Directed Catalytic C–H Functionalization of Organoboronic Acids
Utilizing Removable Directing Groups on the Boron Atom

Hideki Ihara

2014
Preface

Studies presented in this thesis were conducted at Kyoto University under the direction of Professor Michinori Suginome between 2007 and 2009. These studies dealt with the directed catalytic C–H functionalization of organoboronic acids utilizing removable directing groups on the boron atom.

First, the author would like to express his sincere appreciation to Professor Michinori Suginome for his patience, graciousness, generosity as well as his unique and stimulating perception and wonderful insights.

The author would like to acknowledge Associate Professor Toshimichi Ohmura for his constructive suggestions and warm encouragement, Assistant Professor Yuuya Nagata for his generous support and performing the X-ray crystallographic analysis of pyrazolylaniline derivatives, and Assistant Professor Takeshi Yamamoto for his helpful support throughout this thesis.

The author is grateful to Professor Hideki Amii from Gunma University for introducing Professor Suginome to him.

The author was fortunate to have an opportunity to study with Mr. Masashi Koyanagi, and acknowledges his devoted cooperation and great contribution to this work, in particular. The author also wishes to express his gratitude to Mr. Akinori Ueda for earnest collaboration and Dr. Tomotsugu Awano for advice and willing support in the completion of this thesis.

The author wishes to express his gratitude to Dr. Yusuke Tanaka, Dr. Noriyuki Iwadate, Dr. Masaki Daini, Dr. Masamichi Shirakura, Dr. Hiroki Taniguchi, Dr. Tetsuya Yamada, Mr. Satoru Ohashi, Mr. Yuji Komatsu, Mr. Kentaro Sakano, Dr. Kohei Masuda, Dr. Takeharu Toyoshima, Dr. Kazuyuki Oshima, Mr. Takayuki Shioda, Mr. Yuta Takasaki, Mr. Akihito Kijima, Mr. Katsuya Shomizu, Ms. Kanayo Nakada, Mr. Kousuke Hidaka, Mr. Masato Fujita, Mr. Kenta Kuchida, Mr. Ichiro Takase, Mr. Hikaru Takahashi, Mr. Ryosuke Yasui, Mr. Hiroyuki Yanagi, Mr. Yuto Akai, Mr. Yusuke Komori, Mr. Hiroaki Nasu, Dr. Pierrick Nun, Mr. Nils Eichenauer and Ms. Yuki Sakai for their support, kindness, and memorable experiences.
The author would like to thank Ms. Junko Sasaki and Ms. Ayako Oyabu for their overall support, Dr. Keiko Kuwata for mass spectroscopy measurements, Mr. Haruo Fujita for nuclear magnetic resonance (NMR) spectroscopy measurements, and the staff at the Microanalysis Center of Kyoto University for elemental analysis.

The author is grateful to Sumitomo Chemical Co. Ltd for making this challenging opportunity worthwhile.

The author would like to express his gratitude to his parents, Mr. Tadayoshi Ihara and Mrs. Kazuko Ihara, for their encouragement.

Last but not least, the author thanks his wife, Mrs. Tomomi Ihara, for her considerable support and countless words of encouragement and his daughter, Ms. Ako Ihara, for being there for him.

Hideki Ihara

Department of Synthetic Chemistry and Biological Chemistry
Graduate School of Engineering
Kyoto University
Contents

General Introduction 1

Chapter 1 Easily Attachable and Detachable ortho-Directing Agent for Arylboronic Acids in Ruthenium-Catalyzed Aromatic C–H Silylation 9

Chapter 2 Ruthenium-Catalyzed C–H Silylation of Methylboronic Acid Using a Removable α-Directing Modifier on the Boron Atom 33

Chapter 3 Anthranilamide: A Simple, Removable Ortho-Directing Modifier for Arylboronic Acids Serving also as a Protecting Group in Cross-Coupling Reactions 51

Chapter 4 Anthranilamide-Masked o-Iodoarylboronic Acids as Coupling Modules for Iterative Synthesis of ortho-Linked Oligoarenes 87

List of Publications 119
General Introduction

Organoboronic acids\(^1\) play a central role in organic synthesis, and have been utilized in a variety of reactions, including Suzuki–Miyaura cross-coupling,\(^2\) Matteson reaction,\(^3\) Petasis reaction,\(^4\) and Miyaura conjugate addition.\(^5\) They have also been widely used as functional material components and biologically active compounds such as anticancer agents.\(^1\)

Recently, the development of new strategies for the efficient functionalization of organoboronic acids has attracted increasing attention. Many studies have been conducted for an effective C–B bond formation. Although the boronyl group [B(OH)\(_2\)] tolerates various transformations, masking or protecting these functional groups has also been found advantageous during transformations involving organoboronic acids. For example, bulky boronic acid ester\(^6\) and trifluoroborate\(^7\) groups have been utilized to protect boronyl groups during cyclopropanations and oxidations. More recently, boronic acids have been masked efficiently using 1,8-diaminonaphthalene\(^8\) and N-methyliminodiacetic acid,\(^9\) enabling iterative cross-coupling systems for the selective synthesis of oligoarenes.

Since the 1990s, much attention has been paid to C–H bond activation by transition metal complexes using a directing group. This approach enables the site-selective functionalization of more readily available starting materials.\(^10\) In conventional directed C–H activation systems, the directing groups are attached to a substrate in advance, significantly limiting substrate choice. To solve this problem, removable directing groups such as 2-pyridyl\(^11\) and hydrosilyl groups\(^12\) have been developed.\(^13\)

To expand the scope of directed C–H activation strategy, the author was interested in designing new directing groups that are attachable and detachable to the boron atom of organoboronic acids. These removable directing groups facilitate the functionalization of simple and readily available organoboronic acids. Moreover, this strategy enables multiple
post-C–H-activation functionalizations of aromatic compounds through the conversion of boronyl groups into a variety of functional groups by the virtue of their rich reactivity.

This thesis describes boron-based organic syntheses that effectively utilized newly designed directing groups. In this unprecedented strategy, the directing groups were easily removable, traceless, and recyclable. The thesis outline is given below.

Chapter 1 presents the ortho-C–H silylation of arylboronic acids using 2-pyrazol-5-ylaniline as an ortho-directing agent. This directing agent was easily attachable, removable in a traceless manner, and recyclable.

The products of the condensation–dehydration between arylboronic acids and 2-pyrazol-5-ylaniline were allowed to react with hydrosilanes in the presence of RuH₂(CO)(PPh₃)₃ at 135 °C. Regioselective silylation proceeded in good yields at the ortho-position of the modified arylboronic acids. The silylated products were utilized in Suzuki–Miyaura coupling, followed by iodination with ICl (eq 1).
Chapter 2 deals with the ruthenium-catalyzed \( \alpha \)-C–H bond silylation of methyl boronic acid (eq 2). This is the first example of the functionalization of \( \alpha \)-C(sp\(^3\))-H bond to boron atom under neutral conditions, which is usually considered to be difficult.

Chapter 3 reports the use of an anthranilamide as a bifunctional directing group. The anthranilamide also served as a protective group in the Suzuki–Miyaura coupling, and stabilized the boronic acids to a greater extent than pyrazolylaniline, making the products more tolerant to silica gel column chromatography (eq 3).
Chapter 4 describes the transformation of silylboronic acids into ortho-iodoboronic acids. The anthranilamide group acted as a protective group in the iodination step. The resulting ortho-iodophenylboronic acid derivatives served as the coupling module in the synthesis of oligoarenes. Iterative Suzuki–Miyaura coupling sequences produced oligo (o-phenylene)s and oligo (naphthalene-2,3-diyl)s (eq 4).
General Introduction

References and Notes


General Introduction


General Introduction
Easily Attachable and Detachable *ortho*-Directing Agent for Arylboronic Acids in Ruthenium-Catalyzed Aromatic C-H Silylation

**Abstract:** *Ortho*-C–H silylation of arylboronic acids has been achieved using 2-pyrazol-5-ylaniline as an *ortho*-directing agent, which was temporarily attached to the boronyl group via Ru-catalyzed silylation with hydrosilanes. Condensation products of arylboronic acids with 2-pyrazol-5-ylaniline were prepared in situ and subjected to reaction with triorganosilanes in the presence of RuH$_2$(CO)(PPh$_3$)$_3$ at 135 °C. Regioselective silylation at their *ortho*-positions proceeded in good yields for phenylboronic acids bearing *p*-substituents such as chloro, fluoro, methyl, methoxy, and trifluoromethyl groups. *p*-Methoxycarbonyl-substituted phenylboronic acid provided the corresponding silylated product in moderate yield. *m*-Tolyl- and 2-naphthylboronic acids underwent silylation selectively at the less sterically hindered *ortho*-positions. The silylated products were utilized in Suzuki–Miyaura coupling, followed either by iodination with ICl or by Tamao oxidation to furnish iodine or hydroxy-substituted biaryls.
Introduction

Directed metallation is recognized as an efficient strategy in organic synthesis, because of the enhanced reactivity, regioselectivity, and stereoselectivity through coordination of the directing group to a metal. In particular, ortho-directed metallation of aromatic compounds has attracted much attention in the synthesis of functionalized arene derivatives. In addition to stoichiometric metallations such as ortho-lithiation, recent interest has also focused on ortho-C–H activation with transition-metal catalysts. Triggered by the work by Murai and co-workers, ortho-directed C–H functionalization of aromatic compounds has become one of the most actively studied areas in organic synthesis. Although one major drawback of the strategy may be limited substrate scope because of the requirement of the ortho-directing group itself, a removable directing group has been reported to overcome this limitation. It seems highly attractive to produce new directing groups that are easily attachable to the starting materials and detachable from the products.

Results and Discussion

We tested our working hypothesis in ruthenium-catalyzed ortho-C–H silylation. In the original reaction system, various oxygen and nitrogen functionalities served as a directing group in the presence of a Ru₃(CO)₁₂ catalyst with 3,3-dimethyl-1-butene or norbornene as a hydrogen scavenger. We chose a pyrazole group as an ortho-directing element, which could
be introduced onto the boron atom via condensation of phenylboronic acid with 2-pyrazol-5-ylalanine (eq 1). The reaction afforded the condensation product 3a in high yield, which showed reasonable stability toward air and moisture, although it was found to be less stable toward chromatography on silica gel than B(dan) derivatives (dan = naphthalene-1,8-diaminato), which we developed as a protective group for a boronyl group.

\[
\begin{align*}
\text{B(OH)}_2 + \text{Ph}_2\text{N} & \quad \longrightarrow \quad \text{B(pza)} \\
1 & \quad \text{toluene reflux, 1 h} \\
2 (\text{pz}-\text{H}) & \quad 85\% \\
3a (\text{PhB(pza)}) & \quad \equiv \\
\end{align*}
\]

The pza derivative 3a was subjected to catalytic \( o \)-silylation with triethylsilane (eq 2). We found that Ru\(_2\)(CO)(PPh\(_3\))\(_3\) catalyst afforded the corresponding \( o \)-silylation product in high yield, while Ru\(_3\)(CO)\(_{12}\) and [RhCl(cod)]\(_2\) also afforded the same product in much lower yields. It should be remarked that we did not observe silylation at the other positions. All the control experiments using PhB(OH)_2, PhB(pin), and PhB(dan) resulted in no reaction under the same reaction conditions.

In the presence of the ruthenium catalyst, the reaction of 3a with a series of hydrosilanes was examined (eq 3). Phenyl-substituted hydrosilanes afforded the corresponding products 4a’ and 4a’’ in high yields. We also obtained BnMe_2Si-substituted arene 4a’’’, which can be utilized for further transformation by virtue of the ready cleavage of the Bn–Si bond. Although TBDMS derivative 4a’’’ could be obtained in low yield, the use of bulkier TIPS-H resulted in no reaction. Triethoxysilane gave no desired product under the current reaction conditions.

\[
\begin{array}{c|c|c}
\text{catalyst} & \text{NMR yield/\%} \\
\hline
\text{RuH}_2(\text{CO})(\text{PPh}_3)_3 & 93 \quad (2) \\
\text{Ru}_3(\text{CO})_{12} & 53 \\
[\text{RhCl(cod)}]_2 & 16 \\
\end{array}
\]
Table 1. One-Pot ortho-Silylation of Arylboronic Acids by Using Pyrazolylaniline as a ortho-Directing Agent

<table>
<thead>
<tr>
<th>entry</th>
<th>1</th>
<th>% yield</th>
<th>4</th>
<th>% yield</th>
<th>5</th>
<th>isolated product</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PhB(OH)2 (1a)</td>
<td>97 (89)</td>
<td>–</td>
<td>4a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>(1b)</td>
<td></td>
<td>94</td>
<td>80</td>
<td>(5b)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>(1c)</td>
<td></td>
<td>83</td>
<td>77</td>
<td>(5c)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>(1d)</td>
<td></td>
<td>86</td>
<td>71</td>
<td>(5d)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>(1e)</td>
<td></td>
<td>85</td>
<td>78</td>
<td>(5e)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>(1f)</td>
<td></td>
<td>91</td>
<td>84</td>
<td>(5f)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>(1g)</td>
<td></td>
<td>47</td>
<td>40</td>
<td>(5g)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>(1h)</td>
<td></td>
<td>88</td>
<td>74</td>
<td>(5h)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>(1i)</td>
<td></td>
<td>70</td>
<td>62</td>
<td>(5i)</td>
<td></td>
</tr>
</tbody>
</table>

* 1a (0.25 mmol) and 2 (0.25 mmol) were used for the 1st step. In the 2nd step, RuH₂(CO)(PPh₃)₃ (15 μmol), norbornene (1.25 mmol), hydrosilane (1.25 mmol), and toluene (0.13 mL) were used. ** NMR yield. † Isolated yield. ‡ Isolated yield for 4a in the parenthesis. § RuH₂(CO)(PPh₃)₃ (7.5 μmol).
We then carried out the \( o \)-directed silylation of substituted phenylboronic acid derivatives (Table 1). To facilitate the isolation process, the products were converted into the corresponding pinacolate derivatives by treatment of the reaction mixture with pinacol and TsOH. In the series of reactions shown in Table 1, preparation of the (pza)B derivatives (1 equiv 2) and the subsequent silylation were carried out in one pot without isolating the pza-attached derivatives 3. This protocol was found to work efficiently, as demonstrated in the reaction of 1a (entry 1). Arylboronic acids 1b–e bearing \( p \)-substituents such as methyl, methoxy, trifluoromethyl, chloro, fluoro, and methoxycarbonyl afforded the corresponding \( o \)-silylated products in moderate to high yields (entries 2–7). Although the product yields showed no remarkable dependence upon the electronic nature of the \( para \)-substituents, we observed faster reaction for the more electron-rich arene derivatives. Highly regioselective silylation at the less sterically hindered \( ortho \)-position was observed in the reaction of \( m \)-tolylboronic acid (1h) (entry 8). It should be noted that almost no formation of double silylation products was detected in these reactions. The sluggishness of the second silylation is likely due to steric factors, since no \( o \)-silylation was observed at all with \( o \)-tolylboronic acid. 2-Naphthylboronic acid (1i) underwent silylation at the 3-position (entry 9). 3-Thiopheneboronic acid 6 also underwent the directed silylation selectively at its 2-position, although applying a longer reaction time resulted in further silylation at the 5-position, which was not assisted by the directing group (eq 4).

The silylated areneboronic acids served as convenient building blocks for the synthesis of functionalized biaryl derivatives through Suzuki–Miyaura coupling. Silylated product 4a was transformed into the corresponding boronic acid by an acid treatment and subjected to Suzuki–Miyaura coupling with \( p \)-tolyl bromide (eq 5). In this reaction, pza-H\(_2\) (2) was recovered in 85% yield on acid treatment. The silyl group of 9 was substituted with iodine by treatment with ICl to give biaryl iodide 10. In another transformation, the silyl group of cross-coupling product 11 was converted into a hydroxy group by Tamao–Fleming oxidation, leading to the formation of naphthyl-substituted phenol 12 (eq 6).
Conclusion

In summary, we have reported a new protocol for ortho-C-H functionalization of arylboronic acids by using 2-pyrazol-5-ylaniline as an ortho-directing group. The key feature of the new directing group is the ease of its installation and removal. Generalization of this protocol to other o-C–H functionalizations is now being undertaken in this laboratory.

Experimental Section

General

All reactions were carried out under an atmosphere of nitrogen with magnetic stirring. $^1$H, $^{11}$B and $^{13}$C NMR spectra were recorded on a Varian Mercury vx400 or a JEOL JNM-A500 spectrometer at ambient temperature. $^1$H NMR data are reported as follows: chemical shift in ppm downfield from tetramethylsilane (δ scale), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, sex = sextet, m = multiplet, and br = broad), coupling constant (Hz), and integration. $^{13}$C NMR chemical shifts are reported in ppm.
downfield from tetramethylsilane (δ scale). 11B NMR chemical shifts are reported in ppm downfield from BF₃•OEt₂. All ¹³C NMR spectra were obtained with broadband proton decoupling. High-resolution mass spectra were recorded on a JEOL JMS-SX102A (EI) and JEOL JMS-HX110A (FAB) spectrometer. IR spectra were recorded on a FTIR SHIMADZU DR-8000 spectrometer. Preparative TLC was performed with silica gel 60PF₂₅₄ (Merck). Preparative HPLC was performed with SHIMADZU LC system (LC-10AT, RID-6A, C-R6A) and LiChrosorb®CN (7 μm, 250-25) column. Column chromatography was performed with Ultra Pure Silica Gel (40-63 μm) (Silicycle).

Materials

Toluene and THF were dried and deoxygenized using an alumina/catalyst column system (GlassContour Co.), triethylsilane (TCI), dimethylphenylsilane (Aldrich), diphenylmethylsilane (Aldrich), benzildimethylsilane (Aldrich), tert-butylidimethylsilane (Aldrich), triisopropylsilane (TCI), norbornene (TCI), pinacol (TCI), p-toluenesulfonic acid monohydrate (Nacalai), phenylboronic acid (Wako), 4-methoxylphenylboronic acid (Aldrich), 4-trifluoromethylphenylboronic acid (Wako), 4-chlorophenylboronic acid (Wako), 4-fluorophenylboronic acid (Wako), 4-(methoxylcarbonyl)phenylboronic acid (TCI), 3-methylphenylboronic acid (TCI), 2-naphthaleneboronic acid (TCI), 3-thiopheneboronic acid (TCI), Florisil® (100-200 mesh, Wako), tetrabutylammonium fluoride (1 M in THF, Aldrich), methanol (Nacalai), p-bromotoluene (Wako), CH₂Cl₂ (Nacalai), H₂O₂ (Wako), and KHCO₃ (Nacalai) were used as received from the commercial sources. 1-Bromo-2-methoxynaphtalene,¹⁹ RuH₂(CO)(PPh₃)₃,²⁰ [RhCl(cod)]₂,²¹ [Rh(OH)(cod)]₂,²² and Pd(P′Bu₃)₂ ²³ were prepared by the literature procedures. Cesium fluoride (Wako) was dried in an oven at 300 °C for 5 h in vacuo (1 mmHg).

Preparation of 2-Pyrazol-5-ylaniline (2): The compound was prepared by a literature procedure ²⁴ with some modifications.
3-(Dimethylamino)-1-(2-nitrophenyl)prop-2-en-1-one:
A solution of o–nitroacetophenone (14.85 g, 90 mmol) and \(N,N\)-dimethylformamide dimethyl acetal (9.67g, 81.3 mmol) in DMF (40 mL) was heated at 100 °C for 2 h. The reaction mixture was concentrated, and the resultant solid was washed with Et\(_2\)O and collected by filtration (16.13 g, yellow solid, 90%).

![3-(Dimethylamino)-1-(2-nitrophenyl)prop-2-en-1-one](image)

5-(2-Nitrophenyl)-1\(H\)-pyrazole:
A solution of 3-(Dimethylamino)-1-(2-nitrophenyl)prop-2-en-1-one (16.13 g, 73.3 mmol) and hydrazine monohydrate (4.04 g, 80.6 mmol) in ethanol (73 mL) was refluxed for 9.5 h. The mixture was concentrated, and the resultant residue was subjected to column chromatography on silica gel to give the title compound as dark oil. (hexane-EtOAc (10:1), 12.9 g, 93%)

![5-(2-Nitrophenyl)-1\(H\)-pyrazole](image)

2-(1\(H\)-Pyrazol-5-yl)aniline (2)
A mixture of 5- (2-nitrophenyl)-1\(H\)-pyrazole (12.9 g, 68.3 mmol) and 5% Pd/C (2.6 g) in ethanol (50 mL) was stirred under a hydrogen atmosphere (balloon pressure) at 50 °C for 24 h. The mixture was filtered, and the filtrate was concentrated. Resultant solid residue was subjected to bulb-to-bulb distillation (200-205 °C/6 mmHg). The crude product was washed with hexane-CH\(_2\)Cl\(_2\) and dried to give 2 as white solid. (10.6 g, 98%)

Synthesis of 3a by Condensation of Phenylboronic Acid with 2 (Eq 1):
Chapter 1

A mixture of phenylboronic acid (0.767 g, 6.29 mmol) and 2-Pyrazol-5-ylaniline (1.00 g, 6.29 mmol) in toluene (13mL) was heated under reflux in a Dean-Stark apparatus for 1 h. Distillation of the reaction mixture (170-180 °C/0.3 mmHg) gave 3a (1.31 g, white solid, mp 156°C, 85%).

Procedures for Directed ortho-Silylation:

Synthesis of 4a by Directed ortho-Silylation of 3a with Triethylsilane (Eq 2): A mixture of 3a (61.3 mg, 0.25 mmol), metal catalyst (6 mol%), norbornene (118 mg, 1.25 mmol), triethylsilane (199 µL, 1.25 mmol), and anisole (13.6 µL, internal standard) in toluene (0.13 mL) was heated in a glass tube sealed with a J-Young Teflon stopper at 135°C for 6 h. A portion of the sample was taken in an NMR tube and diluted with CDCl₃ to determine the NMR yields.

Control experiments

Instead of 3a, PhB(OH)₂ (0.25 mmol, 30.5 mg), PhB(pin) (0.25 mmol, 51.0 mg), or PhB(dan) (0.25 mmol, 61.0 mg) was reacted under the same reaction conditions as 2.3.1. All reactions resulted in complete recovery of the starting materials.

Effect of exogenous additives

A reaction of 3a (61.3 mg, 0.25 mmol) with triethylsilane (199 µL, 1.25 mmol) was carried out in the presence of pyridine (0.25mmol, 20 µL) or acetophenone (0.25mmol, 29.1 µL) under the same reaction conditions. The reaction was more sluggish than the corresponding reaction in the absence of the additives, resulting in 35 and 9% yields of 4a, respectively, after 12 h at 135 °C.

Synthesis of 4a′–4a'' by Directed ortho-Silylation of 3a with Triorganosilanes (Eq 3): A mixture of 2 (61.3 mg, 0.25 mmol), RuH₂(CO)(PPh₃)₃ (13.8 mg, 0.0015 mmol), norbornene (118 mg, 1.25 mmol), hydrosilane (1.25 mmol), and anisole (13.6 µL, internal standard) in toluene (0.13 mL) was heated in a glass tube sealed with a J-Young Teflon stopper at 135 °C for 6–12 h. The NMR yields of the silylated compounds were determined by ¹H NMR spectroscopy as described in 2.3.1. The products were identified after converting into the corresponding pinacol esters 5a′–5a''.
The following procedure was applied: To the reaction mixture were added pinacol (59 mg, 0.50 mmol), p-toluenesulfonic acid monohydrate (95 mg, 0.50 mmol), and THF (1 mL) at room temperature. After stirring for 3 h, the reaction mixture was passed through a short pad of Florisil® (Hexane-AcOEt, 10:1). The filtrate was concentrated, and the residue was purified by preparative HPLC (hexane, 10 mL/min) to give the pinacol esters of 5a’–5a’’’. The NMR yields for the pza derivatives 4a’–4a’’’ are given in eq 3. The isolated yields for the pinacol esters 5a’–5a’’’ were 87% (oil), 84% (oil), 75% (white solid, mp 105 °C), and 35% (oil), respectively.

Procedures for the One-Pot ortho-Silylation of Arylboronic Acids and Thiopheneboronic Acid by Using Pyrazolylaniline as a ortho-Directing Agent (Table 1 and Eq 4)

A mixture of arylboronic acid (0.25 mmol) and 2-pyrazol-5-ylaniline (2) (39.8 mg, 0.25 mmol) in toluene (1 mL) was heated under reflux with a Dean-Stark condenser for 1 h. After being cooled to room temperature, the solvent was evaporated in vacuo. To the residue, RuH2(CO)(PPh3)3 (13.8 mg, 0.0015 mmol) was added. After filling dry nitrogen in the glass tube, norbornene (118 mg, 1.25 mmol), triethylsilane (199 μL, 1.25 mmol), anisole (13.6 μL, internal standard) and toluene (0.13 mL) were added under a nitrogen atmosphere. The mixture was heated at 135 °C for 12 h.

The products were converted into the corresponding pinacol esters. The following procedure was applied: To the reaction mixture were added pinacol (59 mg, 0.50 mmol), p-toluenesulfonic acid monohydrate (95 mg, 0.50 mmol), and THF (1 mL) at room temperature. After stirring for 3 h, the reaction mixture was passed through a short pad of Florisil® (Hexane-AcOEt, 10:1). The filtrate was concentrated, and the residue was purified by preparative HPLC (hexane, 10 mL/min).

ortho-Silylation of Phenylboronic Acid (Entry 1, Table 1): The silylation product 4a was prepared according the general procedure with modification to the amount of the catalyst used (5 mol% Ru catalyst). 4a (97% NMR yield) was isolated by bulb-to-bulb distillation (280-290 °C/4.7 mmHg, white solid, mp 138 °C, 89%) without converting it into the corresponding pinacol ester.

ortho-Silylation of p-Tolylboronic Acid (Entry 2, Table 1): The product 4b was prepared
Chapter 1

according to the general procedure (2.3.3) (94% NMR yield). The corresponding pinacol ester $5b$ (67.2 mg, oil, 80%) was prepared and isolated according to the general procedure.

**ortho-Silylation of $p$-Methoxyphenylboronic Acid (Entry 3, Table 1):** The product $4c$ (83% NMR yield) was prepared according to the general procedure (2.3.3). The corresponding pinacol ester $5c$ (67.0 mg, oil, 77%) was prepared and isolated according to the general procedure.

**ortho-Silylation of $p$-Trifluoromethylphenylboronic Acid (Entry 4, Table 1):** The product $4d$ (86% NMR yield) was prepared according to the general procedure (2.3.3). The corresponding pinacol ester $5d$ (69.2 mg, oil, 71%) was prepared and isolated according to the general procedure.

**ortho-Silylation of $p$-Chlorophenylboronic Acid (Entry 5, Table 1):** The product $4e$ (85% NMR yield) was prepared according to the general procedure (2.3.3). The corresponding pinacol ester $5e$ (68.8 mg, oil, 78%) was prepared and isolated according to the general procedure.

**ortho-Silylation of $p$-Fluorophenylboronic Acid (Entry 6, Table 1):** The product $4f$ (91% NMR yield) was prepared according to the general procedure (2.3.3). The corresponding pinacol ester $5f$ (71.3 mg, oil, 84%) was prepared and isolated according to the general procedure.

**ortho-Silylation of $p$-(Methoxycarbonyl)phenylboronic Acid (Entry 7, Table 1):** The product $4g$ (47% NMR yield) was prepared according to the general procedure (2.3.3). The corresponding pinacol ester $5g$ (37.6 mg, oil, 40%) was prepared and isolated according to the general procedure. The regioselectivity of the reaction was checked with an nOe experiment as shown below.
**ortho-Silylation of \( m \)-Tolylphenylboronic Acid (Entry 8, Table 1):** The product 4h (88% NMR yield) was prepared according to the general procedure (2.3.3). The corresponding pinacol ester 5h (61.5 mg, oil, 74%) was prepared and isolated according to the general procedure.

**ortho-Silylation of 2-Naphthaleneboronic Acid (Entry 9, Table 1):** The product 4i (70% NMR yield after 24 h) was prepared according to the general procedure (2.3.3). The corresponding pinacol ester 5i (57.6 mg, oil, 62%) was prepared and isolated according to the general procedure.

**ortho-Silylation of o-Tolylboronic Acid (result not shown in Table 1 but shown in the main text):** Reaction of o-tolylboronic acid was carried out according to the general procedure, resulting in no reaction. In the presence of more catalysts (20 mol%), no ortho-silylation product was formed, but benzylic silylation product S-13 (spectral data shown below) was isolated in 7% yield (oil, 3 days) after converting into the corresponding pinacol ester.

**ortho-Silylation of 3-Thiopheneboronic Acid (Eq 4):** The product 7 (54% NMR yield after 72 h) was prepared according to the general procedure (2.3.3). Double silylation product 8 (12% NMR yield) was also formed in the reaction. These primary products were identified after converting into the corresponding pinacol esters S-14 and S-15.

The regiochemistry of double silylated product 8 was unambiguously assigned by converting 8 into known 2,5-bis(triethylsilyl)thiophene by Rh-catalyzed protodeborylation. The following procedure was applied for the protodeborylation. A mixture of 8 (2.0 mg, 0.0046 mmol), \([\text{Rh(OH)}(\text{cod})]_2\) (0.2 mg, 0.0004 mmol) in THF (0.1 ml)-H\(_2\)O(0.01 ml) was
heated at 80 °C for 40 h. The reaction afforded protodeborylation product exclusively, which was identified as 2,5-bis(triethylsilyl)thiophene by $^1$H NMR and GC-MS.$^{25}$

**Synthesis of 10 by Suzuki–Miyaura Cross-Coupling Followed by Iododesilylation (Eq 5):**

\[
\begin{align*}
\text{SiEt}_3
\end{align*}
\]

A solution of 5-(2-(triethylsilyl)phenyl)-5,6-dihydrobenzo[e]pyrazole[1,5-c][1,3,2]-diazaborinine 4a (50 mg, 0.139 mmol) and 5N HCl (0.1 mL) in THF (1 mL) was stirred at room temperature for 2 h. The reaction mixture was extracted with Et$_2$O, dried over Na$_2$SO$_4$, concentrated to give a boronic acid as white solid. The acidic aqueous layer was basified with saturated aqueous NaHCO$_3$, and the solution was extracted with ethyl acetate. The organic layer was dried over Na$_2$SO$_4$ and evaporated. The crude recovered pyrazolylaniline 2 was isolated in pure form (18.9 mg, 85%) by recrystallization from ethyl acetate.

A mixture of the boronic acid, Pd($t$-Bu$_3$P)$_2$ (3.55 mg, 0.00695 mmol), CsF (42.3 mg, 0.278 mmol), and THF (0.28 mL) was heated at 80° C for 15 h. Preparative TLC (Hexane-AcOEt, 10:1) of the reaction mixture afforded the coupling product 9 (32.0 mg, oil, 82%).

\[
\begin{align*}
\text{I}
\end{align*}
\]

A solution of ICl (25 mg, 0.085 mmol) in CH$_2$Cl$_2$ (0.17 mL) was added to 9 (12.0 mg, 0.0426 mmol) at room temperature. The mixture was stirred for 15 h at room temperature. Preparative TLC (Hexane) of reaction mixture afforded the coupling product 10 (9.0 mg, oil, 71%).

**Synthesis of 13 by Suzuki–Miyaura Cross-Coupling Followed by Tamao-Fleming Oxidation (Eq 6):**
A solution of benzyldimethyl(2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)silane 5a’’’ (48.9 mg, 0.139 mmol), 1-bromo-2-methoxynaphtalene (36.2 mg, 0.153 mmol), Pd(t-Bu3P)2 (3.55 mg, 0.00695 mmol), and CsF (42.3 mg, 0.278 mmol) in THF (0.28 mL) was heated at 80 °C for 24 h. Preparative TLC (Hexane-AcOEt, 10:1) of reaction mixture afforded coupling product 11 (45.0 mg, oil, 84%).

2-(2-Methoxynaphthalen-1-yl)phenol

Tetrabutylammonium fluoride (1.0M solution in THF, 0.47 mL) was added to 11 (45.0 mg, 0.117 mmol) at room temperature under air. After being stirred for 15 min, methanol (1.2 mL), KHCO3 (23.4 mg, 0.234 mmol), and H2O2 (30%, 133 mg) were added, and the mixture was stirred for 12 h at room temperature. After quenching the reaction by adding Na2S2O3 aq into the reaction mixture, organic materials were extracted with ether. Purification of the resulting mixture by preparative TLC (Hexane-AcOEt, 3:1) gave 12 (24.6 mg, waxy solid, 84%).
Spectral Data for New Compounds

5-Phenyl-5,6-dihydrobenzo[e]pyrazolo[1,5-c][1,3,2]diazaborinine (3a):

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.29-8.26 (2H, m), 8.13 (1H, d, $J$ = 2.0 Hz), 7.97-7.95 (1H, m), 7.56-7.52 (3H, m), 7.44-7.40 (1H, m), 7.26-7.22 (2H, m), 7.17 (1H, brs), 6.97 (1H, d, $J$ = 2.0 Hz); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 145.7, 145.1, 136.4, 134.3, 130.6, 128.8, 128.0, 124.8, 122.2, 117.6, 116.9, 100.0; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 30.4; IR (KBr) 3416, 3319, 1513, 1355, 911, 756, 698; HREIMS Calcd. for C$_{15}$H$_{12}$BN$_3$ (M$^+$): 245.1124, Found: 245.1125.

5-(2-(Triethylsilyl)phenyl)-5,6-dihydrobenzo[e]pyrazolo[1,5-c][1,3,2]diazaborinine (4a):

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.01 (1H, d, $J$ = 1.6 Hz), 7.99-7.97 (1H, m), 7.45-7.40 (3H, m), 7.29-7.25 (1H, m), 7.17-7.15 (1H, m), 6.95 (1H, d, $J$ = 1.6 Hz), 6.87 (1H, brs), 0.83 (9H, t, $J$ = 7.8 Hz), 0.59 (6H, q, $J$ = 7.8 Hz); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 145.8, 144.4, 140.6, 136.0, 135.4, 132.7, 128.9, 128.2, 127.9, 125.0, 122.5, 117.6, 117.2, 10 0.2, 7.4, 4.0; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 31.5; IR (KBr) 3280, 2955, 1521, 1362, 911, 748; HREIMS Calcd. for C$_{15}$H$_{12}$BN$_3$ (M$^+$): 359.1989, Found: 359.1991.

1-Dimethylphenylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5a':)
Chapter 1

$\text{SiMe}_2\text{Ph}$

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.92-7.89 (1H, m), 7.58-7.56 (1H, m), 7.47-7.44 (2H, m), 7.42-7.36 (2H, m), 7.31-7.30 (3H, m), 1.10 (12H, s), 0.60 (6H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 144.7, 141.3, 136.4, 134.5, 130.1, 128.8, 128.6, 127.9, 84.1, 25.0, 0.0; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 31.2; IR (KBr) 2978, 1349, 1249, 1108, 734; HRFABMS Calcd. For C$_{20}$H$_{27}$BO$_2$Si (M$^+$): 337.1910, Found: 337, 337.1915.

1-Methyldiphenylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5a’’’):

$\text{SiMePh}_2$

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 7.94-7.92 (1H, m), 7.47-7.45 (4H, m), 7.41-7.37 (1H, m), 7.34-7.28 (8H, m), 0.97 (15H, m); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 142.4, 138.6, 137.6, 135.9, 135.1, 129.7, 128.6, 128.4, 127.6, 83.6, 24.4, -2.3; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 31.4; IR (neat) 2978, 1350, 1248, 1108, 727; HREIMS Calcd. for C$_{25}$H$_{29}$BO$_2$Si(M$^+$): 400.2030, Found: 400.2025.

1-Benzyltrimethylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5a’’’’):

$\text{SiMe}_2\text{Bn}$

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.01-7.99 (1H, m), 7.57-7.55 (1H, m), 7.41-7.39 (2H, m), 7.19 (2H, t, $J$ = 8.0 Hz), 7.08-7.01 (3H, m), 2.57 (2H, s), 1.43 (12H, s), 0.30 (6H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 145.1, 140.9, 136.4, 134.8, 129.8, 128.4, 128.4, 128.0, 127.9, 123.7, 83.9, 26.3, 25.0, -1.91; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 31.9; IR (KBr) 2976, 1348, 1142, 830; HRFABMS Calcd. For C$_{21}$H$_{30}$BO$_2$Si (M$^+$): 353.2108, Found: 353.2113.
1-tert-Butyldimethylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5a’’’):

\[
\begin{align*}
\text{H} & \text{NMR (400 MHz, CDCl}_3\text{)} \; \delta 7.80-7.78 \text{ (1H, m)}, 7.61-7.58 \text{ (1H, m)}, 7.38-7.30 \text{ (2H, m)}, 1.35 \text{ (12H, s)}, 0.90 \text{ (9H, s)}, 0.34 \text{ (6H, s)}; \\
\text{C} & \text{NMR (126 MHz, CDCl}_3\text{)} \; \delta 143.1, 136.0, 135.2, 128.6, 127.6, 83.7, 27.3, 25.0, 17.5, -3.1; \\
\text{B} & \text{NMR (128 MHz, CDCl}_3\text{)} \; \delta 31.5; \\
\text{IR (neat)} & 2926, 1347, 1249, 1146, 825; \\
\text{HREIMS Calcd. for C}_{21}\text{H}_{29}\text{BO}_2\text{Si (M}^+\text{): 319.2264, Found: 319.2267.}
\end{align*}
\]

5-Methyl-1-triethylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5b):

\[
\begin{align*}
\text{H} & \text{NMR (400 MHz, CDCl}_3\text{)} \; \delta 7.80 \text{ (1H, d, } J = 7.6 \text{ Hz)}, 7.36 \text{ (1H, m)}, 7.16-7.14 \text{ (1H, m)}, 2.35 \text{ (3H, s)}, 1.33 \text{ (12H, s)}, 0.93-0.90 \text{ (15H, m)}; \\
\text{C} & \text{NMR (126 MHz, CDCl}_3\text{)} \; \delta 143.7, 139.1, 136.3, 128.4, 83.5, 24.9, 21.8, 7.8, 4.3; \\
\text{B} & \text{NMR (128 MHz, CDCl}_3\text{)} \; \delta 31.7; \\
\text{IR (neat)} & 2953, 1593, 1343, 1145, 733; \\
\text{HRFABMS Calcd. For C}_{21}\text{H}_{29}\text{BO}_2\text{Si (M}^+\text{): 332.2343, Found: 332.2345.}
\end{align*}
\]

5-Methoxy-1-triethylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5c):

\[
\begin{align*}
\text{H} & \text{NMR (400 MHz, CDCl}_3\text{)} \; \delta 7.89 \text{ (1H, d, } J = 8.4 \text{ Hz)}, 7.12 \text{ (1H, d, } J = 2.8 \text{ Hz)}, 6.84 \text{ (1H, dd, } J = 8.4 \text{ Hz, 2.8 Hz)}, 3.82 \text{ (3H, s)}, 1.33 \text{ (12H, s)}, 0.92 \text{ (15H, s)}; \\
\text{C} & \text{NMR (126 MHz, CDCl}_3\text{)} \; \delta 160.4, 146.2, 138.3, 122.3, 111.6, 83.5, 54.8, 24.8, 7.8, 4.2; \\
\text{B} & \text{NMR (128 MHz, CDCl}_3\text{)} \; \delta 31.9; \\
\text{IR (neat)} & 2953, 1584, 1345, 1145, 731; \\
\text{HREIMS Calcd. For C}_{19}\text{H}_{35}\text{BO}_3\text{Si (M}^+\text{): 348.2292, Found: 348.2303.}
\end{align*}
\]
5-Trifluoromethyl-1-triethylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5d):

\[ \text{H NMR (400 MHz, CDCl}_3\text{)} \delta 7.99 (1H, d, J = 7.6 Hz), 7.77 (1H, m), 7.58-7.55 (1H, m), 1.37 (12H, s), 0.95-0.93 (15H, m); \text{C NMR (126 MHz, CDCl}_3\text{)} \delta 145.1, 136.0, 131.3 (m), 130.9 (q, J = 31.2), 124.4 (q, J = 272.7), 124.1 (m), 84.2, 24.9, 7.7, 4.1; \text{B NMR (128 MHz, CDCl}_3\text{)} \delta 31.6; \text{IR (neat) 2956, 1324, 1129, 733; HRFABMS Calcd. for C}_{19}\text{H}_{29}\text{BF}_3\text{O}_2\text{Si (M}^+\text{): 385.1982, Found: 385.1991.}

5-Chloro-1-triethylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5e):

\[ \text{H NMR (400 MHz, CDCl}_3\text{)} \delta 7.83 (1H, d, J = 8.0 Hz), 7.49 (1H, d, J = 2.2 Hz), 7.30 (1H, dd, J = 8.0 Hz, 2.2 Hz), 1.35 (12H, s), 0.92 (15H, s); \text{C NMR (126 MHz, CDCl}_3\text{)} \delta 146.7, 137.6, 136.5, 135.1, 127.6, 83.9, 24.9, 8.0, 4.1; \text{B NMR (128 MHz, CDCl}_3\text{)} \delta 31.4; \text{IR (neat) 2954, 1569, 1339, 1111, 731; HRFABMS Calcd. for C}_{18}\text{H}_{29}\text{BClO}_2\text{Si (M}^+\text{)} : 351.1718, Found: 351.1721.}

5-Fluoro-1-triethylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5f):

\[ \text{H NMR (400 MHz, CDCl}_3\text{)} \delta 7.90 (1H, dd, J = 8.0 Hz, 6.4 Hz), 7.23 (1H, dd, J = 10.4 Hz, 2.8 Hz), 7.01-6.97 (1H, m), 1.34 (12H, s), 0.91 (15H, s); \text{C NMR (126 MHz, CDCl}_3\text{)} \delta 163.9 (d, J = 252.5), 147.9 (d, J = 4.9), 138.6 (d, J = 6.8), 122.2 (d, J = 17.6), 114.3 (d, J = 19.5), 83.8, 24.9, 7.7, 4.1; \text{B NMR (128 MHz, CDCl}_3\text{)} \delta 31.1; \text{IR (neat) 2953, 1570, 1343,
5-(Methoxycarbonyl)-1-triethylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5g):

\[ \text{MeO}_2C \]
\[ \text{SiEt}_3 \]

\(^1\)H NMR (400 MHz, CDCl\(_3\)) \( \delta \) 8.20 (1H, m), 7.97-7.90 (2H, m), 3.92 (3H, s), 1.36 (12H, s), 0.95-0.91 (15H, m); \(^{13}\)C NMR (126 MHz, CDCl\(_3\)) \( \delta \) 167.6, 144.1, 135.9, 135.8, 130.3, 128.4, 84.1, 52.1, 24.9, 7.7, 4.1; \(^{11}\)B NMR (128 MHz, CDCl\(_3\)) \( \delta \) 31.7; IR (neat) 2952, 1727, 1284, 1120, 730; HREIMS Calcd. for C\(_{20}\)H\(_{33}\)BO\(_4\)Si\((\text{M}^+\)): 376.2241, Found: 376.2245.

4-Methyl-1-triethylsilyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzene (5h):

\[ \text{Me} \]
\[ \text{SiEt}_3 \]

\(^1\)H NMR (400 MHz, CDCl\(_3\)) \( \delta \) 7.74 (1H, s), 7.48 (1H, d, \( J = 7.6 \) Hz), 7.22 (1H, d, \( J = 7.6 \) Hz), 2.35 (3H, s), 1.36 (12H, s), 0.93-0.91 (15H, m); \(^{13}\)C NMR (126 MHz, CDCl\(_3\)) \( \delta \) 139.9, 137.2, 136.9, 135.6, 130.3, 83.7, 24.9, 21.2, 7.8, 4.3; \(^{11}\)B NMR (128 MHz, CDCl\(_3\)) \( \delta \) 32.3; IR (neat) 2951, 1340, 1145, 856, 731; HRFABMS Calcd. for C\(_{19}\)H\(_{35}\)BO\(_2\)Si\((\text{M}^+)\): 332.2343, Found: 332.2352.

2-Triethylsilyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)naphtalene (5i):

\[ \text{SiEt}_3 \]

\(^1\)H NMR (400 MHz, CDCl\(_3\)) \( \delta \) 8.43 (1H, s), 8.01 (1H, s), 7.86-7.80 (2H, m), 7.52-7.45 (2H, m), 1.39 (12H, s), 1.03-0.92 (15H, m); \(^{13}\)C NMR (126 MHz, CDCl\(_3\)) \( \delta \) 138.9, 137.1, 136.0, 133.6, 132.4, 128.2, 127.8, 126.9, 126.2, 83.8, 24.9, 7.9, 4.3; \(^{11}\)B NMR (128 MHz, CDCl\(_3\))
2-Triethylsilyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)thiophene (S-14):

\[
\begin{align*}
\text{H NMR (400 MHz, CDCl}_3\text{) } & \delta 8.05 (1H, d, J = 2.4 \text{ Hz}), 7.44 (1H, d, J = 2.4 \text{ Hz}), 1.33 (12H, s), 0.95-0.84 (15H, m); \\
\text{C NMR (126 MHz, CDCl}_3\text{) } & \delta 142.6, 138.6, 133.9, 83.5, 24.8, 7.7, 3.9; \\
\text{B NMR (128 MHz, CDCl}_3\text{) } & \delta 29.7; \\
\text{IR (neat) } & 2952, 1475, 1259, 1145, 1007, 732;
\end{align*}
\]

HRFABMS Calcd. for C_{22}H_{33}BO_{2}Si (M^+): 368.2343, Found: 368.2340.

2,5-Bis(triethylsilyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)thiophene (S-15):

\[
\begin{align*}
\text{H NMR (400 MHz, CDCl}_3\text{) } & \delta 7.70 (1H, s), 1.33 (12H, s), 1.01-0.97 (9H, m), 0.95 (15H, s), 0.84-0.78 (6H, m); \\
\text{C NMR (126 MHz, CDCl}_3\text{) } & \delta 154.9, 143.5, 140.6, 83.4, 24.9, 7.7, 7.5, 4.60, 4.55; \\
\text{B NMR (128 MHz, CDCl}_3\text{) } & \delta 29.8; \\
\text{IR (neat) } & 2954, 1495, 1232, 1136, 1019, 736;
\end{align*}
\]

HRFABMS Calcd. for C_{22}H_{43}BO_{2}Si_{2} (M^+): 438.2615, Found: 438.2617.

Triethyl(4'-methylbiphenyl-2-yl)silane (9):

\[
\begin{align*}
\text{H NMR (400 MHz, CDCl}_3\text{) } & \delta 7.56-7.54 (1H, m), 7.38-7.29 (2H, m), 7.21-7.18 (1H, m), 7.16
\end{align*}
\]
Chapter 1

(4H, s), 2.41 (3H, s), 0.81 (9H, t, $J = 8.0$ Hz), 0.47 (6H, q, $J = 8.0$ Hz); $^{13}$C NMR (126 MHz, CDCl$_3$) δ 149.7, 141.7, 136.6, 135.7, 135.1, 129.8, 129.0, 128.24, 128.20, 125.9, 21.2, 7.5, 4.2; IR (neat) 2952, 1464, 1237, 1003, 721; HREIMS Calcd. for C$_{19}$H$_{26}$Si (M$^+$): 282.1804, Found: 282.1814.

Benzyl(2-(2-methoxynaphthalen-1-yl)phenyl)dimethylsilane (11):

\[
\begin{align*}
\text{OMe} & \quad \text{SiMe}_2\text{Bn} \\
\end{align*}
\]

$^1$H NMR (400 MHz, CDCl$_3$) δ 7.92 (1H, d, $J = 9.2$ Hz), 7.83-7.81 (1H, m), 7.65-7.63 (1H, m), 7.52-7.48 (1H, m), 7.43-7.39 (1H, m), 7.35 (1H, d, $J = 8.8$ Hz), 7.33-7.26 (2H, m), 7.22-7.20 (1H, m), 7.18-7.16 (1H, m), 7.09-7.06 (2H, m), 7.00-6.96 (1H, m), 6.71-6.69 (2H, m), 3.83 (3H, s), 1.88 (1H, d, $J = 13.6$ Hz), 1.83 (1H, d, $J = 13.6$ Hz), -0.31 (3H, s), -0.44 (3H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) δ 153.8, 142.9, 140.2, 138.8, 135.2, 134.6, 130.9, 129.2, 129.1, 128.5, 128.3, 127.8, 127.7, 126.4, 126.3, 126.2, 125.7, 123.7, 123.4, 112.7, 55.9, 25.9, -2.7, -2.9; IR (neat) 3055, 2895, 1593, 1508, 1260, 908, 734; HREIMS Calcd. for C$_{26}$H$_{26}$OSi (M$^+$): 382.1753, Found: 382.1754

2-(2-Methoxynaphthalen-1-yl)phenol (12):

\[
\begin{align*}
\text{OMe} & \quad \text{OH} \\
\end{align*}
\]

$^1$H NMR (400 MHz, CDCl$_3$) δ 7.96 (1H, d, $J = 9.2$ Hz), 7.87-7.83 (1H, m), 7.52-7.47 (1H, m), 7.42-7.36 (4H, m), 7.21 (1H, dd, $J = 7.6$ Hz, 1.6 Hz), 7.10 (1H, dd, $J = 8.0$ Hz, 1.2 Hz), 7.09-7.05 (1H, m), 4.93 (1H, s), 3.90 (3H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) δ 154.5, 153.7, 133.7, 132.1, 130.5, 129.4, 128.0, 127.0, 124.9, 124.0, 122.3, 120.5, 118.4, 116.0, 113.4, 56.7; IR (neat) 3506, 3058, 2936, 1593, 1508, 1260, 1067, 811, 753; HREIMS Calcd. for
Chapter 1

C_{17}H_{14}O_2 (M^+) : 250.0994, Found: 250.0991.

Triethyl(2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzyl)silane (S-13):

\[
\text{\includegraphics[width=0.5\textwidth]{image.png}}
\]

\( ^1H \text{NMR (400 MHz, CDCl}_3 \) \( \delta 7.74 \text{ (dd, } J = 7.4, 1.6 \text{ Hz, } 1H), 7.27-7.23 \text{ (m, } 1H), 7.05-6.99 \text{ (m, } 2H) 2.57 \text{ (s,} 2H), 1.34 \text{ (s, } 12H), 0.87 \text{ (t, } J = 8.0, 9H), 0.51 \text{ (q, } J = 8.0, 6H); \)

\( ^13C \text{NMR (126 MHz, CDCl}_3 \) \( \delta 148.3, 136.4, 130.6, 128.7, 122.9, 83.3, 24.9, 21.4, 7.3, 3.2; \)

\( ^11B \text{NMR (128 MHz, CDCl}_3 \) \( \delta 31.5; \)

IR (neat) 2952, 1597, 1347, 1146, 773; HREIMS Calcd. for C_{19}H_{33}BO_2Si (M^+) : 332.2343. Found: 332.2340.

References


6) For removable directing groups for C–H and C–C activation, see: (a) Oi, S.; Ogino, Y.; Fukita, S.; Inoue, Y. Org. Lett. 2002, 4, 1783.  (b) Kakiuchi, F.; Matsumoto, M.; Tsuchiya,
Chapter 1


10) 2-Pyrazol-5-ylaniline was prepared via three steps from o-nitroacetophenone in 83% overall yield.

11) PhB(pza) showed no decomposition over at least 10 months on storage in a vial in air.


14) Some of the produced B(pin) derivatives were still unstable toward silica gel column chromatography.

15) Silylation of the benzylic C–H bond proceeded slowly in low yield.

16) Non-directed, Ir-catalyzed silylation of thiophenes has been reported.  Lu, B.; Falck, J. R. *Angew. Chem., Int. Ed.* **2008**, *47*, 7508.


21) Schenck, T. G.; Downes, J. M.; Milne, C. R. C.; MacKenzie, P. B.; Boucher, H.; Whelan,


Abstract: Ruthenium-catalyzed C–H silylation of methylboronic acid was achieved by use of 2-(1H-pyrazol-3-yl)aniline as a removable α-directing modifier on the boron atom. Cross-coupling of the product, i.e., (phenyldimethylsilyl)methylpinacolborane, with aryl halides proceeded in the presence of a PdCl₂(dppf) catalyst and CsOH as a base.
**Introduction**

Directed catalytic functionalization of the $sp^3$-C–H bond is an attractive strategy for the synthesis of functionalized alkanes in organic synthesis. Functional groups such as pyridyl, quinolinyl, oxazolinyl, carboxyl, aminocarbonyl, and imino groups are attached to alkanes as directing groups for C–H functionalization through arylation, amination, silylation, acetoxylation, halogenation, etc. Despite the remarkable acceleration of the catalytic reaction by the directing groups, the need for their installation in the substrates significantly limits the scope of the reaction. It is likely that the development of “traceless” or “convertible” directing groups will make directed C–H activation really useful and applicable to organic synthesis.

We have developed removable $o$-directing groups, which are attached to the boron atoms of arylboronic acids, for Ru-catalyzed $o$-C–H silylation at their $sp^2$-carbon atoms. 2-(1H-Pyrazol-3-yl)aniline and anthranilamide form six-membered diazaborine structures (1 and 2) containing N–B–N linkages upon condensation with arylboronic acids. The nitrogen atoms in the attached directing group coordinate to the transition metal catalysts and enable the C–H functionalization reaction at the ortho positions. It would be highly attractive if the strategy could be extended to activation of alkylboronic acids. In particular, such a synthetic strategy is most attractive for the synthesis of $\alpha$-functionalized methylboronic acids (Figure 1), because they are not accessible by hydroboration unlike the higher alkylboronic acids. It has been shown that even strong bases are not able to abstract $\alpha$-hydrogen atoms of methylboronic acid esters. It should be noted that, in spite of its potential usefulness, no catalytic C–H-functionalization at the $\alpha$-hydrogen of alkylboronic acids has been reported. Herein, we describe $\alpha$-C–H silylation of methylboronic acid using an $\alpha$-directing modifier that is attached to the boron atom.
Figure 1. $\alpha$-C–H Functionalization of methylboronic acid via introduction of a directing group (DG) to the boron atom.

Results and Discussion

Methylboronic acid was condensed with 2-$(1H$-pyrazol-3-yl)aniline and anthranilamide, giving MeB(pza) (1) and MeB(aam) (2), respectively, in high yields (eqs 1 and 2). A phenol analogue MeB(pzp) (3) of 1 was also prepared by the reaction with commercially available 2-$(1H$-pyrazol-3-yl)phenol in high yield (eq 1).

\[
\begin{align*}
\text{CH}_3\text{B(OH)}_2 & + \quad \begin{array}{c}
\text{X} \quad \text{H} \\
\text{H} \\
\text{N} - \text{N} \\
\text{CH}_3
\end{array} & \xrightarrow{\text{toluene reflux, 1h}} & \quad \begin{array}{c}
\text{X} \\
\text{B} - \text{N} - \text{N} \\
\text{CH}_3
\end{array} \\
& \text{MeB(pza) (1) (X = NH: 89\%)} \\
& \text{MeB(pzp) (3) (X = O: 87\%)}
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3\text{B(OH)}_2 & + \quad \begin{array}{c}
\text{X} \quad \text{H} \\
\text{H} \\
\text{N} - \text{NH}_2
\end{array} & \xrightarrow{\text{toluene reflux, 1h}} & \quad \begin{array}{c}
\text{X} \\
\text{B} - \text{NH} \\
\text{CH}_3
\end{array} \\
& \text{MeB(aam) (2) (80\%)}
\end{align*}
\]
Chapter 2

The modified methylboronic acids 1–3 were subjected to Ru-catalyzed reaction with triorganosilanes in the presence of norbornene as a hydrogen scavenger (Table 1). With the [RhCl(cod)]₂ catalyst, a trace amount of the expected α-silylation product was detected by ¹H NMR (entry 1). Ruthenium catalysts were found to be more effective for α-silylation. The RuH₂(CO)(PPh₃)₃ catalyst, which served as the best catalyst in the o-C–H silylation of PZA- and AAM-modified arylboronic acids, afforded the α-silylation product in high yield after 12 h under reflux in toluene (entry 3). Attempts at lowering the catalyst loading resulted in a decrease in the product yields (entries 4 and 5). It should be remarked that the AAM-modified methylboronic acid 2 completely failed to give the α-silylation product (entry 6). It is presumed that a four-membered metallacyclic intermediate or transition state, in which the AAM group assists the activation of the α-C–H bond, is not favorable, in contrast to the favorable formation of a five-membered metallacycle in the PZA-assisted reactions. It should also be noted that 3, a phenol analogue of 1, was found to be totally unreactive in the α-silylation reaction despite our expectation of forming a favorable five-membered metallacycle, which is quite similar to that formed in the PZA-assisted reaction. The contrasted reactivity can be rationalized by the observed difference in the ¹¹B chemical shifts between 1 and 3. The phenol analogue 3 showed its ¹¹B signal at 4.2 ppm in chloroform-d, which is unusually higher than typical three-coordinating organoboronic acid derivatives, including MeB(pza) (1, 32.7 ppm) and MeB(aam) (2, 32.3 ppm). The high-field shift of the ¹¹B signal can be ascribed to the formation of a four-coordinating species, in which the pyrazolyl nitrogen atoms coordinate to the boron atoms. Presumably, the lower donating ability of oxygen compared with nitrogen makes the boron atom of 3 more acidic than 1, allowing the coordination of the pyrazolyl nitrogen to the boron atom.
Table 1. Reaction of methylboronic acid derivatives 1–3 with dimethylphenylsilane in the presence of transition metal catalysts

<table>
<thead>
<tr>
<th>entry</th>
<th>substrate</th>
<th>catalyst (mol% metal)</th>
<th>NMR yield/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>[RhCl(cod)]₂ (6)</td>
<td>trace</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Ru₃(CO)₁₂ (6)</td>
<td>37</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>RuH₂(CO)(PPh₃)₃ (6)</td>
<td>97</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>RuH₂(CO)(PPh₃)₃ (3)</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>RuH₂(CO)(PPh₃)₃ (1)</td>
<td>52</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>RuH₂(CO)(PPh₃)₃ (6)</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>RuH₂(CO)(PPh₃)₃ (6)</td>
<td>0</td>
</tr>
</tbody>
</table>

---

a 1–3 (0.25 mmol), a catalyst (15 μmol), norbornene (120 mg, 1.3 mmol), PhMe₂SiH (1.3 mmol), and anisole (13.6 μL, internal standard) in toluene (0.13 mL) were heated at 135 °C for 12 h.

Under the optimized reaction conditions, α-C–H silylation with various hydrosilanes was carried out (Table 2). For these examinations, the primary silylation products were treated with pinacol in the presence of TsOH and isolated as pinacol esters. In the reactions with PhMe₂SiH, the one-pot procedure afforded the pinacol ester of (phenyldimethylsilyl)methylboronic acid in 85% isolated yield (entry 1). Likewise, Et₃SiH afforded the corresponding product in good yield (entry 2). Silyl hydride having a benzyl group, which is easily convertible to a fluorine group for further transformation, also provided the corresponding product in high yield (entry 3). In the reaction of Ph₂MeSiH, a slight decrease in yield was encountered, presumably because of steric hindrance (entry 4). With a more bulky silyl hydride such as t-BuMe₂SiH, the silylated product was obtained only in low yield (entry 5). Neither (EtO)₃SiH nor (Me₃Si)Me₂SiH gave the silylated product at all under these reaction conditions.
Table 2. Ru-catalyzed α-silylation of MeB(pza) (1) with silyl hydrides

<table>
<thead>
<tr>
<th>entry</th>
<th>silane</th>
<th>NMR yield /%</th>
<th>isolated yield /%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PhMe₂SiH</td>
<td>97</td>
<td>85 (4a)</td>
</tr>
<tr>
<td>2</td>
<td>Et₃SiH</td>
<td>95</td>
<td>81 (4b)</td>
</tr>
<tr>
<td>3</td>
<td>BnMe₂SiH</td>
<td>94</td>
<td>86 (4c)</td>
</tr>
<tr>
<td>4</td>
<td>Ph₂MeSiH</td>
<td>73</td>
<td>67 (4d)</td>
</tr>
<tr>
<td>5</td>
<td>t-BuMe₂SiH</td>
<td>29</td>
<td>28 (4e)</td>
</tr>
</tbody>
</table>

1 (46 mg, 0.25 mmol), RuH₂(CO)(PPh₃)₃ (14 mg, 15 µmol), norbornene (120 mg, 1.3 mmol), silane (1.3 mmol), and anisole (13.6 µL, internal standard) in toluene (0.13 mL) were heated at 135 °C for 12 h. The reaction mixture was treated with pinacol (59 mg, 0.5 mmol) and TsOH•H₂O (95 mg, 0.5 mmol) at r.t. for 1 h.

We attempted the reaction of PZA-derivatives of ethylboronic acid and cyclohexylboronic acid under the same reaction conditions. In the reaction of EtB(pza) (5), two silylated products via α- and β-silylation (6a and 6b) were obtained, although the consumption of EtB(pza) was sluggish and incomplete (eq 3). Reaction of CyB(pza) was found to be extremely slow under the standard reaction conditions. Use of 20 mol% catalyst without solvent resulted in C–H silylation at the pyrazolyl group (eq 4). After treatment with pinacol, silylated pyrazolylaniline 8 was isolated in 36% yield. No product formed via silylation at the cyclohexane ring was found in the reaction mixture.
We then tried to optimize Suzuki–Miyaura coupling of the pinacol ester of \( \alpha \)-silylmethylboronic acid with aryl halides.\(^\text{13}\) We found that the coupling of 4a with 1-naphthyl bromide proceeded in good yield in the presence of \( \text{PdCl}_2(\text{dppf}) \) as a catalyst and \( \text{CsOH} \) as a base (eq 5). Use of \( \text{Cs}_2\text{CO}_3 \) as a base or \( \text{PdCl}_2(\text{PPh}_3)_2 \) as a catalyst lowered the yields significantly. These reaction conditions could be applied to the coupling of 3-bromoacetophenone with 4a, which afforded the products in 61% yield (eq 6). Although use of an excess amount of Ag(I) salt\(^\text{14}\) or use of the corresponding trifluoroborates\(^\text{15}\) has been recommended for cross-coupling of alkylboronic acid derivatives because of their low reactivity, we found that the coupling of silylmethylboronic ester 4a proceeded without applying such modified reaction conditions.\(^\text{16,17}\)
Conclusion

In summary, we have established that use of 2-(1H-pyrazol-3-yl)aniline as a modifier on the boron atom of methylboronic acid allows α-silylation with silyl hydrides in the presence of a ruthenium catalyst. The corresponding reaction of EtB(pza) afforded a mixture of α- and β-silylated products. In the silylation of PZA-modified cyclohexylboronic acid, silylation takes place at the PZA group rather than at the methyl group. Cross-coupling of the α-silylated products with aryl halides has been achieved with a PdCl₂(dpdpf) catalyst and CsOH as a base. Exploration of more efficient and selective C–H functionalization of alkylboronic acids is now being undertaken in this laboratory.

Experimental Section

General

All reactions were carried out under an atmosphere of nitrogen with magnetic stirring. ¹H, ¹¹B and ¹³C NMR spectra were recorded on a Varian Mercury vx400 or a JEOL JNM-A500 spectrometer at ambient temperature. ¹H NMR data are reported as follows: chemical shift in ppm downfield from tetramethylsilane (δ scale), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, sex = sextet, m = multiplet, and br = broad), coupling constant (Hz), and integration. ¹³C NMR chemical shifts are reported in ppm downfield from tetramethylsilane (δ scale). ¹¹B NMR chemical shifts are reported in ppm downfield from BF₃•OEt₂. All ¹³C NMR spectra were obtained with broadband proton decoupling. High-resolution mass spectra were recorded on a JEOL JMS-SX102A (EI) and
JEOL JMS-HX110A (FAB) spectrometer. IR spectra were recorded on a FTIR SHIMADZU DR-8000 spectrometer. Preparative TLC was performed with silica gel 60PF\textsubscript{254} (Merck). Recycling Preparative GPC was performed with JAI LC-908 equipped with JAIGEL-1H and -2H columns in a series (CHCl\textsubscript{3}). Column chromatography was performed with Ultra Pure Silica Gel (40-63 \(\mu\text{m}\)) (Silicycle).

Materials

Toluene and THF were dried and deoxygenized using an alumina/catalyst column system (GlassContour Co.). Triethylsilane (TCI), dimethylphenylsilane (Aldrich), diphenylmethylsilane (Aldrich), benzyltrimethylsilane (Aldrich), tert-butyldimethylsilane (Aldrich), triethoxysilane (TCI), pentamethyldisilane (Aldrich), norbornene (TCI), pinacol (TCI), \(p\)-toluenesulfonic acid monohydrate (Nacalai), methylboronic acid (TCI), ethylboronic acid (Wako), cyclohexylboronic acid (Aldrich), 1-bromonaphthalene (Wako), 3'-bromoacetophenone (TCI), Florisil\textsuperscript{\textregistered} (100-200 mesh, Wako), CsOH•H\textsubscript{2}O (Nacalai), Ru\textsubscript{3}(CO)\textsubscript{12} (Aldrich), and PdCl\textsubscript{2}(dppf) (Wako) were used as received from the commercial sources. RuH\textsubscript{2}(CO)(PPh\textsubscript{3})\textsubscript{3}, \cite{1} [RhCl(cod)]\textsubscript{2}, \cite{2} and 2-(1H-pyrazol-3-yl)aniline \cite{3} were prepared by the literature procedures.

Procedures for the Synthesis of Modified Methylboronic Acids 1–3

Synthesis of 5-Methyl-5,6-dihydrobenzo[e]pyrazolo[1,5-c][1,3,2]diazaborinine (1): A
mixture of methylboronic acid (0.24 g, 4.0 mmol) and 2-(1H-pyrazol-3-yl)aniline (0.64 g, 4.0 mmol) in toluene (8 mL) was heated for 1 h under reflux with azeotropic removal of water. After evaporation of volatile material under reduced pressure, the residual solid was subjected to bulb-to-bulb distillation (190-200 °C / 1.4 mmHg), giving the title compound 1 as white solid (0.65 g, 89%).  

1:  

1H NMR (CDCl$_3$) $\delta$ 8.45 (d, $J$ = 1.7 Hz, 1H), 7.89 (dd, $J$ = 1.3 Hz, 8.0 Hz, 1H), 7.41-7.34 (m, 1H), 7.23-7.16 (m, 1H), 7.15 (d, $J$ = 8.3 Hz, 1H), 6.89 (d, $J$ = 1.7 Hz, 1H), 6.89 (brs, 1H), 1.11 (s, 3H). 

13C NMR (CDCl$_3$) $\delta$ 145.3, 144.0, 136.4, 128.8, 124.9, 121.9, 117.3, 116.7, 100.0. The boron-bound carbon was not detected due to quadrupolar relaxation.  

11B NMR (CDCl$_3$) $\delta$ 32.7. IR (KBr) 3258, 1620, 1524, 1481, 750 cm$^{-1}$. HRMS (EI) $m/z$ calcld for C$_{10}$H$_{10}$BN$_3$ (M$^+$): 183.0968, found: 183.0971.

**Synthesis of 2,3-dihydro-2-methylbenzo[d][1,3,2]diazaborinin-4(1H)-one (2):** A mixture of methylboronic acid (90.0 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol) in toluene (0.25 mmol/mL, 6 mL) was heated under reflux in a Dean-Stark apparatus for 1 h. After cooling a mixture to room temperature, the precipitates were collected by filtration to give 2 (191 mg, 80%).  

2:  

1H NMR (400 MHz, CDCl$_3$) $\delta$ 8.18 (dd, $J$ = 4.0 Hz, 1.6 Hz, 1H), 7.48 (ddd, $J$ = 8.4 Hz, 7.2 Hz, 1.6 Hz, 1H), 7.21 (1H, brs), 7.10 (ddd, $J$ = 8.0 Hz, 7.2 Hz, 1.2 Hz, 1H), 6.97 (dd, $J$ = 4.0 Hz, 0.8 Hz, 1H), 6.44 (brs, 1H), 0.57 (s, 3H); 13C NMR (126 MHz, CDCl$_3$) $\delta$ 166.6, 144.5, 133.8, 129.2, 121.5, 118.7, 117.2; 11B NMR (128 MHz, CDCl$_3$) $\delta$ 32.3; IR (KBr) 3269, 1620, 1524, 1481, 748; HREIMS Calcd. for C$_8$H$_9$BN$_2$O (M$^+$): 160.0808, Found: 160.0807.

**Synthesis of 5-Methyl-5H-benzo[e]pyrazolo[1,5-c][1,3,2]oxazaborinine (3):** A mixture of methylboronic acid (0.12 g, 2.0 mmol) and 2-(1H-pyrazol-3-yl)phenol (0.32 g, 2.0 mmol) in
toluene (4 mL) was heated for 1 h under reflux with azeotropic removal of water. After evaporation of volatile material under reduced pressure, the residual solid was subjected to bulb-to-bulb distillation, giving the title compound 3 as white solid (0.32 g, 87%). 

4: $^1$H NMR (CDCl$_3$) $\delta$ 7.95 (d, $J = 2.6$ Hz, 1H), 7.54 (dd, $J = 1.6$ Hz, 7.6 Hz, 1H), 7.35-7.28 (m, 1H), 7.07 (d, $J = 8.0$ Hz, 1H), 6.99-6.92 (m, 1H), 6.61 (d, $J = 2.6$ Hz, 1H), 0.26 (s, 3H). $^{13}$C NMR (CDCl$_3$) $\delta$ 154.1, 142.1, 133.4, 131.3, 125.2, 119.8, 119.5, 116.0, 100.9. The boron-bound carbon was not detected due to quadrupolar relaxation.

11B NMR (CDCl$_3$) $\delta$ 4.2. IR (KBr) 1616, 1500, 1305, 1057, 751 cm$^{-1}$. HRMS (EI) $m/z$ calcd for C$_{10}$H$_9$BN$_2$O (M$^+$): 184.0808, found: 184.0806.

Synthesis of 5-Ethyl-5,6-dihydrobenzo[e]pyrazolo[1,5-c][1,3,2]diazaborinine (5):

According to a procedure similar to that for 1, 5 (0.26 g, 87%) was prepared from ethylboronic acid (0.11 g, 1.5 mmol) and 2-(1H-pyrazol-3-yl)aniline (0.24 g, 1.5 mmol). The compound 5 was isolated by bulb-to-bulb distillation (180-190 °C / 2.2 mmHg) as white solid. 5: $^1$H NMR (CDCl$_3$) $\delta$ 8.03 (d, $J = 1.6$ Hz, 1H), 7.87 (d, $J = 7.6$ Hz, 1H), 7.37-7.34 (m, 1H), 7.19-7.15 (m, 2H), 6.92 (brs, 1H), 6.87 (d, $J = 1.6$ Hz, 1H), 1.70 (q, $J = 8.0$ Hz, 2H), 1.25 (t, $J = 8.0$ Hz, 3H). $^{13}$C NMR (CDCl$_3$) $\delta$ 145.2, 144.0, 136.4, 128.7, 124.8, 122.0, 117.4, 116.8, 99.9, 81.1. The boron-bound carbon was not detected due to quadrupolar relaxation. 11B NMR (CDCl$_3$) $\delta$ 33.5. IR(KBr) 3250, 1617, 1520, 1482, 752 cm$^{-1}$. Anal. Calcd for C$_{11}$H$_{12}$BN$_3$: C, 67.05; H, 6.14; N, 21.33. Found: C, 67.27; H, 6.13; N, 21.25.

Synthesis of 5-Cyclohexyl-5,6-dihydrobenzo[e]pyrazolo[1,5-c][1,3,2]diazaborinine (7):

According to a procedure similar to that for 1, 7 (0.44 g, 87%) was prepared from
cyclohexylboronic acid (0.26 g, 2.0 mmol) and 2-(1H-pyrazol-3-yl)aniline (0.32 g, 2.0 mmol). The compound 7 was isolated by bulb-to-bulb distillation (240-260 °C / 1.6 mmHg) as white solid. 7: \(^1\)H NMR (CDCl\(_3\)) \(\delta 8.04\) (d, \(J = 1.5\) Hz, 1H), 7.88 (d, \(J = 7.8\) Hz, 1H), 7.42-7.32 (m, 1H), 7.24-7.12 (m, 2H), 6.87 (d, \(J = 1.5\) Hz, 1H), 6.78 (brs, 1H), 2.16-2.01 (m, 3H), 1.87-1.77 (m, 3H), 1.58-1.24 (m, 5H). \(^13\)C NMR (CDCl\(_3\)) \(\delta 145.1, 144.2, 136.3, 128.7, 124.8, 122.0, 117.5, 116.8, 99.9, 28.6, 27.4, 26.9\). The boron-bound carbon was not detected due to quadrupolar relaxation. \(^{11}\)B NMR (CDCl\(_3\)) \(\delta 32.6\). IR (KBr) 3251, 2917, 1620, 1517, 1480, 751 cm\(^{-1}\). HRMS (EI) \(m/z\) calcd for C\(_{15}\)H\(_{18}\)BN\(_3\) (M\(^+\)): 251.1594, found: 251.1597.

Ruthenium-catalyzed o-Silylation

**Synthesis of 4,4,5,5-Tetramethyl-2-[(dimethylphenylsilyl)methyl]-1,3,2-dioxaborolane (4a) (Table 2):** To a mixture of 1 (46 mg, 0.25 mmol) and RuH\(_2\)(CO)(PPh\(_3\))\(_3\) (14 mg, 15 \(\mu\)mol) in a reaction tube sealed with a J-Young Teflon stopper was added norbornene (0.12 g, 1.3 mmol), dimethylphenylsilane (0.19 mL, 1.3 mmol), toluene (0.13 mL) and anisole (internal standard, 13.6 mL, 0.125 mmol) under a nitrogen atmosphere. The mixture was stirred at 135 °C for 12 h. The crude mixture was transferred into screw-capped vial with THF (1 mL) after cooling to room temperature, then added pinacol (59 mg, 0.5 mmol) and p-TsOH·H\(_2\)O (95 mg, 0.5 mmol). After stirring the mixture at room temperature for 1 h, water was added to dissolve a precipitate followed by extraction with Et\(_2\)O. The organic phase was dried over MgSO\(_4\) and then filtered. The concentrated residue was subjected to flash column chromatography on Florisil® (hexane : AcOEt = 20 : 1), then purified by HPLC (LiChrosorb\(^\text{®}\) CN, hexane only), giving the compound 4a as colorless liquid (59 mg, 85% in 2 steps). 4a: \(^1\)H NMR (CDCl\(_3\)) \(\delta 7.58-7.51\) (m, 2H), 7.36-7.31 (m, 3H), 1.18 (s, 12H), 0.36 (s, 2H), 0.33 (s, 6H). \(^{13}\)C NMR (CDCl\(_3\)) \(\delta 140.2, 133.4, 128.8, 127.6, 82.8, 24.9, -0.9\). The boron-bound carbon was not detected due to quadrupolar relaxation. \(^{11}\)B NMR (CDCl\(_3\)) \(\delta 33.8\). IR (neat) 2977, 1309, 1147, 1113, 847 cm\(^{-1}\). HRMS (FAB) \(m/z\) calcd for C\(_{15}\)H\(_{24}\)BO\(_2\)Si ([M-H]\(^+\)): 275.1639, found: 275.1637.
Synthesis of 4,4,5,5-Tetramethyl-2-[(triethylsilyl)methyl]-1,3,2-dioxaborolane (4b):
According to a procedure similar to that for 4a, 4b (53 mg, 81% in 2 steps) was obtained by
using triethylsilane (0.20 mL, 1.3 mmol) instead of dimethylphenylsilane. The compound 4b
was isolated by HPLC (LiChrosorb® CN, hexane only) as colorless liquid. 4b: 1H NMR
(CDCl₃) δ 1.23 (s, 12H), 0.94 (t, J = 8.0 Hz, 9H), 0.54 (q, J = 8.0 Hz, 6H), 0.04 (s, 2H). 13C
NMR (CDCl₃) δ 82.6, 24.9, 7.4, 5.0. The boron-bound carbon was not detected due to
quadrupolar relaxation. 11B NMR (CDCl₃) δ 34.0. IR (neat) 2952, 13.8, 1148, 847, 754 cm⁻¹.
HRMS (FAB) m/z calcd for C₁₃H₃₀BO₂Si ([M+H]⁺): 257.2108, found: 257.2106. The
detached directing group 3 (36 mg, 90%) was recovered from the aqueous phase by
re-extraction with AcOEt after basifying with NaHCO₃ (s), followed by column
chromatography on Florisil® (hexane : AcOEt = 1 : 1).

Synthesis of 4,4,5,5-Tetramethyl-2-[(benzyldimethylsilyl)methyl]-1,3,2-dioxaborolane (4c):
According to a procedure similar to that for 4a, 4c (63 mg, 86% in 2 steps) was obtained by
using benzyldimethylsilane (0.20 mL, 1.3 mmol) instead of dimethylphenylsilane. The compound 4c
was isolated by HPLC (LiChrosorb® CN, hexane only) as colorless liquid. 4c: 1H NMR
(CDCl₃) δ 7.23-7.17 (m, 2H), 7.06 (d, J = 7.4 Hz, 1H), 7.02 (d, J = 7.1 Hz, 2H), 2.12
(s, 2H), 1.24 (s, 12H), 0.09 (s, 2H), 0.02 (s, 6H). 13C NMR (CDCl₃) δ 140.2, 128.1, 128.1,
123.8, 82.8, 27.3, 24.9, -1.8. The boron-bound carbon was not detected due to quadrupolar
relaxation. 11B NMR (CDCl₃) δ 33.9. IR (neat) 2988, 1308, 1146, 846 cm⁻¹. HRMS (FAB) m/z
Synthesis of 4,4,5,5-Tetramethyl-2-[(methyldiphenylsilyl)methyl]-1,3,2-dioxaborolane (4d): According to a procedure similar to that for 4a, 7d (57 mg, 67% in 2 steps) was obtained by using methyldiphenylsilane (0.25 mL, 1.3 mmol) instead of dimethylphenylsilane. The compound 4d was isolated by HPLC (LiChrosorb® CN, hexane only) as colorless liquid. 4d: \(^1\)H NMR (CDCl\(_3\)) \(\delta\) 7.58-7.51 (m, 4H), 7.37-7.28 (m, 6H), 1.08 (s, 12H), 0.65 (s, 2H), 0.63 (s, 3H). \(^13\)C NMR (CDCl\(_3\)) \(\delta\) 138.1, 134.4, 129.0, 127.6, 82.9, 24.8, -2.3. The boron-bound carbon was not detected due to quadrupolar relaxation. \(^11\)B NMR (CDCl\(_3\)) \(\delta\) 33.9. IR (neat) 2976, 1308, 1146, 796, 699 cm\(^{-1}\). Anal. Calcd for C\(_{20}\)H\(_{27}\)BO\(_2\)Si: C, 71.00; H, 8.04. Found: C, 71.07; H, 8.00.

Synthesis of 4,4,5,5-Tetramethyl-2-[(tert-butyldimethylsilyl)methyl]-1,3,2-dioxaborolane (4e): According to a procedure similar to that for 4a, 4e (18 mg, 28% in 2 steps) was obtained by using tert-butyldimethylsilane (0.21 mL, 1.3 mmol) instead of dimethylphenylsilane. The compound 4e was isolated by HPLC (LiChrosorb® CN, hexane only) as colorless liquid. 4e: \(^1\)H NMR (CDCl\(_3\)) \(\delta\) 1.24 (s, 12H), 0.87 (s, 9H), 0.07 (s, 2H), 0.01 (s, 6H). \(^13\)C NMR (CDCl\(_3\)) \(\delta\) 82.7, 26.2, 24.9, 16.8, -4.5. The boron-bound carbon was not detected due to quadrupolar relaxation. \(^11\)B NMR (CDCl\(_3\)) \(\delta\) 34.0. IR (neat) 2928, 1308, 1148, 847 cm\(^{-1}\). HRMS (FAB) \(m/z\) calcd for C\(_{13}\)H\(_{30}\)BO\(_2\)Si ([M+H]\(^+\)): 257.2108, found: 257.2113.

Reaction of 5 (eq 4): To a mixture of 5 (49 mg, 0.25 mmol) and RuH\(_2\)(CO)(PPh\(_3\))\(_3\) (14 mg, 15 mmol) in a sealed tube was added norbornene (0.12 g, 1.3 mmol), dimethylphenylsilane (0.19 mL, 1.3 mmol) and toluene (0.13 mL) under a nitrogen atmosphere. The mixture was stirred at 135 °C for 36 h. To the crude mixture was then added pinacol (59 mg, 0.5 mmol), THF (0.25 mL) and p-TsOH·H\(_2\)O (95 mg, 0.5 mmol) after cooling to room temperature. After stirring the mixture at room temperature for 1 h, water was added to dissolve a precipitate followed by extraction with Et\(_2\)O. The organic phase was dried over MgSO\(_4\) and then filtered. The concentrated residue was subjected to flash column chromatography on Florisil® (hexane : AcOEt = 10 : 1), then purified by HPLC (LiChrosorb® CN, hexane only), giving the a-silylated product 6a (16 mg, 21%) and b-silylated product 6b (15 mg, 21%).
4,4,5,5-Tetramethyl-2-[1-(dimethylphenylsilyl)ethyl]-1,3,2-dioxaborolane (6a): $^1$H NMR (CDCl$_3$) $\delta$ 7.56-7.50 (m, 2H), 7.36-7.30 (m, 3H), 1.19 (s, 6H), 1.17 (s, 6H), 1.01 (d, $J = 7.2$ Hz, 3H), 0.60 (q, $J = 7.2$ Hz, 1H), 0.32 (s, 3H), 0.31 (s, 3H). $^{13}$C NMR (CDCl$_3$) $\delta$ 138.9, 133.9, 128.7, 127.5, 82.7, 25.0, 24.8, 9.3, -2.6, -3.8. The boron-bound carbon was not detected due to quadrupolar relaxation. $^{11}$B NMR (CDCl$_3$) $\delta$ 34.5. IR (neat) 2958, 1342, 1146, 816, 699 cm$^{-1}$. HRMS (El) $m/z$ calcd for C$_{16}$H$_{27}$BO$_2$Si (M$^+$): 290.1873, found: 290.1878.

4,4,5,5-Tetramethyl-2-[2-(dimethylphenylsilyl)ethyl]-1,3,2-dioxaborolane (6b): $^1$H NMR (CDCl$_3$) $\delta$ 7.53-7.46 (m, 2H), 7.35-7.30 (m, 3H), 1.22 (s, 12H), 0.83-0.71 (m, 4H), 0.25 (s, 6H). $^{13}$C NMR (CDCl$_3$) $\delta$ 139.4, 133.6, 128.7, 127.6, 82.9, 24.8, 8.5, -3.6. The boron-bound carbon was not detected due to quadrupolar relaxation. $^{11}$B NMR (CDCl$_3$) $\delta$ 34.3. IR (neat) 2977, 1361, 1320, 1147, 835, 699 cm$^{-1}$. HRMS (FAB) $m/z$ calcd for C$_{16}$H$_{26}$BO$_2$Si ([M-H]$^-$): 289.1795, found: 289.1799.

**Reaction of 7 (eq 5):** To 7 (63 mg, 0.25 mmol) in a sealed tube was added RuH$_2$(CO)(PPh$_3$)$_3$ (14 mg, 15 $\mu$mol), norbornene (0.12 g, 1.3 mmol), dimethylphenylsilane (0.19 mL, 1.3 mmol) and anisole (13.6 mL, 0.125 mmol) under a nitrogen atmosphere. The mixture was stirred at 160 °C for 24 h. The crude mixture was transferred into screw-capped vial with THF (1 mL) after cooling to room temperature, then added pinacol (59 mg, 0.5 mmol) and p-TsOH·H$_2$O (95 mg, 0.5 mmol). After stirring the mixture at room temperature for 1 h, satd. NaHCO$_3$ aq. was added followed by extraction with AcOEt. The organic phase was dried over Na$_2$SO$_4$ and then filtered. From the concentrated residue was detected both cyclohexylboronic acid and 8 by GC-MS analysis. The compound 8 was isolated by column chromatography on silica gel (27 mg, 36% in 2 steps) as viscous dark green liquid.
**Chapter 2**

![Diagram 8](image)

2-(3-Dimethylphenylsilyl-1H-pyrazol-5-yl)aniline (8): $^1$H NMR (CDCl$_3$) $\delta$ 7.60-7.54 (m, 3H), 7.47-7.37 (m, 3H), 7.13-7.07 (m, 1H), 6.82 (s, 1H), 6.81-6.73 (m, 2H), 0.62 (s, 6H). $^{13}$C NMR (CDCl$_3$) $\delta$ 152.7, 144.7, 140.8, 135.6, 134.0, 130.0, 128.4, 128.3, 128.2, 117.3, 116.5, 116.4, 111.5, -2.4. IR (neat) 3330, 1615, 813, 703 cm$^{-1}$. HRMS (EI) m/z calcd for C$_{17}$H$_{19}$N$_3$Si (M$^+$): 293.1348, found: 293.1345.

**Suzuki-Miyaura Cross-Coupling of 4a**

![Diagram 9](image)

1-(Dimethylphenylsilylmethyl)naphthalene (9) (eq 6): To PdCl$_2$(dppf)·CH$_2$Cl$_2$ (16 mg, 20 $\mu$mol) in a sealed tube was added 4a (55 mg, 0.20 mmol) with dissolving in THF (1 mL), then CsOH·H$_2$O (0.10 g, 0.6 mmol), 1-bromonaphthalene (42 mL, 0.3 mmol) and H$_2$O (0.1 mL) under a nitrogen atmosphere. After stirring the mixture at 80 °C for 24 h, the organic phase which was extracted with Et$_2$O was dried over MgSO$_4$ and then filtered. Evaporation of the volatile material under vacuum followed by purification by preparative TLC (hexane : ether = 30 : 1) afforded 9 (44 mg, 78%) as colorless liquid. 9: $^1$H NMR (CDCl$_3$) $\delta$7.86 (d, $J$ = 8.0 Hz, 1H), 7.81 (d, $J$ = 7.6 Hz, 1H), 7.61 (d, $J$ = 8.0 Hz, 1H), 7.51-7.47 (m, 2H), 7.45-7.29 (m, 6H), 7.09 (d, $J$ = 6.8 Hz, 1H), 2.79 (s, 2H), 0.21 (s, 6H). $^{13}$C NMR (CDCl$_3$) $\delta$ 138.7, 136.4, 133.9, 133.6, 131.7, 129.1, 128.5, 127.8, 125.7, 125.4, 125.3, 125.0, 124.9, 124.7, 22.7, -2.9. IR (neat) 2959, 1249, 1114, 835, 775 cm$^{-1}$. HRMS (EI) m/z calcd for C$_{19}$H$_{20}$Si (M$^+$): 276.1334, found: 276.1332.
3-(Dimethylphenylsilylmethyl)acetophenone (10) (eq 7): To PdCl$_2$(dppf) (15 mg, 20 μmol) in a sealed tube was added 4a (55 mg, 0.20 mmol) with dissolving in THF (1 mL), then CsOH·H$_2$O (0.10 g, 0.6 mmol), 3’-bromoacetophenone (53 mL, 0.4 mmol) and H$_2$O (0.1 mL) under a nitrogen atmosphere. After stirring the mixture at 80 °C for 24 h, the organic phase which was extracted with CH$_2$Cl$_2$ was dried over MgSO$_4$ and then filtered. Evaporation of the volatile material under vacuum followed by purification by preparative TLC (hexane : AcOEt = 5 : 1) afforded 10 (33 mg, 61%) as colorless liquid. 10: $^1$H NMR (CDCl$_3$) δ 7.66 (d, $J$ = 7.6 Hz, 1H), 7.46-7.31 (m, 6H), 7.29-7.23 (m, 1H), 7.11 (d, $J$ = 7.6 Hz, 1H), 2.47 (s, 3H), 2.36 (s, 2H), 0.27 (s, 6H). $^{13}$C NMR (CDCl$_3$) δ 140.2, 137.8, 136.9, 133.7, 132.9, 129.2, 128.3, 128.1, 127.8, 124.2, 26.6, 26.3, -3.7. IR (neat) 2956, 1683, 1274, 837, 696 cm$^{-1}$. HRMS (EI) m/z calced for C$_{17}$H$_{20}$OSi (M$^+$): 268.1283, found: 268.1279.

References and Notes


Successful use of PdCl₂(dppf) with carbonates such as Cs₂CO₃ and K₂CO₃ in cross-coupling of alkylboronic acids with aryl triflates and halides was reported. G. A. Molander, C.-S. Yun, *Tetrahedron* 2002, 58, 1465.


Anthranilamide: A Simple, Removable Ortho-Directing Modifier for Arylboronic Acids Serving also as a Protecting Group in Cross-Coupling Reactions

Abstract: Anthranilamide (AAM) serves as a bifunctional modifier on the boron atom in catalytic transformations of arylboronic acids. It makes boronyl groups unreactive in Suzuki-Miyaura coupling and promotes Ru-catalyzed ortho-silylation. Suzuki-Miyaura coupling of AAM-modified bromophenylboronic acids with tolylboronic acid gave 1,1’-biaryl-4-boronic acid bearing AAM on the boron atom, which subsequently underwent Ru-catalyzed o-silylation at the 3-position by virtue of the o-directing effect of the AAM group.
Chapter 3

Introduction

Scheme 1. Use of a removable modifier on the boron atom that serves both as protecting and o-directing groups for the synthesis of highly functionalized arene derivatives.

Much interest has focused on the synthesis and use of arylboronic acids in organic synthesis. In addition to the conventional synthesis using transmetalation with more nucleophilic organometallic reagents such as Grignard and organolithium reagents, catalytic C–B bond formation reactions have gained increasing attention. Transition-metal-catalyzed C–H and C–X borylations are recognized as the most promising, efficient access to arylboronic acids. Efforts are now devoted to the synthesis of organoboronic acids with retention of the boron functionality throughout the synthesis. For this purpose, robust protecting groups for organoboronic acids especially in the Suzuki–Miyaura cross-coupling reaction have been developed. They have made possible the synthesis of rather complex organoboronic acids through iterative Suzuki–Miyaura coupling. As a new boron-retaining strategy, we recently reported use of 2-(pyrazol-5-yl)aniline (PZA) as an agent for Ru-catalyzed o-silylation, in which coordination of the $sp^2$-nitrogen atom of PZA to the catalyst is crucial.
These boron-retaining syntheses of arylboronic acids are particularly useful in the synthesis of elaborated arylboronic acids that are otherwise difficult to synthesize. Our interest has focused on finding a simple modifier on the boron atom serving both as an $o$-directing group in the $o$-C–H functionalization reactions and as a protecting group in the cross-coupling reactions (Scheme 1). Such a bifunctional modifier would allow us to develop new synthetic access to highly elaborated arylboronic acids, which is in turn beneficial for the synthesis of highly functionalized arene derivatives. Herein, we describe the use of anthranilamide as such a bifunctional agent for arylboronic acid synthesis. It shows a higher ability for $o$-direction and much higher robustness toward SMC and isolation procedures than PZA.

**Results and Discussion**

After brief screening of some 1,3,2-diazaboracyclohexane structures, we found that PhB(aam) 1a (see Scheme 2 and Table 1 for the structure), which was prepared by condensation of PhB(OH)$_2$ with commercially available anthranilamide in toluene under reflux in high yield, shows high stability toward moisture, oxygen, and even chromatography.
The stabilities of the cyclic diaminoborane derivatives were compared in DMSO/D$_2$O (10/1) at room temperature (Scheme 2). To our surprise, even PhB(pin) decomposed gradually under these reaction conditions. The half-life was determined to be 78 h by $^1$H NMR measurement. In contrast, PhB(dan) showed no hint of decomposition under the same reaction conditions. PhB(mida) (mida: $N$-methyliminodiacetato) was also robust, although it too underwent slow hydrolysis ($t_{1/2} = 140$ h). Although being less stable than the DAN and MIDA protecting groups, AAM exhibited much higher stability than the previous directing group PZA.
Table 1. *ortho*-Silylation of Arylboronic Acids Using Anthranilamide as an *ortho*-Directing Agent.$^a$

![Image](https://via.placeholder.com/150)

<table>
<thead>
<tr>
<th>entry</th>
<th>1</th>
<th>HSiR$_3$</th>
<th>% yield$^b$</th>
<th>isolated product</th>
</tr>
</thead>
<tbody>
<tr>
<td>1$^c$</td>
<td></td>
<td>HSiMe$_2$Ph</td>
<td>(88)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>HSiEt</td>
<td>(64)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>HSiMe$_2$Ph</td>
<td>90 (80)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>(1a)</td>
<td>HSiMe$_2$Bu-t</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>(1b)</td>
<td>HSiMe$_2$Ph</td>
<td>97 (91)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>HSiMe$_2$Ph</td>
<td>94 (77)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>(1d)</td>
<td>HSiMe$_2$Ph</td>
<td>96 (88)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>(1e)</td>
<td>HSiMe$_2$Ph</td>
<td>95 (85)</td>
<td></td>
</tr>
<tr>
<td>9$^d$</td>
<td>(1f)</td>
<td>HSiMe$_2$Ph</td>
<td>91 (81)</td>
<td></td>
</tr>
<tr>
<td>10$^e$</td>
<td>(1g)</td>
<td>HSiMe$_2$Ph</td>
<td>32 (19)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>(1h)</td>
<td>HSiMe$_2$Ph</td>
<td>97 (90)</td>
<td></td>
</tr>
<tr>
<td>12$^f$</td>
<td>(1i)</td>
<td>HSiMe$_2$Ph</td>
<td>54 (30)</td>
<td></td>
</tr>
</tbody>
</table>

$^a$ 1 (0.25 mmol), RuH$_2$(CO)(PPh$_3$)$_3$ (15 µmol), norbornene (1.25 mmol), hydrosilane (1.25 mmol), and toluene (0.13 mL) at 135 °C (bath temperature) for 20 h unless otherwise noted. $^b$ NMR yield. Isolated yields in parenthesis. $^c$ 3 h. $^d$ 37 h. $^e$ 51 h.
Scheme 3. AAM-directed silylation of 3-thiopheneboronic acid derivative 1j.

Scheme 4. Acid-mediated conversion of ArB(aam) to ArB(pin).

Ru-catalyzed o-silylation of PhB(aam) (1a) with dimethylphenylsilane proceeded in high yield in the presence of RuH₂(CO)(PPh₃)₃ with norbornene as a hydrogen scavenger at 135 °C (Table 1). The o-silylated product 2aa was isolated by silica gel flash column chromatography. Among the hydroxilanes examined for the reaction, dimethylphenylsilane showed the highest reactivity. Triethylsilane, which was the most reactive in the PZA-directed reaction, resulted in a slightly lower yield. It should be remarked here that no silylation at the phenyl ring of phthalimide took place at all. Using dimethylphenylsilane, isolated AAM-modified substituted arylboronic acids were subjected to the silylation reaction. Arylboronic acids having electron-donating and electron-withdrawing groups at their para-positions afforded the corresponding o-silylated products in high yields (entries 5–8). Meta-tolylboronic acid derivative 1f underwent silylation at the less sterically demanding o-position selectively in high yield (entry 9). Although the yield was low, o-Me substituted 1g afforded o-silylated 1,2,3-trisubstituted benzene derivative 2g (entry 10). Note that PZA-modified o-tolylboronic acid does not give the desired o-silylation product at all. The
2-naphthyl derivative was silylated at the 3-position selectively in good yield (entry 11) as observed in the PZA system. 1-Naphthylboronic acid gave the 2-silylated product 2i selectively, albeit in low yield, whereas the corresponding PZA derivative was not reactive at all (entry 12). A remarkable difference between the present AAM and the previous PZA system has been demonstrated by the reaction of 3-thienyl derivative 1j (Scheme 3). In both systems, the first silylation takes place at the 2-positions. The second silylation in the AAM system took place at the 4-position of the thiophene ring, in contrast to exclusive silylation at the 5-position in the PZA system via non-directed silylation. This clearly suggests that the AAM group has a stronger directing ability than does PZA. In these syntheses of o-silylated organoboronic acids, the AAM group on the boron atoms was readily converted into the PIN group by acid-catalyzed ligand exchange (Scheme 4). Hydrolysis of 2aa was accomplished cleanly in the presence of aqueous acid at room temperature, giving the corresponding arylboroxine in high yield.

Scheme 5. Cross-coupling/silylation sequence with bromo-substituted arylboronic acids.
Attempted $o$-silylation of $p$-bromophenylboronic acid derivative 1k resulted in the substitution of the bromine group by a silyl group (Scheme 5). Instead, we carried out Suzuki–Miyaura coupling of 1k with $p$-tolylboronic acid. In the presence of SPhos (2-dicyclohexylphosphino-2′,6′-dimethoxy-1,1′-biphenyl) as a ligand, the coupling proceeded at room temperature with complete retention of the AAM group on the boron atom. The isolated AAM derivative of biphenylboronic acid 4k underwent Ru-catalyzed silylation selectively at the $ortho$ position, giving silylborylbiphenyl 5k. The sequential cross-coupling/$o$-silylation protocol could also be applied to $m$-bromoboronic acid derivative 1l, affording 5l (room temperature, 14 h). The B(aam) group was completely retained even in the attempted cross-coupling of 1l with $p$-tolylboronic acid at 80 °C, giving the same coupling product in 94% yield (1.5 h). In the corresponding transformation of $o$-bromophenylboronic acid, the first step, i.e., coupling with TolB(OH)$_2$, proceeded in high yield, although $o$-silylation afforded the silylated biphenyl only in low yield. In these examples, the AAM group serves not only as a directing group but also as a protecting group for the boronyl group in the Suzuki–Miyaura coupling reaction.

To gain insight into the origin of the directing effect of the AAM group, we compared two $N$-methylated derivatives 6a and 6b of anthranilamides in the $o$-silylation reactions (Scheme 6). Anthranilamide 6a bearing a methyl group on the aniline nitrogen atom underwent the $o$-silylation smoothly under the same reaction conditions as those for the parent anthranilamide. In contrast, its isomer 6b bearing a methyl group on the amide nitrogen was not reactive at all. These results suggest that the amide nitrogen rather than the aniline
nitrogen serves as the coordinating element in the Ru-catalyzed o-silylation. It may be presumed that a tautomerized form, which carries an \( sp^2 \) lone pair on the nitrogen atom, may play a key role in coordination to the catalyst.

**Conclusion**

In summary, anthranilamide has been established as a new directing agent for transition-metal-catalyzed o-C–H silylation. The B(aam) group exhibited higher ability in o-direction in comparison with the previously reported B(pza) group. The stronger directing effect resulted in o-silylation of sterically demanding arylboronic acids such as o-tolylboronic acid and 1-naphthylboronic acid, albeit in low yields, which could not be achieved with the B(pza) group. Furthermore, a sharp switch of regioselectivity was observed in the silylation of 2-silylated 3-thiopheneboronic acid. The AAM group also serves as a protecting group in the Suzuki–Miyaura coupling reaction, enabling the synthesis of silylated biphenylboronic acids through a cross-coupling/o-silylation sequence. Application of these directing groups in other catalytic C–H functionalizations is being undertaken in this laboratory.

**Experimental Section**

**General**

All reactions were carried out under an atmosphere of nitrogen with magnetic stirring. \(^1\)H, \(^{11}\)B and \(^{13}\)C NMR spectra were recorded on a Varian Mercury vx400 or a JEOL JNM-A500 spectrometer at ambient temperature. \(^1\)H NMR data are reported as follows: integration , chemical shift in ppm downfield from tetramethylsilane (\( \delta \) scale), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, sex = sextet, m = multiplet, and br = broad), and coupling constant (Hz). \(^{13}\)C NMR chemical shifts are reported in ppm downfield from tetramethylsilane (\( \delta \) scale). \(^{11}\)B NMR chemical shifts are reported in ppm downfield from \( BF_3\cdot OEt_2 \). All \(^{13}\)C NMR spectra were obtained with broadband proton decoupling. High-resolution mass spectra were recorded on a JEOL JMS-SX102A (EI) and JEOL
JMS-HX110A (FAB) spectrometer. IR spectra were recorded on a FTIR SHIMADZU DR-8000 spectrometer. Preparative TLC was performed with silica gel 60PF_{254} (Merck). Recycling Preparative GPC was performed with JAI LC-908 equipped with JAIGEL-1H and -2H columns in a series(CHCl_{3}).

Column chromatography was performed with Ultra Pure Silica Gel (40-63 μm) (Silicycle).

Materials

Toluene and THF were dried and deoxygenized using an alumina/catalyst column system (GlassContour Co.). Anthranilamide (TCI), triethylsilane (TCI), dimethylphenylsilane (Aldrich), diphenylmethysilane (Aldrich), tert-butyldimethylsilane (Aldrich), norbornene (TCI), pinacol (TCI), p-toluenesulfonic acid monohydrate (Nacalai), phenylboronic acid (Wako), 4-methoxyphenylboronic acid (Aldrich), 4-trifluoromethylphenylboronic acid (Wako), 4-chlorophenylboronic acid (Wako), 4-methylphenylboronic acid (Wako), 4-bromophenylboronic acid (Aldrich), 3-bromophenylboronic acid (Aldrich), 3-methylphenylboronic acid (TCI), 2-methylphenylboronic acid (Wako), 2-naphthaleneboronic acid (TCI), 1-naphthaleneboronic acid (Aldrich), 3-thiopheneboronic acid (TCI), Florisil® (75-150 μm, Kanto), Pd(OAc)_{2} (Tanaka Rare-metal) and SPhos (Strem) were used as received from the commercial sources. RuH_{2}(CO)(PPh_{3})_{3},^{16} were prepared by the literature procedures. Potassium phosphate (Nacalai) was dried in an oven at 300 °C for 5 h in vacuo (1 mmHg).

Experimental Procedures

Determination of the stabilities of the phenylboronic acid derivatives by \textsuperscript{1}H NMR in DMSO/D\textsubscript{2}O (10/1) (eq 1):

To a solution of PhBX\textsubscript{2} (0.020 mmol) and dibenzylether (3.81 μL, internal standard) in DMSO-\textit{d}_{6} (0.70 mL) was added D\textsubscript{2}O (0.07 mL) at 24 °C. Conversion of PhBX\textsubscript{2} was monitored by \textsuperscript{1}H NMR spectroscopy.

Stability of PhB(pin)

The half-life of PhB(pin) (4.08 mg) was determined to be 78 h.
Stability of PhB(dan)

No hydrolysis or decomposition of PhB(dan) (4.88 mg) was observed after 60 days.

Stability of PhB(mida)

The half-life of PhB(mida) (4.66 mg) was determined to be 140 h.
Stability of PhB(aam)
The half-life of PhB(aam) (4.88 mg) was determined to be 10 h.

![Figure S3. The stability of PhB(aam)](image)

Stability of PhB(pza)
The half-life of PhB(pza) (4.90 mg) was determined to be 4 min.

![Figure S4. The stability of PhB(pza)](image)

General Procedure for the Synthesis of 1 by Condensation of Arylboronic Acid with
Anthranilamide:
A mixture of arylboronic acid (30 mmol) and anthranilamide (4.08 g, 30 mmol) in toluene (0.25 mL/mmol, 7.5 mL) was heated under reflux in a Dean-Stark apparatus for 1 h. After cooling a mixture to room temperature, the precipitates were collected by filtration to give 1.

Synthesis of 1a
According to the general procedure, 1a (6.11 g, 91%) was prepared from phenylboronic acid (3.66 g, 30.0 mmol) and anthranilamide (4.08 g, 30.0 mmol).

Synthesis of 1b
According to the general procedure, 1b (361 mg, 94%) was prepared from 4-chlorophenylboronic acid (234 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).

Synthesis of 1c
According to the general procedure, 1c (415 mg, 95%) was prepared from 4-trifluoromethylphenylboronic acid (285 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).

Synthesis of 1d
According to the general procedure, 1d (337 mg, 95%) was prepared from 4-methylphenylboronic acid (204 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).

Synthesis of 1e
According to the general procedure, 1e (335 mg, 88%) was prepared from 4-methoxyphenylboronic acid (228 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).

Synthesis of 1f
According to the general procedure, 1f (335 mg, 94%) was prepared from 3-methylphenylboronic acid (204 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).

Synthesis of 1g
According to the general procedure, 1g (264 mg, 74%) was prepared from 2-methylphenylboronic acid (204 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).
Synthesis of 1h
According to the general procedure, 1h (384 mg, 94%) was prepared from 2-naphthaleneboronic acid (258 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).

Synthesis of 1i
According to the general procedure, 1i (364 mg, 89%) was prepared from 1-naphthaleneboronic acid (258 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).

Synthesis of 1j
According to the general procedure, 1j (310 mg, 90%) was prepared from 3-thiopheneboronic acid (192 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).

Synthesis of 1k
According to the general procedure, 1k (439 mg, 97%) was prepared from 4-bromophenylboronic acid (300 mg, 1.5 mmol) and anthranilamide (204 mg, 1.5 mmol).

Synthesis of 1l
According to the general procedure, 1l (814 mg, 90%) was prepared from 3-bromophenylboronic acid (600 mg, 3.0 mmol) and anthranilamide (408 mg, 3.0 mmol).

Synthesis of 6a
According to the general procedure, 6a (532 mg, 75%) was prepared from phenylboronic acid (366 mg, 3.0 mmol) and 2-(methylamino)benzamide (450 mg, 3.0 mmol).

Synthesis of 6b
According to the general procedure, 6b (436 mg, 62%) was prepared from phenylboronic acid (336 mg, 3.0 mmol) and 2-amino-N-methylbenzamide (450 mg, 3.0 mmol).

General procedure for C–H silylation of ArB(aam) (Table 1):
A mixture of 1 (0.25 mmol), RuH$_2$(CO)(PPh$_3$)$_3$ (13.8 mg, 0.015 mmol), norbornene (118 mg, 1.25 mmol), and hydrosilane (1.25 mmol) in toluene (0.13 mL) was heated in a glass tube.
sealed with a J-Young Teflon stopper at 135 °C. The reaction was run for 20 h unless otherwise noted. After cooling to temperature, the mixture was subjected to column chromatography on Florisil® (hexane/EtOAc), giving o-silylated product 2.

Synthesis of 2aa (entry 1, Table 1)
According to the general procedure, a mixture of 1a (333mg, 1.5 mmol), RuH₂(CO)(PPh₃)₃ (82.6 mg, 0.090 mmol), norbornene (707 mg, 7.5 mmol), and dimethylphenylsilane (140 mL) in toluene (0.78 ml) was heated for 3 h. 2aa (470 mg, 88%) was isolated by column chromatography on silica gel (hexane-AcOEt, 10:1 – 2:1).

Synthesis of 2ab (entry 2, Table 1)
According to the general procedure, a mixture of 1a (55.5 mg), RuH₂(CO)(PPh₃)₃, norbornene, and triethylsilane (199 µL) in toluene (0.13 mL) was heated. 2aa (54.3 mg, 64%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 2:1).

Synthesis of 2ac (entry 3, Table 1)
According to the general procedure, a mixture of 1a (55.5 mg), RuH₂(CO)(PPh₃)₃, norbornene, and methyldiphenylsilane (249 µL) in toluene (0.13 mL) was heated. 2ac (83.6 mg, 80%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 2:1).

Synthesis of 2b (entry 5, Table 1)
According to the general procedure, a mixture of 1b (64.0 mg), RuH₂(CO)(PPh₃)₃, norbornene, and dimethylphenylsilane (191 µL) in toluene (0.13 mL) was heated. 2b (88.7 mg, 91%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 2:1).

Synthesis of 2c (entry 6, Table 1)
According to the general procedure, a mixture of 1c (72.5 mg), RuH₂(CO)(PPh₃)₃, norbornene, and dimethylphenylsilane (191 µL) in toluene (0.13 mL) was heated. 2c (82.0 mg, 77%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 3:1).

Synthesis of 2d (entry 7, Table 1)
According to the general procedure, a mixture of 1d (59.0 mg), RuH₂(CO)(PPh₃)₃,
norbornene, and dimethylphenylsilane (191 µL) in toluene (0.13 mL) was heated. 2d (81.5 mg, 88%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 2:1).

Synthesis of 2e (entry 8, Table 1)
According to the general procedure, a mixture of 1e (63.0 mg), RuH₂(CO)(PPh₃)₃, norbornene, and dimethylphenylsilane (191 µL) in toluene (0.13 mL) was heated. 2e (82.2 mg, 85%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 2:1).

Synthesis of 2f (entry 9, Table 1)
According to the general procedure, a mixture of 1f (59.0 mg), RuH₂(CO)(PPh₃)₃, norbornene, and dimethylphenylsilane (191 µL) in toluene (0.13 mL) was heated for 37 h. 2f (75.2 mg, 81%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 5:1).

Synthesis of 2g (entry 10, Table 1)
According to the general procedure, a mixture of 1g (59.0 mg), RuH₂(CO)(PPh₃)₃, norbornene, and dimethylphenylsilane (191 µL) in toluene (0.13 mL) was heated for 51 h. The reaction mixture was passed through a short pad of Florisil® (hexane-AcOEt, 10:1 – 5:1) and then 2g (18.1 mg, 19%) was isolated by preparative GPC.

Synthesis of 2h (entry 11, Table 1)
According to the general procedure, a mixture of 1h (68.0 mg), RuH₂(CO)(PPh₃)₃, norbornene, and dimethylphenylsilane (191 µL) in toluene (0.13 mL) was heated. 2h (92.1 mg, 90%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 4:1).

Synthesis of 2i (entry 12, Table 1)
According to the general procedure, a mixture of 1i (68.0 mg), RuH₂(CO)(PPh₃)₃, norbornene, and dimethylphenylsilane (191 µL) in toluene (0.13 mL) was heated for 51 h. The reaction mixture was passed through a short pad of Florisil® (hexane-AcOEt, 10:1 – 5:1) and then 2i (31.0 mg, 30%) was isolated by preparative GPC.

Synthesis of 2j (eq 2)
According to the general procedure, a mixture of 1j (57.0 mg), RuH$_2$(CO)(PPh$_3$)$_3$, norbornene, and dimethylphenylsilane (191 μL) in toluene (0.13 mL) was heated for 1 h. 2j (77.5 mg, 85%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 5:1).

**Synthesis of 3j (eq 2)**

According to the general procedure, a mixture of 1j (57.0 mg), RuH$_2$(CO)(PPh$_3$)$_3$, norbornene, and dimethylphenylsilane (191 μL) in toluene (0.13 mL) was heated for 40 h. 3j (98.4 mg, 79%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 5:1).

**Identification of the structure of 3j**

3j was converted into the corresponding 2,4-bis(dimethylphenylsilyl)thiophene S1. The following procedure was applied: A mixture of 3j (98.0 mg, 0.20 mmol), [Rh(OH)(cod)]$_2$ (9.0 mg, 0.02 mmol) in THF/H$_2$O (THF 0.6 mL, H$_2$O 0.06 mL) was heated at 80 °C for 18 h. After extraction with diethyl ether, the organic phase was dried over MgSO$_4$. S1 (52.0 mg, 74%) was isolated by column chromatography of Florisil® (hexane-AcOEt, 10:1). The $^1$H NMR of the obtained material revealed the formation of unsymmetrical bis(dimethylphenylsilyl)thiophene S1.

**Synthesis of 7a (eq 4)**

According to the general procedure, a mixture of 6a (59.0 mg), RuH$_2$(CO)(PPh$_3$)$_3$, norbornene, and dimethylphenylsilane (191 μL) in toluene (0.13 mL) was heated. 7a (79.8 mg, 86%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1).

**Conversion of the AAM group on the boron atom**

**Conversion into PIN group (eq 3):**
A mixture of **2aa** (107 mg, 0.30 mmol), pinacol (70.8 mg, 0.60 mmol), *p*-toluenesulfonic acid monohydrate (62.7 mg, 0.33 mmol) in THF (0.6 mL) was stirred at room temperature for 17 h. After extraction with diethyl ether, the organic phase was dried over Na₂SO₄. Filtration, evaporation, and purification by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 1:2) gave the pinacolate derivative (85.8 mg, 84%) with a small amount of anthlanilamide. NaHCO₃ was added to the water phase and organic maetrials were extracted with ethyl acetate. The organic phase was dried over Na₂SO₄, filtered, and evaporated, giving additional anthlanilamide (total recovery of anthranilamide, 37 mg, 90%).

**Acidic Hydrolysis:**
To a solution of **2aa** (71.2 mg, 0.2 mmol) in THF (1.0 mL) was added HCl aq. (5 N, 160 µL, 0.8 mmol) at room temperature. The reaction mixture was stirred at room temperature for 48 h. Water (1 mL) and ether (2 mL) were added to the reaction mixture, and the organic phase was separated. The aqueous phase was extracted with ether (2 mL) three times. The organic phase was combined and dried over Na₂SO₄. After filtration and evaporation, the residual oil was kept under vacuum for 5 h at room temperature, giving 2,4,6-tris[2-(dimethylphenylsilyl)phenyl]boroxine (46.1 mg, 96%).

![2,4,6-tris[2-(dimethylphenylsilyl)phenyl]boroxine](image)

**2,4,6-tris[2-(dimethylphenylsilyl)phenyl]boroxine:** ¹H NMR (400 MHz, CDCl₃) δ 7.62 (3H, dd, J = 7.2 Hz, 0.8 Hz), 7.53 (3H, dd, J = 7.2 Hz, 0.8 Hz), 7.44 (3H, ddd, J = 7.4 Hz, 7.4 Hz, 1.2 Hz), 7.36 (3H, ddd, J = 7.4 Hz, 7.4 Hz, 1.2 Hz), 7.30-7.25 (6H, m), 7.21-7.12 (9H, m), 0.43 (18H, s); ¹³C NMR (126 MHz, CDCl₃) δ 143.9, 139.5, 135.6, 135.4, 134.5, 129.8, 129.0, 128.1, 127.8, -0.35; ¹¹B NMR (128 MHz, CDCl₃) δ 30.0; IR (neat) 3047, 1334, 1120, 813, 731, 700; HRFABMS Calcd. for C₄₂H₄₅B₃NaO₃Si₃(M+Na): 737.2853, Found: 737.2838.

**Procedure for one-pot cross-coupling/o-silylation of p-BrC₆H₄B(aam):**
A mixture of **1k** (90 mg, 0.30 mmol), *p*-tolylboronic acid (61.2 mg, 0.45 mmol), Pd(OAc)₂ (2.0 mg, 0.009mmol), SPhos (7.4 mg, 0.018mmol), and K₃PO₄ (127mg, 0.60 mmol) in THF
(0.6 ml) was stirred for 14 h at room temperature. After being cooled to room temperature, the solvent was evaporated in vacuo. The residue was washed with Et₂O and then dried by azeotropic removal of water (toluene, twice). After filling dry nitrogen in the glass tube, norbornene (141 mg, 1.50 mmol), dimethylphenylsilane (229 µL, 1.50 mmol) and toluene (0.15 mL) were added under a nitrogen atmosphere. The mixture was heated at 135 °C for 12 h. After being cooled to room temperature, the solution was directly subjected to column chromatography on Florisil® (Hexane:AcOEt = 10:1 then hexane:AcOEt = 2:1), giving (102 mg, 76 %).

Procedure for one-pot cross-coupling/o-silylation of m-BrC₆H₄B(aam):
A mixture of 1l (90 mg, 0.30 mmol), p-tolylboronic acid (61.2 mg, 0.45 mmol), Pd(OAc)₂ (2.0 mg, 0.009 mmol), SPhos (7.4 mg, 0.018 mmol), and K₃PO₄ (127 mg, 0.60 mmol) in THF (0.6 ml) was stirred for 14 h at room temperature. After being cooled to room temperature, the solvent was evaporated in vacuo. The coupling product (87.6 mg, 93 %) was isolated by column chromatography on silica gel (chloroform). The same cross-coupling reaction was also carried out at 80 °C. The reaction was complete within 1.5 h and gave product in 94% yield after isolation by silica gel column chromatography.

According to the general procedure (2.3), a mixture of 1a (78.0 mg), RuH₂(CO)(PPh₃)₃, norbornene, and dimethylphenylsilane (191 µL) in toluene was reacted. 5I (70.6 mg, 63%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 5:1).

Spectral Data for New Compounds

2-[2-(dimethylphenylsilyl)phenyl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (2aa):

\[ \text{HN-} \text{B} \text{NH} \]
\[ \text{HN-} \text{B} \text{NH} \]
\[ \text{SiMe₂Ph} \]

\(^1\text{H NMR (400 MHz, CDCl₃)} \delta 8.17 (1H, dd, \_J = 8.0 \text{ Hz, 1.6 Hz}), 7.84-7.79 (1H, m), 7.56-7.34 (9H, m), 7.20 (1H, ddd, \_J = 8.0 \text{ Hz, 7.2 Hz, 1.2 Hz}), 7.07 (1H, brs), 6.23 (1H, dd, \_J \]
Chapter 3

= 8.0 Hz, 0.6 Hz), 5.96 (1H, brs), 0.49 (6H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 166.2, 143.4, 141.4, 140.0, 135.3, 134.0, 133.6, 132.8, 129.4, 128.9, 128.8, 128.4, 121.7, 118.7, 117.6, -1.4; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 31.5; IR (KBr) 3272, 2953, 1660, 1515, 1259, 759; HREIMS Calcd. for C$_{21}$H$_{21}$BN$_2$OSi (M$^+$): 356.1516, Found: 356.1515.

2,3-dihydro-2-[2-(triethylsilyl)phenyl]benzo[d][1,3,2]diazaborinin-4(1H)-one (2ab):

![Image of 2,3-dihydro-2-[2-(triethylsilyl)phenyl]benzo[d][1,3,2]diazaborinin-4(1H)-one (2ab)](image)

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.28 (1H, d, $J = 8.0$ Hz), 7.62-7.59 (1H, m), 7.58-7.54 (1H, m), 7.49-7.45 (1H, m), 7.44-7.37 (1H, m), 7.22-7.18 (1H, m), 7.15 (1H, brs), 7.02 (1H, d, $J = 8.0$ Hz), 6.48 (1H, brs), 0.93-0.89 (6H, m), 0.78-0.72 (9H, m); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 166.1, 143.9, 140.1, 135.4, 133.9, 132.2, 129.3, 128.3, 128.0, 122.0, 118.9, 1117.5, 7.5, 4.3; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 32.3; IR (KBr) 3315, 2953, 1638, 1524, 1486, 722; HREIMS Calcd. for C$_{19}$H$_{25}$BN$_2$OSi (M$^+$): 336.1829, Found: 336.1832.

2,3-dihydro-2-[2-(methyldiphenylsilyl)phenyl]benzo[d][1,3,2]diazaborinin-4(1H)-one (2ac):

![Image of 2,3-dihydro-2-[2-(methyldiphenylsilyl)phenyl]benzo[d][1,3,2]diazaborinin-4(1H)-one (2ac)](image)

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.15-8.11 (1H, m), 7.58-7.54 (1H, m), 7.53-7.34 (14H, m), 7.08 (1H, ddd, $J = 8.0$ Hz, 7.2 Hz, 0.8 Hz), 6.99 (1H, brs), 6.05 (1H, d, $J = 8.0$ Hz), 5.96 (1H, brs), 0.69 (3H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 166.2, 143.4, 140.1, 137.0, 136.8, 135.2, 133.6, 133.0, 129.7, 129.1, 128.9, 128.7, 128.3, 121.7, 118.7, 117.5, -2.4; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 31.6; IR (KBr) 3396, 1046, 1665, 1524, 1486, 722; HREIMS Calcd. for C$_{26}$H$_{23}$BN$_2$OSi (M$^+$): 418.1673, Found: 418.1674.
Chapter 3

2-(4-chlorophenyl)-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (1b):

![Structure of 1b]

$^1$H NMR (400 MHz, DMSO-d$_6$) $\delta$ 9.77 (1H, s), 9.38 (1H, m), 8.09-8.05 (2H, m), 8.01 (1H, dd, $J =$ 8.0 Hz, 1.6 Hz), 7.61-7.55 (1H, m), 7.55-7.51 (2H, m), 7.44-7.39 (1H, m), 7.15-7.09 (1H, m); $^{13}$C NMR (126 MHz, DMSO-d$_6$) $\delta$ 167.2, 146.3, 136.6, 136.2, 134.4, 128.9, 122.0, 119.7, 119.1; $^{11}$B NMR (128 MHz, DMSO-d$_6$) $\delta$ 34.4; IR (KBr) 3330, 3245, 1636, 1489, 1270, 757; HREIMS Calcd. for C$_{13}$H$_{10}$BClN$_2$O (M$^+$): 256.0575, Found: 256.0576.

2-[4-chloro-2-(dimethylphenylsilyl)phenyl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin–4(1H)-one (2b):

![Structure of 2b]

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.18-8.14 (1H, m), 7.76-7.73 (1H, m), 7.46-7.36 (8H, m), 7.12 (1H, ddd, $J =$ 8.0 Hz, 7.2 Hz, 1.2 Hz), 7.00 (1H, brs), 6.24-6.19 (1H, m), 5.88 (1H, brs), 0.49 (6H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 166.1, 144.4, 143.3, 139.2, 135.7, 135.0, 134.3, 133.9, 133.7, 129.7, 129.0, 128.9, 128.5, 121.9, 118.7, 117.6, -1.6; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 32.1; IR (KBr) 3418, 3198, 1654, 1513, 1402, 772; HREIMS Calcd. for C$_{21}$H$_{20}$BClN$_2$OSi (M$^+$): 390.1126, Found: 390.1129.

2,3-dihydro-2-(4-trifluoromethylphenyl)benzo[d][1,3,2]diazaborinin–4(1H)-one (1c):
Chapter 3

$^1$H NMR (400 MHz, DMSO-d$_6$) $\delta$ 9.88 (1H, s), 9.51 (1H, s), 8.27-8.22 (2H, m), 8.03 (1H, dd, $J = 8.0$ Hz, 1.2 Hz), 7.80 (2H, d, $J = 8.0$ Hz), 7.59 (1H, ddd, $J = 8.0$ Hz, 7.2 Hz, 1.6 Hz), 7.43 (1H, dd, $J = 7.6$ Hz, 0.8 Hz), 7.13 (1H, ddd, $J = 7.6$ Hz, 7.2 Hz, 1.2 Hz); $^{13}$C NMR (126 MHz, DMSO-d$_6$) $\delta$ 167.2, 146.2, 138.2, 135.0, 134.4, 131.4 (q, $J = 31.2$ Hz), 128.9, 125.2, 125.2 (q, $J = 277.2$ Hz), 122.1, 119.9, 119.2; $^{11}$B NMR (128 MHz, DMSO-d$_6$) $\delta$ 37.2; IR (KBr) 3334, 1634, 1323, 1116, 1132, 764; HREIMS Calcd. for C$_{14}$H$_{10}$BF$_3$N$_2$O (M$^+$): 290.0838, Found: 290.0844.

$^2$-[2-(dimethylphenylsilyl)-4-trifluoromethylphenyl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (2c):

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.20-8.15 (1H, m), 8.03-8.00 (1H, m), 7.74-7.69 (1H, m), 7.63 (1H, d, $J = 7.6$ Hz), 7.45-7.33 (6H, m), 7.14 (1H, ddd, $J = 8.0$ Hz, 7.2 Hz, 1.2 Hz), 7.00 (1H, brs), 6.27-6.23 (1H, m), 5.89 (1H, brs), 0.53 (6H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 166.2, 143.4, 143.3, 139.0, 134.1, 133.9, 133.2, 131.2, 130.8 (q, $J = 37.8$ Hz), 129.9, 129.1, 128.6, 125.5, 124.4 (q, $J = 340.2$ Hz), 122.2, 118.9, 117.8, -1.4; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 31.8; IR (KBr) 3415, 3209, 1655, 1515, 1326, 772; HREIMS Calcd. for C$_{22}$H$_{20}$BF$_3$N$_2$OSi (M$^+$): 424.1390, Found: 424.1393.

2,3-dihydro-2-(4-methylphenyl)benzo[d][1,3,2]diazaborinin-4(1H)-one (1d):
Chapter 3

\[ \text{HN} \quad \text{BN} \quad \text{O} \]

\[ \begin{align*}
\text{'H NMR (400 MHz, CDCl}_3\text{)} & \delta 8.27-8.22 (1\text{H}, \text{ m}), 7.60 (2\text{H}, \text{ d, } J = 7.6 \text{ Hz}), 7.55 (1\text{H}, \text{ ddd, } J = 8.0 \text{ Hz, 7.2 Hz, 1.6 Hz}), 7.49 (1\text{H}, \text{ brs}), 7.33-7.28 (2\text{H}, \text{ m}), 7.20-7.13 (1\text{H}, \text{ m}), 7.12-7.07 (1\text{H}, \text{ m}), 6.75 (1\text{H}, \text{ brs}), 2.42 (3\text{H}, \text{ s}); \quad \text{'}\text{C NMR (126 MHz, DMSO-}d\text{)}_6 \text{)} & \delta 167.3, 146.5, 141.1, 134.3, 134.3, 129.4, 128.9, 121.6, 119.6, 119.0, 22.1; \quad \text{'}\text{B NMR (128 MHz, DMSO-}d\text{)}_6 \text{)} & \delta 33.1; \quad \text{IR (KBr) } 3332, 1638, 1490, 755; \quad \text{HREIMS Calcd. for } C_{14}H_{13}BN_2O \text{ (M}^+\text{): 236.1121, Found: 236.1120.}
\end{align*} \]

2-[2-(dimethylphenylsilyl)-4-methylphenyl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1 H)-one (2d):

\[ \begin{align*}
\text{'H NMR (400 MHz, CDCl}_3\text{)} & \delta 8.18-8.13 (1\text{H}, \text{ m}), 7.64-7.61 (1\text{H}, \text{ m}), 7.48-7.34 (7\text{H}, \text{ m}), 7.32-7.28 (1\text{H}, \text{ m}), 7.09 (1\text{H}, \text{ ddd, } J = 8.0 \text{ Hz, 7.2 Hz, 0.8 Hz}), 7.04 (1\text{H}, \text{ brs}), 6.19-6.15 (1\text{H}, \text{ m}), 5.91 (1\text{H}, \text{ brs}), 2.46 (3\text{H}, \text{ s}), 0.48 (6\text{H}, \text{ s}); \quad \text{'}\text{C NMR (126 MHz, CDCl}_3\text{)} & \delta 166.3, 143.5, 141.3, 140.2, 138.4, 136.2, 134.0, 133.5, 133.0, 129.6, 129.4, 128.9, 128.4, 121.6, 118.6, 117.5, 21.6, -1.4; \quad \text{'}\text{B NMR (128 MHz, CDCl}_3\text{)} & \delta 31.8; \quad \text{IR (KBr) } 3277, 1653, 1517, 761; \quad \text{HREIMS Calcd. for } C_{22}H_{23}BN_2OSi \text{ (M}^+\text{): 370.1673, Found: 370.1669.}
\end{align*} \]

2,3-dihydro-2-(4-methoxyphenyl)benzo[d][1,3,2]diazaborinin-4(1H)-one (1e):
Chapter 3

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.26-8.22 (1H, m), 7.66-7.62 (2H, m), 7.57-7.51 (1H, m), 7.44 (1H, brs), 7.16 (1H, ddd, $J$ = 8.0 Hz, 7.2 Hz, 0.8 Hz), 7.11-7.07 (1H, m), 7.04-6.99 (2H, m), 6.69 (1H, brs), 3.87 (3H, s); $^{13}$C NMR (126 MHz, DMSO-d$_6$) $\delta$ 166.4, 161.3, 145.6, 135.1, 133.3, 127.9, 120.6, 118.6, 118.0, 113.5, 55.0; $^{11}$B NMR (128 MHz, DMSO-d$_6$) $\delta$ 30.7; IR (KBr) 3306, 1645, 1509, 1490, 758; HREIMS Calcd. for C$_{14}$H$_{13}$BN$_2$O$_2$ (M$^+$) : 252.1070, Found: 252.1072.

2-[2-(dimethylphenylsilyl)-4-methoxyphenyl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (2e):

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.18-8.12 (1H, m), 7.50 (1H, d, $J$ = 8.0 Hz), 7.48-7.35 (7H, m), 7.11-7.07 (1H, m), 7.05 (1H, brs), 7.01 (1H, dd, $J$ = 8.0 Hz, 2.8 Hz), 6.14 (1H, d, $J$ = 8.4 Hz), 5.91 (1H, brs), 3.90 (3H, s), 0.48 (6H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 166.3, 159.8, 143.5, 143.4, 139.8, 134.7, 133.9, 133.5, 129.5, 128.8, 128.4, 122.4, 121.5, 118.6, 117.5, 113.0, 55.0, -1.4; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 31.6; IR (KBr) 3413, 1653, 1514, 1222, 800; HREIMS Calcd. for C$_{22}$H$_{23}$BN$_2$O$_2$Si (M$^+$): 386.1622, Found: 386.1623.

2,3-dihydro-2-(3-methylphenyl)benzo[d][1,3,2]diazaborinin-4(1H)-one (1f):
$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.28-8.24 (1H, m), 7.59-7.47 (4H, m), 7.41-7.31 (2H, m), 7.17 (1H, ddd, $J$ = 8.0 Hz, 7.2 Hz, 0.8 Hz), 7.13-7.09 (1H, m), 6.78 (1H, brs), 2.43 (3H, s); $^{13}$C NMR (126 MHz, DMSO-d$_6$) $\delta$ 166.4, 145.6, 136.7, 134.0, 133.4, 131.1, 130.4, 128.0, 127.7, 120.8, 118.8, 118.2, 21.1; $^{11}$B NMR (128 MHz, DMSO-d$_6$) $\delta$ 33.1; IR (KBr) 3332, 1638, 1490, 755; HREIMS Calcd. for C$_{14}$H$_{13}$BN$_2$O (C): 236.1121, Found: 236.1115.

2-[2-(dimethylphenylsilyl)-5-methylpheny]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (2f):

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.19-8.14 (1H, m), 7.71 (1H, d, $J$ = 7.6 Hz), 7.47-7.32 (8H, m), 7.12-7.07 (1H, m), 7.05 (1H, brs), 6.20-6.16 (1H, m), 5.92 (1H, brs), 2.40 (3H, s), 0.46 (6H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 166.3, 143.5, 140.3, 138.7, 137.7, 135.5, 133.9, 133.9, 133.5 129.5, 129.4, 128.9, 128.4, 121.7, 118.7, 117.6, 21.4, -1.38; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 32.0; IR (KBr) 3392, 1665, 1519, 1486, 759; HREIMS Calcd. for C$_{22}$H$_{23}$BN$_2$OSi (M$^+$): 370.1673, Found: 370.1677.

2,3-dihydro-2-(2-methylphenyl)benzo[d][1,3,2]diazaborinin-4(1H)-one (1g):

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.25-8.29 (1H, m), 7.56 (1H, ddd, $J$ = 8.0 Hz, 7.2 Hz, 1.6 Hz),
7.48-7.45 (1H, m), 7.39-7.34 (1H, m), 7.28-7.23 (3H, m), 7.19 (1H, ddd, \(J = 8.0\) Hz, 7.2 Hz, 0.8 Hz), 7.08-7.04 (1H, m), 6.60 (1H, brs), 2.49 (3H, s); \(^{13}\)C NMR (126 MHz, DMSO-\(d_6\)) \(\delta\) 166.9, 146.4, 141.5, 134.2, 134.0, 130.1, 130.0, 128.9, 125.7, 121.8, 119.7, 119.0, 23.1; \(^{11}\)B NMR (128 MHz, DMSO-\(d_6\)) \(\delta\) 38.7; IR (KBr) 3206, 1641, 1522, 1261, 746; HREIMS Calcd. for C\(_{14}\)H\(_{13}\)BN\(_2\)O (M\(^+\)): 236.1121, Found: 236.1127.

2-[2-(dimethylphenylsilyl)-6-methylphenyl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (2g):

\[
\text{HN} \quad \text{NH} \\
\text{SiMe}_2\text{Ph} \\
\text{Me}
\]

\(^{1}\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 7.59 (1H, d, \(J = 7.2\) Hz), 7.46-7.41 (1H, m), 7.38 (1H, dd, \(J = 7.6\) Hz, 7.6 Hz), 7.32-7.20 (7H, m), 7.14 (1H, ddd, \(J = 8.0\) Hz, 7.6 Hz, 1.2 Hz), 6.88 (1H, brs), 6.44-6.40 (1H, m), 5.84 (1H, brs), 2.30 (3H, s), 0.45 (6H, s); \(^{13}\)C NMR (126 MHz, CDCl\(_3\)) \(\delta\) 166.0, 143.7, 141.8, 140.3, 139.8, 134.0, 133.7, 132.4, 130.6, 129.1, 128.6, 128.1, 122.0, 118.9, 117.8, 22.7, -1.7 \(\delta\); \(^{11}\)B NMR (128 MHz, CDCl\(_3\)) \(\delta\) 30.3; IR (KBr) 3274, 1654, 1487, 765; HRFABMS Calcd. for C\(_{22}\)H\(_{23}\)BO\(_2\)Si (M\(^+\)): 370.1673, Found: 370.1674.

2,3-dihydro-2-(naphthalen-2-yl)benzo[d][1,3,2]diazaborinin-4(1H)-one (1h):

\[
\text{HN} \quad \text{NH} \\
\text{B}
\]

\(^{1}\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 8.30-8.27 (1H, m), 8.23 (1H, s), 7.97-7.87 (3H, m), 7.76-7.72 (1H, m), 7.69 (1H, brs), 7.61-7.53 (3H, m), 7.23-7.18 (1H, m), 7.15-7.14 (1H, m), 6.92 (1H, brs); \(^{13}\)C NMR (126 MHz, DMSO-\(d_6\)) \(\delta\) 166.4, 145.6, 134.4, 134.1, 133.4, 132.5, 129.9, 129.6, 128.4, 128.0, 127.6, 127.0, 126.9, 126.1, 120.9, 118.9, 118.2; \(^{11}\)B NMR (128 MHz, DMSO-\(d_6\)) \(\delta\) 28.9; IR (KBr) 3338, 1641, 1526, 739; HRESIMS Calcd. for C\(_{17}\)H\(_{13}\)BN\(_2\)NaO (M+Na):
2-[3-(dimethylphenylsilyl)naphthalen-2-yl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (2h):

![Chemical Structure]

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.29 (1H, s), 8.21-8.17 (1H, m), 8.04 (1H, s), 7.96-7.91 (1H, m), 7.88-7.84 (1H, m), 7.62-7.55 (2H, m), 7.50-7.35 (6H, m), 7.17 (1H, brs), 7.11 (1H, ddd, $J$ = 8.0 Hz, 7.2 Hz, 0.8 Hz), 6.18-6.14 (1H, m), 5.96 (1H, brs), 0.57 (6H, s); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 166.5, 143.6, 140.2, 137.5, 136.4, 134.2, 133.7, 133.6, 133.1, 133.0, 129.7, 129.1, 128.7, 128.2, 128.0, 127.4, 127.3, 121.9, 118.9, 117.8, -1.2; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 30.1; IR (KBr) 3398, 1669, 1514, 799; HRESIMS Calcd. for C$_{25}$H$_{23}$BN$_2$NaOSi (M+Na): 429.1570, Found: 429.1554.

2,3-dihydro-2-(naphthalen-1-yl)benzo[d][1,3,2]diazaborinin-4(1H)-one (1i):

![Chemical Structure]

$^1$H NMR (400 MHz, DMSO-d$_6$) $\delta$ 9.66 (1H, s), 9.43 (1H, s), 8.07 (1H, dd, $J$ = 8.0 Hz, 1.2 Hz), 8.04-7.94 (3H, m), 7.74-7.69 (1H, m), 7.61-7.51 (4H, m), 7.35 (1H, d, $J$ = 8.0 Hz), 7.18-7.12 (1H, m); $^{13}$C NMR (126 MHz, DMSO-d$_6$) $\delta$ 167.0, 146.4, 136.0, 135.3, 134.3, 133.7, 132.6, 130.0, 129.3, 128.9, 127.0, 126.6, 126.2, 121.9, 119.9, 119.1; $^{11}$B NMR (128 MHz, DMSO-d$_6$) $\delta$ 33.3; IR (KBr) 3373, 1611, 1514, 767; HRESIMS Calcd. for C$_{17}$H$_{13}$BN$_2$O (M$^+$): 272.1121, Found: 272.1118.

2-[2-(dimethylphenylsilyl)naphthalen-1-yl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H
78

Chapter 3

)-one (2i):

\[
\begin{array}{c}
\text{HN} \\
\text{B} \\
\text{HN} \\
\text{SiMe}_2\text{Ph}
\end{array}
\]

\[^{1}\text{H NMR (400 MHz, CDCl}_3\text{) }\delta 8.26-8.22 (1\text{H, m}), 7.95 (1\text{H, dd}, J = 8.0 \text{ Hz}, 0.8 \text{ Hz}), 7.90-7.86 (1\text{H, m}), 7.90-7.86 (1\text{H, m}), 7.84 (1\text{H, d}, J = 8.4 \text{ Hz}), 7.81-7.77 (1\text{H, m}), 7.53-7.39 (3\text{H, m}), 7.37-7.33 (2\text{H, m}), 7.31-7.15 (4\text{H, m}), 7.07 (1\text{H, brs}), 6.51-6.47 (1\text{H, m}), 6.08 (1\text{H, brs}), 0.58 (3\text{H, s}), 0.5 (3\text{H, s}); \text{^{13}C NMR (126 MHz, CDCl}_3\text{) }\delta 165.7, 143.6, 140.5, 139.4, 135.4, 133.9, 133.6, 133.0, 130.8, 129.2, 129.1, 128.4, 128.1, 128.0, 126.5, 126.2, 122.0, 118.9, 117.7, 0.6, -1.7; \text{^{11}B NMR (128 MHz, CDCl}_3\text{) }\delta 30.1; \text{IR (KBr) 3269, 1651, 1512, 1486, 733; HREIMS Calcd. for C}_{25}\text{H}_{23}\text{BN}_2\text{OSi (M}^+\text{): 406.1673, Found: 406.1679.} \]

2,3-dihydro-2-(thiophen-3-yl)benzo[d][1,3,2]diazaborinin-4(1H)-one (1j):

\[
\begin{array}{c}
\text{HN} \\
\text{B} \\
\text{HN} \\
\text{S}
\end{array}
\]

\[^{1}\text{H NMR (400 MHz, CDCl}_3\text{) }\delta 8.27-8.22 (1\text{H, m}), 7.84 (1\text{H, dd}, J = 2.8 \text{ Hz}, 1.2 \text{ Hz}), 7.61 (1\text{H, brs}), 7.55 (1\text{H, ddd}, J = 8.4 \text{ Hz}, 7.2 \text{ Hz}, 1.6 \text{ Hz}), 7.50 (1\text{H, dd}, J = 4.8 \text{ Hz}, 2.4 \text{ Hz}), 7.41 (1\text{H, dd}, J = 4.8 \text{ Hz}, 1.2 \text{ Hz}), 7.17 (1\text{H, ddd}, J = 8.0 \text{ Hz}, 7.6 \text{ Hz}, 1.2 \text{ Hz}), 7.10 (1\text{H, ddd}, J = 8.0 \text{ Hz}, 0.8 \text{ Hz}, 0.4 \text{ Hz}), 6.72 (1\text{H, brs}); \text{^{13}C NMR (126 MHz, DMSO-d}_6\text{) }\delta 166.3, 145.5, 134.9, 133.4, 131.7, 128.0, 128.0, 126.1, 120.7, 118.8, 118.0; \text{^{11}B NMR (128 MHz, DMSO-d}_6\text{) }\delta 27.2; \text{IR (KBr) 3349, 1639, 1533, 755; HRESIMS Calcd. for C}_{11}\text{H}_9\text{BN}_2\text{NaOS (M+Na): 251.0426, Found: 251.0419.} \]

2-[2-(dimethylphenylsilyl)thiophen-3-yl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (2j):

78
\[ \begin{align*}
\text{Chapter 3} \\
\text{H NMR (400 MHz, CDCl}_3\text{) } & \delta 8.15 (1H, dd, J = 8.0 Hz, 1.6 Hz), 7.76 (1H, d, J = 4.8 Hz), 7.60-7.55 (2H, m), 7.51-7.43 (4H, m), 7.39 (1H, ddd, J = 8.0 Hz, 7.2 Hz, 1.6, Hz), 7.17 (1H, brs), 7.09 (1H, ddd, J = 8.0 Hz, 7.2 Hz, 1.2 Hz), 6.21 (1H, d, J = 8.4 Hz), 6.06 (1H, brs), 0.60 (6H, s); \\
\text{13C NMR (126 MHz, CDCl}_3\text{) } & \delta 166.6, 144.8, 143.9, 138.9, 134.1, 133.7, 131.2, 130.2, 129.0, 128.8, 121.8, 118.8, 117.5, -0.81; \\
\text{11B NMR (128 MHz, CDCl}_3\text{) } & \delta 28.3; \\
\text{IR (KBr) } & 3382, 1654, 1518, 754; \\
\text{HRESIMS Calcd. for C}_{19}H_{19}BN_2NaOSSi (M+Na): 385.0978, Found: 385.0969. \\
\end{align*} \]

\[ \begin{align*}
\text{2-[2,4-bis(dimethylphenylsilyl)thiophen-3-yl]-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (3j):} \\
\text{H NMR (400 MHz, CDCl}_3\text{) } & \delta 8.10 (1H, d, J = 8.0 Hz), 7.95 (1H, s), 7.49-7.23 (11H, m), 7.09 (1H, dd, J = 7.6 Hz, 7.6 Hz), 6.18 (1H, d, J = 8.0 Hz), 5.62 (1H, brs), 0.54 (6H, s), 0.47 (6H, s); \\
\text{13C NMR (126 MHz, CDCl}_3\text{) } & \delta 165.5, 145.8, 145.5, 143.5, 139.6, 138.9, 138.4, 134.0, 133.9, 133.5, 129.7, 129.5, 129.0, 128.2, 121.8, 118.7, 117.6, -0.65, -1.38; \\
\text{11B NMR (128 MHz, CDCl}_3\text{) } & \delta 30.0; \\
\text{IR (KBr) } & 3294, 1648, 1486, 775; \\
\text{HRESIMS Calcd. for C}_{27}H_{29}BN_2NaOSSi_2 (M+Na): 519.1530, Found: 519.1521. \\
\end{align*} \]

\[ \begin{align*}
\text{thiophene-2,4-diylbis(dimethylphenylsilane) (S1):} \\
\text{H NMR (400 MHz, CDCl}_3\text{) } & \delta 7.72 (1H, d, J = 0.8 Hz), 7.58-7.49 (4H, m), 7.40-7.32 (6H, m), 7.34 (1H, d, J = 1.2 Hz), 0.59 (6H, s), 0.53 (6H, s) s; \\
\text{13C NMR (126 MHz, CDCl}_3\text{) } & \delta 140.4, \\
\end{align*} \]
2-(4-bromophenyl)-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (1k):

2-\{3-(dimethylphensilyl)-4'-methyl-[1,1'-biphenyl]-4-yl\}-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (5k):

\[1^\text{HNMR} (400 \text{ MHz, DMSO-}d_6)\ \delta 9.77 (1\text{H, s)}, 9.38 (1\text{H, s}), 8.03-7.97 (3\text{H, m}), 7.68-7.64 (2\text{H, m}), 7.57 (1\text{H, ddd, } J = 8.4 \text{ Hz}, 7.2 \text{ Hz}, 1.6 \text{ Hz}), 7.43-7.39 (1\text{H, m}), 7.11 (1\text{H, ddd, } J = 8.0 \text{ Hz}, 7.2 \text{ Hz}, 1.2 \text{ Hz}); \] \[13^\text{C NMR} (126 \text{ MHz, DMSO-}d_6) \ \delta 166.2, 145.3, 135.4, 133.4, 130.8, 127.9, 124.7, 121.0, 118.8, 118.2; \] \[11^\text{B NMR} (128 \text{ MHz, DMSO-}d_6) \ \delta 31.4; \] IR (KBr) 3333, 1635, 1490, 755; HREIMS Calcd. for C_{13}H_{10}BBrN_{2}O \ (M^+): 300.0070, Found: 300.0073.

1H NMR (400 MHz, CDCl_3) \(\delta \) 8.20-8.16 (1H, m), 8.01 (1H, dd, \( J = 1.6 \text{ Hz}, 0.8 \text{ Hz})\), 7.69 (1H, dd, \( J = 7.6 \text{ Hz}, 2.0 \text{ Hz})\), 7.60 (1H, dd, \( J = 7.6 \text{ Hz}, 0.4 \text{ Hz})\), 7.59-7.55 (2H, m), 7.50-7.46 (2H, m), 7.40-7.35 (4H, m), 7.34-7.29 (2H, m), 7.14-7.07 (2H, m), 6.20 (1H, dd, \( J = 8.0 \text{ Hz}, 0.8 \text{ Hz})\), 5.96 (1H, brs), 2.43 (3H, s), 0.53 (6H, s); \[13^\text{C NMR} (126 \text{ MHz, CDCl}_3) \ \delta 166.5, 143.6, 142.2, 141.4, 140.1, 138.1, 137.7, 134.1, 134.0, 133.7, 133.6, 129.8, 129.6, 129.1, 128.6, 127.5, 127.2, 121.9, 118.8, 117.7, 21.3, -1.2; \] \[11^\text{B NMR} (128 \text{ MHz, CDCl}_3) \ \delta 30.3; \] IR (KBr)
2-(3-bromophenyl)-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (1l):

\[
\text{\textsuperscript{1}H NMR (400 MHz, CDCl}_3\text{) } \delta 8.26 (1\text{H}, d, J = 7.6 \text{ Hz}), 7.83 (1\text{H}, s), 7.68-7.49 (4\text{H}, m), 7.37 (1\text{H}, dd, J = 7.6 \text{ Hz, 7.6 Hz}), 7.20 (1\text{H}, dd, J = 7.6 \text{ Hz, 7.6 Hz}), 7.12 (1\text{H}, d, J = 7.6 \text{ Hz}), 6.77 (1\text{H, brs}); \text{\textsuperscript{13}C NMR (126 MHz, DMSO-d}_6\text{) } \delta 166.3, 145.3, 135.8, 135.4, 133.4, 133.2, 132.2, 130.1, 128.0, 122.2, 121.0, 118.9, 118.2; \text{\textsuperscript{11}B NMR (128 MHz, DMSO-d}_6\text{) } \delta 28.5; \text{ IR (KBr) } 3327, 1635, 1528, 758; \text{ HRESIMS Calcd. for C}_{13}\text{H}_{10}\text{BBrN}_2\text{NaO (M+Na)}: 322.9967, \text{ Found: 322.9967.}
\]

2,3-dihydro-2-[4'-methyl-(1,1'-biphenyl)-3-yl]benzo[d][1,3,2]diazaborinin-4(1H)-one (4l):

\[
\text{\textsuperscript{1}H NMR (400 MHz, CDCl}_3\text{) } \delta 8.27 (1\text{H}, dd, J = 8.0 \text{ Hz, 1.6 Hz}), 7.90, (1\text{H}, s), 7.73 (1\text{H}, ddd, J = 7.6 \text{ Hz, 1.6 Hz, 1.2 Hz}), 7.66 (1\text{H}, ddd, J = 7.2 \text{ Hz, 1.2 Hz, 1.2 Hz}), 7.60-7.51 (4\text{H, m}, 7.29 (2\text{H, d, J = 7.6 Hz}), 7.18 (1\text{H}, ddd, J = 8.0 \text{ Hz, 7.2 Hz, 0.8 Hz}) 7.13 (1\text{H}, d, J = 8.0 \text{ Hz}, 6.86 (1\text{H, brs}), 2.42 (3\text{H, s}); \text{\textsuperscript{13}C NMR (126 MHz, DMSO-d}_6\text{) } \delta 166.4, 145.5, 139.5, 137.2, 136.7, 133.4, 132.0, 131.4, 129.4, 128.4, 128.3, 127.9, 126.7, 120.8, 118.8, 118.1, 20.7; \text{\textsuperscript{11}B NMR (128 MHz, DMSO-d}_6\text{) } \delta 26.7; \text{ IR (KBr) } 3334, 1635, 1525, 1486, 755; \text{ HRESIMS Calcd. for C}_{10}\text{H}_{17}\text{BN}_2\text{NaO (M+Na): 335.1332, Found: 335.1332.}
\]
Chapter 3

2-\{4-(dimethylphenylsilyl)-4'-methyl-[1,1'-biphenyl]-3-yl\}-2,3-dihydrobenzo[d][1,3,2]diazaborinin-4(1H)-one (5l):

\[
\begin{array}{c}
\text{HN} \\
\text{B} \quad \text{NH}
\end{array}
\]

\[
\begin{array}{c}
\text{SiMe}_2\text{Ph}
\end{array}
\]

\(^1\text{H} \text{NMR} (400 \text{ MHz, CDCl}_3) \delta 7.87 (1 \text{H}, \text{ dd, } J = 7.6 \text{ Hz, 0.4 Hz}), 7.76 (1 \text{H}, d, J = 1.6 \text{ Hz}), 7.72 (1 \text{H}, \text{ dd, } J = 7.6 \text{ Hz, 2.0 Hz}), 7.56-7.52 (2 \text{H, m}), 7.51-7.46 (2 \text{H, m}), 7.46-7.35 (5 \text{H, m}), 7.28 (2 \text{H, d, } J = 8.0 \text{ Hz}), 7.19 (1 \text{H, brs}), 7.11 (1 \text{H, ddd, } J = 8.0 \text{ Hz, 7.2 Hz, 0.8 Hz}), 6.23 (1 \text{H, dd}, J= 8.0 \text{ Hz, 0.8 Hz}), 6.01 (1 \text{H, brs}), 2.41 (3 \text{H, s}), 0.52 (6 \text{H, s}); ^{13}\text{C} \text{NMR} (126 \text{ MHz, CDCl}_3) \delta 166.5, 143.6, 141.5, 140.2, 139.8, 137.7, 137.7, 136.1, 134.2, 133.7, 131.6, 129.8, 129.6, 129.1, 128.6, 127.2, 127.1, 121.9, 118.9, 117.7, 21.3, -1.2; ^{11}\text{B} \text{NMR} (128 \text{ MHz, CDCl}_3) \delta 29.8; \text{ IR} (\text{KBr}) 3404, 1654, 1513, 815; \text{ HRAPCIMS Calcd. for C}_{28}\text{H}_{28}\text{BN}_2\text{OSi (M+H): 447.2064, Found: 447.2049.}
\]

2,3-dihydro-1-methyl-2-phenylbenzo[d][1,3,2]diazaborinin-4(1H)-one (6a):

\[
\begin{array}{c}
\text{HN} \\
\text{B} \quad \text{NH}
\end{array}
\]

\[
\begin{array}{c}
\text{SiPh}
\end{array}
\]

\(^1\text{H} \text{NMR} (400 \text{ MHz, CDCl}_3) \delta 8.36 \ (1 \text{H}, \text{ ddd, } J = 7.6 \text{ Hz, 1.6 Hz, 0.4 Hz}), 7.69 (1 \text{H, ddd, } J = 8.4 \text{ Hz, 7.2 Hz, 1.6 Hz}), 7.61-7.56 (2 \text{H, m}), 7.50-7.44 (3 \text{H, m}), 7.32 (1 \text{H, d, } J = 8.0 \text{ Hz}), 7.28-7.21 (2 \text{H, m}), 3.40 (3 \text{H, s}); ^{13}\text{C} \text{NMR} (126 \text{ MHz, DMSO-d}_6) \delta 165.2, 146.4, 133.7, 133.1, 129.0, 128.4, 127.7, 121.2, 120.0, 115.2, 34.3; ^{11}\text{B} \text{NMR} (128 \text{ MHz, DMSO-d}_6) \delta 31.5; \text{ IR (KBr) 3202, 1663, 1481, 757; HRESIMS Calcd. for C}_{14}\text{H}_{13}\text{BN}_2\text{NaO (M+Na): 259.1019, Found: 259.1011.}
\]

2,3-dihydro-3-methyl-2-phenylbenzo[d][1,3,2]diazaborinin-4(1H)-one (6b):

\[
\begin{array}{c}
\text{HN} \\
\text{B} \quad \text{NH}
\end{array}
\]

\[
\begin{array}{c}
\text{SiPh}
\end{array}
\]
Chapter 3

\[ \text{HNBO} \]
\[ \text{HN} \]
\[ \text{B} \]
\[ \text{N} \]
\[ \text{SiMe}_2\text{Ph} \]

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.33-8.28 (1H, m), 7.63-7.56 (2H, m), 7.54-7.48 (1H, m), 7.48-7.42 (3H, m), 7.20-7.14 (1H, m), 7.02 (1H, d, $J = 8.0$ Hz), 6.61 (1H, brs), 3.29 (3H, s); $^{13}$C NMR (126 MHz, DMSO-d$_6$) $\delta$ 166.2, 144.3, 135.3, 133.0, 132.8, 129.1, 128.0, 127.7, 121.0, 118.2, 117.8, 31.5; $^{11}$B NMR (128 MHz, DMSO-d$_6$) $\delta$ 31.5; IR (KBr) 3281, 3040, 1620, 1520, 751; HRESIMS Calcd. for C$_{14}$H$_{13}$BN$_2$NaO (M+Na): 259.1019, Found: 259.1009.

2-[2-(dimethylphenylsilyl)phenyl]-2,3-dihydro-1-methylbenzo[\textbf{d}][1,3,2]diazaborinin-$^{11}$H-one (7a):

\[ \text{HNBO} \]
\[ \text{HN} \]
\[ \text{B} \]
\[ \text{N} \]
\[ \text{SiMe}_2\text{Ph} \]

$^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.30-8.26 (1H, m), 7.56-7.20 (1H, m), 7.59 (1H, dddd, $J = 8.4$ Hz, 7.2 Hz, 1.6 Hz, 0.4 Hz), 7.48-7.38 (2H, m), 7.37-7.32 (3H, m), 7.23-7.18 (1H, m), 7.12-7.06 (3H, m), 7.02 (1H, d, $J = 8.4$ Hz), 6.82 (1H, brs), 2.80 (3H, s), 0.54-0.47 (6H, m); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 165.4, 146.3, 141.6, 137.8, 135.2, 134.1, 133.8, 131.7, 129.5, 129.2, 128.6, 128.1, 127.7, 121.6, 120.1, 114.6, 34.5, -1.16, -1.49; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 31.3; IR (KBr) 3197, 2955, 1664, 1482, 816; HRESIMS Calcd. for C$_{22}$H$_{23}$BN$_2$NaOSi (M+Na): 393.1570, Found: 393.1557.

**References and Notes**


Chapter 3


15) Non-directed, Ir-catalyzed silylation of thiophenes has been reported. Lu, B.; Falck, J. R. Angew. Chem., Int. Ed. **2008**, 47, 7508.

Chapter 3
Chapter 4

Anthranilamide-Masked \( o \)-Iodoarylboronic Acids as Coupling Modules for Iterative Synthesis of \( o\)-Linked Oligoarenes

**Abstract:** Anthranilamide (AAM)-masked \( o \)-iodoarylboronic acids were prepared from AAM-masked arylboronic acids via Ru-catalyzed \( o \)-C-H silylation followed by iododesilylation with ICl. Suzuki-Miyaura coupling of AAM-masked \( o \)-haloarylboronic acids with arylboronic acids proceeded under ligand-free conditions. Oligo(\( o \)-phenylene)s and oligo(naphthalene-2,3-diyl)s were synthesized via iterative Suzuki-Miyaura coupling sequences.
Introduction

Increasing interest has been focused on the synthesis and structure of ortho-linked oligoarenes and hetarenes.\textsuperscript{1-4} They cannot adopt planar structure, but form helical structures due to the steric repulsion of the substituents on the aromatic rings. In addition to their static helical structures, dynamic change of the helical structures has gained increasing attention from the viewpoint of application to functional materials.\textsuperscript{5} For instance, we have recently established solvent-dependent, reversible switch of helical conformation of poly(quinoxaline-2,3-diyl)s with high molecular weight.\textsuperscript{6} This system was successfully applied to a new chiral catalyst system in which either enantiomer can be produced with high enantioselectivity from a single enantiomer of the chiral catalyst.\textsuperscript{7} Although being attractive, ortho-linked oligoarenes and hetarenes have not been explored in-depth yet, mainly because of paucity of robust synthetic approaches. Therefore, it is highly desirable to establish general, efficient synthetic methods which would also allow synthesis of functionalized oligoarenes in a sequence selective manner.

We have been interested in the development of cross-coupling-based organic synthesis including iterative synthesis of oligoarene derivatives on the basis of boron-masking strategy using 1,8-diaminonaphthalene (DAN) as a highly effective masking group.\textsuperscript{8} We subsequently established a removable ortho-directing group (o-DG), which is attached to the boron atom of the boronyl group and allows Ru-catalyzed o-silylation.\textsuperscript{9} Although pyrazolylaniline (PZA) was reported also as the first-generation o-DG, we later on showed that anthranilamide (AAM) exhibited higher ability of o-direction as well as higher stability, which allowed us to utilize AAM as a protective group in Suzuki-Miyaura coupling.\textsuperscript{10} We envisioned that AAM-protected o-haloarylboronic acids 3 may serve as highly convenient building modules in the synthesis of helical oligo(o-arene)s via iterative Suzuki-Miyaura cross-coupling. The modules 3 may be obtained directly by halodesilylation of AAM-protected o-silylarylboronic acids 2, which in turn are conveniently prepared by o-silylation of AAM-protected arylboronic acids 1. It should be noted that a report on direct ortho-iodination of unprotected arylboronic acids has appeared recently.\textsuperscript{11,12} The direct iodination, however, still requires use of silver salt to promote the reaction and encounters difficulty in iodination of electron-poor and electron-neutral arenes. In this paper, we demonstrate convenient synthesis of AAM-protected o-idoarylboronic acids and their use in
iterative Suzuki-Miyaura coupling for the synthesis of oligo(o-phenylene)s and oligo(naphthalene-2,3-diy1)s.

\[
\begin{align*}
R & \quad \text{B(aam)} \\
1 & \quad \overset{\text{ortho-}}{\xrightarrow{\text{silylation}}} \\
 & \quad \text{R} \\
 & \quad \text{B(aam)} \\
 & \quad \text{SiR}_3 \\
 & \quad \overset{\text{halo-}}{\xrightarrow{\text{desilylation}}} \\
 & \quad \text{R} \\
 & \quad \text{B(aam)} \\
 & \quad X \\
3 & \quad \overset{\text{Iterative}}{\xrightarrow{\text{coupling}}} \\
 & \quad \text{oligo(o-arene)s}
\end{align*}
\]

**Figure 1.** Synthetic strategies of oligo(o-arene)s.

**Results and Discussion**

AAM-protected o-silylarylboronic acids 2 were prepared according to the reported procedure for Ru-catalyzed o-silylation of arylboronic acids.\(^{10}\) In addition to the o-silylboronic acids 2a, 2b, 2d, 2g, and 2k reported in the previous paper, we also synthesized new derivatives in good yields from the corresponding AAM-protected arylboronic acids (Table 1). Iododesilylation was accomplished efficiently by use of ICl at low temperature.\(^{12}\) Attempted use of I\(_2\) or Br\(_2\) failed to give the corresponding o-halogenated products in reasonable yields. In the iododesilylation, use of the electron-deficient AAM group rather than the electron-rich PZA group was essential to avoid undesirable iodination on the masking group. The present synthesis of o-idoarylboronic acids through iododesilylation was found to be complementary to Hall's silver-mediated direct iodination, which requires electron-donating substituents such as alkoxy and amino groups on the aromatic rings. Our method could successfully be applied to alkyl- (entries 2 and 8), aryl- (entry 10), chloro-
(entries 5 and 11), and even fluoro-substituted arylboronic acids (entry 6), in addition to alkoxy-substituted arylboronic acids (entries 3 and 9). Note that attempted iododesilylation of the phenyldimethylsilyl group on the electron-deficient aromatic ring failed (entry 4), leading to iodination at the phenyl group of the PhMe$_2$Si group. This problem was overcome by use of Et$_3$Si derivative (entries 5, 6, 7 and 11). It should also be noted that AAM-masked 5,8-dimethylnaphthyl-2-boronic acid, which was used for the synthesis of 21 (entry 13) was conveniently prepared from 1,4-dimethylnaphthalene via Ir-catalyzed aromatic C–H borylation. This example demonstrates that the synthetic utility of the ortho-C–H silylation is significantly enhanced by combining it with the C–H borylation chemistry.
Table 1. Iododesilylation of AAM-protected o-silylarylboron acids produced by Ru-catalyzed o-directed silylation of AAM-protected aryloboronic acids.\textsuperscript{4}

\[
\begin{align*}
\text{entry} & \quad \text{product 2} & \quad \text{yield}^a & \quad \text{product 3} & \quad \text{yield}^f \\
1 & \quad \text{H} & \quad 80^c & \quad \text{H} & \quad 87 \\
2 & \quad \text{Me} & \quad 88^c & \quad \text{Me} & \quad 96 \\
3 & \quad \text{C}_6\text{H}_4\text{O}^- & \quad 90 & \quad \text{C}_6\text{H}_4\text{O}^- & \quad 90 \\
4 & \quad \text{Cl} & \quad 91^c & \quad \text{Cl} & \quad 0 \\
5 & \quad \text{Cl} & \quad 82 & \quad 3d & \quad 95 \\
6 & \quad \text{F} & \quad 65 & \quad \text{F} & \quad 94 \\
7 & \quad \text{F} & \quad 53 & \quad \text{F} & \quad 71 \\
8 & \quad \text{Me} & \quad 81^c & \quad \text{Me} & \quad 94 \\
9 & \quad \text{MeO} & \quad 87 & \quad \text{MeO} & \quad 94 \\
10 & \quad \text{Me} & \quad 63 & \quad \text{Me} & \quad 92 \\
11 & \quad \text{Cl} & \quad 83 & \quad \text{Cl} & \quad 97 \\
12 & \quad \text{Me} & \quad 90 & \quad \text{Me} & \quad 84 \\
13 & \quad \text{Me} & \quad 72 & \quad \text{Me} & \quad 86 \\
\end{align*}
\]

\textsuperscript{a}2 (0.1 mmol), ICl (0.2 mmol), CH\textsubscript{2}Cl\textsubscript{2} (0.5 mL), –78 °C, 18 h. \textsuperscript{b}–78 to –9 °C. \textsuperscript{c}–78 °C to room temperature. \textsuperscript{d}Isolated yield of 2 in Ru-catalyzed ortho-silylation of the corresponding ArB(aam). \textsuperscript{e}Reported in reference 10. \textsuperscript{f}Isolated yield.
Chapter 4

Table 2. Optimization of cross-coupling of o-halophenylboronic acid 3a' with p-tolyboronic acid.

<table>
<thead>
<tr>
<th>entry</th>
<th>reaction conditions</th>
<th>% yield 4 (1b)%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pd(OAc)$_2$ (3 mol%), SPhos (6 mol%), K$_3$PO$_4$ (2 equiv), THF, rt, 89 h</td>
<td>0 (98)</td>
</tr>
<tr>
<td>2</td>
<td>Pd(OAc)$_2$ (3 mol%), SPhos (6 mol%), K$_3$PO$_4$ (2 equiv), THF, 50 °C, 62 h</td>
<td>0 (65)</td>
</tr>
<tr>
<td>3</td>
<td>Pd(P$_{t}$Bu$_3$)$_2$ (5 mol%), CsF (2 equiv), THF, rt, 19 h</td>
<td>0 (0)</td>
</tr>
<tr>
<td>4</td>
<td>Pd(OAc)$_2$ (3 mol%), K$_3$PO$_4$ (2 equiv), THF, rt, 19 h</td>
<td>96 (0)</td>
</tr>
</tbody>
</table>

*a*Isolated yield of 4. NMR yield of 1b is in the parenthesis.

We then examined cross-coupling of AAM-protected o-halophenylboronic acids with arylboronic acids. An initial trial under the reaction conditions utilized for the coupling of AAM-protected p- and m-bromophenylboronic acids completely failed giving no desired coupling products. Indeed, the attempted coupling of AAM-protected o-bromophenylboronic acid 3a' in the presence of SPhos (P/Pd = 2) as a ligand at room temperature resulted in transfer of the AAM group from 3a' to p-tolyboronic acid, giving AAM-protected p-tolylboronic acid 1b with no formation of the coupling product (entry 1, Table 2). Applying higher reaction temperature did not improve the reaction outcome at all (entry 2). Use of the $t$-Bu$_3$P/CsF system gave no desirable product, although no AAM-transfer product was formed either (entry 3). We finally found that a ligand-free palladium catalyst worked efficiently in the cross-coupling of 3a', giving the AAM-protected biarylboronic acid 4 in high isolated yield (entry 4). The reaction conditions were successfully applied to the cross-coupling of o-iodo derivative 3a, giving the corresponding biaryl product 5 in high yield (Scheme 1). Thus obtained AAM-protected biarylboronic acid
Chapter 4

5 was cross-coupled with various aryl bromides after deprotection of the AAM group by acidic hydrolysis, giving teraryls 6a-c in high yields.

Having established the basis for the preparation and reactivities of AAM-masked o-iodoarylboronic acids, we pursued the iterative synthesis of oligo(naphthalene-2,3-diyl)s using our AAM system. Cross-coupling conditions for the synthesis of oligonaphthalene were further optimized on the basis of the examination for the oligophenylene synthesis. We again observed better outcome with ligand-free palladium catalyst in the coupling of AAM-masked 3-iodo-2-naphthylboronic acid 3k with 6-ethoxy-2-naphthylboronic acid 7. After the coupling, the AAM group remaining untouched was removed by acidic treatment. Use of the unmasked binaphthylboronic acid in cross-coupling with 3k, however, resulted in ill-reproducible results.

![Scheme 1](image)

**Scheme 1.** Synthesis of ter(o-phenylene)s via iterative Suzuki-Miyaura coupling

It turned out that the presence of even a small amount of water led to AAM transfer from 3k to the binaphthylboronic acid, whereas complete dehydration then led to the formation of boroxine 9, which was totally unreactive toward cross-coupling. Indeed, the degree of dehydration after the unmasking step affected the result of subsequent cross-coupling step significantly. We could finally adapt the procedure in which boroxine 9, obtained by complete dehydration, was hydrolyzed to binaphthylboronic acid by adding a stoichiometric amount of water prior to the coupling step. According to this procedure, AAM-masked ternaphthylboronic acid 10 was isolated in high yield. The iterative coupling sequence was terminated by coupling with 2-naphthyl bromide, giving quaternaphthalene 11 bearing a terminal ethoxy group.
Conclusion

In summary, we have established a new synthetic route to ortho-iodoarylboronic acid derivatives via Ru-catalyzed ortho-directed silylation of AAM-masked arylboronic acids followed by iododesilylation with ICl. The present synthesis of ortho-iodoarylboronic acids is complementary to the ortho-directed, Ag-mediated iodination of arylboronic acids\(^ \text{11} \) and show wider applicability to electronically unactivated arylboronic acids. Application to iterative synthesis of oligo(ortho-phenylene)s and oligo(naphthalene-2,3-diyl)s has also been demonstrated. Synthesis of more densely functionalized oligo(ortho-phenylene)s and oligo(naphthalene-2,3-diyl)s including those adapting non-racemic helical structures are now being undertaken in this laboratory.
Experimental Section

General
All reactions were carried out under an atmosphere of nitrogen with magnetic stirring. $^1$H, $^{11}$B and $^{13}$C NMR spectra were recorded on a Varian Mercury vx400 or a JEOL JNM-A500 spectrometer at ambient temperature. $^1$H NMR data are reported as follows: chemical shift in ppm downfield from tetramethylsilane ($\delta$ scale), multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, quint = quintet, sex = sextet, m = multiplet, and br = broad), coupling constant (Hz), and integration. $^{13}$C NMR chemical shifts are reported in ppm downfield from tetramethylsilane ($\delta$ scale). $^{11}$B NMR chemical shifts are reported in ppm downfield from BF$_3$·OEt$_2$. All $^{13}$C NMR spectra were obtained with broadband proton decoupling. High-resolution mass spectra were recorded on a JEOL JMS-SX102A (EI) and Thermo Fisher Scientific EXACTIVE (ESI and APCI) spectrometer. IR spectra were recorded on a FTIR SHIMADZU DR-8000 spectrometer. Preparative TLC was performed with silica gel 60PF$_{254}$ (Merck). Recycling Preparative GPC was performed with JAI LC-908 equipped with JAIGEL-1H and -2H columns in a series(CHCl$_3$). Column chromatography was performed with Ultra Pure Silica Gel (40-63 $\mu$m) (Silicycle).

Materials
Toluene and THF were dried and deoxygenized using an alumina/catalyst column system (GlassContour Co.). Anthranilamide (TCI), hydrochloric acid (Nacalai), iodine monochloride (Wako), 4-bromotoluene (Wako), 4-bromoanisole (TCI), 4-bromobenzotrifluoride (TCI), 2-Bromonaphthalene (TCI), triethylsilane (TCI), dimethylphenylsilane (Aldrich), Bis(pinacolato)diboron (ChemICHIBA), norbornene (TCI), phenylboronic acid (Wako), 4-methoxyphenylboronic acid (Aldrich), 4-trifluoromethylphenylboronic acid (Wako), 4-chlorophenylboronic acid (Wako), 4-fluorophenylboronic acid (Wako), 3-chlorophenylboronic acid (TCI), 4-methylphenylboronic acid (Wako), 3-methylphenylboronic acid (TCI), 2-naphthaleneboronic acid (TCI), 6-ethoxy-2-naphthaleneboronic acid (TCI), 1,4-dimethylnaphthalene (TCI), Florisil® (75-150 $\mu$m, Kanto), Pd(OAc)$_2$ (Tanaka Rare-metal), and SPhos (Strem) were used as received from the commercial sources. RuH$_2$(CO)(PPh$_3$)$_3$, $^{15}$[IrCl(COD)(OMe)]$_2$, $^{16}$ were prepared by the
literature procedures. Potassium phosphate (Nacalai) was dried in an oven at 300 °C for 5 h *in vacuo* (1 mmHg).

**Synthesis of New ArB(aam) by Condensation of Arylboronic Acid with Anthranilamide**

**General Procedure**

A mixture of arylboronic acid (8.8 mmol) and anthranilamide (1.09 g, 8 mmol) in toluene (0.25 mmol/mL, 32 mL) was heated under reflux in a Dean-Stark apparatus for 1 h. After cooling the mixture to room temperature, the precipitates were collected by filtration to give 1.

**Synthesis of 1c**

According to the general procedure, 1c (2.27 g, 88%) was prepared from 4-hexyloxyphenylboronic acid (1.95 g) and anthranilamide (1.09 g). mp 204.1-207.3 °C; \(^1\)H NMR (400 MHz, DMSO-\(d_6\)) \(\delta\) 9.60 (1H, s), 9.19 (1H, s), 8.01 (3H, d, \(J = 8.4\) Hz), 7.54 (1H, ddd, \(J = 8.4\) Hz, 7.2 Hz, 1.6 Hz), 7.41 (1H, d, \(J = 7.6\) Hz), 7.07 (1H, ddd, \(J = 8.0\) Hz, 7.6 Hz, 1.2 Hz), 6.98 (2H, d, \(J = 8.8\) Hz), 3.99 (2H, t, \(J = 6.8\) Hz), 1.73-1.66 (2H, m), 1.43-1.36 (2H, m), 1.30-1.26 (4H, m), 0.86 (3H, t); \(^13\)C NMR (100 MHz, DMSO-\(d_6\)) \(\delta\) 166.3, 160.8, 145.6, 135.1, 133.3, 127.9, 123.4, 120.5, 118.6, 118.0, 113.9, 67.3, 31.0, 28.6, 25.2, 22.1, 13.9; \(^{11}\)B NMR (128 MHz, DMSO-\(d_6\)) \(\delta\) 25.0; IR (ATR) 3300, 1645, 1487, 758; HRESIMS Calcd. for C\(_{19}\)H\(_{24}\)BN\(_2\)O\(_2\) ([M+H])\(^+\): 323.1925, Found: 323.1920.

**Synthesis of 1e**
According to the general procedure, 1e (608 mg, 84%) was prepared from 4-fluorophenylboronic acid (462 mg, 3.3 mmol) and anthranilamide (408 g, 3.0 mmol). mp 228.0-233.0 °C; \(^1\)H NMR (400 MHz, DMSO-\(d_6\)) \(\delta\) 9.75 (1H, s), 9.32 (1H, s), 8.14-8.10 (2H, m), 8.03 (1H, dd, \(J = 8.0\) Hz, 1.2 Hz), 7.52 (1H, ddd, \(J = 8.4\) Hz, 7.6 Hz, 1.6 Hz), 7.41 (1H, d, \(J = 7.6\) Hz), 7.25-7.21 (2H, m), 7.08-7.04 (1H, m); \(^13\)C NMR (100 MHz, DMSO-\(d_6\)) \(\delta\) 166.5, 164.1 (d, \(J = 247\) Hz), 145.5, 135.9 (d, \(J = 7.9\) Hz), 133.4, 128.6, 128.0, 120.9, 118.8, 118.2, 114.8 (d, \(J = 19.7\) Hz); \(^{11}\)B NMR (128 MHz, DMSO-\(d_6\)) \(\delta\) 29.4; IR (ATR) 3333, 1616, 1458, 758; HRESIMS Calcd. for \(C_{13}H_{11}BFN_2O ([M+H]^+)\): 241.0943, Found: 241.0939.

**Synthesis of 1h**

According to the general procedure, 1h (1.12 g, 88%) was prepared from 3-methoxyphenylboronic acid (832 mg, 5.5 mmol) and anthranilamide (680 mg, 5.0 mmol). mp 189.9-193.2 °C; \(^1\)H NMR (400 MHz, DMSO-\(d_6\)) \(\delta\) 9.78 (1H, s), 9.33 (1H, s), 8.05 (1H, dd, \(J = 8.0\) Hz, 0.8 Hz), 7.68-7.64 (2H, m), 7.57 (1H, ddd, \(J = 8.4\) Hz, 6.8 Hz, 1.6 Hz), 7.46 (1H, dd, \(J = 8.0\) Hz, 0.4 Hz), 7.36 (1H, dd, \(J = 7.6\) Hz, 7.6 Hz), 7.11 (1H, ddd, \(J = 8.0\) Hz, 6.8 Hz, 1.2 Hz), 7.03 (1H, ddd, \(J = 8.4\) Hz, 2.8 Hz, 0.8 Hz), 3.83 (3H, s); \(^13\)C NMR (100 MHz, DMSO-\(d_6\)) \(\delta\) 166.4, 159.0, 145.5, 133.7, 133.4, 129.0, 128.0, 125.6, 120.9, 118.8, 118.3, 118.2, 116.5, 55.1; \(^{11}\)B NMR (128 MHz, DMSO-\(d_6\)) \(\delta\) 28.4; IR (ATR) 3333, 1616, 1483, 761; HRESIMS Calcd. for \(C_{14}H_{14}BN_2O_2 ([M+H]^+)\): 253.1143, Found: 253.1137.
Synthesis of 1j

According to the general procedure, 1j (502 mg, 98%) was prepared from 3-chlorophenylboronic acid (343 mg, 3.3 mmol) and anthranilamide (272 mg, 3.0 mmol). mp 219.9-222.5 °C; \(^1\)H NMR (400 MHz, DMSO-\(d_6\)) \(\delta\) 9.82 (1H, s), 9.53 (1H, s), 8.16 (1H, s), 8.05 (2H, d, \(J = 7.6\) Hz), 7.57 (1H, ddd, \(J = 8.8\) Hz, 7.2 Hz, 1.6 Hz), 7.52-7.43 (3H, m), 7.11 (1H, ddd, \(J = 8.0\) Hz, 6.8 Hz, 1.2 Hz); \(^13\)C NMR (100 MHz, DMSO-\(d_6\)) \(\delta\) 166.3, 145.4, 135.0, 133.4, 133.3, 132.9, 131.9, 130.3, 129.8, 127.9, 121.0, 118.9, 118.3; \(^{11}\)B NMR (128 MHz, DMSO-\(d_6\)) \(\delta\) 26.7; IR (ATR) 3325, 1616, 1479, 756; HRESIMS Calcd. for C\(_{13}\)H\(_{11}\)BClN\(_2\)O ([M+H]+): 257.0647, Found: 257.0641.

Synthesis of ArB(aam) (1l) via Ir-catalyzed Aromatic C–H Borylation\(^{17}\)

\[
\text{Me} \quad \text{B}_2(\text{pin})_2 (1.1 \text{ equiv}) \\
\text{Ir(OMe)COD}_2 (5 \text{ mol%}) \\
dtbpy (10 \text{ mol%}) \\
\text{cyclohexane} \\
80 \degree \text{C, 16 h} \\
\text{Me} \quad \text{B(pin)} \\
\text{S1 82%} \\
1) \text{NaIO}_4, \text{HCl aq} \\
\text{THF, H}_2\text{O} \\
2) \text{anthranilamide} \\
\text{toluene, reflux} \\
\text{Me} \quad \text{B(aam)} \\
1l
\]

Scheme S1. Synthesis of 1l

\(o\)-C–H Borylation of 1,4-Dimethylnaphthalene

A mixture of [Ir(COD)(OMe)]\(_2\) (33.1 mg, 0.05 mmol), 4,4’-di-tert-butyl-2,2’-bipyridine (26.8 mg, 0.1 mmol), bispinacolatoborane (279 mg, 1.1 mmol) and 1,4-dimethylnaphthalene (154 \(\mu\)L, 1.0 mmol) in cyclohexane (3.8 mL) was heated for 20 h at 60 °C. After being cooled to
room temperature, the solvent was evaporated in vacuo. The borylated product \( S1 \) (231 mg, 82\%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 9:1). mp 70.8-72.0 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \( \delta \) 8.60 (1H, s), 8.40 (1H, dd, \( J = 8.4 \) Hz, 0.4 Hz), 7.97 (1H, dd, \( J = 8.4 \) Hz, 1.2 Hz), 7.28-7.23 (2H, m), 2.78 (s, 3H), 2.70 (s, 3H), 1.45 (s, 12H); \(^1\)C NMR (100 MHz, CDCl\(_3\)) \( \delta \) 134.5, 133.4, 132.9, 132.2, 132.1, 130.2, 127.5, 126.3, 123.8, 84.0, 25.0, 19.7, 19.5; \(^1\)B NMR (128 MHz, CDCl\(_3\)) \( \delta \) 31.6; IR (ATR) 2979, 1342, 1139, 692; HREIMS Calcd. for C\(_{18}\)H\(_{23}\)BO\(_2\) (M\(^+\)): 282.1791, Found: 282.1794.

**Conversion of ArB(pin) to ArB(aam)**

\( S1 \) (231 mg, 0.82 mmol) and sodium perodate (525 mg, 2.46 mmol) were stirred in 5.3 mL of a mixture of THF and water for 30 min, at which time aqueous hydrochloric acid (1 N, 573 \( \mu \)L, 0.57 mmol) was added to the suspension. The reaction mixture was stirred at room temperature for 17 h. The reaction mixture was diluted with water (3 mL) and extracted with ethyl acetate (3 x 6 mL). The combined extracts were washed with water (2 x 3 mL) and brine (3 mL), dried over sodium sulfate, filtered, and concentrated to dryness by evaporation. The material was used for condensation of arylboronic acid with anthranilamide without further purification. A mixture of arylboronic acid and anthranilamide (106 mg, 0.78 mmol) in toluene (5 mL) was heated under reflux in a Dean-Stark apparatus for 1 h. After cooling a mixture to room temperature, the precipitates were collected by filtration to give \( 11 \) (229 mg, 93\%). mp 208.2-210.0 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \( \delta \) 8.38 (1H, s), 8.29 (1H, dd, \( J = 8.0 \) Hz, 1.2 Hz), 8.08, (1H, d, \( J = 8.4 \) Hz), 7.88 (1H, brs), 7.77 (1H, dd, \( J = 8.4 \) Hz, 1.2 Hz), 7.59-7.55 (1H, m), 7.31-7.25 (2H, m), 7.21-7.17 (2H,m), 7.02 (1H, brs), 2.75 (3H, s), 2.68 (3H, s); \(^1\)C NMR (100 MHz, CDCl\(_3\)) \( \delta \) 167.0, 144.6, 134.1, 134.0, 133.0, 132.5, 132.3, 129.8, 129.4, 127.8, 127.4, 127.1, 125.0, 122.0, 119.2, 117.8, 19.6, 19.4; \(^1\)B NMR (128 MHz, CDCl\(_3\)) \( \delta \) 29.5; IR (ATR) 3334, 1620, 1529, 750; HREIMS Calcd. for C\(_{19}\)H\(_{17}\)BN\(_2\)O (M\(^+\)): 300.1434, Found: 300.1432.
C–H silylation of AAM-Protected Arylboronic Acids (Table 1)

**General Procedure**

A mixture of 1 (0.25 mmol), RuH$_2$(CO)(PPh$_3$)$_3$ (13.8 mg, 0.015 mmol), norbornene (118 mg, 1.25 mmol), and hydrosilane (1.25 mmol) in toluene (0.13 mL) was heated in a glass tube sealed with a J-Young Teflon stopper at 135 °C. The reaction was run for 20 h unless otherwise noted. After cooling to temperature, the mixture was subjected to column chromatography on Florisil® (hexane/EtOAc), giving o-silylated product 2.

**Synthesis of 2c**

According to the general procedure, a mixture of 1c (1.29 g, 4.0 mmol), RuH$_2$(CO)(PPh$_3$)$_3$ (220 mg, 0.24 mmol), norbornene (1.88g, 20 mmol), and dimethylphenylsilane (3.1 mL) in toluene (2.0 mL) was heated. 2c (1.48 g, 81%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1). mp 137.2-139.3 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 8.14 (1H, dd, J = 8.0 Hz, 1.2 Hz), 7.48-7.44 (3H, m), 7.43-7.34 (5H, m), 7.08-7.02 (2H, m), 6.97 (1H, dd, J = 8.0 Hz, 2.8 Hz), 6.12 (1H, dd, J = 8.0 Hz, 0.8 Hz), 5.90 (1H, brs), 4.03 (2H, t, J = 6.4 Hz), 1.83 (2H, quint, J = 7.2 Hz), 1.53-1.46 (2H, m), 1.39-1.33 (4H, m), 0.93-0.89 (3H, m), 0.48 (6H, s); $^{13}$C NMR (100 MHz, CDCl$_3$) δ 166.5, 159.6, 143.7, 143.5, 140.1, 134.9, 134.1, 133.6, 129.6, 129.0, 128.6, 123.1, 121.7, 118.8, 117.7, 113.8, 67.9, 31.7, 29.4, 25.9, 22.8, 14.2, -1.2; $^{11}$B NMR (128 MHz, CDCl$_3$) δ 30.3; IR (KBr) 3201, 1652, 1512, 767; HRESIMS Calcd. for C$_{27}$H$_{34}$BN$_2$O$_2$Si ([M+H]$^+$): 457.2477, Found: 457.2469.

**Synthesis of 2d’**
According to the general procedure, a mixture of 1d (192 mg), RuH₂(CO)(PPh₃)₃, norbornene and triethylsilane (597 µL) in toluene was heated. 2d' (229 mg, 82%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – 4:1 – 3:1). mp 189.0-192.3 °C; ¹H NMR (400 MHz, CDCl₃) δ 8.29-8.27 (1H, m), 7.57 (1H, ddd, J = 8.8 Hz, 7.2 Hz, 0.8 Hz), 7.54 (1H, dd, J = 2.0 Hz, 0.8 Hz), 7.42-7.35 (2H, m), 7.22 (1H, ddd, J = 8.0 Hz, 7.2 Hz, 0.8 Hz), 7.11 (1H, brs), 7.02 (1H, dd, J = 8.0 Hz, 0.8 Hz) 6.45 (1H, m), 0.93-0.89 (9H, m), 0.78-0.71 (6H, m); ¹³C NMR (100 MHz, CDCl₃) δ 166.1, 143.9, 143.4, 135.5, 135.3, 134.2, 133.8, 129.5, 128.3, 122.4, 119.0, 117.7, 7.6, 4.3; ¹¹B NMR (128 MHz, CDCl₃) δ 30.5; IR (ATR) 3371, 1651, 1517, 725; HRESIMS Calcd. for C₁₉H₂₅BCIN₂OSi ([M+H]+): 371.1512, Found: 371.1502.

**Synthesis of 2e’**

According to the general procedure, a mixture of 1e (180 mg), RuH₂(CO)(PPh₃)₃, norbornene and triethylsilane (597 µL) in toluene was heated. 2e' (230 mg, 86%) was isolated by column chromatography on Florisil® (hexane-AcOEt, 8:1 – 5:1 – 4:1). mp 169.5-173.5 °C; ¹H NMR (400 MHz, CDCl₃) δ 8.29-8.27 (1H, m), 7.57 (1H, ddd, J = 8.8 Hz, 7.2 Hz, 1.6 Hz), 7.47 (1H, dd, J = 8.0 Hz, 5.6 Hz), 7.29 (1H, ddd, J = 9.6 Hz, 2.4 Hz), 7.21 (1H, ddd, J = 8.0 Hz, 7.6 Hz, 1.2 Hz), 7.12 (1H, brs), 7.08 (1H, ddd, J = 8.8 Hz, 8.8 Hz, 2.4 Hz), 7.02 (1H, dd, J = 8.0 Hz, 0.8Hz) 6.45 (1H, brs), 0.93-0.89 (9H, m), 0.78-0.72 (6H, m); ¹³C NMR (100 MHz, CDCl₃) δ 165.9, 163.0 (d, J = 250 Hz), 144.1 (d, J = 3.5 Hz), 143.8, 134.3 (d, J = 6.5 Hz), 134.0,
129.3, 122.1, 122.0 (d, \( J = 17.4 \) Hz), 118.9, 117.5, 115.0 (d, \( J = 20.4 \) Hz), 7.4, 4.1; \(^{11}\)B NMR (128 MHz, CDCl\(_3\)) \( \delta \) 30.8; IR (ATR) 3288, 1635, 1521, 719; HRESIMS Calcd. for C\(_{19}\)H\(_{25}\)BFN\(_2\)OSi ([M+H]\(^+\)): 355.1808, Found: 355.1800.

**Synthesis of 2f**

According to the general procedure, a mixture of 1f (218 mg), RuH\(_2\)(CO)(PPh\(_3\))\(_3\), norbornene and triethylsilane (597 \( \mu\)L) in toluene was heated. 2f (231 mg, 83%) was isolated by column chromatography on Florisil\(^\oplus\) (hexane-AcOEt, 10:1 – 4:1 – 3:1). mp 199.6-203.5 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \( \delta \) 8.26 (1H, dd, \( J = 8.4 \) Hz, 1.2 Hz), 7.79 (1H, dd, \( J = 0.8 \) Hz, 0.8 Hz), 7.63-7.54 (3H, m), 7.21 (1H, ddd, \( J = 8.4 \) Hz, 7.2 Hz, 0.8 Hz), 7.15 (1H, brs), 7.03 (1H, dd, \( J = 8.4 \) Hz, 2.4 Hz), 6.50 (1H, brs), 0.92-0.87 (9H, m), 0.79-0.72 (6H, m); \(^{13}\)C NMR (100 MHz, CDCl\(_3\)) \( \delta \) 165.9, 143.8, 142.0, 134.3, 132.5, 131.5 (q, \( J = 3.5 \) Hz), 130.5 (q, \( J = 31.7 \) Hz), 129.5, 124.7 (q, \( J = 271 \) Hz), 124.4 (q, \( J = 3.6 \) Hz), 122.5, 119.1, 117.7, 7.57, 4.25; \(^{11}\)B NMR (128 MHz, CDCl\(_3\)) \( \delta \) 30.3; IR (ATR) 3294, 1649, 1521, 734; HRESIMS Calcd. for C\(_{20}\)H\(_{25}\)BF\(_3\)N\(_2\)OSi ([M+H]\(^+\)): 405.1776, Found: 405.1771.

**Synthesis of 2h**

According to the general procedure, a mixture of 1h (189 mg), RuH\(_2\)(CO)(PPh\(_3\))\(_3\), norbornene and dimethylphenylsilane (573 \( \mu\)L) in toluene was heated. 2h (250 mg, 87%) was isolated by column chromatography on Florisil\(^\oplus\) (hexane-AcOEt, 10:1 – 4:1 – 3:1). mp 170.2-173.0 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \( \delta \) 8.15 (1H, dd, \( J = 8.0 \) Hz, 0.8 Hz), 7.72 (1H, d, \( J = 8.0 \) Hz),
7.44-7.32 (6H, m), 7.11-7.01 (4H, m), 6.17 (1H, d, J = 8.4 Hz), 5.93 (1H, brs), 3.84 (3H, s), 0.44 (6H, s); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 166.4, 160.2, 143.5, 140.7, 137.3, 134.1, 133.7, 132.2, 129.5, 129.0, 128.5, 121.9, 118.9, 118.8, 117.8, 114.2, 55.2, -1.1; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 30.1; IR (ATR) 3394, 1652, 1517, 761; HRESIMS Calcd. for C$_{22}$H$_{24}$BN$_2$O$_2$Si ([M+H]$^+$): 387.1695, Found: 387.1686.

**Synthesis of 2j’**

According to the general procedure, a mixture of 1j (192 mg), RuH$_2$(CO)(PPh$_3$)$_3$, norbornene and triethylsilane (597 $\mu$L) in toluene was heated. 2j’ (231 mg, 83%) was isolated by column chromatography on Florisil$^\text{®}$ (hexane-AcOEt, 10:1 – 8:1). mp 193.8-197.8 ºC; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.27-8.25 (1H, m), 7.59-7.55 (1H, m), 7.52 (1H, d, J = 8.0 Hz), 7.46 (1H, d, J = 2.4 Hz), 7.38 (1H, dd, J = 8.4 Hz, 2.4 Hz), 7.22-7.17 (2H, m), 7.05 (1H, d, J = 8.0 Hz) 6.59 (1H, brs), 0.91-0.85 (9H, m), 0.76-0.69 (6H, m); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 166.0, 143.8, 138.5, 137.1, 134.9, 134.2, 132.2, 129.5, 128.6, 122.4, 119.1, 117.7, 7.6, 4.4; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 29.9; IR (ATR) 3292, 1637, 1519, 759; HRESIMS Calcd. for C$_{19}$H$_{25}$BCIN$_2$OSi ([M+H]$^+$): 371.1512, Found: 371.1503.

**Synthesis of 2l**

According to the general procedure, a mixture of 1l (150 mg, 0.5 mmol), RuH$_2$(CO)(PPh$_3$)$_3$ (27.5 mg, 0.03mmol), norbornene (236 mg, 2.5 mmol), and dimethylphenylsilane (260 $\mu$L) in toluene was reacted. Silylated product 2l (158 mg, 72%) was isolated by column chromatography on Florisil$^\text{®}$ (hexane-AcOEt, 10:1 – 3:1). mp 235.1-240.3 ºC; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.24-8.19 (1H, m), 7.56-7.52 (1H, m), 7.51 (1H, d, J = 8.0 Hz), 7.45 (1H, d, J = 2.4 Hz), 7.35-7.31 (1H, d, J = 8.0 Hz), 7.20-7.16 (2H, m), 7.04 (1H, d, J = 8.0 Hz) 6.57 (1H, brs), 0.90-0.84 (9H, m), 0.77-0.68 (6H, m); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 166.2, 143.8, 138.5, 137.1, 134.9, 134.2, 132.2, 129.5, 128.6, 122.0, 119.1, 117.7, 7.6, 4.4; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 29.9; IR (ATR) 3292, 1637, 1519, 759; HRESIMS Calcd. for C$_{19}$H$_{25}$BCIN$_2$OSi ([M+H]$^+$): 371.1503, Found: 371.1503.
MHZ, CDCl$_3$) $\delta$ 8.47 (1H, s), 8.21-8.19 (2H, m), 7.50-7.37 (6H, m), 7.33-7.29 (2H, m), 7.26 (1H, brs), 7.12 (1H, dd, $J = 7.6$ Hz, 7.6 Hz), 6.16 (1H, d, $J = 8.0$ Hz), 6.01 (1H, brs), 2.76 (3H, s), 2.68 (3H, s), 0.59 (6H, s); $^{13}$C NMR (100 MHZ, CDCl$_3$) $\delta$ 166.6, 143.6, 140.4, 136.8, 134.2, 133.8, 132.9, 132.7, 132.6, 132.2, 132.1, 130.3, 129.7, 129.1, 128.7, 127.8, 121.9, 118.8, 117.8, 19.3, 19.2, –1.2; $^{11}$B NMR (128 MHZ, CDCl$_3$) $\delta$ 30.3; IR (ATR) 3396, 1666, 1512, 729; HRESIMS Calcd. for C$_{27}$H$_{28}$BN$_2$OSi ([M+H]$^+$): 435.2058, Found: 435.2056.

Iododesilylation of AAM-Protected $o$-Silylarylboronic Acids (Table 1)

General Procedure

ICl (10 $\mu$L, 0.2 mmol) was added to a solution of ArB(aam) (0.1 mmol) in CH$_2$Cl$_2$ at –78 °C. After being stirred for 18 h, 2-metyl-2 -butene (32 $\mu$L, 0.3 mmol) was added, and the mixture was stirred for 5 min at room temperature. The mixture was subjected to column chromatography on Florisil$^\text{®}$ (hexane/EtOAc, 10:1 - chloroform), giving $o$-iodonated product $3$.

Synthesis of 3a

According to the general procedure, 3a (30.3 mg, 87%) was prepared from 2a (35.6 mg). mp 164.0-167.2 °C; $^1$H NMR (400 MHZ, CDCl$_3$) $\delta$ 8.30-8.26 (1H, m), 7.89 (1H, d, $J = 8.0$ Hz), 7.57 (1H, ddd, $J = 8.0$ Hz, 7.2 Hz, 1.2 Hz), 7.45-7.34 (2H, m), 7.32 (1H, brs), 7.21 (1H, ddd, $J = 8.0$ Hz, 7.2 Hz, 0.8 Hz), 7.15 (1H, ddd, $J = 8.0$ Hz, 6.8 Hz, 2.4 Hz), 7.09 (1H, dd, $J = 8.0$ Hz, 0.4 Hz) 6.73 (1H, brs); $^{13}$C NMR (100 MHZ, CDCl$_3$) $\delta$ 166.4, 144.0, 139.3, 134.2, 134.1, 131.6, 129.3, 127.7, 122.3, 119.1, 117.9, 99.9; $^{11}$B NMR (128 MHZ, CDCl$_3$) $\delta$ 30.2; IR (ATR) 3310, 1654, 1521, 754; HRMS (APCI) Calcd. for C$_{13}$H$_{11}$BIN$_2$O ([M+H]$^+$): 349.0004, Found: 349.0006.

Synthesis of 3b
According to the general procedure, **3b** (34.8 mg, 96%) was prepared from **2b** (37.0 mg). mp 186.3-189.5 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 8.25 (1H, dd, $J = 8.0$ Hz, 1.2 Hz), 7.72 (1H, s), 7.55 (1H, ddd, $J = 8.8$ Hz, 7.2 Hz, 1.6 Hz), 7.36 (1H, brs), 7.28 (1H, d, $J = 7.6$ Hz), 7.22-7.16 (2H, m), 7.10 (1H, d, $J = 8.0$ Hz), 6.85 (1H, brs), 2.33 (3H, s); $^{13}$C NMR (100 MHz, CDCl$_3$) δ 166.4, 144.1, 142.2, 140.0, 134.1, 134.0, 129.3, 128.7, 122.2, 119.0, 117.8, 100.0, 21.0; $^{11}$B NMR (128 MHz, CDCl$_3$) δ 30.0; IR (ATR) 3413, 1656, 1508, 750; HRESIMS Calcd. for C$_{14}$H$_{13}$BIN$_2$O ([M+H]$^+$): 363.0160, Found: 363.0156.

**Synthesis of 3c**

According to the general procedure, **3c** (40.7 mg, 96%) was prepared from **2c** (45.6 mg). mp 125.0-127.8 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 8.24 (1H, dd, $J = 8.0$ Hz, 1.2 Hz), 7.54 (1H, ddd, $J = 8.4$ Hz, 7.2 Hz, 1.6 Hz), 7.41 (1H, d, $J = 2.4$ Hz), 7.38 (1H, brs), 7.29 (1H, d, $J = 8.4$ Hz), 7.17 (1H, ddd, $J = 8.0$ Hz, 7.2 Hz, 0.8 Hz), 7.09 (1H, d, $J = 8.0$ Hz), 6.93 (1H, dd, $J = 8.4$ Hz, 2.4 Hz), 6.86 (1H, brs), 3.95 (2H, t, $J = 6.4$ Hz), 1.78 (2H, quint, $J = 6.8$ Hz), 1.49-1.42 (2H, m), 1.37-1.32 (4H, m), 0.93-0.90 (3H, m); $^{13}$C NMR (100 MHz, CDCl$_3$) δ 166.3, 160.7, 144.0, 135.0, 133.8, 129.1, 125.6, 122.0, 118.9, 117.7, 114.2, 100.1, 68.2, 31.5, 29.0, 25.6, 22.6, 14.0; $^{11}$B NMR (128 MHz, CDCl$_3$) δ 29.6; IR (ATR) 3386, 1651, 1589, 758; HRESIMS Calcd. for C$_{19}$H$_{23}$BIN$_2$O$_2$ ([M+H]$^+$): 449.0892, Found: 451.0891.

**Synthesis of 3d**
ICl (10 μL, 0.2 mmol) was added to a solution of 2d’ (37.0 mg, 0.1 mmol) in CH₂Cl₂ at -78 °C. After the reaction was warmed to -9 °C, and further stirred for 1h. 2-Methyl-2-butene (32 μL, 0.3 mmol) was added, and the mixture was stirred for 5 min at room temperature. The mixture was subjected to column chromatography on Florisil® (hexane/EtOAc, 10:1 - chloroform), giving 3d (36.6 mg, 95%). mp 230.5-234.2 °C; ¹H NMR (400 MHz, CDCl₃) δ 8.27 (1H, dd, J = 8.0 Hz, 1.2 Hz), 7.90 (1H, d, J = 2.0 Hz), 7.57 (1H, ddd, J = 8.8 Hz, 7.2 Hz, 1.6 Hz), 7.41 (1H, dd, J = 8.0 Hz, 2.0 Hz), 7.31 (1H, d, J = 8.0 Hz), 7.29-7.19 (2H, m), 7.09 (1H, dd, J = 8.0 Hz, 0.4 Hz), 6.68 (1H, brs); ¹³C NMR (100 MHz, DMSO-d₆) δ 165.7, 145.0, 136.5, 135.2, 134.2, 133.3, 127.9, 127.1, 121.1, 119.0, 118.1, 101.2; ¹¹B NMR (128 MHz, DMSO-d₆) δ 27.4; IR (ATR) 3386, 1678, 1515, 756; HRESIMS Calcd. for C₁₃H₁₀BClIN₂O ([M+H]+): 382.9614, Found: 382.9613.

**Synthesis of 3e**

ICl (10 μL, 0.2 mmol) was added to a solution of 2e’ (35.4 mg, 0.1 mmol) in CH₂Cl₂ at -78 °C. After the reaction was warmed to -9 °C, and further stirred for 1h. 2-Methyl-2-butene (32 μL, 0.3 mmol) was added, and the mixture was stirred for 5 min at room temperature. The mixture was subjected to column chromatography on Florisil® (hexane/EtOAc, 10:1 – chloroform), giving 3e (34.4 mg, 94%). mp 198.9-201.2 °C; ¹H NMR (400 MHz, CDCl₃) δ 8.27 (1H, dd, J = 8.0 Hz, 1.6 Hz), 7.63 (1H, dd, J = 8.4 Hz, 1.6 Hz), 7.57 (1H, ddd, J = 8.8 Hz, 7.6 Hz, 1.6 Hz), 7.37 (1H, dd, J = 8.4 Hz, 6.4 Hz), 7.29-7.19 (2H, m), 7.15 (1H, ddd, J =
10.8 Hz, 8.4 Hz, 2.4 Hz), 7.10-7.07 (1H, m), 6.68 (1H, brs); $^{13}$C NMR (100 MHz, DMSO-$d_6$) \(\delta\) 165.7, 162.0 (d, \(J = 249\) Hz), 145.1, 139.7, 135.5 (d, \(J = 7.8\) Hz), 133.3, 127.9, 124.5 (d, \(J = 22.1\) Hz), 121.0, 118.9, 118.1, 114.3 (d, \(J = 19.6\) Hz), 100.5 (d, \(J = 7.3\) Hz); $^{11}$B NMR (128 MHz, DMSO-$d_6$) \(\delta\) 29.7; IR (ATR) 3390, 1651, 1519, 752; HREIMS Calcd. for C$_{13}$H$_{10}$BF$_2$N$_2$O ([M+H]$^+$): 366.9909, Found: 366.9909.

**Synthesis of 3f**

\[
\text{ICl (40 \mu L, 0.8 mmol) was added to a solution of 2f (80.8 mg, 0.2 mmol) in CH}_2\text{Cl}_2 \text{ at } -78 \degree \text{C. After the reaction was warmed to rt, and further stirred for 1h. 2-Metyl-2-butene (126 \mu L, 1.2 mmol) was added, and the mixture was stirred for 5 min at room temperature. The mixture was subjected to column chromatography on Florisil}\textsuperscript{®} (hexane/EtOAc, 10:1 – chloroform) and then 3f (59.1 mg, 71%) was isolated by preparative GPC. mp 209.3-213.5 \degree \text{C; } \textbf{^1}H NMR (400 MHz, CDCl}_3 \text{) } \delta\text{ 8.30-8.28 (1H, m), 8.12 (1H, s), 7.68 (1H, ddd, } J = 8.4 \text{ Hz, 0.8 Hz, 0.4 Hz), 7.60 (1H, ddd, } J = 8.8 \text{ Hz, 7.2 Hz, 1.6 Hz) 7.50 (1H, d, } J = 8.0 \text{ Hz), 7.30-7.22 (2H, m), 7.11-7.09 (1H, m), 6.67 (1H, brs); } ^{13}C \text{ NMR (100 MHz, CDCl}_3 \text{) } \delta\text{ 165.7, 148.6, 145.0, 134.5, 133.5, 133.4, 130.7 (q, } J = 32.0 \text{ Hz), 128.0, 123.5 (q, } J = 3.5 \text{ Hz), 123.1 (q, } J = 271 \text{ Hz), 121.2, 119.1, 118.1, 100.9; } ^{11}B \text{ NMR (128 MHz, CDCl}_3 \text{) } \delta\text{ 25.5; IR (ATR) 3173, 1684, 1506, 1105, 756; HREIMS Calcd. for C}_{14}\text{H}_{10}\text{BF}_3\text{N}_2\text{O ([M+H]}^+\text{): 416.9877, Found: 416.9865.**

**Synthesis of 3g**
According to the general procedure, **3g** (34.1 mg, 94%) was prepared from **2g** (37.0 mg). mp 173.8-177.2 °C; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.24 (1H, dd, $J$ = 8.0 Hz, 1.6 Hz), 7.70 (1H, d, $J$ = 8.0 Hz), 7.55 (1H, ddd, $J$ = 8.8 Hz, 7.6 Hz, 1.6 Hz), 7.37 (1H, brs), 7.22 (1H, d, $J$ = 2.0 Hz), 7.17 (1H, ddd, $J$ = 8.0 Hz, 6.8 Hz, 1.2 Hz), 7.11 (1H, d, $J$ = 8.4 Hz), 6.91-6.70 (2H, m), 2.30 (3H, s); $^{13}$C NMR (100 MHz, CDCl$_3$) $\delta$ 166.4, 144.1, 139.1, 137.6, 135.3, 134.0, 132.6, 129.2, 122.2, 119.1, 117.9, 95.8, 21.1; $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 29.4; IR (ATR) 3151, 1654, 1508, 754; HREIMS Calcd. for C$_{14}$H$_{13}$B$_2$O ($[\text{M+H}]^+$): 363.0160, Found: 363.0156.

**Synthesis of 3h**

![Image of 3h](image)

According to the general procedure, **3h** (35.8 mg, 94%) was prepared from **2h** (38.6 mg). mp 229.1–231.5 °C; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.28–8.26 (1H, m), 7.73 (1H, d, $J$ = 8.8 Hz), 7.57 (1H, ddd, $J$ = 8.8 Hz, 7.2 Hz, 1.6 Hz), 7.30 (1H, brs), 7.21 (1H, ddd, $J$ = 8.0 Hz, 7.2 Hz, 1.2 Hz), 7.10-7.08 (1H, m), 6.94 (1H, d, $J$ = 3.2 Hz), 6.74-6.71 (2H, m), 3.81 (3H, s); $^{13}$C NMR (100 MHz, DMSO-$d_6$) $\delta$ 165.7, 158.5, 145.1, 138.6, 133.3, 127.9, 121.0, 119.8, 118.9, 118.1, 117.1, 89.0, 55.2; $^{11}$B NMR (128 MHz, DMSO-$d_6$) $\delta$ 27.2; IR (ATR) 3361, 1647, 1515, 754; HRESIMS Calcd. for C$_{14}$H$_{13}$B$_2$O$_2$ ($[\text{M+H}]^+$): 379.0109, Found: 379.0109.

**Synthesis of 3i**

![Image of 3i](image)

According to the general procedure, **3i** (40.3 mg, 92%) was prepared from **2i** (44.6 mg). mp 227.8-233.7 °C; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.27 (1H, dd, $J$ = 8.0 Hz, 1.6 Hz), 7.91 (1H, d,
$J = 8.4$ Hz), 7.60-7.54 (2H, m), 7.48-7.39 (3H, m), 7.34 (1H, dd, $J = 8.4$ Hz, 2.4 Hz), 7.27-7.25 (2H, m), 7.20 (1H, ddd, $J = 8.0$ Hz, 7.2 Hz, 1.2 Hz), 7.10 (1H, d, $J = 8.0$ Hz), 6.82 (1H, brs), 2.40 (3H, s); $^{13}$C NMR (100 MHz, DMSO-$d_6$) $\delta$ 165.8, 145.1, 138.7, 138.3, 137.2, 136.3, 133.3, 132.1, 129.6, 128.8, 127.9, 126.3, 121.0, 119.0, 118.1, 99.3, 20.7; $^{11}$B NMR (128 MHz, DMSO-$d_6$) $\delta$ 26.0; IR (ATR) 3303, 1649, 1485, 760; HRESIMS Calcd. for C$_{20}$H$_{17}$BIN$_2$O ([M+H]$^+$): 439.0473, Found: 439.0473.

**Synthesis of 3j**

ICl (10 $\mu$L, 0.2 mmol) was added to a solution of 2j* (37.0 mg, 0.1 mmol) in CH$_2$Cl$_2$ at –78 °C. After the reaction was warmed to –9 °C, and further stirred for 1h. 2-metyl-2-butene (32 $\mu$L, 0.3 mmol) was added, and the mixture was stirred for 5 min at room temperature. The mixture was subjected to column chromatography on Florisil® (hexane/EtOAc, 10:1 - chloroform), giving 3j (37.1 mg, 97%). mp 214.3-217.9 °C; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.28 (1H, dd, $J = 8.0$ Hz, 1.6 Hz), 7.79 (1H, d, $J = 8.4$ Hz), 7.58 (1H, ddd, $J = 8.8$ Hz, 7.2 Hz, 0.8 Hz), 7.37 (1H, d, 2.8 Hz), 7.30-7.20 (2H, m), 7.12 (1H, dd, $J = 8.4$ Hz, 2.8 Hz), 7.09 (1H, dd, $J = 8.0$ Hz, 0.8 Hz), 6.68 (1H, brs); $^{13}$C NMR (100 MHz, DMSO-$d_6$) $\delta$ 165.7, 145.0, 139.5, 133.5, 133.4, 132.7, 130.6, 127.9, 121.1, 119.0, 118.1, 98.5; $^{11}$B NMR (128 MHz, DMSO-$d_6$) $\delta$ 28.4; IR (ATR) 3386, 1678, 1515, 756; HRESIMS Calcd. for C$_{13}$H$_{10}$BClIN$_2$O ([M+H]$^+$): 382.9614, Found: 382.9614.

**Synthesis of 3k**

According to the general procedure, 3k (37.2 mg, 93%) was prepared from 2k (37.2 mg), mp 217.6-220.1 °C; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 8.42 (1H, s), 8.30 (1H, dd, $J = 8.0$ Hz, 1.6 Hz),
7.91 (1H, s) 7.84-7.81 (1H, m), 7.77-7.74 (1H, m), 7.61-7.52 (3H, m), 7.40 (1H, brs), 7.22 (1H, ddd, \( J = 8.0 \) Hz, 7.2 Hz, 1.2 Hz), 7.12 (1H, dd, \( J = 8.0 \) Hz, 0.8 Hz) 6.81 (1H, brs); \(^{13}\)C NMR (100 MHz, DMSO-\( d_6 \)) \( \delta \) 165.8, 145.2, 136.3, 134.7, 133.7, 133.4, 131.3, 128.0, 127.9, 127.1, 126.7, 126.5, 121.1, 119.0, 118.1, 97.6; \(^{11}\)B NMR (128 MHz, DMSO-\( d_6 \)) \( \delta \) 26.2; IR (ATR) 3411, 1672, 1512, 748; HRESIMS Calcd. for \( C_{17}H_{13}B\text{IN}_2\text{O}(\text{M+H}): 399.0160 \), Found: 399.0160.

**Synthesis of 3l**

According to the general procedure (3), ICl (14 \( \mu \)L, 0.28 mmol) was added to a solution of 9 (60.8 mg, 0.14 mmol) in CH\(_2\)Cl\(_2\) at -78 °C. After being stirred for 18 h, 2-metyl-2-butene (44 \( \mu \)L, 0.42 mmol) was added, and the mixture was stirred for 5 min at room temperature. The mixture was subjected to column chromatography on Florisil\(^{\circledR}\) (hexane/EtOAc, 10:1 – chloroform), giving \( o \)-iodonated product 3l (51.1 mg, 86%). mp 255.0-256.9 °C; \(^1\)H NMR (400 MHz, DMSO-\( d_6 \)) \( \delta \) 9.56 (1H, s), 9.35 (1H, s), 8.47-8.46 (1H, m), 8.07-8.04 (2H, m), 7.58 (1H, dd, \( J = 8.0 \) Hz, 8.0 Hz), 7.35-7.33 (1H, m), 7.29 (2H, s), 7.14 (1H, dd, \( J = 7.6 \) Hz, 7.6 Hz), 2.62 (3H, s), 2.60 (3H, s); \(^{13}\)C NMR (100 MHz, DMSO-\( d_6 \)) \( \delta \) 165.8, 145.2, 134.1, 133.4, 132.3, 130.8, 130.7, 130.5, 128.0, 127.5, 127.0, 121.0, 119.0, 118.2, 97.9, 18.8; \(^{11}\)B NMR (128 MHz, DMSO-\( d_6 \)) \( \delta \) 26.5; IR (ATR) 3264, 1643, 1517, 748; HRESIMS Calcd. for \( C_{19}H_{17}B\text{IN}_2\text{O}([\text{M+H}]^+): 427.0473 \), Found: 427.0466.

**Procedure for Cross-Coupling of \( o \)-BrC\(_6\)H\(_4\)B(aam) (Table 2)**

**Synthesis of 3a’**
According to the general procedure (3.1), 3a’ (1.63 g, 90%) was prepared from 2-bromophenylboronic acid (1.20 g, 6.0 mmol) and anthranilamide (816 mg, 6.0 mmol). mp 178.0-180.9 °C; \(^1\)H NMR (400 MHz, DMSO-d\(_6\)) \(\delta\) 9.48 (1H, s), 9.30 (1H, s), 8.00 (1H, dd, \(J = 7.2\) Hz, 1.2 Hz), 7.60 (1H, dd, \(J = 8.0\) Hz, 0.8 Hz), 7.52 (1H, ddd, \(J = 8.4\) Hz, 7.2 Hz, 1.6 Hz), 7.48 (1H, dd, \(J = 7.2\) Hz, 1.6Hz), 7.39 (1H, ddd, \(J = 8.8\) Hz, 7.6 Hz, 1.6 Hz), 7.33 (1H, ddd, \(J = 9.6\) Hz, 7.6 Hz, 2.0 Hz), 7.28 (1H, d, \(J = 8.0\) Hz), 7.09 (1H, ddd, \(J = 8.0\) Hz, 6.8 Hz, 1.2 Hz); \(^{13}\)C NMR (100 MHz, DMSO-d\(_6\)) \(\delta\) 165.8, 145.2, 137.9, 134.7, 133.3, 131.0, 127.9, 126.7, 126.2, 121.1, 118.9, 118.1; \(^{11}\)B NMR (128 MHz, DMSO-d\(_6\)) \(\delta\) 29.2; IR (ATR) 3417, 1651, 1515, 744; HRESIMS Calcd. for C\(_{13}\)H\(_{11}\)BBrN\(_2\)O ([M+H]\(^+\)): 301.0142, Found: 301.0135.

Synthesis of 4

A mixture of 3a’ (60.0 mg, 0.20 mmol), p-tolylboronic acid (40.8 mg, 0.30 mmol), Pd(OAc)\(_2\) (1.34 mg, 6 \(\mu\)mol), and \(\text{K}_3\text{PO}_4\) (84.8mg, 0.40 mmol) in THF (0.4 ml) was stirred for 19 h at room temperature. After being cooled to room temperature, the solvent was evaporated in vacuo. The coupling product (60.3 mg, 96 \%) was isolated by column chromatography on silica gel (hexane-AcOEt, 10:1 – 2:1). mp 195.3-199.9 °C; \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 8.18 (1H, dd, \(J = 8.0\) Hz, 1.2 Hz), 7.66, (1H, d, \(J = 7.2\) Hz), 7.54-7.40 (4H, m), 7.27 (2H, d, \(J = 6.8\) Hz), 7.19 (2H, d, \(J = 6.8\) Hz), 7.14-7.10 (1H, m), 7.08 (1H, brs) 6.80 (1H, d, \(J = 8.0\) Hz), 6.30 (1H, brs), 2.38 (3H, s); \(^{13}\)C NMR (100 MHz, CDCl\(_3\)) \(\delta\) 166.4, 146.8, 144.3, 139.4, 137.6, 133.8, 133.4, 129.7, 129.4, 129.1, 129.0, 127.0, 121.8, 118.7, 117.6, 21.3; \(^{11}\)B NMR (128 MHz, CDCl\(_3\)) \(\delta\) 30.2; IR (ATR) 3311, 1643, 1519, 1485, 740; HRESIMS Calcd. for C\(_{20}\)H\(_{18}\)BN\(_2\)O ([M+H]\(^+\)): 313.1507, Found: 313.1499.

Synthesis of Ter(o-phenylene)s via Iterative Suzuki-Miyaura Coupling (Scheme 1)

Synthesis of 5
A mixture of 3a (69.6 mg, 0.20 mmol), phenylboronic acid (29.3 mg, 0.24 mmol), Pd(OAc)$_2$ (2.24 mg, 0.01 mmol), and K$_3$PO$_4$ (84.8 mg, 0.40 mmol) in THF (0.4 ml) was stirred for 11 h at 50 °C. After being cooled to room temperature, the solvent was evaporated in vacuo. The coupling product 5 (55.1 mg, 92 %) was isolated by column chromatography on silica gel (hexane-AcOEt, 10:1 – chloroform). mp 187.0-189.0 °C; $^1$H NMR (400 MHz, DMSO-d$_6$) $\delta$ 8.99 (1H, s), 8.94 (1H, s), 7.94, (1H, dd, $J$ = 8.0 Hz, 1.6 Hz), 7.61 (1H, dd, $J$ = 7.2 Hz, 0.8 Hz), 7.54-7.40 (6H, m), 7.37-7.33 (2H, m), 7.29-7.25 (1H, m), 7.17 (1H, dd, $J$ = 8.0 Hz, 0.8 Hz), 7.06 (1H, ddd, $J$ = 8.4 Hz, 7.2 Hz, 1.2 Hz); $^{13}$C NMR (100 MHz, DMSO-d$_6$) $\delta$ 165.5, 145.3, 145.2, 142.5, 133.4, 133.1, 129.2, 128.7, 128.6, 128.2, 127.8, 127.0, 126.3, 120.7, 118.5, 117.9; $^{11}$B NMR (128 MHz, DMSO-d$_6$) $\delta$28.8; IR (ATR) 3311, 1647, 1517, 734; HRESIMS Calcd. for C$_{19}$H$_{16}$BN$_2$O ([M+H]$^+$): 299.1350, Found: 299.1343.

Hydrolysis of 5
To a solution of 5 (298 mg, 1.0 mmol) in THF (10 mL) was added HCl aq. (5N, 1.0 mL 5.0 mmol) at room temperature. The reaction mixture was stirred at room temperature for 20 h. After extraction with diethyl ether, the organic phase was dried over MgSO$_4$. Filtration and evaporation gave the 2-biphenylboronic acid. A portion of the material was used for cross coupling reaction without further purification.

General Procedure for Synthesis of 6$^{18}$
A mixture of aryl bromide (0.20 mmol), 2-biphenylboronic acid (47.5 mg, 0.24 mmol), Pd(OAc)$_2$ (2.24 mg, 0.01 mmol), SPhos (4.93 mg, 0.012 mmol) and K$_3$PO$_4$ (84.8 mg, 0.40 mmol) in THF (0.4 ml) was stirred for 20 h at 60 °C. After being cooled to room temperature, the solvent was evaporated in vacuo. The coupling product was isolated by column chromatography on silica gel (hexane-Et$_2$O).

Synthesis of 6a
According to the general procedure, a mixture of \( p \)-bromotoluene (34.0 mg), 2-biphenylboronic acid, Pd(OAc)\(_2\), SPhos and K\(_3\)PO\(_4\) in THF was heated. \( 6a \) (47.1 mg, 96\%) was isolated by column chromatography on silica gel (hexane-\( \text{Et}_2\)O, 40:1).

**Synthesis of 6b**

According to the general procedure, a mixture of \( p \)-bromoanisole (37.0 mg), 2-biphenylboronic acid, Pd(OAc)\(_2\), SPhos and K\(_3\)PO\(_4\) in THF was heated. \( 6b \) (50.2 mg, 96\%) was isolated by column chromatography on silica gel (hexane-\( \text{Et}_2\)O, 20:1).

**Synthesis of 6c**

According to the general procedure, a mixture of \( p \)-bromobenzotrifluoride (44.8 mg), 2-biphenylboronic acid, Pd(OAc)\(_2\), SPhos and K\(_3\)PO\(_4\) in THF was heated. \( 6c \) (58.5 mg, 98\%) was isolated by column chromatography on silica gel (hexane-\( \text{Et}_2\)O, 20:1).

**Synthesis of Quarter(naphthalene-2,3-diyl) via Iterative Suzuki-Miyaura Coupling (Scheme 2)**

**Synthesis of 8**
According to the general procedure (7.3), a mixture of 3k (39.8 mg, 0.1 mmol), 6-ethoxynaphthaleneboronic acid (25.9 mg, 0.12 mmol), Pd(OAc)$_2$ (1.12 mg, 0.005 mmol), and K$_3$PO$_4$ (42.4 mg, 0.2 mmol) in THF (0.2 ml) was stirred for 11 h at 50 °C. After being cooled to room temperature, the solvent was evaporated in vacuo. The coupling product 8 (39.9 mg, 92 %) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – chloroform). mp 228.8-231.2 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 8.23 (1H, s), 8.18-8.16 (1H, m), 7.99 (1H, s), 7.94-7.91 (3H, m), 7.77 (1H, d, $J$ = 9.2 Hz), 7.73 (1H, d, $J$ = 8.8 Hz), 7.62-7.54 (2H, m), 7.52-7.49 (1H, m), 7.43-7.38 (1H, m), 7.21-7.14 (3H, m), 7.09 (1H, ddd, $J$ = 8.0 Hz, 7.2 Hz, 0.8 Hz), 6.64 (1H, dd, $J$ = 0.8 Hz) 6.21 (1H, brs), 4.18 (2H, q, $J$ = 7.2 Hz), 1.50 (3H, q, $J$ = 7.2 Hz); $^{13}$C NMR (100 MHz, DMSO-$d_6$) δ 166.5, 156.6, 145.3, 142.2, 137.4, 134.0, 133.4, 133.2, 131.3, 129.5, 128.3, 127.9, 127.8, 127.7, 127.4, 127.1, 126.8, 126.4, 126.1, 120.7, 119.2, 118.5, 118.0, 106.4, 63.1, 14.6; $^{11}$B NMR (128 MHz, DMSO-$d_6$) δ 25.2; IR (ATR) 3230, 1668, 1512, 759; HRESIMS Calcd. for C$_{29}$H$_{24}$BN$_2$O$_2$ ([M+H]$^+$): 443.1925, Found: 443.1916.

**Hydrolysis of 8**

To a solution of 8 (950 mg, 2.15 mmol) in THF (22 mL) was added HCl aq. (5N, 2.2 mL 11.0 mmol) at room temperature. The reaction mixture was stirred at room temperature for 12 h. After extraction with chloroform, the organic phase was dried over MgSO$_4$. Filtration and evaporation gave the corresponding boroxine 9. A portion of the material was used for cross coupling reaction without further purification.

**Synthesis of 10**
A solution of 9 (44.5 mg, 0.13 mmol) and water (1.1 µL, 0.06 mmol) in THF (0.2 mL) was heated at 50 °C. After 30 min, to the solution was added 3k (39.8 mg, 0.1 mmol), Pd(OAc)$_2$ (1.12 mg, 0.005 mmol), and K$_3$PO$_4$ (42.4 mg, 0.2 mmol). The mixture was stirred for 15 h at 60 °C. After being cooled to room temperature, the solvent was evaporated in vacuo. The coupling product 10 (50.2 mg, 88 %) was isolated by column chromatography on Florisil® (hexane-AcOEt, 10:1 – chloroform). mp 169.8-172.3 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 8.17-8.11 (3H, m), 8.01-7.99 (2H, m), 7.93-7.90 (2H, m), 7.82 (1H, d, J = 8.0 Hz), 7.76 (1H, s), 7.65-7.52 (4H, m), 7.33-7.25 (2H, m), 7.20 (1H, d, J = 8.4 Hz), 7.10-7.06 (1H, m), 7.02-7.00 (1H, m), 6.94 (1H, d, J = 2.0 Hz), 6.89 (1H, dd, J = 8.8 Hz, 2.4 Hz), 6.84 (1H, dd, J = 8.4 Hz, 2.0 Hz), 6.37 (1H, brs), 6.18 (1H, d, J = 8.4 Hz), 5.41 (1H, brs), 4.11 (2H, q, J = 7.2 Hz), 1.47 (3H, q, J = 7.2 Hz); $^{13}$C NMR (100 MHz, CDCl$_3$) δ 165.9, 157.3, 144.3, 142.6, 139.5, 139.3, 135.5, 134.5, 133.6, 135.5, 133.2, 133.1, 132.9, 132.0, 130.2, 129.8, 129.5, 129.0, 128.8, 128.7, 128.2, 128.1, 128.0, 127.9, 127.4, 126.9, 126.5, 125.9, 121.5, 119.2, 118.5, 117.8, 106.1, 63.6, 15.0; $^{11}$B NMR (128 MHz, CDCl$_3$) δ 25.8; IR (ATR) 3402, 1660, 1485, 744; HRESIMS Calcd. for C$_{39}$H$_{30}$BN$_2$O$_2$([M+H]$^+$): 569.2395, Found: 569.2385.

Synthesis of 11

To a solution of 10 (103 mg, 0.18 mmol) in THF (1.8 mL) was added HCl aq. (5N, 0.18 mL 0.9 mmol) at room temperature. After the reaction was warmed to room temperature, the
reaction mixture was stirred at room temperature for 12 h. After extraction with chloroform, the organic phase was dried over MgSO₄. Filtration and evaporation gave the corresponding arylboronic acid. A portion of arylboronic acid was used for cross coupling reaction without further purification. A mixture of arylboronic acid (23.4 mg, 0.05 mmol), 2-bromonaphthalene (20.6 mg, 0.1 mmol), Pd(dba)₂ (0.56 mg, 2.5 μmol), SPhos (2.06 mg, 5.0 μmol) and K₃PO₄ (42.4 mg, 0.2 mmol) in 1,4-dioxane/H₂O (v/v = 10/1, 0.22 ml) was stirred for 24 h at 110 °C. After being cooled to room temperature, the solvent was evaporated in vacuo. The coupling product 11 (22.1 mg, 80 %) was isolated by column chromatography on silica gel (hexane-CH₂Cl₂, 10:1 – 5:1 – 4:1 – 2:1). mp 141.0-143.3 °C; ¹H NMR (400 MHz, CDCl₃) δ 8.22 (2H, s), 8.01 (2H, d, J = 8.0 Hz), 7.85-7.82 (2H, m), 7.67 (1H, d, J = 8.0 Hz), 7.62 (2H, d, J = 12.0 Hz), 7.60-7.50 (4H, m), 7.40 (1H, ddd, J = 8.0 Hz, 6.8 Hz, 1.2 Hz), 7.27 (1H, ddd, J = 8.0 Hz, 6.8 Hz, 1.2 Hz), 7.23 (1H, d, J = 8.4 Hz), 7.12-7.09 (2H, m), 6.97 (1H, s), 6.94 (1H, s), 6.93 (1H, s), 6.76 (1H, d, J = 1.2 Hz), 6.66 (1H, dd, J = 8.4 Hz, 1.2 Hz), 6.63-6.60 (2H, m), 4.18-4.12 (2H, m), 1.51 (3H, t, 6.8 Hz); ¹³C NMR (100 MHz, CDCl₃) δ 156.9, 139.8, 139.7, 139.5, 139.4, 138.5, 136.3, 133.3, 133.2, 133.2, 133.0, 132.9, 132.8, 131.8, 130.9, 129.7, 129.1, 129.0, 128.8, 128.3, 128.2, 128.1, 128.0, 127.9, 127.8, 127.8, 127.5, 127.3, 126.5, 126.3, 126.2, 125.6, 125.5, 125.4, 118.6, 106.0, 63.5, 15.0; IR (ATR) 3055, 1603, 850, 744; HREIMS Calcd. for C₄₂H₃₀O (M⁺): 550.2297, Found: 550.2297.

References and Notes
Chapter 4


List of Publications

Chapter 1
Easily Attachable and Detachable ortho-Directing Agent for Arylboronic Acids in Ruthenium-Catalyzed Aromatic C–H Silylation
Hideki Ihara, Michinori Suginome

Chapter 2
Ruthenium-Catalyzed C–H Silylation of Methylboronic Acid Using a Removable \(a\)-Directing Modifier on the Boron Atom
Hideki Ihara, Akinori Ueda, Michinori Suginome

Chapter 3
Anthranilamide: A Simple, Removable Ortho-Directing Modifier for Arylboronic Acids Serving also as a Protecting Group in Cross-Coupling Reactions
Hideki Ihara, Masashi Koyanagi, Michinori Suginome

Chapter 4
Anthranilamide-Masked \(o\)-Iodoarylboronic Acids as Coupling Modules for Iterative Synthesis of ortho-Linked Oligoarenes
Masashi Koyanagi, Nils Eichenauer, Hideki Ihara, Takeshi Yamamoto, Michinori Suginome
*Chem. Lett.* **2013**, *42*, 541-543.