Explorations into the Nucleophilicity of Aziridine and Utilization of Boron-Containing Building Blocks in Organic Synthesis

by

Kowan Thomas Vernon O’Keefe

A thesis submitted in conformity with the requirements for the degree of Master of Science
Department of Chemistry
University of Toronto

© Copyright by Kowan Thomas Vernon O’Keefe 2016
Explorations into the Nucleophilicity of Aziridine and Utilization of Boron-Containing Building Blocks in Organic Synthesis

Kowan Thomas Vernon O’Keefe

Master of Science

Department of Chemistry
University of Toronto

2016

Abstract

Synthetic methods that achieve a high level of molecular complexity in a minimal number of steps using simple starting materials are highly valuable transformations in organic chemistry. Borylated ketenimines, representing a new class of [1,2]-amphoteric reagents, have been shown to be valuable intermediates in the rapid synthesis of α-borylazetidimines and 3-boryliminocoumarins. Herein, a successful expansion of the scope of these reactions has been demonstrated through trapping the borylated ketenimine intermediate \textit{in situ} with various imines and salicylaldehyde derivatives. In addition, efforts toward synthesizing MIDA-boryl formate and MIDA-boryl formic acid (both [1,1]-amphoteric) via oxidation of hydroxymethyl MIDA boronate are reported. This led to the synthesis of a diboronate ester containing a BC(O)O structural motif. Also, for the purpose of better understanding the reactivity of aziridine aldehydes ([1,3]-amphoteric reagents), preliminary investigations into quantifying the nucleophilicity of aziridine suggest its nucleophilic character is weaker than that of other small, cyclic secondary amines.
Acknowledgments

I would like to thank Dr. Andrei Yudin for his guidance and support during the course of my Masters degree. I would also like to thank Dr. Jik Chin for taking the time to read my thesis. In addition, I would like to thank my undergraduate supervisor at Minot State University, Dr. Mikhail Bobylev, for first giving me the opportunity to do research in organic chemistry.

I have been fortunate to have an incredible group of lab mates to work with in the Yudin lab. I would like to thank Dr. Rodrigo Mendoza-Sanchez, Dr. Conor Scully, and Dr. John Frost for helpful discussions about chemistry. Most importantly, I want to thank Mr. Sherif Kaldas for his guidance and helpful conversations regarding our chemistry. He has been an exceptional mentor for me over the course of my Masters degree.

Finally, I would like to thank my brother, Karson, as well as my parents, Brian and Janet, for their unwavering support and encouragement. I am extremely grateful for all that they have done for me over the years.
# Table of Contents

Acknowledgements................................................................................................................................. iii

Table of Contents....................................................................................................................................... iv

List of Tables.................................................................................................................................................. v

List of Figures.............................................................................................................................................. vi

List of Appendices........................................................................................................................................ vii

1 Introduction................................................................................................................................................ 1

2 Results and Discussion................................................................................................................................ 4

  2.1 Kinetics of Aziridine Nucleophilicity................................................................................................. 4

  2.2 Efforts toward Synthesis of BC(O)O Structural Motif...................................................................... 8

  2.3 Synthesis and Reactivity of Borylated Ketenimines........................................................................... 11

    2.3.1 Synthesis of $\alpha$-Borylazetidimines......................................................................................... 12

    2.3.2 Synthesis of 3-Boryliminocoumarins....................................................................................... 15

3 Conclusion.................................................................................................................................................. 16

4 Experimental Procedures........................................................................................................................... 16

  4.1 Protocols for Kinetics of Aziridine Nucleophilicity.......................................................................... 17

  4.2 Protocols for Efforts toward Synthesis of BC(O)O Structural Motif............................................ 18

  4.3 Protocols for Borylated Ketenimine Reactions............................................................................... 20

References.................................................................................................................................................... 45
List of Tables

**Table 2.1** Rate constants for the reactions of 1 with pyrrolidine, 4, and 3 in DMSO (Dual beam UV/Vis spectrophotometer, 25 °C, λ = 436 nm) .................................................................................................................................................. 7

**Table 2.2** Rate constants for the reactions of 1 with 4, and 3 in DMSO at significantly increased concentration, and 60 eq. of DIPEA (Dual beam UV/Vis spectrophotometer, 25 °C, λ = 436 n) .................................................................................................................................................. 7

**Table 2.3** Substrate scope for α-borylazetidimine formation. Reactions were run for 24 h at room temperature. Yields determined by crude 1H NMR using trichloroethylene as internal standard. 

\[ a \] cis product lost during isolation. \[ b \] trans product lost during isolation ......................................................................................................................... 13

**Table 2.4** Scope of nosyl deprotections. Reactions were complete in 5 hours at 65 °C. Yields are isolated ........................................................................................................................................................................................................... 14

**Table 2.5** Substrate scope for 3-boryliminocoumarin formation. Reactions were complete in 24 hours at room temperature. Yields determined by crude 1H NMR using trichloroethylene as internal standard ........................................................................................................................................................................................................... 15
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Amphoteric molecules</td>
<td>1</td>
</tr>
<tr>
<td>1.2</td>
<td>Dimerization of aziridine aldehydes</td>
<td>2</td>
</tr>
<tr>
<td>1.3</td>
<td>Synthetic Utility of aziridine aldehydes</td>
<td>2</td>
</tr>
<tr>
<td>1.4</td>
<td>[1,1]-amphoteric molecules</td>
<td>3</td>
</tr>
<tr>
<td>1.5</td>
<td>Diverse array of products accessible through borylated ketenimine intermediate</td>
<td>4</td>
</tr>
<tr>
<td>2.1</td>
<td>Basic reaction scheme for kinetic experiments</td>
<td>5</td>
</tr>
<tr>
<td>2.2</td>
<td>Determination of second order rate constants for piperidine and pyrrolidine</td>
<td>6</td>
</tr>
<tr>
<td>2.3</td>
<td>Substituted secondary amines 3 and 4</td>
<td>6</td>
</tr>
<tr>
<td>2.4</td>
<td>Unsuccessful dithiane deprotections</td>
<td>8</td>
</tr>
<tr>
<td>2.5</td>
<td>Unsuccessful oxidations of 5</td>
<td>9</td>
</tr>
<tr>
<td>2.6</td>
<td>Unsuccessful aerobic oxidation of 5</td>
<td>9</td>
</tr>
<tr>
<td>2.7</td>
<td>Aerobic oxidation of 5 with stoichiometric amounts of all reagents</td>
<td>10</td>
</tr>
<tr>
<td>2.8</td>
<td>Aerobic oxidation of 5 with stoichiometric amounts of all reagents, under oxygen atmosphere</td>
<td>10</td>
</tr>
<tr>
<td>2.9</td>
<td>Aerobic oxidation of 5 in trifluoroethanol</td>
<td>10</td>
</tr>
<tr>
<td>2.10</td>
<td>Oxidation of 5 using trichloroisocyanuric acid</td>
<td>11</td>
</tr>
<tr>
<td>2.11</td>
<td>Plausible catalytic cycle for borylated ketenimine formation</td>
<td>12</td>
</tr>
<tr>
<td>2.12</td>
<td>α-borylazetidimine and 3-boryliminocoumarin formation</td>
<td>12</td>
</tr>
<tr>
<td>2.13</td>
<td>Epimerization to trans-α-borylazetidimine</td>
<td>14</td>
</tr>
</tbody>
</table>
List of Appendices

Appendix I: $^1$H NMR & $^{13}$C NMR Spectra, and Data for Kinetics Experiments........................................47

Appendix II: $^1$H NMR & $^{13}$C NMR Spectra of Hydroxymethyl MIDA Boronate Oxidation Product.................................................................................................................................54

Appendix III: $^1$H NMR & $^{13}$C NMR Spectra of Ketenimine Products.................................................................55
1 Introduction

Small organic molecules are commonly found constituents of agrochemicals, therapeutic agents, and materials. Accordingly, there is a considerable interest in developing new synthetic methods to access such compounds and to do so in an environmentally responsible manner. One idea that has generated tremendous interest is the use of “Lego-like” kits for modular construction of complex molecules. The development of sophisticated new building blocks and understanding their reactivity is one of the challenging goals of contemporary organic synthesis. An opportunity to rapidly put together complex structures will empower applications in the design of materials and pharmaceuticals.

Over the past decade, the concept of kinetic amphoterism has been a key topic of study in our laboratory. Amphoteric molecules are unique because they contain both nucleophilic and electrophilic centers that are in close proximity to each other, but are prevented from prematurely reacting with each other due to kinetic constraints. The Yudin lab has developed a wide range of amphoteric small molecules including aziridine aldehydes, α-boryl aldehydes, and acyl boronates (Figure 1.1). The amphoteric nature of these compounds is classified by counting the number of atoms between nucleophilic and electrophilic centers.

![Figure 1.1 Amphoteric molecules](image)

Aziridine aldehydes were the first amphoteric reagents developed by the Yudin group, and are classified as [1,3]-amphoteric. Typically, amino aldehydes are unstable due to condensation pathways resulting in reactive imine, iminium, and enamine intermediates. However, ring strain prevents the aziridine nitrogen from condensing with the aldehyde. This kinetic constraint forces orthogonality between the two reactive centers, allowing the nucleophilic amine and electrophilic aldehyde to co-exist. Aziridine aldehydes dimerize rapidly in solution, resulting in homochiral, bench-stable amino aldehydes (Figure 1.2). Their synthetic utility has been demonstrated in the synthesis of a wide range of compounds such as vicinal aziridine-containing vinyl diamines, C-
vinyl aziridines, C-ethynyl aziridines, and peptidomimetic conjugates just to name a few (Figure 1.3).\textsuperscript{2,3}

**Figure 1.2** Dimerization of aziridine aldehydes

![Dimerization of aziridine aldehydes](image)

**Figure 1.3** Synthetic Utility of aziridine aldehydes

Multi-component reactions (MCR) are classified as reactions in which three or more components come together to form one product. This convergence of three or more reactants in one pot serves to greatly increase molecular complexity in one step. One of our long-standing goals in the Yudin lab has been to develop MCRs that utilize aziridine aldehyde as a linchpin, bringing together the other two components of the reaction. However, to rationally develop new reactions of this type, it would be beneficial to quantify the nucleophilicity of aziridine, as it would provide some valuable information as to the reactivity of these compounds relative to other nucleophiles. The strained ring geometry in aziridine results in the lone pair of electrons on nitrogen having
increased s-character, which should reduce its nucleophilicity to some degree.\(^4\) However, as a result of this geometry the nitrogen lone pair is more sterically accessible than in other cyclic secondary amines, which may increase its nucleophilicity. These two opposing factors make it difficult to predict the nucleophilicity of aziridine relative to other cyclic secondary amines. Herein we report the results of preliminary kinetic investigations into the determination of the nucleophilicity of aziridine relative to other cyclic secondary amines through UV/Vis spectroscopy. The kinetic experiments we performed are based on experiments reported by Dr. Herbert Mayr, who has utilized these kinetic experiments in the development of his scales of nucleophilicity and electrophilicity.\(^5\)

Since their discovery in 2011, α-boryl aldehydes ([1,2]-amphoteric) were shown to be effective building blocks in organic synthesis.\(^6\) From these molecules, α-boryl isocyanides have been accessed and utilized in the synthesis of boron-containing peptides and boron-containing heterocycles.\(^7\) Acyl boronates ([1,1]-amphoteric) have also proved valuable toward the rapid assembly of enzyme inhibitors.\(^8\) This chemistry is enabled by the N-methyliminodiacetyl (MIDA) group on boron. This ligand attenuates the Lewis acidity of boron’s empty \(p\)-orbital, allowing these molecules to tolerate a wide range of chemical conditions by way of its ability to force boron to adopt a tetracoordinate geometry, thus preventing coordination to Lewis bases.\(^9\)

Through exploiting the stabilizing effects of MIDA, we have attempted the synthesis of [1,1]-amphoteric MIDA-boryl formate and MIDA-boryl formic acid in order to investigate their synthetic utility in the synthesis of boron-containing molecules with BC(\(\text{O}\))O structural motifs (Figure 1.4). During this investigation, we screened different oxidations of hydroxymethyl MIDA boronate, to varying degrees of success. Herein we report efforts in this regard.

![Figure 1.4][1,1]-amphoteric molecules

In addition, Mr. Sherif Kaldas has developed a procedure for the rapid access to previously unreported borylated ketenimines. These borylated ketenimines represent a new class of [1,2]-amphoteric molecules, and have proven to be valuable reactive intermediates that can be trapped
in situ with different reaction partners to access $\alpha$-borylazetidimines and 3-boryliminocoumarins (Figure 1.5). My efforts in this project were centered around probing the scope of the reaction that Mr. Sherif Kaldas has developed. I have demonstrated the compatibility of this reaction with a wide range of substrates, now comprising a large collection of $\alpha$-borylazetidimines and 3-boryliminocoumarins.

![Figure 1.5 Diverse array of products accessible through borylated ketenimine intermediate.](image)

2 Results and Discussion

2.1 Kinetics of Aziridine Nucleophilicity

Aziridines are cyclic secondary amines, and little is known about the nucleophilic character of the lone pair of electrons on its nitrogen. In order to better understand this phenomenon, we can compare the rates of reaction of aziridine to those of other small, cyclic secondary amines, such as piperidine and pyrrolidine.

Dr. Herbert Mayr has done extensive work on developing scales of nucleophilicity and electrophilicity for a wide range of organic compounds.\(^5\) In the Mayr scale of nucleophilicity there are experimentally determined nucleophilicity parameters for both piperidine and pyrrolidine, however, no results have been published relating to aziridine in this regard. It would be useful to understand aziridine’s strength as a nucleophile relative to other small, cyclic secondary amines, as this information could potentially aid in the rational design of MCRs with aziridine aldehydes.

Past efforts in our lab attempting to understand the nucleophilicity of aziridine were based on amine acylation reactions with benzoyl chloride or naphthoyl chloride. These were monitored
by UV/Vis spectroscopy. The problem encountered was that there was insufficient resolution between the absorbance of the benzoyl/naphthoyl chloride and the amide product.

In 2013, in a paper published by Dr. Herbert Mayr, kinetic experiments between amines and \textit{p}-nitrophenyl benzoate monitored by UV/Vis spectroscopy were reported.\textsuperscript{5} Piperidine and pyrrolidine, two examples of small, cyclic secondary amines were included in this study.\textsuperscript{5} When an amine reacts with \textit{p}-nitrophenyl benzoate, the products are an amide and a \textit{p}-nitrophenolate anion, which absorbs strongly at 436 nm (Figure 2.1). There is no interference from any of the other reaction components at this wavelength.

\textbf{Figure 2.1} Basic reaction scheme for kinetic experiments

First, we reproduced the experiments of \textit{p}-nitrophenyl benzoate (1) with piperidine and pyrrolidine. In both cases, the kinetic experiments were run with the amine in large excess to ensure pseudo-first order reaction conditions. For both piperidine and pyrrolidine, the experiments were run with 20, 30, 40, 50, and 60 equivalents of amine. The slope of the initial linear region of the plot of absorbance vs. time was determined to be the rate constant, \(k_{\text{obs}}\). Then, each of the five \(k_{\text{obs}}\) values were plotted against their respective amine concentrations, and the slope was determined to be the second order rate constant, \(k_2\) (Figure 2.2). The second order rate constant was 2.90 x 10\textsuperscript{1} s\textsuperscript{-1} M\textsuperscript{-1} for piperidine and 1.07 x 10\textsuperscript{2} s\textsuperscript{-1} M\textsuperscript{-1} for pyrrolidine. These results indicate that pyrrolidine is a better nucleophile than piperidine, as it reacts faster with 1.
Figure 2.2 Determination of second order rate constants for piperidine and pyrrolidine

We then attempted to measure $k_{\text{obs}}$ and $k_2$ for azetidine and 2-methylaziridine, which we had access to as hydrochloride salts. However, we were unable to neutralize and isolate the amines due to their volatility as free bases. Instead of proceeding with those compounds, we obtained cyclic secondary amines that were prepared by Dr. Benjamin Chung during his time as a graduate student in our lab (Figure 2.3).

Figure 2.3 Substituted secondary amines 3 and 4

For the purpose of comparing the reaction rates of the $(2R,3R)$-$N$-butyl-3-methylaziridine-2-carboxamide (3) and $(S)$-$N$-butylpyrrolidine-2-carboxamide (4), only the magnitude of the rate constant, $k_{\text{obs}}$, is needed, as the concentrations of all reagents are kept constant and the only component differing between the two experiments is the amine being used. For the purposes of comparing the nucleophilicity of these two amines to pyrrolidine, we performed the experiments...
under the same conditions as before, using 60 eq. of amine. Under these conditions, the \( k_{\text{obs}} \) value for pyrrolidine was determined to be 2.65 \( \times 10^{-2} \text{ s}^{-1} \), and 4.65 \( \times 10^{-5} \text{ s}^{-1} \) for 4 (Table 2.1). This data shows pyrrolidine reacting over 500 times faster than 4. Surprisingly, the reactivity of 3 was exceedingly poor under these conditions, as after one hour the absorbance had not changed.

Table 2.1 Rate constants for the reactions of 1 with pyrrolidine, 4, and 3 in DMSO (Dual beam UV/Vis spectrophotometer, 25 °C, \( \lambda = 436 \text{ nm} \)).

<table>
<thead>
<tr>
<th>amine (2.00 x 10^{-3} M)</th>
<th>[1]_0 (M)</th>
<th>[amine]_0 / [1]_0</th>
<th>( k_{\text{obs}} ) (s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>pyrrolidine</td>
<td>3.34 x 10^{-5}</td>
<td>60</td>
<td>2.65 x 10^{-2}</td>
</tr>
<tr>
<td>4</td>
<td>3.34 x 10^{-5}</td>
<td>60</td>
<td>4.65 x 10^{-5}</td>
</tr>
<tr>
<td>3</td>
<td>3.34 x 10^{-5}</td>
<td>60</td>
<td>No Reaction</td>
</tr>
</tbody>
</table>

Due to the poor reactivity of 3 at low concentration in the cuvette (3.34 x 10^{-5} M 1), we repeated the reaction of both amines 3 and 4 at significantly higher concentration – 1 eq. 1 (1.00 x 10^{-3} M), 60 eq. amine, and 60 eq. Hünig’s base. Without the addition of base, the reaction with 3 did not proceed. The \( k_{\text{obs}} \) was 2.14 \( \times 10^{-2} \text{ s}^{-1} \) for 4, and 6.08 \( \times 10^{-4} \) for 3 (Table 2.2). In this case, the aziridine-containing compound (3) reacts about 35 times slower than the pyrrolidine-containing compound (4).

Table 2.2 Rate constants for the reactions of 1 with 4, and 3 in DMSO at significantly increased concentration, and 60 eq. of DIPEA (Dual beam UV/Vis spectrophotometer, 25 °C, \( \lambda = 436 \text{ nm} \)).

<table>
<thead>
<tr>
<th>amine (6 x 10^{-2} M)</th>
<th>[1]_0 (M)</th>
<th>[amine]_0 / [1]_0</th>
<th>( k_{\text{obs}} ) (s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.00 x 10^{-3}</td>
<td>60</td>
<td>2.14 x 10^{-2}</td>
</tr>
<tr>
<td>3</td>
<td>1.00 x 10^{-3}</td>
<td>60</td>
<td>6.08 x 10^{-4}</td>
</tr>
</tbody>
</table>

These results suggest that aziridine is a weaker nucleophile than pyrrolidine. Further analysis is warranted to get a clear understanding of aziridine’s nucleophilicity. It would be valuable to compare the rates of amine acylation between piperidine, pyrrolidine, azetidine, and aziridine, then repeat that same set of experiments with all of the amines having identical
substitution patterns. It may be the case that the methyl groups in 2-methylaziridine and 2-methylpiperidine have varying effects on reducing their respective nucleophilicities. Coming back to the original goal of this study, it is necessary to run these kinetic experiments with the aziridine aldehyde dimer as that is ultimately the compound that we would have interest in using to rationally design MCRs.

2.2 Efforts toward Synthesis of BC(O)O Structural Motif

MIDA-boryl formate and MIDA-boryl formic acid, if they could be prepared, would both be examples of [1,1]-amphoteric molecules. As these are among two of the simplest B(MIDA) building blocks one could potentially make, having the ability to investigate their synthetic utility would be a worthwhile venture. Despite the fact we were unsuccessful in synthesizing both MIDA-boryl formate and MIDA-boryl formic acid, we were successful in preparing a unique ester from the oxidation of hydroxymethyl MIDA boronate. These investigations are reported in this work.

Before screening different oxidation conditions to try to obtain MIDA-boryl formate and MIDA-boryl formic acid, initial attempts to access MIDA-boryl formate began with trying a dithiane deprotection of a MIDA-boryl dithiane compound prepared by Dr. Shinya Adachi (Figure 2.4).

![Figure 2.4](image_url) Unsuccessful dithiane deprotections

First, the reaction was run in acetonitrile, with mercury (II) oxide as well as with mercury (II) chloride. Mercury (II) oxide resulted in recovery of the starting material, while with mercury (II) chloride a new compound appeared by TLC, but with low conversion. After observing that solubility in acetonitrile may have been an issue, the reaction was repeated with mercury (II)
chloride in DMSO. Unfortunately, none of these conditions yielded MIDA-boryl formate in isolable yield.

All subsequent efforts to synthesize MIDA-boryl formate were based on the oxidation of hydroxymethyl MIDA boronate (5), which was prepared according to literature procedures.\textsuperscript{8b} We were unsuccessful in preparing MIDA-boryl formate via the Ley oxidation and the Pfitzner-Moffatt oxidation (Figure 2.5). Both sets of conditions resulted in recovery of starting material.

![Figure 2.5 Unsuccessful oxidations of 5](image)

The most promising results that we obtained came through utilizing a set of mild aerobic oxidation conditions published by Dr. Shannon Stahl’s group in 2011.\textsuperscript{10} This seemed like a potentially promising method to oxidize 5 to MIDA-boryl formate, but when we performed the reaction with catalytic amounts of the reagents, we only recovered starting material (Figure 2.6). Repeating these conditions under oxygen atmosphere yielded the same result.

![Figure 2.6 Unsuccessful aerobic oxidation of 5](image)

We then modified the reaction using stoichiometric amounts of each of the reagents, and after 2.5 hours we observed complete conversion to a new TLC spot, slightly less polar than the starting material. We isolated the product via column chromatography, and identified it by $^1$H NMR, $^{11}$B NMR, and $^{13}$C NMR as an ester containing two B(MIDA) groups (6) (Figure 2.7), and the BC(O)O structural motif. Considering the fact that the yield was low, only 18%, we repeated
the reaction under oxygen atmosphere. Gratifyingly, the reaction was completed in just 30 minutes and the isolated yield increased to 42% (Figure 2.8).

![Figure 2.7](image_url) Aerobic oxidation of 5 with stoichiometric amounts of all reagents

![Figure 2.8](image_url) Aerobic oxidation of 5 with stoichiometric amounts of all reagents, under oxygen atmosphere.

It would appear that 6 is formed by first oxidation of 5 to MIDA-boryl formate or MIDA-boryl formic acid before being trapped by another molecule 5. Based on this hypothesis we repeated the reaction in trifluoroethanol instead of acetonitrile. The result was a trifluoroethanol-containing ester (7) with an isolated yield of 23% (Figure 2.9). We ran into problems purifying 7 as the reaction was not clean, and the small amount that we isolated still had impurities. We were not able to get a clean $^{13}$C NMR spectrum, but $^1$H NMR and $^{11}$B NMR point to the formation of the mixed ester product.

![Figure 2.9](image_url) Aerobic oxidation of 5 in trifluoroethanol

One general issue that we encountered using this chemistry is that due to the high amounts of copper catalyst needed in the reaction, the product is often contaminated with copper. It is difficult to remove entirely. An aqueous workup with a saturated solution of ammonium chloride
is often used to remove copper from organic compounds, however, this caused decomposition of 6. These difficulties prompted the investigation into another oxidation of 5, originally tried by Dr. Shinya Adachi during his time in our lab. This protocol uses trichloroisocyanuric acid (Figure 2.10), and the difficulty with this method is that the product is contaminated with isocyanuric acid, a byproduct of the reaction.

![Figure 2.10 Oxidation of 5 using trichloroisocyanuric acid](image)

Although we were unsuccessful in synthesizing MIDA-boryl formate and MIDA-boryl formic acid, we were successful in synthesizing 6, which is important because it contains the BC(O)O structural motif. It would be interesting to further investigate the chemistry of this compound, particularly to see if the right ester hydrolysis conditions can be found to furnish the coveted MIDA-boryl formic acid compound.

## 2.3 Synthesis and Reactivity of Borylated Ketenimines

Borylated ketenimines can be synthesized *in situ* utilizing copper catalysis from sulfonyl azides and ethynyl MIDA boronate. Borylketenimines represent a new class of [1,2]-amphoteric compounds. They differ from previously reported [1,2]-amphoteric molecules based on the oxidation state of the carbons separating the nucleophilic and electrophilic centers. These intermediates can be utilized to quickly access a diverse range of structurally complex products such as α-borylazetidimines and 3-boryliminocoumarins from simple starting materials. In Figure 2.11, a plausible catalytic cycle for the formation of the borylated ketenimine is shown. The key step in this mechanism is the irreversible extrusion of N₂.

![Chemical structure](image)

Specifically, I contributed to this work by probing the scope of the reaction of the borylketenimine intermediates by trapping them *in situ* with imines to form α-borylazetidimines and with salicylaldehyde derivatives to form 3-boryliminocoumarins (Figure 2.12).
2.3.1 Synthesis of $\alpha$-Borylated Azetidimines

Ketenimines have been shown in the past to undergo formal [2+2] cyclizations with imines to form azetidimines.$^{11}$ Mr. Sherif Kaldas has demonstrated that the borylated ketenimine intermediate could be trapped in situ with a biphenyl imine to furnish $\alpha$-borylated azetidimines. With this chemistry in hand, I sought to probe the scope of the reaction for the purpose of determining its compatibility with a wide range of imines, and develop a collection of $\alpha$-borylated azetidimines (Table 2.3). All imines were prepared according to literature procedures.$^{12}$
Table 2.3 Substrate scope for α-borylazetidimine formation. Reactions were run for 24 h at room temperature. Yields determined by crude $^1$H NMR using trichloroethylene as internal standard. $^a$ cis product lost during isolation. $^b$ trans product lost during isolation.

Excellent selectivity for the trans-α-borylazetidimine was observed when the borylated ketenimine was trapped with aniline-derived imines. When the imine that is employed is derived from an aliphatic amine, the reaction proceeds faster, however, the trans:cis selectivity drops off substantially. This is attributed to the increased basicity of the imine nitrogen in those with aliphatic groups on nitrogen compared to the basicity of the imine nitrogen in the aniline-derived imines.

In order to determine the origin of trans:cis control in this reaction, a sample of 11k (1:1.1 trans:cis) was subjected to 2 equivalents of triethylamine for 24 hours. The result was complete epimerization to the trans-isomer of 11k (Figure 2.13), suggesting that the trans-α-borylazetidimine is the thermodynamically favored product.
Following the synthesis of a collection of $\alpha$-borylazetidimines, Mr. Sherif Kaldas optimized a procedure for removing the nosyl protecting group from the nosyl-protected $\alpha$-borylazetidimines using cesium carbonate and SiliaMetS® Thiol (Table 2.4). By TLC, the deprotections showed quantitative conversion to the free N-H $\alpha$-borylazetidimine after 5 hours. The reactions were quite clean, showing only minor protodeborylation, however, due to the high polarity of the compounds, the isolated yields were low, and do not correspond to the efficiency of the reaction.

Table 2.4 Scope of nosyl deprotections. Reactions were complete in 5 hours at 65 °C. Yields are isolated.
This work shows that the protocol for preparing α-borylazetidimines with aryl imines as reaction partners gives excellent selectivity for the *trans* product across a range of different substrates. When paired with aliphatic imines, the reaction proceeds faster, but with reduced *trans:cis* selectivity. Through probing the scope of the reaction I successfully showed its compatibility with a wide range of different substrates. This demonstrates the synthetic utility of the protocol developed by Mr. Sherif Kaldas in the preparation of α-borylazetidimines that are otherwise synthetically challenging to prepare.

### 2.3.2 Synthesis of 3-Boryliminocoumarins

In addition to trapping the borylated ketenimine *in situ* with pre-formed imines, Mr. Sherif Kaldas showed that it could be successfully trapped with salicylaldehyde, furnishing a 3-boryliminocoumarin. This procedure is identical to that of the α-borylazetidimine formation, however, it was found that Hünig’s base was more suitable for this reaction than N-methylmorpholine. I expanded the scope of this reaction by showing the compatibility of this procedure with a collection of different salicylaldehyde derivatives (Table 2.5). This further expands the synthetic utility of the protocol developed by Mr. Sherif Kaldas.

**Table 2.5** Substrate scope for 3-boryliminocoumarin formation. Reactions were complete in 24 hours at room temperature. Yields determined by crude ¹H NMR using trichloroethylene as internal standard.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Reaction</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="14a" /></td>
<td>R¹ = Ts, 93%</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="14b" /></td>
<td>R¹ = Ts, 75%</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="14c" /></td>
<td>R¹ = Ts, 23%</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="14d" /></td>
<td>R¹ = Ts, 66%</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="14e" /></td>
<td>R¹ = Ns, 47%</td>
<td></td>
</tr>
</tbody>
</table>
3 Conclusion

Preliminary investigations into the nucleophilicity of aziridine suggest that it is less nucleophilic compared to other small, cyclic secondary amines. Further investigation will be needed to determine this for certain by employing a wide range of small, cyclic secondary amines with different substitution patterns.

Efforts toward synthesizing MIDA-boryl formate and MIDA-boryl formic acid were unsuccessful. However, through aerobic oxidation of hydroxymethyl MIDA boronate, we successfully prepared an ester product with two B(MIDA) groups. This compound is unique because it contains the BC(O)O structural motif. Further investigation into hydrolysis of this ester is warranted, as success with that would yield MIDA-boryl formic acid.

The procedure developed by Mr. Sherif Kaldas for the rapid synthesis of borylated ketenimine intermediates was utilized to successfully synthesize a collection of α-borylazetidimines and 3-boryliminocoumarins. I probed the scope of these reactions and extended their synthetic utility. By trapping the borylated ketenimine intermediate in situ with imines to form α-borylazetidimines, the procedure was shown to be compatible with a wide range of substrates. With aryl-imines, excellent selectivity for the trans-α-borylazetidimine was observed. With aliphatic-imines, the reaction proceeded faster, but with diminished trans:cis selectivity. In addition, in the procedure developed by Mr. Sherif Kaldas to rapidly access 3-boryliminocoumarins, I demonstrated its tolerance to a collection of different salicylaldehyde derivatives.

4 Experimental Procedures

**General Information:** Acetonitrile was purchased and kept over 3Å molecular sieves, under Argon. All other solvents were of reagent grade quality. Unless otherwise noted, all reagents were purchased from commercial sources and used as received.

**Chromatography:** Flash column chromatography was performed using Silicycle 230-400 mesh silica gel. Thin-layer chromatography (TLC) was performed on Machery Nagel pre-coated glass backed TLC plates (SIL G/UV254, 0.25 mm) and visualized using a UV lamp (254 nm). KMnO₄ or curcumin stain were used when necessary.
Nuclear Magnetic Resonance Spectroscopy: $^1$H NMR experiments were performed on Bruker Advance III 400 MHz or Varian 300, 400, or 500 MHz spectrometers. $^1$H NMR spectra chemical shifts are reported in parts per million (ppm) with deuterated solvents, referenced to the residual protonated solvent peak (Chloroform-$d$, $\delta = 7.26$ ppm; DMSO-$d_6$, $\delta = 2.50$ ppm; Acetonitrile-$d_3$, $\delta = 1.94$ ppm). All $^1$H NMR spectral data is reported as: chemical shift (ppm), multiplicity (s = singlet; d = doublet; t = triplet; q = quartet; dd = doublet of doublets; dt = doublet of triplets; dq = doublet of quartets; ddd = doublet of doublet of doublets; dddd = doublet of doublet of doublet of doublets; ddt = doublet of doublet of triplets; dt = triplet of doublets; tt = triplet of triplets; ttt = triplet of triplet of triplets), coupling constant ($J$) in Hz, and integration. $^{13}$C NMR experiments were performed on Bruker Advance III 400 MHz or Varian 500 MHz spectrometers. $^{13}$C NMR spectra chemical shifts are reported in ppm with deuterated solvents (Chloroform-$d$, $\delta = 77.16$ ppm; DMSO-$d_6$, $\delta = 39.52$ ppm; Acetonitrile-$d_3$, $\delta = 118.26$ ppm). $^{11}$B NMR spectra were recorded on a Bruker Advance III 400 MHZ spectrometer and referenced to an external standard of BF$_3$·Et$_2$O. $^{11}$B NMR spectra chemical shifts are reported in ppm.

Mass Spectrometry: High resolution mass spectra were obtained using an ABI/Sciex Qstar mass spectrometer with ESI source, MS/MS and accurate mass capabilities, or alternatively using a JEOL AccuTOF-DART instrument.

UV/Vis Spectroscopy: Kinetic data was collected every 0.1 seconds using a Lambda 25 UV/Vis Spectrometer with spectral range of 190 nm to 1100 nm (double beam instrument) with 10 mm light path. All kinetic measurements were carried out in glass cuvettes at 436 nm.

4.1 Protocols for Kinetics of Aziridine Nucleophilicity

Preparation of $p$-nitrophenyl benzoate (1): To a 50-mL round-bottom flask was added $p$-nitrophenol (10 mmol, 1.0 eq.) and benzoyl chloride (11 mmol, 1.1 eq.). After dissolving in toluene (30 mL, 0.33 M), 4-dimethylaminopyridine (0.5 mmol, 0.05 eq.) was added. The reaction mixture was stirred at reflux for 7 h, at which time all of the starting material had been consumed. Then, 20 mL of hexane was added to crash out the DMAP-HCl that formed during the reaction. The contents of the flask were filtered through a pad of celite, and the filtrate was concentrated under reduced pressure. The crude residue was purified via column chromatography (silica gel, hexane:ether v/v: 19:1, 9:1, 17:3, 1:1). 70% isolated yield.
1  **p-Nitrophenyl benzoate**

$^1$H NMR (500 MHz, DMSO-$d_6$) $\delta$ 8.38 – 8.34 (m, 2H), 8.19 – 8.15 (m, 2H), 7.81 – 7.76 (m, 1H), 7.66 – 7.62 (m, 4H).

$^{13}$C NMR (126 MHz, DMSO-$d_6$) $\delta$ 163.93, 155.51, 145.19, 134.43, 130.00, 129.05, 128.30, 125.31, 123.39.

**Protocol for Kinetic Experiments:** $p$-Nitrophenyl benzoate (1) is the electrophile used in all kinetic experiments. The rates of its reaction with different amines in DMSO were determined using UV/Vis spectroscopy. The reaction is tracked by the appearance of the 1 anion which absorbs strongly at 436 nm. Stock solutions of 1 were prepared immediately prior to running the kinetic studies. The kinetics studies were performed under pseudo-first order conditions by using excess amine (20–60 equivalents). In order to determine the first order rate constants, $k_{\text{obs}}$, time was plotted vs. absorbance. The slope of the initial linear region of the plot is equal to $k_{\text{obs}}$. The second-order rate constants, $k_2$ were determined for both piperidine and pyrrolidine by plotting the $k_{\text{obs}}$ vs. amine concentration. From these plots, the value of $k_2$ is equal to the slope. All experiments were run in triplicate. Piperidine and pyrrolidine were distilled prior to use.

**Protocol for NMR-Scale Reactions:** To show that the 1 benzoate reacts completely with the amine nucleophiles under study, an NMR scale reaction was done with each nucleophile. The general protocol for these experiments with piperidine and pyrrolidine was to mix 1 (0.04 mmol, 1.0 eq.) with each amine nucleophile (0.08 mmol, 2.0 eq.) in 0.6 mL deuterated DMSO. For the reactions with the other two amines 3 and 4, 2.0 eq. of DIPEA was also added to the mixture to accurately reflect the conditions used for the kinetic experiments.

### 4.2 Protocols for Efforts toward the Synthesis of BC(O)O Structural Motif

**Preparation of 6:** To a solution of 5 (1.0 mmol, 1.0 eq.) in dry acetonitrile (1 mL), was added the following:
1. [Cu(MeCN)$_4$]PF$_6$ (1.0 mmol, 1.0 eq.) in 1 mL dry acetonitrile

2. 2,2'-dipyridyl (1.0 mmol, 1.0 eq.) in 1 mL dry acetonitrile

3. TEMPO (1.0 mmol, 1.0 eq.) in 1 mL dry acetonitrile

4. N-methylimidazole (1.0 mmol, 1.0 eq.) in 1 mL dry acetonitrile

The reaction mixture was stirred vigorously at room temperature, under oxygen atmosphere, for 30 min. The reaction mixture will be brown in color at the beginning and will slowly turn blue. The reaction is monitored by TLC (1:1 acetonitrile:ethyl acetate, curcumin stain), and upon completion, the reaction mixture is concentrated under reduced pressure. The crude residue was purified by column chromatography (silica gel, ethyl acetate; 3:2 ethyl acetate:acetonitrile; acetonitrile). Isolated yield of 42%.

6 (6-methyl-4,8-dioxo-1,3,6,2-dioxazaborocan-2-yl)methyl 6-methyl-4,8-dioxo-1,3,6,2-dioxazaborocane-2-carboxylate

$^1$H NMR (400 MHz, DMSO-$d_6$) $\delta$ 4.39 (d, $J = 17.2$ Hz, 2H), 4.32 (d, $J = 17.1$ Hz, 2H), 4.03 (d, $J = 17.2$ Hz, 2H), 3.92 (d, $J = 17.0$ Hz, 2H), 3.66 (s, 2H), 2.95 (s, 3H), 2.85 (s, 3H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 10.99, 5.56.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 169.02, 168.76, 63.08, 62.82, 47.95, 47.04.

**Alternative Procedure for Preparation of 6:** To a solution of 5 (0.27 mmol, 1.0 eq.) in dry acetonitrile (2.5 mL), was added TEMPO (0.027 mmol, 0.1 eq.) and trichloroisocyanuric acid (0.027 mmol, 1.05 eq.). The reaction mixture was stirred at room temperature for 2 hours. Upon completion, the reaction mixture was concentrated under reduced pressure. The crude residue was purified by column chromatography (silica gel, 1:1 hexane:ethyl acetate; ethyl acetate; 9:1 ethyl acetate:acetonitrile; 7:3 ethyl acetate:acetonitrile; 1:1 ethyl acetate:acetonitrile). Isolated yield of 41%.
4.3 Protocols for Borylated Ketenimine Reactions

Procedure A for Imine Formation\textsuperscript{12a}: To a solution of amine (1.0 eq.) in toluene (0.5 M) in a round-bottom flask, aldehyde (1.0 eq.) was added. The mixture was refluxed for 24 h using a Dean Stark water separator. After 24 h, the reaction mixture was concentrated under reduced pressure, yielding the imine product.

\begin{center}
\includegraphics[width=0.2\textwidth]{image}
\end{center}

10c/d \textit{(E)-1-(2-fluorophenyl)-N-phenylmethanimine} \\
100% isolated yield. \\
\textsuperscript{1}H NMR (500 MHz, Chloroform-\textit{d}) \(\delta\) 8.84 (s, 1H), 8.29 – 8.23 (m, 1H), 7.50 – 7.43 (m, 3H), 7.32 – 7.25 (m, 4H), 7.18 – 7.14 (m, 1H).
\textsuperscript{13}C NMR (126 MHz, Chloroform-\textit{d}) \(\delta\) 163.90, 161.89, 153.45, 151.96, 132.98, 129.22, 127.93, 126.35, 124.52, 124.01, 121.05, 115.89.

\begin{center}
\includegraphics[width=0.2\textwidth]{image}
\end{center}

11e/f \textit{(E)-1-phenyl-N-(3-(trifluoromethyl)phenyl)methanimine} \\
98% isolated yield. \\
\textsuperscript{1}H NMR (500 MHz, Chloroform-\textit{d}) \(\delta\) 8.46 (s, 1H), 7.96 – 7.91 (m, 2H), 7.56 – 7.46 (m, 6H), 7.40 – 7.36 (m, 1H).
\textsuperscript{13}C NMR (126 MHz, Chloroform-\textit{d}) \(\delta\) 161.88, 152.64, 135.87, 132.01, 129.81, 129.15, 128.99, 124.29, 124.28, 122.54, 122.51, 117.91.

\begin{center}
\includegraphics[width=0.2\textwidth]{image}
\end{center}

11g/h \textit{(E)-1-(3-methoxyphenyl)-N-phenylmethanimine} \\
99% isolated yield.
$^1$H NMR (500 MHz, Chloroform-$d$) $\delta$ 8.45 (s, 1H), 7.59 (dd, $J = 2.7, 1.4$ Hz, 1H), 7.47 – 7.39 (m, 4H), 7.31 – 7.26 (m, 3H), 7.09 (ddd, $J = 8.1, 2.7, 1.2$ Hz, 1H), 3.90 (s, 3H).

$^{13}$C NMR (126 MHz, Chloroform-$d$) $\delta$ 160.27, 160.01, 151.97, 137.65, 129.74, 129.18, 126.01, 122.37, 120.93, 118.30, 111.89, 55.37.

10i/j  \( (E)-N-(4\text{-bromo-2-methylphenyl})-1\text{-phenylmethanimine} \)

95% isolated yield.

$^1$H NMR (500 MHz, Chloroform-$d$) $\delta$ 8.34 (s, 1H), 7.95 – 7.90 (m, 2H), 7.52 – 7.46 (m, 3H), 7.40 – 7.36 (m, 1H), 7.33 (dd, $J = 8.3, 2.2$ Hz, 1H), 6.81 (d, $J = 8.2$ Hz, 1H), 2.35 (d, $J = 0.9$ Hz, 3H).

$^{13}$C NMR (126 MHz, Chloroform-$d$) $\delta$ 159.93, 150.18, 136.31, 134.36, 133.09, 131.61, 129.72, 128.94, 128.92, 119.28, 118.87, 17.84.

**Procedure B for Imine Formation**$^{12b}$: To a solution of aldehyde (1.0 eq.) in dichloromethane (0.33 M) over 4 Å molecular sieves in a round-bottom flask, amine (1.0 eq.) was added. The mixture was stirred at room temperature for 6-24 h under nitrogen. Upon completion, the reaction mixture was filtered through a pad of celite and concentrated under reduced pressure to yield the imine product.

10a/b  \( (E)-1\text{-}(4\text{-methoxyphenyl})-N\text{-phenylmethanimine} \)

89% isolated yield.

$^1$H NMR (500 MHz, Chloroform-$d$) $\delta$ 8.39 (t, $J = 0.4$ Hz, 1H), 7.90 – 7.85 (m, 2H), 7.42 – 7.36 (m, 2H), 7.25 – 7.19 (m, 3H), 7.01 – 6.97 (m, 2H), 3.88 (s, 3H).

$^{13}$C NMR (126 MHz, Chloroform-$d$) $\delta$ 162.42, 159.81, 130.70, 129.39, 129.23, 125.71, 120.99, 115.19, 114.32, 55.55.
10k/l (E)-N-cyclohexyl-1-phenylmethanimine
88% isolated yield.
$^1$H NMR (500 MHz, Chloroform-$d$) $\delta$ 8.32 (d, $J = 0.7$ Hz, 1H), 7.78 – 7.72 (m, 2H), 7.43 – 7.37 (m, 3H), 3.26 – 3.17 (m, 1H), 1.91 – 1.82 (m, 2H), 1.81 – 1.73 (m, 2H), 1.73 – 1.58 (m, 3H), 1.46 – 1.24 (m, 3H).
$^{13}$C NMR (126 MHz, Chloroform-$d$) $\delta$ 158.53, 136.65, 130.30, 128.50, 128.06, 69.99, 34.41, 25.70, 24.84.

10m/n (E)-1-(4-chlorophenyl)-N-cyclohexylmethanimine
100% isolated yield.
$^1$H NMR (500 MHz, Chloroform-$d$) $\delta$ 8.27 – 8.25 (m, 1H), 7.68 – 7.63 (m, 2H), 7.38 – 7.33 (m, 2H), 3.18 (tt, $J = 10.5, 4.1$ Hz, 1H), 1.87 – 1.79 (m, 2H), 1.76 – 1.64 (m, 3H), 1.63 – 1.52 (m, 2H), 1.41 – 1.21 (m, 3H).
$^{13}$C NMR (126 MHz, Chloroform-$d$) $\delta$ 157.28, 136.28, 135.21, 129.34, 128.85, 70.03, 34.43, 25.73, 24.86.

10o/p (E)-N-(4-methylbenzyl)-1-phenylmethanimine
88% isolated yield.
$^1$H NMR (500 MHz, Chloroform-$d$) $\delta$ 8.43 (s, 1H), 7.86 (h, $J = 4.0, 3.2$ Hz, 2H), 7.48 (dt, $J = 6.6, 3.1$ Hz, 3H), 7.31 (d, $J = 7.8$ Hz, 2H), 7.26 – 7.19 (m, 2H), 4.86 (s, 2H), 2.41 (s, 3H).
$^{13}$C NMR (126 MHz, Chloroform-$d$) $\delta$ 161.81, 136.59, 136.25, 130.77, 129.25, 128.63, 128.35, 128.04, 64.82, 21.19.
10q/r  
\((E)-N-t\text{-butyl-(4-methoxyphenyl)methanimine}\)

72% isolated yield.

\(^1\)H NMR (500 MHz, Chloroform-\(d\)) \(\delta\) 8.22 (s, 1H), 7.73 – 7.66 (m, 2H), 6.95 – 6.89 (m, 2H), 3.82 (s, 3H), 1.29 (s, 9H).

\(^{13}\)C NMR (126 MHz, Chloroform-\(d\)) \(\delta\) 161.35, 154.54, 130.22, 129.44, 113.94, 56.98, 55.38, 29.90.

10s/t  
\((E)-N-t\text{-butyl-(4-nitrophenyl)methanimine}\)

90% isolated yield.

\(^1\)H NMR (500 MHz, Chloroform-\(d\)) \(\delta\) 8.33 (s, 1H), 8.27 – 8.23 (m, 2H), 7.94 – 7.89 (m, 2H), 1.32 (s, 9H).

\(^{13}\)C NMR (126 MHz, Chloroform-\(d\)) \(\delta\) 153.03, 148.92, 142.78, 128.74, 123.92, 58.36, 29.64.

**General Procedure for \(\alpha\)-Borylazetidimine Formation:** To a flame-dried 5-mL round-bottom flask equipped with a Teflon-coated stir bar and septum, was added sulfonyl azide (0.5 mmol, 1 eq.), dry acetonitrile (0.5 M), N-methylmorpholine (1 mmol, 2 eq.), ethynylboronic acid MIDA ester (0.5 mmol, 1 eq.), the appropriate imine (0.75 mmol, 1.5 eq.), and copper (I) iodide (0.05 mmol, 0.1 eq.), sequentially. The reaction mixture was stirred for 24 h at room temperature under Argon. After 24 h there was complete consumption of the starting material. The reaction mixture was concentrated under reduced pressure, and dried under high vacuum for 30 minutes before NMR analysis of the crude mixture.

NMR yields were determined using trichloroethylene as an internal standard. The NMR sample was prepared by adding 1 eq. of trichloroethylene (in relation to the starting material) directly into the crude reaction mixture using an analytical balance. The entire mixture was dissolved in
deuterated acetonitrile. A 0.7 mL aliquot of the mixture was then transferred to a 5 mm NMR tube for $^1$H NMR analysis.

Products were isolated from the crude residue via column chromatography (silica gel, toluene:acetonitrile v/v (1% triethylamine) – 19:1, 9:1, 17:3, 5:1, 4:1). Yields reported in this section are isolated yields, many are diminished due to isolation difficulties.

11a $N$-((3S,4S,E)-4-(4-methoxyphenyl)-3-(4-methyl-2,6-dioxotetrahydro-2H-4λ_4,8λ_4-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-1-phenylazetidin-2-ylidene)-4-methylbenzenesulfonamide

Isolated Yield 77%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) δ 7.90 – 7.84 (m, 2H), 7.43 – 7.35 (m, 4H), 7.32 – 7.22 (m, 4H), 7.12 – 7.05 (m, 1H), 6.94 – 6.88 (m, 2H), 5.46 (d, $J = 2.3$ Hz, 1H), 4.29 (d, $J = 16.6$ Hz, 1H), 4.09 (d, $J = 17.4$ Hz, 1H), 4.05 – 3.94 (m, 2H), 3.76 (s, 3H), 3.33 (d, $J = 2.3$ Hz, 1H), 3.10 (s, 3H), 2.43 (s, 3H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) δ 11.38.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) δ 168.90, 168.28, 167.46, 160.89, 144.14, 141.23, 138.10, 130.47, 130.28, 129.95, 128.65, 127.09, 125.92, 119.23, 115.35, 65.19, 63.98, 63.78, 55.93, 47.60, 30.85, 21.49.

HRMS (ESI) [MH]$^+$ calculated 562.17, found 562.1819
11b  \[N-((3R,4S,E)-4-(4-methoxyphenyl)-3-(4-methyl-2,6-dioxotetrahydro-2H-4\lambda_4,8\lambda_4-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-1-phenylazetidin-2-ylidene)-4-nitrobenzenesulfonamide\]

Isolated Yield 30%.

\(^1\)H NMR (400 MHz, Acetonitrile-\(d_3\)) \(\delta\) 8.39 – 8.33 (m, 2H), 8.23 – 8.18 (m, 2H), 7.43 – 7.37 (m, 2H), 7.35 – 7.31 (m, 2H), 7.30 – 7.25 (m, 2H), 7.14 – 7.09 (m, 1H), 6.95 – 6.89 (m, 2H), 5.49 (d, \(J = 2.2\) Hz, 1H), 4.18 (d, \(J = 16.7\) Hz, 1H), 4.09 (d, \(J = 17.5\) Hz, 1H), 4.06 – 3.94 (m, 2H), 3.76 (s, 3H), 3.40 (d, \(J = 2.2\) Hz, 1H), 3.04 (s, 3H).

\(^{11}\)B NMR (128 MHz, Acetonitrile-\(d_3\)) \(\delta\) 11.34.

\(^{13}\)C NMR (126 MHz, Acetonitrile-\(d_3\)) \(\delta\) 168.89, 168.34, 168.09, 161.00, 150.86, 149.51, 137.77, 130.04, 129.87, 129.73, 129.17, 128.82, 128.57, 126.39, 126.21, 125.25, 119.53, 115.40, 64.88, 63.87, 62.44, 55.95, 48.79, 47.63, 21.41.

HRMS (ESI) [MH]^+ calculated 593.14, found 593.1510

11c  \[N-((3R,4S,E)-4-(2-fluorophenyl)-3-(4-methyl-2,6-dioxotetrahydro-2H-4\lambda_4,8\lambda_4-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-1-phenylazetidin-2-ylidene)-4-methylbenzenesulfonamide\]

Isolated Yield 46%.

\(^1\)H NMR (400 MHz, Acetonitrile-\(d_3\)) \(\delta\) 7.89 – 7.83 (m, 2H), 7.38 (dddd, \(J = 7.7, 7.0, 3.6, 2.7\) Hz, 5H), 7.29 – 7.23 (m, 2H), 7.22 – 7.16 (m, 2H), 7.16 – 7.06 (m, 2H), 5.71 (d, \(J = 2.3\) Hz, 1H), 4.27 (d, \(J = 16.7\) Hz, 1H), 4.11 (d, \(J = 17.5\) Hz, 1H), 4.00 (t, \(J = 17.3\) Hz, 2H), 3.59 (d, \(J = 2.3\) Hz, 1H), 3.12 (s, 3H), 2.43 (s, 3H).

\(^{11}\)B NMR (128 MHz, Acetonitrile-\(d_3\)) \(\delta\) 11.03.
13C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 168.82, 168.32, 167.47, 162.90, 160.93, 144.15, 141.20, 138.86, 138.11, 131.68, 130.45, 130.05, 129.86, 129.75, 129.17, 127.06, 126.20, 125.97, 125.21, 118.84, 117.13, 116.96, 65.24, 64.17, 59.71, 47.83, 21.49.

HRMS (DART) [MH]$^+$ calculated 550.15, found 550.16125

11d  $\text{N-}((3R,4S,E)-4-(2\text{-fluorophenyl})-3-(4\text{-methyl}-2,6\text{-dioxotetrahydro-}2H-4\lambda_4,8\lambda_4\text{-}[1,3,2]\text{oxazaborolo}[2,3-b][1,3,2]\text{oxazaborol-8-yl})-1\text{-phenylazetidin-2-yldiene)-4-nitrobenzenesulfonamide}$

Isolated Yield 31%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) $\delta$ 8.39 – 8.33 (m, 2H), 8.22 – 8.17 (m, 2H), 7.44 – 7.35 (m, 4H), 7.31 – 7.26 (m, 2H), 7.22 – 7.16 (m, 2H), 7.15 – 7.11 (m, 1H), 5.72 (d, $J = 2.2$ Hz, 1H), 4.19 – 4.12 (m, 1H), 4.07 (d, $J = 3.3$ Hz, 1H), 4.01 (d, $J = 6.6$ Hz, 1H), 3.97 – 3.83 (m, 1H), 3.64 (d, $J = 2.2$ Hz, 1H), 3.07 (s, 3H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 11.04.

13C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 168.80, 168.48, 168.15, 162.92, 160.96, 150.86, 149.47, 137.78, 131.93, 131.86, 130.14, 129.97, 129.86, 129.16, 128.53, 126.44, 126.20, 126.00, 125.24, 124.71, 124.61, 119.14, 117.18, 117.01, 64.93, 64.02, 62.43, 59.96, 48.78, 47.82, 30.84, 21.40.

HRMS (ESI) [MH]$^-$ calculated 581.12, found 581.1323

11e  $4\text{-methyl-N-}((3R,4S,E)-3-(4\text{-methyl}-2,6\text{-dioxotetrahydro-}2H-4\lambda_4,8\lambda_4\text{-}[1,3,2]\text{oxazaborolo}[2,3-b][1,3,2]\text{oxazaborol-8-yl})-4\text{-phenyl-1-(3-}(\text{trifluoromethyl} \text{phenyl)azetidin-2-yldiene)benzenesulfonamide}$

Isolated Yield 39%.
\textbf{11f} \textit{N-((3R, 4S, E)-3-(4-methyl-2,6-dioxotetrahydro-2\textit{H}-4λ, 8λ-[1,3,2]oxazaborolo[2,3-\textit{b}][1,3,2]oxazaborol-8-yl)-4-phenyl-1-(3-(trifluoromethyl)phenyl)azetidin-2-ylidene)-4-nitrobenzenesulfonamide}

Isolated Yield 21%.

\textsuperscript{1}H NMR (400 MHz, Acetonitrile-d\textsubscript{3}) \(\delta\) 8.40 – 8.34 (m, 2H), 8.24 – 8.19 (m, 2H), 7.75 – 7.71 (m, 1H), 7.59 (dt, \(J = 7.8, 1.7\) Hz, 1H), 7.49 – 7.43 (m, 1H), 7.41 (dt, \(J = 1.7, 0.8\) Hz, 2H), 7.41 – 7.39 (m, 2H), 7.28 – 7.22 (m, 1H), 7.21 – 7.16 (m, 1H), 5.63 (d, \(J = 2.3\) Hz, 1H), 4.18 (d, \(J = 16.7\) Hz, 1H), 4.11 (d, \(J = 17.5\) Hz, 1H), 4.04 (d, \(J = 16.8\) Hz, 1H), 4.01 – 3.95 (m, 1H), 3.49 (d, \(J = 2.3\) Hz, 1H), 3.05 (s, 3H).

\textsuperscript{11}B NMR (128 MHz, Acetonitrile-d\textsubscript{3}) \(\delta\) 10.94.

\textsuperscript{13}C NMR (126 MHz, Acetonitrile-d\textsubscript{3}) \(\delta\) 168.84, 168.07, 151.00, 149.10, 138.86, 138.29, 137.57, 131.17, 130.21, 129.99, 129.87, 129.17, 128.63, 127.40, 126.21, 125.27, 122.84, 122.62, 116.08, 64.97, 64.42, 63.94, 62.44, 47.78, 21.41.

HRMS (ESI) [MH]\textsuperscript{+} calculated 631.12, found 631.1282
11g  \( N-(3R,4S,E)-4-(3\text{-methoxyphenyl})-3-(4\text{-methyl-2,6-dioxotetrahydro-}2H-4\lambda,8\lambda-\text{[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl})-1\text{-phenylazetidin-2-ylidene})-4\text{-methylbenzenesulfonamide} \)

Isolated Yield 50%.

\( ^1H \) NMR (400 MHz, Acetonitrile-\( d_3 \)) \( \delta \) 7.89 – 7.85 (m, 2H), 7.41 – 7.36 (m, 4H), 7.29 – 7.24 (m, 3H), 7.09 (ddt, \( J = 7.8, 7.0, 1.2 \) Hz, 1H), 6.91 (dt, \( J = 7.6, 1.3 \) Hz, 1H), 6.89 – 6.86 (m, 2H), 5.48 (d, \( J = 2.3 \) Hz, 1H), 4.28 (d, \( J = 16.7 \) Hz, 1H), 4.11 (d, \( J = 17.5 \) Hz, 1H), 4.02 (d, \( J = 12.6 \) Hz, 1H), 4.00 – 3.95 (m, 1H), 3.72 (s, 3H), 3.35 (d, \( J = 2.3 \) Hz, 1H), 3.10 (s, 3H), 2.42 (s, 3H).

\( ^{11}B \) NMR (128 MHz, Acetonitrile-\( d_3 \)) \( \delta \) 11.31.

\( ^{13}C \) NMR (126 MHz, Acetonitrile-\( d_3 \)) \( \delta \) 168.87, 168.29, 167.40, 161.10, 144.17, 141.19, 140.38, 138.12, 131.32, 130.47, 129.98, 129.17, 127.08, 125.97, 119.13, 118.99, 114.59, 113.02, 65.23, 64.04, 63.92, 55.84, 47.68, 21.49.

HRMS (DART) [MH]+ calculated 561.17, found 562.18153

11h  \( N-(3R,4S,E)-4-(3\text{-methoxyphenyl})-3-(4\text{-methyl-2,6-dioxotetrahydro-}2H-4\lambda,8\lambda-\text{[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl})-1\text{-phenylazetidin-2-ylidene})-4\text{-nitrobenzenesulfonamide} \)

Isolated Yield 28%.

\( ^1H \) NMR (500 MHz, Acetonitrile-\( d_3 \)) \( \delta \) 8.38 – 8.34 (m, 2H), 8.23 – 8.19 (m, 2H), 7.43 – 7.38 (m, 2H), 7.32 – 7.26 (m, 3H), 7.20 – 7.10 (m, 2H), 6.91 – 6.87 (m, 2H), 5.50 (d, \( J = 2.2 \) Hz, 1H), 4.17 (d, \( J = 16.7 \) Hz, 1H), 4.10 (d, \( J = 17.5 \) Hz, 1H), 4.03 (d, \( J = 16.7 \) Hz, 1H), 4.00 – 3.95 (m, 1H), 3.73 (s, 3H), 3.41 (d, \( J = 2.2 \) Hz, 1H), 3.05 (s, 3H).

\( ^{11}B \) NMR (128 MHz, Acetonitrile-\( d_3 \)) \( \delta \) 11.12.
$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 168.85, 168.30, 168.10, 161.12, 149.45, 139.85, 137.80, 131.40, 130.08, 129.87, 129.17, 128.57, 126.44, 125.26, 119.43, 119.06, 114.67, 113.31, 64.93, 64.00, 63.90, 62.44, 55.88, 47.71.

$$\text{N-}((3R,4S,E)-(4\text{-bromo-2-methylphenyl}-3-(4\text{-methyl}-2,6\text{-dioxotetrahydro-2H-}4\lambda_4,8\lambda_4-[1,3,2]\text{oxazaborolo[2,3-b][1,3,2]}\text{oxazaborol}-8\text{-yl})-4\text{-phenylazetidin-2-ylidene})-4\text{-methylbenzenesulfonamide}$$

Isolated Yield 24%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) $\delta$ 7.72 – 7.67 (m, 2H), 7.46 – 7.41 (m, 2H), 7.40 – 7.37 (m, 1H), 7.36 – 7.34 (m, 1H), 7.32 (s, 2H), 7.32 (t, $J = 1.0$ Hz, 1H), 7.26 – 7.16 (m, 2H), 7.00 (d, $J = 8.5$ Hz, 1H), 5.41 (d, $J = 2.3$ Hz, 1H), 4.18 (d, $J = 16.7$ Hz, 1H), 4.10 (d, $J = 17.5$ Hz, 1H), 4.02 (d, $J = 16.6$ Hz, 1H), 3.94 (d, $J = 17.5$ Hz, 1H), 3.47 (d, $J = 2.4$ Hz, 1H), 3.12 (s, 3H), 2.41 (s, 3H), 2.21 (s, 3H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 10.97.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 168.99, 168.36, 168.25, 143.97, 141.16, 138.86, 138.43, 137.77, 135.33, 134.69, 130.34, 130.12, 130.05, 129.95, 129.86, 129.17, 128.77, 128.38, 126.95, 126.20, 122.17, 118.26, 67.11, 64.78, 63.90, 47.76, 21.47, 18.83.

HRMS (ESI) $[\text{MH}]^+$ calculated 624.09, found 624.0959

$$\text{N-}((3R,4S,Z)-1\text{-cyclohexyl-3-(4\text{-methyl}-2,6\text{-dioxotetrahydro-2H-}4\lambda_4,8\lambda_4-[1,3,2]\text{oxazaborolo[2,3-b][1,3,2]}\text{oxazaborol-8-yl})-4\text{-phenylazetidin-2-ylidene})-4\text{-methylbenzenesulfonamide}$$
Isolated Yield 23%.

$^1$H NMR (500 MHz, Acetonitrile-$d_3$) $\delta$ 7.81 – 7.76 (m, 2H), 7.41 – 7.38 (m, 4H), 7.38 – 7.35 (m, 3H), 4.99 (d, $J$ = 2.1 Hz, 1H), 4.19 (d, $J$ = 16.6 Hz, 1H), 4.03 (d, $J$ = 17.4 Hz, 1H), 3.97 (d, $J$ = 16.6 Hz, 1H), 3.89 (d, $J$ = 17.4 Hz, 1H), 3.71 (tt, $J$ = 11.7, 3.6 Hz, 1H), 3.04 (s, 3H), 3.00 (d, $J$ = 2.1 Hz, 1H), 2.42 (d, $J$ = 0.7 Hz, 3H), 1.86 (ddt, $J$ = 12.4, 3.5, 1.8 Hz, 1H), 1.69 (ddt, $J$ = 13.3, 3.5, 1.9 Hz, 1H), 1.55 – 1.44 (m, 4H), 1.25 – 1.15 (m, 1H), 1.15 – 1.04 (m, 1H), 0.98 – 0.86 (m, 2H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 10.94.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 169.21, 169.02, 168.28, 143.54, 141.96, 139.97, 130.31, 129.78, 129.58, 127.82, 126.82, 64.68, 63.73, 62.41, 56.13, 47.45, 31.29, 31.00, 25.78, 25.60, 21.44.

HRMS (DART) [MH]$^+$ calculated 538.21, found 538.21772

$^{11}$k $\text{N}((3R,4R,Z)-1$-cyclohexyl-3-(4-methyl-2,6-dioxotetrahydro-2H-4λ₄,8λ₄-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-4-phenylazetidin-2-ylidene)-4-methylbenzenesulfonamide

Isolated Yield 31%.

$^1$H NMR (500 MHz, Acetonitrile-$d_3$) $\delta$ 7.78 – 7.75 (m, 2H), 7.48 – 7.45 (m, 2H), 7.38 – 7.32 (m, 5H), 5.16 (d, $J$ = 5.4 Hz, 1H), 3.91 (tt, $J$ = 12.1, 3.8 Hz, 1H), 3.86 (d, $J$ = 16.5 Hz, 1H), 3.77 (d, $J$ = 9.3 Hz, 1H), 3.74 (d, $J$ = 8.4 Hz, 1H), 3.61 (d, $J$ = 17.4 Hz, 1H), 3.51 (d, $J$ = 5.4 Hz, 1H), 3.01 (s, 3H), 2.42 (d, $J$ = 0.7 Hz, 3H), 1.92 – 1.86 (m, 1H), 1.74 – 1.63 (m, 2H), 1.50 (ddtd, $J$ = 19.1, 12.8, 3.3, 1.9 Hz, 2H), 1.36 (dt, $J$ = 13.0, 12.1, 3.7 Hz, 1H), 1.18 (qt, $J$ = 13.2, 3.6 Hz, 1H), 1.13 – 1.03 (m, 1H), 0.95 – 0.80 (m, 2H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 10.41.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 169.02, 168.48, 168.24, 143.59, 141.77, 138.50, 130.30, 129.48, 129.21, 128.82, 126.78, 63.61, 63.06, 61.83, 57.73, 47.73, 32.12, 30.98, 25.98, 25.93, 25.79, 21.43.
**N-(3R,4S,E)-1-cyclohexyl-3-(4-methyl-2,6-dioxotetrahydro-2H-4λ₄,8λ₄-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-4-phenylazetidin-2-ylidene)-4-nitrobenzenesulfonamide**

Isolated Yield 45%

1H NMR (500 MHz, Acetonitrile-d₃) δ 8.36 – 8.32 (m, 2H), 8.14 – 8.10 (m, 2H), 7.44 – 7.34 (m, 5H), 5.02 (d, J = 2.0 Hz, 1H), 4.08 (d, J = 16.7 Hz, 1H), 4.03 (d, J = 17.5 Hz, 1H), 3.97 (d, J = 16.7 Hz, 1H), 3.89 (d, J = 17.5 Hz, 1H), 3.69 (tt, J = 11.8, 3.8 Hz, 1H), 3.09 (d, J = 2.0 Hz, 1H), 2.98 (s, 3H), 1.88 (dtt, J = 12.4, 4.0, 1.9 Hz, 1H), 1.70 (dtd, J = 13.3, 3.6, 1.9 Hz, 1H), 1.61 – 1.45 (m, 4H), 1.28 – 1.16 (m, 1H), 1.16 – 1.06 (m, 1H), 1.01 – 0.90 (m, 2H).

11B NMR (128 MHz, Acetonitrile-d₃) δ 11.09.

13C NMR (126 MHz, Acetonitrile-d₃) δ 170.18, 168.96, 168.13, 150.60, 150.23, 139.35, 129.85, 129.74, 128.27, 127.91, 125.15, 64.56, 63.69, 62.79, 56.22, 47.52, 31.23, 30.95, 25.74, 25.56, 25.54.

HRMS (ESI) [MH]+ calculated 569.18, found 569.1879

---

**N-(3R,4R,E)-1-cyclohexyl-3-(4-methyl-2,6-dioxotetrahydro-2H-4λ₄,8λ₄-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-4-phenylazetidin-2-ylidene)-4-nitrobenzenesulfonamide**

Isolated Yield 21%

1H NMR (400 MHz, Acetonitrile-d₃) δ 8.37 – 8.31 (m, 2H), 8.12 – 8.07 (m, 2H), 7.47 (dq, J = 6.3, 2.8, 2.4 Hz, 2H), 7.40 – 7.33 (m, 3H), 5.20 (d, J = 5.3 Hz, 1H), 3.91 – 3.82 (m, 1H), 3.80 – 3.71 (m, 3H), 3.61 – 3.51 (m, 2H), 2.98 (s, 3H), 1.92 – 1.89 (m, 1H), 1.81 – 1.74 (m, 1H), 1.70 (dt, J =
13.3, 2.9 Hz, 1H), 1.60 – 1.45 (m, 2H), 1.45 – 1.33 (m, 1H), 1.28 – 1.04 (m, 2H), 1.04 – 0.81 (m, 2H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 10.69.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 169.20, 168.81, 168.43, 150.65, 150.00, 138.11, 129.49, 129.34, 128.94, 128.24, 125.18, 63.70, 63.19, 62.38, 57.77, 47.87, 32.08, 30.85, 25.93, 25.87, 25.77.

11m $N$-((3R,4S,E)-4-(4-chlorophenyl)-1-cyclohexyl-3-(4-methyl-2,6-dioxotetrahydro-2H-4λ₄,8λ₄-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)azetidin-2-ylidene)-4-methylbenzenesulfonamide

Isolated Yield 19%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) $\delta$ 7.80 – 7.75 (m, 2H), 7.40 (d, $J = 1.3$ Hz, 4H), 7.38 – 7.34 (m, 2H), 5.00 (d, $J = 2.1$ Hz, 1H), 4.17 (d, $J = 16.6$ Hz, 1H), 4.03 (d, $J = 17.5$ Hz, 1H), 3.96 (d, $J = 16.6$ Hz, 1H), 3.88 (d, $J = 17.4$ Hz, 1H), 3.70 (tt, $J = 11.7$, 3.6 Hz, 1H), 3.04 (s, 3H), 2.99 (d, $J = 2.1$ Hz, 1H), 2.42 (s, 3H), 1.90 – 1.81 (m, 1H), 1.74 – 1.63 (m, 1H), 1.58 – 1.39 (m, 4H), 1.27 – 1.04 (m, 2H), 1.02 – 0.85 (m, 2H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 11.02.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 169.16, 168.97, 168.26, 143.60, 141.86, 139.06, 134.63, 130.32, 129.81, 129.55, 126.83, 64.72, 63.77, 61.67, 56.14, 47.50, 31.33, 31.01, 25.75, 25.61, 21.44.

HRMS (DART) [MH]$^+$ calculated 571.17, found 572.18058
11m \( \text{N-}((3R,4R,E)-4\text{-}(4\text{-chlorophenyl})\text{-}1\text{-cyclohexyl}-3\text{-}(4\text{-methyl}-2,6\text{-dioxotetrahydro-}2H-4\lambda_4,8\lambda_4\text{-}[1,3,2]\text{oxazaborolo}[2,3-b][1,3,2]\text{oxazaborol-8-yl} \text{azetidin-2-ylidene})\text{-}4\text{-methylbenzenesulfonamide} \)

Isolated Yield 28%.

\(^1\)H NMR (400 MHz, Acetonitrile-\(d_3\)) \( \delta \) 7.78 – 7.73 (m, 2H), 7.45 (d, \( J = 8.5 \) Hz, 2H), 7.39 – 7.33 (m, 4H), 5.16 (d, \( J = 5.4 \) Hz, 1H), 3.94 – 3.85 (m, 2H), 3.80 (d, \( J = 11.7 \) Hz, 1H), 3.75 (d, \( J = 10.8 \) Hz, 1H), 3.66 (d, \( J = 17.4 \) Hz, 1H), 3.53 (d, \( J = 5.4 \) Hz, 1H), 3.02 (s, 3H), 2.42 (s, 3H), 1.88 (d, \( J = 13.1 \) Hz, 1H), 1.68 (m, 2H), 1.58 – 1.45 (m, 2H), 1.33 (td, \( J = 12.1, 3.6 \) Hz, 1H), 1.21 – 1.13 (m, 1H), 1.07 (ddd, \( J = 13.2, 9.8, 3.4 \) Hz, 1H), 0.96 – 0.85 (m, 2H).

\(^{11}\)B NMR (128 MHz, Acetonitrile-\(d_3\)) \( \delta \) 10.37.

\(^{13}\)C NMR (126 MHz, Acetonitrile-\(d_3\)) \( \delta \) 168.93, 168.44, 168.31, 143.67, 141.67, 137.79, 134.28, 131.16, 130.32, 128.82, 126.79, 63.72, 63.11, 61.12, 57.66, 47.77, 32.14, 30.96, 25.96, 25.92, 25.77, 21.44.

11n \( \text{N-}((3R,4S,E)-4\text{-}(4\text{-chlorophenyl})\text{-}1\text{-cyclohexyl}-3\text{-}(4\text{-methyl}-2,6\text{-dioxotetrahydro-}2H-4\lambda_4,8\lambda_4\text{-}[1,3,2]\text{oxazaborolo}[2,3-b][1,3,2]\text{oxazaborol-8-yl} \text{azetidin-2-ylidene})\text{-}4\text{-nitrobenzenesulfonamide} \)

Isolated Yield 29%.

\(^1\)H NMR (400 MHz, Acetonitrile-\(d_3\)) \( \delta \) 8.36 – 8.32 (m, 2H), 8.13 – 8.09 (m, 2H), 7.42 (m, 4H), 5.03 (d, \( J = 2.0 \) Hz, 1H), 4.05 (dd, \( J = 18.3, 17.1 \) Hz, 2H), 3.96 (d, \( J = 16.7 \) Hz, 1H), 3.88 (d, \( J = 17.4 \) Hz, 1H), 3.69 (tt, \( J = 11.7, 3.5 \) Hz, 1H), 3.08 (d, \( J = 2.1 \) Hz, 1H), 2.97 (s, 3H), 1.88 (d, \( J =
12.6 Hz, 1H), 1.71 (d, \(J = 13.6\) Hz, 1H), 1.61 – 1.41 (m, 4H), 1.29 – 1.19 (m, 1H), 1.11 (ddd, \(J = 12.3, 9.5, 3.0\) Hz, 1H), 1.03 – 0.91 (m, 2H).

\(\text{\textsuperscript{11}B}\) NMR (128 MHz, Acetonitrile-\(d_3\)) \(\delta\) 11.15.

\(\text{\textsuperscript{13}C}\) NMR (126 MHz, Acetonitrile-\(d_3\)) \(\delta\) 170.16, 168.92, 168.11, 150.63, 150.12, 138.44, 134.81, 129.88, 129.77, 129.67, 129.17, 128.46, 128.28, 125.23, 125.16, 64.61, 63.73, 62.04, 56.24, 47.58, 31.27, 30.97, 25.71, 25.55.

HRMS (DART) \([\text{MH}]^+\) calculated 602.14, found 603.14946

\[\text{11\text{o} 4-methyl-N-((3R,4S,E)-3-(4-methyl-2,6-dioxotetrahydro-2H-4\lambda_4,8\lambda_4-1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-1-(4-methylbenzyl)-4-phenylazetidin-2-ylidene)benzenesulfonamide}\]

Isolated Yield 19%.

\(\text{\textsuperscript{1}H}\) NMR (400 MHz, Acetonitrile-\(d_3\)) \(\delta\) 7.81 – 7.76 (m, 2H), 7.42 – 7.33 (m, 5H), 7.27 – 7.22 (m, 2H), 7.13 – 7.09 (m, 2H), 7.03 (d, \(J = 8.1\) Hz, 2H), 4.95 (d, \(J = 15.3\) Hz, 1H), 4.73 (d, \(J = 2.1\) Hz, 1H), 4.11 (d, \(J = 16.6\) Hz, 1H), 4.02 (d, \(J = 17.4\) Hz, 1H), 3.99 – 3.89 (m, 2H), 3.86 (d, \(J = 17.4\) Hz, 1H), 3.09 (d, \(J = 2.1\) Hz, 1H), 3.01 (s, 3H), 2.42 (s, 3H), 2.30 (s, 3H).

\(\text{\textsuperscript{11}B}\) NMR (128 MHz, Acetonitrile-\(d_3\)) \(\delta\) 11.16.

\(\text{\textsuperscript{13}C}\) NMR (126 MHz, Acetonitrile-\(d_3\)) \(\delta\) 168.95, 168.94, 168.19, 143.75, 141.56, 138.51, 137.82, 132.44, 130.34, 130.13, 129.94, 129.66, 129.19, 127.72, 126.90, 64.50, 63.73, 62.90, 48.16, 47.58, 21.46, 21.09.

HRMS (ESI) \([\text{MH}]^+\) calculated 560.19, found 560.2031
11o 4-methyl-N-((3R,4R,E)-3-(4-methyl-2,6-dioxotetrahydro-2H-4λ₄,8λ₄-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-1-(4-methylbenzyl)-4-phenylazetidin-2-ylidene)benzenesulfonamide

Isolated Yield 24%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) $\delta$ 7.81 – 7.74 (m, 2H), 7.41 – 7.33 (m, 5H), 7.32 – 7.27 (m, 2H), 7.11 – 7.06 (m, 2H), 7.00 – 6.93 (m, 2H), 5.29 (d, $J = 15.2$ Hz, 1H), 4.82 (d, $J = 5.5$ Hz, 1H), 4.06 (d, $J = 15.2$ Hz, 1H), 3.80 – 3.72 (m, 3H), 3.60 (d, $J = 17.3$ Hz, 1H), 3.46 (d, $J = 5.4$ Hz, 1H), 2.96 (s, 3H), 2.43 (s, 3H), 2.29 (s, 3H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 10.77.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 169.03, 168.31, 167.35, 143.84, 141.43, 138.65, 135.97, 132.33, 130.38, 130.13, 129.48, 129.22, 129.19, 129.14, 126.86, 63.30, 62.96, 61.45, 49.55, 47.75, 21.47, 21.09.

11p N-((3R,4S,E)-3-(4-methyl-2,6-dioxotetrahydro-2H-4λ₄,8λ₄-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-1-(4-methylbenzyl)-4-phenylazetidin-2-ylidene)-4-nitrobenzenesulfonamide

Isolated Yield 58%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) $\delta$ 8.33 – 8.28 (m, 2H), 8.11 – 8.06 (m, 2H), 7.43 – 7.36 (m, 3H), 7.31 – 7.26 (m, 2H), 7.13 – 7.08 (m, 2H), 7.04 (d, $J = 8.1$ Hz, 2H), 4.91 (d, $J = 15.4$ Hz, 1H), 4.80 (d, $J = 2.0$ Hz, 1H), 4.07 – 4.00 (m, 2H), 4.00 – 3.94 (m, 2H), 3.86 (d, $J = 17.5$ Hz, 1H), 3.19 (d, $J = 1.9$ Hz, 1H), 2.97 (s, 3H), 2.30 (s, 3H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 10.67.
$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) δ 170.08, 168.86, 168.10, 150.66, 149.76, 138.62, 137.32, 132.25, 130.18, 129.99, 129.82, 129.12, 128.36, 127.85, 125.14, 64.46, 63.74, 63.40, 48.14, 47.70, 21.07.

HRMS (ESI) [MH]$^+$ calculated 591.16, found 591.1730

11p $N$-((3$R,4R,E$)-3-(4-methyl-2,6-dioxotetrahydro-$2H$-4$\lambda_4,8\lambda_4$-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-1-(4-methylbenzyl)-4-phenylazetidin-2-ylidene)-4-nitrobenzenesulfonamide

Isolated Yield 4%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) δ 8.36 – 8.28 (m, 2H), 8.08 (dq, $J = 9.3, 2.3$ Hz, 2H), 7.41 – 7.30 (m, 5H), 7.08 (d, $J = 7.8$ Hz, 2H), 7.01 – 6.93 (m, 2H), 5.22 (d, $J = 15.3$ Hz, 1H), 4.91 (d, $J = 5.3$ Hz, 1H), 4.12 (d, $J = 15.3$ Hz, 1H), 3.77 (dd, $J = 17.0, 3.3$ Hz, 2H), 3.68 (d, $J = 16.7$ Hz, 1H), 3.61 – 3.51 (m, 2H), 2.95 (s, 3H), 2.28 (s, 3H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) δ 10.78.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) δ 168.86, 168.45, 168.33, 150.73, 149.56, 138.74, 135.68, 132.12, 130.16, 129.38, 129.21, 128.32, 125.21, 63.38, 63.07, 62.09, 49.44, 47.88, 21.05.

11q $N$-((3$R,4S,E$)-1-(tert-butyl)-4-(4-methoxyphenyl)-3-(4-methyl-2,6-dioxotetrahydro-$2H$-4$\lambda_4,8\lambda_4$-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)azetidin-2-ylidene)-4-methylbenzenesulfonamide

Isolated Yield 51%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) δ 7.82 – 7.77 (m, 2H), 7.39 – 7.33 (m, 2H), 7.29 – 7.24 (m, 2H), 6.95 – 6.89 (m, 2H), 5.00 (d, $J = 2.0$ Hz, 1H), 4.31 (d, $J = 16.6$ Hz, 1H), 4.03 (d, $J = 17.4$ Hz,
1H), 3.99 – 3.88 (m, 2H), 3.78 (s, 3H), 3.06 (s, 3H), 2.97 (d, $J = 1.9$ Hz, 1H), 2.42 (s, 3H), 1.18 (s, 9H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) δ 11.33.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) δ 170.31, 169.03, 168.32, 160.70, 143.35, 142.32, 132.33, 130.24, 128.87, 126.71, 115.11, 64.99, 63.66, 63.53, 57.08, 55.93, 47.19, 27.46, 21.43.

HRMS (ESI) [M+H]$^+$ calculated 542.21, found 542.2118

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) δ 7.79 – 7.74 (m, 2H), 7.52 – 7.46 (m, 1H), 7.37 – 7.31 (m, 2H), 7.16 (d, $J = 7.9$ Hz, 1H), 6.96 – 6.90 (m, 1H), 6.85 (dd, $J = 8.3$, 2.7 Hz, 1H), 5.17 (d, $J = 5.1$ Hz, 1H), 4.23 (d, $J = 16.5$ Hz, 1H), 3.80 – 3.76 (m, 4H), 3.74 (d, $J = 3.1$ Hz, 1H), 3.71 (d, $J = 5.1$ Hz, 1H), 3.63 (d, $J = 17.4$ Hz, 1H), 3.19 (s, 3H), 2.41 (s, 3H), 1.15 (s, 9H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) δ 10.81.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) δ 169.98, 168.75, 168.65, 160.40, 143.36, 142.14, 132.43, 131.43, 130.19, 129.15, 126.68, 114.53, 114.02, 65.00, 63.57, 57.52, 55.86, 47.55, 27.44, 21.41.

Isolated Yield 19%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) δ 7.79 – 7.74 (m, 2H), 7.52 – 7.46 (m, 1H), 7.37 – 7.31 (m, 2H), 7.16 (d, $J = 7.9$ Hz, 1H), 6.96 – 6.90 (m, 1H), 6.85 (dd, $J = 8.3$, 2.7 Hz, 1H), 5.17 (d, $J = 5.1$ Hz, 1H), 4.23 (d, $J = 16.5$ Hz, 1H), 3.80 – 3.76 (m, 4H), 3.74 (d, $J = 3.1$ Hz, 1H), 3.71 (d, $J = 5.1$ Hz, 1H), 3.63 (d, $J = 17.4$ Hz, 1H), 3.19 (s, 3H), 2.41 (s, 3H), 1.15 (s, 9H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) δ 10.81.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) δ 169.98, 168.75, 168.65, 160.40, 143.36, 142.14, 132.43, 131.43, 130.19, 129.15, 126.68, 114.53, 114.02, 65.00, 63.57, 57.52, 55.86, 47.55, 27.44, 21.41.

Isolated Yield 14%.
$^1$H NMR (400 MHz, Acetonitrile-$d_3$) $\delta$ 8.39 – 8.30 (m, 2H), 8.14 – 8.06 (m, 2H), 7.48 (dd, $J = 8.7$, 2.4 Hz, 1H), 7.17 (d, $J = 7.9$ Hz, 1H), 6.98 – 6.82 (m, 2H), 5.20 (d, $J = 5.0$ Hz, 1H), 4.12 (d, $J = 16.7$ Hz, 1H), 3.80 – 3.77 (m, 4H), 3.77 – 3.73 (m, 2H), 3.54 (d, $J = 17.4$ Hz, 1H), 3.14 (s, 3H), 1.17 (s, 9H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 10.92.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 170.77, 168.58, 160.51, 150.52, 150.30, 131.77, 131.42, 129.26, 129.00, 128.13, 128.12, 125.08, 115.18, 114.69, 114.06, 64.86, 63.87, 63.68, 57.89, 55.89, 47.73, 27.51, 27.49.

11s  
$N$-((3R,4S,E)-1-(tert-butyl)-3-(4-methyl-2,6-dioxotetrahydro-2H-4\lambda_4,8\lambda_4-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-4-(4-nitrophenyl)azetidin-2-ylidene)-4-methylbenzenesulfonamide

Isolated Yield 49%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) $\delta$ 8.25 – 8.19 (m, 2H), 7.82 – 7.77 (m, 2H), 7.62 – 7.57 (m, 2H), 7.40 – 7.33 (m, 2H), 5.23 (d, $J = 2.0$ Hz, 1H), 4.32 (d, $J = 16.6$ Hz, 1H), 4.06 (d, $J = 17.4$ Hz, 1H), 3.95 (t, $J = 17.1$ Hz, 2H), 3.07 (s, 3H), 3.06 – 3.04 (m, 1H), 2.43 (s, 3H), 1.22 (s, 9H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 11.04.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 170.11, 168.88, 168.28, 148.87, 148.67, 143.59, 141.92, 130.31, 128.48, 126.73, 125.07, 65.21, 63.80, 62.84, 57.50, 47.34, 27.44, 21.44.

HRMS (ESI) [MH]$^+$ calculated 557.18, found 557.1877
11s  \( N-((3R,4R,E)-1-(\text{tert-butyl})-3-(4\text{-methyl}-2,6\text{-dioxotetrahydro}-2H-4\lambda_4,8\lambda_4-\[1,3,2\]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl})-4-(4\text{-nitrophenyl})azetidin-2\text{-ylidene})-4\text{-methylbenzenesulfonamide} \)

Isolated Yield 17%.

\(^1\text{H} \text{NMR} \ (400 \text{ MHz, Acetonitrile-}d_3) \ \delta \ 8.19 \ (\text{ddd, } J = 16.3, 8.5, 2.5 \text{ Hz, } 2\text{H}), \ 7.81 \ (\text{dd, } J = 8.6, 2.0 \text{ Hz, } 1\text{H}), \ 7.79 \sim 7.75 \ (m, 2\text{H}), \ 7.50 \ (\text{dd, } J = 8.4, 2.0 \text{ Hz, } 1\text{H}), \ 7.38 \sim 7.33 \ (m, 2\text{H}), \ 5.33 \ (d, J = 5.3 \text{ Hz, } 1\text{H}), \ 4.35 \ (d, J = 16.6 \text{ Hz, } 1\text{H}), \ 3.88 \ (d, J = 5.3 \text{ Hz, } 1\text{H}), \ 3.83 \sim 3.75 \ (m, 2\text{H}), \ 3.70 \ (d, J = 17.5 \text{ Hz, } 1\text{H}), \ 3.22 \ (s, 3\text{H}), \ 2.41 \ (s, 3\text{H}), \ 1.16 \ (s, 9\text{H}).

\(^{11}\text{B} \text{NMR} \ (128 \text{ MHz, Acetonitrile-}d_3) \ \delta \ 10.40.

\(^{13}\text{C} \text{NMR} \ (126 \text{ MHz, Acetonitrile-}d_3) \ \delta \ 170.11, \ 168.70, \ 168.30, \ 149.16, \ 148.61, \ 143.61, \ 141.77, \ 131.04, \ 130.26, \ 129.12, \ 126.69, \ 124.03, \ 65.07, \ 63.76, \ 63.05, \ 57.90, \ 47.75, \ 27.44, \ 21.42.

11t  \( N-((3R,4S,E)-1-(\text{tert-butyl})-3-(4\text{-methyl}-2,6\text{-dioxotetrahydro}-2H-4\lambda_4,8\lambda_4-\[1,3,2\]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl})-4-(4\text{-nitrophenyl})azetidin-2\text{-ylidene})-4\text{-nitrobenzenesulfonamide} \)

Isolated Yield 28%.

\(^1\text{H} \text{NMR} \ (500 \text{ MHz, Acetonitrile-}d_3) \ \delta \ 8.36 \sim 8.34 \ (m, 2\text{H}), \ 8.25 \sim 8.21 \ (m, 2\text{H}), \ 8.13 \sim 8.11 \ (m, 2\text{H}), \ 7.63 \sim 7.61 \ (m, 2\text{H}), \ 5.25 \ (d, J = 1.9 \text{ Hz, } 1\text{H}), \ 4.18 \ (d, J = 16.7 \text{ Hz, } 1\text{H}), \ 4.06 \ (d, J = 17.5 \text{ Hz, } 1\text{H}), \ 3.98 \ (d, J = 16.7 \text{ Hz, } 1\text{H}), \ 3.92 \ (d, J = 17.5 \text{ Hz, } 1\text{H}), \ 3.13 \ (d, J = 2.0 \text{ Hz, } 1\text{H}), \ 3.00 \ (s, 3\text{H}), \ 1.24 \ (s, 9\text{H}).

\(^{11}\text{B} \text{NMR} \ (128 \text{ MHz, Acetonitrile-}d_3) \ \delta \ 10.94.
$^{13}$C NMR (126 MHz, DMSO-$d_6$) $\delta$ 171.58, 170.12, 169.00, 167.45, 149.20, 149.00, 147.42, 147.16, 127.99, 127.42, 127.28, 127.21, 124.54, 124.25, 124.20, 63.11, 62.12, 60.49, 56.46, 45.83, 26.92.

**General Procedure for $\alpha$-Borylazetidimine Nosyl Deprotection:** To a flame-dried 2-dram vial equipped with a Teflon-coated stir bar and septum, was added the appropriate nosyl-protected azetidimine (0.13 mmol, 1.0 eq.), cesium carbonate (0.521 mmol, 4.0 eq.), SiliaMetS$^\text{®}$ Thiol (0.521 mmol, 4.0 eq.), and dry acetonitrile (2.6 mL, 0.05 M). The reaction mixture was stirred under Argon for 5 h at 65 °C. Upon completion, the reaction mixture was cooled to room temperature and filtered through a pad of celite, and concentrated under reduced pressure. The product was isolated from the crude residue via reverse phase liquid chromatography (eluents, water and acetonitrile).

![Chemical structure](image)

**12d** 8-((2S,3R)-2-(2-fluorophenyl)-4-imino-1-phenylazetidin-3-yl)-4-methyldihydro-4$\lambda_4$8$\lambda_4$-[1,3,2]oxazaborolo[2,3-$b$][1,3,2]oxazaborole-2,6(3H,5H)-dione

Isolated Yield 33%.

$^1$H NMR (400 MHz, Acetonitrile-$d_3$) $\delta$ 8.11 (s, 1H), 7.52 – 7.46 (m, 1H), 7.40 – 7.29 (m, 2H), 7.29 – 7.24 (m, 2H), 7.22 – 7.12 (m, 3H), 7.02 – 6.95 (m, 1H), 5.30 (d, $J = 2.6$ Hz, 1H), 4.13 – 3.95 (m, 3H), 3.89 (d, $J = 17.3$ Hz, 1H), 2.97 (s, 3H), 2.94 (m, 1H).

$^{11}$B NMR (128 MHz, Acetonitrile-$d_3$) $\delta$ 10.99.

$^{13}$C NMR (126 MHz, Acetonitrile-$d_3$) $\delta$ 169.22, 168.38, 163.61, 140.19, 131.17, 131.10, 130.12, 129.23, 127.28, 125.93, 123.40, 116.88, 116.68, 63.35, 63.17, 53.65, 47.25.
12f 8-((3R,4S)-2-imino-4-phenyl-1-(3-(trifluoromethyl)phenyl)azetidin-3-yl)-4-methyldihydro-4λ4,8λ4-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborole-2,6(3H,5H)-dione

Isolated Yield 37%.

\[ ^{1}H \text{NMR (500 MHz, Acetonitrile-}d_{3}^{3}) \delta 7.72 (s, 1H), 7.53 - 7.46 (m, 2H), 7.42 - 7.30 (m, 6H), 7.21 (d, \ J = 7.5 \text{ Hz, 1H}), 5.09 (d, \ J = 3.3 \text{ Hz, 1H}), 4.11 - 4.00 (m, 2H), 4.00 - 3.89 (m, 2H), 2.87 (s, 3H), 2.84 (d, \ J = 3.3 \text{ Hz, 1H}). \]

\[ ^{11}B \text{NMR (128 MHz, Acetonitrile-}d_{3}^{3}) \delta 11.35. \]

\[ ^{13}C \text{NMR (126 MHz, Acetonitrile-}d_{3}^{3}) \delta 169.15, 168.30, 141.39, 140.54, 130.76, 129.97, 129.53, 129.30, 127.45, 127.33, 119.67, 113.23, 63.36, 63.04, 59.26, 55.98, 47.46. \]

12n 8-((2S,3R)-2-(4-chlorophenyl)-1-cyclohexyl-4-iminoazetidin-3-yl)-4-methyldihydro-4λ4,8λ4-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborole-2,6(3H,5H)-dione

Isolated Yield 47%.

\[ ^{1}H \text{NMR (400 MHz, Acetonitrile-}d_{3}^{3}) \delta 8.45 (s, 1H), 7.49 (t, \ J = 9.0 \text{ Hz, 2H}), 7.45 - 7.39 (m, 2H), 4.95 (s, 1H), 4.25 (d, \ J = 16.6 \text{ Hz, 1H}), 4.18 - 3.95 (m, 2H), 3.89 (d, \ J = 17.4 \text{ Hz, 1H}), 3.63 (t, \ J = 11.9 \text{ Hz, 1H}), 2.89 (s, 3H), 2.67 (dd, \ J = 6.5, 1.7 \text{ Hz, 1H}), 1.92 (d, \ J = 8.5 \text{ Hz, 2H}), 1.70 (dd, \ J = 24.3, 12.9 \text{ Hz, 2H}), 1.54 (d, \ J = 24.0 \text{ Hz, 2H}), 1.34 - 1.25 (m, 1H), 1.19 - 1.12 (m, 1H), 1.06 - 0.88 (m, 2H). \]

\[ ^{11}B \text{NMR (128 MHz, Acetonitrile-}d_{3}^{3}) \delta 10.69. \]

\[ ^{13}C \text{NMR (126 MHz, Acetonitrile-}d_{3}^{3}) \delta 169.54, 169.10, 168.16, 167.44, 142.12, 138.57, 134.93, 133.71, 130.04, 129.83, 129.67, 129.43, 63.64, 63.13, 60.44, 55.72, 47.39, 31.26, 30.40, 27.15, 26.77, 25.61, 25.51. \]
General Procedure for 3-Boryliminocoumarin Formation: To a flame-dried 5-mL round-bottom flask equipped with a Teflon-coated stir bar and septum, was added sufonyl azide (0.25 mmol, 1.0 eq.), dry acetonitrile (1 mL, 0.25 M), ethynylboronic acid MIDA ester (0.375 mmol, 1.5 eq.), the appropriate salicylaldehyde (0.375 mmol, 1.5 eq.), N,N-diisopropylethylamine (0.5 mmol, 2.0 eq.) and copper (I) iodide (0.025 mmol, 0.1 eq.), sequentially. The reaction mixture was stirred for 24 h at room temperature under Argon. After 24 h there was complete consumption of the starting material.

NMR yields were determined using trichloroethylene as an internal standard. The NMR sample was prepared by taking a 20 µL aliquot of the reaction mixture, and then concentrating the aliquot under reduced pressure. After drying the aliquot residue under high vacuum, 1.35 µL of trichloroethylene was added, and the sample was dissolved in 0.2 mL deuterated acetonitrile and transferred to a 3 mm NMR tube for $^1$H NMR analysis.

The product precipitates out of the reaction mixture, and is isolated through filtration without the need for further purification.

![Product Structure](image)

14a  (Z)-4-methyl-N-(3-(4-methyl-2,6-dioxotetrahydro-2H-4λ,8λ-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-2H-benzo[g]chromen-2-ylidene)benzenesulfonamide

Isolated Yield 62%.

$^1$H NMR (400 MHz, DMSO-$d_6$) δ 8.96 (s, 1H), 8.52 (d, $J$ = 8.5 Hz, 1H), 8.31 (d, $J$ = 9.2 Hz, 1H), 8.12 (d, $J$ = 8.1 Hz, 1H), 7.97 (d, $J$ = 8.2 Hz, 2H), 7.81 (t, $J$ = 7.6 Hz, 1H), 7.70 (dd, $J$ = 14.1, 8.1 Hz, 2H), 7.42 (d, $J$ = 8.1 Hz, 2H), 4.44 (d, $J$ = 16.8 Hz, 2H), 4.09 (d, $J$ = 16.9 Hz, 2H), 2.88 (s, 3H), 2.35 (s, 3H).

$^{11}$B NMR (128 MHz, DMSO-$d_6$) δ 10.56.

$^{13}$C NMR (126 MHz, DMSO-$d_6$) δ 168.88, 160.07, 152.39, 145.13, 143.29, 138.48, 134.62, 130.40, 129.51, 129.02, 128.87, 128.18, 127.41, 126.88, 122.17, 115.63, 113.84, 63.72, 46.62, 21.03.

HRMS (DART) [MH]$^+$ calculated 504.12, found 505.12401
14b  (Z)-N-(8-methoxy-3-(4-methyl-2,6-dioxotetrahydro-2H-4λ₄,8λ₄-1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-2H-chromen-2-ylidene)-4-methylbenzenesulfonamide

Isolated Yield 65%.

1H NMR (500 MHz, DMSO-d₆) δ 8.27 (s, 1H), 8.01 – 7.96 (m, 2H), 7.44 – 7.37 (m, 5H), 4.43 (d, J = 17.0 Hz, 2H), 4.14 (d, J = 16.9 Hz, 2H), 4.05 (s, 3H), 2.86 (s, 3H), 2.35 (s, 3H).

11B NMR (128 MHz, DMSO-d₆) δ 10.38.

13C NMR (126 MHz, DMSO-d₆) δ 168.78, 159.68, 149.99, 146.55, 143.31, 141.99, 137.74, 129.12, 127.79, 126.06, 120.24, 120.04, 118.05, 115.41, 63.67, 56.43, 46.43, 21.02, 1.15.

HRMS (DART) [M+H]⁺ calculated 514.12, found 515.12951

14c  (Z)-N-(5,7-dimethoxy-3-(4-methyl-2,6-dioxotetrahydro-2H-4λ₄,8λ₄-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-2H-chromen-2-ylidene)-4-methylbenzenesulfonamide

Isolated Yield 18%.

1H NMR (400 MHz, DMSO-d₆) δ 8.26 (s, 1H), 7.93 (d, J = 7.7 Hz, 2H), 7.40 (d, J = 7.7 Hz, 2H), 6.63 (d, J = 10.5 Hz, 2H), 4.37 (d, J = 18.1 Hz, 2H), 4.00 (d, J = 17.0 Hz, 2H), 3.93 (s, 6H), 3.69 (s, 1H), 2.81 (s, 3H), 2.36 (s, 3H).

11B NMR (128 MHz, DMSO-d₆) δ 10.76.

13C NMR (126 MHz, DMSO-d₆) δ 168.83, 164.61, 160.37, 157.08, 154.96, 144.11, 143.19, 138.56, 129.45, 127.42, 104.28, 96.48, 92.40, 63.58, 56.49, 46.42, 21.04.

HRMS (DART) [MH]⁺ calculated 514.12, found 515.12951
**14d**  (Z)-4-methyl-N-(3-(4-methyl-2,6-dioxotetrahydro-2H-4λ,8λ-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-6-nitro-2H-chromen-2-ylidene)benzenesulfonamide

Isolated Yield 49%.

**1H** NMR (400 MHz, DMSO-\textit{d}6) δ 8.89 (d, \(J = 2.7\) Hz, 1H), 8.51 – 8.41 (m, 2H), 7.93 (d, \(J = 8.1\) Hz, 2H), 7.76 (d, \(J = 9.1\) Hz, 1H), 7.43 (d, \(J = 8.1\) Hz, 2H), 4.41 (d, \(J = 17.0\) Hz, 2H), 4.03 (d, \(J = 17.0\) Hz, 2H), 2.84 (s, 3H), 2.37 (s, 3H).

**11B** NMR (128 MHz, DMSO-\textit{d}6) δ 8.81.

**13C** NMR (126 MHz, DMSO-\textit{d}6) δ 168.72, 158.95, 155.50, 148.86, 144.52, 143.76, 137.82, 129.65, 127.43, 127.36, 125.15, 119.80, 117.37, 63.60, 46.72, 21.08.

HRMS (DART) [MH]+ calculated 499.09, found 500.09481

---

**14e**  (Z)-N-(3-(4-methyl-2,6-dioxotetrahydro-2H-4λ,8λ-[1,3,2]oxazaborolo[2,3-b][1,3,2]oxazaborol-8-yl)-6-nitro-2H-chromen-2-ylidene)-4-nitrobenzenesulfonamide

Isolated Yield 47%.

**1H** NMR (400 MHz, DMSO-\textit{d}6) δ 8.92 (s, 1H), 8.55 (s, 1H), 8.47 (d, \(J = 10.4\) Hz, 1H), 8.42 (d, \(J = 8.3\) Hz, 2H), 8.31 (d, \(J = 8.5\) Hz, 2H), 7.81 (d, \(J = 9.2\) Hz, 1H), 4.42 (d, \(J = 17.0\) Hz, 2H), 4.03 (d, \(J = 16.9\) Hz, 2H), 2.83 (s, 3H).

**11B** NMR (128 MHz, DMSO-\textit{d}6) δ 11.50, 10.20.

**13C** NMR (126 MHz, DMSO-\textit{d}6) δ 168.71, 160.26, 155.49, 150.00, 149.89, 146.04, 144.60, 129.11, 127.49, 125.16, 124.49, 119.91, 117.50, 63.57, 47.00.

HRMS (DART) [MH]+ calculated 530.06, found 531.06251
References


Appendix I: $^1$H NMR & $^{13}$C NMR Spectra, and Data for Kinetics Experiments
Table AI.1 Rate constants for the reactions of \( p \)-nitrophenyl benzoate (1) with piperidine in DMSO (Dual beam UV/Vis spectrophotometer, 25 °C, \( \lambda = 436 \text{ nm} \)).

<table>
<thead>
<tr>
<th>[piperidine] (_0) (M)</th>
<th>([1]_0) (M)</th>
<th>[piperidine] (_0)/[1] (_0)</th>
<th>(k_{\text{obs}}) (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.67 (\times) 10(^{-4})</td>
<td>3.34 (\times) 10(^{-5})</td>
<td>20</td>
<td>2.03 (\times) 10(^{-3})</td>
</tr>
<tr>
<td>1.00 (\times) 10(^{-3})</td>
<td>3.34 (\times) 10(^{-5})</td>
<td>30</td>
<td>3.15 (\times) 10(^{-3})</td>
</tr>
<tr>
<td>1.33 (\times) 10(^{-3})</td>
<td>3.34 (\times) 10(^{-5})</td>
<td>40</td>
<td>4.11 (\times) 10(^{-3})</td>
</tr>
<tr>
<td>1.67 (\times) 10(^{-3})</td>
<td>3.34 (\times) 10(^{-5})</td>
<td>50</td>
<td>4.84 (\times) 10(^{-3})</td>
</tr>
<tr>
<td>2.00 (\times) 10(^{-3})</td>
<td>3.34 (\times) 10(^{-5})</td>
<td>60</td>
<td>6.03 (\times) 10(^{-3})</td>
</tr>
</tbody>
</table>

\(k_2 = 2.90 \times 10^1\ \text{M}^{-1}\ \text{s}^{-1}\)

Figure AI.1 Plot of piperidine concentration vs. \(k_{\text{obs}}\). Slope = \(k_2\)
Table A1.2 Rate constants for the reactions of 1 with pyrrolidine in DMSO (Dual beam UV/Vis spectrophotometer, 25 °C, $\lambda = 436$ nm).

<table>
<thead>
<tr>
<th>[pyrrolidine]₀ (M)</th>
<th>[1]₀ (M)</th>
<th>[pyrrolidine]₀/[1]₀</th>
<th>$k_{\text{obs}}$ (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6.78 \times 10^{-4}$</td>
<td>$3.34 \times 10^{-5}$</td>
<td>20</td>
<td>$1.21 \times 10^{-2}$</td>
</tr>
<tr>
<td>$1.02 \times 10^{-3}$</td>
<td>$3.34 \times 10^{-5}$</td>
<td>31</td>
<td>$1.79 \times 10^{-2}$</td>
</tr>
<tr>
<td>$1.36 \times 10^{-3}$</td>
<td>$3.34 \times 10^{-5}$</td>
<td>41</td>
<td>$2.17 \times 10^{-2}$</td>
</tr>
<tr>
<td>$1.70 \times 10^{-3}$</td>
<td>$3.34 \times 10^{-5}$</td>
<td>51</td>
<td>$2.47 \times 10^{-2}$</td>
</tr>
<tr>
<td>$2.03 \times 10^{-3}$</td>
<td>$3.34 \times 10^{-5}$</td>
<td>61</td>
<td>$2.65 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

$k_2 = 1.05 \times 10^2$ M⁻¹ s⁻¹

Figure A1.2 Plot of pyrrolidine concentration vs. $k_{\text{obs}}$. Slope = $k_2$
Figure A1.3 Reaction of piperidine with 1

Figure A1.4 $^1$H NMR spectrum for reaction of piperidine with 1 stacked above $^1$H NMR spectrum for 1 for purpose of showing complete reaction of starting material
Figure A1.5 Reaction of pyrrolidine with 1

Figure A1.6 $^1$H NMR spectrum for reaction of pyrrolidine with 1 stacked above $^1$H NMR spectrum for 1 for purpose of showing complete reaction of starting material.
Figure AI.7 Reaction of 4 with 1

Figure AI.8 $^1$H NMR spectrum for reaction of 4 with 1 stacked above $^1$H NMR spectrum for 1 for purpose of showing complete reaction of starting material
**Figure A1.9** Reaction of 3 with 1

**Figure A1.10** $^1$H NMR spectrum for reaction of 3 with 1 benzoate stacked above $^1$H NMR spectrum for 1 for purpose of showing complete reaction of starting material
Appendix II: $^1$H NMR & $^{13}$C NMR Spectra of Hydroxymethyl MIDA Boronate Oxidation Product
Appendix III: $^1$H NMR & $^{13}$C NMR Spectra of Ketenimine Products