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Reducing Characteristics of Borohydride Exchange Resin–$CuSO_4$ in Methanol

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Reducing characteristics of borohydride exchange resin (BER)–$CuSO_4$ (cat.) were studied in methanol at room temperature. Carbon–carbon double bonds conjugated with benzene or carbonyl group were more rapidly reduced than was the case with isolated double bonds. Carbonyl groups were readily reduced, whereas esters and amides were inert, and nitriles were slowly reduced. High chemoselectivity was also observed in halide reductions: *p*-bromochlorobenzene and *p*-bromoiodobenzene were reduced quantitatively to chlorobenzene and bromobenzene, respectively. Aliphatic epoxides were inert to this reagent; however, styrene oxide derivatives were readily reduced to the corresponding deoxygenated products. Aliphatic azides were reduced slowly during 6 h, whereas phenyl azide was transformed to aniline in 1 h. Nitrocyclohexane was reduced at room temperature, but nitrobenzene, nitrosobenzene, azobenzene, and azoxybenzene required an elevated temperature (65 °C) for rapid reductions (1 h). Similarly, *N*,*N*-dimethylaniline *N*-oxide was reduced at room temperature, whereas pyridine *N*-oxide required refluxing. Finally, among the sulfur compounds tested, only diphenyl disulfide was reduced readily, and sulfide, aliphatic disulfide, sulfoxide, sulfone, and tosylate were inert to this reducing system.

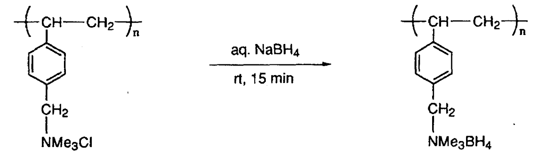
Unlike lithium aluminum hydride, sodium borohydride is a very mild reducing agent.[1] It reduces aldehydes, ketones, and acyl halides, but is inert to almost all other functional groups; its reducing power is greatly enhanced in the presence of transition metal halides.[2] For this purpose, nickel chloride,[3,4] cobalt chloride,[5] copper chloride,[6,7] and other metal salts[8] have been used with $NaBH_4$. For example, when nickel chloride (or acetate) is present, the nickel salt is rapidly reduced to nickel boride (Ni_2B), and the $NaBH_4$–Ni_2B system reduces nitro and azido compounds readily to the corresponding amines,[3] whereas $NaBH_4$ itself is inert to the nitro group[9] and does not give a good yield of amines in its reaction with aliphatic azides.[10]

Recently, we have found borohydride exchange resin (BER), a quaternary ammonium borohydride, prepared by treating an anion exchange resin (chloride from) with aqueous $NaBH_4$, is relatively stable in methanol even in the presence of transition metal salts, in contrast to the rapid decomposition of $NaBH_4$.[11] BER is also much more stable than the soluble quaternary ammonium borohydride, tetrabutylammonium borohydride, in methanol in the presence of a transition metal salt. And we have also found that BER–Ni(OAc)$_2$ system in methanol is a better reducing agent than the $NaBH_4$–Ni_2B system[3] not only for the selective reduction of nitro[12] and azido compounds[13] to the corresponding amines, but also for the reduction of halides.[14] This prompted us to explore the reducing characteristics of the BER–$CuSO_4$ system in methanol.

Results and Discussion

Preparation and Stability of Borohydride Exchange Resin (BER):

Preparation and Stability of Borohydride Exchange Resin (BER): BER was prepared by treating an anion exchange resin (Amberlite IRA-400) with aqueous $NaBH_4$ solution (Eq. 1). BER thus prepared had on the average 3.0 mmol of BH_4^- per gram of resin (estimated by hydride content). Therefore BER is a quaternary ammonium borohydride, the BH_4^- being attached on the surface of the resin. When BER (5 molar amount) was added to the methanol solution of $CuSO_4$ (0.1 molar amount), a black coating of copper on BER and slow hydrogen evolution due to the decomposition of BER were observed. The stability of BER and $NaBH_4$ in methanol in the presence and absence of a catalytic amount of $CuSO_4$ (0.02 molar amount) was compared. BER decomposed approximately 42% in 1 h and 55% in 2 h, whereas $NaBH_4$ decomposed completely within 5 min (Fig. 1).



Anion Exchange Resin

Borohydride Exchange Resin (BER)

(1)

Reduction of Organic Compounds Containing Representative Functional Groups: In order to study the reducing characteristics of BER–$CuSO_4$, each representative organic compound was reacted with 5.0 molar amount of BER and 0.1 molar amount of $CuSO_4$ in methanol at room temperature. After an appropriate reaction time (1, 3, or 6 h), the reaction mixture was analyzed by GLPC. In the preparative runs (10 mmol scale), BER–Cu was filtered after the

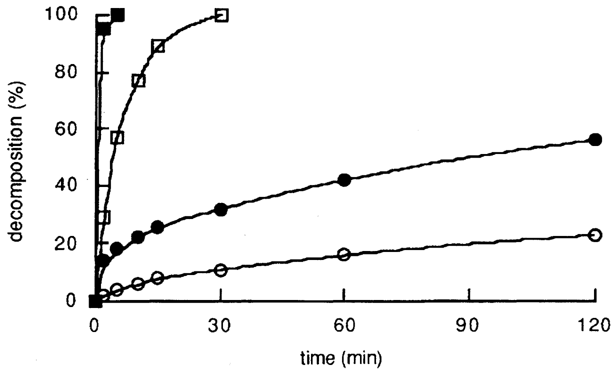


Fig. 1. Rate of decomposition of BER (circle) and $NaBH_4$ (square) in methanol in the presence (black) and absence (white) of $CuSO_4$ (0.02 molar amount).

reduction, and simple evaporation of methanol resulted in a highly pure product in most cases.[14]

Alkenes and Alkynes: First we examined various carbon–carbon multiple bonds (Table 1). 1-Octene was slowly reduced, producing 47% of octane in 3.0 h, whereas, the disubstituted terminal olefin, 2-methyl-1-pentene, reacted more slowly, and limonene and internal olefins such as 2-octene and cyclohexene were inert to this reducing system (Entries 1—5). The reaction of 1-octene was repeated under H_2 (1 atm) and no further reaction was noticed, confirming that the reaction is not a catalytic hydrogenation over copper. On the other hand, styrene was rapidly reduced to ethylbenzene selectively in the presence of 1-decene; this reduction did not occur at all in ethanol, showing that the methanol solvent is essential (Entries 6—8). It is interesting to note that $NaBH_4$–$CuSO_4$–EtOH system required 3.0 h refluxing for the reduction of styrene.[7] Although chlorobenzene is inert to this reducing system (as shown in halide section), *p*-chlorostyrene was reduced to give a mixture of *p*-chloroethylbenzene and ethylbenzene (Entry 9). Conjugated dienes such as 1,3-cyclohexadiene, 1,3-cyclooctadiene, or *p*-mentha-1,5-diene were partially reduced to the corresponding monoenes in quantitative yields (Entries 10,11, and 13); sterically hindered conjugated dienes such as *p*-mentha-1,3-diene were inert to this reducing system (Entry 14). Isoprene gave a mixture of 2-methyl-2-butene and 2-methyl-1-butene, showing the competition of 1, 4-reduction and 1, 2-reduction (Entry 12). However, cyclohexadiene can be reduced to

Table 1. Reduction of Representative Alkenes and Alkynes with BER–$CuSO_4$ in Methanol at Room Temperature[a)]

Entry	Substrate	Product	Time/h	Yield/%[b)]
1	1-Octene	Octane	1	42
			3	47(48)[c)]
2	2-Methyl-1-pentene	2-Methylpentane	1	15
			3	17
3	(*R*)-(+)-Limonene		3	N.r.
4	2-Octene		3	N.r.
5	Cyclohexene		3	N.r.
6	Styrene	Ethylbenzene	1	100
7[d)]	Styrene		3	N.r.
8[e)]	Styrene	Ethlybenzene	3	100
	1-Decene	Decane		2
9	*p*-Chlorostyrene	*p*-Chloroethlbenzene	1	56
		Ethlbenzene		44
10	1,3-Cyclohexadiene	Cyclohexene	1	100
11	1,3-Cyclooctadiene	Cyclooctene	1	100
12	Isoprene	2-Methyl-1-butene	1	38
		2-Methyl-2-butene		62
13	*p*-Mentha-1,5-diene	*p*-Menth-1-ene	1	100
14	*p*-Mentha-1,3-diene		3	N.r.
15[e)]	1,3-Cyclohexadiene	Cyclohexene	3	99
	1-Decene	Decane		2
16	1,3,5-Cycloheptatriene	Cycloheptene	1(6)	7(85)
		1,3-Cycloheptadiene		65(0)
		1,4-Cycloheptene		15(15)
17	1-Heptyne	1-Heptene	3	8
18	Phenylacetylene	Styrene	3	18
19	*p*-Methylstyrene		1	N.r.
	1-Heptyne	1-Heptene		3
20	Ethyl crotonate	Ethyl butyrate	0.5	100
	1-Decene	Decane		5
21[e)]	Crotononitrile	Butyronitrile	1	98
	1-Decene	Decane		4
22	Crotononitrile	Butyronitrile	1	99
	Cyclohexene			N.r.
23	Ethyl Crotonate	Ethyl Butyrate	3	14
	1-Heptyne	1-Heptene		9

a) Reduction was carried out using 5.0 molar amount of BER and 0.1 molar amount of $CuSO_4$. b) Yields were estimated by GLPC using appropriate internal standards. c) Under 1 atm H_2. d) In ethanol. e) 3.0 molar amount of BER and 0.07 molar amount of $CuSO_4$ used.

cyclohexene selectively in the presence of 1-decene (Entry 15). Cycloheptatriene was first reduced mainly to 1,3-cycloheptadiene in 1 h and further reduced to cycloheptene (85%) in 6 h (Entry 16). Acetylenes were reduced very slowly to give the corresponding olefins (Entries 17 and 18). Therefore we expected the selective reduction of *p*-methylstyrene in the presence of 1-heptyne; however, to our surprise, *p*-methylstyrene was not reduced in the presence of 1-heptyne (Entry 19). Presumably copper is all occupied by the triple bond of 1-heptyne and will not be available to *p*-methylstyrene. A similar result was observed in the case of competitive reduction of ethyl crotonate and 1-heptyne (Entry 23). Ethyl crotonate and crotononitrile could be rapidly hydrogenated selectively in the presence of 1-decene or cyclohexene (Entries 20—22).[15] However, BER–Ni$_2$B showed a poor selectivity in the competitive reduction of ethyl crotonate and 1-decene. This type of reduction can be also carried out by catalytic hydrogenations and by reaction of other reducing agents including metal hydrides. However, the former would hydrogenate simultaneously other carbon–carbon multiple bonds in the same molecule, and the latter may not compete in selectivity with the present method which requires only mild borohydride.

Aldehydes and Ketones: The reactions with representative aldehydes and ketones are summarized in Table 2. Unhindered aldehydes and ketones tested were all reduced rapidly, but the hindered ketone, *d*-camphor was inert to this reagent (Entries 1—7). The stereochemistry of ketone reduction was similar but slightly more selective than that in the case of BER alone and NaBH$_4$.[16] The conjugated double bonds of cinnamaldehyde and 2-cyclohexenone were simultaneously reduced to give the corresponding saturated alcohols (Entries 8 and 9).[17] However, the corresponding saturated ketones could be obtained in good to excellent yields by using a limited amount of BER (2.0 molar amount) (Entries 10—12 and 14). It is interesting to note that *trans*-4-hexen-3-one and 4-methyl-3-penten-2-one were reduced to the corresponding allylic alcohol with BER (in the absence of Cu) in 84 and 96% yield, respectively (Entries 13 and 15). Finally cyclohexenone could be reduced selectively in the presence of a terminal alkene, 1-decene (Entry 16).

Acid Derivatives: Seven representative acid derivatives were examined with this hydride system (Table 3). Both aliphatic and aromatic esters and amides were inert (Entries 1—5). Hexanenitrile showed sluggish reduction (Entries 6 and 7), and benzonitrile was slowly reduced to give a mixture of benzylamine and dibenzylamine (Entry 8), but the reduction of benzonitrile could be completed by increasing the amount of copper (Entry 9).

Halides: The reduction of representative halides were examined with this hydride system; the results are summarized in Table 4. As shown in the Table 4, the primary chloride was inert but the primary bromide was reduced readily to the corresponding hydrocarbon (Entries 1 and 2). The excellent chemoselectivity was proved by the reduction of 1-bromo-4-chlorobutane (Entry 3). Bromocyclohexane was also reduced readily; a small amount (15%) of cyclohexene was also formed (Entry 4). The reduction of benzyl chloride gave 1,2-diphenylethane (8%) together with toluene (83%), the simple reduction product. This suggests the participation of radical intermediates (Entry 5). Ethyl 2-chloropropionate, an α-halo ester tested, was also reduced quantitatively in 1.0 h (Entry 6). Chlorobenzene was inert to this reducing system, while bromobenzene was slowly reduced at room temperature; quantitative reduction was observed in 1.0 h at 65 °C (Entries 8—10). Iodobenzene was readily reduced at room temperature (Entry 11). A similar tendency was also reported previously with NaBH$_4$–CuSO$_4$ system in methanol.[18] Excellent chemoselectivity of this system was proved by the selective reduction of *p*-bromoiodobenzene and *p*-bromo-

Table 2. Reduction of Representative Aldehydes and Ketones with BER–CuSO$_4$ in Methanol at Room Temperature[a]

Entry	Substrate	Product	Time/h	Yield/%[b]
1	Benzaldehyde	Benzyl alcohol	1	99
2	2-Heptanone	2-Heptanol	1	98
3	2-Methylcyclohexanone	2-Methylcyclohexanol	1	100[c]
4	4-*t*-Butylcyclohexanone	4-*t*-Butylcyclohexanol	1	99[d]
5	Norcamphor	Norborneol	1	99[e]
6	*d*-Camphor		6	N.r.
7	Acetophenone	1-Phenylethanol	1	100
8	Cinnamaldehyde	3-Phenyl-1-propanol	1	100
9	Cyclohexenone	Cyclohexanol	1	98
10[f]	Cyclohexenone	Cyclohexanone	0.25	60[g]
11[f]	Cyclopentenone	Cyclopentanone	0.25	85[g]
12[f]	*trans*-4-Hexen-3-one	3-Hexanone	0.25	93[g]
13[h]	*trans*-4-Hexen-3-one	*trans*-4-Hexen-3-ol	3	84[g]
14[h]	4-Methyl-3-penten-2-one	4-Methyl-2-pentanone	0.25	95[g]
15[h]	4-Methyl-3-penten-2-one	4-Methyl-3-penten-2-ol	8	96
16[i]	Cyclohexenone	Cyclohexanol	0.5	98
	1-Decene	Decane		2

a,b) Same as Table 1. c,d) *Cis/trans* ratios were 47/53 and 23/77 respectively. e) *Endo/exo* ratio was 94/6. f) Reduction with 2.0 molar amount of BER. g) Remainder was the corresponding saturated alcohol. h) In the absence of Cu. i) 3.0 molar amount of BER and 0.07 molar amount of CuSO$_4$ used.

Table 3. Reduction of Representative Acid Derivatives with BER–CuSO$_4$ in Methanol at Room Temperature[a)]

Entry	Acid derivative	Product	Time/h	Yield/%[b)]
1	Ethyl hexanoate		3	N.r.
2	Methyl phenylacetate		3	N.r.
3	Ethyl benzoate		3	N.r.
4	Benzamide		3	N.r.
5	*N*,*N*-Dimethylacetamide		3	N.r.
6	Hexanenitrile	Hexylamine	3	13
7[c)]	Hexanenitrile	Hexylamine	3	35
			6	38
8	Benzonitrile	Benzylamine	3	17
		Dibenzylamine		5
9[c)]	Benzonitrile	Benzylamine	3	58
		Dibenzylamine		21

a,b) Same as Table 1. c) A half molar amount of CuSO$_4$ was used.

Table 4. Reduction of Representative Halides with BER–CuSO$_4$ in Methanol at Room Temperature[a)]

Entry	Halide	Product	Time/h	Yield/%[b)]
1	1-Chlorooctane		3	N.r.
2	1-Bromooctane	Octane	1	99
3	1-Bromo-4-chlorobutane	1-Chlorobutane	1	95
4	Bromocyclohexane	Cyclohexane	1	82
		Cyclohexane		15
5	Benzyl chloride	Toluene	1	83
		1,2-Diphenylethane		8
6	Ethyl 2-chloropropionate	Ethyl propionate	1	96
7	Chlorobenzene		3	N.r.
8	Bromobenzene	Benzene	3	36
9[c)]	Bromobenzene	Benzene	1	55
10[c,d)]	Bromobenzene	Benzene	1	100
11	Iodobenzene	Benzene	1	99
12[c,d)]	*p*-Bromochlorobenzene	Chlorobenzene	1	99
13	*p*-Bromoiodobenzene	Bromobenzene	1	97

a.b) Same as Table 1. c) Under reflux. d) A half molar amount of CuSO$_4$ was used.

chlorobenzene (Entries 12 and 13). The selectivity of this reduction system is higher than the 85% yield of bromobenzene from *p*-bromoiodobenzene by using NaBH$_4$–Cp$_2$TiCl$_2$[19)] previously reported, and the 96% yield of chlorobenzene in the selective reduction of 2-bromochlorobenzene was obtained by using Ni complex reducing agent.[20)] On the other hand, *p*-bromochlorobenzene was reduced to give a mixture of 56% of chlorobenzene and 19% of benzene by using BER–Ni$_2$B.

Epoxides: Representative aliphatic epoxides and styrene oxides were examined (Table 5). Aliphatic epoxides are generally inert to this reducing system, as shown in the reactions with 1-decene oxide, cyclohexene oxide, and 3-phenylpropene oxide (Entries 1—3). However, styrene oxide was reduced rapidly to ethylbenzene quantitatively (Entry 4). In order to obtain a better understanding of this reaction, we repeated the reaction with a limited amount of BER (2 molar amount) and observed the formation of styrene (27%) and ethylbenzene (11%) in 30 min (Entry 5). Apparently the deoxygenation of styrene oxide to styrene preceded the hydrogenation of styrene to give ethylbenzene. β-Methylstyrene oxide was reduced to give a mixture of β-methylstyrene and propylbenzene (Entry 7). However, α-methylstyrene oxide gave a mixture of α-methylstyrene and corresponding alcohols (Entry 6). By increasing the amount of reagent and elevating the reaction temperature, 100% of propylbenzene and 89% of isopropylbenzene could be obtained from these oxides. And selective deoxygenation of β-methylstyrene oxide could be accomplished in the presence of cyclohexene oxide (Entry 8). On the other hand, 4-chlorostyrene oxide rapidly gave the mixture of 4-chloroethylbenzene (59%) and ethylbenzene (41%) (Entry 9). Since exactly the same mixture of products can be obtained from the reduction of *p*-chlorostyrene (Table 1), there will be no doubt that styrene is the intermediate in the reduction of styrene oxide with this system. Finally, ethyl 3-phenyl-2,3-epoxypropionate was also reduced readily to give ethyl 3-phenylpropionate (Entry 10). Therefore, reductions of styrene oxide derivatives seem to be susceptible to the steric and electronic environments of epoxides. It was reported that styrene oxide could be reduced to ethylbenzene by hydrogenation over PtO$_2$ in 70% yield,[21)] and *trans*-stilbene oxide was quantitatively reduced to 1,2-diphenylethane with Et$_3$SiH/BF$_3$ in 7 d.[22)] On the other hand, BER–Ni$_2$B reduced styrene oxide to give a mixture of 89% of phenethyl alcohol and 11% of ethylbenzene.

Azides: Reductions of azides are summarized in Table 6. Octyl azide and benzyl azide were reduced moderately, giving quantitative yields of the corresponding amines in 6.0 h (Entries 1 and 3). A rapid reduction was observed at 65 °C, but a small amount of the corresponding dialkylamine (3%) was contaminated in the products (Entry 2). Phenyl azide

Table 5. Reduction of Representative Epoxides with BER–$CuSO_4$ in Methanol at Room Temperature$^{a)}$

Entry	Substrate	Product	Time/h	Yield/%$^{b)}$
1	1-Decene oxide		3	N.r.
2	Cyclohexene oxide	Cyclohexanol	3	N.r.(2)$^{c)}$
3	3-Phenylpropene oxide		3	N.r.
4	Styrene oxide	Ethylbenzene	1	98
5$^{d)}$	Styrene oxide	Ethylbenzene	0.5	11
		Styrene		27
6	α-Methylstyrene oxide	α-Methylstyrene	3	51
		Isopropylbenzene		0(89)$^{c)}$
		2-Phenyl-1-propanol		46(11)$^{c)}$
		2-Phenyl-2-propanol		3
7	β-Methylstyrene oxide	β-Methylstyrene	3	14
		Propylbenzene		49(100)$^{c)}$.
8$^{c)}$	β-Methylstyrene oxide	Propylbenzene	1	99
	Cyclohexene oxide	Cyclohexanol		1
9	4-Chlorostyrene oxide	4-Chloroethylbenzene	1	59
		Ethlbenzene		41
10	Ethyl 3-phenyl-2,3-epoxypropionate	Ethyl 3-phenylpropionate	1	67(96)$^{e,f)}$
			3	74

a.b) Same as Table 1. c) Reduction was carried out with 10 molar amount of BER and 0.5 molar amount of $CuSO_4$ in 1 h at 65 °C. d) Two molar amounts of BER was used. e) A fifth molar amount of $CuSO_4$ was used. f) Isolated yield.

Table 6. Reduction of Representative Azides with BER–$CuSO_4$ in Methanol at Room Temperature$^{a)}$

Entry	Substrate	Product	Time/h	Yield/%$^{b)}$
1	Octyl azide	Octylamine	3	74
			6	97
2$^{c)}$	Octyl azide	Octylamine	1	93
		Dioctylamine		3
3	Benzyl azide	Benzylamine	3	85
			6	99
4	Octyl azide	Octylamine	6	98
	1-Decene			N.r.
5	*p*-Chlorobenzyl azide	*p*-Chlorobenzylamine	6	94$^{d)}$
6	Phenyl azide	Aniline	1	97

a.b) Same as Table 1. c) Under reflux. d) Isolated yield.

was also readily reduced at room temperature, as reported earlier.[23] These azides could be reduced selectively in the presence of olefin and aryl chloride (Entries 4 and 5). These selective reductions are not expected by BER–Ni_2B.[13,14,24]

Nitro and Other Nitrogen Compounds: Nitro and other related nitrogen compounds were examined (Table 7). Nitroalkanes are readily reduced to the corresponding amines quantitatively and selectively at room temperature even in the presence of olefins (Entries 1 and 2). On the other hand, nitrobenzene, nitrosobenzene, azobenzene, and azoxybenzene were reduced slowly at room temperature but rapidly at 65 °C (Entries 3—11). *p*-Bromo- and *p*-chloronitrobenzene were cleanly reduced to *p*-bromo- and *p*-chloroaniline, showing the excellent chemoselectivity (Entries 4 and 5). Sometimes ago, $NaBH_4$–$CuSO_4$ system was reported for the reduction of nitro compounds.[7] On the other hand, the selective reduction of *p*-bromonitrobenzene to *p*-bromoaniline was only possible at 0 °C using BER–Ni_2B.[12] *N*,*N*-Dimethylaniline *N*-oxide and pyridine *N*-oxide were readily deoxygenated to the corresponding amines (Entries 12—14).[25] Cyclohexanone oxime was reduced very slowly, producing a mixture of cyclohexylamine and dicyclohexylamine (Entry 15). Since this system is inert to esters, amides, most epoxides, and most sulfur compounds and reacts slowly with aliphatic nitriles and oximes, these nitro compounds and related compounds are expected to be reduced selectively in the presence of these functional groups.

Sulfur Compounds: Six representative sulfur compounds were reduced with this system (Table 8). Sulfur compounds tested were all inert to this reducing system except diphenyl disulfide. Diphenyl disulfide was also reduced with BER in the absence of Cu.[26]

Conclusion

BER is a milder reducing agent than $NaBH_4$, but the addition of catalytic amounts of $CuSO_4$ (0.1 molar amount) in methanol gives a black coating of copper on BER. This BER–$CuSO_4$ (cat.) in methanol is a versatile reducing system capable of many valuable selective reductions. It is inert to esters, amides, chlorides, aliphatic epoxides, and most sulfur compounds, and reacts only sluggishly with acetylenes, di- or trisubstituted olefins. However, it readily hydrogenates carbon–carbon double bonds conjugated with benzene or carbonyl group. It readily reduces aldehydes and ketones, and halides (Br and I). Styrene oxides are easily reduced to the corresponding deoxygenated products, and azides and nitro compounds can be reduced to the amino compounds selectively by this system. This system also has the additional

Table 7. Reduction of Representative Nitro and Other Nitrogen Compounds with BER–CuSO$_4$ in Methanol at Room Temperature$^{a)}$

Entry	Substrate	Product	Time/h	Yield/%$^{b)}$
1	Nitrocyclohexane	Cyclohexylamine	3	98
2	Nitrocyclohexane 1-Decene	Cyclohexylamine	3	98 N.r.
3$^{c)}$	Nitrobenzene	Aniline	3	95
4$^{c)}$	*p*-Bromonitrobenzene	*p*-Bromoaniline	3	95$^{d)}$
5$^{c)}$	*p*-Chloronitrobenzene	*p*-Chloroaniline	3	96$^{d)}$
6	Nitrosobenzene	Aniline	24	100
7$^{c)}$	Nitrosobenzene	Aniline	1	100
8	Azobenzene	Aniline	24	100
9$^{c,e)}$	Azobenzene	Aniline	1	100
10	Azoxybenzene	Aniline	24	99
11$^{c,e)}$	Azoxybenzene	Aniline	1	100
12	*N,N*-Dimethylaniline *N*-Oxide	*N,N*-Dimethylaniline	1	94$^{d)}$
13	Pyridine *N*-oxide	Pridine	6	93
14$^{c)}$	Pyridine *N*-oxide	Pridine	3	99
15	Cyclohexanone oxime	Cyclohexylamine Dicyclohexylamine	24	8 24

a.b) Same as Table 1. c) Under reflux. d) Isolated yield. e) A half molar amount of CuSO$_4$ was used.

Table 8. Reduction of Representative Sulfur Compounds with BER–CuSO$_4$ in Methanol at Room Temperature$^{a)}$

Entry	Substrate	Product	Time/h	Yield/%$^{b)}$
1	Methyl *p*-tolyl sulfide		3	N.r.
2	Dimethyl sulfoxide		3	N.r.
3	Diphenyl disulfide	Benzenethiol	3	100
4	Dibutyl disulfide		3	N.r.
5	Diphenyl sulfone		3	N.r.
6	Octyl tosylate		3	N.r.

a.b) Same as Table 1.

advantage of simple work up.

Experimental

Preparation of BER. An aqueous solution of sodium borohydride (1 M, 500 mL) (1 M=1 mol dm^{-3}) was stirred with wet chloride form anion exchange resin (Amberlite IRA-400 [20—50 mesh], 200 g) for 15 min. The resulting resin was washed thoroughly with distilled water to remove excess NaBH$_4$ and then washed once with ethanol. The borohydride exchange resin was then dried under vacuum at 60 °C for 5 h to give 102 g of dried borohydride exchange resin (BER). The dried resin was analyzed for borohydride content by hydrogen evolution on acidification with 2 M HCl. The average hydride content of BER was found to be 3.0 mmol of BH$_4^-$ per gram. The dried resin was stored under nitrogen in a refrigerator (ca. 4 °C). The hydride content was constant for more than 6 weeks.

Stability of BER. Methanol (10 mL) and methanol (10 mL) containing 0.02 mmol of CuSO$_4$·5H$_2$O were added to the two reaction flasks which contain one mmol each of BER. The rate of decomposition was followed by measuring the hydrogen evolution at room temperature. The measurement was repeated with NaBH$_4$ in the place of BER. BER decomposed 16% in 1 h, 23% in 2 h, and 42% in 1 h, 55% in 2 h in the presence of CuSO$_4$·5H$_2$O. In contrast, NaBH$_4$ decomposed completely in 2 min and 30 min in the presence and absence of CuSO$_4$·5H$_2$O respectively. And the soluble quaternary ammonium borohydride, tetrabutylammonium borohydride, in methanol decomposed 89% in 5 min, completely in 10 min in the presence of CuSO$_4$·5H$_2$O.

General Procedure. (A) Analytical: Reduction of 1-octene is described as a representative case. BER (1.62 g, 5.0 mmol) was added to a methanol solution (10 mL) of CuSO$_4$·5H$_2$O (0.025 g, 0.1 mmol), and the mixture was stirred slowly at room temperature. The yellowish BER particles immediately turned black, and slow hydrogen evolution due to the decomposition of BER was observed. After 1 min, one mmol each of 1-octene and mesitylene (internal standard) in methanol (2 mL) was added. After the reaction mixture was stirred for 1 h at room temperature, the GLPC analysis of the mixture on column HP-1 showed 42% of octane.

(B) Isolation: Reduction of ethyl 3-phenyl-2,3-epoxypropionate is described as a representative case. BER (16.2 g, 50.0 mmol) was added to a methanol solution (100 mL) of CuSO$_4$·5H$_2$O (0.499 g, 2.0 mmol), and the mixture was stirred slowly at room temperature. After 1 min, ethyl 3-phenyl-2,3-epoxypropionate (1.92 g, 10.0 mmol) in methanol (20 mL) was then added. After the reaction mixture was stirred for 1 h at room temperature, the resin was removed by filtration and methanol was evaporated under reduced pressure to give ethyl 3-phenylpropionate (1.71 g, 96%); ^{1}H NMR (200 MHz, CDCl$_3$) δ=1.24 (3H, t, J=7.1 Hz), 2.63 (2H, t, J=7.1 Hz), 2.96 (2H, t, J=7.2 Hz), 4.14 (2H, q, J=7.1 Hz), 7.17—7.34 (5H, m); MS (EI) *m/z* (rel intensity) 178 (M$^+$; 36), 133 (13), 107 (42), 104 (100), 91 (52), 77 (11). Found: C, 74.19; H, 8.09%. Calcd for C$_{11}$H$_{14}$O$_2$: C, 74.13; H, 7.92%.

***p*-Chlorobenzylamine:** ^{1}H NMR (200 MHz, CDCl$_3$) δ=2.53 (2H, s), 3.84 (2H, s), 7.21—7.37 (4H, m); MS (EI) *m/z* (rel intensity) 143 (6), 142 (42), 141 (M$^+$; 20), 140 (55), 106 (100), 105 (21), 104 (14), 89 (5). Found: C, 59.01; H, 5.73; N, 9.97%. Calcd for C$_7$H$_8$NCl: C, 59.38; H, 5.69; N, 9.89%.

***p*-Bromoaniline:** ^{1}H NMR (200 MHz, CDCl$_3$) δ=3.63—3.66

(2H, m), 6.56—6.59 (2H, m), 7.21—7.26 (2H, m); MS (EI) *m/z* (rel intensity) 173 (82), 171 (M^+; 86), 92 (59), 87 (11), 86 (11), 66 (10), 65 (100), 63 (22). Found: C, 41.78; H, 3.61; N, 8.01%. Calcd for C_6H_6NBr: C, 41.89; H, 3.52; N, 8.14%.

***p*-Chloroaniline:** ^{1}H NMR (200 MHz, $CDCl_3$) δ=3.59—3.61 (2H, m), 6.59—6.64 (2H, m), 7.08—7.12 (2H, m); MS (EI) *m/z* (rel intensity) 129 (31), 127 (M^+; 100), 100 (10), 92 (13), 65 (20). Found: C, 56.61; H, 4.66; N, 10.79%. Calcd for C_6H_6NCl: C, 56.49; H, 4.74; N, 10.98%.

***N*,*N*-Dimethylaniline:** ^{1}H NMR (200 MHz, $CDCl_3$) δ=2.96 (9H, s), 6.67—6.79 (3H, m), 7.22—7.30 (2H, m); MS (EI) *m/z* (rel intensity) 121 (M^+; 79), 120 (100), 105 (11), 104 (12), 91 (2), 77 (7), 51 (4). Found: C, 79.02; H, 9.19; N, 11.47%. Calcd for $C_8H_{11}N$: C, 79.29; H, 9.15; N, 11.56%.

(C) Competitive Reduction: Competitive reduction of ethyl crotonate and 1-decene is described as a representative. BER (0.97 g, 3.0 mmol) was added to a methanol solution (10 mL) of $CuSO_4\cdot 5H_2O$ (0.018 g, 0.07 mmol), and the mixture was stirred slowly at room temperature. After 1 min, one mmol each of ethyl crotonate, 1-decene, and mesitylene (internal standard) in methanol (2 mL) was added. After the reaction mixture was stirred for 30 min at room temperature, the GLPC analysis of the mixture on column HP-1 showed 100% of ethyl butylate and 5% of decane. The competitive reduction was repeated using BER–Ni_2B. BER (1.62 g, 5.0 mmol) was added to a methanol solution (10 mL) of $Ni(OAc)_2\cdot 4H_2O$ (0.025 g, 0.1 mmol), and the mixture was stirred slowly at room temperature. The yellowish BER particles immediately turned black, and slow hydrogen evolution due to the decomposition of BER particles immediately turned black, and slow hydrogen evolution due to the decomposition of BER was observed. After 1 min, one mmol each of ethyl crotonate, 1-decene, and mesitylene (internal standard) in methanol (2 mL) was added. After the reaction mixture was stirred for 30 min at room temperature, the GLPC analysis of the mixture showed 100% of ethyl butylate and 99% of decane.

(D) Selective Reduction of *p*-Bromochlorobenzene: BER (1.62 g, 5.0 mmol) was added to a methanol solution (10 mL) of $CuSO_4\cdot 5H_2O$ (0.125 g, 0.5 mmol), and the mixture was stirred slowly at room temperature. After 1 min, one mmol each of *p*-bromochlorobenzene and mesitylene (internal standard) in methanol (2 mL) was added. After the reaction mixture was stirred for 1 h at 65 °C, the GLPC analysis of the mixture on column HP-1 showed 99% of chlorobenzene. The same selective reduction was repeated using BER (5 mmol) and $Ni(OAc)_2\cdot 4H_2O$ (0.1 mmol). After 3 h at room temperature, the GLPC analysis of the mixture showed 56% of chlorobenzene, 19% of benzene, and 25% of *p*-bromochlorobenzene.

(E) Reduction of Styrene Oxide: BER (1.62 g, 5.0 mmol) was added to a methanol solution (10 mL) of $CuSO_4\cdot 5H_2O$ (0.025 g, 0.1 mmol), and the mixture was stirred slowly at room temperature. After 1 min, one mmol each of styrene oxide and mesitylene (internal standard) in methanol (2 mL) was added. After the reaction mixture was stirred for 1 h at room temperature, the GLPC analysis of the mixture on column HP-1 showed 98% of ethylbenzene. This reduction was repeated using BER (5 mmol) and $Ni(OAc)_2\cdot 4H_2O$ (0.1 mmol). After 1 h at room temperature, the GLPC analysis of the mixture showed 89% of phenethyl alcohol and 11% of ethylbenzene.

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