New Enantiomerically Pure Allylboronic Esters in Allyl Additions: Synthesis and NMR Investigation of Intermediates

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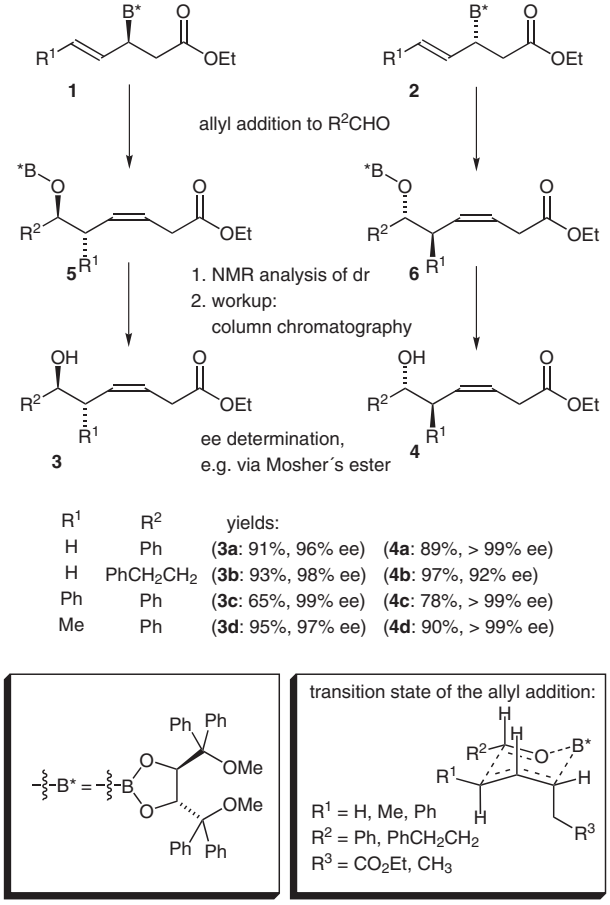
Dedicated to Professor Dr. Steven V. Ley on the occasion of his 60th birthday

Abstract: Enantiomerically pure allylboronic esters **1** + **2** with a stereogenic center α to the boron moiety can be obtained by a sigmatropic rearrangement of boron containing allyl alcohols. Allyl additions with the new reagents are highly selective, which was shown via the direct measurement of the diastereoisomeric ratio of the intermediates **5** + **6** by characteristic NMR chemical shifts. The observations are not limited to ester containing reagents, but holds also true for hydrocarbon side-chains (e.g. in **11** + **12**) that were readily obtained by reducing the ester.

Key words: spectroscopy, allylations, boron, stereoselectivity

One of the key reactions in organic synthesis is the allyl addition, especially using allylboronic esters; regularly homoallylic alcohols are conveniently formed in high yield and enantiomeric excess.[1–6] Reagents having a stereogenic center in the position α to the boronic ester are less often used since they are more difficult to prepare in enantiomerically pure form.[7–14] We have recently demonstrated that highly stable reagents of the general type **1** or **2** are readily available via a Johnson rearrangement of the corresponding boron-substituted allyl alcohols.[15–17] The derivatives are easy to handle and store, and add highly selectively to a number of aldehydes giving either homoallylic alcohol **3** or **4** with the enantiomeric excess ranging from 92 to >99% (Scheme 1). The formation of the *Z*-double bond and the configuration of the newly formed stereogenic centers were unambiguously proven by means of chemical correlation. The results could also be rationalized by a transition state as shown in Scheme 1 – the substituent in position α to boron is preferentially axial – which is in full agreement with a previous report by Hofmann and Weidmann.[7]

A drawback of the procedure was the fact that the enantiomeric excess of homoallylic alcohols was regularly determined – as it is common practice – by forming diastereoisomeric Mosher ester[18,19] (when direct methods fail) and thus only indirectly establishing the stereochemical outcome of the transformation. Obviously, there are two problems associated with the approach: A diastereomeric discrimination of the ester formation must be ruled out and, more importantly, the hydrolysis of the intermediate boric esters (in our case **5** and **6**) must occur with similar rates. In many cases this might not be a problem; however, occasionally we observed a rate difference that would lead to incorrect results, even when direct methods to determine the enantiomeric excess were used. An obvious solution to the problem would be the utilization of the formed diastereoisomeric intermediates **5** and **6** that should show distinct differences in their NMR spectra. Hence we decided to start a NMR investigation of the reaction before work-up and especially chromatographic separation.



Scheme 1 Allyl additions of **1** or **2**.

First, we investigated the most simple derivatives **5a** and **6a** (Figure 1) and found that almost all signals in the proton NMR (500 MHz) show distinct differences in the

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chemical shift. Generally, the most telling signals correspond to the proton of the newly formed stereogenic center (6-H) and also the adjacent protons (5-H). However, the 5-H protons can usually not be used to determine the diastereomeric ratio since the multiplicity of the signals make the integration imprecise. It is interesting to note that also signals of relatively remote groups show an impressive difference in chemical shifts for the two diastereoisomers. At this point it can be speculated whether the carbonyl group of the ester moiety is coordinated to the electrophilic boron. Nevertheless, the most important result can be observed when comparing the spectra in the region around 6-H: within the accuracy of the NMR method, neither of the diastereoisomers **5a** or **6a** is contaminated with the other!

We were pleased to find that the observation was not singular. As a matter of fact it was rather general, independent of the aldehyde (Figure 2; diastereoisomers **5b** and **6b**) or the kind of reagent (diastereoisomers **5c** + **d** and **6c** + **d**) used. It is interesting to note that the Δ ppm value is diagnostic and the relative shifts are generally showing the same trend. The only exceptions are the 5-H protons of compounds **5c** and **6c** with the phenyl group obviously inducing a different conformation and thus influencing the magnetic environment. Both 5,6-disubstituted derivatives **5c** + **d** and **6c** + **d** are most conveniently interpreted, because of the reduced multiplicity: The 6-H protons (e.g. in **5c** and **6c**) or even the 5-Me group in **5d** and **6d** give simple doublets that allow a reliable determination of the diastereoisomeric ratio. It should be noted that for convenience in all cases the arithmetic means of diastereotopic protons were used in the tables in Figures 1 and 2 since the configuration of the individual protons could not be established.

It was mentioned above that the ester group might influence the conformation of the intermediates. Furthermore, one could speculate whether the group is actually essential for the high selectivity of the allyl addition. To prove the generality of the concept, it would be essential to remove any group that would be able to coordinate to the boron moiety. Consequently, the esters **1a** and **2a** were used as starting materials for the realization of the task (Scheme 2). Reduction with diisobutylaluminum hydride (DIBAL-H) gave the corresponding alcohols **7** and **8** in high yield (92 and 94%, respectively), without touching the boron moiety. Activation of the alcohols as methylsulfonates **9** and **10** (95 and 93%, respectively) allowed the consecutive reduction with super hydride furnishing the allylboronic esters **11** and **12** (68% and 74%, respectively) with an ethyl side-chain. All boron derivatives were sta-

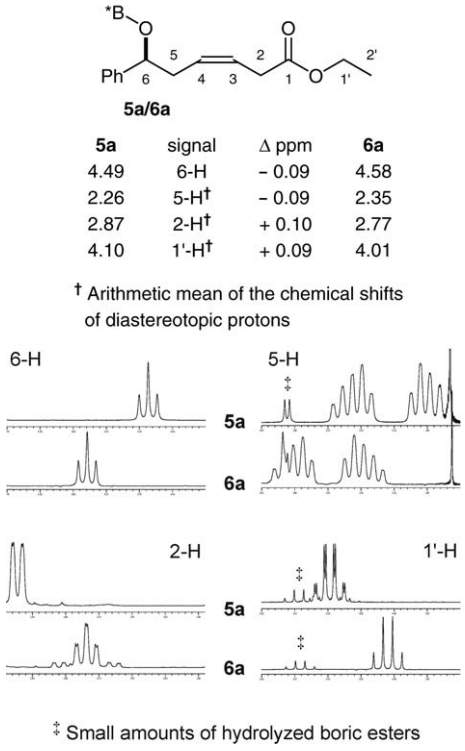


Figure 1 Characteristic NMR data of diastereoisomeric boric esters **5a** and **6a**.

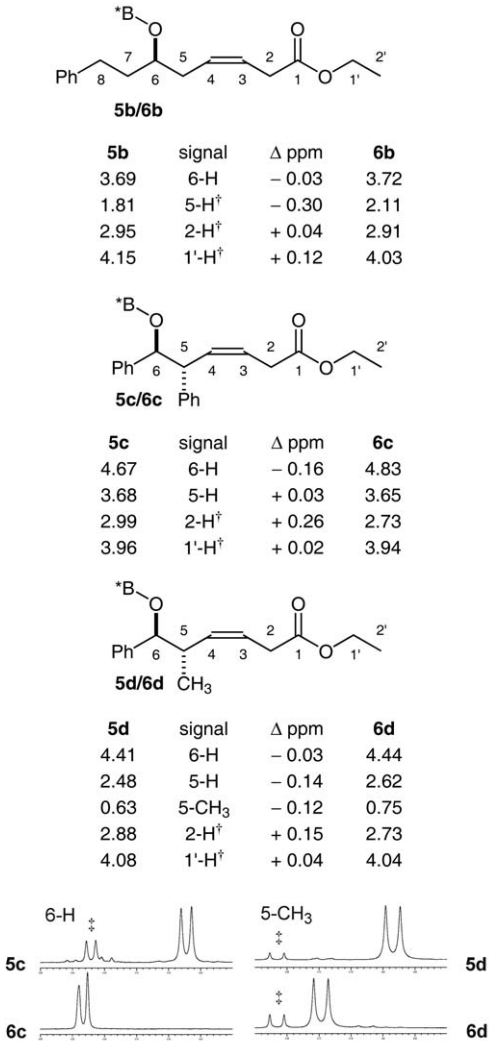
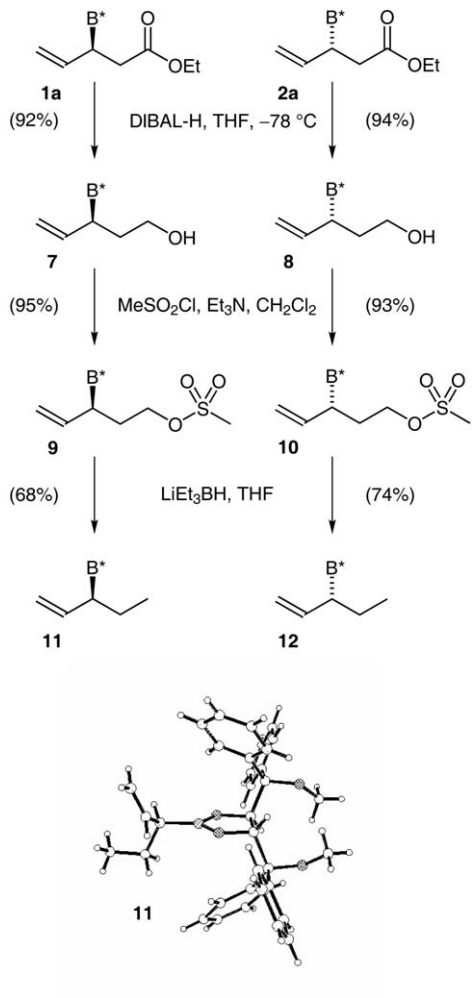


Figure 2 Characteristic NMR data of diastereoisomeric boric esters **5b–d** and **6b–d**; explanations for symbols used, see Figure 1.

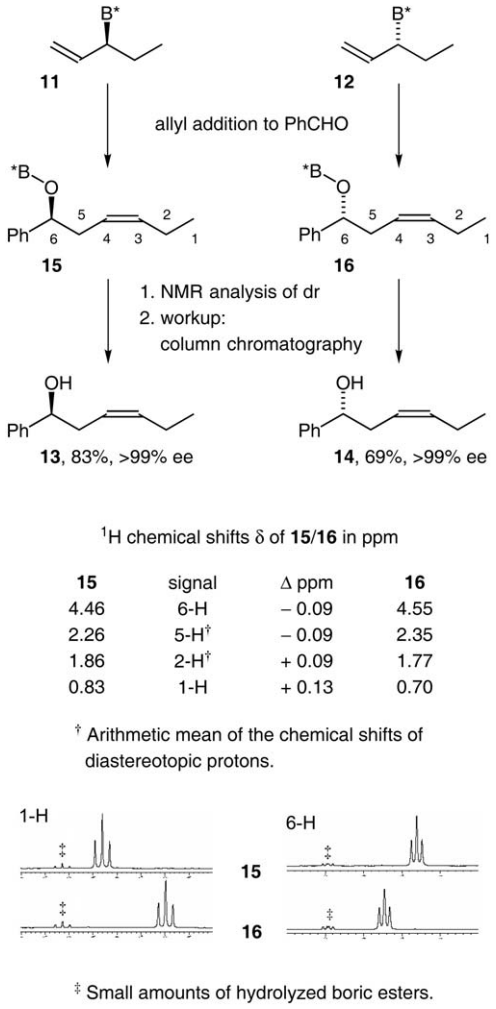
ble, could easily be purified and were hence isolated in microanalytically pure form. Again, the configuration of the two diastereoisomeric series could be confirmed by the NMR data that show the same characteristic chemical shift differences as previously observed, e.g. for **1a** and **2a**. Furthermore, the stereochemical integrity was unambiguously verified by an X-ray crystallographic analysis of boronic ester **11**.[20]

The new reagents **11** and **12** were tested by using benzaldehyde, thus leading to the known homoallylic alcohols **13** (83%) and **14** (69%) (Scheme 3).[21,22] The NMR analysis of the intermediate boric esters **15** and **16** was in full agreement with the previous observations: Various protons proved to be diagnostic and showed a distinct difference in both diastereoisomers. Especially useful were protons 1-H (Δ ppm: +0.13) and 6-H (Δ ppm: –0.09); again the respective other diastereoisomer could not be detected (ee >95%). The results were independently validated by an HPLC and GC investigation of the alcohols **13** and **14** on chiral stationary phases and the more precise values could be determined (>99% and >99% ee, respectively). The observation underlines a) that characteristic NMR traces are a valuable general tool to follow this type of diastereoselective allylation and b) that there is no limitation to reagents bearing a carboxylic ester side-chain: Both the analytical tool remains and the selectivity is high for the addition step. We are currently trying to further extend the scope of the method, seeking for other alternative reagents. It should be noted that in all cases we can obtain either enantiomer from one given auxiliary.

Finally, it was shown that the approach can potentially be extended to generally determine the enantiomeric excess of secondary alcohols. In a preliminary experiment, the commercially available enantiomers of substituted propargylic alcohols **17** and **18** were esterified to boric esters **19** and **20**, respectively, by stirring the alcohols in $CDCl_3$ at room temperature with an excess of boric acid **21**[17] (Figure 3). Again, the diastereoisomeric derivatives show different NMR chemical shifts, especially for the protons attached to the stereogenic center (Δ ppm: –0.10 for **19a**/**20a** and +0.04 for **19b**/**20b**), but also – and this will sometimes prove more practical for analytical purposes – for more remote groups (e.g. the CH_3 group – 1-H – in **19b**/**20b**; Δ ppm: +0.11). Obviously, direct methods will al-



Scheme 2 Transformation of esters **1** and **2**; X-ray crystallographic analysis of **11**.[20]



Scheme 3 Allyl addition of **11** and **12** to benzaldehyde and representative NMR data of the intermediates **15** and **16**.

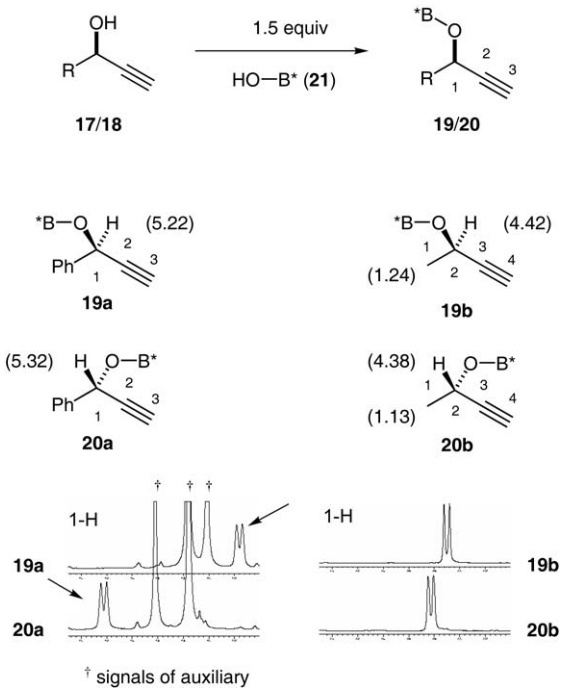


Figure 3 Synthesis and NMR data of boric esters **19** and **20**.

ways be superior to the approach presented; however, should these fail, diastereoisomeric boric esters might be a valuable alternative.

In summary, we did describe the synthesis of a new pair of allylation reagents **11** and **12** by a convenient sequence starting from the known, diastereoisomerically pure boron derivatives **1** and **2**. The high yields and selectivities observed for the consecutive allylation were thus not limited to reagents bearing a carboxylic ester group. Furthermore, in view of potential problems occurring during the investigation of the stereochemical course of the addition using indirect methods, a reliable direct NMR approach was presented. By analyzing the intermediate boric esters, erroneous data for a transformation can be omitted. While it is especially practical for allyl additions, it might also be extended for indirectly measuring the enantiomeric excess of secondary alcohols in general.

The reactions were carried out by using standard Schlenk techniques under dry N_2 with magnetic stirring. Glassware was oven-dried at 120 °C overnight. Solvents were dried and purified by conventional methods prior to use; THF was freshly distilled from sodium/benzophenone. Common solvents for chromatography (PE, EtOAc) were distilled prior to use; PE refers to a fraction with a boiling point between 40–60 °C. Flash column chromatography was performed on silica gel 60, 0.040–0.063 mm (230–400 mesh). TLC (monitoring the course of the reactions) was performed on precoated plastic sheets (Polygram® SIL G/UV$_{254}$, Macherey–Nagel) with detection by UV (254 nm) or by coloration with cerium molybdenum solution [phosphomolybdic acid (25 g), $Ce(SO_4)_2 \cdot H_2O$ (10 g), conc. H_2SO_4 (60 mL), H_2O (940 mL)]. Preparative medium pressure liquid chromatography (MPLC) was performed with a Labomatic pump (MD80/100), a packed column (39 × 400 mm or 23 × 250 mm), LiChroprep, Si60 (15–25 μm) and UV-detector (254 nm). HPLC was performed on a Pharmacia device equipped with a CHIRALCEL OD column. ^{1}H and ^{13}C NMR spectra were recorded at 20 °C in $CDCl_3$ on a Bruker ARX 300/500 spectrometer. Chemical shifts are given in ppm relative to TMS as internal standard (^{1}H) or relative to the resonance of the solvent (^{13}C: $CDCl_3$ = 77.0 ppm); coupling constants J are given in Hz. Higher order δ and J values are not corrected. ^{13}C signals were assigned by means of H–H and C–H COSY spectroscopy. Microanalyses and gas chromatographic determinations were performed at the Institut für Organische Chemie, Stuttgart. Melting points or softening ranges (Büchi 510) are not corrected. Specific rotations were measured at 20 °C. IR spectra were obtained on a Perkin-Elmer 283 spectrometer. MS were recorded on a Finnigan MAT 95 (FAB, EI) or a Varian MAT 711 (EI) spectrometer.

X-ray Crystallographic Analysis[20]

The crystal data for compound **11** were determined with a Siemens P4 diffractometer with graphite monochromator in the ω-scan mode with Cu-$K\alpha$ (λ = 1.54178 Å) radiation. $C_{35}H_{37}BO_4$, M_r = 532.48, colorless, T = 293 K, crystal size 0.50 × 0.25 × 0.02 mm, monoclinic, P2(1), a = 10.3707(6), b = 16.2076(19), c = 18.5250(14) Å, V = 3105.2(5) Å^3, Z = 4, D_{calcd} = 1.139 g·cm^{-3}, μ = 0.570 mm^{-1}, F(000) = 1136, θ range = 3.63–59.99°, 4963 measured/independent reflections, 1691 reflections with [$I > 2\sigma(I)$]. The structure was solved by direct methods and refined by full-matrix least squares on F^2 for all data weights to R = 0.1718, wR = 0.2130, S = 0.981, H atoms were treated as riding atoms, max. shift/error <0.002, residual $\rho_{max.}$ = 0.186 Å^{-3}.

(*i*-Bu)$_2$AlH-Reduction of 1a and 2a; General Procedure A

A solution of ester **1a** or **2a** (1.00 equiv) in THF (10 mL/mmol **1a/2a**) was cooled to –78 °C and DIBAL-H (1 M solution in heptane, 3.00 equiv) was added. The reaction mixture was warmed to 4 °C over 2 h. Dilution with Et_2O (10 mL/mmol **1a/2a**) and careful addition of H_2O [70 μL/mmol DIBAL-H], 2 M aq NaOH solution [1.40 μL/mmol DIBAL-H] and H_2O [70μL/mmol DIBAL-H] led to a precipitate after 20 min. The mixture was filtered, the solvent of the filtrate was evaporated and the crude product was purified by flash column chromatography.

(3*S*,4′*R*,5′*R*)-3-[4′,5′-Bis(methoxydiphenylmethyl)-1′,3′,2′-dioxaborolan-2′-yl]pent-4-en-1-ol (7)

Prepared according to the general procedure A. Ester **1a** (3.00 g, 5.08 mmol) and DIBAL-H (1 M solution in heptane, 15.2 mL, 15.2 mmol) in THF (51 mL) were used. Purification by flash column chromatography on silica gel (51 g, PE–EtOAc, 85:15) yielded 2.57 g (92%) of **7** as spectroscopically pure colorless solid foam. MPLC of a small sample (PE–EtOAc, 80:20) gave the analytically pure colorless solid foam; recrystallization from pentane–CH_2Cl_2 yielded colorless crystals; mp 130 °C; R_f 0.10 (PE–EtOAc, 85:15); $[\alpha]_D^{20}$ –129 (c = 0.08, $CHCl_3$).

IR (KBr): 3570, 3070, 3040, 3010, 2950, 2925, 2915, 2890, 2810, 1625, 1590, 1570, 1480, 1435, 1060, 740, 680 cm^{-1}.

^{1}H NMR (500 MHz, $CDCl_3$): δ = 1.30–1.41 (m, 3 H, OH, 2-H), 1.43–1.50 (m, 1 H, 3-H), 3.01 (s, 6 H, OCH_3), 3.35 (m, 2 H, 1-H), 4.73 (ddd, ^3J = 17.2 Hz, ^2J = 1.7 Hz, ^4J = 1.3 Hz, 1 H, 5-H$_Z$), 4.77 (ddd, ^3J = 10.3 Hz, ^2J = 1.7 Hz, ^4J = 1.0 Hz, 1 H, 5-H$_E$), 5.32 (s, 2 H, 4′-H, 5′-H), 5.50 (ddd, ^3J = 17.2 Hz, ^3J = 10.3 Hz, ^3J = 8.3 Hz, 1 H, 4-H), 7.25–7.35 (m, 20 H$_{arom}$).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 26.1 (br, C-3), 31.5 (C-2), 51.7 (OCH_3), 62.1 (C-1), 77.6 (C-4′, C-5′), 83.3 (CPh_2OMe), 113.3 (C-5), 127.3, 127.3, 127.6, 127.8, 128.4, 129.7 (CH_{arom}), 138.7 (C-4), 141.1, 141.1 (C_{arom}).

MS (FAB, matrix: NBA + NaI): m/z (%) = 571 (43, [M$^+$ + Na]), 197 (100, [CPh_2OMe^+]), 167 (10, [Ph_2CH^+]), 105 (11, [$PhCO^+$]), 77 (6, [Ph^+]).

Anal. Calcd for $C_{35}H_{37}BO_5$ (548.48): C, 76.64; H, 6.80. Found: C, 76.41; H, 6.77.

(3*R*,4′*R*,5′*R*)-3-[4′,5′-Bis(methoxydiphenylmethyl)-1′,3′,2′-dioxaborolan-2′-yl]pent-4-en-1-ol (8)

Prepared according to the general procedure A. Ester **2a** (3.00 g, 5.08 mmol) and DIBAL-H (1 M solution in heptane, 15.2 mL, 15.2 mmol) in THF (51 mL) were used. Purification by flash column chromatography on silica gel (49 g, PE–EtOAc, 85:15) yielded 2.62 g (94%) of **8** as spectroscopically pure colorless solid foam. MPLC of a small sample (PE–EtOAc, 80:20) gave the analytically pure alcohol **8**. Softening range: 62–78 °C; R_f 0.10 (PE–EtOAc, 85:15); $[\alpha]_D^{20}$ –140 (c = 0.92, $CHCl_3$).

IR (KBr): 3540, 3070, 3040, 3000, 2950, 2920, 2880, 2850, 2810, 1625, 1590, 1575, 1480, 1435, 1060, 740, 680 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 1.32–1.40 (m, 2 H, OH, 2-H_a), 1.41–1.48 (m, 2 H, 2-H_b, 3-H), 3.00 (s, 6 H, OCH_3), 3.29–3.34 (m, 1 H, 1-H_a), 3.37–3.42 (m, 1 H, 1-H_b), 4.73 (ddd, ^3J = 17.0 Hz, ^2J = 1.8 Hz, ^4J = 1.2 Hz, 1 H, 5-H_Z), 4.75 (dd, ^3J = 10.3 Hz, ^2J = 1.8 Hz, 1 H, 5-H_E), 5.33 (s, 2 H, 4′-H, 5′-H), 5.39 (ddd, ^3J = 17.0 Hz, ^3J = 10.3 Hz, ^3J = 8.4 Hz, 1 H, 4-H), 7.24–7.35 (m, 20 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 26.5 (br, C-3), 32.4 (C-2), 51.8 (OCH_3), 62.7 (C-1), 77.8 (C-4′, C-5′), 83.4 (*C*Ph_2OMe), 113.6 (C-5), 127.3, 127.4, 127.6, 127.8, 128.5, 129.7 (CH_{arom}), 138.5 (C-4), 141.2, 141.2 (C_{arom}).

MS (EI, 70 eV): *m*/*z* (%) = 548 (0.1, [M^+]), 516 (2, [M^+ – MeOH]), 197 (100, [CPh_2OMe^+]), 167 (3, [Ph_2CH^+]), 105 (13, [$PhCO^+$]), 77 (5, [Ph^+]).

Anal. Calcd for $C_{35}H_{37}BO_5$ (548.48): C, 76.64; H, 6.80. Found: C, 76.47; H, 6.84.

Methanesulfonic Esters 9 and 10; General Procedure B

To a solution of the alcohol **7** or **8** (1.00 equiv) in CH_2Cl_2 (2 mL/mmol **7/8**) was added Et_3N (1.50 equiv) and $MeSO_2Cl$ (1.50 equiv) at 4 °C. The reaction mixture was allowed to warm to r.t. within 0.5 h and diluted with Et_2O (5 mL/mmol **7/8**). A half sat. aq solution of $NaHCO_3$ (5 mL/mmol **7/8**) was added and the mixture stirred vigorously for 0.5 h. The aqueous phase was extracted with Et_2O (3 × 5 mL/mmol **7/8**). The combined organic layers were washed with sat. aq solution of NH_4Cl (5 mL/mmol **7/8**) and brine (5 mL/mmol **7/8**), and dried ($MgSO_4$). After filtration and evaporation of the solvent, the crude product was purified by flash column chromatography.

(3*S*,4′*R*,5′*R*)-3-[4′,5′-Bis(methoxydiphenylmethyl)-1′,3′,2′-dioxaborolan-2′-yl]pent-4-en-1-yl Methanesulfonate (9)

Prepared according to the general procedure B. Alcohol **7** (2.51 g, 4.58 mmol), Et_3N (952 μL, 695 mg, 6.87 mmol) and $MeSO_2Cl$ (534 μL, 787 mg, 6.87 mmol) in CH_2Cl_2 (9.16 mL) were used. Purification by flash column chromatography on silica gel (100 g, PE–EtOAc, 86:14) yielded 2.72 g (95%) of **9** as analytically pure colorless solid foam. Softening range: 54–65 °C; R_f 0.25 (PE–EtOAc, 85:15); $[\alpha]_D^{20}$ –100 (c = 1.65, $CHCl_3$).

IR (KBr): 3070, 3040, 3010, 2950, 2940, 2920, 2880, 2810, 1620, 1590, 1570, 1480, 1435, 1345, 1165, 1060, 740, 680 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 1.42–1.51 (m, 2 H, 2-H_a, 3-H), 1.53–1.60 (m, 1 H, 2-H_b), 2.78 (s, 3 H, SO_2CH_3), 3.01 (s, 6 H, OCH_3), 3.86 (m, 2 H, 1-H), 4.73 (ddd, ^3J = 17.2 Hz, ^2J = 1.6 Hz, ^4J = 1.2 Hz, 1 H, 5-H_Z), 4.83 (ddd, ^3J = 10.3 Hz, ^2J = 1.6 Hz, ^4J = 0.8 Hz, 1 H, 5-H_E), 5.33 (s, 2 H, 4′-H, 5′-H), 5.42 (ddd, ^3J = 17.2 Hz, ^3J = 10.3 Hz, ^3J = 7.8 Hz, 1 H, 4-H), 7.26–7.32 (m, 20 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 24.9 (br, C-3), 27.9 (C-2), 36.9 (SO_2CH_3), 51.7 (OCH_3), 69.2 (C-1), 77.9 (C-4′, C-5′), 83.3 (*C*Ph_2OMe), 114.2 (C-5), 127.3, 127.4, 127.6, 127.8, 128.5, 129.7 (CH_{arom}), 137.1 (C-4), 141.0 (C_{arom}).

MS (EI, 70 eV): *m*/*z* (%) = 626 (0.2, [M^+]), 594 (9, [M^+ – MeOH]), 429 (2, [M^+ – $MeOPh_2C$]), 197 (100, [$MeOPh_2C^+$]), 167 (4, [Ph_2HC^+]), 105 (11, [$PhCO^+$]).

Anal. Calcd for $C_{36}H_{39}BO_7S$ (626.25): C, 69.01; H, 6.27. Found: C, 68.72; H, 6.28.

(3*R*,4′*R*,5′*R*)-3-[4′,5′-Bis(methoxydiphenylmethyl)-1′,3′,2′-dioxaborolan-2′-yl]pent-4-en-1-yl Methanesulfonate (10)

Prepared according to the general procedure B. Alcohol **7** (2.61 g, 4.75 mmol), Et_3N (988 μL, 721 mg, 7.13 mmol) and $MeSO_2Cl$ (554 μL, 817 mg, 7.13 mmol) in CH_2Cl_2 (9.51 mL) were used. Purification by flash chromatography on silica gel (100 g, PE–EtOAc, 86:14) yielded 2.77 g (93%) of **10** as analytically pure colorless solid foam. Softening range: 53–66 °C; R_f 0.25 (PE–EtOAc, 85:15); $[\alpha]_D^{20}$ –114 (c = 1.05, $CHCl_3$).

IR (KBr): 3070, 3040, 3010, 2940, 2920, 2890, 2810, 1620, 1590, 1570, 1480, 1435, 1345, 1165, 1060, 740, 680 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 1.41–1.51 (m, 2 H, 2-H_a, 3-H), 1.58–1.65 (m, 1 H, 2-H_b), 2.85 (s, 3 H, SO_2CH_3), 3.00 (s, 6 H, OCH_3), 3.89 (ddd, ^2J = 9.6 Hz, ^3J = 7.3 Hz, ^3J = 7.2 Hz, 1 H, 1-H_a), 3.94 (ddd, ^2J = 9.6 Hz, ^3J = 7.8 Hz, ^3J = 5.0 Hz, 1 H, 1-H_b), 4.73 (ddd, ^3J = 17.1 Hz, ^2J = 1.6 Hz, ^4J = 1.2 Hz, 1 H, 5-H_Z), 4.81 (ddd, ^3J = 10.3 Hz, ^2J = 1.6 Hz, ^4J = 0.9 Hz, 1 H, 5-H_E), 5.31 (ddd, ^3J = 17.1 Hz, ^3J = 10.3 Hz, ^3J = 8.3 Hz, 1 H, 4-H), 5.33 (s, 2 H, 4′-H, 5′-H), 7.25–7.33 (m, 20 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 25.3 (br, C-3), 28.3 (C-2), 37.1 (SO_2CH_3), 51.8 (OCH_3), 69.2 (C-1), 77.9 (C-4′, C-5′), 83.4 (*C*Ph_2OMe), 114.6 (C-5), 127.4, 127.4, 127.6, 127.8, 128.5, 129.7 (CH_{arom}), 136.8 (C-4), 141.1, 141.1 (C_{arom}).

MS (FAB, matrix: NBA + NaI): *m*/*z* (%) = 652 (84, [M^+ + Na]), 197 (100, [$MeOPh_2C^+$]), 167 (9, [Ph_2HC^+]), 105 (12, [$PhCO^+$]).

Anal. Calcd for $C_{36}H_{39}BO_7S$ (626.25): C, 69.01; H, 6.27. Found: C, 68.67; H, 6.30.

Reduction of Methanesulfonic Esters 9 and 10 with $LiEt_3BH$; General Procedure C

To a vigorously stirred solution of the methanesulfonic ester **9** or **10** (1.00 equiv) in THF (1.00 mL/mmol **9/10**) at r.t. was added $LiEt_3BH$ (1 M solution in THF, 2.00 equiv) in one batch. A colorless solid precipitated from the solution. After 1 h, a 3 M aq solution of NaOH (0.80 mL/mmol **9/10**) and a 30% aq solution of H_2O_2 (0.8 mL/mmol **10**) was added to the mixture. Stirring was continued for 1 h and then the mixture was diluted with Et_2O (5 mL/mmol **9/10**) and H_2O (5 mL/mmol **9/10**). The aqueous phase was extracted with Et_2O (3 × 5 mL/mmol **9/10**) and the combined organic layers were dried ($MgSO_4$). After filtration and evaporation of the solvents, the crude product was purified by flash column chromatography.

(3*S*,4′*R*,5′*R*)-3-[4′,5′-Bis(methoxydiphenylmethyl)-1′,3′,2′-dioxaborolan-2′-yl]pent-1-ene (11)

Prepared according to the general procedure C. Methanesulfonic ester **9** (2.73 g, 4.36 mmol) and $LiEt_3BH$ (1 M solution in THF, 8.71 mL, 8.71 mmol) in THF (4.36 mL) were used. Purification by flash column chromatography on silica gel (85 g, PE–EtOAc, 95:5 to 85:15) yielded 1.57 g (68%) of **11** as colorless solid foam. Softening range: 50–62 °C; R_f 0.38 (PE–EtOAc, 95:5); $[\alpha]_D^{20}$ –140 (c = 1.30, $CHCl_3$). Recrystallization from pentane–EtOH yielded crystals suitable for X-ray crystallographic analysis; mp 116–119 °C.

IR (KBr): 3070, 3040, 3015, 3005, 2940, 2920, 2890, 2850, 2810, 1620, 1590, 1570, 1480, 1435, 1060, 740, 680 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 0.64 (t, ^3J = 7.2 Hz, 3 H, 5-H), 1.06 (dqd, ^2J = 14.7 Hz, ^3J = 7.2 Hz, ^3J = 3.1 Hz, 1 H, 4-H_a), 1.17–1.25 (m, 2 H, 3-H, 4-H_b), 3.00 (s, 6 H, OCH_3), 4.68 (ddd, ^3J = 17.1 Hz, ^2J = 2.2 Hz, ^4J = 1.1 Hz, 1 H, 1-H_Z), 4.75 (dd, ^3J = 10.3 Hz, ^2J = 2.2 Hz, 1 H, 1-H_E), 5.29 (s, 2 H, 4-H′, 5′-H), 5.43 (ddd, ^3J = 17.1 Hz, ^3J = 10.3 Hz, ^3J = 8.3 Hz, 1 H, 2-H), 7.22–7.35 (m, 20 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 13.2 (C-5), 21.8 (C-4), 31.4 (C-3), 51.7 (OCH_3), 77.7 (C-4′, C-5′), 83.4 (*C*Ph_2OMe), 113.0 (C-1), 127.2, 127.3, 127.4, 127.7, 128.5, 129.7 (CH_{arom}), 139.1 (C-2), 141.3, 141.5 (C_{arom}).

MS [DCI (CH_4)]: *m*/*z* (%) = 532 (0.14, [M^+]), 500 (8, [M^+ – MeOH]), 197 (100, [$MeOPh_2C^+$]), 167 (5, [Ph_2HC^+]), 105 (5, [$PhCO^+$]).

Anal. Calcd for $C_{35}H_{37}BO_4$ (532.48): C, 78.95; H, 7.00. Found: C, 78.78; H, 7.03.

(3*R*,4′*R*,5′*R*)-3-[4′,5′-Bis(methoxydiphenylmethyl)-1′,3′,2′-dioxaborolan-2′-yl]pent-1-ene (12)

Prepared according to the general procedure C. Methanesulfonic ester **10** (1.58 g, 2.52 mmol) and $LiEt_3BH$ (1 M solution in THF, 5.04 mL, 5.04 mmol) in THF (2.52 mL) were used. Purification by flash column chromatography on silica gel (83 g, PE–EtOAc, 95:5 to 85:15) yielded 1.00 g (74%) of **12** as colorless solid foam. Softening range: 47–62 °C; R_f 0.38 (PE–EtOAc, 95:5); $[\alpha]_D^{20}$ –146 (*c* = 1.14, $CHCl_3$).

IR (KBr): 3070, 3040, 3010, 2940, 2920, 2890, 2850, 2810, 1620, 1590, 1570, 1480, 1435, 1060, 740, 680 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 0.63 (t, ^3J = 7.3 Hz, 3 H, 5-H), 1.06 (ddq, ^2J = 13.1 Hz, ^3J = 9.1 Hz, ^3J = 7.3 Hz, 1 H, 4-H_a), 1.17–1.22 (m, 1 H, 3-H), 1.26 (dqd, ^2J = 13.1 Hz, ^3J = 7.3 Hz, ^3J = 5.1 Hz, 1 H, 4-H_b), 2.99 (s, 6 H, OCH_3), 4.69 (dm, ^3J = 17.1 Hz, 1 H, 1-H_Z), 4.74 (dd, ^3J = 10.3 Hz, ^2J = 2.1 Hz, 1 H, 1-H_E), 5.29 (s, 2 H, 4′-H, 5′-H), 5.35 (ddd, ^3J = 17.1 Hz, ^3J = 10.3 Hz, ^3J = 8.6 Hz, 1 H, 2-H), 7.23–7.35 (m, 20 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 13.3 (C-5), 22.2 (C-4), 31.8 (C-3), 51.8 (OCH_3), 77.7 (C-4′, C-5′), 83.4 (*C*Ph_2OMe), 113.3 (C-1), 127.2, 127.3, 127.4, 127.7, 128.5, 129.7 (CH_{arom}), 139.0 (C-2), 141.4, 141.5 (C_{arom}).

MS (FAB, matrix: NBA + NaI): *m*/*z* (%) = 555 (0.21, [M^+ + Na]), 501 (2, [M^+ – MeO]), 469(1, [M^+ – MeO – MeOH]), 423 (1, [M^+ – MeOH – Ph]), 197 (100, [$MeOPh_2C^+$]), 167 (8, [Ph_2HC^+]), 105 (7, [$PhCO^+$]).

Anal. Calcd for $C_{35}H_{37}BO_4$ (532.48): C, 78.95; H, 7.00. Found: C, 78.89; H, 7.02.

Allyl Addition of 11 and 12 to Aldehydes; General Procedure D

To a stirred solution of the allylboronic ester **11** or **12** (1.00 equiv) in CH_2Cl_2 (0.50 mL/mmol **11**/**12**) at 4 °C was added the aldehyde (1.20 equiv). The solution was stirred at 4 °C overnight and 2 d at r.t. The solvents were evaporated; the crude product was investigated by NMR and purified by column chromatography.

(1*S*,3*Z*)-1-Phenylhex-3-en-1-ol (13)

Prepared according to the general procedure D. Allylboronic ester **11** (196 mg, 0.37 mmol) and benzaldehyde (45 μL, 47 mg, 0.44 mmol) in CH_2Cl_2 (184 μL) were used. Purification by column chromatography on silica gel (30 g, PE–EtOAc, 95:5 to 85:15) yielded 54 mg (83%) of **13** of slightly impure product; the spectroscopic data were in full agreement to those previously reported;[21,22] R_f 0.10 (PE–EtOAc, 95:5); $[\alpha]_D^{20}$ –58 (*c* = 1.80, $CHCl_3$); ee >99% [HPLC (CHIRACEL OD, hexane–*i*-PrOH, 99.4:0.6): t_R = 12.5 min, and GC (Bondex-un-α, 40 °C, 1′ iso, then 1.5 °C·min^{-1}): t_R = 63.9 min].

IR (film): 3530, 3070, 3040, 3010, 2990, 2940, 2910, 2850, 1645, 1590, 1480, 1440, 1030, 735, 680 cm^{-1}.

^1H NMR (500 MHz, $CDCl_3$): δ = 0.91 (t, ^3J = 7.5 Hz, 3 H, 6-H), 2.01 (dqdd, ^2J = 14.6 Hz, ^2J = 7.5 Hz, ^3J = 7.3 Hz, ^4J = 1.6 Hz, 1 H, 5-H_a), 2.03 (dqdd, ^2J = 14.6 Hz, ^2J = 7.5 Hz, ^3J = 7.3 Hz, ^4J = 1.6 Hz, 1 H, 5-H_b), 2.12 (d, ^3J = 2.6 Hz, 1 H, OH), 2.45 (dddd, ^2J = 14.3 Hz, ^3J = 6.9 Hz, ^3J = 5.4 Hz, ^4J = 1.6 Hz, 1 H, 2-H_a), 2.55 (dddd, ^2J = 14.3 Hz, ^3J = 6.9 Hz, ^3J = 7.8 Hz, ^4J = 1.6 Hz, 1 H, 2-H_b), 4.67 (ddd, ^3J = 7.8 Hz, ^3J = 5.4 Hz, ^3J = 2.6 Hz, 1 H, 1-H), 5.34 (dtt, ^3J = 10.8 Hz, ^3J = 6.9 Hz, ^4J = 1.6 Hz, 1 H, 3-H), 5.54 (dtt, ^3J = 10.8 Hz, ^3J = 7.3 Hz, ^4J = 1.6 Hz, 1 H, 4-H), 7.23–7.27, 7.31–7.36 (m, 5 H_{arom}).

^{13}C NMR (126 MHz, $CDCl_3$): δ = 14.1 (C-6), 20.6 (C-5), 37.1 (C-2), 73.9 (C-1), 124.0 (C-3), 125.8, 127.4, 128.3 (CH_{arom}), 135.2 (C-4), 144.1 (C_{arom}).

MS [CI (NH_3)]: *m*/*z* (%) = 370.3 (2, [(2M + NH_4)$^+$]), 352 (27, [(2M)$^+$]), 317 (9), 194 (26, [(M + NH_4)$^+$]), 176 (100, [M^+]), 159 (45, [(M + H – H_2O)$^+$]).

HRMS (EI, 70 eV): *m*/*z* calcd for $C_{12}H_{16}O$: 176.1201; found: 176.1202.

(1*R*,3*Z*)-1-Phenylhex-3-en-1-ol (14)

Prepared according to the general procedure D. Allylboronic ester **12** (193 mg, 0.36 mmol) and benzaldehyde (44 μL, 46 mg, 0.44 mmol) in CH_2Cl_2 (181 μL) were used. Purification by column chromatography on silica gel (31 g, PE–EtOAc, 95:5 to 85:15) and MPLC (PE–EtOAc, 95:5) yielded 44 mg (69%) of **14** as spectroscopically pure colorless oil; $[\alpha]_D^{20}$ +65 (*c* = 0.76, $CHCl_3$); ee = >99% [HPLC (CHIRACEL OD, hexane–*i*-PrOH, 99.4:0.6): t_R = 9.4 min; and GC (Bondex-un-α, 40 °C, 1′ iso, then 1.5 °C·min^{-1}): t_R = 64.4].

For the remaining data, see those of the enantiomeric compound (1*S*,3*Z*)-1-phenylhex-3-en-1-ol (**13**).

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