maining are unreactive toward CH_3OH ($k < 10^{-11}$ cm^3/(molecule sec)). Considering that the deuteron-transfer reaction involving the cyclic ion

$$\text{c-}C_3D_6^+ + CH_3OH \rightarrow CH_3OHD^+ + \text{c-}C_3D_5 \qquad \Delta H = +7 \text{ kcal/mol} \quad (6)$$

is endothermic, this observation confirms our view that approximately 15–16% of the c-$C_3D_6^+$ ions undergo ring opening at 10.6 eV.

The $C_4D_8^+$ results (Table I) can be interpreted in the same manner as the C_3D_6 data. Here again we find that $C_4D_8^+$ ions formed *via* photoionization of the various butene isomers react with NH_3 nearly exclusively by deuteron transfer. On the other hand, more than 30% of the $C_4D_8^+$ ions formed in the 10-eV photoionization of methylcyclopropane react in a manner analogous to reaction 1.

$$C_4D_8^+ + NH_3 \longrightarrow CD_2NH_2^+ + C_3D_6H \quad (7)$$

If one assumes, by analogy with the cyclopropane system, that the $C_4D_8^+$ ions participating in a reaction such as (7) have maintained their cyclic structure, then $\Delta H_{rxn} = -13$ to -18 kcal/mol. The energetically less favorable reaction

$$C_4D_8^+ + NH_3 \longrightarrow CD_2NH_3^+ + C_3D_6 \qquad \Delta H \cong -7 \text{ kcal/mol} \quad (8)$$

occurs with a much lower probability.

In cyclobutane, only 10% of the $C_4D_8^+$ ions obtained *via* photoionization at 10.6 eV undergo reactions 1 and 2. The relative probability is reduced to less than 5% at 11.6–11.8 eV. This result is in accord with those of a recent photoionization study[7] carried out in a static system in which it was shown that at least 95% of the cyclobutane parent ions isomerize to the *i*-$C_4H_8^+$, 2-$C_4H_8^+$, and 1-$C_4H_8^+$ structures at 11.6–11.8 eV.

We can tentatively conclude from the data presented here that the fraction of $C_3H_6^+$ and $C_4H_8^+$ ions which transfer a proton to NH_3 or to other proton acceptors can be considered as an accurate measure of the fraction of ions which exhibit an acyclic structure under the particular conditions (pressure, temperature, etc.) of the experiment.

(7) S. G. Lias and P. Ausloos, *J. Res. Nat. Bur. Stand., Sect. A*, **75**, 591 (1971).

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Lithium Tri-*sec*-butylborohydride. A New Reagent for the Reduction of Cyclic and Bicyclic Ketones with Super Stereoselectivity. A Remarkably Simple and Practical Procedure for the Conversion of Ketones to Alcohols in Exceptionally High Stereochemical Purity

Sir:

Addition of 1 mol equiv of tri-*sec*-butylborane to a tetrahydrofuran (THF) solution of lithium trimethoxyaluminohydride (LTMA) at room temperature results in a facile and rapid displacement of aluminum methoxide, producing the new reagent, lithium tri-*sec*-butylborohydride, in quantitative yield. This highly hindered lithium trialkylborohydride, first reagent of its kind to be reported, is an active reducing agent and exhibits essentially enzyme-like stereoselectivity in the reduction of cyclic and bicyclic ketones. Thus even ketones with an alkyl group relatively remote from the reaction center, such as 3-methyl- and 4-*tert*-butylcyclohexanone, are reduced in ≥95% stereoselectivity, producing the less stable epimer. This appears to be the first nucleophilic reagent capable of reducing such cyclic ketones with such high stereoselectivity.[1] Hindered ketones, such as 2-methylcyclohexanone, 3,3,5-trimethylcyclohexanone, camphor, etc., are reduced rapidly and quantitatively with this new reagent with over 99.5% stereoselectivity to the corresponding less stable isomers. Thus, the lithium trimethoxyaluminohydride–tri-*sec*-butylborane combination provides a new simple practical procedure for the conversion of ketones to alcohols with the highest stereospecificity realized.

We recently reported that lithium perhydro-9b-boraphenalylhydride (PBPH), prepared from *cis,cis,-trans*-perhydro-9b-boraphenalene and lithium hydride, reduces cyclic and bicyclic ketones with high stereoselectivity, rapidly and quantitatively.[2] Since then this new reagent and related trialkylborohydrides have been used extensively for the stereoselective reduction of ketones to the alcohol function, including two major applications in the synthesis of prostaglandins, where the use of all other previously known reagents had failed.[3–5]

It appeared possible that a more hindered trialkylborohydride might improve the stereoselectivity. Unfortunately, we encountered a major synthetic difficulty. The more hindered trialkylboranes failed to react at any appreciable rate with lithium hydride in THF. Thus, the reactions of triethyl-, tri-*n*-butyl-, and triisobutylboranes proceeded rapidly and quantitatively with lithium hydride in refluxing THF, whereas the corresponding reaction with tri-*sec*-butylborane proceeded only 10% in 24 hr (eq 1). (Sodium hydride

$$\text{LiH} + \textit{sec}\text{-Bu}_3\text{B} \xrightarrow[\substack{\text{reflux} \\ \text{24 hr}}]{\text{THF}} \underset{10\%}{\text{Li-}\textit{sec}\text{-Bu}_3\text{BH}} \quad (1)$$

failed to react under these conditions.) Yet preliminary results indicated that the stereoselectivity achieved by lithium tri-*sec*-butylborohydride was much better than that achieved by the other three trialkylborohydrides.

We recently observed that the addition of a molar amount of triethylborane to a THF solution of LTMA results in an instantaneous vigorous exothermic reaction forming a gel.[6] Analysis of the reaction mixture revealed that a displacement reaction had taken place to form the corresponding lithium triethylborohydride and a polymeric gel of aluminum methoxide.[7] Accordingly, we examined this reaction with a repre-

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(1) For a comprehensive review, see J. D. Morrison and H. S. Mosher, "Asymmetric Organic Reactions," Prentice-Hall, Englewood Cliffs, N. J., 1971, pp 84–132.

(2) H. C. Brown and W. C. Dickason, *J. Amer. Chem. Soc.*, **92**, 709 (1970).

(3) R. E. Ireland, D. R. Marshall, and J. W. Tilley, *ibid.*, **92**, 4754 (1970).

(4) E. J. Corey, S. M. Albonico, U. Koelliker, T. K. Schaaf, and R. K. Varma, *ibid.*, **93**, 1491 (1971).

(5) E. J. Corey and R. K. Varma, *ibid.*, **93**, 7319 (1971).

(6) H. C. Brown, S. Krishnamurthy, and R. A. Coleman, *ibid.*, **94**, 1750 (1972).

(7) H. C. Brown and S. Krishnamurthy, *Chem. Commun.*, 868 (1972).

Table I. Reduction of Various Cyclic and Bicyclic Ketones with Lithium Tri-*sec*-butylborohydride in Tetrahydrofuran

Ketone[a]	Temp,[a] °C	Time, hr	Major isomer,[c] %	Temp,[b] °C	Time, hr	Major isomer,[c] %
2-Methylcyclopentanone	0	1.0	98, cis	−78	1.0	99.3, cis
2-Methylcyclohexanone	0	0.5	99.3, cis			
3-Methylcyclohexanone	0	1.0	85, trans	−78	2.0	94.5, trans
4-Methylcyclohexanone	0	1.0	80.5, cis	−78	1.0	90, cis
4-*tert*-Butylcyclohexanone	0	3.0	93, cis	−78	3.0	96.5, cis
3,3,5-Trimethylcyclohexanone	0	3.0	99.8, trans			
Norcamphor	0	0.5	99.6, endo			
Camphor	0	1.0	99.6, exo			

[a] Ratio of hydride to ketone was 1.25. [b] Ratio of hydride to ketone was 2.0. [c] Analysis by glpc. In all cases, total yield was essentially quantitative.

sentative series of trialkylboranes. In all cases, lithium trialkylborohydride was formed rapidly and quantitatively (eq 2).

$$\mathrm{LiAlH(OMe)_3} + \mathrm{R_3B} \xrightarrow[15\ \mathrm{min},\ 25^\circ]{\mathrm{THF}} \underset{100\%}{\mathrm{LiR_3BH}} + \mathrm{Al(OMe)_3} \qquad (2)$$

The remarkable rapidity of this new reaction is indicated by the observation that the addition of the highly hindered tri-*sec*-butylborane to a THF solution of LTMA results in an immediate temperature rise, with formation of lithium tri-*sec*-butylborohydride in 100% yield in 15 min (eq 3).

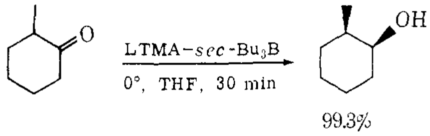
$$\mathrm{LiAlH(OMe)_3} + sec\text{-}\mathrm{Bu_3B} \xrightarrow[15\ \mathrm{min}]{\mathrm{THF},\ 25^\circ} \underset{100\%}{\mathrm{Li}\text{-}sec\text{-}\mathrm{Bu_3BH}} + \mathrm{Al(OMe)_3} \qquad (3)$$

Since the aluminum methoxide appeared to be inert, we tested the reaction mixture for the stereoselective reduction of ketones. Indeed, addition of 2-methylcyclohexanone to the mixture at 0° resulted in the rapid and quantitative reduction of the ketone with formation of the cis alcohol in an isomeric purity of ≥99%!

Alternatively, the reagent can be prepared by the reaction of *tert*-butyllithium with the hindered trialkylborane.[4]

The results of this investigation clearly reveal that unlike with lithium trialkoxyaluminohydrides,[8] increasing the size of the alkyl substitution on boron enhances the stereoselectivity of the borohydride anion to the carbonyl group. It is also evident from the results that the presence of aluminum methoxide does not interfere in any manner in the stereoselective nature of the borohydride anion, since exactly identical isomeric ratios are realized using the trialkylborohydride prepared from either lithium hydride or LTMA. Further, it is evident that lithium tri-*sec*-butylborohydride is an excellent reagent for achieving essentially enzyme-like stereoselectivity.

Reduction of 2-methylcyclohexanone with LTMA at 0° gives rather poor stereoselectivity yielding 69% of *cis*-2-methylcyclohexanol. Addition of *sec*-$\mathrm{Bu_3B}$ dramatically enhances the stereoselectivity to 99.3% (eq 4).

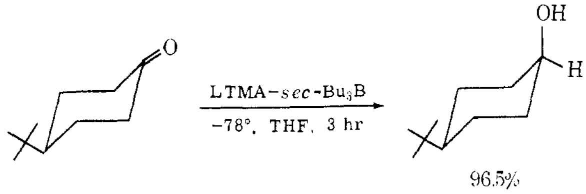


(4)

Similarly, 2-methylcyclopentanone is readily converted to *cis*-2-methylcyclopentanol in 98% stereospecificity at 0°. Lowering the reaction temperature to −78° resulted in the formation of the cis isomer in 99.3% purity.

Similarly, norcamphor, camphor, and 3,3,5-trimethylcyclohexanone were reduced with equally high stereoselectivities.

Even in the case of simple unhindered cyclohexanones containing a single alkyl substituent in the 3 or 4 position, this reagent attacks predominantly (>90%) from the equatorial side. Thus, at 0° 4-*tert*-butylcyclohexanone is reduced to *cis*-4-*tert*-butylcyclohexanol in 93% isomeric purity, as compared to only 37% with diisopinocamphenylborane and 54% with PBPH.[2] Lowering the temperature to −78° resulted in the enhancement of cis isomer to 96.5% (eq 5). This is a remarkable development. Enzymatic reduction of 4-*tert*-butylcyclohexanone with a reduced form of nicotinamide adenine dinucleotide (NADH) catalyzed by horse liver dehydrogenase proceeds with only 95% stereospecificity![9]



(5)

The results are summarized in Table I.

The following procedure is representative. To 5.0 ml of 1.0 *M* lithium trimethoxyaluminohydride[8] in THF (under nitrogen) was added 1.25 ml of tri-*sec*-butylborane (5.0 mmol). After 30 min, the flask was cooled to −78° and 1.25 ml of a 2.0 *M* solution of 4-*tert*-butylcyclohexanone (2.5 mmol) was introduced. The reaction mixture was stirred for 3 hr. Hydrolysis at 25°, followed by oxidation of the organoborane, yielded 96.5% of *cis*- and 3.5% of *trans*-4-*tert*-butylcyclohexanol.

In conclusion, it should be pointed out that the LTMA-*sec*-$\mathrm{Bu_3B}$ combination is highly advantageous over previously available stereoselective reducing agents, since the reagent can be made *in situ* with readily

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(8) H. C. Brown and H. R. Deck, *J. Amer. Chem. Soc.*, 87, 5620 (1965).

(9) For a detailed discussion on this subject, see R. Bentley, "Molecular Asymmetry in Biology," Vol. II, Academic Press, New York, N. Y., 1970, Chapter I; J. M. H. Graves, A. Clark, and H. J. Ringold, *Biochemistry*, 4, 2655 (1965).

available chemicals and utilized directly for the reduction of ketone without isolation. Furthermore, the product is often sufficiently pure to be used directly without further purification.

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Novel Iron Carborane μ and π Complexes Derived from *nido*-$C_2B_4H_8$. A Paramagnetic Small Carborane Sandwich Compound

Sir:

Several transition metal–small carborane π complexes obtained from $C_2B_3H_7$[1] or $C_2B_4H_8$[2] in the gas phase and from 2-$CH_3C_3B_3H_6$[3,4] or its monoanion derivative[4] have been described recently. We now report a new approach to the preparation of such complexes, based on the readiness of the $C_2B_4H_7^-$ anion to undergo heteroatom insertion,[5,6] which yields the first known small carborane sandwich species as well as two stable and structurally novel metallocarborane intermediates. The reaction of sodium dicarbahexaborate(1−) with π-cyclopentadienyliron dicarbonyl iodide in tetrahydrofuran at 25° generates a moderately air-stable yellow solid, μ-[(π-C_5H_5)Fe(CO)$_2$]$C_2B_4H_7$ (I), in which the iron atom is evidently bound to the cage by a three-center two-electron B–Fe–B bond. Under ultraviolet irradiation *in vacuo*, I loses 2 mol equiv of CO and rearranges to a sublimable orange solid, (π-C_5H_5)Fe^{II}(π-$C_2B_4H_7$) (II), and a brown crystalline paramagnetic species, (π-C_5H_5)Fe^{III}(π-$C_2B_4H_6$) (III). The conversion of II to III also occurs during thick-layer chromatography of II on silica gel. Complex I is obtained in >50% yield, while the total yield of II and III, which form in approximately equal amounts from I, is >90%.

$$\text{2,3-}C_2B_4H_8 + NaH \longrightarrow Na^+C_2B_4H_7^- + H_2$$

$$Na^+C_2B_4H_7^- + (\pi\text{-}C_5H_5)Fe(CO)_2I \xrightarrow[-NaI]{25^\circ} \mu\text{-}[(\pi\text{-}C_5H_5)Fe(CO)_2]C_2B_4H_7$$

$$\mu\text{-}[(\pi\text{-}C_5H_5)Fe(CO)_2]C_2B_4H_7 \xrightarrow[-2CO]{uv} (\pi\text{-}C_5H_5)Fe^{II}(\pi\text{-}C_2B_4H_7) + (\pi\text{-}C_5H_5)Fe^{III}(\pi\text{-}C_2B_4H_6)$$

The proposed structures of the three complexes (Figure 1) are based on mass spectroscopic, nmr, and infrared evidence. Complexes I, II, and III exhibit mass spectroscopic parent peaks at *m/e* 252, 196, and 195, respectively, and in each case the profile is consistent with the indicated formulas (since both iron and boron are polyisotopic, the profile in the parent region is highly characteristic for a given composition). The empirical formulas are further supported by an exact mass determination of III (calcd for $^{56}Fe^{12}C_7{}^{11}B_4{}^1H_{11}$, 195.058; found, 195.060).

The 32.1-MHz ^{11}B nmr spectrum of I in CCl_4 solution contains doublets of approximately equal areas at δ −16.4 ppm relative to external $BF_3 \cdot O(C_2H_5)_2$ (J = 139 Hz): −3.2 (165); −1.6 (178); and +52.0 (181). The high-field resonance is attributed to the apex B–H group, but specific assignment of the low-field peaks is ambiguous at present. The location of the iron substituent at a bridging, rather than terminal, position is indicated by the fact that all of the boron resonances are doublets arising from terminal B–H groups. The presence of two CO groups is evidenced by mass spectral peak groupings having local cutoffs at *m/e* 224 and 196, corresponding to the loss of one and two CO units, respectively; in addition, strong peaks are observed at *m/e* 121 and 56, arising from $Fe(C_5H_5)^+$ and Fe^+.

The 100-MHz proton nmr spectrum of I contains a sharp C_5H_5 singlet at δ −4.83 relative to external $(CH_3)_4Si$; a cage C–H peak at −6.52; H–B quartets centered at −3.27 (J = 147 Hz) and +0.98 (J = 169 Hz); and a broad B–H–B resonance at +0.91. The characteristic infrared absorptions (CCl_4 solution *vs.* CCl_4) are at 3030 (m, cyclopentadienyl C–H), 3115 (w, carboranyl C–H), 2580 (s, B–H), 2010 (vs, CO), and 1965 (vs, CO) cm^{-1}.

The ^{11}B nmr spectrum of II in CCl_4 consists of two well-resolved doublets in a 3:1 area ratio, the larger centered at δ +8.49 (167), assigned to the basal B–H groups, and the smaller at +20.0 (153), assigned to the apex B–H. The 100-MHz proton nmr spectrum of II contains sharp singlets at δ −4.82 and −4.10, assigned to the cage C–H and cyclopentadienyl groups, respectively, and a moderately broad band at +14.40 assigned to the unique hydrogen, discussed below. The H–B quartets are not well resolved and are partly obscured by the H–C resonances.

The gross "sandwich" structure of II is strongly supported by the ^{11}B and ^1H nmr spectra, which indicate, respectively, the pseudo-equivalence[7] of the basal B–H groups in the carborane ligand and of the five cyclopentadienyl protons in a rapidly rotating C_5H_5 ring. However, the location of the seventh, or anomalous, carboranyl hydrogen presents an intriguing problem which cannot be completely resolved from the spectral data. The total absence in the ^{11}B nmr spectrum of the secondary splitting normally associated with B–H–B bridging groups indicates that such a feature is probably not present in a fixed sense, although hydrogen tautomerism between two equivalent bridging positions is conceivable. However, the singlet resonance at high field in the proton nmr spectrum is strongly reminiscent of Fe–H bonding as is found in metal hydride complexes[8] such as $HFe(\pi\text{-}C_5H_5)_2^+$,[9] an isoelectronic analog of II.[10] An intermediate possibility,

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(1) D. A. Franz, V. R. Miller, and R. N. Grimes, *J. Amer. Chem. Soc.*, **94**, 412 (1972).

(2) R. N. Grimes, *ibid.*, **93**, 261 (1971).

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(6) A. Tabereaux and R. N. Grimes, *J. Amer. Chem. Soc.*, **94**, 4768 (1972).

(7) This effect, in which the ^{11}B resonances of structurally nonequivalent borons are effectively superimposed, has also been observed in the spectra[2] of (π-$C_2B_4H_6$)Fe(CO)$_3$ and (π-$C_2B_3H_7$)Fe(CO)$_3$ (the structure of the latter compound has been confirmed by an X-ray study; see ref 1, footnote 11a). In all of these cases the boron atoms in question are those bonded directly to the metal atom.

(8) For a review, see M. L. H. Green and D. J. Jones, *Advan. Inorg. Chem. Radiochem.*, 7, 115 (1965).

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(10) Protonation of the $[(C_2B_9H_{11})_2Fe]^{2-}$ ion gives a $[(C_2B_9H_{11})_2FeH]^-$ species which may contain an Fe–H bond: M. F. Hawthorne, L. F. Warren, Jr., K. P. Callahan, and N. F. Travers, *ibid.*, **93**, 2407 (1971).