Studies of Reduction with Dimethoxyborane–Transition Metal Boride Systems

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The reduction of a variety of functional groups with new dimethoxyborane–transition metal boride systems was investigated. These systems reduced olefin, aldehyde, ketone and nitrile functionalities to afford the corresponding reduction products under mild conditions. In particular, olefins bearing ketone, carboxylic acid and nitrile functionalities were selectively reduced with the dimethoxyborane–nickel boride system using 1/5 mol eq of nickel boride.

Keywords reduction; dimethoxyborane–nickel boride system; dimethoxyborane–cobalt boride system; olefin, aldehyde; ketone; nitrile

The combination of sodium borohydride with transition metal halides has been employed to reduce nitrile, amide, olefin and nitro compounds[1a–f] which are inert to sodium borohydride alone. However, the nature of the actual reducing species in these systems remaine obscure. It has been reported that transition metal salts are reduced with sodium borohydride to afford the corresponding metal borides,[2a–c] and these metal borides catalyze the reduction of carbonyl compounds[3] and olefins.[4] The catalytic activity is highest in the case of cobalt boride (Co_2B), somewhat less for nickel boride (Ni_2B) and least for iron, manganese and copper borides.[2b] Heinzman and Ganem[1f] reported that *tert*-butylamine-borane reduced nitriles in the presence of Co_2B and suggested that reductant might be boride surface-generated borane (BH_3).

In the previous papers, we reported that the diborane–methanol system selectively reduced imines and the actual reductant in this system was dimethoxyborane ($BH(OCH_3)_2$).[5] Further, the $BH(OCH_3)_2$–nickelous chloride system reduced nitrile, aldehyde, olefin and ketone, while the $BH(OCH_3)_2$–cobaltous chloride system selectively reduced nitrile and aldehyde.[6] It was also reported that aromatic nitro compounds were selectively reduced by the sodium borohydride–Ni_2B system[7] or Ni_2B in hydrochloric acid or ammonium hydroxide.[8] As a continuation of these studies, the present paper deals with the reduction of olefin, aldehyde, ketone and nitrile with the new $BH(OCH_3)_2$–transition metal boride system.

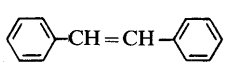
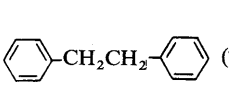
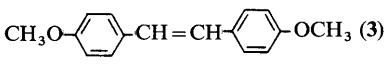
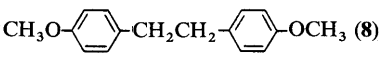
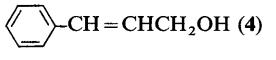
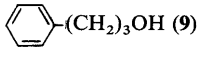
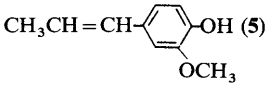
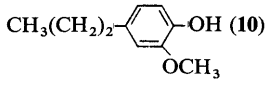
As shown in Table I, the reduction of 1-dodecene (**1**) proceeded smoothly with a catalytic amount of 1/100 mol eq of Ni_2B or Co_2B and 4 mol eq of $BH(OCH_3)_2$ in methanol at room temperature. Similarly, olefins (**2**—**5**) were reduced with this system to afford the corresponding alkanes (**6**—**10**) in good yields. The yields of products increased with increasing amount of $BH(OCH_3)_2$, and it is assumed that the reducing reactivity of the $BH(OCH_3)_2$–Ni_2B system is greater than that of the $BH(OCH_3)_2$–Co_2B system.

Similarly, as shown in Table II, aldehydes (**11**—**15**) were reduced with the $BH(OCH_3)_2$–Ni_2B system to afford the corresponding alcohols (**16**—**19**) and **9** in good yields.

As shown in Table III, ketones (**20**—**22**) were similarly reduced with this system to afford the corresponding alcohols (**24**—**27**) in good yields. However, on the reduction of *p*-chloroacetophenone (**23**) using 8 mol of $BH(OCH_3)_2$ and 1/5 mol eq of Ni_2B, the yield of product **27** was unsatisfactory.

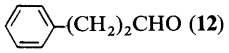
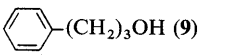
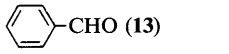
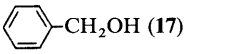
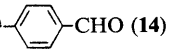
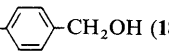
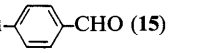
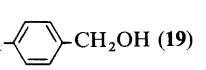
Furthermore, as shown in Table IV, nitriles (**28**—**30**) were reduced with the $BH(OCH_3)_2$–Ni_2B or Co_2B system to afford the corresponding primary amines (**32**—**33**) and secondary amines (**34**—**36**). However, the yields of these products were unsatisfactory and *p*-chlorobenzyl cyanide (**31**) was not reduced with the $BH(OCH_3)_2$–Ni_2B system. In contrast with the previous finding[6] that nitriles were reduced with the $BH(OCH_3)_2$–cobaltous or nickelous

TABLE I. Reduction of Olefins with the $BH(OCH_3)_2$–TMB[a] System

Compound (No.)	Ni_2B (eq mol)	Co_2B (eq mol)	$BH(OCH_3)_2$[b] (eq mol)	Product (No.)	Yield (%)
$CH_2=CH(CH_2)_9CH_3$ (**1**)	1/5		3	$CH_3(CH_2)_{10}CH_3$ (**6**)	60.5
	1/10		4		81.5
	1/100		4		82.2
		1/100	6		78.6
 (**2**)	1/5		4	 (**7**)	74.4
	1/5		8		93.2
		1/5	8		77.5
 (**3**)	1/5		10	 (**8**)	82.2
 (**4**)	1/10		4	 (**9**)	91.5
 (**5**)	1/2		4	 (**10**)	98.2

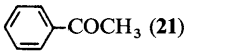
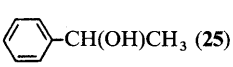
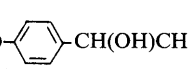
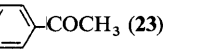
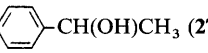
a) TMB=Transition metal boride. *b*) Reactions were carried out in methanol for 30 min at room temperature.

TABLE II. Reduction of Aldehydes with the $BH(OCH_3)_2$–Ni_2B System

Compound (No.)	Ni_2B (eq mol)	$BH(OCH_3)_2$[a] (eq mol)	Product (No.)	Yield (%)
$CH_3(CH_2)_6CHO$ (**11**)	1/5	4	$CH_3(CH_2)_7OH$ (**16**)	69.1
	1/5	8		81.0
 -$(CH_2)_2CHO$ (**12**)	1/5	8	 -$(CH_2)_3OH$ (**9**)	58.4
 -CHO (**13**)	1/10	4	 -CH_2OH (**17**)	85.1
CH_3O-  -CHO (**14**)	1/5	4	CH_3O-  -CH_2OH (**18**)	90.3
Cl-  -CHO (**15**)	1/5	4	Cl-  -CH_2OH (**19**)	53.2
	1/5	8		78.1

a) Reactions were carried out in methanol for 30 min at room temperature.

TABLE III. Reduction of Ketones with the $BH(OCH_3)_2$–TMB[a] System

Compound (No.)	Ni_2B (eq mol)	Co_2B (eq mol)	$BH(OCH_3)_2$[b] (eq mol)	Product (No.)	Yield (%)
$CH_3CO(CH_2)_5CH_3$ (**20**)	1/5		4	$CH_3CH(OH)(CH_2)_5CH_3$ (**24**)	67.5
	1/5		8		82.5
		1/5	8		80.5
 -$COCH_3$ (**21**)	1/5		4	 -$CH(OH)CH_3$ (**25**)	32.6
	1/5		8		98.4
CH_3O-  -$COCH_3$ (**22**)	1/5		4	CH_3O-  -$CH(OH)CH_3$ (**26**)	11.1
	1/5		8		70.7
Cl-  -$COCH_3$ (**23**)	1/5		4		Recovery
	1/5		8	Cl-  -$CH(OH)CH_3$ (**27**)	53.5

a) TMB = Transition metal boride. b) Reactions were carried out in methanol for 30 min at room temperature.

TABLE IV. Reduction of Nitriles with the $BH(OCH_3)_2$–TMB[a] System

$$R\text{–}CN \xrightarrow{BH(OCH_3)_2,TMB^{a)}} R\text{–}CH_2NH_2 + (R\text{–}CH_2)_2NH$$

Compound R (No.)	Ni_2B (eq mol)	Co_2B (eq mol)	$BH(OCH_3)_2$[b] (eq mol)	Product (No.) Yield (%) prim Amine	sec Amine
C_6H_5 (**28**)	1/5		8		(**34**) 48.5
		1/5	8	(**32**) 15.2	(**34**) 40.2
p-$CH_3C_6H_4$ (**29**)	1/5		8		(**35**) 52.0
$C_6H_5CH_2$ (**30**)	1/5		8	(**33**) 7.8	(**36**) 15.8
		1/5	8	(**33**) 31.6	(**36**) 32.3
p-$ClC_6H_4CH_2$ (**31**)	1/5		8	Recovery	

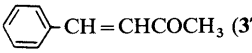
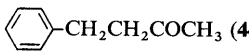
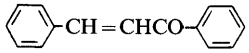
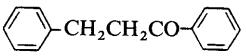
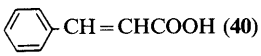
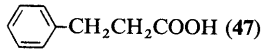
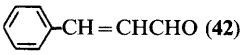
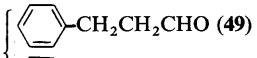
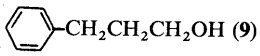
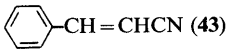
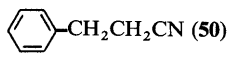
a) TMB = Transition metal boride. b) Reactions were carried out in methanol for 30 min at room temperature.

chloride system to afford the primary amines as the major products in good yields, the reductions of the nitriles **28** and **29** using Ni_2B afforded the corresponding secondary amines only and in the other cases, the corresponding secondary amines were the major products.

With regard to the reduction of other functional groups, such as carboxylic acid (benzoic acid), amide (benzamide and benzylacetamide), ester (ethyl octanoate) and a heterocyclic compound (quinaldine), not even a trace amount of the reduction product was detected and the starting materials were recovered unchanged when 8 mol eq of $BH(OCH_3)_2$ and 1/5 mol eq of Ni_2B were used. As shown in Table I, the reduction of 1-dodecene **1** proceeded smoothly with a catalytic amount of Ni_2B or Co_2B. Therefore, based on the results described above, the expected selective reduction of the olefin moiety of the compounds (**37**—**43**) bearing ketone, aldehyde, carboxylic acid or nitrile functionality was attained under similar conditions. As shown in Table V, the olefin moiety was selectively reduced in these reactions to afford the corresponding saturated products (**44**—**50**) in good yields. However, the reductions of 2-ethylhexenal **41** and cinnamaldehyde **42** also afforded 2-ethylhexanol (**51**) and 3-phenylpropanol (**9**), in which both the olefin and aldehyde moieties were reduced.

As described above, the olefin derivatives bearing other

TABLE V. Selective Reduction of Olefins Bearing Other Functionalities with the $BH(OCH_3)_2$–Ni_2B System

Compound (No.)	Ni_2B (eq mol)	$BH(OCH_3)_2$[a] (eq mol)	Product (No.)	Yield (%)
 (37)	1/5	8	 (44)	93.2
 (38)	1/5	16	 (45)	93.7
$CH_3CO(CH_2)_2CH=C(CH_3)_2$ (39)	1/5	12	$CH_3CO(CH_2)_3CH(CH_3)_2$ (46)	79.0
 (40)	1/5	16	 (47)	92.0
$CH_3(CH_2)_2CH=C(Et)CHO$ (41)	1/2	8	$CH_3(CH_2)_3CH(Et)CHO$ (48) $CH_3(CH_2)_3CH(Et)CH_2OH$ (51)	51.2 40.9
 (42)	1/10	6	 (49)  (9)	37.2 60.1
 (43)	1/5	32	 (50)	60.3

a) Reactions were carried out in methanol for 30 min at room temperature.

functionalities were predominantly reduced with the $BH(OCH_3)_2$–Ni_2B system. Accordingly, it can be assumed that the relative reactivity of this system toward olefin (and aldehyde) is higher than that toward ketone, carboxylic acid and nitrile functionalities under the conditions employed. It is presumed that the mechanism of the $BH(OCH_3)_2$–Ni_2B or Co_2B system might involve coordination of the metal boride to the carbon–carbon double bond and then the hydride ion of $BH(OCH_3)_2$ attacks this complex, since metal boride and trimethoxyborane were recovered in these reductions. As reported previously,[6] the $BH(OCH_3)_2$–cobaltous chloride system did not reduce olefin, and therefore, the present results suggest a difference of coordination ability of cobaltous chloride and metal boride toward the carbon–carbon double bond.

We know of no previous report on reduction using $BH(OCH_3)_2$–transition metal boride. As described above, the combination of $BH(OCH_3)_2$ and metal boride increased the reduction activity compared with the $BH(OCH_3)_2$–methanol system[5] and the $BH(OCH_3)_2$–Ni_2B system can provide a useful method for the selective reduction of olefins bearing other functionalities.

Experimental

Commercially available $NiCl_2 \cdot 6H_2O$, $CoCl_2 \cdot 6H_2O$ and $NaBH_4$ were used throughout this work. Melting points were determined on a Yanagimoto micro-melting point apparatus, model MP-S3, and are uncorrected. Infrared (IR) spectra were measured in Nujol mulls or as liquid films with a JASCO A-100 (Nihon Bunko) infrared spectrometer, and ultraviolet (UV) spectra were recorded on a JASCO Uvidec-505 ultraviolet spectrometer. Gas chromatography was done on a JEOL JGC-20K gas chromatograph. Yields of amines were calculated by gas chromatography on a glass column, packed with SE-30, at 140 °C (column temperature) and 0.8 kg/cm^2 nitrogen pressure, by comparison with standard amounts of authentic samples. Nuclear magnetic resonance (NMR) spectra were recorded on a Hitachi R20-A spectrometer.

Ni_2B and Co_2B Ni_2B and Co_2B were prepared from $NaBH_4$ and $NiCl_2 \cdot 6H_2O$ or $CoCl_2 \cdot 6H_2O$ according to a published procedure.[2c]

Reduction of Olefins (1—5) The procedure for the reduction of 1-dodecene (**1**) is described in detail as a typical example. Compound **1** (1.34 g, 8 mmol) and freshly prepared Ni_2B (104 mg, 0.8 mmol) were suspended in methanol (30 ml) and the suspension was stirred for 10 min. Then, diborane[9] (32 mmol) was passed into the methanol solution at −20 °C with stirring and stirring was continued for 30 min at room temperature. After removal of the solvent, the residue was extracted with ether and the extract was dried over anhydrous magnesium sulfate. The ether was evaporated off and the residue was distilled under reduced pressure to give 1.11 g (81.5%) of dodecane (**6**), bp 95—97 °C (15 mmHg) (lit.[10] bp 100—102 °C (17 mmHg)). MS *m/z*: 170 (M^+). This was identical with an authentic sample (IR spectral comparison).

The following products were similarly obtained, and the yields are listed in Table I. 1,2-Diphenylethane (**7**), mp 52—52.5 °C (from EtOH) (lit.[11] mp 52.5—53 °C); 1,2-di(*p*-methoxyphenyl)ethane (**8**), mp 125.5—126 °C (from EtOH) (lit.[12] mp 126—126.5 °C); 3-phenyl-1-propanol (**9**), bp 118—119 °C (12 mmHg) (lit.[13] bp 233—235 °C (740 mmHg)); 2-methoxy-4-propylphenol (**10**), bp 121—123 °C (12 mmHg) (lit.[14] bp 125—126 °C (13 mmHg)). These products were identical with authentic samples on the basis of comparisons of thier IR, NMR and mass spectra.

Reduction of Aldehydes (11—15) and Ketones (20—23) Compounds **11—15** and **20—23** were reduced with $BH(OCH_3)_2$–Ni_2B or Co_2B under similar conditions as shown in Tables II and III, followed by treatment in the manner described above. The following products were similarly obtained, and the yields are listed in Tables II and III. Octanol (**16**), bp 100—101 °C (20 mmHg) (lit.[15] bp 195.28 °C); 4-methoxybenzyl alcohol (**18**), bp 128—130 °C (19 mmHg) (lit.[16] bp 150—151 °C (27 mmHg)); *p*-chlorobenzyl alcohol (**19**), mp 71—72 °C (from EtOH) (lit.[17] mp 69—71 °C); 2-octanol (**24**), bp 84—85 °C (20 mmHg) (lit.[17] bp 175—177 °C); 1-phenylethanol (**25**), bp 88—90 °C (8 mmHg) (lit.[18] bp 93 °C (12 mmHg)); 1-(*p*-methoxyphenyl)ethanol (**26**), bp 138—139 °C (18 mmHg) (lit.[19] bp 95 °C (1 mmHg)); 1-(*p*-chlorophenyl)ethanol (**27**), bp 122—124 °C (15 mmHg) (lit.[20] bp 125 °C (15 mmHg)). These products were identical with the corresponding authentic samples on the basis of comparisons of their IR, NMR and mass spectra.

Reduction of Nitriles (28—31) Compounds **28—31** were reduced with $BH(OCH_3)_2$–Ni_2B or Co_2B under similar conditions. After removal of the solvent, 10% hydrochloric acid (20 ml) was added at 0 °C, and the precipitates were collected and washed with ether. Recrystallization from EtOH gave di-*p*-methylbenzylamine (**35**) hydrochloride mp 275—276 °C (lit.[21] mp 276.5—278.8 °C) from **29**, and di-β-phenethylamine (**36**) hydrochloride mp 270 °C (lit.[22] mp 271 °C) from **30**. The precipitates were suspended in water, and the suspensions were basified by the addition of 10% sodium hydroxide, followed by extraction with ether. The extracts were dried over anhydrous magnesium sulfate. After removal of the ether, the residues were distilled under reduced pressure to give the following secondary amines; dibenzylamine (**34**) bp 152—154 °C (4 mmHg) (lit.[21] bp 113—114 °C (0.1 mmHg)) from **28**; di-*p*-methylbenzylamine (**35**) bp 185—188 °C (2 mmHg) (lit.[21] bp 135—137 °C (0.1 mmHg)), mp 32—35 °C (from cyclohexane) (lit.[21] mp 34.5—36.5 °C) from **29**; di-β-phenethylamine (**36**) bp 171—173 °C (8 mmHg) (lit.[23] bp 170—175 °C (8 mmHg)) from **30**. The acidic aqueous layers described above were basified by the addition of concentrated ammonium hydroxide, followed by extraction with ether.

The extracts were dried over anhydrous magnesium sulfate. After removal of the ether, the residues were distilled to give the following primary amines; benzylamine (**32**) bp 79—80 °C (7 mmHg) from **28**; β-phenethylamine (**33**) bp 197—198 °C (lit.[24] bp 98 °C (29 mmHg)), hydrochloride mp 215—217 °C (lit.[25] mp 217 °C) from **30**. These results are listed in Table IV, and all spectral data for products **32**—**36** were identical with those for corresponding authentic samples.

Selective Reduction of Olefin Derivatives (37—43) Compounds **37**—**43** were reduced with the $BH(OCH_3)_2$–Ni_2B system under conditions similar to those described above. The products and yields are listed in Table V, and the products were identical with corresponding authentic samples based on comparisons of IR, NMR spectra and gas chromatographic behavior. The reduction mixtures of aldehydes **41** and **42** were separated by chromatography on a neutral alumina column. 4-Phenyl-2-butanone (**44**) bp 112—113 °C (12 mmHg) (lit.[26] bp 63 °C (0.7 mmHg)); 1,3-diphenyl-1-propanone (**45**) mp 70—71 °C (from 95% EtOH) (lit.[27] mp 70—71 °C); 6-methyl-2-heptanone (**46**) bp 64—65 °C (20 mmHg) (lit.[28] bp 164—164.5 °C (757 mmHg)); 3-phenylpropanoic acid (**47**) mp 46.5—47 °C (from petroleum ether) (lit.[29] mp 46—47 °C); 2-ethylhexanal (**48**) bp 64—67 °C (25 mmHg) (lit.[30] bp 160 °C); 2-ethyl-1-hexanol (**51**) bp 96—99 °C (24 mmHg) (lit.[31] bp 84—86 °C (15 mmHg)); 3-phenylpropiononitrile (**50**) bp 125—126 °C (12 mmHg) (lit.[32] bp 142 °C (25 mmHg)).

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