborolane (Table 4.2, entry 4) 342
2-(4-methoxyphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.2, entry 5) 345
4,4,5,5-tetramethyl-2-(phenanthren-1-yl)-1,3,2-dioxaborolane (Table 4.2, entry 6) 348
2-hexyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.2, entry 7) 352
2-cyclohexyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.2, entry 8) 355
2-tert-butyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.2, entry 9) 358
4,4,5,5-tetramethyl-2-(pentan-3-yl)-1,3,2-dioxaborolane (Table 4.2, entry 10) 361

Table 4.3

2-(4-ethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.3, Entry 1) 364
4,4,5,5-tetramethyl-2-m-tolyl-1,3,2-dioxaborolane (Table 4.3, Entry 2) 367
4,4,5,5-tetramethyl-2-(pyren-2-yl)-1,3,2-dioxaborolane (Table 4.3, Entry 3) 370
2-(biphenyl-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.3, Entry 4) 373

331
2-(4-methoxy-2-methylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.3, Entry 5) 376
2-(4-(dimethoxymethyl)phenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.3, Entry 6) 379
4,4,5,5-tetramethyl-2-octyl-1,3,2-dioxaborolane (Table 4.3, Entry 7) 382
1,4-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (Table 4.3, Entry 8) 385
4,4,5,5-tetramethyl-2-(1-phenylethyl)-1,3,2-dioxaborolane (Table 4.3, Entry 9) 388
4,4,5,5-tetramethyl-2-(thiophen-2-yl)-1,3,2-dioxaborolane (Table 4.3, Entry 10) 391
2-(5-chlorothiophen-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.3, Entry 11) 394
4,4,5,5-tetramethyl-2-(1-phenylvinyl)-1,3,2-dioxaborolane (Table 4.3, Entry 12) 397

Table 4.4.
2-allyl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (Table 4.4, entry 1) 400
3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-but-1-ene (Table 4.4, entry 3) 402
4,4,5,5-tetramethyl-2-(2-methylallyl)-1,3,2-dioxaborolane (Table 4.4, entry 4) 404
3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-3-methylbut-1-ene (Table 4.4, entry 5) 407
5,5-dimethyl-2-m-tolyl-1,3,2-dioxaborinane ester (Scheme 4.6) 413
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$^{11}$B NMR of neat PinBH after 7 months 23 days stored at 10 °C 418
$^{11}$B NMR Non-stirring conditions, formation of trialkylborohydride 419
Table 4.2, entry 1
Table 4.2, entry 1

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Schematic diagram
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Table 4.2, entry 2
Table 4.2, entry 2
Table 4.2, entry 3
Table 4.2, entry 3
Table 4.2, entry 3

Bpin
Table 4.2, entry 4

Bpin
Table 4.2, entry 4
Table 4.2, entry 4
Table 4.2, entry 5
Table 4.2, entry 5
Table 4.2, entry 5
Table 4.2, entry 6
Table 4.2, entry 6

BPin
Table 4.2, entry 6
Table 4.2, entry 6
Table 4.2, entry 7
Table 4.2, entry 7
Table 4.2, entry 8

33.943 ppm (f1)
Table 4.2, entry 8

![Cyclohexene molecule diagram]
Table 4.2, entry 8
Table 4.2, entry 9
Table 4.2, entry 9
Table 4.2, entry 9
Table 4.2, entry 10
Table 4.2, entry 10

3-methylhydronic phenoxy ester

Pulse sequence: signal
Table 4.2, entry 10
Table 2, entry 1

Bpin

Table 4.3, entry 1

30.869
Table 2, entry 1

Bpin
Et

CDCl₃, 500 MHz

Table 4.3, entry 1
Table 4.3, entry 1
Table 4.3, entry 2

Bpin
Table 4.3, entry 2

CDCl₃, 500 MHz
Table 4.3, entry 3

CDCl₃, 160 MHz
Table 4.3, entry 3
Table 4.3, entry 3
Table 4.3, entry 4
Table 4.3, entry 4

BPin

[Chemical structure diagram]
Table 4.3, entry 4
Table 4.3, entry 5

Table 2, entry 5
Bpin
MeO
Table 2, entry 5

Bpin
MeO

Table 4.3, entry 5
Table 4.3, entry 5

Table 4.3, entry 5
Table 4.3, entry 6
Table 4.3, entry 6
Table 4.3, entry 6
Table 4.3, entry 7
Table 4.3, entry 7
Table 4.3, entry 7
Table 4.3, entry 8
Table 4.3, entry 8
Table 4.3, entry 8
Table 4.3, entry 9

BPn

388
Table 4.3, entry 9
BPin
Table 2, entry 9

Table 4.3, entry 9
Table 4.3, entry 10
Table 4.3, entry 10
Table 4.3, entry 10
Table 4.3, entry 11

\[ \text{Cl-S-Bpin} \]
Table 4.3, entry 11
Table 4.3, entry 11

\[ \text{Chart of data here} \]
Table 4.3, entry 12
Table 4.3, entry 12
Table 4.3, entry 12
Table 4.4, entry 1

Bpin
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Table 4.4, entry 1
Table 4.4, entry 3

CDCl3, 500 MHz

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[Chemical structure image]
Table 3, Entry 3
CDCl₃, 160 MHz

Table 4.4, entry 3
Table 4.4, entry 4
Table 4.4, entry 4

Bpin

Table 3, Entry 4

CDCl3, 160 MHz
Table 4.4, entry 4

Bpin

CDCl₃, 160 MHz
Table 3, Entry 5
CDCl3, 160 MHz
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Table 4.4, entry 5
Table 3, Entry 5

CDCl₃, 160 MHz

Bpin
Table 4.4, entry 5
Scheme 4.6
neopentylglycolborane
Scheme 4.6
5,5-dimethyl-2-m-tolyl-1,3,2-dioxaborinane ester
Scheme 4.6
5,5-dimethyl-2-m-tolyl-1,3,2-dioxaborinane ester
Scheme 4.6
5,5-dimethyl-2-m-tolyl-1,3,2-dioxaborinane ester
Figure S1. Pinacolborane stability study by $^{11}$B NMR analysis

Table S2. Decomposition of pinacolborane$^a$

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$^a$Percentage values determined by intigration of $^{11}$B NMR
$^{11}$B NMR of neat PinBH after 7 months 23 days stored at 10 °C

CDCl$_3$, 160 MHz
Formation of trialkylborohydride
Bibliography


Aldrich Technical Information Bulletin AL-123.


Brown, H. C.; Park, W. S.; Cha, J. S.; Cho, B. T.


Chen, A.; Ren, Li; Crudden, C. M. J. Org. Chem. 1999, 64, 9704-9710.


Clary, J. W.; Rettenmaier, T. J.; Eagon, S.; Murphy, C.; Bailey, C. L.; Singaram, B. Manuscript in Preparation.


Dang, L.; Zhao, H.; Lin, Z.; Marder, T. B. Organometallics 2007, 26, 2824-2832.


Diborane, B₂H₆, MSDS reference: 040, chemical abstracts 19287-45-7, UN no. 1911.


Liu, Z.; Marder, T. B. *Angew. Chem. Int. Ed.* **2008**, *47*, 242-244.


Mkhalid, I. A.; Barnard, J. H.; Marder, T. B.; Murphy, J. M.; Hartwig, J. F. Chem. Rev. 2010, 110, 890-931.


Staubitz, A.; Robertson, A. P. M.; Sloan, M. E.; Manners, I. Chem. Rev. 2010, 110, 4023-4078.


