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Review

INVESTIGATIONS IN THE SYNTHESIS OF ALKYL-SUBSTITUTED BOROHYDRIDES *

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Contents

1. Introduction

1.1. General survey

The discovery of sodium borohydride [1] in 1942 and lithium aluminum hydride [2] in 1945 brought about a revolutionary change in procedures for the reduction of functional groups in organic molecules [3,4]. Today, faced with the problem of reducing an organic functional group, such as CO, COOR

* Dedicated to Prof. R.C. Mehrotra on the occasion of his 60th birthday (February 16th, 1982).

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or CN, the synthetic organic chemist will rarely undertake to use the conventional techniques, such as the Meerwein-Ponndorf-Verley reaction (aldehydes and ketones), the Bouveault-Blanc procedure (esters) or catalytic hydrogenation (nitriles). The two complex hydrides (sodium borohydride and lithium aluminum hydride) provide a simple and convenient route for the reduction of such functional groups and they are invariably used in laboratory syntheses involving such transformations.

However, despite their great convenience, these two reagents suffer from certain limitations. As first described by W.G. Brown et al. [4], lithium aluminum hydride is an exceedingly powerful reducing agent, capable of reducing practically all organic functional groups. Consequently, it is quite difficult to apply this reagent for the selective reduction of multifunctional molecules. On the other hand, sodium borohydride is a remarkably mild reducing agent [4]. It readily reduces only aldehydes, ketones and acid chlorides. Consequently, it is useful primarily for selective reductions involving these relatively reactive groups.

$NaBH_4$	$LiAlH_4$
very mild	very powerful

These two reagents represent two extremes of a possible broad spectrum. Either by decreasing the reducing power of $LiAlH_4$ or by increasing that of $NaBH_4$, or both, the organic chemist would have available a more complete spectrum of reagents for selective reductions. One of the means of controlling the reducing power of the complex hydrides is to introduce substituents in the complex ion that might exert marked steric and electronic influences upon the reactivity of the substituted complex ion. By introducing alkyl substituents in the borohydride ion, alkyl-substituted borohydrides can be obtained. Synthesis of the alkyl-substituted borohydrides have assumed increased importance since their utility as versatile, selective reducing agents [5] and synthetic intermediates [6] has been demonstrated. Moreover, investigations in our laboratory have established the ability of hindered and highly hindered alkyl-substituted borohydrides to introduce major steric control into the reduction of cyclic and bicyclic ketones [7]. In this respect, these reagents are unequalled by any other reagents currently available. Our aim here is to review the procedures which have been developed for the synthesis of alkyl-substituted borohydrides.

1.2. Early explorations

Lithium trimethylborohydride and sodium triethylborohydride were the members of this new class of compounds first synthesized during war research (1942—1945) [8] (eq. 1 and 2). Since then, a few more reports on the synthesis

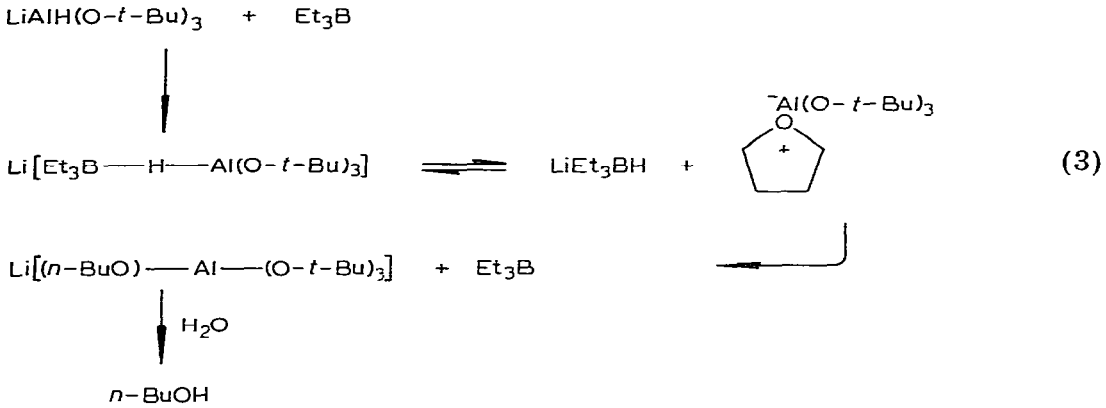
$$LiH + Me_3B \rightarrow LiMe_3BH \quad (1)$$

$$NaH + Et_3B \rightarrow NaEt_3BH \quad (2)$$

of alkyl-substituted borohydrides have appeared in the literature [9]. Unfortunately, the majority of these studies were carried out utilizing relatively drastic reaction conditions or in vacuum lines. It was shown later [10] that the reaction between trialkylboranes and alkali metal hydrides proceeds far better

in ether solvents than in hydrocarbon solvents or neat [9]. A brief study of lithium triethylborohydride indicated it to be a considerably more powerful reducing agent than the parent hydride, lithium borohydride [11].

The exceptional characteristics of alkyl-substituted borohydrides were first appreciated during our research involving the hydride-induced carbonylation of organoboranes [12]. It was observed that the addition of an equimolar quantity of triethylborane to a tetrahydrofuran (THF) solution of lithium tri-t-butoxyaluminohydride (LTBA) resulted in a vigorous exothermic reaction and the rapid disappearance of active hydride. Hydrolysis of the reaction mixture indicated the concurrent formation of 1-butanol (from reductive cleavage of THF). Further research in this direction revealed that the reaction involved $LiEt_3BH$ and monomeric aluminum t-butoxide as intermediates [13] (eq. 3).



(3)

The reductive cleavage of tetrahydropyran (THP) is quite sluggish. Consequently, the LTBA-Et_3B system was used in THP to reductively cleave more reactive cyclic ethers. These investigations led us to believe that $LiEt_3BH$ should possess exceptional hydride transfer ability. Accordingly, we undertook a major new program to synthesize a variety of alkyl-substituted borohydrides and to explore their chemistry. Because of their superior hydridic qualities, these reagents have been called "Super Hydrides", a term truly representative of their extraordinary hydridic activity.

2. Reaction of metal hydrides with organoboranes

A simple approach for the synthesis of these derivatives would be the reaction between alkali metal hydrides and the organoboranes. Hydroboration of olefins has made available trialkyl-, dialkyl- and monoalkyl-boranes with various structural features [14,15]. Accordingly, we undertook a systematic examination of the reaction of alkali metal hydrides with organoboranes of increasing steric requirements under standard conditions. It was evident from our previous work [16] and work elsewhere [10] that the reaction between trialkylboranes and alkali metal hydrides proceeds far better in ether solvents than in hydrocarbon media or neat [9]. Lithium hydride, as well as lithium deuteride, reacts with a variety of unhindered trialkylboranes to give lithium trialkylborohydrides and deuterides [17,18]. The yields are essentially quantitative. However, with

hindered trialkylboranes, such as tri-s-butylborane, we encountered a major synthetic difficulty [17] (eq. 4, 5 and 6).

$$LiH + R_3B \xrightarrow[0.25\text{—}6.0\ h]{THF,\ 65°C} \underset{>95\%}{LiR_3BH} \quad (4)$$

R = Me, Et, n-Bu, i-Bu

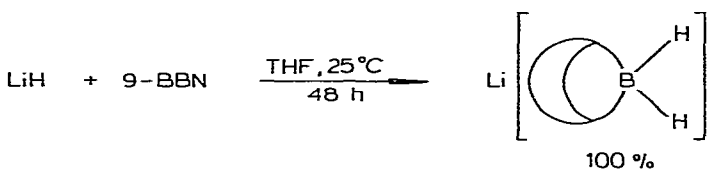
$$LiD + Et_3B \xrightarrow[1\ h]{THF,\ 65°C} LiEt_3BD \quad (5)$$

$$LiH + s\text{-}Bu_3B \xrightarrow[24\ h]{THF,\ 65°C} \underset{10\%}{Li\text{-}s\text{-}Bu_3BH} \quad (6)$$

The rate of the reaction is strongly influenced by the steric requirement of the trialkylboranes (Table 1).

Lithium trialkylborohydrides can be isolated as 1:1 [16] or 1:2 [19] solvates with ether solvents. The solvents can be removed by pumping at moderate temperature without loss of the organoboranes, providing the corresponding unsolvated borohydrides. These materials can then be dissolved in hydrocarbon solvents, such as benzene, toluene and n-hexane, to give solutions which are difficult to obtain directly by the reaction of lithium hydride and trialkylboranes in these solvents [16]. Unsolvated $LiMe_3BH$ and $LiEt_3BH$ readily dissociate into lithium hydride and the corresponding organoboranes at moderate temperatures. Lithium hydride thus prepared is enormously more reactive than the commercial lithium hydride and readily reacts with Me_3B and Et_3B, even in the absence of solvents, to form the corresponding unsolvated alkylborohydrides [16].

Lithium hydride reacts completely with the dialkylborane, 9-borabicyclo-[3.3.1]nonane (9-BBN), and the monoalkylborane, thexylborane ($ThxBH_2$) at 25°C in 48 h [20] (eq. 7 and 8). Dicyclohexylborane (Chx_2BH), disiamyl-



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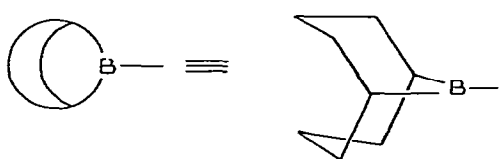
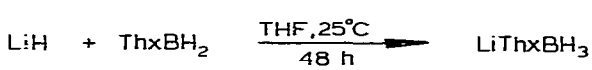




(8)

borane [bis(3-methyl-2-butyl)borane, Sia_2BH] and diisopinocampheylborane (Ipc_2BH) are almost inert to lithium hydride under these conditions [21]. Consequently, the reaction of mono- and di-alkylboranes with lithium hydride was examined in THF under reflux. Under these conditions, lithium hydride reacts

TABLE 1

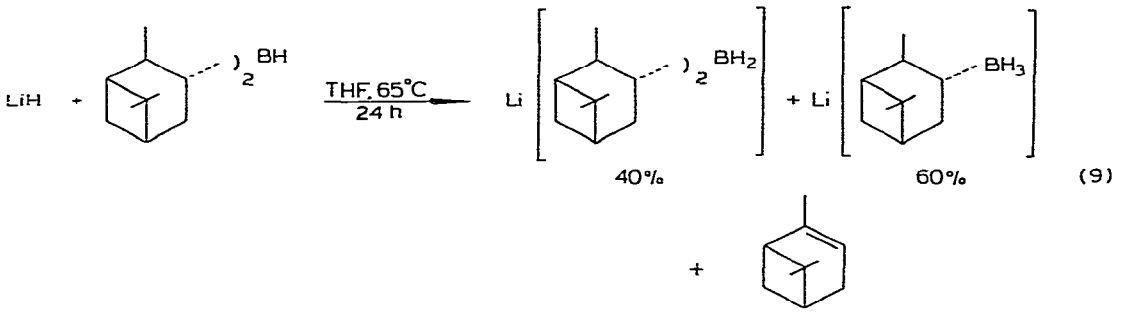
REACTION OF SALINE HYDRIDES WITH REPRESENTATIVE TRIALKYLBORANES IN THF [a]

Trialkyiborane	Metal hydride	Temp. (°C)	Trialkylborohydride formed (%) [b]								Ref.
			0.25 h	0.5 h	1.0 h	2.0 h	3.0 h	6.0 h	12.0 h	24.0 h	
Triethylborane	LiH	25		55	73	78	85	90	92	98	17
	LiH	65	97	98	98		98				17
	LiD	65			100						17
	NaH	25	100	100							17
	KH	25	93	96	96						24
Tri-n-butylborane	LiH	25					50	74	80	90	17
	LiH	65	36	65	92		95	97			17
	NaH	25	98	99	100						17
	KH	25	95	98	98						24
Tri-i-butylborane	LiH	25						25	79	91	17
	LiH	65	20		74		88	98	99		17
	NaH	25	87	89	93	96			100		17
	KH	25	96	100	99						24
Tri-s-butylborane	LiH	25					0			0	17
	LiH	65		0	0		2		7	10	17
	NaH	25			2		5				17
	NaH	65	82	90	94	97	100	100			17
	KH	25	82	93	100						24
Tricyclohexylborane	LiH	65					2		5	8	17
	NaH	65	100	100							17
	KH	25	96	96	96						24
Perhydro-9b-bora-phenalene	LiH	65		100	100						18
	NaH	25	100	100	100						17
	KH	25	100	100							24
Tris(*trans*-2-methyl-cyclopentyl)borane	LiH	65							0	0	17
	NaH	65							0	0	17
	KH	25					10	20		50	24
Trisiamylborane	LiH	65							0	0	17
	NaH	65							0	0	17
	KH	25			2		4			9	24

[a] Solutions were 1.0 *M* in R_3B and approximately 50% excess of metal hydride was utilized. [b] Monitored by GLC by measuring the n-octane formed after quenching with n-octyl iodide, or in some cases, by hydrolysis of the clear reaction mixture after filtration.

rapidly with 9-BBN and $ThxBH_2$, with the reaction being complete in 12 h and 3 h, respectively. However, this procedure proved not to be suitable for the preparation of the lithium dialkylborohydrides derived from Chx_2BH, Sia_2BH and Ipc_2BH. Unlike 9-BBN, these organoboranes are thermally unstable. They undergo rapid redistribution and/or elimination of alkyl groups at higher temperatures. As a result, a mixture of products is invariably formed [20] (eq. 9).

The reaction of organoboranes with sodium hydride is far more facile than the corresponding reactions involving lithium hydride [17]. Thus, sodium hydride reacts essentially with all unhindered trialkylboranes and with a number of hindered trialkylboranes, even at 25°C (Table 1). Other hindered trialkyl-



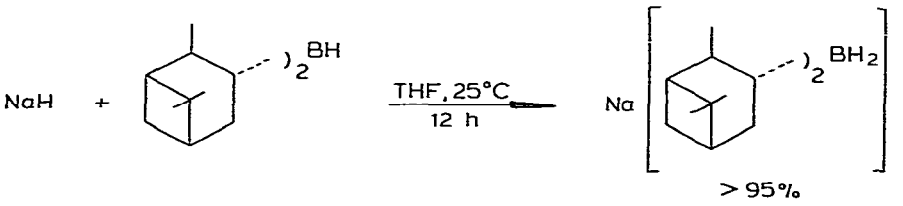
(9)

boranes, such as s-Bu_3B, react with sodium hydride in refluxing THF rapidly and quantitatively (eq. 10).

$$\text{s-Bu}_3\text{B} + \text{NaH} \xrightarrow[3\text{ h}]{\text{THF, 65°C}} \underset{100\%}{\text{Na-s-Bu}_3\text{BH}} \qquad (10)$$

Highly hindered boranes, such as trisiamylborane (Sia_3B), are inert toward both lithium hydride and sodium hydride, even in refluxing THF.

Sodium hydride also exhibits greater reactivity than lithium hydride in its reaction with mono- and di-alkylboranes [20] (Table 2). The rates of these reactions vary with the structure of the alkyl group on boron. However, even relatively hindered dialkylboranes, such as Ipc_2BH, react quantitatively with sodium hydride at 25°C (eq. 11).



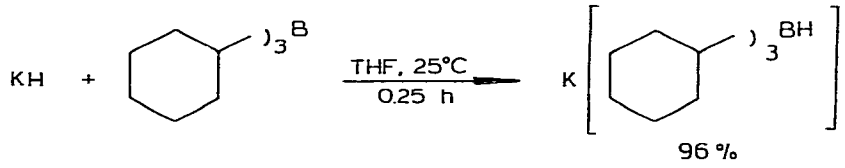
(11)

Trends in the lattice energy of saline hydrides suggest that the reactivity should increase rapidly in the series, lithium hydride < sodium hydride < potassium hydride [22]. It was shown in a preliminary investigation that potassium hydride is exceptionally reactive, even towards weak Lewis acids of boron [23]. Unhindered trialkylboranes, such as perhydro-9b-boraphenalene-, triethyl-, tri-n-butyl- and tri-i-butyl-boranes react with potassium hydride almost instantly and quantitatively in THF at 25°C [24] (eq. 12).

$$\text{KH} + \text{i-Bu}_3\text{B} \xrightarrow[<0.5\text{ h}]{\text{THF, 25°C}} \text{K-i-Bu}_3\text{BH} \qquad (12)$$

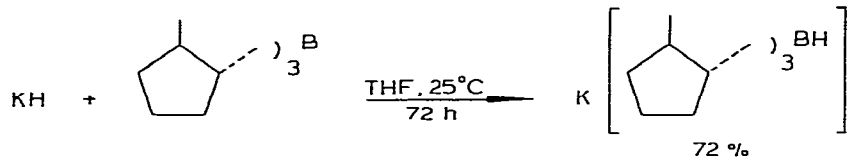
All of the hindered trialkylboranes examined, tri-s-butyl-, tricyclopentyl-, tricyclohexyl- and tri-exo-2-norbornyl-boranes react rapidly and quantitatively at 25°C (eq. 13 and 14). However, the reaction of highly hindered trialkylboranes with potassium hydride is quite sluggish. Thus, the reaction of tris-

$$\text{KH} + \text{s-Bu}_3\text{B} \xrightarrow[1\text{ h}]{\text{THF, 25°C}} \underset{100\%}{\text{K-s-Bu}_3\text{BH}} \qquad (13)$$



(14)

(*trans*-2-methylcyclopentyl)borane proceeds to the extent of 72% in 72 h at 25°C. Trisiamylborane is essentially inert towards potassium hydride under these conditions (eq. 15 and 16). As shown by the data for the reaction of the



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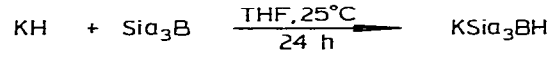


(16)

three alkali metal hydrides with tri-s-butylborane at 25°C: lithium hydride,

TABLE 2

REACTION OF SALINE HYDRIDES WITH REPRESENTATIVE MONO- AND DI-ALKYLBORANES IN THF [20]

Mono- or di-alkylborane [a]	Metal hydride	Temp. (°C)	Mono- or di-alkylborohydride found (%) [b]							
			0.25 h	0.5 h	1.0 h	2.0 h	3.0 h	6.0 h	12.0 h	24.0 h
9-Borabicyclo[3.3.1]-nonane	LiH	25	0	0	0	0	0	0	30	81
	LiH	65	0	4	30	38	54	97	97	
	NaH	25	0	0	0	56	100	100		
	KH	25	100	100						
Dicyclohexylborane	LiH	25	0	0	0	0	0	0	0	20
	LiH	65	0	24	42	58	65	70		
	NaH	25	0	0	0	4	29	98	98	
	KH	25	100	100						
Disiamylborane	LiH	25	0	0	0	0	0	0	12	49
	LiH	65	0	8	73	98	98			
	NaH	25	0	14	27	47	63	89	100	100
	KH	25	100	100						
Diisopinocampheylborane	LiH	25	0	0	14	25	34	49	68	89
	LiH	65	0	12	26	61	95	100		
	NaH	25	0	0	0	12	28	70	99	
	KH	0	0	65	100	100				
Thexylborane	LiH	25	0	0	0	0	0	0	0	0
	LiH	65	0	0	22	78	98	98		
	NaH	25	0	0	0	20	40	100	100	
	KH	25	100	100						
Monoisopinocampheyl-borane	NaH	25	0	5	10	18	27	55	99	99
	KH	25	80	100	100					

[a] Solutions were 0.5 *M* in organoborane and approximately 50% excess of alkali metal hydride was utilized.
[b] Monitored by hydrolysis of the centrifuged reaction mixture and by ^{11}B NMR spectroscopy.

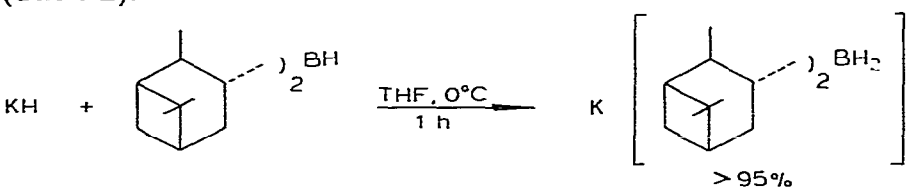
0% in 24 h, sodium hydride, 8% in 2 h; potassium hydride, 100% in 1 h (Table 1).

Potassium hydride reacts almost instantly and quantitatively with mono- and di-alkylboranes [20]. Indeed, reactions are so rapid and vigorous that care is needed in controlling the reaction by cooling the flask efficiently in a bath (~20°C) (eq. 17 and 18). Even such cooling is not adequate for the reaction

$$KH + Sia_2BH \xrightarrow[<0.25\ h]{THF,\ 25°C} \underset{100\%}{KSia_2BH_2} \quad (17)$$

$$KH + ThxBH_2 \xrightarrow[<0.25\ h]{THF,\ 25°C} KThxBH_3 \quad (18)$$

between Ipc_2BH and potassium hydride, which proceeds vigorously, resulting in up to 20% dehydroboration. However, this side reaction could be minimized by mixing the reactants at 0°C and maintaining that temperature for 1 h (eq. 19) (Table 2).



(19)

3. Metal hydride transfer reaction

3.1. Reaction of lithium trimethoxyaluminohydride with organoboranes

As pointed out in the previous section, alkali metal hydrides fail to react with the highly hindered trialkylboranes (eq. 20). Investigations in our labora-

$$MH + Sia_3B \xrightarrow[24\ h]{THF,\ 25°C} \underset{0—10\%}{MSia_3BH} \quad (20)$$

(M = Li, Na or K)

tory have established the importance of hindered and highly hindered alkyl-substituted borohydrides for the stereoselective reduction of cyclic ketones [5,6]. Consequently, we became interested in exploring various procedures for the general synthesis of alkyl-substituted lithium borohydrides, applicable to unhindered, hindered and highly hindered trialkylboranes.

Recently we reported that the reductive cleavage of THF and related ethers by lithium tri-t-butoxyaluminohydride (LTBA) induced by Et_3B proceeds through the formation of $LiEt_3BH$ [13]. We also observed that the addition of a molar amount of triethylborane to a THF solution of lithium trimethoxy-aluminohydride (LTMA) results in an instantaneous, vigorous, exothermic reaction, forming a gel. However, no reductive cleavage of THF or loss of hydride was noted. Analysis of the reaction mixture indicated that a metal hydride transfer reaction had taken place to form the corresponding lithium triethylborohydride and a polymeric gel of aluminum methoxide [25]. Our preliminary studies with other trialkylboranes indicated that even in the case

of hindered trialkylboranes the reaction is essentially complete in about 15 min at 25°C, the rate being far faster than that involving the direct reaction with lithium hydride (eq. 21). Encouraged by this preliminary study, the reaction of

$$\text{s-Bu}_3\text{B} \begin{cases} \xrightarrow[25^\circ\text{C, 24 h}]{\text{LiH, THF}} \text{Li-s-Bu}_3\text{BH} \\ \quad\sim 0\% \\ \xrightarrow[25^\circ\text{C, 0.25 h}]{\text{LiAlH(OCH}_3)_3\text{, THF}} \text{Li-s-Bu}_3\text{B} \\ \quad 100\% \end{cases} \qquad (21)$$

LTMA with representative series of trialkylborane was examined in detail [26].

The results summarized in Table 3 clearly indicate that the metal hydride transfer from LTMA to trialkylboranes is exceedingly rapid, essentially complete in less than 15 min at room temperature. All of the trialkylboranes examined, unhindered, hindered and highly hindered, underwent rapid and essentially quantitative hydride transfer [26] (eq. 22, 23 and 24). The rate is

$$\text{LiAlH(OCH}_3)_3 + \text{Et}_3\text{B} \xrightarrow[0.25\text{ h}]{\text{THF, 25°C}} \underset{96\%}{\text{LiEt}_3\text{BH}} \qquad (22)$$

$$\text{LiAlH(OCH}_3)_3 + \text{s-Bu}_3\text{B} \xrightarrow[0.25\text{ h}]{\text{THF, 25°C}} \underset{98\%}{\text{Li-s-Bu}_3\text{BH}} \qquad (23)$$

$$\text{LiAlH(OCH}_3)_3 + \text{Sia}_3\text{B} \xrightarrow[0.25\text{ h}]{\text{THF, 25°C}} \underset{98\%}{\text{LiSia}_3\text{BH}} \qquad (24)$$

far faster than that involving direct reaction with lithium hydride. The greatly enhanced reactivity of LTMA over lithium hydride may be attributed to the solubility of the former in THF. The LTMA solution in THF can be con-

TABLE 3

REACTION OF $LiAlH(OCH_3)_3$ [26] AND $KHB(O\text{-}i\text{-}Pr)_3$ WITH REPRESENTATIVE TRIALKYLBORANES IN THF

Trialkylborane	From $LiAlH(OCH_3)_3 + R_3B$ [a]			From $KHB(O\text{-}i\text{-}Pr)_3 + R_3B$ [a]		
	Temp. (°C)	Time (h)	MR_3BH formed [b] (%)	Temp. (°C)	Time (h)	MR_3BH formed [c] (%)
Triethylborane	25	15	95	25	5	>98
Tri-n-butylborane	25	15	99	25	5	>98
Tri-i-butylborane	25	15	94	25	5	>98
Tri-s-butylborane	25	15	98	25	5	>98
Tricyclopentylborane	25	15	100			
Tricyclohexylborane	25	15	98			
Tri-*exo*-2-norbornylborane	25	15	100			
Tris(*trans*-2-methylcyclopentyl)borane	25	15	98	25	5	>98
Trisiamylborane	25	15	99	25	5	>98

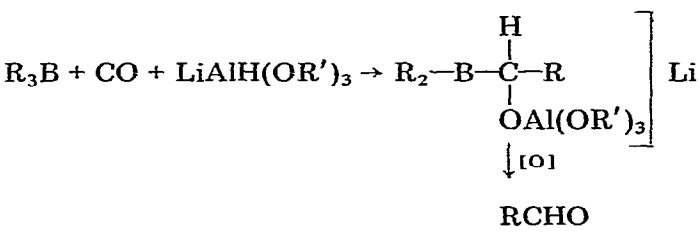
[a] Solutions were equimolar in concentrations, approximately 0.5 *M*. [b] Monitored by GLC by measuring cyclohexanol or 2-butanol formed after quenching with cyclohexane oxide or 1,2-epoxybutane, respectively. [c] Monitored by ^{11}B NMR.

sidered a soluble complex of lithium hydride. Moreover, aluminum methoxide is a weaker Lewis acid than trialkylborane. Consequently, the trialkylborane can extract the hydride ion from the LTMA molecule.

It was pointed out earlier that the mixtures of lithium trialkylborohydride and aluminum methoxide are sometimes quite viscous or become gels, probably due to the formation of aluminum methoxide polymers. The polymeric aluminum methoxide is inert and does not interfere in the further reactions of the trialkylborohydrides. Occasionally we encountered difficulty in stirring the reaction mixture efficiently. This difficulty can be circumvented by adding lithium methoxide, which causes dissolution of the gel, producing a clear solution. Examination of the clear solution indicated that the lithium tetramethoxyaluminate formed is solubilized by lithium trialkylborohydride. The corresponding reaction of LTMA with mono- and di-alkylboranes has not yet been investigated.

3.2. Reaction of lithium tri-t-butoxyaluminohydride with organoboranes

Both LTMA and lithium tri-t-butoxyaluminohydride (LTBA) have been utilized to achieve the carbonylation of organoboranes (eq. 25). In the case of LTMA, it has been established that there occurs a rapid transfer of metal



$$R_3B + CO + LiAlH(OR')_3 \rightarrow R_2-B-\underset{\displaystyle OAl(OR')_3}{\overset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}-R \;\Big]\; Li \qquad (25)$$

$$\downarrow [O]$$

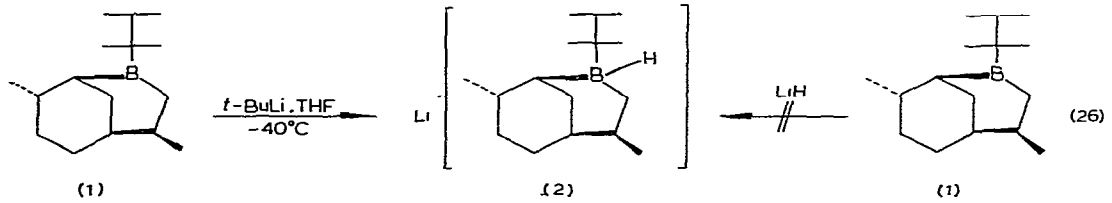
$$RCHO$$

hydride from LTMA to the organoborane to form the corresponding alkyl-substituted lithium borohydride [26]. It was of interest to examine whether LTBA also transfers metal hydride to the organoborane as an essential step in the carbonylation reaction. Initial study revealed that the addition of an equimolar or catalytic quantity of trialkylboranes to a THF solution of LTBA results in a rapid loss of hydride with concurrent formation of n-butanol (from the reductive cleavage of THF). The rate of reductive cleavage of THF decreases with increasing steric requirements of the organoborane.

In contrast to THF, tetrahydropyran (THP) is cleaved sluggishly. Consequently, this solvent can be used to follow the course of the reaction of LTBA with trialkylboranes of different steric requirements [27]. The results clearly indicate that a complete metal hydride transfer from LTBA to the trialkylborane occurs rapidly only in the case of unhindered trialkylboranes. Thus the above reaction, while interesting, is not a useful method for borohydride preparation.

3.3. Reaction of organometals with organoboranes

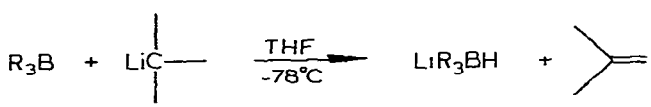
Corey et al. [28] have reported that the reaction of thexyllimonylborane (**1**) with lithium hydride fails to give the corresponding trialkylborohydride (**2**). However, treatment of the same organoborane with t-butyllithium at −40°C gives the desired trialkylborohydride (**2**) (eq. 26).



(1) (2) (1)

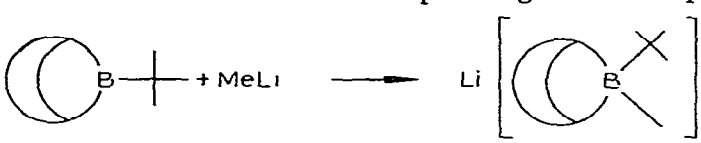
This borohydride was used in the selective reduction of prostaglandin intermediates, but few experimental details concerning its preparation have been presented. Other trialkylborohydrides were prepared in a similar manner, again with little experimental information [29].

It is apparent that the reaction of trialkylboranes with t-butyllithium is potentially an extremely important method for the preparation of lithium trialkylborohydrides. Accordingly, we undertook a systematic study of this reaction to determine its scope and limitations [30]. Representative trialkylboranes possessing widely differing steric requirements were selected for this study. The reaction was followed by ^{11}B NMR spectroscopy. It was found that this reaction occurs rapidly in ether solvents, even at −78°C, with formation of the corresponding lithium borohydrides. It is necessary to maintain the reaction temperature below −20°C to achieve quantitative formation of the trialkylborohydride. This synthesis is highly general, accommodating even strongly hindered trialkylboranes such as trisiamylborane. The only by-product, isobutene, is innocuous and can be easily removed (eq. 27).



(27)

It was of interest to understand whether the transfer of metal hydride from t-butyllithium to trialkylborane was a thermodynamic or kinetic phenomenon. For this purpose, we examined two systems by ^{11}B NMR. Addition of methyllithium to B-t-butyl-9-borabicyclo[3.3.1]nonane [B-t-Bu-9-BBN (**3**)] resulted in the formation of the corresponding "ate" complex (**4**) (eq. 28). No trialkyl-

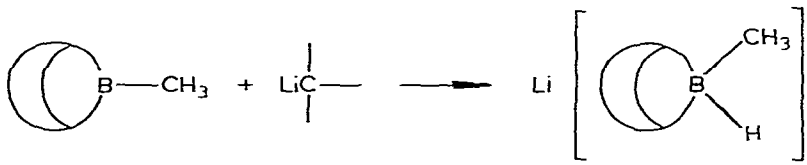


(28)

(3) (4)

^{11}B NMR : δ − 16.7 ppm

borohydride was observed. However, attempts to synthesize the same compound via treatment of *B*-methyl-9-borabicyclo[3.3.1]nonane [*B*-Me-9-BBN (**5**)] with t-butyllithium produced the corresponding trialkylborohydride (**6**) exclusively (eq. 29). Consequently, the pathway for these reactions is not



(29)

(5) (6)

^{11}B NMR : δ − 15.8 ppm (d)

determined by the nature of the product formed (thermodynamic control), but by the properties of the reactants (kinetic control).

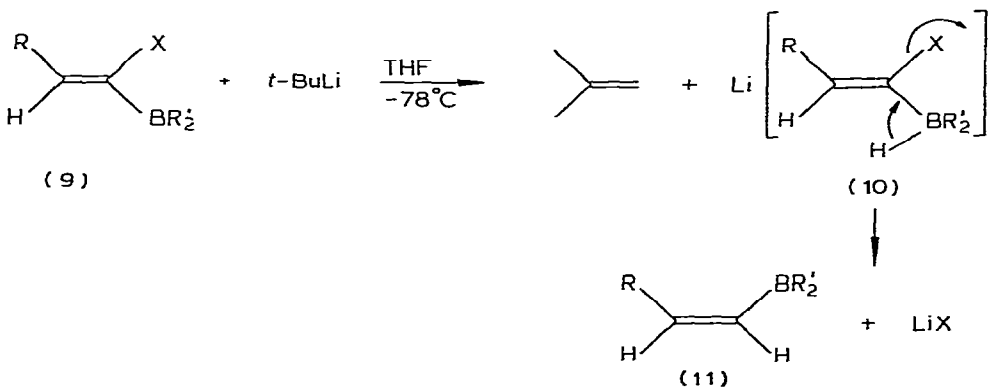
A similar metal hydride transfer reaction has been reported using s-butyllithium [31]. Thus di-s-butyl-mono-n-butylborane (**7**) reacts with s-butyllithium to give the corresponding trialkylborohydride (**8**) rather than the lithium tetraalkylborate (eq. 30). Here again the reaction is controlled by kinetic factors

$$(\text{s-Bu})_2\text{-}B\text{-n-Bu} + \text{s-BuLi} \rightarrow \text{Li}\left[\text{s-Bu}_2\text{B}(\text{n-Bu})(\text{H})\right] \qquad (30)$$

(**7**) (**8**)

rather than by thermodynamic factors.

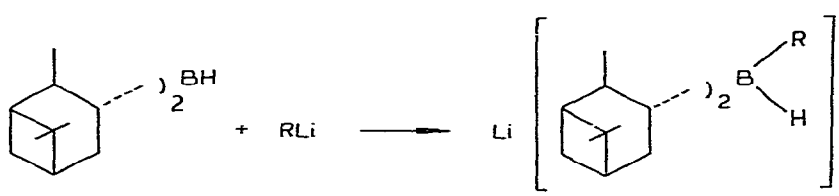
Recently the synthesis of trialkylborohydrides with t-BuLi has been used to prepare *cis*-alkenyldialkylboranes [32]. Thus, 1-halo-1-alkenyldialkylboranes (**9**) react with t-BuLi at −78°C to give the corresponding trialkylborohydrides (**10**). These borohydrides undergo anionotropic rearrangement to give the corresponding *cis*-1-alkenyldialkylboranes (**11**) (eq. 31).



(31)

The metal hydride transfer from an organometallic reagent to a trialkylborane appears to be a general reaction [33]. It depends on the nature of the organometallic compound and increases regularly within the series: primary < secondary < tertiary.

Until recently, it was assumed that dialkylboranes could be easily converted into trialkylborohydrides via alkylation with organolithium reagents (eq. 32). This route has been used by several workers in attempts to prepare selective reducing agents [28,29] and asymmetric reducing agents [34]. Thus, Grundon et al. [35] claimed that a new class of chiral reducing agents, lithium alkyldiisopinocampheylborohydrides, can be prepared by the direct reaction of alkyllithium reagents with Ipc_2BH (eq. 32). The reagents prepared in this way



(32)

were used to reduce unsymmetrical ketones to the optically active alcohol with optical yields in the range of 5—45% [35]. In all cases the proposed borohydrides did not possess the speed or selectivity typical of the lithium trialkylborohydrides in the reduction of alkyl halides [36,37].

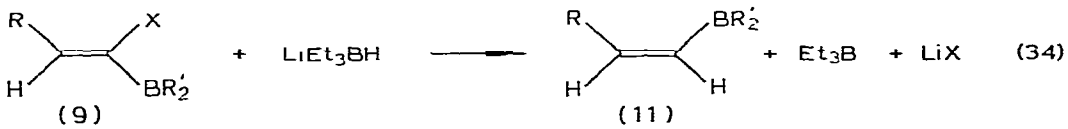
In view of this observation, an investigation was undertaken to establish the nature of the product from the reaction of dialkylboranes with organolithium reagents [21]. The dialkylboranes, 9-BBN, Chx_2BH and Sia_2BH, were selected for the study. Each was treated with methyllithium, n-butyllithium, phenyllithium and t-butyllithium and the reaction was followed by ^{11}B NMR. The reaction of these dialkylboranes with primary and aryl organolithium agents did not produce the expected trialkylborohydride. Instead, the products proved to be equal amounts of mixed lithium tetraalkylborate and lithium dialkylborohydride (eq. 33). The reaction of dialkylboranes with t-butyllithium appears to

$$R_2BH + R'Li \rightarrow LiR_2BH_2 + LiR_2R'_2B \qquad (33)$$

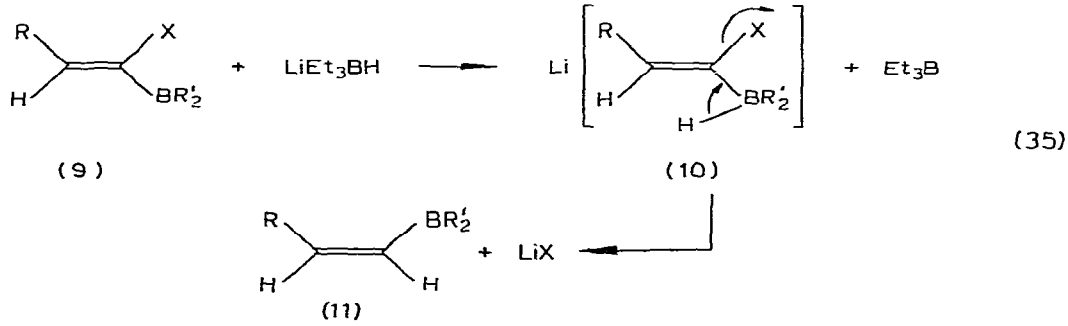
be more complex and is not fully understood.

3.4. Reaction of alkyl or alkoxy borohydrides with organoboranes

Certain alkyl borohydrides can react with an organoborane, transferring metal hydride, to produce the alkyl-substituted borohydride derived from the organoborane. Negishi has developed a synthesis of *cis*-1-alkenylboranes involving the reaction of 1-halo-1-alkenylboranes with lithium triethylborohydride [38] (eq. 34). This reaction apparently proceeds through a metal hydride trans-



fer from lithium triethylborohydride to the 1-halo-1-alkenylborane, followed by rearrangement [32] (eq. 35).



Similarly, metal hydride transfer is also observed in the reaction of a trialkylborohydride with a dialkylborane [39] (eq. 36). The same transfer is also ob-

$$MR_3BH + R'_2BH \rightarrow MR'_2BH_2 + R_3B \qquad (36)$$

served in the reaction of a dialkylborohydride with a monoalkylborane [39] (eq. 37). In general, the metal hydride is transferred from a weaker Lewis acid

$$MR_2BH_2 + R'BH_2 \rightarrow MR'BH_3 + R_2BH \qquad (37)$$

to a stronger Lewis acid. Similarly, in the reaction between sodium trialkylalkynylborate (**12**) and diethylborane, a trialkylborohydride (**13**) is formed [40] (eq. 38). The trialkylborohydrides (**13**) are valuable intermediates, since

$$\underset{\textbf{(12)}}{NaEt_3B{-}C{\equiv}C{-}CH_3} + Et_2BH \rightarrow Na\left[\underset{\textbf{(13)}}{\begin{matrix}H\\|\\Et_2B{-}C{\equiv}C{-}CH_3\end{matrix}}\right] + Et_3B \qquad (38)$$

they can produce dialkylalkynylboranes (**14**), which are difficult [41,42] to prepare (eq. 39).

$$Na\left[\underset{\textbf{(13)}}{\begin{matrix}H\\|\\Et_2B{-}C{\equiv}C{-}CH_3\end{matrix}}\right] + CH_3I \rightarrow \underset{\textbf{(14)}}{Et_2B{-}C{\equiv}C{-}CH_3} + CH_4 + NaI \qquad (39)$$

Another example of this metal hydride transfer is the reaction of potassium tri-i-propoxyborohydride [$KHB(O\text{-}i\text{-}Pr)_3$] with trialkylboranes [43]. Thus, the addition of $i\text{-}Bu_3B$ to one equivalent of $KHB(O\text{-}i\text{-}Pr)_3$ in THF at 25°C results in a rapid, quantitative metal hydride transfer to yield an equimolar mixture of potassium tri-i-butylborohydride and tri-i-propoxyborane (eq. 40). The reaction can be monitored by ^{11}B NMR. Even organoboranes with greater steric hindrance

$$KHB(O\text{-}i\text{-}Pr)_3 + i\text{-}Bu_3B \xrightarrow[<5\ min]{THF,\ 25^\circ C} K\text{-}i\text{-}Bu_3BH + B(O\text{-}i\text{-}Pr)_3 \qquad (40)$$

than $i\text{-}Bu_3B$ undergo rapid quantitative metal hydride transfer from $KHB(O\text{-}i\text{-}Pr)_3$. In this manner, trialkylboranes too hindered to undergo direct reaction with potassium hydride [24] are readily converted to the corresponding trialkylborohydrides (Table 3). This reaction is in line with the previous examples shown. Trialkylboranes are much stronger Lewis acids than tri-i-propoxyborane and therefore abstract metal hydride readily from $KHB(O\text{-}i\text{-}Pr)_3$ to form the potassium trialkylborohydrides.

The reaction of $KHB(O\text{-}i\text{-}Pr)_3$ with mono- and di-alkylboranes has not yet been explored. The formation of the corresponding alkyl-substituted borohydrides is anticipated.

3.5. Reaction of lithium aluminum hydride with organoboranes

It has been reported that lithium aluminum hydride reacts with trimethylborane to give complex products [44] (eq. 41). More recently, lithium alumi-

$$LiAlH_4 + Me_3B \rightarrow LiMeBH_3 + Me_2AlH \qquad (41)$$

num hydride was evaluated for its applicability in the hydride-induced carbonylation of organoboranes [45]. The subsequent discovery that other complex hydrides used in this reaction [LTMA, LTBA and $KHB(O\text{-}i\text{-}Pr)_3$] transfer alkali metal hydride to the trialkylborane [26,27,43] generated interest in a systematic investigation of the reaction of $LiAlH_4$ with representative organoboranes as a potential route to the lithium alkyl-substituted borohydrides.

Addition of a THF solution of $LiAlH_4$ to triethylborane resulted in a moderately exothermic reaction. Examination of the clear, colorless solution by ^{11}B

NMR unexpectedly revealed a triplet (δ 16.7 ppm, J 67 Hz) instead of the anticipated doublet. Other trialkylboranes with a primary alkyl group gave similar results. Evidently the reaction proceeds as shown in equation 42.

$$LiAlH_4 + R_3B \xrightarrow[0.25\ h]{THF,\ 25^\circ C} LiR_2BH_2 + RAlH_2 \qquad (42)$$

Trialkylboranes having a secondary alkyl group behaved somewhat differently. Addition of $LiAlH_4$ caused vigorous exothermic reactions and formation of white precipitates. Examination of the supernatant solutions by ^{11}B NMR revealed apparent mixtures of dialkyl- and trialkyl-borohydrides. The above reaction was carried out at —78°C and the solution examined as rapidly as possible by ^{11}B NMR. Initially a doublet signal, attributed to the desired trialkylborohydride, is observed. This disappears rapidly to give rise to the triplet due to dialkylborohydride. These results established that the reaction proceeds with the initial formation of the desired trialkylborohydride (eq. 43), followed by a transfer of an alkyl group (eq. 44).

$$LiAlH_4 + R_3B \xrightarrow[-78^\circ C]{THF} LiR_3BH + AlH_3 \qquad (43)$$

$$LiR_3BH + AlH_3 \xrightarrow[25^\circ C]{THF} LiR_2BH_2 + RAlH_2 \qquad (44)$$

This result indicated that a new synthesis of lithium trialkylborohydride might be achieved if the aluminum hydride could be trapped as soon as formed so as to avoid the fast subsequent reaction. We had recently observed that triethylenediamine (TED) rapidly and quantitatively precipitates aluminum hydride as TED·AlH_3 from diethyl ether (EE) and THF [47]. Accordingly, the lithium aluminum hydride solution (EE) was added to an EE solution of trialkylborane containing 1.0 equivalent of TED at 0°C. A voluminous white precipitate of TED·AlH_3 formed rapidly. The supernatant liquid, examined by ^{11}B NMR and IR, revealed the quantitative formation of the trialkylborohydride. Initially, the precipitate is present as a voluminous gel, difficult to separate from the solution. However, on standing for approximately 12 h, it becomes granular, easily separated by centrifugation from the reaction mixture. The resulting solution contains the product in pure form. This reaction is general and is applicable to a wide variety of trialkylboranes [46].

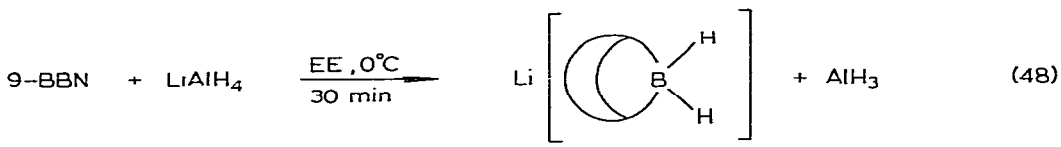
In an analogous manner, mono- and di-alkylboranes react with lithium aluminum hydride, in the presence of TED, to form the corresponding alkyl-substituted borohydrides [48]. To prepare the lithium dialkylborohydrides, the reactions were generally run by adding a solution of TED in EE to the dialkylborane in EE with constant stirring. The resulting clear solution was then treated at 0°C with a solution of lithium aluminum hydride in EE. A voluminous white precipitate of TED·AlH_3 formed rapidly. Initially, the precipitate was present as a voluminous gel. However, on standing for approximately 12 h, it became granular, readily centrifuged from the reaction mixture. Apparently the reaction proceeds as shown in equations 45, 46 and 47. In the case of

$$R_2BH + TED \xrightarrow[10\ min]{EE,\ 25^\circ C} TED{\cdot}BHR_2 \qquad (45)$$

$$TED \cdot BHR_2 + LiAlH_4 \xrightarrow[30\ min]{EE,\ 0^\circ C} LiRBH_2 + AlH_3 + TED \quad (46)$$

$$AlH_3 + TED \xrightarrow{EE,\ 0^\circ C} TED \cdot AlH_3\downarrow \quad (47)$$

9-BBN, the formation of the TED complex took more than 1 h for completion. If the lithium aluminum hydride were added before the complete formation of TED·9-BBN, a mixture of products was obtained. Alternatively, 9-BBN can be reacted directly with an EE solution of $LiAlH_4$ and the resulting solution treated with TED in EE to remove aluminum hydride (eq. 48). This reaction



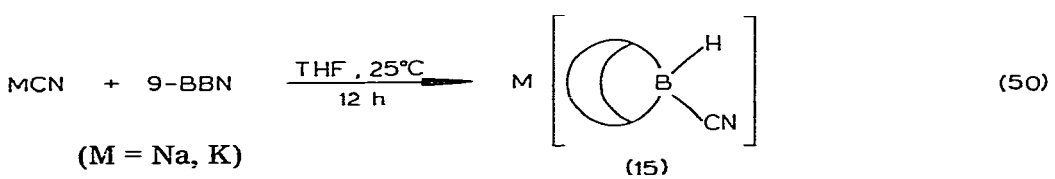
establishes that, unlike many trialkylborohydrides examined [46], this dialkylborohydride does not undergo rapid exchange reaction with free aluminum hydride.

All of the monoalkylboranes selected for the reaction with lithium aluminum hydride were prepared and used as their triethylenediamine adducts ($TED \cdot BH_2R$ [48]. The reaction between $TED \cdot BH_2R$ and lithium aluminum hydride is relatively slow at 25° C. Consequently, the reaction was examined in refluxing THF. Under these conditions, the reaction is complete in 1—3 h (eq. 49).

$$TED \cdot BH_2R + LiAlH_4 \xrightarrow[1-3\ h]{THF,\ 65^\circ C} LiRBH_3 + TED \cdot AlH_3\downarrow \quad (49)$$

4. Miscellaneous methods

Alkyl-substituted borohydrides can also be formed by the addition of certain metal salts to dialkylboranes. Thus 9-BBN reacts with sodium or potassium cyanide in THF to form the corresponding 9-cyano-9-hydrido-9-borabicyclo-



[3.3.1]nonane (**15**) (eq. 50), which is a useful reagent for reducing allylic halides [49]. However, this borohydride has not been prepared in pure form and no ^{11}B NMR data is available [49]. Similar reactions have been carried out using Chx_2BH, Sia_2BH [50,51] and Ipc_2BH [52], but no ^{11}B NMR data are available to characterize the product.

The corresponding reaction of monoalkylboranes with alkali metal cyanides has not been described.

It has been reported that diethylmagnesium reacts with diborane in EE at 25° C to give colorless ether-soluble magnesium alkyl-substituted borohydrides (**16** and **17**) (eq. 51) [53]. The borohydrides **16** and **17** decomposed above

$$Et_2Mg + B_2H_6 \longrightarrow \underset{(16)}{Mg[EtBH_3]_2} + \underset{(17)}{EtMg[EtBH_3]} \quad (51)$$

80°C to MgH_2 and Et_2BH. Pure borohydride **16** was formed at a magnesium—boron ratio of 1 or less. A mixture of **16** and **17** was obtained at a magnesium—boron ratio of 1 to 6. No further alkylation occurred at higher ratio.

More recently, Goel [54] reported that the reaction of alkylmagnesium hydrides (RMgH) with borane-tetrahydrofuran ($THF \cdot BH_3$) gave magnesium alkyl-substituted borohydrides (eq. 52). The stabilities of these compounds are

$$RMgH + THF \cdot BH_3 \rightarrow HMg[RBH_3] \quad (52)$$

(R = Me, Et, i-Pr, Ph)

dependent on the alkyl groups. Thus, when the alkyl groups are Et, i-Pr or Ph, the magnesium borohydrides are stable. When the alkyl group is methyl, the borohydride disproportionates according to the equation 53.

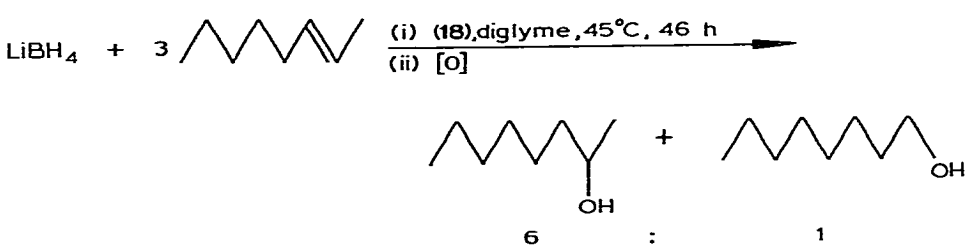
$$2\ HMg[MeBH_3] \rightarrow MgH_2 + Mg[MeBH_3]_2 \quad (53)$$

Recently it was reported that the reagent system generated from dicyclopentadienyltitanium dichloride (Cp_2TiCl_2) and two molar equivalents of lithium borohydride promoted the catalytic hydroboration of olefins with lithium borohydride to give lithium alkyl-substituted borohydrides [55] (eq. 54 and 55). The reaction occurs predominantly in the anti-Markovnikov fashion.

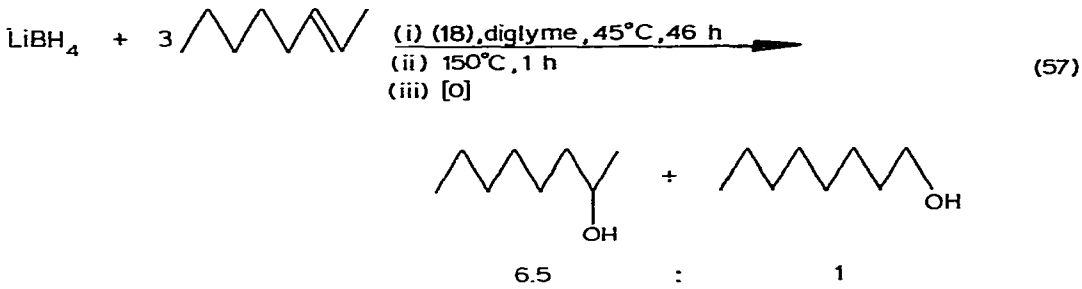
$$Cp_2TiCl_2 + 2\ LiBH_4 \xrightarrow[1\ h]{THF,\ 25^\circ C} \underset{(18)}{\text{“Titanium-Boron Complex”}} \quad (54)$$

$$LiBH_4 + 3\ \text{olefin} \xrightarrow[21\ h]{(18),\ 45^\circ C} LiR_3BH \quad (55)$$

The possibility that alkylboranes are produced as primary products of this catalytic reaction is ruled out by the observation that the hydroboration of 2-octene with $LiBH_4$ gives the same products having similar isomeric distribution at 45°C and 150°C (eq. 56 and 57). It is known that tri-2-octylborane readily isomerizes to tri-1-octylborane at 150°C and would lead to 1-octanol after oxidation [56]. However, 2-octanol was observed as the major product, even at 150°C (eq. 57). Hence, it was concluded that tri-2-octylborane was not produced during the reaction and the tri-2-octylborohydride was formed by the direct hydroboration of 2-octene with $LiBH_4$. (This conclusion should be



(56)



(57)

accepted with caution since tri-2-octylborane isomerizes rapidly only in the presence of diborane or boron-hydrogen moieties.) No ^{11}B NMR data was presented to substantiate the formation of lithium alkylborohydrides in the catalytic reaction of $LiBH_4$ with olefins.

5. Spectral data

5.1. Infrared spectra

Alkali metal alkyl-substituted borohydrides display a strong and broad absorption in the infrared region due to the B—H stretch in the borohydride anion. This absorption is typical of this new class of compounds. For example, trialkylborohydrides [17,24] exhibit a characteristic absorption around 2000 cm^{-1}. The exact frequency depends on various factors, such as the solvent and nature of the alkyl group and the cation [9]. Dialkylborohydrides [20] exhibit a B—H absorption around 2100 cm^{-1}, while the monoalkylborohydrides [20] absorb at 2200 cm^{-1} and sodium borohydride at 2300 cm^{-1}. The regular change in the B—H frequency, as we go from trialkylborohydride to unsubstituted borohydride, is interesting and may be related to the inductive effect of the alkyl substituent (Tables 4 and 5).

5.2. ^{11}B NMR spectra

Trialkylboranes exhibit a very broad singlet around δ 80 ppm ($EE \cdot BF_3$). Solutions of trialkylborohydrides exhibit sharp signals between δ —6 to —17 ppm. Potassium trialkylborohydrides exhibit clean sharp doublets (due to boron—hydrogen coupling) [24]. Similarly, all of the sodium trialkylborohydrides exhibit well-defined doublets [17]. However, lithium trialkylborohydrides, as normally prepared, exhibit singlets [17]. It was observed by C.A. Brown [57] that addition of even a trace of triethylborane to a sample of potassium triethylborohydride resulted in the collapse of the doublet to a singlet due to exchange. A similar fast exchange was also observed for the K-n-Bu_3BH—n-Bu_3B system. The rate of exchange was remarkably sensitive to increases in the steric requirements of the alkyl groups on boron [57].

Thus, the singlet observed for the lithium trialkylborohydrides, prepared from lithium hydride and trialkylboranes, presumably results from the presence of a small quantity of free trialkylborane, which rapidly exchanges with the lithium trialkylborohydride, resulting in the coalescence of the doublet. Addition of a minute amount of t-butyllithium, a procedure that converts free trialkylboranes into borohydrides [28], converts the singlet into a clean doublet.

(Continued on p. 63)

TABLE 4

INFRARED AND ^{11}B NMR SPECTRAL DATA OF TRIALKYLBOROHYDRIDES

Trialkylborane	LiR_3BH		Ref.	NaR_3BH		Ref.	KR_3BH		Ref.
	ν(B—H) (cm^{-1})	Chemical [a] shift (δ, ppm) (multiplicity)		ν(B—H) (cm^{-1})	Chemical [a] shift (δ, ppm) (multiplicity)		ν(B—H) (cm^{-1})	Chemical [a] shift (δ, ppm) (multiplicity)	
Triethylborane	2010	−13.4(d)	46	1960	−12.7(d)	17	2020	−12.8(d)	24
Tri-n-butylborane	2010	−15.4(d)	46	2000	−14.7(d)	17	2015	−15.5(d)	24
Tri-i-butylborane	1990	−18.2(d)	46	2000	−17.7(d)	17	2040	−18.4(d)	24
Tri-s-butylborane	2000	−6.3(d)	46	2025	−6.32(d)	17	2030	−7.5(d)	24
Tricyclopentylborane	2050	−9.3(d)	46	2010	−10.1(d)	17	2040	−10.6(d)	24
Tricyclohexylborane	2020	−5.9(d)	46	2020	−6.47(d)	17	2030	−8.0(d)	24
Tri-*exo*-2-norbornylborane	2030	−7.9(d)	46	2020	−8.4(d)	17	2025	−9.5(d)	24
Perhydro-9b-boraphenalene [b]	2050	−10.2 −11.2(d)	46	2030	−10.6 −11.7(d)	17	2030	−10.5 −11.8(d)	24
Tris(*trans*-2-methylcyclopentyl)borane [c]	2100	−12.4 −14.3(d)	46				2050	−12.2 −11.9(d)	24
Trisiamylborane [d]	2060	−12.6 −13.9(d)	46					−11.9 −13.6(d)	43

[a] All chemical shifts relative to $EE \cdot BF_3$ with those upfield assigned as negative. [b] Probably isomeric pair. [c] Diastereomeric pair. [d] Diastereomeric pair.

TABLE 5

INFRARED AND ^{11}B NMR SPECTRAL DATA OF MONO- AND DI-ALKYLBOROHYDRIDES

Mono- and di-alkylboranes	$LiR_nBH_{(4-n)}$		Ref.	$NaR_nBH_{(4-n)}$		Ref.	$KR_nBH_{(4-n)}$		Ref.
	ν(B—H) (cm^{-1})	Chemical [a] shift (δ, ppm) (multiplicity)		ν(B—H) (cm^{-1})	Chemical [a] shift (δ, ppm) (multiplicity)		ν(B—H) (cm^{-1})	Chemical [a] shift (δ, ppm) (multiplicity)	
9-Borabicyclo[3.3.1]nonane (9-BBN)	2148	−14.2(t)	48	2125	−18.4(t)	20	2145	−16.3(t)	20
Dicyclohexylborane (Chx_2BH)	2108	−9.3(t)	48	2100	−14.9(t)	20	2125		
Disiamylborane (Sia_2BH)	2120	−12.2(t)	48	2115	−11.8(t)	20	2125	−13.1(t)	20
Diisopinocampheylborane (Ipc_2BH)	2100	−5.7(t)	48					−4.8(t)	20
Monocyclopentylborane		−26.6(q)	48						
Monocyclohexylborane	2230	−25.4(q)	48						
Mono-*exo*-2-norbornylborane		−25.7(q)	48						
Monosiamylborane ($SiaBH_2$)		−27.5(q)	48						
Monoisopinocampheylborane ($IpcBH_2$)		−23.5(q)	48					−21.2(q)	20
Thexylborane ($ThxBH_2$)	2200	−24.4(q)	48	2225	−25.7(q)	20	2200	−21.7(q)	20

[a] All chemical shifts relative to $EE \cdot BF_3$ with those upfield assigned as negative.

The lithium trialkylborohydrides prepared from trialkylboranes and LTMA [26], t-butyllithium [30] or $LiAlH_4$ [46] exhibit sharp doublets. This is taken as evidence for the completeness of the reaction [58] (Tables 4 and 5).

Mono- and di-alkylboranes exhibit signals between δ 20 to 35 ppm, whereas the corresponding borohydrides exhibit signals between δ −5 to −22 ppm. Consequently, the reactions could be easily followed by the disappearance of the mono- or di-alkylborane signal with complete formation of the borohydride signal in the ^{11}B NMR spectra [20]. All of the lithium dialkylborohydrides exhibit triplets and the lithium monoalkylborohydrides display sharp quartets in the ^{11}B NMR spectra (Tables 4 and 5).

6. Conclusions

The objective of this review was to trace major developments, largely in our own research program, which led from the initial observation of the exceptional reducing action of alkyl-substituted borohydrides to the present time when we have numerous reagents, methods and applications based on such "Super Hydrides" for selective reductions in organic chemistry. In this review, particular emphasis has been given to the development of practical synthetic routes to alkyl-substituted borohydrides which make such hydride reducing agents readily available to the organic chemist. Still we are in constant search of new synthetic routes to these selective reducing agents that are capable of reacting with a specific functional group in the presence of other functional groups, as well as achieving exceptional stereoselectivities in the reductions.

7. References

1 H.I. Schlesinger, H.C. Brown, H.R. Hoekstra and L.R. Rapp, J. Amer. Chem. Soc., 75 (1953) 19.
2 A.E. Finholt, A.C. Bond, Jr. and H.I. Schlesinger, J. Amer. Chem. Soc., 69 (1947) 1199.
3 (a) N.G. Gaylord, Reduction with Complex Metal Hydrides, Interscience, New York, 1956. (b) H.O. House, Modern Synthetic Reactions, Benjamin, Menlo Park, California, 1972, 2nd edn., p. 45. (c) C.F. Lane, Chem. Rev., 76 (1976) 773.
4 W.G. Brown, Org. React., 6 (1951) 469.
5 (a) S. Krishnamurthy, Aldrichimica Acta, 7 (1974) 55. (b) S. Krishnamurthy and H.C. Brown, J. Am. Chem. Soc., 98 (1976) 3383. (c) S. Krishnamurthy and H.C. Brown, J. Org. Chem., 41 (1976) 3064. (d) S. Krishnamurthy, F. Vogel and H.C. Brown, Ibid., 42 (1977) 2534. (e) H.C. Brown and S.C. Kim, Syn., (1977) 635.
6 H.C. Brown and S.C. Kim, J. Org. Chem., 42 (1977) 1482.
7 H.C. Brown and S. Krishnamurthy, J. Amer. Chem. Soc., 94 (1972) 7159.
8 H.C. Brown, H.I. Schlesinger, I. Sheft and D.M. Ritter, J. Amer. Chem. Soc., 75 (1953) 192.
9 P. Binger, G. Benedikt, G.W. Rotermund and R. Köster, Justus Liebigs Ann. Chem., 717 (1968) 21 and references cited therein.
10 J.B. Honeycutt, Jr. and J.M. Riddle, J. Amer. Chem. Soc., 83 (1961) 369.
11 A. Khuri, Ph.D. Thesis, Diss. Abstr., 21 (1960) 55.
12 H.C. Brown and R.A. Coleman, J. Amer. Chem. Soc., 91 (1969) 4606.
13 H.C. Brown and S. Krishnamurthy, J. Chem. Soc. Chem. Commun., (1972) 868.
14 H.C. Brown, G.W. Kramer, A.B. Levy and M.M. Midland, Organic Syntheses via Boranes, Wiley-Interscience, New York, 1975.
15 (a) H.C. Brown and B.C. Subba Rao, J. Org. Chem., 22 (1957) 1136. (b) H.C. Brown and B.C. Subba Rao, J. Amer. Chem. Soc., 81 (1959) 6243; 6248.
16 H.C. Brown, A. Khuri and S.C. Kim, Inorg. Chem., 16 (1977) 2229.
17 H.C. Brown, S. Krishnamurthy and J.L. Hubbard, J. Amer. Chem. Soc., 100 (1978) 3343.
18 H.C. Brown and W.C. Dickason, J. Amer. Chem. Soc., 92 (1970) 709.
19 J. Hooz, S. Akiyama, F.J. Cedar, M.J. Bennett and R.M. Tuggle, J. Amer. Chem. Soc., 96 (1974) 274.

20 H.C. Brown, B. Singaram and C.P. Mathew, J. Org. Chem., 46 (1981) 2712.
21 J.L. Hubbard and G.W. Kramer, J. Organometal. Chem., 156 (1978) 81.
22 C.A. Brown, J. Org. Chem., 39 (1974) 3913.
23 C.A. Brown, J. Amer. Chem. Soc., 95 (1973) 4100.
24 C.A. Brown, S. Krishnamurthy, J. Organometal. Chem., 156 (1978) 111.
25 H.C. Brown, S. Krishnamurthy, R.A. Coleman, J. Amer. Chem. Soc., 94 (1972) 1750.
26 H.C. Brown, S. Krishnamurthy and J.L. Hubbard, J. Organometal. Chem., 166 (1979) 271.
27 H.C. Brown, S. Krishnamurthy, J.L. Hubbard and R.A. Coleman, J. Organometal. Chem., 166 (1979) 281.
28 E.J. Corey, S.M. Albonico, U. Koelliker, T.K. Schaaf, R.K. Varma, J. Amer. Chem. Soc., 93 (1971) 1491.
29 (a) E.J. Corey and R.K. Varma, J. Amer. Chem. Soc., 93 (1971) 7319. (b) E.J. Corey, K.B. Becker and R.K. Varma, Ibid., 94 (1972) 8616.
30 H.C. Brown, G.W. Kramer, J.L. Hubbard and S. Krishnamurthy, J. Organometal. Chem., 188 (1980) 1.
31 E. Negishi, K.W. Chiu and T. Yoshida, J. Org. Chem., 40 (1975) 1676.
32 J.B. Campbell, Jr. and G.A. Molander, J. Organometal. Chem., 156 (1978) 71.
33 M.T. Reetz and W. Stephan, Angew. Chem. Int. Ed. Engl., 16 (1977) 44.
34 D.R. Boyd, M.F. Grundon and W.R. Jackson, Tetrahedron Lett., (1967) 2101.
35 M.F. Grundon, W.A. Khan, D.R. Boyd and W.R. Jackson, J. Chem. Soc. (C), (1971) 2557.
36 S. Krishnamurthy, unpublished observations.
37 H.C. Brown and S. Krishnamurthy, J. Amer. Chem. Soc., 95 (1973) 1669.
38 E. Negishi, R.M. Williams, G. Lew and T. Yoshida, J. Organometal. Chem., 92 (1975) C4.
39 B. Singaram, unpublished results.
40 P. Binger and R. Köster, Tetrahedron Lett., (1965) 1901.
41 A. Pelter, R. Hughes, K. Smith and M. Tabata, Tetrahedron Lett., (1976) 4385.
42 J.A. Sinclair and H.C. Brown, J. Org. Chem., 41 (1976) 1078.
43 C.A. Brown and J.L. Hubbard, J. Amer. Chem. Soc., 101 (1979) 3964.
44 T. Wartik and H.I. Schlesinger, J. Amer. Chem. Soc., 75 (1953) 835.
45 R.A. Coleman, Ph.D. Thesis, Purdue University, West Lafayette, Indiana, 1970.
46 H.C. Brown, J.L. Hubbard and B. Singaram, Tetrahedron, 37 (1981) 2359.
47 H.C. Brown and B. Singaram, Inorg. Chem., 19 (1980) 455.
48 H.C. Brown, B. Singaram and C.P. Mathew, J. Org. Chem., 46 (1981) 4541.
49 R.O. Hutchins, D. Kandasamy, C.A. Maryanoff, D. Masilamani and B.E. Maryanoff, J. Org. Chem., 42 (1977) 82.
50 R. Murphy and R.H. Prager, Aust. J. Chem., 34 (1981) 143.
51 A. Pelter and K. Smith, unpublished results.
52 R.A. Mueller, Ger. Patent 2,257,162; 1974; Chem. Abstr., 81 (1974) 25795y.
53 R. Bauer, Z. Naturforsch., 16b (1961) 557; Chem. Abstr., 56 (1962) 6875i.
54 A.B. Goel, Indian J. Chem. Soc. A, 16 (1978) 491.
55 K. Isagawa, H. Sano, M. Hattori and Y. Otsuji, Chem. Lett., (1979) 1069.
56 H.C. Brown and G. Zweifel, J. Amer. Chem. Soc., 88 (1966) 1433.
57 C.A. Brown, J. Organometal. Chem., 156 (1978) C17.
58 H.C. Brown and J.L. Hubbard, J. Org. Chem., 44 (1979) 467.