Organoboranes. 43. A Convenient, Highly Efficient Synthesis of Triorganylboranes via a Modified Organometallic Route

Herbert C. Brown* and Uday S. Racherla

Richard B. Wetherill Laboratory, Purdue University, West Lafayette, Indiana 47907

Received August 23, 1985

A variety of triorganylboranes are prepared in a rapid and highly efficient manner via a modified organometallic route involving the direct reaction of magnesium, organic halide, and boron trifluoride etherate in ethyl ether. Many reactions are complete in 2–3 h, with a few requiring longer periods of time. The yields are essentially quantitative. Reactive halides such as allyl chloride and benzyl chloride are accommodated with little or no coupling observed. The procedure is readily applied to the synthesis of large quantities of organoboranes, even such difficult to handle material as trimethylborane. Ultrasound dramatically accelerates the slow reactions, and the scope and generality of this procedure were explored systematically in the presence and absence of ultrasound. However, even without ultrasound, this procedure provides a simple and direct route to many organoboranes not accessible via hydroboration.

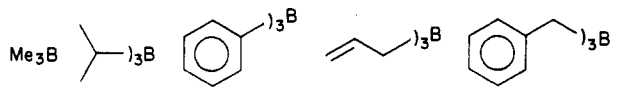
Triorganylboranes are highly valuable intermediates in organic synthesis.[1] Prior to the discovery of hydroboration in ethereal solvents[2] in 1956, the practical methods for the preparation of triorganylboranes involved the reactions of various organometallics with boron esters or halides[3,4] (eq 1–3).

$$3R_2Zn + 2BCl_3 \rightarrow 2R_3B + 3ZnCl_2 \quad (1)$$

$$3RMgBr + B(OMe)_3 \rightarrow R_3B + 3MgBrOMe \quad (2)$$

$$R_3Al + BF_3{\cdot}OEt_2 \rightarrow R_3B + AlF_3{\cdot}OEt_2 \quad (3)$$

In the past, such organometallic routes have not gained widespread applications in organic syntheses, primarily because of the ready availability of most organoboranes via facile hydroborations and also due to the need for the prior preparation of the organometallic reagents. Interestingly, however, the boron chemist's constant need for triorganylboranes containing groups not achievable via hydroboration (such as shown below) has been the reason why organometallic routes are indispensable, even today.



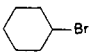
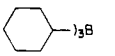
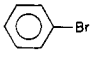
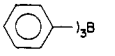
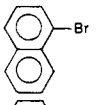
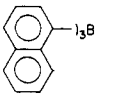
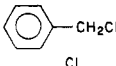
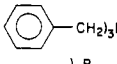
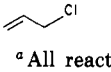
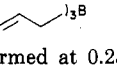
Although it was known that triorganylboranes could be prepared by the reaction of preformed Grignard reagents with boron trifluoride etherate,[3] the preparation of triorganylboranes via the direct reaction of organic halide, magnesium, and $BF_3{\cdot}OEt_2$ (eq 4) was never explored as a general synthetic method.

$$3RX + 3Mg + BF_3{\cdot}OEt_2 \xrightarrow{Et_2O} R_3B + 3FMgBr \quad (4)$$

Recently we reported our preliminary results on the synthesis of triorganylboranes via such a modified organometallic route[5a] and noted that ultrasound[5b-d] achieves such syntheses in a remarkably rapid manner. The present paper describes the scope and generality of this modified organometallic route in the presence and absence of ultrasound. Indeed, the present method provides a facile, highly efficient and direct route to many triorganylboranes not available via hydroboration, even in the absence of ultrasound.

Table I. Preparation of Triorganylboranes via the Modified Organometallic Route[a]

$$3RX \xrightarrow[Et_2O]{Mg,\ BF_3{\cdot}OEt_2} R_3B$$

organic halide	reacn time, h	product	δ, ^{11}B chem shift (in Et_2O)[b]	% yield[c]
CH_3I	0.5	$(CH_3)_3B$	86.3	? (98)[d]
C_2H_5Br	2	$(C_2H_5)_3B$	86.6	99 (95)
n-C_3H_7Br	2	$(n$-$C_3H_7)_3B$	86.7	98
i-C_3H_7Br	2	$(i$-$C_3H_7)_3B$	84.1	95 (82)
n-C_4H_9Br	2	$(n$-$C_4H_9)_3B$	86.6	99
sec-$C_5H_{11}Br$	36	$(sec$-$C_5H_{11})_3B$	84.7	97
	24		81.3	90
	3		67.4	94 (70)
	24		72.7	91
	24		82.8	99 (75)
	3		81.9	94 (85)

[a] All reactions were performed at 0.25 M concentration in refluxing anhydrous ether. [b] Relative to $BF_3{\cdot}OEt_2$ (δ 0 ppm). [c] GC yield. [d] Isolated yields.

Results and Discussion

Preparation of Triorganylboranes in the Absence of Ultrasound. To a mixture of Mg turnings (40 mmol), $BF_3{\cdot}OEt_2$ (10 mmol), and a suitable internal standard (5 mmol) taken into anhydrous ether (35 mL) was added dropwise the organic halide (35 mmol) such that the ether refluxed gently, and the reaction mixture (ca. 0.25 M) was stirred at 25 °C. The progress of the reaction was followed by ^{11}B NMR. In most cases, triorganylborane formation was complete in 2–3 h, while in certain cases longer reaction periods were necessary. Stirring was discontinued following the completion of triorganylborane formation, and the magnesium salts were allowed to settle. The su-

(1) Brown, H. C.; Zaidlewicz, M.; Negishi, E. "Comprehensive Organometallic Chemistry"; Wilkinson, G., Ed; Pergamon Press: New York, 1984; Vol. 7.
(2) Brown, H. C.; Subba Rao, B. C. *J. Org. Chem.* **1957**, *22*, 1136.
(3) Mikhailov, B. M.; Bubnov, Yu. N. "Organoboron Compounds in Organic Synthesis"; Harwood Academic Science Publishers: Switzerland, 1984.
(4) Nesmeyanov, N.; Sokolik, R. A. "Methods of Elemento-Organic Chemistry"; The World Publishing Company: New York, 1967; pp 41–89.
(5) (a) Brown, H. C.; Racherla, U. S. *Tetrahedron Lett*, in press. (b) Brown, H. C.; Rocherla, U. S. *Ibid.* **1985**, *26*, 2187. (c) Petrier, C.; Luche, J.-L.; Dupuy, C. *Ibid.* **1985**, *26*, 3463 and its references. (d) Suslick, K. S.; Johnson, R. E. *J. Am. Chem. Soc.* **1984**, *106*, 6856 and its references.

0022-3263/86/1951-0427$01.50/0

pernatant ether layer was transferred to another flask, the insoluble magnesium salts were washed once again with ether, and the ethereal solutions of the triorganylborane were combined. Ether was pumped off next, THF (20 mL) was added, and the reaction mixture was oxidized. By GC analysis of the corresponding alcohol, the yield of triorganylborane was finally established. Thus, a variety of triorganylboranes could be prepared in a facile and quantitative manner by this modified organometallic procedure (eq 5). Table I summarizes these results.

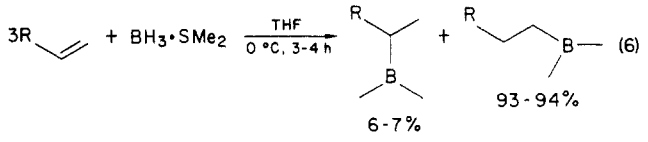
$$3RX \xrightarrow[Et_2O,\ 2\text{-}24\ h]{Mg,\ BF_3\cdot OEt_2} \underset{90\text{-}99\%}{R_3B} \qquad (5)$$

The isolation of triorganylboranes in the above procedure was quite simple. Depending upon the nature of triorganylborane, one of the following two procedures was adopted: (1) If the triorganylborane was not water-sensitive, then a small amount of water saturated with ammonium chloride was added to the reaction mixture (procedure A) at the completion of the reaction to destroy the excess Grignard, and the ether layer was separated. (2) If the triorganylborane was, however, water-sensitive, no water was added to the reaction mixture (procedure B), and the ether layer was transferred to another flask. Ether was then distilled off at atmospheric pressure, and the triorganylborane was isolated by distillation under vacuum.

The present method for the preparation of triorganylboranes has many significant advantages.

Me_3B is a spontaneously flammable and volatile (bp −20 °C) borane. In the past, Me_3B was prepared from methylmagnesium bromide and BF_3-O-n-Bu_2 and isolated at −80 °C.[6] Now, Me_3B can be conveniently made in large quantities directly from MeI, Mg turnings, and $BF_3\cdot OEt_2$ and collected as a gas into anhydrous ether at 0 °C. This now opens the door for many applications of Me_3B.

Symmetrical trialkylboranes such as n-Pr_3B and n-Bu_3B prepared via the hydroboration of 1-propene and 1-butene, respectively, with $BH_3\cdot SMe_2$, are contaminated with 6–7% of the undesired internal regioisomers[8] (eq 6). By using



(6)

the present procedure, n-Pr_3B and n-Bu_3B can be obtained in ≥99% regiochemical purity from commercially available Mg turnings, $BF_3\cdot OEt_2$, and the corresponding halides.

Triisopropylborane, triphenylborane, tribenzylborane, and triallylborane are representative organoboranes which cannot be prepared by hydroboration. These triorganylboranes can now be prepared and isolated in large quantities in a convenient manner by the presently modified organometallic route without requiring the initial preparation of the corresponding Grignard reagents. In the case of highly reactive halides such as allyl and benzyl chlorides, this has a major advantage. Coupling of the Grignard reagent with the reactive halide is avoided.

Next, we investigated variations in the initiation procedure, the effect of concentration changes in the reaction mixture, and the effect of the solvent on the rate and yield of the triorganylborane in the absence of ultrasound. For this purpose, we chose to study the preparation of n-Bu_3B under a variety of conditions.

Table II. Effect of the Method of Initiation on the Rate of Triorganylborane Formation in the Absence of Ultrasound[a]

$$3n\text{-BuBr} \xrightarrow[Et_2O]{Mg,\ BF_3\cdot OEt_2} n\text{-}Bu_3B$$

initiator	init method	reacn time, h	% yield[b]
I_2	A	2	99
I_2	B	2	97
I_2	C	2	93
CH_3I	D	2	95

[a] All reactions were done at 0.25 M concentration. [b] Determined by gas chromatography after oxidation.

Table III. Effect of Concentration on the Rate of Formation of n-Bu_3B in the Absence of Ultrasound

concn, M	reacn time, h	% yield[a]
0.25	2	99
0.50	1	100
1.00	1	93

[a] Determined by gas chromatography after oxidation.

(a) Method of Initiation. The method of initiation plays an important role in the formation of Grignard reagents.[9] Thus, in the preparation of n-Bu_3B from n-BuBr, Mg turnings, and $BF_3\cdot OEt_2$, we investigated four initiation methods.

In method A, Mg turnings were taken into a flask, heated over a flame, and cooled under nitrogen. A crystal of iodine[10a] was then added under nitrogen, followed by anhydrous ether, $BF_3\cdot OEt_2$, and the internal standard. The alkyl halide (RX) was added dropwise, and the progress of the reaction was followed by ^{11}B NMR. The reaction mixture was finally oxidized by using alkaline hydrogen peroxide, and the yield of n-Bu_3B was ascertained by GC analysis for n-butyl alcohol.

In method B,[10b] a solution of iodine dissolved in ether was added to Mg turnings (preheated and cooled under nitrogen), and the mixture was stirred until the color of iodine disappeared. The procedure then followed that described above.

In method C,[11] Mg turnings preactivated with iodine according to Baeyer's method were utilized in the reaction.

In method D,[12] methyl iodide was employed as the initiator.

The results of these experiments (Table II) suggested that the rate of n-Bu_3B formation from n-BuBr is not significantly affected by the method of initiation. In fact, irrespective of the method of initiation, the formation of n-Bu_3B required 2 h for completion. Further, the yield of n-Bu_3B varied only slightly (93–99%), depending upon the method of initiation. However, for the sake of convenience and simplicity, we adopted method A for all of the triorganylborane preparations here described.

(b) Effect of Concentration. To understand the effect of concentration on the rate of triorganylborane formation, the preparation of n-Bu_3B from n-BuBr was examined at 0.25, 0.5, and 1.0 M overall concentrations in ethyl ether.

Thus, while the formation of n-Bu_3B required 2 h for completion at 0.25 M, increasing the concentration of the reaction to 0.5 M achieved this in only 1 h with a quantitative yield. However, at the higher 1 M concentration,

(6) (a) Brown, H. C. *J. Am. Chem. Soc.* **1945**, *67*, 374. (b) Brown, H. C.; Pearsall, H. *Ibid.* **1945**, *67*, 1765.
(7) Brown, H. c.; Hubbard, J. L.; Singaram, B. *J. Org. Chem.* **1979**, *44*, 5004.
(8) Brown, H. C.; Sharp, R. L. *J. Am. Chem. Soc.* **1966**, *88*, 5851.
(9) Kharasch, M. S.; Reinmuth, O. "Grignard Reactions of Nonmetallic Substances"; Prentice-Hall: New York, 1954.
(10) (a) Tissier,; Grignard, V. *C. R. Hebd. Seances Acad. Sci.* **1901**, *132*, 1182. (b) Gilman, H.; Zoellner, E. A. *J. Am. Chem. Soc.* **1931**, *53*, 1583.
(11) Baeyer, A. *Ber. Dtsch. Chem. Ges.* **1905**, *38*, 2759.
(12) Zelinsky, N. *J. Russ. Phys.-Chem. Soc.* **1903**, *35*, 399.

Table IV. Effect of Solvent on the Rate of Formation of *n*-Bu_3B in the Absence of Ultrasound[a]

solvent	reacn time, h	% yield[b] *n*-Bu_3B	% yield[b] *n*-Bu_4BMgBr
ether	2	99	0
THF	2	0	100[c]
pentane	2	5	0

[a] All reactions were done at 0.25 M concentration. [b] Determined by gas chromatography. [c] Unreacted $BF_3{\cdot}OEt_2$ was observed in ^{11}B NMR when 3 equiv of alkylhalide was used.

there was no improvement in the rate of *n*-Bu_3B formation, but the yield of *n*-Bu_3B dropped to 93%. Table III summarizes these results.

(c) Effect of Solvent. The formation of *n*-Bu_3B was systematically examined in three solvents: ethyl ether, THF, and pentane. As already mentioned, *n*-Bu_3B could be prepared in ethyl ether in 99% yield in just 2 h (at 0.25 M concentration). In pentane, however, the formation of *n*-Bu_3B was exceptionally slow (at 0.25 M) and occurred only to an extent of about 5% in 4 h.

In THF (at 0.25 M), the results observed were totally unexpected. Instead of the expected formation of *n*-Bu_3B, the addition of *n*-BuBr to a mixture of Mg turnings and $BF_3{\cdot}OEt_2$ led to the formation of the *n*-$Bu_4BMgBr{\cdot}n$THF complex. In ^{11}B NMR, only the ate complex (δ −17.7) and unreacted $BF_3{\cdot}OEt_2$ were observed (eq 7). Further, by using 4 equiv of *n*-BuBr in this procedure, instead of 3 equiv, a 100% formation of the ate complex could be achieved (eq 8).

$$3n\text{-BuBr} \xrightarrow[\text{THF, 2 h}]{\text{Mg, } BF_3{\cdot}OEt_2} \underset{\delta\ -17.7}{n\text{-}Bu_4BMgBr{\cdot}n\text{THF}} + \underset{\text{unreacted}}{BF_3{\cdot}OEt_2} \quad (7)$$

$$4n\text{-BuBr} \xrightarrow[\text{THF, 2 h}]{\text{Mg, } BF_3{\cdot}OEt_2} \underset{100\%}{n\text{-}Bu_4BMgBr{\cdot}n\text{THF}} \quad (8)$$

Table IV summarizes these results. Clearly the solvent of choice for triorganylborane formation is ethyl ether. We shall soon report the results of our full investigation on the mechanism of triorganylborane formation in this modified organometallic route and the role of the solvent.

Preparation of Triorganylboranes in the Presence of Ultrasound. Since the preparation of triorganylboranes directly from their corresponding halides, Mg turnings and $BF_3{\cdot}OEt_2$, involves the in situ generation of the Grignard reagents and is heterogeneous in nature, it was of interest to us to examine whether the application of ultrasound to such a procedure would significantly accelerate the formation of triorganylboranes. Indeed, we were gratified to observe that ultrasound dramatically accelerates the formation of triorganylboranes in our modified organometallic route (eq 9).

$$3RX \xrightarrow[((\text{, } Et_2O,\ 10\text{-}30\ \text{min}}{\text{Mg, } BF_3{\cdot}OEt_2} \underset{90\text{-}100\%}{R_3B} \quad (9)$$

The apparatus used in these experiments is as shown in Figure 1. Mg turnings, $BF_3{\cdot}OEt_2$, a crystal of iodine, internal standard, and anhydrous ether were placed into the flask under nitrogen. The sonic disruptor (Model TSD-B-250, 250 W, 20 KHz) was switched on, and the organic halide was added dropwise. Following the addition of the organic halide, the progress of the reaction was followed by ^{11}B NMR. In all cases the formation of triorganylborane was complete in 10–30 min. The yield of the triorganylborane was then established by oxidation and GC analysis of the alcohols as described previously. These results are summarized in Table V.

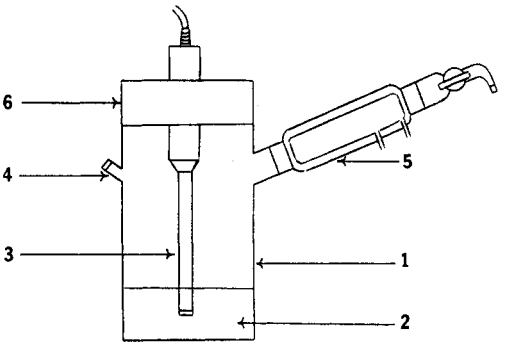
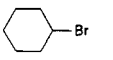
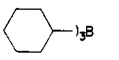
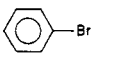
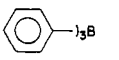
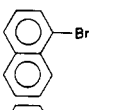
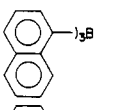
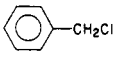
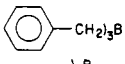
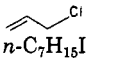
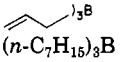


Figure 1. Apparatus used in experiments employing ultrasound: (1) reaction vessel, (2) reaction mixture, (3) ultrasound probe, (4) sidearm, (5) reflux condenser, and (6) rubber stopper.

Table V. Preparation of Triorganylboranes via Modified Organometallic Route Using Ultrasound[a]

$$3RX \xrightarrow[((\text{, } Et_2O}{\text{Mg, } BF_3{\cdot}OEt} R_3B$$

organic halide	reacn time, h	product	% yield[b]
n-C_3H_7Br	0.25	$(n\text{-}C_3H_7)_3B$	100 (92)[c]
n-C_4H_9Br	0.25	$(n\text{-}C_4H_9)_3B$	100
sec-$C_5H_{11}Br$	0.50	$(sec\text{-}C_5H_{11})_3B$	96
	0.50		99
	0.25		97 (87)[c]
	0.50		93
	0.50		99
	0.25		94
n-$C_7H_{15}I$	0.25	$(n\text{-}C_7H_{15})_3B$	90

[a] All reactions were done at 0.25 M concentration. [b] Determined by gas chromatography after oxidation. [c] Isolated yield.

Table VI. Effect of Halogen on the Rate of Formation of *n*-Bu_3B in the Presence of Ultrasound[a]

alkyl halide	reacn time, h	% yield[b]
n-BuCl	1	30
n-BuBr	0.25	100
n-BuI	0.25	82

[a] All reactions were done at 0.25 M concentration. [b] Determined by gas chromatography.

The preparation of triorganylboranes in the above manner using ultrasound is certainly direct, exceptionally rapid, and highly efficient. Thus, trialkylboranes such as *n*-Pr_3B and *n*-Bu_3B can now be prepared in ≥99% purity in just 15 min and can be isolated into ether essentially quantitatively. The preparation of even highly hindered trialkylboranes such as Chx_3B, which requires 24 h via the hydroboration of cyclohexene with $BH_3{\cdot}SMe_2$ at 25 °C in THF, can now be achieved in 0.5 h from cyclohexylbromide by using ultrasound. The triorganylborane synthesis under the application of ultrasound can be applied even for the preparations of exceptionally reactive triorganylboranes such as triallylborane and tribenzylborane.

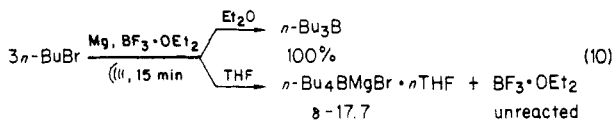
Next, we decided to examine the scope and generality of the preparation of triorganylboranes under the application of ultrasound.

(a) Effect of Halogen. In order to understand the effect of halogen, we investigated the rate of formation of *n*-Bu_3B from three different halides, *n*-BuCl, *n*-BuBr, and *n*-BuI, under the influence of ultrasound. These results

are summarized in Table VI.

In general, the order of reactivity was the following: *n*-BuI > *n*-BuBr > *n*-BuCl. Thus, while a 100% formation of *n*-Bu_3B was realized in 15 min starting from *n*-BuBr, only a 30% formation of *n*-Bu_3B was observed from *n*-BuCl, even in 1 h. Under comparable conditions, the use of *n*-BuI afforded *n*-Bu_3B in 82% yield. It appears that alkyl iodides are susceptible to side reactions under ultrasound conditions. Thus, the results indicate that alkyl bromides offer the best choice for trialkylborane formation with use of ultrasound.

(b) Effect of Solvent. As described earlier, while the reaction of *n*-BuBr with a mixture of Mg turnings and BF_3·OEt_2 in anhydrous ether afforded a 100% formation of *n*-Bu_3B in 15 min under ultrasound, the same reaction performed in THF under identical conditions led to the formation of ate complex (eq 10). When 4 equiv of *n*-



(10)

BuBr was used in THF, it afforded a 100% ate complex. In pentane, even under ultrasound, the formation of *n*-Bu_3B from *n*-BuBr was very slow and incomplete, even in 1 h.

(c) Effect of Metal. We compared the formation of *n*-Bu_3B from *n*-BuBr and BF_3·OEt_2 by using two metals, Li and Mg, under identical conditions. We observed that while the use of Mg affords *n*-Bu_3B in a clean and quantitative fashion, Li affords no trialkylborane at all and gives only coupled products.[13] Under these experimental conditions, lithium is, therefore, not a good metal for triorganylborane formation.

Conclusion

The preparation of triorganylboranes via the classical organometallic route requires the prior preparation of the Grignard reagents:

$$RX + Mg \rightarrow RMgX$$

$$3RMgX + BF_3{\cdot}OEt_2 \rightarrow R_3B + 3MgXF$$

On the contrary, triorganylboranes can now be conveniently prepared by the direct reaction of organic halides, Mg turnings, and BF_3·OEt_2, thus saving a considerable effort and time.

$$3RX + 3Mg + BF_3{\cdot}OEt_2 \rightarrow R_3B + 3MgXF$$

Most of the reactions are complete in 2–3 h, with a few requiring longer periods of time. The yields are essentially quantitative in all cases. Especially important is the fact that even reactive halides such as allyl chloride and benzyl chloride are readily accommodated without any coupling problem. Ultrasound dramatically accelerates the slow reactions and holds the promise of a powerful method in organoborane chemistry for the future.

The triorganylborane formation is very much dependent upon the nature of the solvent and the concentrtion of the reaction. The order of reactivity of organic halides toward triorganylborane formation is the following: RI > RBr > RCl. However, best results are obtained with bromides. In the case of reactive halides (such as allyl and benzyl), the chlorides work most satisfactorily. The use of lithium instead of magnesium for triorganylborane formation in the presence of ultrasound yields no triorganylborane and leads to coupled products.

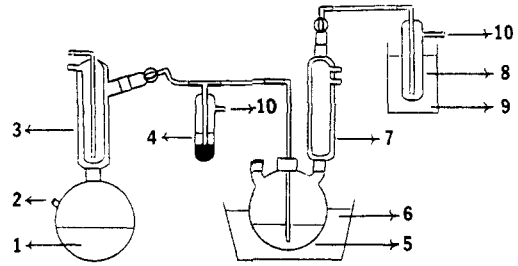
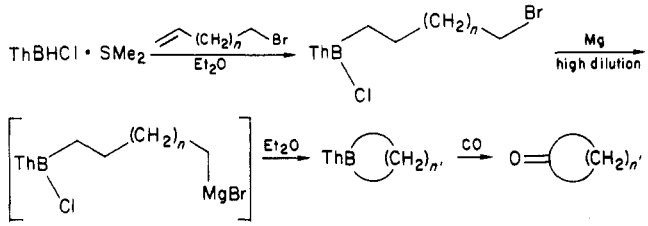


Figure 2. Apparatus used for the preparation of Me_3B: (1) reaction flask, (2) side arm, (3) water condenser (double-walled), (4) safety trap, (5) collector flask, (6) ice bath, (7) reflux condenser, (8) safety trap, (9) dry ice–acetone trap, and (10) fumehood.

Scheme I



As a result of the present study, the preparation and isolation of many organoboranes which are not accessible via hydroboration has been made simpler and more convenient. Even such difficult to handle boranes, as gaseous Me_3B, can now be easily prepared in large quantities directly from the readily available starting materials, and the gas can be collected into ether at 0 °C. This now opens the door for many possible applications of Me_3B, which were so far considered to be impractical.

Above all, the present method for the preparation of triorganylboranes by the direct reaction of organic halide, magnesium turnings, and BF_3·OEt_2 shows promising new applications such as the synthesis of macrocycles under high dilution conditions via intramolecular cyclization (Scheme I) which we hope to explore in the future.

Experimental Section

General Methods. All of the manipulations involving air-sensitive substances were carried out according to standard procedures.[14] The Tekmar sonic disruptor (Model TSD-B-250, 250 W, 20 KHz) equipped with a standard horn (tapped end) was utilized for the generation of ultrasound. The ^{11}B NMR spectra were recorded on a Varian FT-80A instrument. All gas chromatographic analyses were done on a Varian 1200 gas chromatograph (equipped with an FID detector) by using a column ($^1/_8$ in. × 12 ft) packed with 5% Carbowax 20 M on Chromosorb W (100/120 mesh). All boiling points and melting points are uncorrected.

Materials. BF_3·OEt_2 was purchased from Aldrich Chemical Company, distilled over CaH_2, and stored under nitrogen.[14] Industrial-grade Mg turnings were used in all experiments. The organic halides of high purity (+99%) were freshly distilled and used in all experiments. Anhydrous ethyl ether from Mallinckrodt (analytical reagent grade) was used directly. THF was distilled over sodium and benzophenone and stored under nitrogen prior to use.

Preparation of Trimethylborane. The experimental setup shown in Figure 2 was used for the preparation of trimethylborane.

Mg turnings (9.72 g, 400 mmol) were taken into the reaction flask, heated on an open flame, and cooled under a stream of nitrogen. A crystal of iodine, BF_3·OEt_2 (14.2 g, 100 mmol), and anhydrous ether (360 mL) were next introduced into the flask.

(13) Lash, T. D.; Berry, D. *J. Chem. Educ.* **1985**, *62*, 85 and its references.

(14) Brown, H. C.; Kramer, G. W.; Levy, A. B.; Midland, M. M. "Organic Syntheses via Boranes"; Wiley-Interscience: New York, 1975.

Into the first safety trap was added a solution of ethylenediamine (3.0 g, 50 mmol) in THF (20 mL) above the level of mercury. Into the collector flask was taken anhydrous ether (200 mL), and the solution was cooled to 0 °C. Into the second safety trap was taken THF (20 mL), and the solution was maintained at −78 °C by using dry ice and acetone. Methyl iodide (49.7 g, 350 mmol) was then added slowly dropwise to a well-stirred mixture of Mg turnings and BF_3·OEt_2 in ether over a period of 1 h. The reaction began instantly as ether genetly refluxed and Me_3B very smoothly bubbled into ether of 0 °C. Following the completion of addition of methyl iodide, the reaction mixture was stirred for 0.5 h at 25 °C, and then warmed by a lukewarm water bath so as to distill off the residual Me_3B from the reaction flask into the collector flask. Thus, Me_3B was prepared and isolated into ether at 0 °C essentially quantitatively. The formation of Me_3B was confirmed by ^{11}B NMR (δ 86.3). The yield of Me_3B was determined to be 98% by converting it next into a bis adduct of ethylenediamine, $2Me_3B$·EDA complex (bp 46–47°C/0.1 mm; mp 141 °C), a known compound in the literature.[15]

General Procedure for the Preparation of Triorganylboranes in the Absence of Ultrasound. The following are general procedures for the preparation of triorganylboranes without using ultrasound. Procedure A is general for all trialkylboranes which are not moisture-sensitive, while procedure B is general for such triorganylboranes as triallylborane, tribenzylborane, and triphenylborane, which are moisture-sensitive.

(a) Procedure A. The preparation of triisopropylborane is representative. Into a 1-L, three-necked flask fitted with a mechanical stirrer and reflux condenser were taken Mg turnings (9.73 g, 400 mmol), and the mixture was heated on an open flame and cooled under nitrogen. Next, BF_3·OEt_2 (14.2 g, 100 mmol), a crystal of iodine, and anhydrous ether (100 mL) were introduced into the reaction flask while maintaining the nitrogen atmosphere. The reaction was next initiated by a dropwise addition of 4.7 mL of 2-bromopropane while stirring the reaction mixture, and the remainder of 2-bromopropane (36.9 g, 300 mmol) taken into ether (55 mL) was added slowly over a period of 30–45 min, such that the ether refluxed gently. Stirring was continued for an additional 1.5 h following the completion of addition of alkyl halide, and water (1.8 mL, saturated with ammonium chloride) was added. The reaction mixture was allowed to settle, and the clear supernatant ether layer was separated into the distillation flask. The insoluble Mg salts were washed once again with ether (200 mL), and the washings were transferred to the distillation flask. Ether was next distilled off at atmospheric pressure, and the residual triisopropylborane was transferred into a short-path distillation assembly and distilled under vacuum. Thus, triisopropylborane[16] (bp 36 °C at 12 mmHg) was finally isolated in excellent yield (11.5 g, 82%).

(b) Procedure B. The preparation of triallylborane is representative for the preparation of other moisture-sensitive triorganylboranes. The apparatus uses was the same as described in procedure A. Mg turnings (9.73 g, 400 mmol), a crystal of iodine, BF_3·OEt_2 (14.2 g, 100 mmol), and anhydrous ether (300 mL) were taken into the reaction flask, and the reaction was initiated by a dropwise addition of 4.0 mL of neat allyl chloride, while vigorously stirring the reaction mixture. Next, the remaining portion of allyl chloride (22.9 g, 300 mmol) dissolvedin anhydrous ether (50 mL) was added slowly over a period of 1 h,[17] and the ether was allowed to reflux smoothly. The reaction mixture was stirred for an additional 2 h, and stirring was discontinued so as to settle the insoluble Mg salts. The clear ether layer was transferred into the distillation flask. The magnesium salts were washed with anhydrous ether[18] (200 mL), and the washings once again were transferred into the distillation flask. The distillation of ether was done at atmospheric pressure, and finally the distillation under vacuum in a short-path distillation assembly afforded triallylborane[19] (11.2 g, 84%), bp 65 °C at 20 mm.

General Procedure for the Preparation of Triorganylboranes Using Ultrasound. The procedure, as described below, for the preparation of tri-*n*-propylborane is representative. The apparatus used is as shown in Figure1.

Mg turnings (0.97 g, 40 mmol), a crystal of iodine, BF_3·OEt_2 (1.42 g, 10 mmol), and anhydrous ether (34.5 mL) were taken into the reaction flask under nitrogen. The sonic disruptor (250 W, 20 KHz) was switched on (with trimer switch on hold and output control at 5), and 1-bromopropane (4.31 g, 35 mmol) was added dropwise over a 5-min period. The decolorization of iodine was observed when approximately 0.5 mL of alkyl halide was added and ether refluxed rapidly. The formation of *n*-Pr_3B was complete in 10 min, as evidenced by ^{11}B NMR (δ 86.7). Next ultrasound was switched off, and the magnesium salts were allowed to settle. The clear ether layer was transferred into a separate flask. Magnesium salts were washed once again with ether (20 mL), and the washings were transferred into the other flask. Ether was next pumped off under vacuum, and *n*-Pr_3B was isolated by distillation under aspirator vacuum (bp 54–56 °C/12 mmHg)[20] in excellent yield (1.34 g, 96%).

Methods of Initiation. The following are four different methods of initiation utilized in our investigation of the role of initiation in trialkylborane formation in the absence of ultrasound. The preparation of *n*-Bu_3B from *n*-BuBr was the reaction chosen for the study. All reactions were performed on a 10-mmol scale and at 0.25 M overall concentration.

Method A.[10a] Mg turnings (0.97 g, 40 mmol) were taken into the flask, heated on an open flame, and colled under nitrogen. A crystal of I_2, BF_3·OEt_2 (1.42 g, 10 mmol), *n*-dodecane (0.85 g, 5 mmol), and anhydrous ether (35 mL) were next introduced into the flask under nitrogen. While vigorously stirring the contents of the flask, *n*-bromobutane (4.8 g, 35 mmol) was then added dropwise. Decolorization of the iodine was observed when approximately 1 mL of *n*-bromobutane was added, and the ether started to reflux gently. The completion of *n*-Bu_3B formation required 2 h, as evidenced by ^{11}B NMR. At the end of 2 h, the stirring was discontinued, and the reaction mixture was allowed to settle. The supernatant ether layer was next separated into another flask, and the insoluble magnesium salts were washed once again with ether (20 mL). The washings were transferred into the other flask. Ether was pumped off next under vacuum, and anhydrous THF (20 mL) was added. The reaction mixture was then oxidized by alkaline H_2O_2, and the yield of *n*-Bu_3B was ascertained to be 99% by determining the yield of *n*-butanol by GC analysis.

Method B.[10b] A crystal of iodine was dissolved in ether (34 mL) and was added to Mg turnings (0.97 g, 40 mmol) under a nitrogen atmosphere. The mixture was then stirred until the color of iodine disappeared. The rest of the procedure was the same as described above. Completion of the formation of *n*-Bu_3B by this procedure required 2 h. The yield of *n*-Bu_3B in this method was 97%, not very much different from the above method.

Method C.[11] Mg turnings (0.97 g, 40 mmol) and a crystal of iodine were taken into the reaction flask under nitrogen and heated together on an open flame for 1–2 min. The vapors of iodine were instantly evolved, and the Mg turnings developed a gray color. The Mg turnings activated in such a manner and protected from moisture were utilized for the preparation of *n*-Bu_3B from *n*-BuBr. Once again, *n*-Bu_3B formation required 2 h. The yield of *n*-Bu_3B was 93%.

Method D.[12] In this method, 0.1 mL of methyl iodide was used as the initiator. The completion of the formation of *n*-Bu_3B required 2 h by this method. The yield of *n*-Bu_3B was 95%.

Effect of Concentration. The formtion of *n*-Bu_3B from *n*-BuBr was compared on a 10-mmol scale at 0.25, 0.5, and 1.0 M overall concentrations in anhydrous ether in the absence of ultrasound.

At 0.25 M, the formation of *n*-Bu_3B required 2 h for completion, and the yield of *n*-Bu_3B was 99%. At 0.5 M, *n*-Bu_3B was formed in a 100% yield in 1 h. At 1.0 M, the completion of the formation of *n*-Bu_3B required 1 h, but the yield was only 93%.

(15) Goubeau, G.; Zappel, A. *Z. Anorg. Chem.* **1955**, *279*, 38.
(16) Bamford, C. H.; Levi, D. L.; Nevitt, D. M. *J. Chem. Soc.* **1946**, 468. However, atmospheric distillation might have caused thermal isomerization of *i*-Pr_3B.
(17) In the preparation of tribenzylborane, the addition of benzyl chloride was done over a period of 6 h. After this, 10 mL of THF was added to dissolve Grignard.
(18) In the preparation of triphenylborane, this washing was done with a mixture of 50 mL of benzene and 150 mL of ether.
(19) Mikhailov, B. M.; Tutorskaya, F. B. *Dokl. Akad. Nauk SSSR* **1958**, *123*, 480.
(20) Long, L. H.; Dollimore, D. *J. Chem. Soc.* **1953**, 3902.

Effect of Solvent. The effect of solvent was studied both in the presence and absence of ultrasound. All experiments were performed (viz., the preparation of n-Bu_3B from n-BuBr) at 0.25 M concentration in ether, THF, and pentane on a 10-mmol scale. The yields were established by GC analysis, as described above. The quantitative formation of ate complex in THF was determined by ^{11}B NMR.

Effect of Alkyl Halide. The effect of alkyl halide was examined only in the presence of ultrasound. The formation of n-Bu_3B from n-BuCl, n-BuBr, and n-BuI was compared in anhydrous ether at 0.25 M on a 10-mmol scale. In every experiment, n-dodecane was used as internal standard. By determining the yield of n-butyl alcohol by gas chromatography, the yield of n-Bu_3B was ascertained in each case.

Effect of Metal. The metals Li and Mg were compared. Formation of n-Bu_3B from n-BuBr, Mg turnings, and BF_3·OEt_2 works almost quantitatively (99%) in anhydrous ether at 0.25 M, as already described. However, when lithium wire was used instead of magnesium and the procedure was repeated under identical conditions, no n-Bu_3B formation was observed in the presence of ultrasound and only coupled products were obtained. No attempt was made to estimate the yield of the coupled products.

Acknowledgment. We thank the National Science Foundation (Grant CHE 8414171) for the financial support of this research.

Registry No. $(CH_3)_3B$, 593-90-8; $(C_2H_5)_3B$, 97-94-9; $(n\text{-}C_3H_7)_3B$, 1116-61-6; $(i\text{-}C_3H_7)_3B$, 1776-66-5; $(n\text{-}C_4H_9)_3B$, 122-56-5; $(sec\text{-}C_5H_{11})_3B$, 1069-78-9; $(c\text{-}C_6H_{11})_3B$, 1088-01-3; Ph_3B, 960-71-4; $(1\text{-}C_{10}H_7)_3B$, 6962-78-3; $(PhCH_2)_3B$, 1694-84-4; $(H_2C{=}CHCH_2)_3B$, 688-61-9; $(n\text{-}C_7H_{15})_3B$, 3244-73-3; CH_3I, 74-88-4; C_2H_5Br, 74-96-4; $n\text{-}C_3H_7Br$, 106-94-5; $i\text{-}C_3H_7Br$, 75-26-3; $n\text{-}C_4H_9Br$, 109-65-9; $sec\text{-}C_5H_{11}Br$, 10422-35-2; $c\text{-}C_6H_{11}Br$, 108-85-0; PhBr, 108-86-1; $1\text{-}C_{10}H_7Br$, 90-11-9; $PhCH_2$, 100-44-7; $H_2C{=}CHCH_2$, 107-05-1; $n\text{-}C_7H_{15}I$, 4282-40-0; BF_3·OEt_2, 109-63-7; THF, 109-99-9; $n\text{-}C_5H_{12}$, 109-66-0; n-BuCl, 109-69-3; n-BuI, 542-69-8.

Chiral Synthesis via Organoboranes. 5. Asymmetric Allylboration via Chiral Allyldialkylboranes. Synthesis of Homoallylic Alcohols with Exceptionally High Enantiomeric Excess

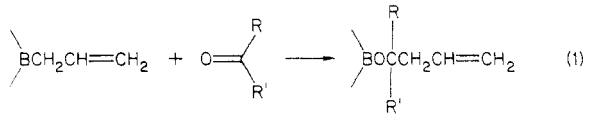
Prabhakar K. Jadhav, Krishna S. Bhat, P. Thirumalai Perumal, and Herbert C. Brown*

Richard B. Wetherill Laboratory, Purdue University, West Lafayette, Indiana 47907

Received July 29, 1985

Allyldiisopinocampheylborane, prepared readily by treatment of methoxydiisopinocampheylborane with allylmagnesium bromide, adds smoothly to aldehydes with remarkable enantioselectivity, transferring an allyl group to the carbonyl carbon with boron going to the oxygen. The enantioselectivity in allylboration varies with the reaction temperature, increasing considerably by decreasing the temperature from 0 °C to −78 °C. However, the enantioselectivity achieved does not vary significantly with the structure of the aldehyde. The enantioselectivity in the condensation of the reagent with representative ketones is less favorable, but in selected cases the results are promising (as high as 75% ee). Condensation of methallyldiisopinocampheylborane and (3,3-dimethylallyl)diisopinocampheylborane with aldehydes proceeds with equally high asymmetric induction, indicating that wide variations in the structure of the allylic moiety can be accommodated. The effect of changes in the chiral ligand on boron has also been studied.

Allylboranes are extremely reactive organoborane intermediates.[1] The high reactivity of allylboranes is manifested in their reactions with water, alcohols, and amines, which occur even at room temperature.[1a] This feature distinguishes them markedly from trialkylboranes, which react with the same substrates only at elevated temperatures. Over the past decade, Mikhailov and coworkers[1a] have extensively examined the chemistry of the simple triallylboranes. They have reported that such allylboranes add smoothly to various carbonyl derivatives in the usual organometallic fashion, transferring an allyl group to the carbonyl carbon with boron going to the oxygen (eq 1). Such allylborations of aldehydes and ketones



(1)

proceed simply, utilizing all three allyl groups in the former case but only two allyl moieties in the latter. The allylboration of other carbonyl derivatives such as nitriles and quinones are not as straightforward, being accompanied by subsequent reactions of the initial products. *B*-Allyl derivatives of 9-borabicyclo[3.3.1]nonane (9-BBN) are known to possess unique advantages over simple triallylboranes in many synthetic applications. Consequently, *B*-allyl derivatives of 9-BBN were systematically investigated in our laboratory.[1b,c]

Allylboranes are extremely valuable intermediates in organic synthesis, particularly for carbon–carbon bond formation. Use of chiral allylboranes for asymmetric carbon–carbon bond formation was not recognized until recently.[2,3] Hoffmann and co-workers[2] used chiral allylboronates for asymmetric carbon–carbon bond formation. We have developed allyldiisopinocampheylborane derivatives for asymmetric allylboration. These chiral allylboranes are highly effective intermediates for asymmetric carbon–carbon bond formation. A portion of our study has appeared in the form of preliminary communica-

(1) (a) Mikhailov, B. M. *Organomet. Chem. Rev Sec. A* **1972**, *8*, 1. (b) Kramer, G. W.; Brown, H. C. *J. Org. Chem.* **1977**, *42*, 2292; (c) *J. Organomet. Chem.* **1977**, *132*, 9.

(2) (a) Herold, T.; Hoffmann, R. W. *Angew. Chem., Int. Ed. Engl.* **1978**, *17*, 768. (b) Herold, T.; Schrott, U.; Hoffmann, R. W. *Chem. Ber.* **1981**, *114*, 359. (c) Hoffmann, R. W.; Herold, T. *Ibid.* **1981**, *114*, 375.

(3) Midland, M. M.; Preston, S. B. *J. Am. Chem. Soc.* **1982**, *104*, 2330.

0022-3263/86/1951-0432$01.50/0