Stereoselective Synthesis of Alcohols, XXXVII[1]

Origins of Stereoselectivity in Reactions of α-Substituted Allylboronates with Aldehydes

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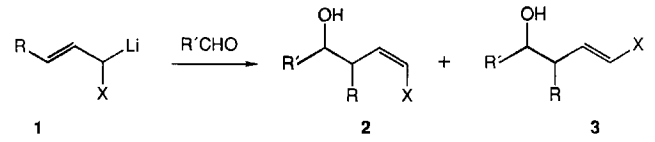
Rate constants for the addition of α-substituted allylboronates **4** (X = H, Cl, Br, OCH_3, SCH_3) to aldehydes have been measured. The results have been used to differentiate between different models that have been advanced to account for the high proportion of (*Z*)-configurated homoallyl alcohols **5** formed in allylboration reactions. Attempts have been made in this context to detect ate-complex formation between benzylboronates and aldehydes.

In the addition of α-substituted allyllithium compounds **1** to aldehydes isomeric homoallyl alcohols **2** and **3** are fromed[2] with sometimes high levels of (*Z*) selectivity.

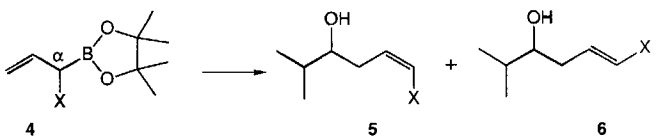
Scheme 1



1 **2** **3**

Similarly, on addition of α-substituted allylboronates **4** to aldehydes the (*Z*) isomers **5** are preferentially formed to a varying degree, depending on the substituent X[3,4]. An interpretation of the factors that govern the stereoselectivity in the addition of α-substituted allylmetallic compounds to aldehydes is hampered[5] in the case of organolithium compounds by unknown aggregation phenomena. A study of the monomeric allylboronates **4** should therefore provide a more detailed understanding.

Scheme 2

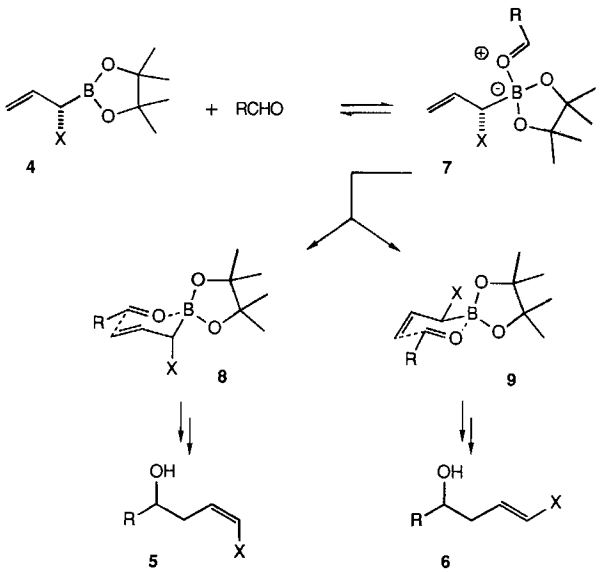


4 **5** **6**

a	X = CH_2=CH_2	60 : 40
b	X = CH_3	79 : 21
c	X = SCH_2CH_3	85 : 15
d	X = Br	96 : 4
e	X = Cl	96 : 4
f	X = OCH_3	>97 : 3

The addition of the allylboronates, such as **4** to aldehydes is assumed to proceed via an ate complex **7** formed in a rapid equilibrium. The subsequent rate-determining carbon—carbon bond-forming step (cf. Scheme 3)[3] is assumed — in analogy to the aldol addition[6] — to procede via a cyclic six-membered transition state, a notion which finds support by recent ab initio calculations[7].

Scheme 3



4 **7** **8** **9** **5** **6**

To account for the predominant formation of the product **4** with (*Z*) configuration, the substituent X must prefer the axial position in a chair-like transition state **8** instead of an equatorial one in transition state **9**. The latter may intuitively appear to be energetically more favorable by analogy with the Claisen rearrangement or the conformer equilibria

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of monosubstituted cyclohexanes. Three models have been advanced to explain this phenomenon[3,4].

The "Steric Model" attributes these effects to greater interactions between the methyl substituents on the 1,3,2-dioxaborolane ring of **4** with the substituent X in an equatorial position, cf. **9**, as opposed to an axial arrangement as in **8**. In accord with this model, the less substituted glycol-derived (α-methylallyl)boronates led to diminished (*Z*) selectivities[4]. Steric effects of the same sort have recently been reported for the reactions of allyl*boranes* with carbonyl compounds[8]. A direct relation between the **5**/**6** ratio to the spatial requirements of the substituent X is, however, not borne out by a plot of the logarithm of the **5**/**6** ratio versus the *A* values[9] of the substituent X (cf. Figure 1). For example, on reaction of **4** (X = Cl), a higher (*Z*) selectivity is found than for X = CH_3, in contrast to the steric requirements of these groups.

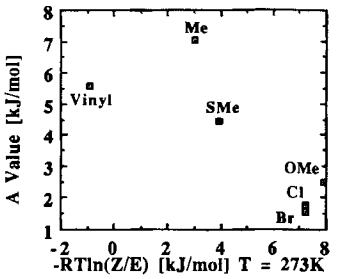
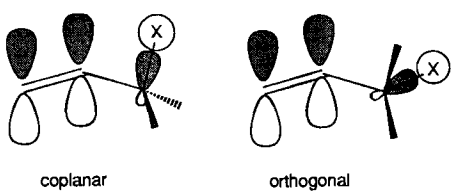


Figure 1. Plot of the logarithm of the **5**/**6** ratio versus the *A* values

The "Polar Model": The relative energy of the transition states **8** and **9** could be affected by differences in their net dipole moments arising from different orientations of the C–X dipole relative to the dipole of the remainder of the transition-state structure. The latter is mainly defined by the various C–O and B–O bond dipole moments.

The "Stereoelectronic Model": The C–C bond formation in the transition states **8** or **9** may be envisioned to proceed by an electrophilic attack of the carbon atom of the carbonyl group on the double bond of the boronate. Hence, the preference of transition state **8** over transition state **9** has been related[3] to a stereoelectronic model that accounts for stereoselectivities on addition of electrophiles to various olefinic compounds[10]. In the frontier-orbital picture, electrophilic attack will proceed the faster the higher the HOMO energy of the reacting double bond is. For the reaction of the allylboronate **4** the latter is influenced by the dihedral angle between the π orbital and the C–X bond. In transition state **9**, the equatorial position of the substituent X allows for overlap between the π orbital and the σ* orbital of the C–X bond (cf. Scheme 4).

Scheme 4



The more polar the C–X bond is, the lower lies its σ* orbital, and interaction with the π orbital could therefore lower the energy of the latter more effectively. This should decrease the reactivity of the double bond towards attack by an electrophile. In contrast, in transition state **8** with an axial C–X bond, overlap should be much smaller because of the almost orthogonal orbital arrangement. In qualitative accord with the data in Scheme 2, reaction via transition state **9** with X in an equatorial position should proceed[11] more and more slowly as X becomes more polar, relative to the reaction via transition state **8**. The arguments are summarized pictorially in Figure 2.

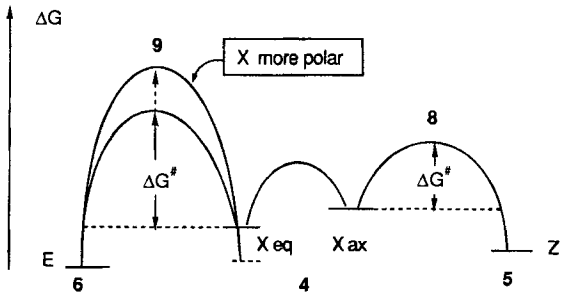


Figure 2. Schematic energy diagram for the reaction of **4** with aldehydes to give **5** and **6**

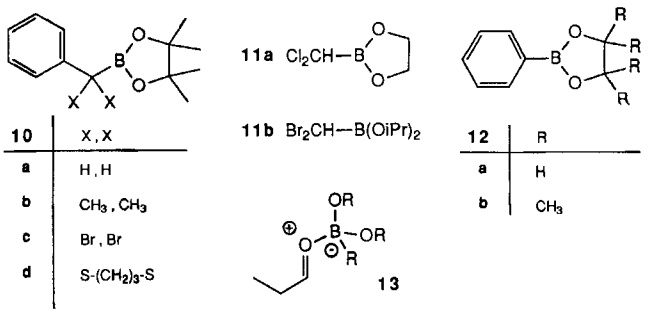
While quantitative information on the energy of σ* orbitals is lacking, AM1 calculations[12] on CH_3–X compounds show an increase in σ*-orbital energies in the following order of X: I < Br < Cl < SH < OH < F. In addition, we do not know whether changes in the polarization and polarizability of the π orbital as a function of the substituent X might be more important than subtle differences in energetics.

In this paper we report experiments designed to test the quantitative implications of the "stereoelectronic model". We also discuss the validity of the "steric" and "polar" models by recourse to conformational equilibria of model compounds[13].

Complex Formation Between Boronates and Aldehydes

Formation of the ate complex **7** is postulated to precede the rate-determining carbon–carbon bond-forming step. We hoped to probe the influence of X on the rate of formation and stability of such ate complexes by testing the interaction of aldehydes with the boronates **10**. These should resemble the allylboronates **4** in their

Scheme 5



complexing capabilities yet would be incapable of undergoing the subsequent carbon–carbon bond-forming step.

After mixing the components in $CDCl_3$, there was no difference observed in the ^1H-, ^{13}C- or ^{11}B-NMR chemical shifts of either the aldehyde or the boronate. Likewise, we were unable to detect any complex formation, employing the more Lewis-acidic and less sterically demanding boronates **11** (cf. Scheme 5). There should be a shift of about 30 ppm to higher field in the ^{11}B-NMR spectrum when going from a trigonal to a tetragonal boron atom[14]. But neither did a twenty-fold excess of propionaldehyde nor cooling to 183 K lead to a noticeable shift in the ^{11}B-NMR signals.

Nitrogen bases were recently reported[15] to form thermodynamically weakly stabilized (unfavorable reaction entropy) and kinetically labile (fast exchange with the constituents on the NMR time scale) complexes with the esters of phenylboronic acid. In qualitative confirmation we found for the adduct from the glycol ester **12a** of phenylboronic acid and quinuclidine two peaks in the ^{11}B-NMR spectrum [δ = 8.9 (major), ca. 30 (minor)] at 183 K. In the absence of quinuclidine, only one absorption of **12a** at δ = 33.0 was detectable. With the sterically more demanding pinacol ester **12b** we could not detect any ate complex formation with quinuclidine. It is therefore not surprising, that ate-complex formation between the boronate esters **10**, **11** and the less Lewis-basic aldehydes could not be detected.

Effect of Substituents in the α Position of Allylboronates on the Kinetics of the Allylboration Reaction

Of the models advanced to explain the stereoselectivity in the addition of α-substituted allylboronates to aldehydes, only the "stereoelectronic" model has clear-cut implications with respect to the kinetics of the reaction (cf. Figure 2). First, the overall rate of reaction should decrease if X becomes more polar. Second, the partial rate constant for the pathway leading to the (*E*)-homoallylic alcohol **6** via the transition state **9** should decrease if X becomes more polar. We therefore determined the rate constants for the addition of α-substituted allylboronates **4b**, **4d–4i** to propionaldehyde in $CDCl_3$ at five different temperatures by ^1H-NMR spectroscopy and the ratios of the product alcohols **14/15** by capillary GC. The results in Tables 1 and 2 show that these data verify neither prediction of the stereoelectronic model. Thus, while this model accounts qualitatively for the observed trend in stereoselectivity, it fails to do so on a quantitative basis, because it may be based on oversimplified or even incorrect assumptions. One of these is, that the HOMO energy of the allyl system in Scheme 4 depends on the cosine (or a related function) of the dihedral angle defined by the π lobes and the C–X σ bond. Preliminary MNDO and ab initio (3-21G) calculations on model compounds[16] indicate that there is no such simple relationship between the orientation of the C–X bond in an allyl system and the HOMO energy of the double bond.

Scheme 6

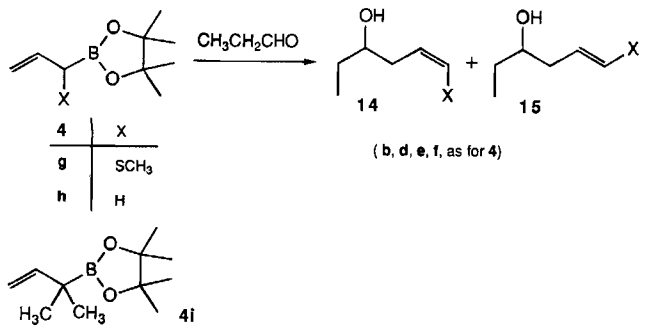


Table 1. Rate constants *k* of the reaction of the allylboronates **4** with propionaldehyde in $CDCl_3$

4	X	T [K]	$10^5 \cdot k$ (l/mol · s) ± σ	r
h	H	253.15	27.3 ± 1.6	0.989
		263.15	35.3 ± 1.6	0.994
		273.15	74.7 ± 2.0	0.997
		283.15	90.8 ± 1.9	0.997
		293.15	169 ± 3.7	0.998
b	CH_3	243.15	26.2 ± 0.9	0.992
		248.15	34.7 ± 0.9	0.998
		253.15	52.8 ± 2.0	0.998
		263.15	72.5 ± 2.7	0.998
		273.15	124 ± 3.3	0.997
		283.15	232 ± 7.3	0.999
		293.65	265 ± 8.0	0.999
e	Cl	243.15	15.2 ± 1.1	0.949
		253.15	42.8 ± 1.3	0.995
		263.15	39.7 ± 1.1	0.990
		273.15	78.5 ± 3.2	0.986
		283.15	127 ± 5.5	0.987
		293.15	133 ± 5.1	0.988
d	Br	263.35	4.42 ± 0.57	0.947
		268.15	6.83 ± 0.55	0.979
		273.15	8.06 ± 0.60	0.979
		278.15	10.6 ± 5.9	0.990
		283.15	9.79 ± 5.8	0.981
		293.15	24.2 ± 6.7	0.998
f	OCH_3	253.15	24.5 ± 1.7	0.987
		263.15	60.0 ± 4.6	0.987
		273.15	115 ± 5.9	0.997
		283.15	268 ± 20	0.993
		293.15	299 ± 13	0.999
g	SCH_3	263.15	16.0 ± 0.8	0.991
		273.15	30.0 ± 1.4	0.994
		278.65	34.7 ± 0.7	0.999
		283.15	38.6 ± 3.4	0.977
		293.15	71.9 ± 7.9	0.985
i	$(CH_3)_2$[a]	253.15	24.3 ± 1.3	0.991
		263.15	38.3 ± 1.5	0.996
		273.15	55.8 ± 3.8	0.983
		283.15	96.9 ± 3.8	0.996
		293.15	131 ± 6.5	0.993

[a] Besides X also H replaced by CH_3 in α position.

(*E*)/(*Z*) Stereoselectivities in the Light of the "Steric" and the "Polar" Model

As the "stereoelectronic model" proved not to be in accord with the kinetic measurements reported above, the validity of the "steric model" and the "polar model" (vide supra) were tested next. A semiquantitative assessment of the steric and polar effects which contribute to the stereoselectivity in the addition of allyboronates **4** to aldehydes appeared to be possible by a study of conformational equilibria on model compounds **16–19**[13].

The choice of the model compounds **18** and **19** was guided by the assumption that the boron atom is tetrahedral in the transition state of the allylboration reaction. This appears to be reasonable in view of X-ray structure analyses of in-

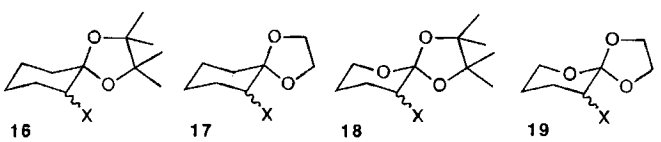
Table 2. Partial rate constants k_{ax}, k_{eq} for the reaction of α-substituted allylboronates **4** with propionaldehyde

4	X	% (Z)	T [K]	$10^4 \cdot k_{ax}$ (l/mol · s)	$10^4 \cdot k_{eq}$ (l/mol · s)
h	H	≡50	295.65	8.45	8.45
			283.15	4.54	4.54
			273.15	3.74	3.74
			263.15	1.77	1.77
			253.15	1.37	1.37
b	CH_3	64.4	295.65	17.1	9.43
		66.3	283.15	15.4	7.82
		64.2	273.15	7.96	4.44
		67.0	263.15	5.03	2.23
		66.2	253.15	4.02	2.05
e	Cl	95.9	295.65	12.7	0.545
		95.8	283.15	12.2	0.533
		91.2	273.15	8.68	0.838
		95.4	263.15	3.79	0.183
		97.1	253.15	4.16	0.124
d	Br	95.4	295.65	2.30	0.111
		95.2	283.15	0.932	0.0470
		84.7	273.15	0.898	0.162
		93.2	263.15	0.412	0.0300
		91.8	253.15	—	—
f	OCH_3 [a]	97.0	295.65	29.0	0.900
g	SCH_3	76.6	295.65	5.51	1.68
		88.4	283.15	3.41	0.448
		84.3	273.15	2.93	0.545
		81.8	263.15	2.45	0.546
		90.1	253.15	—	—
i	$(CH_3)_2$ [b]	≡50	295.65	6.55	6.55
			283.15	4.85	4.85
			273.15	2.79	2.79
			263.15	1.92	1.92
			253.15	1.22	1.22

[a] Ratio for purified alcohol (MPLC); due to signal overlap in both ^{1}H-NMR spectra and in GLC, ratios could not be determined accurately for other temperatures; they stay in the same range, however. — [b] See footnote [a] of Table 1.

tramolecular ate complexes between boronates and carbonyl donor groups[17] and also on the basis of recent ab initio calculations[7] of the transition state for the addition of formaldehyde to allylboronic acid. Hence, the spiro ortholactones **18** and **19**, in which the boron atom of **8** or **9** is replaced by a carbon atom, were considered to be suitable model compounds. A further replacement of the oxygen atom in the six-membered ring by a carbon atom is represented by the spiro acetals **16** and **17**. Comparison of the conformer equilibria of **16** to **17** and of **18** to **19** should allow to quantify the steric effect of residues on the dioxaborolane ring. Comparison of the equilibria of **16** to **18** and of **17** to **19** should provide information on any polar effects involving the intra-ring oxygen atom.

Scheme 7



Steric Effect: The conformer equilibria of the compounds **16** to **19**[13] show that the preference of the substituent X to take up an axial position is markedly influenced by the size of the residues on the glycol component. Thus, an increase in the bulk of the glycol component leads to a lower proportion of the conformer with X in an equatorial position. The steric effect is more pronounced with the acetals **16** and **17** than with the spiro ortholactones.

Polar Effect: In addition to the steric effect an energetically weaker polar effect determines the conformer equilibria of the model compounds **16** to **19**. In the case of the acetals **16** and **17**, the percentage of axial conformer increases with increasing polarity of X. This corresponds to the observed increase in (Z) selectivity on addition of α-substituted boronates **4** to aldehydes with increasing polarity of X.

A polar substituent effect is also noted in the conformer equilibria of the spiro ortholactones **18** and **19**. Surprisingly, the ordering is different: The equatorial position becomes more preferred if X becomes more polar, a trend which does not agree with the stereoselectivities observed in the allylboration reaction. In terms of polar effects, however, **18** and **19** might not come as close to the transition state of the allylboration reaction as might be assumed: It is quite obvious from X-ray analyses of intramolecular ate complexes[17] and from ab initio calculations[7] that the bond from the boron to the oxygen atom of the aldehyde group is considerably longer (by 0.074 and 0.13 Å, respectively) than the other boron–oxygen bond(s). The polar influence of the oxygen atom in the six-membered ring may therefore be higher in the model compounds **18** and **19** than in the transition state they should mimick. As a consequence, we propose that the best model for the steric and polar effects in the transition states of the allylboration reaction would be a blend of the acetals **16** (or **17**) and the orthoesters **18** (or **19**), in which the acetals would be more heavily weighted.

Such a model could account for the stereoselectivity in the formation of the (Z)- and (E)-homoallylic alcohols **5**, **6** on addition of α-substituted allylboronates **4** to aldehydes without making recourse to stereoelectronic considerations. In fact, the relative rates of the allylboration reaction of various representative allylboronates **4** were found not to be in accord with predictions based on the "stereoelectronic model".

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Experimental

All solvents were distilled prior to use and dried by standard procedures where needed. All reactions were performed under dry, oxygen-free nitrogen. The titre of *n*-butyllithium solutions was determined according to ref.[18]. Routine ^{1}H- and ^{13}C-NMR spectra were recorded with a Bruker AC 300. ^{1}H-NMR integrations for kinetic runs were performed with a Bruker WH-400. Solvent peaks were used to calibrate the spectra on the δ scale. Melting points were determined with a Kofler hotstage and are given uncorrected.

Combustion analyses were performed by the Microanalytical Department of the Philipps-Universität, Marburg. For the preparation and characterisation of compounds **10a–d**, **11a,b**, and **12a,b**, see ref.[19].

1. *4,4,5,5-Tetramethyl-2-(1-methyl-2-propenyl)-1,3,2-dioxaborolane* (**4b**): To a solution of 7.66 g (37.9 mmol) of 2-(1-chloro-2-propenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane in 25 ml of dry THF was added with stirring within 30 min at −78°C 50 ml (37.9 mmol) of a 0.757 M solution of methylmagnesium bromide in THF. Stirring was continued for further 30 min at this temperature; the cooling bath was then removed, and stirring was continued for ca. 12 h. The solvent was removed in vacuo, and the residue was taken up in 100 ml of petroleum ether (boiling range 40–60°C) and filtered. The crude product (8.42 g) resulting after removal of the solvent, was fractionated through a 15-cm vacuum-jacketed Vigreux column to yield 5.33 g (77%) of the ester **4b** as a colourless oil of b.p. 61.5–63.5°C/12 Torr. – ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.07 (d, *J* = 7.3 Hz, 3H), 1.21 (s, 12H), 1.87 (br. quint, *J* = 7.2 Hz, 1H), 4.90 (ddd, *J* = 10.3, ca. 1.7, and ca. 1.7 Hz, 1H), 4.95 (ddd, *J* = 17.2, ca. 1.8, and ca. 1.8 Hz, 1H), 5.92 (ddd, *J* = 17.1, 10.3, and 7.3 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 14.1, ca. 23.0 (very br.), 24.6, 83.1, 111.9, 140.9.

$C_{10}H_{19}BO_2$ (182.1) Calcd. C 65.97 H 10.52
Found C 65.83 H 10.69

2. *2-(1-Bromo-2-propenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane* (**4d**) was prepared from 21.4 g (71.5 mmol) of 2-(dibromomethyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane as described[3] by using vinylmagnesium bromide instead of vinylmagnesium chloride. The concentration of the Grignard reagent was kept low, and the reaction mixture was handled at the lowest possible temperature in order to minimize rearrangement of **4d** to (*E*/*Z*)-2-(3-bromo-1-propenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane. Bulb-to-bulb distillation at 0.005 Torr (<35°C) gave 17.4 g (98%) of **4d**, containing 5% of the rearrangement product. – ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.24 (s, 12H), 3.86 (br. d, *J* = 9.8 Hz, 1H), 5.09 (ddd, *J* = 9.9, 0.8, and 0.8 Hz, 1H), 5.28 (ddd, *J* = 16.8, 1.0, and 1.0 Hz, 1H), 6.04 (ddd, *J* = 16.9, 9.9, and 9.9 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 24.4, ca. 33.4 (br.), 84.2, 118.1, 135.3.

$C_9H_{16}BBrO_2$ (246.9) Calcd. C 43.78 H 6.53
Found C 43.91 H 6.68

3. *2-(1-Chloro-2-propenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane* (**4e**) was prepared according to ref.[3] and fractionated through a 1-m spinning-band column to yield the pure ester of b.p. 49.8–50.3°C/2 Torr. – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 24.4, ca. 44.9 (br.), 84.6, 117.0, 134.9.

$C_9H_{16}BClO_2$ (202.5) Calcd. C 53.39 H 7.96
Found C 53.26 H 7.87

4. *2-(1-Methoxy-2-propenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane* (**4f**) was prepared as described in ref.[3]. It was purified by fractionation through a 1-m spinning-band column; b.p. 52.8–55.0°C/23 Torr. – ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.22 (s, 12H), 3.28 (s, 3H), 3.62 (dt, *J* = 7.1, and ca. 1.5 Hz, 1H), 5.12 (ddd, *J* = 10.5, 1.5, and 1.5 Hz, 1H), 5.22 (ddd, *J* = 17.3, 1.6, and 1.6 Hz, 1H), 5.79 (ddd, *J* = 17.4, 10.4 and 7.1 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 24.4, 57.7, ca. 72.6 (br.), 83.9, 115.3, 135.4.

$C_{10}H_{19}BO_3$ (198.1) Calcd. C 60.64 H 9.67
Found C 60.75 H 9.66

5. *4,4,5,5-Tetramethyl-2-(1-methylthio-2-propenyl)-1,3,2-dioxaborolane* (**4g**) was prepared as described for the analogous ethylthio ester[3]. The product **4g** was obtained in 68% yield after distillation at 56°C/0.5 Torr. It was contaminated by ca. 7% of (*E*/*Z*)-2-(3-methylthio-1-propenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane. – ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.20 (s, 12H), 1.97 (s, 3H), 2.72 (d, *J* = 9.4 Hz, 1H), 5.01 (ddd, *J* = 17.4, 1.4, and 0.9 Hz, 1H), 5.01 (ddd, *J* = 9.5, 1.8, and 0.6 Hz, 1H), 5.70 (ddd, *J* = 17.4, 9.4, and 9.4 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 14.4, 24.5, ca. 33.1 (br.), 83.9, 115.9, 135.0.

$C_{10}H_{19}BSO_2$ (214.1) Calcd. C 56.09 H 8.94
Found C 55.58 H 8.79

The rearrangement products showed additional ^{13}C-NMR signals at δ = 24.7, 38.7, 83.1, 147.9 and 24.7, 33.7, 83.0, 148.6.

6. *4,4,5,5-Tetramethyl-2-(2-propenyl)-1,3,2-dioxaborolane* (**4h**) was prepared according to a procedure by Matteson[20]; b.p. 58.5–59.5°C/12 Torr. – ^{1}H NMR (300 MHz, $CDCl_3$): δ = 1.18 (s, 12H), 1.66 (br. d, *J* = 7.5 Hz, 2H), 4.86 (ddt, *J* = 10.0, 2.0 and 1.3 Hz, 1H), 4.93 (ddt, *J* = 17.1, 1.8 and 1.8 Hz, 1H), 5.79 (ddt, *J* = 17.1, 10.0 and 7.5 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = ca. 18.0 (br.), 24.7, 83.2, 114.8, 134.0.

$C_9H_{17}BO_2$ (168.0) Calcd. C 64.33 H 10.20
Found C 64.05 H 10.34

7. *2-(1,1-Dimethyl-2-propenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane* (**4i**): To a solution of 7.30 g (29.3 mmol) of 2-(1-bromo-1-methylethyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane[21] in 20 ml of dry ether was added at −78°C 60 ml (30 mmol) of a 0.5 M solution of vinylmagnesium bromide in THF. The mixture was allowed to warm to room temperature within ca. 12 h. The solvents were removed in vacuo, and the residue was diluted with 10 ml of petroleum ether (boiling range 40–60°C). It was washed with 10 ml each of water and brine, and dried with Na_2SO_4. The solvents were removed in vacuo, and the residue was fractionated through a 15-cm vacuum-jacketed Vigreux column; 3.78 g (66%) of the boronic ester **4i**, b.p. 27°C/0.5 Torr. This product contained minor impurities and was recrystallized from ca. 8.0 ml of petroleum ether (boiling range 40–60°C) at −20°C. Despite of their sharp melting point at 27–28°C, the crystals were still not totally pure as judged by ^{1}H NMR. The total material was therefore chromatographed on 200 g of silica gel with ethyl acetate/petroleum ether (boiling range 40–60°C) (5:95) to yield pure **4i**. – ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.97 (s, 6H), 1.19 (s, 12H), 4.88 (dd, *J* = 17.7 and 1.5 Hz, 1H), 4.88 (dd, *J* = 10.3 and 1.5 Hz, 1H), 5.93 (dd, *J* = 17.7 and 10.3 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 23.5, 24.5, 83.1, 110.0, 146.6 (one signal not visible due to relaxation by the ^{11}B nucleus).

$C_{11}H_{21}BO_2$ (196.1) Calcd. C 67.38 H 10.79
Found C 67.56 H 10.98

Kinetic Measurements. – Typical Run: The data for the reaction of the (α-chloroallyl)boronate **4e** with propanal at 283 K are representative: 200.8 mg (1.0 mmol) of the boronate **4e** and 57.6 mg (1.0 mmol) of propanal (freshly distilled under nitrogen) were separately dissolved in $CDCl_3$ to 5 ml of volume each. The solutions were injected under nitrogen into two separate compartments of a predried glass apparatus. The two compartments were connected to a third one by teflon stopcocks. The apparatus was placed in a cryostat, and the solutions were allowed to reach thermal equilibrium for 10 min. The third compartment was then evacuated, and the first and second were pressurised with nitrogen. By opening of the stopcocks the two solutions were introduced into the third compartment, which was subsequently repressurised with nitrogen. Aliquots were withdrawn in defined time intervals and were injected into evacuated NMR tubes which were cooled with liquid nitrogen. For reactions run at lower temperatures the syringe was precooled with dry ice; the total time for withdrawing the sample and com-

pleted injection never exceeded 10 s. The ^{1}H-NMR spectra of these aliquots were then recorded at −50°C and integrated. The raw data are shown in Table 3. These data were normalized with respect to the aldehyde singlet. (The values of the integrals *AT* were divided by 3.250, *AQ* by 1.985 and *DB* by 2.408, these factors were determined by averaging over all ratios.) According to the formalism of second-order kinetics, the numerical value of *C* was divided by the numbers thus obtained. The results are presented in Table 4. Linear regression analysis yielded a descent of $9.95 \cdot 10^{-3} \pm 2.7 \cdot 10^{-4}$ and a *y* intercept of 1.318 ± 0.044, the correlation coefficient was 0.987. Figure 3 is a plot of these data. – In nearly all other runs, TMS (about 10 mg) was added to the reaction mixture, and its signal was used as a second internal standard.

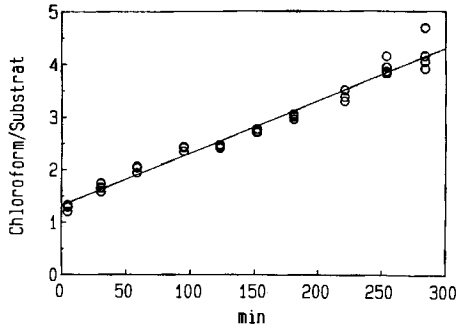

Figure 3. Typical plot of the kinetic data

Table 3. Raw data for the reaction of the (α-chloroallyl)boronate **4e** with propionaldehyde in $CDCl_3$ at 283 K[a]

#	*t* [min]	*AS*	*AT*	*AQ*	*DB*	*C*
1	5	2.102	6.879	4.512	4.949	2.740
2	31	3.550	11.486	7.391	8.115	5.888
3	59	2.956	9.448	6.153	7.028	6.019
4	95	2.484	8.021	5.076	5.935	6.009
5	123	2.393	7.713	4.776	5.644	5.809
6	152	2.161	6.859	4.278	5.163	5.855
7	181	1.903	6.385	3.727	4.637	5.820
8	221	1.713	5.361	3.280	4.229	5.801
9	254	2.934	9.828	5.533	7.213	11.571
10	284	1.380	4.602	2.431	3.532	5.739

[a] *AS, AT, AQ:* aldehyde singlet, triplet and quartet; DB: vinylic protons of the product; C: chloroform.

Table 4. Data used for the regression analysis[a]

#	*t* [min]	*AS*	*AT*	*AQ*	*DB*
1	5	1.3033	1.2944	1.2053	1.3331
2	31	1.6586	1.6660	1.5813	1.7472
3	59	2.0361	2.0703	1.9417	2.0623
4	95	2.4190	2.4349	2.3500	2.4381
5	123	2.4278	2.4477	2.4142	2.4781
6	152	2.7092	2.7744	2.7169	2.7307
7	181	3.0585	2.9620	3.0100	3.0223
8	221	3.3859	3.5165	3.5110	3.3028
9	254	3.9438	3.8266	4.1512	3.8629
10	284	4.1577	4.0528	4.6858	3.9128

[a] See footnote of Table 3.

Determination of the (E)/(Z) Ratios of the Homoallylic Alcohols **15**, **14** *Obtained by Reaction of the Allylboronates* **4** *with Propanal:* To a solution of 1 mmol of the respective α-substituted allylboronate in 1 ml of chloroform (previously treated with activated basic alumina) in a thermostat was added 1 ml of a 1 M solution of propanal in chloroform. The mixture was kept for a period of 24–72 h at a constant temperature ranging between −20 and +22°C, depending on substrate and reaction temperature. The mixture was then diluted with 10 ml of petroleum ether (boiling range 40–60°C) and washed twice with 5 ml each of water. The phases were separated, and the organic layer was dried with Na_2SO_4. The crude product was purified without separation of diastereomers by MPLC (ethyl acetate/petroleum ether). Identification of the produced homoallylic alcohols and assignment of their (*E*)/(*Z*) ratios was then based on the ^{13}C- and ^{1}H-NMR spectra of the mixtures. The isomer ratios were then determined by GLC analyses on the crude unpurified reaction mixtures using a 30-m quartz capillary column. Accuracy in determination of the product ratios by capillary GLC was made difficult, because all the stationary phases used (SE-52, Supel-Cowax 10, and OV 17-01, in conjunction with a Sichromat 3) tended to give symmetry-distorted peaks. Nevertheless, it is obvious that the product ratios changed only marginally with the reaction temperature and that in general good agreement with the values determined by ^{13}C- or ^{1}H-NMR spectroscopy is found. – The products were identified or characterised by their ^{1}H- and ^{13}C-NMR spectra as follows.

(Z)-5-Hydroxy-2-heptene (**14b**): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.88 (t, *J* = 7.5 Hz, 3H), 1.41 (apparent quint, *J* = ca. 7.0 Hz, 2H), 1.56 (ddt, *J* = 6.7, 1.6, and 0.8 Hz, 3H), 2.00 (br. s, 1H), 2.17 (tq, *J* = ca. 7.0, and ca. 0.7 Hz, 2H), 3.48 (quint, *J* = 6.2 Hz, 1H), 5.37 (dtq, *J* = 10.9, 7.5, and 1.7 Hz, 1H), 5.55 (dqt, *J* = 10.9, 6.7, and 1.4 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 9.8, 12.8, 29.4, 34.4, 72.7, 126.2, 126.7.

(E)-5-Hydroxy-2-heptene (**15b**): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.86 (t, *J* = 7.5 Hz, 3H), ca. 1.42 (m, 2H), 1.61 (dq, *J* = 6.1 and ca. 1.1 Hz, 3H), ca. 2.00 (obscured m, 1H), ca. 2.16 (obscured m, 1H), 3.43 (tt, *J* = 7.0, and 4.9 Hz, 1H), ca. 5.36 (obscured, 1H), ca. 5.48 (dqt, *J* = ca. 15, ca. 6.1, and ca. 1 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$). δ = 9.8, 17.8, 29.3, 40.1, 72.2, 127.2, 128.4.

(Z)-1-Bromo-4-hydroxy-1-hexene (**14d**): The spectra agreed with those described in ref.[3].

(E)-1-Bromo-4-hydroxy-1-hexene (**15d**): ^{1}H NMR (300 MHz, $CDCl_3$) all signals obscured, except: 3.54 (tt, *J* = ca. 7 and ca. 5 Hz). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = (9.8), 29.5, 40.2, 71.8, 106.5, 134.3.

(Z)-1-Chloro-4-hydroxy-1-hexene (**14e**): The spectra agreed with those described in ref.[3].

(E)-1-Chloro-4-hydroxy-1-hexene (**15e**): ^{1}H NMR (300 MHz, $CDCl_3$): All signals obscured, except 3.52 (tt, *J* = 7.2 and 5.0 Hz). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = (9.8), 29.5, 38.1, 72.0, 119.0, 130.1.

(Z)-4-Hydroxy-1-methoxy-1-hexene (**14f**): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.88 (t, *J* = 7.4 Hz, 3H), 1.43 (m, 2H), 2.01 (br. s, 1H), 2.16 (m, 2H), 3.48 (apparent quint, 6.3 Hz, 1H), 3.53 (s, 3H), 4.36 (td, *J* = 7.6 and 6.3 Hz, 1H), 5.96 (dt, *J* = 6.3 and 1.3 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 9.9, 29.5, 31.4, 59.4, 72.9, 102.1, 148.1.

(E)-4-Hydroxy-1-methoxy-1-hexene (**15f**): ^{1}H NMR (300 MHz, $CDCl_3$): All signals obscured, except 4.66 (ddd, *J* = 12.8, 8.4, and 7.1 Hz, 1H), 6.30 (dt, *J* = 12.5 and ca. 1 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = (9.9), 29.2, 35.1, 55.9, 72.7, 98.3, 149.3.

(Z)-4-Hydroxy-1-methylthio-1-hexene (**14g**): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.89 (t, *J* = 7.4 Hz, 3H), 1.44 (m, 2H), 1.87 (br. s, 1H), ca. 2.18–2.28 (m, 2H), 2.22 (s, 3H), 3.56 (tt, *J* = 7.1 and

5.1 Hz, 1H), 5.55 (dt, J = 9.5 and 7.3 Hz, 1H), 5.97 (dt, J = 9.5 and 1.3 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = 9.8, 16.9, 29.7, 36.5, 72.6, 124.4, 129.4.

(E)-4-Hydroxy-1-methylthio-1-hexene (**15g**): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.88 (t, J = 7.4 Hz, 3H), ca. 1.44 (obscured m, 2H), 1.87 (br. s, 1H), ca. 2.08–2.32 (m, 2H), 2.19 (s, 3H), 3.48 (tt, J = 7.2 and 4.9 Hz, 1H), 5.35 (dt, J = 14.8 and 7.4 Hz, 1H), 6.04 (dt, J = 15.0 and 1.2 Hz, 1H). – ^{13}C NMR (75 MHz, $CDCl_3$): δ = (9.8), 14.8, 29.3, 40.6, 72.4, 122.4, 127.1.

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4b: 75851-67-1 / **4d**: 87921-49-1 / **4e**: 75927-58-1 / **4f**: 87921-52-6 / **4g**: 129813-20-3 / **4h**: 72824-04-5 / **4i**: 129813-21-4 / **10a**: 87100-28-5 / **10b**: 129813-26-9 / **10c**: 129813-27-0 / **10d**: 129813-28-1 / **14b**: 64884-86-2 / **14d**: 87921-56-0 / **14e**: 87921-54-8 / **14f**: 129813-22-5 / **14g**: 97369-80-7 / **15b**: 64884-87-3 / **15d**: 102787-36-0 / **15e**: 102850-35-1 / **15f**: 129813-23-6 / **15g**: 97370-34-8 / CH_3CH_2CHO: 123-38-6 / 2-(dibromomethyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane: 87921-48-0 / (*E*)-2-(3-methylthio-1-propenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane: 129813-24-7 / (*Z*)-2-(3-methylthio-1-propenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane: 129813-25-8 / 2-(1-bromo-1-methylethyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane: 76347-16-5

[1] For part 36, see: R. W. Hoffmann, A. Schlapbach, *Liebigs Ann. Chem.* **1990**, 1243.
[2] See, for instance: D. D. Ridley, M. A. Smal, *Austr. J. Chem.* **33** (1980) 1345, D. Hoppe, R. Hanko, A. Brönneke, F. Lichtenberg, E. van Hülsen, *Chem. Ber.* **118** (1985) 2822, and references therein.
[3] R. W. Hoffmann, B. Landmann, *Chem. Ber.* **119** (1986) 1039.
[4] R. W. Hoffmann, U. Weidmann, *J. Organomet. Chem.* **195** (1980) 137.
[5] T. Hayashi, N. Fujitaka, T. Oishi, T. Takeshima, *Tetrahedron Lett.* **21** (1980) 303.
[6] See, for example: C. Heathcock in *Asymmetric Syntheses* (J. D. Morrison, Ed.), vol. 3, p. 154, Academic Press, New York 1984.
[7] Y. Li, K. N. Houk, *J. Am. Chem. Soc.* **111** (1989) 1236.
[8] K. K. Wang, Y. G. Gu, C. Liu, *J. Am. Chem. Soc.* **112** (1990) 4424.
[9] J. A. Hirsch, *Top. Stereochem.* **1** (1967) 199; J. Hine, *Structural Effects on Equilibria in Organic Chemistry*, p. 114, J. Wiley, New York 1975.
[10] S. L. Schreiber, K. Satake, *J. Am. Chem. Soc.* **105** (1983) 6723; S. J. Danishefsky, E. Larson, J. D. Springer, *J. Am. Chem. Soc.* **107** (1985) 1274; K. N. Houk, S. R. Moses, Y.-D. Wu, N. G. Rondan, V. Jäger, R. Schohe, F. R. Fronczek, *J. Am. Chem. Soc.* **106** (1984) 3880.
[11] J. I. Seeman, *Chem. Rev.* **83** (1983) 83.
[12] S. F. Nelsen, Madison, personal communication.
[13] J. J. Wolff, G. Frenking, *Chem. Ber.* **124** (1991) 551, preceding publication.
[14] B. Wrackmeyer, R. Köster in *Methoden der Organischen Chemie* (Houben-Weyl), vol. 13/3c, p. 536, G. Thieme Verlag, Stuttgart 1983.
[15] M. Lauer, G. Wulff, *J. Chem. Soc., Perkin Trans. 2*, **1987**, 745.
[16] G. Frenking, K. Köhler, Marburg, personal communication.
[17] See, for example: S. J. Rettig, J. Trotter, *Can. J. Chem.* **54** (1976) 1168, and references therein.
[18] L. Duhamel, J. C. Plaquevent, *J. Org. Chem.* **46** (1981) 1309.
[19] J. J. Wolff, *Dissertation*, Univ. Marburg, 1989.
[20] D. S. Matteson, D. Majumdar, *Organometallics* **2** (1983) 230.
[21] R. W. Hoffmann, H. J. Zeiß, *J. Org. Chem.* **46** (1981) 1309.

[234/90]