Organoboranes. 53. A High-Field Variable-Temperature ^1H and ^{11}B NMR Study of the Effects of Solvent and Structure on Reactivity in Allylboration

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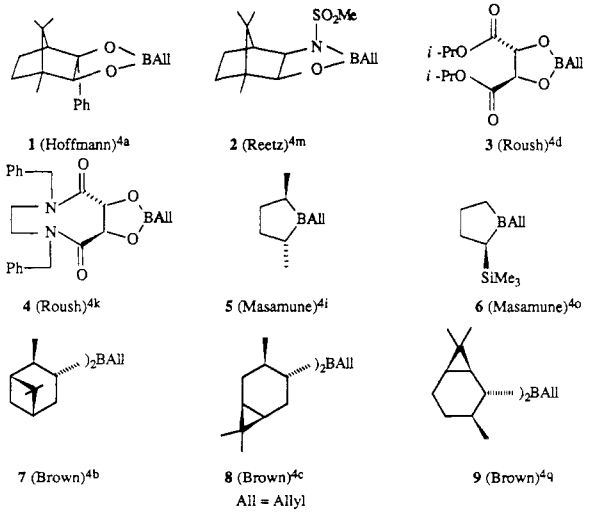
In order to evaluate the importance of solvent, temperature, and structural effects on the rates of allylboration, the reactions of benzaldehyde with structurally representative allylboron reagents were examined under a variety of conditions by high-field variable-temperature ^1H and ^{11}B NMR spectroscopy. In general, polar solvents which are poorly coordinating enhance the rate of allylboration while solvents capable of relatively stronger coordination retard the rate. α-Trisubstituted aldehydes undergo allylboration relatively slowly compared to the less substituted aldehydes. Among cyclic allylboronates, the 1,3,2-dioxaborolane derivatives, **14–17**, undergo allylboration more rapidly compared to the *B*-allyl-1,3,2-dioxaborinane (**11**). In contrast to the cyclic allylboronates **14–16** which exhibit resistance to allylboration at −78 °C, the *B*-allyl-1,3,2-dioxabenzoborole (**17**) undergoes exceptionally rapid allylboration (100%, <30 s, −50 °C). While the reactivity of *B*-allyl-1,3,2-oxazaborolidines **18** and **19** is comparable to that of *B*-allyl-1,3,2-dioxaborolane (**16**), the *B*-allyl-3-(*p*-tolylsulfonyl)-1,3,2-oxazaborolidine (**20**) undergoes allylboration remarkably rapidly, even at −78 °C. The acyclic allylboronates **21–25** undergo, without exception, more rapid allylboration at 0 °C compared to allyl-1,3,2-dioxaborinane (**11**). Moreover, the *B*-allylbis(benzyloxy)borane (**24**) and allylboronic acid (**25**) undergo allylborations relatively rapidly, even at −50 °C. While the tartramide reagent **26** undergoes allylboration at −78 °C relatively slowly, the tartrate ester derivative **3** (Roush's reagent) undergoes effortless allylboration under identical conditions. These individual variations in the rates of allylboration of the boronate derivatives can be rationalized essentially in terms of the relative availability of the lone pairs of electrons on the atoms attached to boron. The *B*-allyldiisopinocampheylborane (**7**) and *B*-allyldi(4-isocaranyl)borane (**8**) undergo instantaneous allylborations at −78 °C and have thus proven to be among the most reactive of the allylboron reagents presently known.

The importance of allyl- and crotylboron reagents in acyclic stereoselection has been amply demonstrated by many research groups over the past few years. Required to support applications in natural product syntheses,[3] efforts are constantly made toward the development of new reagents that can generate contiguous diastereomeric relationships with exceptional selectivity.[4] Interestingly, although many reagents **1–9** have gained prominence,[22] a systematic understanding of the factors controlling reactivity in allylboration, such as the solvent, temperature, the structures of the aldehyde, and that of the chiral auxiliary, is still lacking. Further, it is often very difficult to ascertain from the published reports just how reactive a particular reagent is and at what temperature the allylboration might actually be occurring.[5] Indeed, we believe that a clear understanding of the factors controlling allylboration is vital, both for improving existing methods and for designing new reagents capable of achieving enantio- and diastereoselectivities approaching 100%. Consequently, we report herein the first detailed examination of the effects of solvent, temperature, the structure of the aldehyde, and the structure of the allylboron reagent on the rates of allylborations as determined by high-field variable-temperature ^1H and ^{11}B NMR spectroscopy.



Results and Discussion

Effect of Solvent. To start with, we decided to utilize *B*-allyl-1,3,2-dioxaborinane (**11**) as a model compound and examine its reaction with benzaldehyde **10** (as a model aldehyde) in several representative organic solvents[6] such

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(3) (a) Roush, W. R.; Harris, D. J.; Lesur, B. M. *Tetrahedron Lett.* **1983**, 2227. (b) Moret, E.; Schlosser, M. *Ibid.* **1984**, 4491. (c) Roush, R. W.; Peseckis, S. M.; Walts, A. E. *J. Org. Chem.* **1984**, *49*, 3429. (d) Ditrich, K.; Bube, T.; Stürmer, R.; Hoffmann, R. W. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 1028. (e) Hoffmann, R. W.; Endesfelder, A. *Justus Liebigs Ann. Chem.* **1986**, 1823. (f) Roush, W. R.; Michaelides, M. R.; Tai, D. F.; Chong, W. K. M. *J. Am. Chem. Soc.* **1987**, *109*, 7575. (g) Roush, W. R.; Palkowitz, A. D. *Ibid.* **1987**, *109*, 953. (h) Khandekar, G.; Robinson, G. C.; Stacey, A. N.; Steel, P. G.; Thomas, E. J.; Rather, S. *J. Chem. Soc., Chem. Commun.* **1987**, 877. (i) Merrifield, E.; Steel, P. G.; Thomas, E. J. *Ibid.* **1987**, 1826.

(4) (a) Hoffmann, R. W.; Herold, T. *Chem. Ber.* **1981**, *114*, 375. (b) Brown, H. C.; Jadhav, P. K. *J. Am. Chem. Soc.* **1983**, *105*, 2092. (c) *J. Org. Chem.* **1984**, *49*, 4089. (d) Roush, W. R.; Walts, A. E.; Hoong, L. K. *J. Am. Chem. Soc.* **1985**, *107*, 8786. (e) Brown, H. C.; Bhat, K. S. *Ibid.* **1986**, *108*, 293. (f) Roush, W. R.; Hatterman, R. L. *Ibid.* **1986**, *108*, 294. (g) Brown, H. C.; Bhat, K. S.; Randad, R. S. *J. Org. Chem.* **1987**, *52*, 319. (h) *Ibid.* **1987**, *52*, 3701. (i) Garcia, J.; Kim, B. M.; Masamune, S. *Ibid.* **1987**, *52*, 4831. (j) Brown, H. C.; Jadhav, P. K.; Bhat, K. S. *J. Am. Chem. Soc.* **1988**, *110*, 1535. (k) Roush, W. R.; Banfi, L. *Ibid.* **1988**, *110*, 3979. (l) Roush, W. R.; Ando, K.; Powers, D. B.; Hatterman, R. L.; Palkowitz, A. D. *Tetrahedron Lett.* **1988**, 5579. (m) Reetz, M. T.; Zierke, T. *Chem. Ind.* **1988**, 663. (n) Hoffmann, R. W. *Pure Appl. Chem.* **1988**, *60*, 123 and its references. (o) Short, R. P.; Masamune, S. *J. Am. Chem. Soc.* **1989**, *111*, 1892. (p) Corey, E. J.; Yu, C.-M.; Kim, S. S. *Ibid.* **1989**, *111*, 5495. (q) Brown, H. C.; Randad, R. K.; Bhat, K. S.; Zaidlewicz, M.; Racherla, U. S. *J. Am. Chem. Soc.*, in press.

(5) See for example, (a) Hoffmann, R. W.; Zeiss, H.-J. *J. Org. Chem.* **1981**, *46*, 1309. (b) Reference 4a. (c) Reference 3a. (d) Roush, W. R.; Walts, A. E. *Tetrahedron Lett.* **1985**, 3427. (e) Reference 4m. (f) Roush, W. R.; Adam, M. A.; Walts, A. E.; Harris, D. J. *J. Am. Chem. Soc.* **1986**, *108*, 3422. We are thankful to Professor William Roush for clarifying to us the nature of pinacol crotylboronates.

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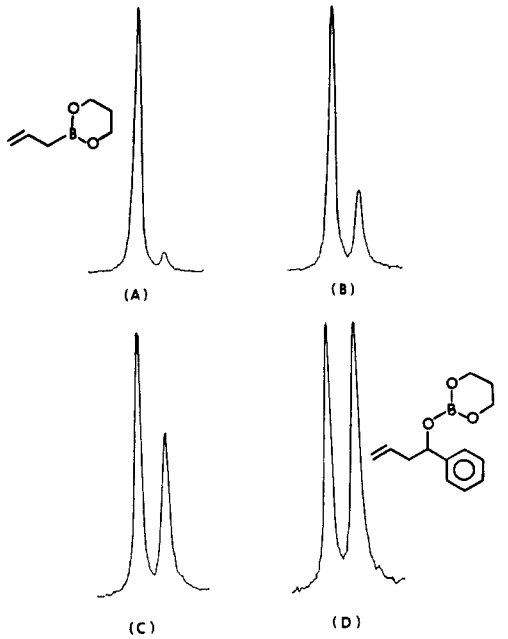
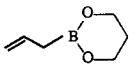


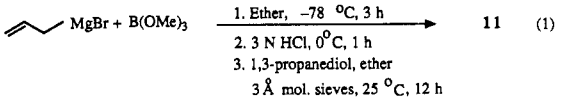
Figure 1. The progress of allylboration of benzaldehyde with *B*-allyl-1,3,2-dioxaborinane (11) in dichloromethane at 25 °C by ^{11}B NMR spectroscopy after (a) 1 min, (b) 10 min, (c) 25 min, and (d) 40 min.

as ether, tetrahydrofuran, carbon disulfide, chloroform, dichloromethane, and toluene at 25 °C by ^{11}B NMR spectroscopy.

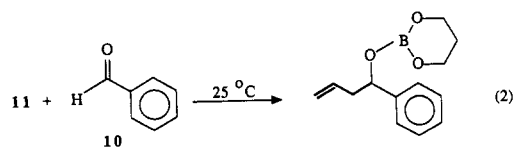


11

Accordingly, *B*-allyl-1,3,2-dioxaborinane (11) was prepared in 46% yield by treating trimethoxyborane with allylmagnesium bromide in ether, followed by hydrolysis with 3 N HCl and esterification with 1,3-propanediol in ether[7] using 3-Å molecular sieves (eq 1).



Next, a 1.0 M solution of the reagent 11 was prepared in each of the above-mentioned representative solvents. Similarly, a 1.0 M solution of benzaldehyde was also prepared in each of these solvents. The rate of reaction was determined in each case by mixing equimolar amounts of *B*-allyl-1,3,2-dioxaborinane (11) and benzaldehyde solutions (giving a reaction mixture which is 0.5 M in each component) at 25 °C and monitoring the reaction (eq 2) continuously by ^{11}B NMR spectroscopy on a Varian FT-80A NMR instrument (Figure 1).



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These results are summarized in Table I. Of the many solvents examined, allylboration occurs relatively rapidly in ether, carbon disulfide, chloroform, and dichloromethane, slower in toluene, and slower still in tetrahydrofuran. Therefore, these results indicate that poorly coordinating or noncoordinating polar solvents enhance the rate of allylboration.[8] The low polarity of toluene is presumably responsible for its relatively slow rate. On the other hand, even a polar solvent which can coordinate with the allylboron reagent, such as tetrahydrofuran, retards the rate.[9]

Table I. A Comparison of the Rates of Allylboration of Benzaldehyde with 11 in Various Common Organic Solvents at 25 °C[a]

solvent	$t_{1/2}$, min, 25 °C[b]	solvent	$t_{1/2}$, min, 25 °C[b]
ether	15	dichloromethane	40
carbon disulfide	20	toluene	90
chloroform	20	tetrahydrofuran	180

[a] [Boronate] = 0.5 M, [benzaldehyde] = 0.5 M in the indicated solvents. [b] Determined by ^{11}B NMR spectroscopy on a Varian FT-80A NMR instrument.

Table II. The Effect of Temperature on the Rate of Allylboration of Benzaldehyde with 11 in Dichloromethane[a]

temp, °C	$t_{1/2}$, min[b]
25	40[c]
0	120
−78	no reaction (12 h)

[a] [Boronate] = 0.5 M, [benzaldehyde] = 0.5 M in dichloromethane-d_2. [b] Determined by ^1H NMR spectroscopy on a Varian XL-200 NMR instrument using hexamethylethane as internal standard. [c] Determined by ^{11}B NMR spectroscopy on the Varian FT-80A instrument.

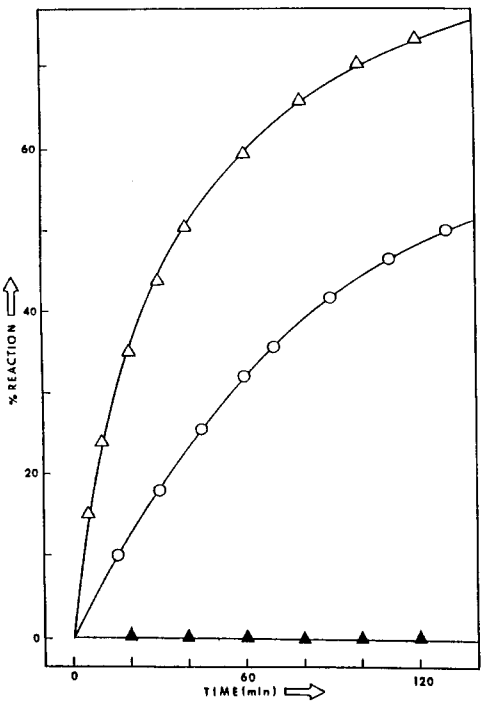


Figure 2. The effect of temperature on the rate of allylboration of benzaldehyde with *B*-allyl-1,3,2-dioxaborinane (11) in dichloromethane-d_2: (a) (△) 25 °C, (b) (○) 0 °C, and (c) (▲) ≃78 °C.

Effect of Temperature. From the above data, it appeared to us that dichloromethane should be the preferred

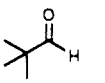
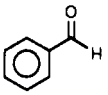
(6) Solvents which were chosen for the study included those which have been utilized in previous allylborations (see ref 4) and those which permit VT NMR.

(7) This procedure is a slightly modified version of the experimental procedure reported for the preparation of 3. See ref 4d.

(8) The dielectric constants of carbon disulfide, chloroform, dichloromethane, and ethyl ether are 2.641, 4.806, 9.08, and 4.335, respectively, at 20 °C (from *CRC Handbook of Chemistry and Physics*, 1979).

(9) Professor Roush informed us of a similar conclusion based on the unpublished experimental findings from his laboratories.

Table III. A Comparison of the Rates of Allylboration of Representative Aldehydes with 11 in Dichloromethane at 25 °C[a]

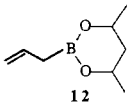
aldehyde	$t_{1/2}$, min, 25 °C[b]	aldehyde	$t_{1/2}$, min, 25 °C[b]
	25		210
	25		40

[a] [Boronate] = 0.5 M, [benzaldehyde] = 0.5 M in dichloromethane. [b] Determined by ^{11}B NMR spectroscopy on a Varian FT-80A NMR instrument.

solvent for our studies for the following reasons: (1) allylboration occurs rapidly in this solvent; (2) it is available in deuterated form (at moderate cost), which permits ^1H NMR investigations; and (3) variable-temperature NMR studies are feasible in this particular solvent up to at least −80 °C. Consequently, the effect of temperature on the rate of allylboration of benzaldehyde with **11** was examined in dichloromethane-d_2 by the ^1H NMR method.

Table II summarizes these results. The rate of allylboration slows down by a factor of three at 0 °C, while at −78 °C, practically no reaction takes place, even in 12 h (Figure 2). Indeed, this is quite surprising in view of an earlier publication, which reported that *B*-allyl-4,6-dimethyl-1,3,2-dioxaborinane (**12**) reacts with benzaldehyde (48%) in toluene at −78 °C in 20–24 h.[4d]

The effect of temperature on the rate of allylboration was investigated in greater detail in the following experiments.



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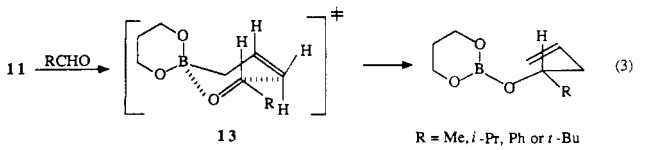
Effect of Aldehyde Structure. In order to understand the effect of the structure of the aldehyde on the rate of allylboration, the reaction of *B*-allyl-1,3,2-dioxaborinane (**11**) was examined in CH_2Cl_2 at 25 °C by ^{11}B NMR spectroscopy with three representative aldehydes: acetaldehyde, 2-methylpropionaldehyde, and 2,2-dimethylpropionaldehyde. The rates thus obtained were compared with the rate of reaction of **11** with benzaldehyde. These results are summarized in Table III.

Indeed, it is surprising that while acetaldehyde (R = Me) and 2-methylpropionaldehyde (R = *i*-Pr) react with **11** at practically identical rates, somewhat faster than benzaldehyde (R = Ph), the reaction of 2,2-dimethylpropionaldehyde (R = *t*-Bu) with **11** proceeds considerably slower.

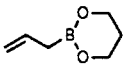
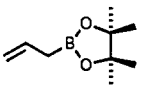
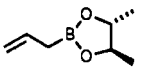
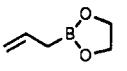
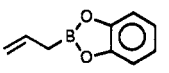
This suggests that with 2,2-dimethylpropionaldehyde (R = *t*-Bu), the steric crowding in the transition state becomes significant, as compared to less substituted aldehydes in which the R groups can rotate to reduce the steric interactions, resulting in the observed retardation of its rate of allylboration (see transition state model **13**, eq 3).



13 R = Me, *i*-Pr, Ph or *t*-Bu (3)

Effect of the Structure of the Chiral Auxiliary. The allylboron reagents reported in the literature[4] for the asymmetric synthesis of homoallylic alcohols can be classified structurally (see **1–9**) into approximately five categories:[22] I, cyclic boronate derivatives; II, oxazaborolidines; III, acyclic boronate derivatives; IV, tartrates and tartramides; V, allyldialkylboranes.

Table IV. A Comparison of the Rates of Allylborations of Benzaldehyde with Representative Cyclic Boronate Derivatives in Dichloromethane[a]

boronate	^{11}B shift (δ)[b]	$t_{1/2}$, min, 25 °C[c]	% reactn at low temp[d]
 **11**	30	40	0, 12 h, −78 °C
 **14**	33	15	0, 12 h, −78 °C
 **15**	33	10	0, 12 h, −78 °C
 **16**	33	5	12, 6 h, −78 °C
 **17**[e]	34	instantaneous	100, <30 s, −50 °C[f]

[a] [Boronate] = 0.5 M, [benzaldehyde] = 0.5 M in dichloromethane. [b] In ppm relative to $BF_3{\cdot}OEt_2$ in dichloromethane. [c] Determined by ^{11}B NMR spectroscopy on a Varian FT-80A instrument. [d] Determined by ^1H NMR spectroscopy on a Varian XL-200 NMR instrument. [e] See ref 19. [f] Determined by ^{11}B NMR spectroscopy on a Varian XL-200 NMR instrument.

In order to understand more precisely the effect of the structure of the chiral auxiliary on the rate of allylboration, we prepared several representative allylboron reagents corresponding to each of the above five categories and examined their reactions with benzaldehyde by high-field variable-temperature ^1H and ^{11}B NMR spectroscopy. Tables IV–VIII summarize these results.

I. Cyclic Boronate Derivatives (Table IV). The allylboronate reagents **14–17** were prepared in 45–60% yields from pinacol,[5f] 2,3-butanediol,[4d] ethylene glycol, and catechol, respectively, following the general procedure outlined for **11** (eq 1). The rates of reactions of these reagents with benzaldehyde were then systematically examined in dichloromethane.

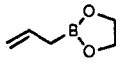
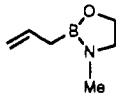
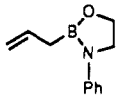
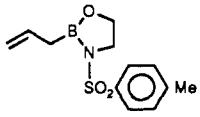
In general, the five-membered cyclic boronate derivatives are more reactive in allylborations than the six-membered. Thus, the reagents **14–17** react with benzaldehyde at 25 °C more rapidly compared to **11**. Among the five-membered cyclic boronate derivatives, the order of reactivity at 25 °C is **17** >>> **16** > **15** > **14**.

Just as with **11**, practically no allylboration could be observed with the reagents **14** and **15** at −78 °C in dichloromethane.[10,11] Interestingly, while **16** shows evidence of slow allylboration at −78 °C (12% in 6 h), the reagent **17** undergoes instantaneous allylboration at −50 °C.

A possible explanation for the above results is as follows. Reagents **14–17**, possessing a five-membered cyclic boronate auxiliary, are comparatively less sterically hindered and may be more electrophilic than **11**, which possesses

(10) Wuts, P. G. M.; Jung, Y. W. *Tetrahedron Lett.* **1986**, 2079.
(11) (a) See ref. 5. (b) Hoffmann, R. W.; Kemper, B.; Matternich, R.; Lehmeier, T. *Justus Liebigs Ann. Chem.* **1985**, 2246. (c) Hoffmann, R. W.; Endesfelder, A. *Ibid.* **1986**, 1823. (d) Hoffmann, R. W.; Landmann, B. *Chem. Ber.* **1986**, *119*, 1039.

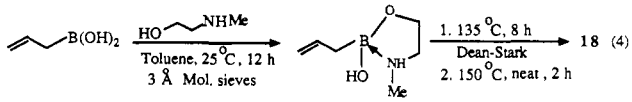
Table V. A Comparison of the Rates of Allylborations of Benzaldehyde with Representative Oxazaborolidines in Dichloromethane[a]

boroxazoline	^{11}B shift (δ)[b]	$t_{1/2}$, min, 25 °C[c]	% reactn at low temp
 **16**	33	5	12, 6 h, −78 °C
 **18**	33	3	
 **19**	33	2	
 **20**	37	instantaneous	100, 10 min, −78 °C

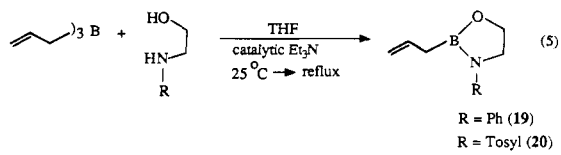
[a] [Boronate] = 0.5 M, [benzaldehyde] = 0.5 M in dichloromethane. [b] In ppm relative to $BF_3{\cdot}OEt_2$ in dichloromethane. [c] Determined by ^{11}B NMR spectroscopy on a Varian FT-80A instrument.

a six-membered cyclic boronate auxiliary. The ^{11}B NMR chemical shifts of **14–17** are consistently downfield by +3 to +4 ppm, compared to **11**. These factors should help the reagents **14–17** in attaining a more compact cyclic transition state in allylboration, compared to **11** (see **13**) and therefore enhance the rate of allylboration relative to **11**. While the minor rate differences in the allylboration of **14–16** may be accounted for on purely steric grounds, some other factor must be introduced to explain why **17** is so much more reactive, as compared to the other reagents. It appears that the delocalization of lone-pairs of electrons from the oxygen atoms onto the phenyl ring significantly reduces the n → p (boron) back-donation and increases the electrophilicity of the boron atom in **17**, a factor which can enhance its rate of allylboration relative to the others.

II. 1,3,2-Oxazaborolidines (Table V). The *B*-allyl-3-methyl-1,3,2-oxazaborolidine (**18**) was prepared in good yield (70%) according to the procedure shown below (eq 4).

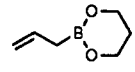
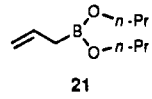
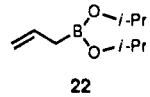
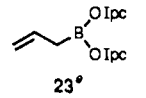
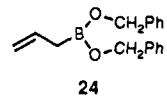
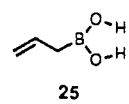


However, the reagents, *B*-allyl-3-phenyl-1,3,2-oxazaborolidine (**19**) and *B*-allyl-3-(*p*-tolylsulfonyl)-1,3,2-oxazaborolidine (**20**), could not be prepared by the above method. Consequently, we prepared these reagents cleanly according to the experimental procedure reported by Reetz and co-workers for the synthesis of **2**[4m] (eq 5).



At 25 °C, the rates of reactions of the oxazaborolidines **18** and **19** with benzaldehyde are approximately comparable with that of *B*-allyl-1,3,2-dioxaborolane (**16**). Interestingly, however, *B*-allyl-3-(*p*-tolylsulfonyl)-1,3,2-oxazaborolidine (**20**) reacts instantaneously with benzaldehyde at 25 °C. In fact, the reagent **20** undergoes allylboration even at −78 °C in an effortless fashion[22] (100% in 10 min). In view of this, it is very likely that Reetz's reagent **2** may also be undergoing the reported allylborations with various aldehydes at −78 °C itself.[4m]

Table VI. A Comparison of the Rates of Allylboration of Benzaldehyde with Representative Acyclic Boronates in Dichloromethane[a]

boronate	^{11}B shift (δ)[b]	$t_{1/2}$, min, 0 °C[c]	% reactn at low temp
 **11**	30	120	
 **21**	30	5	
 **22**	30	9	
 **23**[e]	30	(3)[d]	
 **24**	31	instantaneous	50, 0.5 h, −50 °C
 **25**	32	instantaneous	100, <30 s, −50 °C

[a] [Boronate] = 0.5 M, [benzaldehyde] = 0.5 M in dichloromethane. [b] In ppm relative to $BF_3{\cdot}OEt_2$ in dichloromethane. [c] Determined by ^{11}B NMR spectroscopy on a Varian XL-200 NMR instrument. [d] Half-life at 25 °C. $t_{1/2}$ at 0 °C could not be determined by ^{11}B NMR spectroscopy due to unusual peak broadening. [e] Ipc = isopinocampheyl.

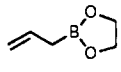
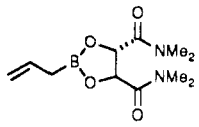
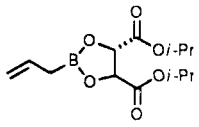
The above results may be rationalized as follows. The steric and electronic environment of boron in reagents **18** and **19** may be somewhat similar to that present in allyl-1,3,2-dioxaborolane (**16**). However, the presence of a powerful electron-withdrawing group, such as tosyl, on the nitrogen atom may significantly enhance the electrophilicity of the reagent **20** and greatly enhance its ability to undergo the allylboration reaction with benzaldehyde, even at −78 °C. In fact, the ^{11}B NMR chemical shift of the reagent **20** (viz., δ 37 ppm) is remarkably downfield compared to that of the others (δ 33 ppm).

III. Acyclic Boronates (Table VI). The acyclic allylboronates **21–25** were prepared in 40–60% isolated yields according to the method already mentioned (eq 1).

An examination of the rates of allylboration of the reagents **21–25** with benzaldehyde at 0 °C revealed that, in general, the acyclic allylboronates undergo allylboration significantly more rapidly[3b] compared to the model reagent **11**. Surprisingly, among the reagents **21–25**, the allylboronic acid (**25**) and *B*-allylbis(benzyloxy)borane (**24**) are far more reactive toward benzaldehyde than the others: **25** > **24** >>> **23** > **22** > **21**.

It appears that these individual variations in the rates of allylborations can, once again, be rationalized in terms of the relative availability of lone pairs of electrons on the oxygen atoms attached to boron. Thus, the absence of +I alkyl groups in the allylboronic acid, and the presence of a −I phenyl group in the benzyloxy ester, both operate to reduce the back-donation of lone pairs of electrons from

Table VII. A Comparison of the Rates of Allylboration of Benzaldehyde with Tartramide 26 and Tartrate 3 in Dichloromethane[a]

reagent	^{11}B shift (δ)[b]	$t_{1/2}$, min, 25 °C[c]	% reactn at low temp[d]
 16	33	5	12, 6 h, −78 °C
 26	33	<1	85, 7 h, −78 °C
 3	37	instantaneous	100, 15 min, −78 °C

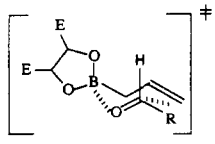
[a] [Reagent] = 0.5 M, [benzaldehyde] = 0.5 M in dichloromethane. [b] In ppm relative to $BF_3{\cdot}OEt_2$ in dichloromethane. [c] Determined by ^{11}B NMR spectroscopy on a Varian FT-80A NMR instrument. [d] Determined by ^{1}H NMR spectroscopy on a Varian XL-200 NMR instrument.

the oxygen atoms to boron and result in the enhanced rates of allylboration.

IV. Tartrate and Tartramides (Table VII). The tartramide reagent **26** was prepared according to the general procedure (eq 1) in 65% yield. The Roush reagent **3** was prepared according to the literature procedure.[4d]

The tartramide reagent **26** (a model for reagent **4**) undergoes allylboration at 25 °C moderately faster than *B*-allyl-1,3,2-dioxaborolane (**16**) in dichloromethane. It is surprising that Roush's reagent **3** reacts with benzaldehyde at 25 °C in an exothermic manner. In fact, a further examination of reaction rates at −78 °C in dichloromethane revealed that the rate of allylboration of the tartramide reagent **26** is considerably slower (85% in 7 h at −78 °C) than the Roush's reagent **3**, which undergoes allylboration very rapidly even at −78 °C[4d] (100% in ~15 min). In view of these results, it is not surprising that the allylboron reagent **4** (derived from *N,N'*-dibenzyl-*N,N'*-ethylenetartramide) reported by Roush and co-workers undergoes incomplete reactions at −78 °C, even after very long reaction periods.[4k] The low solubility of **4** at lower temperatures is doubtless a contributing factor.

From the above results, it appears that the presence of electron-withdrawing substituents on the 1,3,2-dioxaborolane ring increases the Lewis acidity of boron and enhances its ability to form a significantly tighter pericyclic transition state (see **27** below), which should in turn increase the rate of allylboration[9] (compare the reactivities of **16**, **26**, **17**, and **3**). Interestingly, although there is no precise linear relationship between the rates and the ^{11}B NMR chemical shifts, the Roush's reagent **3**, which is the most reactive in this category of compounds, shows a ^{11}B shift of +37 ppm, which is significantly deshielded compared to the others.

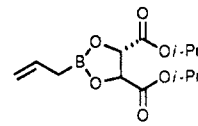
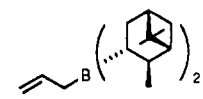
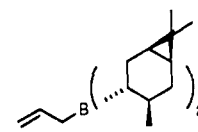


E = electron-withdrawing group

27

V. Allyl Dialkylboranes (Table VIII). *B*-Allyldiisopinocampheylborane (**7**) and *B*-allyldi(4-isocaranyl)borane (**8**) were prepared according to the previously published procedures.[4b,c] Their allylborations of benzaldehyde were directly examined at −78 °C[12] in THF-d_8[13] by ^{1}H NMR spectroscopy.

Table VIII. A Comparison of the Rates of Allylboration of Benzaldehyde with *B*-Allyldiisopinocampheylborane (7) and *B*-Allyldi(4-isocaranyl)borane (8) in Tetrahydrofuran[a]

reagent	^{11}B shift (δ)[b]	% reactn at low temp[d]
 3	37[c]	100, 15 min, −78 °C
 7	80	100, instantaneous, −78 °C
 8	82	100, instantaneous, −78 °C

[a] [Reagent] = 0.5 M, [benzaldehyde] = 0.5 M in tetrahydrofuran. [b] In ppm relative to $BF_3{\cdot}OEt_2$ in tetrahydrofuran. [c] In dichloromethane. [d] Determined by ^{1}H NMR spectroscopy on a Varian XL-200 NMR instrument.

Indeed, it was gratifying to observe that both of these reagents undergo allylboration instantaneously, even at −78 °C in THF. Thus, *B*-allyldiisopinocampheylborane (**7**) and *B*-allyldi(4-isocaranyl)borane (**8**) are more reactive than either Reetz's reagent **2** or Roush's reagent **3** at −78 °C. It appears that the significantly greater reactivity of allyldialkylboranes **7** and **8** (compared to **2** and **3**) can be accounted for in terms of a more electrophilic boron atom (the ^{11}B NMR chemical shifts of both **7** and **8** are at least ~43 ppm downfield relative to the chemical shift of **2** or **3**). From this, it can be understood that Masamune's reagents **5** and **6** should also have reactivities comparable to our own reagents at −78 °C.[4i,o]

Conclusions

The present study has systematically revealed the importance of the nature of the solvent, the structure of the aldehyde, the effect of temperature, and the structure of the auxiliary on boron on the rate of allylboration. Polar solvents, such as $HCCl_3$, CH_2Cl_2, CS_2, and Et_2O, which are either poorly coordinating or noncoordinating, enhance the rate of allylboration, while solvents capable of stronger coordination with boron, such as THF, retard the rate. α-Trisubstituted aldehydes, such as pivaldehyde, undergo allylboration significantly slower than less substituted aldehydes. While allylboration is extremely difficult at −78 °C with cyclic allylboronates such as **11**, **14**, and **15** (compare Hoffmann's reagent **1**),[4a] the *B*-allyl-3-(*p*-tolylsulfonyl)-1,3,2-oxazaborolidine (**20**), (Reetz's reagent **2** type)[4m] undergoes effortless allylboration under identical conditions. In general, acyclic allylboronates are signifi-

(12) The allylborations of these reagents cannot be conducted at 25 °C with benzaldehyde without competitive reduction.

(13) These reagents were normally utilized in ethyl ether. See refs 4b and 4c. For consistency, therefore, we preferred to examine their rates in an etheral solvent (THF-d_8).

(14) Seebach, D.; Kalinowski, H.-O.; Langer, W.; Grass, G.; Wilka, E.-M. *Org. Synth.* **1983**, *61*, 24.

(15) Brown, H. C.; Racherla, U. S. *J. Org. Chem.* **1986**, *51*, 427.

(16) Dietrich, B.; Hosseini, M. W.; Lehn, J.-M.; Sessions, R. B. *Helv. Chim. Acta* **1983**, *66*, 1273.

cantly more reactive compared to the cyclic allylboronate analogues. The *N,N,N',N'*-tetraalkyltartramide **26** (compare Roush's reagent **4**)[4k] undergoes allylboration very sluggishly at −78 °C. On the contrary, Roush's reagent **3**[4d] undergoes remarkably facile allylboration under the same conditions. Evidently, electron-withdrawing groups on the 1,3,2-dioxaborolane ring enhance the rate of allylboration. Finally, the allyldialkylboranes **7** and **8** (our reagents)[4b,c] have proven themselves to be two of the most reactive among reagents presently known (compare Masamune's reagents **5** and **6**).[4i,o] We hope that such an understanding of the factors controlling the rate of allylboration will be helpful for designing reagents capable of achieving 100% enantio- and diastereoselectivities in the future.

Experimental Section

All variable-temperature ^1H and ^{11}B NMR work was performed on a Varian XL-200 broad band NMR spectrometer. The ^{11}B NMR experiments at room temperature were conducted on a Varian FT-80A NMR instrument. All solvents were distilled and stored under nitrogen prior to use. The air-sensitive manipulations were all carried out under a nitrogen or argon atmosphere.[17] The ^1H and ^{13}C NMR spectra for the various allylboron reagents were recorded on a Varian Gemini-200 NMR instrument. The purity of all title compounds was judged by ^1H and ^{13}C NMR spectral determinations to be ≥95%. The mass spectra were recorded on a Finnigan GC/MS spectrometer.

General Procedure for the Synthesis of Allylboron Reagents. The procedure described below[7] for the synthesis of *B*-allyl-1,3,2-dioxaborinane (**11**) is representative for the synthesis of various other allylboron reagents, unless otherwise specified.

***B*-Allyl-1,3,2-dioxaborinane (11).** To freshly distilled trimethoxyborane (5.2 g, 50 mmol) in ether (150 mL) was slowly added allylmagnesium bromide in ether (52 mL, 1.0 M, 52 mmol) at −78 °C while the reaction mixture was mechanically stirred. Following completion of addition (15 min), the reaction mixture was stirred at −78 °C for 3 h and the dry ice–acetone bath was replaced by an ice bath. Next, aqueous hydrochloric acid (50 mL, 3 N, 150 mmol) was added quickly under nitrogen, and the reaction mixture was stirred at 0 °C for 1 h. The ether layer was then separated, and the aqueous layer was extracted with ether (3 × 50 mL) three times. The etheral extracts were combined, dried over anhydrous Na_2SO_4, filtered, and concentrated under aspirator vacuum (20 Torr) to obtain an essentially quantitative yield of allylboronic acid (characterized by ^{11}B NMR peak at δ +32 ppm in dichloromethane).

The allylboronic acid was then dissolved in anhydrous ether (100 mL) and 3-Å molecular sieves (2 g) were added to it, followed by 1,3-propanediol (3.81 g, 50 mmol) under nitrogen. The reaction mixture was stirred for 12 h at 25 °C, and then the stirring was discontinued. The clear supernatant ether layer was transferred into another flask, the molecular sieves were washed once again with ether (100 mL), and the etheral extracts were combined. Evaporation of ether, followed by distillation under reduced pressure (78 °C (25 Torr)), afforded **11** as a colorless oil (2.9 g, 46%): ^{11}B NMR (CH_2Cl_2, 25.517 MHz) δ +30; ^1H NMR ($CDCl_3$, 200 MHz) δ 1.60 (d, *J* = 7.3 Hz, 2 H), 1.93 (m, 2 H), 3.98 (t, *J* = 5.5 Hz, 4 H), 4.73–5.01 (m, 2 H), 5.75–6.00 (m, 1 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 27.44, 62.04, 114.21, 135.99; MS (70 eV, 250 °C) *m/e* 126 (M^+, 35.8), 85 ($M^+ - C_3C_5$, 18.0), 54 (100.0).

***B*-Allyl-1,3,2-dioxaborolane (16)**: yield 2.82 g (50%); bp 44–46 °C (15 Torr); ^1H NMR ($CDCl_3$, 200 MHz) δ 1.81 (d, *J* = 5.3 Hz, 2 H), 4.21 (s, 4 H), 4.88–5.10 (m, 2 H), 5.78–6.02 (m, 1 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 65.87, 115.28, 134.53; MS (70 eV, 250 °C) *m/e* 112 (M^+, 46.2), 68 ($M^+ - C_2H_4O$, 100.0), 55 (72.7), 45 (60.1).

***B*-Allyl-1,3,2-dioxabenzoborole (17)**: yield 4.80 g (60%); ^1H NMR ($CDCl_3$, 200 MHz) δ 2.10–2.52 (d, *J* = 6.7 Hz, 2 H), 4.95–5.48 (m, 2 H), 5.87–6.20 (m, 1 H), 6.90–7.50 (m, 4 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 112.68, 116.76, 123.00, 132.72, 148.60; MS (70 eV, 250 °C) *m/e* 160 (M^+, 90.78), 120 ($M^+ - C_3H_4$, 100.0).

(17) Brown, H. C.; Kramer, G. W.; Levy, A. B.; Midland, M. M. *Organic Syntheses via Boranes*; John Wiley: New York, 1975.

***B*-Allyldi-*n*-propoxyborane (21)**: yield 4.21 g (50%); bp 86 °C (20 Torr); ^1H NMR ($CDCl_3$, 200 MHz) δ 0.92 (t, *J* = 7.3 Hz, 6 H), 1.50–1.82 (m, 6 H), 3.79 (t, *J* = 6.6 Hz, 4 H), 4.85–5.10 (m, 2 H), 5.80–6.07 (m, 1 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 10.35, 24.91, 65.40, 114.40, 135.86; MS (CI, 70 eV, 250 °C) 171 (M^+ + H, 10.9), 129 (M^+ + H − C_3H_6, 100.0).

***B*-Allyldiisopropoxyborane (22)**: yield 3.40 g (40%); bp 74–76 °C (15 Torr); ^1H NMR ($CDCl_3$, 200 MHz) δ 1.16 (d, *J* = 6.2 Hz, 12 H), 1.70 (d, *J* = 6.6 Hz, 2 H), 4.27–4.52 (m, 2 H), 4.82–5.02 (m, 2 H), 5.78–6.05 (m, 1 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 24.58, 65.43, 114.14, 136.16.

***B*-Allylbis(isopinocampheyloxy)borane (23)**: yield 10.02 g (56%); ^1H NMR ($CDCl_3$, 200 MHz) δ 0.80–1.36 (m, 18 H), 1.55–2.60 (m, 14 H), 4.46 (m, 2 H), 4.80–5.10 (m, 2 H), 5.75–6.05 (m, 1 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 20.53, 23.86, 27.78, 33.97, 38.34, 38.45, 41.83, 46.33, 47.95, 72.24, 114.14, 136.29; MS (70 eV, 250 °C) *m/e* 358 (M^+, 0.09), 317 ($M^+ - C_3H_5$, 0.10), 137 (78.54), 81 (100.0).

***B*-Allylbis(benzyloxy)borane (24)**: yield 5.89 g (44%); bp 190 °C (0.3 Torr); ^1H NMR ($CDCl_3$, 200 MHz) δ 1.81 (d, *J* = 7.3 Hz, 2 H), 4.90–5.01 (m, 6 H), 5.81–6.10 (m, 1 H), 7.21–7.28 (m, 10 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 65.73, 114.98, 126.83, 127.59, 128.69, 135.14, 140.05; MS (70 eV, 250 °C) *m/e* 266 (M^+, 0.27), 225 ($M^+ - C_3H_5$, 0.87), 91 (C_7H_7, 100.0).

***B*-Allyl-1,3,2-dioxaborolane (26) Derived from *N,N,N',N'*-Tetramethyltartaric Acid Diamide**: yield 6.99 g (55%); ^1H NMR ($CDCl_3$, 200 MHz) δ 1.81 (d, *J* = 7.1 Hz, 2 H), 2.99 (s, 6 H), 3.20 (s, 6 H), 4.85–5.06 (m, 2 H), 5.56 (s, 2 H), 5.70–5.98 (m, 1 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 36.01, 37.17, 76.13, 115.73, 133.57, 168.61; MS (70 eV, 250 °C) *m/e* 254 (M^+, 1.4), 213 ($M^+ - C_3H_5$, 2.2), 182 ($M^+ - CONMe_2$, 32.5), 72 ($CONMe_2$, 100.0).

***B*-Allyl-3-methyl-1,3,2-oxazaborolidine (18).** Allylboronic acid (4.2 g, 50 mmol) was prepared according to the procedure described above for **11**. Next, the boronic acid was dissolved in toluene (25 mL), and 2-(methylamino)ethanol (1.88 g, 25 mmol) was added to it, followed by 3-Å molecular sieves (1 g). The reaction mixture was stirred at 25 °C for 12 h, at the end of which ^{11}B NMR showed a clean species at δ 6.3 (see eq 4). Next, stirring was stopped, and the toluene layer was separated into another flask. Once again, molecular sieves were washed with additional toluene (50 mL), nd the washings were combined. The toluene solution was heated at 135 °C for 8 h in a Dean–Stark apparatus, and then toluene was distilled off. The residue was heated at 150 °C for 2 h to complete the reaction, and finally distilled under vacuum (80–82 °C (20 Torr)) to obtain allylboronate **18** as a colorless oil (2.2 g, 70%): ^1H NMR ($CDCl_3$, 200 MHz) δ 1.71 (d, *J* = 7.2 Hz, 2 H), 2.69 (s, 3 H), 3.21 (t, 2 H), 4.18 (t, 2 H), 4.86–5.06 (m, 2 H), 5.78–6.02 (m, 1 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 32.23, 51.53, 65.72, 114.40, 135.83.

***B*-Allyl-3-phenyl-1,3,2-oxazaborolidine (19).** To freshly distilled triallylborane[15] (0.67 g, 5 mmol) in anhydrous tetrahydrofuran (20 mL) was added a catalytic amount of Et_3N (0.1 mL), followed by 2-(phenylamino)ethanol (0.68 g, 5 mmol) in a dropwise manner over a period of 10 min. Then the reaction mixture was refluxed for 2 h, cooled under argon, and stripped free of solvent to obtain a colorless oil of **19** quantitatively: ^1H NMR ($CDCl_3$, 200 MHz) δ 2.06 (d, *J* = 7.2 Hz, 2 H), 3.70 (m, 2 H), 4.30 (m, 2 H), 4.85–5.15 (m, 2 H), 5.85–6.10 (m, 1 H), 6.85–7.45 (m, 5 H); ^{13}C NMR ($CDCl_3$, 200 MHz) δ 48.98, 65.27, 115.20, 118.82, 121.94, 129.35, 135.20, 144.63; MS (70 eV, 250 °C) *m/e* 187 (M^+, 100.0), 172 (76.17), 91 (27.10), 77 (29.08).

***B*-Allyl-3-(*p*-tolylsulfonyl)-1,3,2-oxazaborolidine (20).** The reaction of triallylborane (0.67 g, 5 mmol) with 2-(*p*-toluenesulfonamido)ethanol[16] (1.08 g, 5 mmol) in THF (20 mL), in the presence of a catalytic amount of triethylamine (0.1 mL), according to the above procedure, furnished a pale yellow oil of **20** in quantitative yield: ^1H NMR ($CDCl_3$, 200 MHz) δ 2.23 (d, *J* = 7.6 Hz, 2 H), 2.46 (s, 3 H), 3.59 (m, 2 H), 4.25 (m, 2 H), 4.92–5.16 (m, 2 H), 5.78–6.10 (m, 1 H), 7.35 (d, *J* = 8.4 Hz, 2 H), 7.78 (d, *J* = 8.4 Hz, 2 H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 21.61, 46.90, 65.70, 115.89, 127.43, 130.25, 134.05, 136.73, 144.52; MS (70 eV, 250 °C) *m/e* 265 (M^+, 8.68), 224 ($M^+ - C_3H_5$, 92.46), 152 (37.83), 91 (100.0), 77 (6.10).

General Procedure for the Determination of Rates of Allylborations by the ^{11}B NMR Method. At the desired temperature, the solution of the allylboron reagent (0.5 mL, 1.0 M,

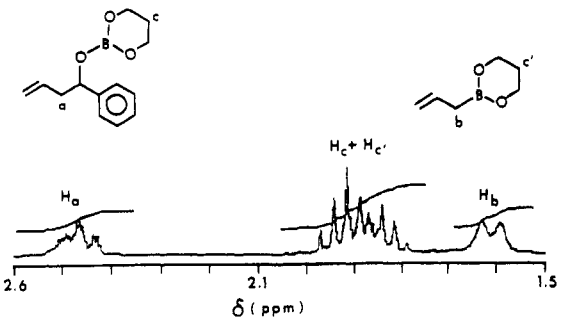


Figure 3. The progress of allylboration of benzaldehyde with *B*-allyl-1,3,2-dioxaborinane (**11**) in dichloromethane-d_2 at 0 °C by 200-MHz ^{1}H NMR spectroscopy.

0.5 mmol) and the solution of benzaldehyde (0.5 mL, 1.0 M, 0.5 mmol) were mixed together (by using standard syringing techniques[17]) in an NMR tube, and the progress of the reaction was continuously monitored by ^{11}B NMR[18] (on either Varian FT-80A or Varian XL-200 NMR instruments) by quantifying the relative amounts of starting material and product peaks (see for example, Figure 1). Thus the reaction mixtures were 0.5 M in each of the two components. No attempt was made to correct for the minor variations in concentrations resulting from the contraction of solutions at low temperatures.

General Procedures for the Determination of Rates of Allylborations by ^{1}H NMR Method. Two procedures were found to be reliable by ^{1}H NMR for quantifying the progress of allylborations:

Procedure A.[20] Benzaldehyde (0.1062 g, 1 mmol) and hexamethylethane (0.0155 g, 0.1357 mmol) were weighed into a 1-mL volumetric flask and dichloromethane-d_2 (or tetrahydrofuran-d_8) was added up to the mark to obtain a 1.0 M solution of the aldehyde. Next, the solution of the allylboron reagent (0.5 mL, 1.0 M, 0.5 mmol) and the solution of benzaldehyde (0.5 mL, 1.0 M, 0.5 mmol) were mixed in an NMR tube at the desired temperature (note: prior to mixing, the reagent and aldehyde solutions were maintained at the desired temperature for 2 h in all cases), and the progress of the reaction was monitored by ^{1}H NMR (on the Varian XL-200 NMR instrument) continuously by quantifying the relative amount of the aldehyde against the internal standard peak.

Procedure B.[20,21] In this method, no internal standard was taken. The solutions of the reagent (0.5 mL, 1.0 M, 0.5 mmol) and the aldehyde (0.5 mL, 1.0 M, 0.5 mmol) were mixed together at the desired temperature in an NMR tube, and the progress of the reaction was continuously monitored by ^{1}H NMR spectroscopy (on Varian XL-200 NMR instrument) by quantifying the relative amounts of the peaks corresponding to the allylic protons of the starting material and product (viz., the boron adduct resulting from the addition of allylboron reagent to benzaldehyde). Since the allylic protons of the starting material and the product are well resolved in the 200-MHz ^{1}H NMR spectrum in most cases (without interference from other protons; see, for example, Figure 3) this method was more commonly employed for the rate studies.

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Supplementary Material Available: ^{1}H NMR and ^{13}C NMR spectra for the title compounds **11**, **16–24**, and **26** (22 pages). Ordering information is given on any current masthead page.

(18) The boronates (δ 30–37 ppm) and the borinates (δ 18–24 ppm) are well resolved in ^{11}B NMR and permit quantification, generally up to −50 °C. However, we have found that, due to quadrupolar broadening effects, ^{11}B NMR does not permit reliable quantitative rate determinations below −50 °C.

(19) This reagent was prepared in dichloromethane and used without isolation as it was unstable in distillation.

(20) Procedures A and B gave identical results for **11** at 0 °C.

(21) The ^{11}B NMR method and the ^{1}H NMR method (procedure B) also gave essentially identical results for **11** at 0 °C.

(22) After we completed the present work, Corey and co-workers reported yet another reagent for the asymmetric allylation of aldehydes. See ref 4p. Although this reagent falls into the category of 1,3,2-diazaborolidines, it can be, for practical purposes, treated as a homologue of the reagent **20**, in the category of 1,3,2-oxazaborolidines.

$W(CO)_6$-Mediated Desulfurdimerization of Dithioketals. Evidence for a Thione Intermediate†,1

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Upon treatment with $W(CO)_6$, dithioketals undergo desulfurdimerization to give the corresponding dimeric olefins in good to excellent yields. The mechanism of this newly discovered reaction has been investigated. Thioketones have been isolated from the reactions of highly crowded dithioketals. The mechanism for the formation of thioketones has been shown to occur via a new type of radical fragmentation process of dithiolane. Thermolysis of 2,2-dimethylindan-1-yl 2-thiophenoxyethyl sulfide in the presence of *tert*-butyl adamantane-1-peroxycarboxylate (a typical radical initiator) has been studied for comparison. Thioketones react with $W(CO)_6$, giving dimeric olefins and/or undergoing carbene-like insertion reactions.

Transition-metal-mediated C–S bond cleavage reactions are useful in organic synthesis.[4] Various metal carbonyls have been shown to be thiophilic, hence, organosulfur compounds can be reduced under different conditions.[4] Upon treatment with metal carbonyls, certain thioethers[5a] and thioketones[5b,c] readily undergo desulfurdimerization

† Dedicated to Professor Wei Chuan Lin on the occasion of his 70th birthday.

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(3) Recipient of the Croucher Foundation studentship, 1987–89.

(4) For a review, see: Luh, T.-Y.; Ni, Z.-J. *Synthesis*, in press.

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