Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Selected Organic Compounds Containing Representative Functional Groups

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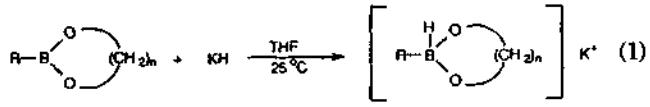
The approximate rates and stoichiometry of the reaction of excess potassium 2-thexyl-1,3,2-dioxaborinane hydride (KTDBNH) with 55 selected compounds containing representative functional groups under standardized conditions (tetrahydrofuran, 0℃, reagent : compound = 4 : 1) was examined in order to define the characteristics of the reagent for selective reductions. Benzyl alcohol and phenol evolve hydrogen immediately. However, primary, secondary and tertiary alcohols evolve hydrogen slowly, and the rate of hydrogen evolution is in order of 1°>2°>3°. *n*-Hexylamine is inert toward the reagent, whereas the thiols examined evolve hydrogen rapidly. Aldehydes andd ketones are reduced rapidly and quantitatively to give the corresponding alcohols. Cinnamaldehyde is rapidly reduced to cinnamyl alcohol, and further reduction is slow under these conditions. The reaction with *p*-benzoquinone dose not show a clean reduction, but anthraquinone is cleanly reduced to 9,10-dihydro-9,10-anthracenediol. Carboxylic acids liberate hydrogen immediately, further reduction is very slow. Cyclic anhydrides slowly consume 2 equiv of hydride, corresponding to reduction to the caboxylic acid and alcohol stages. Acid chlorides, esters, and lactones are rapidly and quantitatively reduced to the corresponding carbinols. Epoxides consume 1 equiv hydride slowly. Primary amides evolve 1 equiv of hydrogen readily, but further reduction is slow. Tertiary amides are also reduced slowly. Both aliphatic and aromatic nitriles consume 1 equiv of hydride rapidly, but further hydride uptake is slow. Analysis of the reaction mixture with 2,4-dinitrophenylhydrazine yields 64% of caproaldehyde and 87% of benzaldehyde, respectively. 1-Nitropropane utilizes 2 equiv of hydride, one for hydrogen evolution and the other for reduction. Other nitrogen compounds examined are also reduced slowly. Cyclohexanone oxime undergoes slow reduction to N-cyclohexylhydroxyamine. Pyridine ring is slowly attacked. Disulfides examined are reduced readily to the correponding thiols with rapid evolution of 1 equiv hydrogen. Dimethyl sulfoxide is reduced slowly to dimethyl sulfide, whereas the reduction of diphenyl sulfone is very slow. Sulfonic acids only liberate hydrogen qutitatively without any reduction. Finally, cyclohexyl tosylate is inert to this ragent. Consequently, potassium 2-thexyl-1,3,2-dioxaborinane hydride, a monoalkyldialkoxyborohydride, shows a unique reducing characteristics. The reducing power of this reagent exists somewhere between trialkylborohydrides and trialkoxyborohydride. Therefore, the reagent should find a useful application in organic synthesis, especially in the field of selective reduction.

Introduction

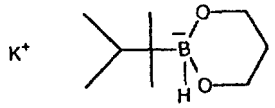
Trisubstituted borohydrides such as trialkylborohydrides, dialkylmonoalkoxyborohydrides, and trialkoxyborohydrides constitute a highly atrractive class of reducing agents in organic synthesis. Trialkylborohydrides have proven to be very powerful selective reducing agents.[1] On the other hand, trialkoxyborohydrides were proved to be very mild reducing agents.[2] 9-Alkoxy-9-borabicyclo[3.3.1]nonanes, a class of stable dialkylmonoalkoxyborohydrides, have appeared to be highly stereoselective reducing agents which are less powerful than trialkylborohydrides.[3]

Some years ago, we reported a general synthesis of potassium dialkoxymonoalkylborohydrides,[4] by treating the corresponding cyclic boronic esters with excess potassium hydride in THF (Eq. 1).



(1)

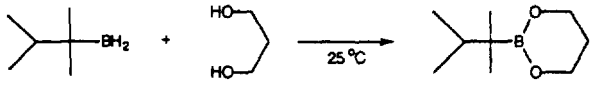
In view of those remarkable differences in reducing power among trisubstituted borohydride examined, it was desirable to undertake a systematic exploration of the reducing characteristics of dialkoxymonoalkylborohydrides. Because of the easier method of preparation, potassium 2-thexyl-1,3,2-dioxaborinanehydride (KTDBNH) was chosen as the reagent of choice in the present study.



We undertook a detailed study of the rate and stoichiometry in the reaction of KTDBNH with representative functional groups and compared its reducing properties with other trisubstituted borohydrides.

Results and Discussion

Preparation and Stability of the Reagent. The reagent is readily prepared by reaction of 2-thexyl-1,3,2-dioxaborinane with excess potassium hydride (free of oil) in THF at 25℃. The cyclic boronic ester was synthesized by direct reaction of thexyborane with propanediol[4] (Eq. 2).



(2)

The reagent was stable for at least months provided the

Table 1. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Representative Active Hydrogen Compounds in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydride used for reduction[b]
1-hexanol	0.5	0.86	0.86	0.00
	1.0	0.98	0.98	0.00
	3.0	1.00	1.00	0.00
benzyl alcohol	0.5	1.01	1.01	0.00
	1.0	1.01	1.01	0.00
3-hexanol	0.5	0.24	0.24	0.00
	1.0	0.42	0.42	0.00
	3.0	0.59	0.59	0.00
	6.0	0.81	0.81	0.00
	12.0	1.00	1.00	0.00
3-ethyl-3-pentanol	0.5	0.16	0.16	0.00
	1.0	0.33	0.33	0.00
	3.0	0.49	0.49	0.00
	6.0	0.57	0.57	0.00
	12.0	0.66	0.66	0.00
	24.0	0.82	0.82	0.00
	48.0	1.01	1.01	0.00
phenol	0.5	1.02	1.02	0.00
	1.0	1.01	1.02	0.00
n-hexylamine	0.5	0.00	0.00	0.00
	24.0	0.00	0.00	0.00
1-hexanethiol[d]	0.5	0.97	0.97	0.00
	1.0	1.00	1.00	0.00
benzenethiol[d]	0.5	1.01	1.01	0.00
	1.0	1.01	1.01	0.00

[a]5.0 Mmol of compound to 20 mmol of KTDBNH (20 mmol of hydride) in 40.0 ml of solution; 0.125 M in compound and 0.5 M in hydride. [b]Mmol/mmol of compound. [c]Hydrogen evolved from blank minus the hydrogen evolved on hydrolysis the reaction mixture after the indicated reaction period. [d,e]A white gel-like precipitate formed immediately.

THF solution of the borohydride reagent was maintained over excess KH under a positive pressure of nitrogen at room temperature. The ^{11}B-NMR spectrum of KTDBNH in THF showed a broad doublet centered at δ 7.3 ppm (J_{B-H}=74 Hz) relative to $BF_3 \cdot OEt_2$ as a reference.

Procedure for Rate and Stoichiometry Studies. The general procedure adopted was to add 5 mmol of the compound under investigation to 20 mmol of KTDBNH in sufficient THF to give 40 ml of solution. The mixtures were maintained at 0℃. This made the reaction mixture 0.125 M in compound and 0.5 M in KTDBNH. Any hydrogen evolved was noted. Aliquots were then removed at appropriate intervals of time and analyzed for residual hydride by hydrolysis. From the difference in the volume of hydrogen in the two intervals, the hydride used for reduction by the compound was calculated. In this manner, it was possible to estimate a value for the number of moles of the hydride utilized for the reduction and the rate at which reduction proceeds.

Alcohols, Phenols, Amines, and Thiols (Active Hydrogen Compounds). Benzyl alcohol and phenol evolved hydrogen rapidly and quantitatively. However, primary, secondary and tertiary alcohols evolved hydrogen slowly. The rate of hydrogen evolution for alcohols decreases in the order primary>secondary>tertiary. This is in agreement with the usual interpretation that the acidity of the hydroxylic hydrogen in these alcohols decreases in this order. *n*-Hexylamine was inert toward the reagent, whereas the thiols examined evolved hydrogen rapidly. These results are summarized in Table 1.

Table 2. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Representative Aldehydes and Ketones in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydride used for reduction[b]
caproaldehyde	0.5	0.00	1.01	1.01
	1.0	0.00	1.01	1.01
benzaldehyde	0.5	0.00	1.02	1.02
	1.0	0.00	1.01	1.01
2-heptanone	0.5	0.00	0.99	0.99
	1.0	0.00	1.00	1.00
norcamphor	0.5	0.01	1.04	1.03
	1.0	0.01	1.04	1.03
acetophenone	0.5	0.00	1.01	1.01
	1.0	0.00	1.01	1.01
benzophenone	0.5	0.02	1.02	1.00
	1.0	0.02	1.02	1.00
cinnamaldehyde	0.5	0.00	1.02	1.02
	1.0	0.00	1.02	1.02
	3.0	0.00	1.09	1.09
	6.0	0.00	1.16	1.16
	12.0	0.00	1.21	1.21
	24.0	0.00	1.28	1.28

[a-c]See the corresponding footnotes in Table 1.

Lithium triethylborohydride ($LiEt_3BH$),[1g] a trialkylborohydride, showed a similar trend even though it evolved hydrogen in a much faster rate than KTDBNH. On the other hand, potassium triisopropoxyborohydride (KIPBH),[2c] a trialkoxyborohydride, evolved hydrogen only partially, even after a long period of time.

Aldehydes and Ketones. All of the saturated aldehydes and ketones examined utilized 1 equiv of hydride rapidly to proceed to the alcohol stage. Hydrolysis of the reaction mixtures provided the corresponding alcohols in quantitative yield. Norcamphor was reduced with excellent stereoselectivity, yielding 99% *endo*- and 1% *exo*-norborneol. Similarly, 2-methylcyclohexanone was quantitatively reduced to give a mixture of 82% *cis*- and 18% *trans*-2-methylcyclohexanol. In general, sequence for stereoselectivity toward cyclic ketones is trialkylborohydride[5]>dialkylmonoalkoxyborohydride[3]>monoalkyldialkoxyborohydride[4]>trialkoxyborohydride.[2b]

Cinnamaldehyde utilized 1 equiv of hydride rapidly, with a slow uptake of the second hydride. This corresponds to a rapid initial reduction to the cinnamyl alcohol stage, followed by a slow addition of the reagent to the double bond. Such a trend was also observed with $LiEt_3BH$[1g] and KIPBH.[2c]

Table 3. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Representative Quinones in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydride used for reduction[b]
p-benzoquinone[d]	0.5[e,h]	0.03	0.98	0.95
	1.0	0.03	1.05	1.02
	24.0	0.03	1.06	1.03
	0.5[f]	0.20	1.13	0.93
	1.0	0.28	1.47	1.19
	3.0	0.41	1.77	1.36
	6.0	0.67	2.03	1.36
	12.0	0.67	2.03	1.36
anthraquinone[f]	0.5[g]	0.00	1.57	1.57
	1.0	0.00	1.68	1.68
	3.0	0.00	2.01	2.01
	6.0	0.00	2.01	2.01

[a-c]See the corresponding footnotes in Table 1. [d]Each measurement was done separately, and the reaction mixture was hydrolyzed in a flask. [e]Color changed to dark green immediately and a precipitate was formed, and then color changed to violet. [f]Inversion addition : solution of reagent added to a suspension of anthraquinone. [g]Color changed into dark green immediately. [h]At 0℃. [i]At room temperature.

The experimental results are summarized in Table 2.

Quinones. Two examples of quinones were examined and the results are summarized in Table 3. *p*-Benzoqinone consumed only 1 equiv of hydride for reduction without any significant hydrogen evolution at 0℃. At room temperature the quinone consumed 1.36 equiv of hydride, of which 0.67 equiv was utilized for hydrogen evolution. Therefore, it seems that the reaction proceeded not to clean reduction to either hydroquinone stage or 1,4-dihydroxycyclohexadiene stage.

Anthraquinone, on the other hand, readily utilized 2 equiv of hydride without any hydrogen evolution, indicating a clean reduction to 9,10-dihydro-9,10-dihydroxyanthracene. $LiEt_3BH$[1g] and KIPBH[2c] also showed a similar trend. However, sequence for reactivity is $LiEt_3BH \gg KTDBNH \geq KIPBH$.

Carboxylic Acids and Acyl Derivatives. Carboxylic acids instantly evolved 1 equiv of hydrogen to form their salts, with immediate formation of white gel-like precipitate. However, the reduction was quite slow. It is interesting to note that carboxylic acids reacted with $LiEt_3BH$ to evolve hydrogen instantly, but they were inert toward reduction.[1g] On the other hand, KIPBH reacted to evolve hydrogen only slowly and incompletely with a very slow reduction.[2c]

Acetic anhydride was slowly reduced to 2 moles of ethanol in 3 days at 0℃, whereas cyclic anhydrides such as succinic and phthalic anhydrides slowly consumed 2 equiv of hydride, corresponding to reduction to the carboxylic acid and alcohol stages. $LiEt_3BH$ also consumed 2 equiv of hydride rapidly without further uptake,[1g] however the reduction with KIPBH was very slow.[2c]

Acid chlorides utilized 2 equiv of hydride readily, yielding the corresponding alcohols in quantitative yield. $LiEt_3BH$ reduced them rapidly,[1g] but the reaction with KIPBH was quite slow.[2c] In this case, the reactivity is also in order of $LiEt_3BH > KTDBNH \gg KIPBH$.

Table 4. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Representative Carboxylic Acids and Acyl Derivatives in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydride used for reduction[b]
caproic acid[d]	0.5	1.01	1.19	0.18
	1.0	1.01	1.27	0.26
	3.0	1.01	1.41	0.40
	6.0	1.01	1.52	0.51
	24.0	1.01	1.81	0.80
	48.0	1.01	2.06	1.05
benzoic acid[e]	0.5	1.00	1.34	0.34
	1.0	1.00	1.42	0.42
	3.0	1.00	1.49	0.49
	6.0	1.00	1.51	0.51
	24.0	1.00	1.74	0.74
	48.0	1.00	2.22	1.22
	72.0	1.00	2.44	1.44
acetic anhydride	0.5	0.00	3.26	3.26
	1.0	0.00	3.37	3.37
	12.0	0.00	3.58	3.58
	24.0	0.00	3.64	3.64
	72.0	0.00	4.01	4.01
succinic anhydride[f]	0.5	0.00	1.14	1.14
	3.0	0.00	1.42	1.42
	12.0	0.00	1.63	1.63
	24.0	0.00	1.82	1.82
	48.0	0.00	1.97	1.97
	72.0	0.00	2.01	2.01
phthalic anhydride	0.5	0.00	1.11	1.11
	1.0	0.00	1.24	1.24
	6.0	0.00	1.46	1.46
	24.0	0.00	1.65	1.65
	48.0	0.00	1.73	1.73
	72.0	0.00	1.89	1.89
caproyl chloride	0.5	0.00	1.62	1.62
	1.0	0.00	1.86	1.86
	3.0	0.00	2.01	2.01
benzoyl chloride	0.5	0.00	2.03	2.03
	1.0	0.00	2.02	2.02

[a-c]See the corresponding footnotes in Table 1. [d,e]A white gel-like precipitate formed immediatly. [f]Color changed to light yellow.

The experimental results are summarized in Table 4.

Esters and Lactones. Esters and lactones readily took up 2 equiv of hydride, undergoing reduction to the alcohol and diol stages, respectively. In this case, we tested the possibility for a partial reduction to the aldehyde stage using a limited amount of the reagent. A 2,4-DNP test failed to indicate the formation of significant amount of aldehyde. Isopropenyl acetate rapidly utilized 2 equiv of hydride and further uptake of hydride was slow.

$LiEt_3BH$ showed an exceptionally high reactivity toward ester groups,[1g] whereas KIPBH showed very little reactivity.[2c]

The experimental results are summarized in Table 5.

Table 5. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Representative Esters and Lactones in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydride used for reduction[b]
ethyl caproate	0.5	0.00	1.58	1.58
	1.0	0.00	1.91	1.91
	3.0	0.00	2.02	2.02
ethyl benzoate[d]	0.5	0.00	1.42	1.42
	1.0	0.00	1.99	1.99
	3.0	0.00	2.01	2.01
phenyl acetate	0.5	0.00	1.98	1.98
	1.0	0.00	2.00	2.00
	3.0	0.00	2.01	2.01
γ-butyrolactone	0.5	0.00	2.02	2.02
	1.0	0.00	2.02	2.02
phthalide	0.5	0.00	2.05	2.05
	3.0	0.00	2.02	2.02
isopropenyl acetate[e]	0.5	0.01	2.09	2.08
	1.0	0.01	2.29	2.28
	3.0	0.01	2.54	2.53
	24.0	0.01	2.58	2.57
	48.0	0.01	2.65	2.64

[a-c] See the corresponding footnotes in Table 1. [d,e] Color changed to yellow.

Table 6. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Representative Epoxides in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydridde used for reduction[b]
1,2-butylene oxide	0.5	0.00	0.44	0.44
	3.0	0.00	0.61	0.61
	12.0	0.00	0.70	0.70
	48.0	0.00	0.85	0.85
	96.0[d]	0.00	1.01	1.01
styrene oxide	0.5	0.00	0.90	0.90
	1.0	0.00	0.95	0.95
	3.0[e]	0.00	1.00	1.00
	6.0	0.00	1.00	1.00
cyclohexene oxide	0.5	0.00	0.63	0.63
	1.0	0.00	0.84	0.84
	3.0	0.00	0.97	0.97
	6.0	0.00	1.01	1.01
	12.0	0.00	1.01	1.01
1-methyl-1,2-cyclohexene oxide	0.5	0.00	0.54	0.54
	1.0	0.00	0.86	0.86
	6.0	0.00	0.92	0.92
	12.0[f]	0.00	1.01	1.01

[a-c] See the corresponding footnotes in Table 1. [d] 2-Butanol 99%, 1-butanol 1%. [e] 1-Phenylethanol 83%, 2-phenylethanol 17%. [f] Only 1-methylcyclohexanol was detected.

Epoxides. All of the epoxides examined except for 1,2-butylene oxide utilized 1 equiv of hydride relatively fast. 1,2-Butylene oxide required 4 days for complete ring opening. The ring of epoxide was opened at the less hindered site to yield the Markovnikov alcohol as a major product. Thus, 1,2-butylene oxide gave 99% 2-butanol and 1% 1-butanol, and 1-methyl-1,2-cyclohexene oxide gave 1-methylcyclohexanol exclusively. However, the reduction of styrene oxide gave a mixture of 83% 1-phenylethanol and 17% 2-phenylethanol. The results are summarized in Table 6.

The reaction of epoxides with $LiEt_3BH$ yielded the Markovnikov alcohol exclusively in about 5 min at 0℃.[1g] However, KIPBH did not react with any of the epoxides studied.[2c]

Table 7. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Representative Amides and Nitriles in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydride used for reduction[b]
caproamide[d]	0.5	0.86	1.37	0.51
	1.0	0.99	1.64	0.65
	3.0	1.00	1.74	0.74
	6.0	1.00	1.81	0.81
	12.0	1.00	1.99	0.99
	24.0	1.00	2.20	1.20
	72.0	1.00	2.28	1.28
benzamide[e]	0.5	0.91	1.36	0.45
	1.0	0.98	1.50	0.52
	6.0	0.98	1.65	0.67
	24.0	0.98	1.74	0.76
	72.0	0.98	1.77	0.79
N,N-dimethyl caproamide	0.5	0.00	0.31	0.31
	1.0	0.00	0.43	0.43
	6.0	0.00	0.52	0.52
	24.0	0.00	0.68	0.68
	72.0	0.00	1.00	1.00
N,N-dimethyl benzamide	0.5	0.00	0.54	0.54
	1.0	0.00	0.62	0.62
	3.0	0.00	0.75	0.75
	24.0	0.00	0.82	0.82
	72.0	0.00	0.85	0.85
capronitrile[f]	0.5	0.00	0.94	0.94
	1.0	0.00	1.01	1.01
	3.0	0.00	1.02	1.02
	6.0	0.00	1.25	1.25
	48.0	0.00	1.48	1.48
	72.0	0.00	1.54	1.54
benzonitrile[g]	0.5	0.00	1.42	1.42
	1.0	0.00	1.51	1.51
	3.0	0.00	1.58	1.58
	6.0	0.00	1.66	1.66
	48.0	0.00	1.86	1.86
	72.0	0.00	2.00	2.00

[a-c] See the corresponding footnotes in Table 1. [d] A white gel-like precipitate formed immediately. [e] Color changed to yellow.

Amides and Nitriles. Primary amides evolved 1 equiv of hydrogen rapidly, but underwent a slow reduction. The

Table 8. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Representative Nitro Compounds and Their Derivatives in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydride used for reduction[b]
1-nitropropane[d]	0.5	0.77	1.12	0.35
	1.0	0.91	1.31	0.40
	3.0	1.02	1.51	0.49
	12.0	1.02	1.75	0.73
	24.0	1.02	1.94	0.92
	48.0	1.02	2.03	1.01
nitrobenzene[e]	0.5	0.36	1.62	1.26
	1.0	0.45	1.95	1.50
	6.0	0.45	1.94	1.49
	24.0	0.45	1.93	1.48
	48.0	0.45	1.96	1.51
azobenzene[f]	0.5	0.00	0.24	0.24
	1.0	0.00	0.40	0.40
	3.0	0.00	0.61	0.61
	12.0	0.00	0.76	0.76
	24.0	0.00	0.84	0.84
	72.0	0.00	0.97	0.97
azoxybenzene[g]	0.5	0.00	0.34	0.34
	1.0	0.00	0.51	0.51
	3.0	0.00	0.62	0.62
	24.0	0.00	0.93	0.93
	72.0	0.00	1.06	1.06

[a-c] See the corresponding footnotes in Table 1. [d] A white gel-like precipitate formed immediately. [e] Color changed to dark green. [f] Dark brown precipitate. [g] Color changed to brown.

Table 9. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Other Nitrogen Compounds in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydride used for reduction[b]
cyclohexane oxime[d]	0.5	0.67	0.86	0.19
	1.0	0.83	1.08	0.25
	3.0	1.01	1.35	0.34
	6.0	1.01	1.54	0.53
	24.0	1.01	1.73	0.72
	48.0	1.01	2.04	1.03
phenyl isocyanate	0.5	0.00	1.08	1.08
	1.0	0.00	1.32	1.32
	3.0	0.00	1.41	1.41
	12.0	0.00	1.49	1.49
	24.0	0.00	1.58	1.58
	48.0	0.00	1.61	1.61
	120.0	0.00	1.93	1.93
pyridine	0.5	0.00	0.33	0.33
	1.0	0.00	0.41	0.41
	6.0	0.00	0.52	0.52
	24.0	0.00	0.59	0.59
	48.0	0.00	0.67	0.67
4-picoline N-oxide[e]	0.5	0.00	1.66	1.66
	1.0	0.00	1.72	1.72
	24.0	0.00	1.73	1.73
	48.0	0.00	1.76	1.76
	96.0	0.00	1.92	1.92

[a-c] See the corresponding footnotes in Table 1. [d] A white gel-like precipitate formed gradually. [e] Color changed to yellow.

reaction with tertiary amides was also slow. In these cases, 2,4-DNP analysis of these reaction mixtures indicated the formation of only a small amount of the aldehydes. Surprisingly, the reaction of $LiEt_3BH$ with primary amides underwent a very sluggish reduction after evolving 1 equiv of hydrogen almost instantly.[1g] On the contrary, the reaction with tertiary amides proceeded rapidly. On the other hand, the reaction of both primary and tertiary amides with KIPBH was extremely sluggish.[2c]

In the case of reaction with capronitrile and benzonitrile, one hydride utilization was fast, with a second equivalent of hydride being taken up only quite slow. This stoichiometry appeared to indicate that the reduction must be proceeding to the aldehyde stage. Therefore, we reacted them with the reagent in a limiting amount and analyzed the reaction mixtures with 2,4-dinitrophenylhydrazine. A 64% of caproaldehyde and a 87% of benzaldehyde were realized. No further attempt was made to maximize the yield.

These experimental data are summarized in Table 7.

Nitro Compounds and Their Derivatives. 1-Nitropropane evolved 1 equiv of hydrogen, forming a white precipitate, with hydride consumed slowly for reduction. Nitrobenzene utilized 1.5 equiv of hydride for reduction with slight hydrogen evolution, and the values did not change with time. Azobenzene was slowly reduced, utilizing 1 equiv of hydride for reduction in 6 h. This corresponds to reduction to the hydrazobenzene stage. Azoxybenzene also utilized 1 equiv of hydride, presumably proceeding to the azobenzene stage. The results are summarized in Table 8.

It is interesting to note that $LiEt_3BH$ rapidly evolved 1 equiv of hydrogen without reduction taking place.[1g] The reaction of nitrobenzene, azobenzene, and azoxybenzene with $LiEt_3BH$ underwent a relatively fast reduction. KIPBH was inert to all of these compounds.[2c]

Other Nitrogen Compounds. Cyclohexanone oxime liberated 1 equiv of hydrogen, with utilizing 1 equiv of hydride for reduction in 48 h at 0℃, apparently being reduced to the corresponding N-hydroxylamine stage. Phenyl isocyanate was slowly reduced, utilizing about 2 equiv of hydride in 5 days at 0℃, corresponding to reduction to the N-methylaniline stage. Pyridine and 4-picoline N-oxide underwent a moderate reduction without hydrogen evolution, apparently the pyridine ring being attacked. These results are summarized in Table 9.

Lithium triethylborohydride reacted with cyclohexanone oxime rapidly to liberate 1 equiv of hydrogen, without undergoing reduction.[1g] Phenyl isocyanate was also rapidly reduced but to the formanilide stage. Pyridine was also reduced with remarkable ease. However potassium triisopropoxyborohydride did not reduce any of these compounds.[2c]

Sulfur Derivatives. Disulfides were rapidly reduced to the thiol stage, utilizing 2 equiv of hydride, one for reduction

Table 10. Reaction of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride with Representative Surfur Derivatives in Tetrahydrofuran at 0℃

Compound[a]	Time, hr	Hydrogen evolved[b,c]	Hydride used[b]	Hydride used for reduction[b]
di-*n*-butyl	0.5	0.97	1.91	0.94
disulfide[d]	1.0	1.00	2.01	1.01
	3.0	1.00	2.01	1.01
diphenyl	0.5	0.96	1.96	1.00
disulfide[e]	1.0	0.96	1.96	1.00
dimethyl	0.5	0.00	0.12	0.12
sulfoxide	3.0	0.00	0.53	0.53
	12.0	0.00	0.62	0.62
	48.0	0.00	1.00	1.00
	72.0	0.00	1.01	1.01
diphenyl	0.5	0.00	0.29	0.29
sulfone[f]	3.0	0.00	0.54	0.54
	6.0	0.00	0.70	0.70
	24.0	0.00	0.99	0.99
	72.0	0.00	1.35	1.35
	120.0	0.00	1.47	1.47
methanesulfonic	0.5	0.94	0.94	0.00
acid[g]	1.0	1.00	1.00	0.00
	3.0	1.00	1.00	0.00
p-toluenesulfonic	0.5	2.98	2.98	0.00
acid,	1.0	3.05	3.05	0.00
monohydrate[g]	3.0	3.05	3.05	0.00
cyclohexyl	0.5	0.00	0.00	0.00
tosylate	24.0	0.00	0.00	0.00

[a-c] See the corresponding footnotes in Table 1. [d-g] A white gel-like precipitate formed immediately. [f] Color changed to light orange. [g] A white precipitate formed, and then changed to clear solution.

and one for hydrogen evolution.[6] Dimethyl sulfoxide and diphenyl sulfone were also reduced slowly to the corresponding sulfide without hydrogen evolution. Methanesulfonic acid liberated the theoretical amount of hydrogen rapidly, but no hydride uptake for reduction was observed. *p*-Toluenesulfonic acid monohydrate rapidly evolved 3 equiv of hydrogen without any sign of reduction. It is interesting to note that $LiEt_3BH$, the most powerful reducing agent in the trisubstituted borohydrides, evolved only 2 equiv of hydrogen.[1g] However, KIPBH, the least powerful one, evolved slowly but continuously more than 2 equiv of hydrogen, approaching to 3 equiv.[2c] Finally, cyclohexyl tosylate was absolutely inert to KTDBNH under these conditions. These experimental data are summarized in Table 10.

$LiEt_3BH$ rapidly reduced disulfides to the thiol stage with evolution of 1 equiv hydrogen.[1g] However, surprisingly, dimethyl sulfoxide was inert to such a strong reducing agent. It is noteworthy that KIPBH, a very mild reducing agent, can reduce disulfides to thiols readily with some hydrogen evolution, whereas other sulfur compounds are actually inert to this reagent.[2c]

Conclusion

The reducing properties of potassium 2-thexyl-1,3-2-dioxaborinane hydride (KTDBNH) in tetrahydrofuran are now broadly characterized and compared with those of lithium triethylborohydride ($LiEt_3BH$)[1g] and potassium triisopropoxyborohydride (KIPBH).[2c] Generally, the reducing power of KTDBNH, a dialkoxymonoalkylborohydride, appears to exist somewhere between $LiEt_3BH$, a trialkylborohydride, and KIPBH, a trialkoxyborohydride. The reducing properties of KTDBNH are also quite different from those of other trisubstituted borohydrides. Thus, the reducing power and properties are significantly varied with the number of alkoxy and alkyl group in the trisubstituted borohydrides. The presence of alkyl group seems to enhance the rate in these reactions. Consequently, each class of trisubstituted borohydrides possesses its own unique characteristics in reactivity and selectivity toward organic functional groups. Therefore, this systemetic study permits not only a ready comparision of rate and stoichiometry of the reaction of KTDBNH to other trisubstituted borohydrides, but also a useful guide-line to determine which reagent be adequate to selective reduction of a target group in a complex molecule.

Experimental Section

Materials. Tetrahydrofuran was dried over a 4 Å molecular sieve and distilled from benzophenone-sodium ketyl prior to use. Potassium hydride was purchased from Alfa and was freed from the mineral oil according to the published procedure.[7] Most of the organic compounds utilized in this study were commercial products of the highest available purity. They were further purified by distillation or recrystallization when necessary. Some compounds, such as 1-methyl-1,2-cyclohexene oxide, tertiary amides and cyclohexyl tosylate, were synthesized by using standard procedures.

General Methods. All glassware was dried thoroughly in a drying oven, assembled hot, dried further with a flame and cooled under a stream of nitrogen. All reactions were carried out under a nitrogen atmosphere. Special experimental techniques used in handling air-sensitive material are described in detail elsewhere.[8]

Instruments. GC analyses were carried out on a Hewlett-Packard Model 5790A FID chromatograph equipped with a Hewlett-Packard 3390A integrator/plotter, using CW 20 M on 100/120 mesh Supelcoport or 15% THEED on 100/120 mesh Supelcoport (0.125 in. x 12 ft. columns). All GC yields were determined with use of suitable internal standard and authentic samples. NMR spectrometer used was a Bruker WP 80 SY for ^{11}B-NMR spectrum.

Preparation of 2-Thexyl-1,3,2-dioxaborinane.[4] A 250 *ml*, round-bottomed flask was maintained at 0℃ using an ice both and was charged with 10 M borane-dimethyl sulfide complex (500 mmol). A total of 42.15 g of 2,3-dimethyl-2-butene (500 mmol) was added slowly and the mixture was stirred for 1 h at 0℃. 1,3-Propanediol (38.83 g, 500 mmol) was added dropwise with vigorous stirring with control of the H_2 evolution at 25℃ and the mixture was stirred for 1 h. Removal of the volatiles by water aspirator, followed by distillation yielded 76.1 g of 2-thexyl-1,3,2-dioxaborinane (90%): ^{11}B-NMR δ 31.6; bp. 76-79℃ /15 min [lit[4g] bp. 79-80℃ / 16 mm].

Table 11. Stability of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride in Tetrahydrofuran at Room Temperature

Time, day	0	1	3	7	30	90	180
Hydride Concentration[a]	0.87 (100)[b]	0.87 (100)	0.88 (102)	0.86 (98)	0.87 (100)	0.86 (98)	0.84 (96)

[a]Mmol of hydride per ml of solution. [b]Figures in parentheses are percentage of concentration, compared with initial concentration.

Preparation of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride in THF.[4] To an oven-dried, 500 ml, round-bottomed flask was charged 77 g of KH (685 mmol, 50% excess) as an oil dispersion. The mineral oil was removed by washing with pentane (3×100 ml). To the suspension of KH in 220 ml THF was added 76.1 g of 2-thexyl-1,3,2-dioxaborinane (450 mmol) and the suspension was stirred vigorously for 2 h at room temperature to give a slightly viscous THF solution. The ^{11}B-NMR spectrum of the clean supernatant after the settling of excess KH showed a broad doublet centered at δ 7.3 ppm (J_{B-H}=74 Hz) and the solution IR of the product exhibited a strong B-H stretching absorption at 2010 cm^{-1}, indicating the formation of potassium 2-thexyl-1,3,2-dioxaborinane hydride (KTDBNH). The hydride concentration was measured by hydrolyzing an aliquot with THF-glycerine-2 N HCl to give 0.87 M. This solution was used for reactions in the present study.

Stability of Potassium 2-Thexyl-1,3,2-dioxaborinane Hydride (KTDBNH) Solution in THF. The solution of KTDBNH in THF thus prepared was kept over the unused portion of KH under a positive pressure of nitrogen at room temperature and the hydride content was measured periodically by hydrolyzing a known quantity of the solution. As summarized in Table 11, the hydride concentration of the solution was stable for at least 1 month at room temperature. The ^{11}B-NMR examination showed no detectable change in the spectrum.

Procedure for Determination of Rates and Stoichiometry-Representative. A dried, 100 ml, round-bottomed flask fitted with rubber syringe cap on an inert port, a magnetic stirring bar, and a bent adaptor connected to a gas buret through a reflux condenser, was immersed into an ice bath. To this flask was charged with 12 ml of THF and 23 ml of the reagent solution (20 mmol, 0.87 M), and finally 5 ml of 1 M solution of caproaldehyde in THF (5 mmol) was added with stirring at 0℃. No hydrogen was evolved. After 1h, the analysis showed no difference in the residual hydride, which indicate that the reaction was completed. This results are summarized in Table 2.

Reduction of 1,2-Butylene Oxide. The following experiment illustrates the technique utilized in cases where reaction mixture was subjected to identification of products by GC.

Utilizing the above general procedure, the reduction of 1,2-butylene oxide with KTDBNH was performed for 4 days at 0℃. The reaction mixture was then quenched with H_2O and organoborane was oxidized with NaOH-H_2O_2. The GC analysis of the organic layer showed the presence of 99% of 2-butanol and 1% of 1-butanol in a total yield of 99%.

In cases where a single product in the reaction mixture was apparent, we did not perform the product identification further.

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