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# (Z)- $\alpha$ -Boryl-crotylboron reagents via Z-selective alkene isomerization and application to stereoselective syntheses of (E)- $\delta$ -boryl-syn-homoallylic alcohols<sup>†</sup>

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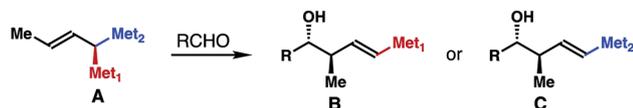
Stereoselective synthesis of (Z)- $\alpha$ -boryl-crotylboronate is developed. Ni-catalyzed Z-selective alkene isomerization of  $\alpha$ -boryl substituted homoallylboronate provided the targeted (Z)-crotylboronate with high selectivity. Stereoselective addition of the novel crotylboron reagent to aldehydes gave (E)- $\delta$ -boryl-substituted syn-homoallylic alcohols with excellent diastereoselectivities. The vinyl boronate unit in the products can be directly used for a subsequent C–C bond-forming transformation as illustrated in the synthesis of the C<sub>1–7</sub> fragment of the natural products nannocystin A and nannocystin Ax.

## Introduction

1,1-Bismetallc crotylation reagents, such as **A** (Scheme 1), are an important class of molecules that have recently attracted considerable attention. In contrast to the traditional crotyl organometallics,<sup>1</sup> addition of these 1,1-bismetallc crotylation reagents to carbonyl compounds (*e.g.*, aldehydes) will produce homoallylic alcohol products (*i.e.*, **B** or **C**) with a functionalized alkene group that can directly engage in a C–C bond-formation event, for example, a cross-coupling reaction. In the case of Met<sub>1</sub>  $\neq$  Met<sub>2</sub>, reagent **A** is chiral and reactions of carbonyl compounds with **A** typically proceed through chirality transfer. The enantiomeric excess of the alcohol products will largely depend on the optical purity of the starting agent **A**. Additionally, depending on the different electronic properties and reactivities of the metal substituents, either  $\delta$ -substituted homoallylic alcohol **B** or **C** can be produced selectively. Owing to their versatile reactivities, several types of 1,1-bismetallc crotylation reagents have been developed in the past three decades,

including B/Si,<sup>2</sup> B/Sn,<sup>3</sup> Si/Sn,<sup>4</sup> Si/Si,<sup>5</sup> and Sn/Sn-substituted crotylation reagents.<sup>6</sup> Importantly, many of these reagents have been successfully applied to the syntheses of bioactive natural products, which highlights the synthetic utilities of these reagents.<sup>7</sup>

One subset of 1,1-bismetallc crotylation reagents is  $\alpha$ -boryl substituted crotylboronates **2a** and **2b** (Scheme 2; Met<sub>1</sub>, Met<sub>2</sub> = Bpin). An attractive feature of boronates **2** is that they are achiral, and their reactions with carbonyl compounds should proceed by way of the well-established, six-membered transition state<sup>8</sup> to give  $\delta$ -boryl-substituted homoallylic alcohols. In spite of their apparent synthetic potential, the synthesis of (*E*)-reagent **2a** has only been disclosed recently.<sup>9</sup> The Murakami<sup>9a,b</sup> and Cho<sup>9c</sup> groups independently showed that (*E*)-crotylboronate **2a** can be generated *via* transition-metal catalyzed alkene transposition from the homoallylic bisboronate precursor **1** (Scheme 2). Addition of **2a** to aldehydes provided  $\delta$ -boryl-substituted (*Z*)-*anti*-homoallylic alcohols (*anti*-1,2-oxaborinan-3-enes **D** after intramolecular cyclization) with high selectivities. On the other hand, reactions of



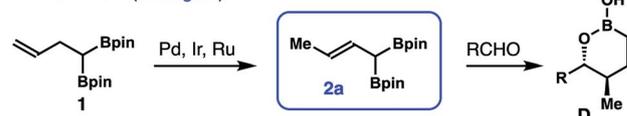
Scheme 1 1,1-Bismetallc crotylation reagents.

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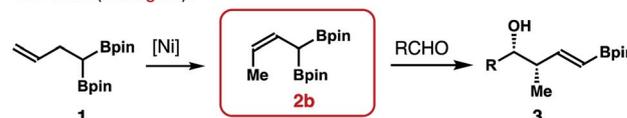
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Previous work (*E*-reagent):



This work (*Z*-reagent):

Scheme 2 Recent development of  $\alpha$ -boryl substituted crotylboron reagents.

(*Z*)-reagent **2b** with aldehydes should form  $\delta$ -boryl-substituted (*E*)-*syn*-homoallylic alcohols **3** (Scheme 2) that would be highly useful in the construction of polyketide natural products. However, methods that could efficiently produce reagent **2b** are still not available. Therefore, the development of methods that can allow access to such a reagent and  $\delta$ -boryl-substituted (*E*)-*syn*-homoallylic alcohols **3** would be desirable. With our continuing efforts in developing novel allylboron reagents,<sup>10</sup> we have developed and reported herein stereoselective synthesis of (*Z*)- $\alpha$ -boryl crotylboronate **2b** and studies on crotylboration of aldehydes with reagent **2b**.

## Results and discussion

We envisaged a *Z*-selective alkene isomerization approach to access (*Z*)- $\alpha$ -boryl crotylboronate **2b** from homoallylic bisboronate precursor **1** given its ready availability (Scheme 2). It has been shown by Hilt and co-workers that terminal alkenes can undergo transition metal-catalyzed olefin isomerization to give (*Z*)-2-alkene isomers with moderate to high selectivity.<sup>11</sup> Inspired by their studies, we decided to pursue a Ni-catalyzed isomerization of 1,1-di(boryl)but-3-ene **1**<sup>12</sup> to prepare (*Z*)-crotylboronate reagent **2b**. As shown in Table 1, in the presence of 10 mol% of NiCl<sub>2</sub> and dppp, 5 mol% Ph<sub>2</sub>PH, and 20 mol% of Zn and ZnI<sub>2</sub>, isomerization of homoallylboronate **1** did not form any product in CH<sub>2</sub>Cl<sub>2</sub> at -20 °C for 24 h (entry 1, Table 1). However, when NiCl<sub>2</sub> was replaced by NiBr<sub>2</sub>, the isomerization reaction occurred to give a 5 : 1 inseparable mixture of **2b** and **2a** in 70% yield, favouring the *Z*-isomer **2b** (entry 2). Encouraged by the initial success, reactions with several Ni catalysts were examined next. The reaction with Ni(OAc)<sub>2</sub> as the catalyst gave

a 2 : 1 mixture of **2b** and **2a** in low yield (entry 3). An improved *Z*/*E* ratio (6 : 1) was achieved when Ni(acac)<sub>2</sub> was employed as the catalyst (entry 4). A similar *Z*/*E* ratio (7 : 1) was obtained with NiCl<sub>2</sub>·glyme as the catalyst, albeit in a low yield (entry 5). Intriguingly, reactions with preformed Ni catalysts, Ni(dppp)Cl<sub>2</sub> or Ni(dppe)Cl<sub>2</sub>, gave inferior results (entries 6 and 7). When NiBr<sub>2</sub>·diglyme and dppp were used as the catalyst/ligand combination, a 7 : 1 mixture of **2b** and **2a** was obtained in 58% yield (entry 8). Gratifyingly, when 1,2-dichloroethane was used as the solvent, isomerization of homoallylic bisboronate **1** gave an excellent *Z*/*E* ratio (**2b** : **2a** > 20 : 1) in the presence of NiBr<sub>2</sub>·diglyme and dppp. Reagent **2b** was isolated in 70% yield (entry 9). A 2 mmol-scale reaction produced (*Z*)-crotylboronate **2b** in 74% yield (entry 10).

After obtaining (*Z*)- $\alpha$ -boryl-crotylboronate **2b**, we conducted subsequent studies on aldehyde crotylboration with reagent **2b**. In initial experiments, treatment of benzaldehyde with 1.3 equiv. of reagent **2b** in toluene for 12 h provided (*E*)- $\delta$ -boryl-*syn*-homoallylic alcohol **3a** in 90% yield. The olefin geometry in product **3a** was assigned as *E* based on <sup>1</sup>H NMR analysis of the coupling constant of olefinic protons. The stereochemical relationship of **3a** was assigned as *syn* after comparing to the literature data.<sup>9a,b</sup>

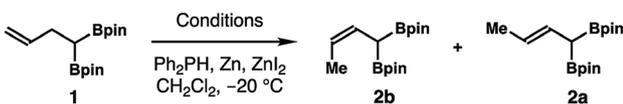
The scope of an aldehyde that participates in this reaction was explored, and the results are summarized in Scheme 3. In general, the reaction worked well with a broad spectrum of aldehydes, including aromatic, heteroaromatic and  $\alpha,\beta$ -unsaturated aldehydes. Reactions of **2b** with aromatic aldehydes at ambient temperature in toluene gave alcohol products **3a–h** in 78–94% yields. Alkenyl or alkynyl aldehydes reacted with **2b** to furnish homoallylic alcohols **3i–k** in 58–91% yields. Importantly, a variety of heteroaromatic aldehydes also participated in the reaction to provide alcohols **3l–r** in 67–91% yields. Formation of other isomeric products was not observed in any of these reactions.

Reactions of aliphatic aldehydes with boronate **2b** were examined next. As shown in Scheme 4, aliphatic aldehydes including primary alkyl aldehydes,  $\beta$ -branched alkyl aldehydes, and secondary alkyl aldehydes all reacted with reagent **2b** in toluene at ambient temperature to give homoallylic alcohols **3s–z** in 51–92% yield with excellent diastereoselectivities and *E*/*Z* selectivities in all cases.

The alkene isomerization and crotylation reaction sequence can be conducted in one pot. As illustrated in Scheme 5, alkene isomerization in the presence of benzaldehyde at -20 °C for 24 h gave product **3a** in 64% yield as a single isomer. Detectable amounts of other isomers were not formed from this one-pot procedure.

The high *E*-selectivity of this reaction can be rationalized by the following transition state analysis. Among the two competing transition states (**TS-1** and **TS-2**; Scheme 6) that lead to the formation of products **3** and **4**, **TS-2** suffers from a severe A<sup>1,3</sup> allylic strain<sup>13</sup> between the pseudo-axially oriented -Bpin group and the methyl group (shown in red in **TS-2**). In contrast, the A<sup>1,3</sup> allylic strain in **TS-1** is only between the methyl group and the H atom (shown in light blue in **TS-1**). Although a *gauche* interaction may also be involved in **TS-1**, it is apparent that

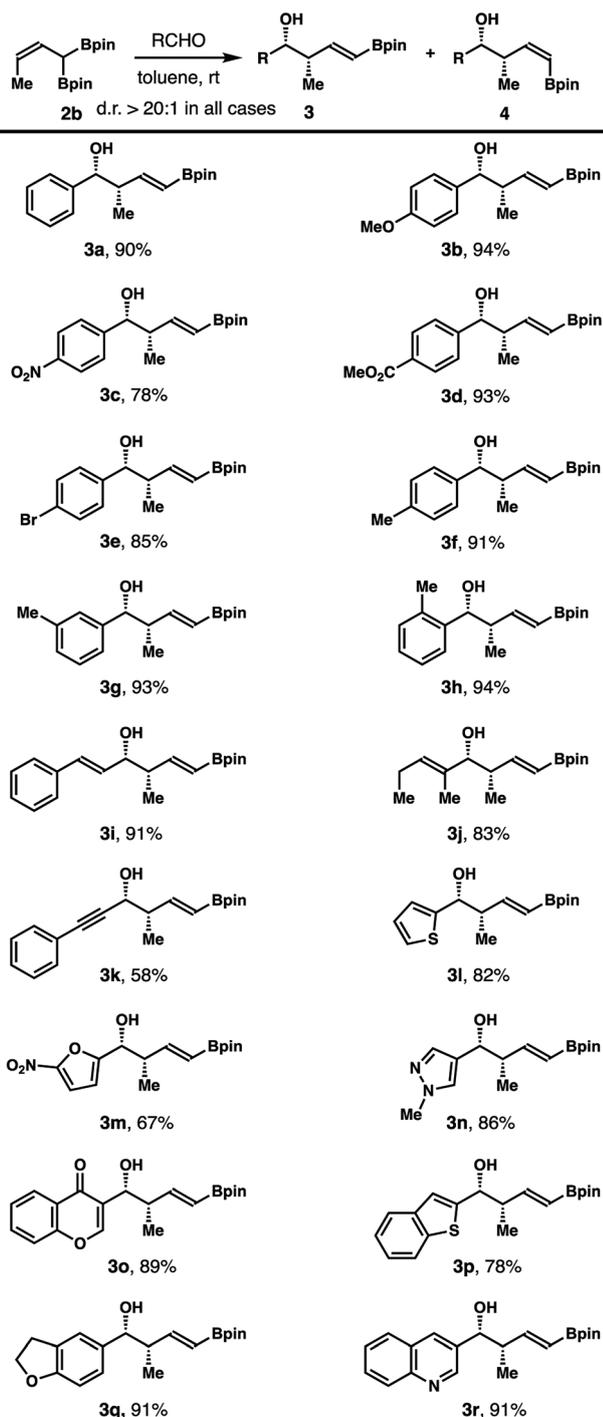
Table 1 Evaluation of reaction conditions for the synthesis of (*Z*)- $\alpha$ -boryl crotylboronate **2b**<sup>a</sup>



Entry	Conditions	<b>2b</b> : <b>2a</b> <sup>b</sup>	Yield <sup>c</sup> (%)
1	NiCl <sub>2</sub> , dppp	N.D.	N.R.
2	NiBr <sub>2</sub> , dppp	5 : 1	70
3	Ni(OAc) <sub>2</sub> , dppp	2 : 1	38
4	Ni(acac) <sub>2</sub> , dppp	6 : 1	76
5	NiCl <sub>2</sub> ·glyme, dppp	7 : 1	36
6	Ni(dppp)Cl <sub>2</sub>	3 : 1	56
7	Ni(dppe)Cl <sub>2</sub>	3 : 1	64
8	NiBr <sub>2</sub> ·diglyme, dppp	7 : 1	58
9 <sup>d</sup>	NiBr <sub>2</sub> ·diglyme, dppp	>20 : 1	70
10 <sup>e</sup>	NiBr <sub>2</sub> ·diglyme, dppp	>20 : 1	74

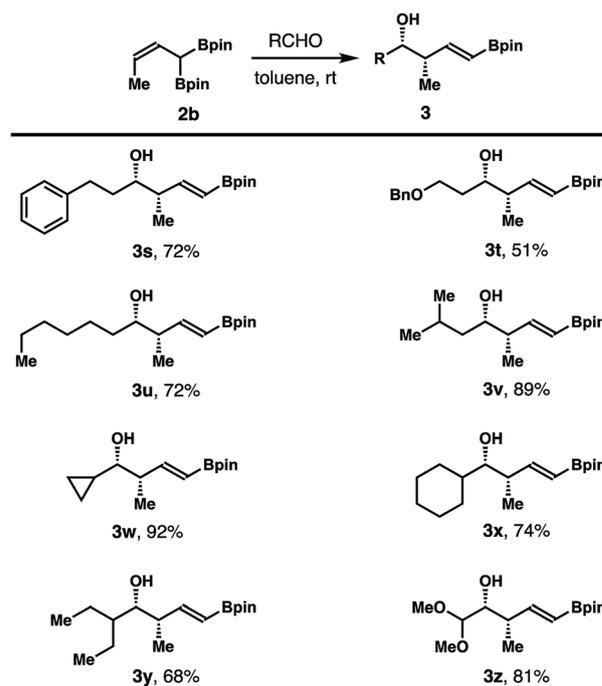
<sup>a</sup> Reaction conditions: boronate **1** (0.2 mmol, 1.0 equiv.), catalyst (10 mol%), ligand (10 mol%), Ph<sub>2</sub>PH (5 mol%), Zn (20 mol%), ZnI<sub>2</sub> (20 mol%), CH<sub>2</sub>Cl<sub>2</sub> (0.5 mL), -20 °C. <sup>b</sup> The *Z*/*E* ratios were determined by <sup>1</sup>H NMR analysis of the crude reaction products. <sup>c</sup> Yields of isolated products are listed. <sup>d</sup> DCE was used as the solvent. <sup>e</sup> The reaction was conducted on a 2 mmol scale in DCE. dppp: 1,3-bis(diphenylphosphino)propane; dppe: 1,2-bis(diphenylphosphino)ethane.



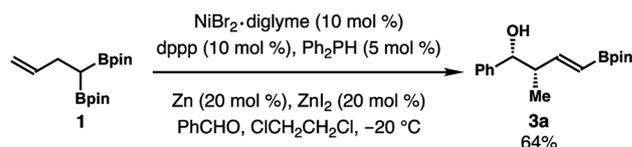


Scheme 3 Scope of aromatic, heteroaromatic and  $\alpha,\beta$ -unsaturated aldehydes for the reactions with (*Z*)- $\alpha$ -boryl-crotylboronate **2b**. (a) Reaction conditions: crotylboronate **2b** (0.13 mmol, 1.3 equiv.), aldehyde (0.1 mmol, 1.0 equiv.), toluene (0.3 mL), rt. (b) The diastereoselectivities and *E/Z* selectivities were determined by  $^1\text{H}$  NMR analysis of the crude reaction products. (c) Yields of isolated products are listed.

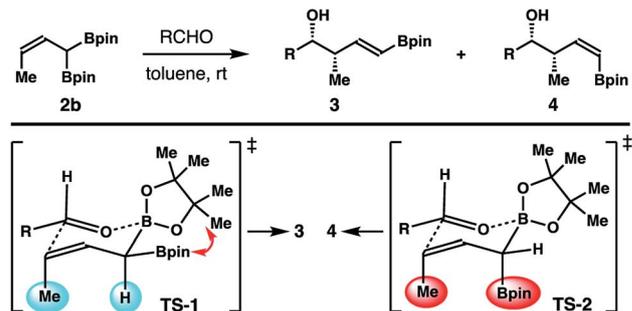
the  $A^{1,3}$  allylic strain between the -Bpin and methyl groups is severe enough to overcome the *gauche* interactions. As a result, crotylboration of aldehydes with reagent **2b** proceeded through



Scheme 4 Scope of aliphatic aldehydes for the reactions with (*Z*)-crotylboronate **2b**. (a) Reaction conditions: allyl boronate **2b** (0.13 mmol, 1.3 equiv.), aldehyde (0.1 mmol, 1.0 equiv.), toluene (0.3 mL), rt. (b) The diastereoselectivities and *E/Z* selectivities were determined by  $^1\text{H}$  NMR analysis of the crude reaction products. (c) Yields of isolated products are listed.



Scheme 5 One-pot alkene isomerization and aldehyde allylboration.

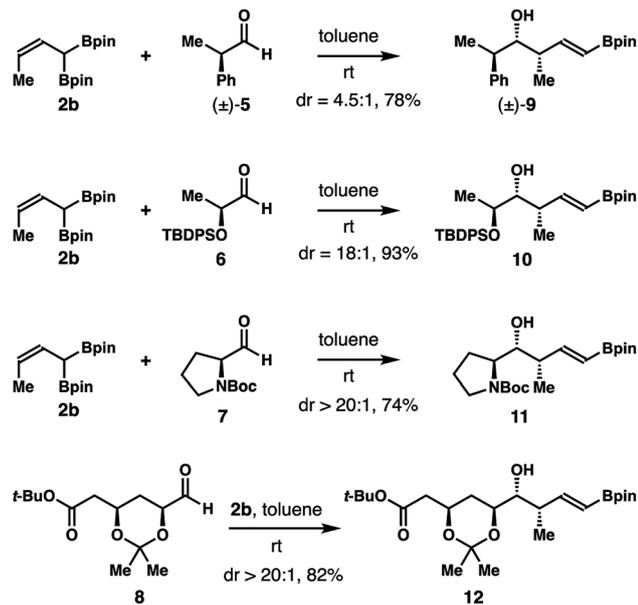


Scheme 6 Transition state analyses for selective formation of homoallylic alcohols **3** from crotylboronate **2b**.

the lower energy transition state **TS-1** to give product **3** with high selectivity.

Studies on reactions of crotylboron reagent **2b** with several chiral aldehydes (**5**–**8**) were also conducted. As illustrated in Scheme 7, the reaction of crotylboronate **2b** with racemic 2-

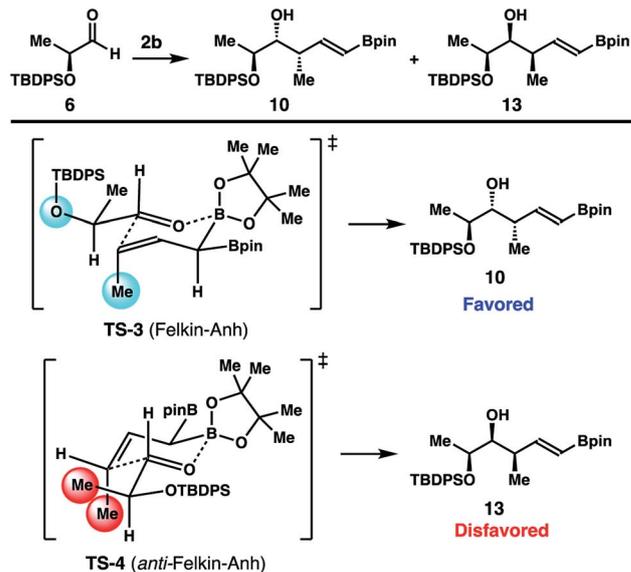




Scheme 7 Diastereoselective crotylboration of chiral aldehydes with (Z)-crotylboronate **2b**.

phenylpropionaldehyde (**5**) gave product **9** in 78% yield with 4.5 : 1 diastereoselectivity. The enantioenriched, lactate-derived aldehyde **6** reacted with reagent **2b** to provide an 18 : 1 mixture, with isomer **10** as the major product in 93% yield. Addition of reagent **2b** to *N*-Boc-*L*-proline (**7**) generated alcohol **11** in 74% yield with excellent diastereoselectivity ( $dr > 20 : 1$ ). Finally, the reaction of reagent **2b** with a more advanced chiral, nonracemic aldehyde **8** delivered isomer **12** as the only product ( $dr > 20 : 1$ ). Homoallylic alcohol **12** was obtained in 82% yield after purification. The stereochemistry of **9** and **11** was assigned by comparing to the literature data after protodeboronation.<sup>14</sup> The absolute configuration of the newly formed secondary hydroxyl groups of **10** and **12** was assigned by Mosher ester analysis.<sup>15</sup> Importantly, the mild reaction conditions and high diastereoselectivities of these reactions with chiral aldehydes augur well for further application of reagent **2b** in the syntheses of complex natural products and medicinally relevant agents.

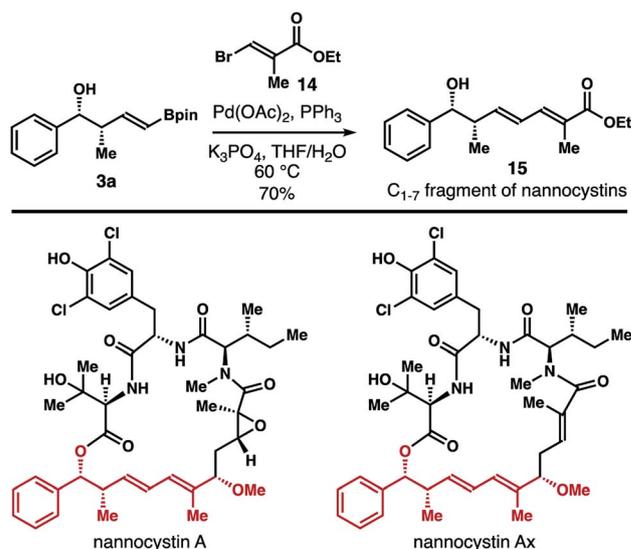
A stereochemical model for the high diastereoselectivities in the reactions with enantioenriched aldehydes **6–8** is delineated in Scheme 8. The reaction of aldehyde **6** with reagent **2b** could proceed through two potential transition states (**TS-3** and **TS-4**; Scheme 8) to produce two alcohol products, **10** and **13**. **TS-3** operates under Felkin–Anh<sup>16</sup> control to give homoallylic alcohol **10**, while the competing transition state **TS-4** is under *anti*-Felkin–Anh control to furnish the diastereomeric alcohol product **13**. Upon close examination of the two transition states, it is apparent that **TS-4** suffers from an unfavourable *gauche*-pentane interaction<sup>17</sup> between the methyl group of aldehyde **6** and the methyl group of reagent **2b** (shown in red in **TS-4**). In contrast, **TS-3** operates under favourable Felkin–Anh control and only with minimal *gauche*-pentane interactions (shown in light blue in **TS-3**) between the methyl group of reagent **2b** and the oxygen atom of aldehyde **6** (with the large TBDPS group pointing away from the methyl group of reagent **2b**). Therefore,



Scheme 8 Transition state analyses for the reaction of chiral aldehyde **6** with crotylboronate **2b**.

the reaction with aldehyde **6** proceeded through the favourable transition state, **TS-3**, to give product **10** with high diastereoselectivity. Based on this analysis, when the substituent of the aldehyde substrate is sterically much more demanding than a methyl group (*e.g.*, aldehydes **7** and **8**), **TS-4** is more destabilized relative to **TS-3** because of more severe *gauche*-pentane interactions. Consequently, reactions with these aldehydes should generate Felkin–Anh controlled products with higher selectivities. This prediction is fully consistent with the results obtained from the reactions of aldehydes **7** and **8**.

The products (*e.g.*, **3**) generated from the reaction of reagent **2b** with aldehydes contain a vinyl boronate group, which can be



Scheme 9 Synthesis of the C<sub>1–7</sub> fragment of nannocystin A and nannocystin Ax.



used directly for a variety of subsequent transformations.<sup>18</sup> To further demonstrate the synthetic utility of this method, synthesis of the C<sub>1-7</sub> fragment of the natural products nannocystin A and nannocystin Ax was carried out.<sup>19,20</sup> As shown in Scheme 9, Pd-catalyzed Suzuki coupling<sup>21</sup> of free alcohol **3a** with vinyl bromide **14**<sup>22</sup> provided compound **15**, the C<sub>1-7</sub> fragment of nannocystin A and nannocystin Ax, in 70% yield (prepared in two steps from commercially available benzaldehyde).

## Conclusions

In summary, we developed a Ni-catalyzed, (*Z*)-selective olefin isomerization approach to synthesize a novel (*Z*)- $\alpha$ -borylcrotylboron reagent **2b**. Under optimized conditions, boronate **2b** was obtained in good yield with exclusive (*Z*)-selectivity. Subsequent allylboration of aldehydes with reagent **2b** gave (*E*)- $\delta$ -boryl-*syn*-homoallylic alcohols **3** in high yields with excellent diastereoselectivities. Reactions with several enantioenriched aldehydes proceeded under Felkin-Anh control to give homoallylic alcohol products with high diastereoselectivities. The vinyl boronate in products **3** can be directly used for subsequent C–C bond-forming transformations as illustrated in the synthesis of the C<sub>1-7</sub> fragment of the natural products nannocystins A and Ax. Studies on asymmetric crotylation using reagent **2b** are currently on-going.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

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