Aminoborohydrides as Reducing Agents. 1. Sodium (Dimethylamino)- and (*tert*-Butylamino)borohydrides as Selective Reducing Agents[1a]

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Replacement of a hydride in borohydride by an electron-donating alkylamino group greatly enhances the reducing ability of the resulting reagents. Thus, sodium (dimethylamino)- and (*tert*-butylamino)borohydrides (1, NaDMAB, and 2, NaTBAB, respectively) not only reduce aldehydes and ketones to alcohols but also are effective for the conversion of esters to alcohols and primary amides to amines in good to excellent yields. Tertiary amides are reduced to alcohols (i.e., *N,N*-dimethylamides) or amines (i.e. *N,N*-diisopropylamides) depending on the steric bulk of the alkyl substituents on nitrogen. However, secondary amides are not reduced by the reagents allowing selective conversion of primary and tertiary amides in the presence of secondary amides. Nitriles are attacked by the reagents but do not afford synthetically useful amounts of amine products. Aryl halides are slowly converted to arenes, but alkyl halides and epoxides undergo unusual reactions with the amino portion of the reagents.

Introduction

The substitution of one or more of the hydrides on borohydride with other substituents to either increase (electron-supplying groups, i.e., alkyl,[2a] alkoxy[2b]) or temper (withdrawing groups, i.e., CN,[2c] O_2CR[2d]) the hydride delivering ability has attracted considerable interest over the years, and this has supplied a wide range of boron hydride choices.[3] One heteroatom-substituted class that has essentially escaped attention is (alkylamino)borohydrides although such derivatives offer potentially useful characteristics. Thus, nitrogen is less electronegative than oxygen (3.07 vs. 3.50)[4] and concomitantly better able to donate the lone electron pair toward boron. This combination suggests that aminoborohydrides should demonstrate considerable enhancement of hydride delivering ability compared to either borohydride or alkoxy derivatives.[5] Furthermore, alkylamine groups may be introduced sequentially so that the corresponding mono-, di-, and triaminoborohydrides are conceptually available with wide structural variances. This paper reports investigations with two simple (alkylamino)borohydrides, sodium (dimethylamino)- and (*tert*-butylamino)borohydride (1, NaDMAB- and 2, NaTBAB, respectively), and demonstrates that the introduction of only one alkylamine group substantially enhances the reducing capabilities and, in addition, allows certain unique selective reductions to be obtained.

Results and Discussion

Reagents. The sodium derivatives 1[6] and 2 are readily prepared from the corresponding commercial amine–boranes by treatment with NaH in dry THF (eq 1) followed

$$RR_1NHBH_3 \xrightarrow{\text{NaH, THF}} (RR_1NBH_3)^-Na^+ \quad (1)$$

1, R = R_1 = CH_3

2 R = t-C_4H_9, R_1 = H

by filtration or centrifugation under argon to remove excess NaH. The reagents are stable under anhydrous conditions in aprotic solvents but are very moisture sensitive and thus are best stored and utilized in THF by using syringe techniques. The hydride content of such solutions may be monitored via a standard hydrolysis procedure,[7] and very little hydride loss occurs over several months. Since amine–boranes are available from virtually any aliphatic and many aromatic primary or secondary amines, a wide variety of structural and electronic features may be incorporated into derivatives analogous to 1 and 2.

The general reaction conditions for reductions with 1 and 2 were usually straightforward and standard (Experimental Section). Reaction solutions were 0.1 M (THF) in the substrate, and the hydride concentration was adjusted by syringe addition of standarized solutions of the hydride (THF) to values displayed in the later sections and tables. Progress of the reactions was monitored by GC or TLC to completion. Successful product isolations were found to require prior acid hydrolysis (experimental) to eliminate contamination by boron-containing side products. Results for various functional groups are categorized separately below.

Reduction of Aldehydes and Ketones. As expected, aliphatic and aromatic aldehydes and ketones are readily reduced by 1 at room temperature to afford high yields of alcohols (Table I). Experimentation demonstrated that although all three hydrides are available for reduction (entry 5), higher hydride concentrations (1–4 M excess) provided higher yields in short reaction times. The stereoselectivity exhibited with cyclic ketones (entries 9–11) was similar to other unhindered hydride reagents[3b,8] giving

(1) (a) Presented at the 186th National Meeting of the American Chemical Society, Washington, D.C., Sept 1983; American Chemical Society: Washington, DC. 1983; OGN No. 273. (b) Visiting Associate Professor of Organic Chemistry on leave from Cairo University, 1982–1984.

(2) (a) Brown, H. C.; Krishnamurthy, S. *J. Am. Chem. Soc.* **1973**, *95*, 1669. Krishnamurthy, S.; Schubert, R. M.; Brown, H. C. *Ibid.* **1973**, *95*, 8486. Brown, H. C.; Kim, S. C.; Krishnamurthy, S. *J. Org. Chem.* **1980**, *45*, 1. (b) Brown, H. C.; Mead, E. J. *J. Am. Chem. Soc.* **1953**, *75*, 6263. Bell, R. A.; Gravestock, M. B. *Can. J. Chem.* **1969**, *47*, 2099. (c) Hutchins, R. O.; Natale, N. R. *Org. Prep. Proced. Int.* **1979**, *11*, 201. (d) Gribble, G. W.; Lord, P. D.; Skotnicki, J.; Dietz, W. E.; Eaton, J. T.; Johnson, J. L. *J. Am. Chem. Soc.* **1974**, *96*, 7812. Nutaitis, C. F.; Gribble, G. W. *Tetrahedron Lett.* **1983**, *24*, 4287.

(3) For reviews of reducing capabilities of various reagents see: (a) Walker, E. R. H. *Chem. Soc. Rev.* **1976**, *5*, 23. (b) Hajos, A. "Complex Hydrides"; Elsevier: New York, 1979.

(4) Allred, A. L.; Rochow, E. G. *J. Inorg. Nucl. Chem.* **1958**, *5*, 264.

(5) Aminoboranes are weaker Lewis acids than borane or alkoxyboranes; see, for example: Davis, F. A.; Turchi, I. J.; Greeley, D. N. *J. Org. Chem.* **1971**, *36*, 1300. Therefore, the corresponding aminoborohydrides should be better hydride transferring agents. This was qualitatively observed several years ago by Callery Chemical Co., but not fully exploited; see the bulletin, "Amine Boranes" published by Callery Chemical Co., 1977.

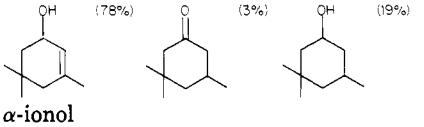
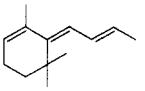
(6) Reagent 1 is also commercially available as a solution in THF from Callery Chemical Co. whom we thank for an initial gift of the reagent.

(7) Brown, H. C. "Organic Synthesis Via Boranes"; Wiley-Interscience: New York, 1975; Chapter 9.

(8) For excellent review concerning the factors controlling the stereochemistry of ketone reductions see ref 3b, chapter 12 and: Boone, J. R.; Ashby, E. C. *Top. Stereochem.* **1979**, *11*, 53. Wigfield, D. C. *Tetrahedron* **1979**, *35*, 449.

0022-3263/84/1949-2438$01.50/0

Table I. Reduction of Aldehydes and Ketones with NaDMAB in Tetrahydrofuran at Room Temperature

entry	carbonyl	molar ratio NaDMAB/carbonyl	time, h	product(s)	% yield[a] (GC)
1	benzaldehyde	1.0	0.5	benzyl alcohol	90
2	benzaldehyde	4.0	0.25	benzyl alcohol	(90)
3	2-undecanone	1.0	1.0	2-undecanol	86
4	2-undecanone	4.0	1.0	2-undecanol	(99)
5	acetophenone	0.34	11.5	1-phenylethanol	80
6	acetophenone	3.0	2.5	1-phenylethanol	89
7	benzophenone	1.0	2.0	benzhydrol (99%), diphenylmethane (1%)	89
8	benzophenone	3.0	2.5	benzhydrol	99
9	4-*tert*-butylcyclohexanone	1.0	5.0	4-*tert*-butylcyclohexanol (cis:trans = 7:93)	82
10	3,3,5-trimethylcyclohexanone	2.0	11.0	3,3,5-trimethylcyclohexanol (cis:trans = 33:67)	88
11	camphor	1.0	1.5	borneol (9%), isoborneol (91%)	88
12	isophorone	1.4	15[c]		26[d]
13	α-ionone	1.0	5	α-ionol	93
14	β-ionone	2.0	2	 (84)[d]	84

[a] Isolated, purified yields unless indicated otherwise. [b] Reaction conducted at reflux temperature. [c] 45% starting material recovered. [d] The remaining 16% composed of six minor unidentified products.

Table II. Reduction of Esters with 1 and 2 in Tetrahydrofuran

entry	ester	reagent (molar ratio hydride/substrate)	conditns h (°C)	product(s) (rel yields)	% yield
1	ethyl decanoate	**1** (0.68)	14 (25)	decanol	63
2	ethyl decanoate	**1** (1.0)	13 (25)	decanol	71
3	ethyl decanoate	**2** (1.4)	24 (25)	decanol	88
4	ethyl decanoate	**1** (1.4)	1 (66)	decanol	77
5	methyl stearate	**1** (1.2)	15 (25)	octadecanol	73
6	methyl stearate	**2** (1.0)	20 (25)	octadecanol	90
7	methyl benzoate	**1** (1.2)	15 (25)	benzyl alcohol	71
8	methyl benzoate	**1** (1.4)	2.5 (66)	benzyl alcohol	(82)
9	benzyl benzoate	**1** (1.2)	12 (25)	benzyl alcohol	71[b]
10	benzyl benzoate	**2** (1.2)	24 (25)	benzyl alcohol	86[b]
11	methyl cinnamate	**1** (1.4)	12 (25)	cinnamyl alcohol (86%), 3-phenylpropanol (14%)	45
12	methyl cinnamate	**2** (1.4)	48 (25)	cinnamyl alcohol (63%), 3-phenylpropanol (37%)	48
13	coumarin	**1** (3.0)	48 (66)		*c*
14	dihydrocoumarin	**2** (3.0)	64 (66)	3-(*o*-hydroxyphenyl)-1-propanol	31

[a] Isolated, purified yields except entry 8 which was determined by GC. [b] The total yield divided by 2. [c] No products isolated; a gelatinous material observed prior to workup.

primarily *trans*-4-*tert*-butylcyclohexanol (93%, entry 9), *trans*-3,3,3,5-trimethylcyclohexanol (67%, entry 10), and isoborneol (91%, entry 11) from the corresponding ketones. Limitations and problems arose with α,β-unsaturated ketones. Thus, with isophorone (entry 12), the product isophorol was contaminated with saturated alcohol and ketone resulting from conjugate hydride attack, a problem often encountered with borohydride-type reagents.[9] Furthermore, the low yield (26%) and recovered starting material (45%) suggested that **1** behaves as a base, generating an enolate anion that resists reduction. A second problem involved the doubly conjugated β-ionone (entry 14) that afforded mostly a triene and no β-ionol. This evidently arises from elimination induced by acid hydrolysis necessary for product isolation, and, in fact, β-ionol was dehydrated by exposure to the workup procedure.

Thus, although successful in most cases, the reduction of aldehydes and ketones with **1** does not offer any advantages over more conventional reagents. Our continued interest in such conversions stems from the possibility of asymmetric reductions by incorporating chiral amines into the reagents, an area we are currently exploring.

Reduction of Esters. Unlike the usual situation with sodium borohydride,[3,10] aliphatic and aromatic esters are reduced by **1** and **2** in THF to primary alcohols in moderate to high yields (Table II). Although conversions were successful with stoichiometric quantities of reagent at room temperature (entry 1), best results in short reaction times (1–2.5 h) were obtained with 1–1.4 M excesses of reagent at 66 °C (entries 2–10). With α,β-unsaturated esters and

(9) For a discussion regarding the misconceptions of conjugate additions by borohydride see: Meyer, G. R. *J. Chem. Educ.* **1981**, *58*, 628 and references cited therein.

(10) Esters are reduced by $NaBH_4$ in many cases by prolonged reaction times, large reagent excesses or special structural features; see: Todd, D. *Synthesis* **1979**, *56*, 540 and references cited therein.

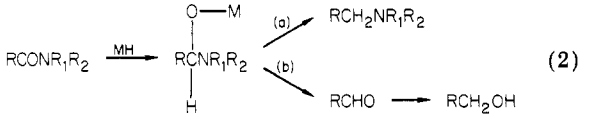
Table III. Reduction of Amides with 1 and 2[a]

entry	amide	reagent (molar ratio hydride/substrate)	conditns,[b] h (°C)	product(s) (rel yields)	% yield[c] (% st mat. recovered)
1	benzamide	1 (4.0)	7 (66)	benzylamine	77[d]
2	benzamide	2 (5.0)	96 (66)	benzylamine	21
3	decanamide	1 (4.0)	16 (66)	decylamine	46 (3)
4	decanamide	2 (5.0)	120 (66)	decylamine	46
5	acetanilide	1 (3.0)	44 (66)	*N*-ethylaniline	1 (98)
6	*N*-phenylbenzamide	1 (3.0)	70 (101)[e]	*N*-phenylbenzylamine	3 (91)
7	*N*-pentyldecanamide	1 (3.0)	50 (66)		0 (97)
8	*N,N*-dimethylbenzamide	1 (1.0)	45 (25)	benzyl alcohol (99%), *N,N*-dimethylbenzylamine (1%)	98
9	*N,N*-dimethylbenzamide	2 (3.0)	96 (66)	benzyl alcohol (99%), *N,N*-dimethylbenzylamine (1%)	91
10	*N,N*-dimethylbenzamide	1 (1.0)	5 (66)	benzyl alcohol, *N,N*-dimethylbenzylamine (tr)	99
11	*N,N*-diethylbenzamide	1 (1.0)	7 (66)	benzyl alcohol (80%), *N,N*-diethylbenzylamine (20%)	89
12	*N,N*-diethylbenzamide	2 (3.0)	64 (66)	benzyl alcohol (52%), *N,N*-diethylbenzylamine (48%)	94
13	2,6-dichloro-*N,N*-diethylbenzamide	1 (3.0)	69 (101)[e]	2,6-dichloro-*N,N*-diethylbenzylamine (60%), 2-chloro-*N,N*-diethylbenzylamine (27%), *N,N*-diethylbenzylamine (13%)	37
14	*N,N*-dimethyldecanamide	1 (1.0)	55 (66)	1-decanol (98%), *N,N*-dimethyldecylamine (2%)	88
15	*N,N*-diethyldecanamide	1 (1.0)	25 (66)	1-decanol (26%), *N,N*-diethyldecylamine (74%)	91
16	*N,N*-diethyldecanamide	2 (1.0)	96 (66)	1-decanol (49%), *N,N*-diethyldecylamine (51%)	94
17	*N,N*-diisopropyldecanamide	1 (2.0)	67 (101)[e]	1-decanol (5%), *N,N*-diisopropyldecylamine (95%)	97 (2)
18	*N,N*-dimethyldodecanamide	1 (1.0)	44.5 (25)	1-dodecanol (99%), *N,N*-dimethyldodecylamine (1%)	86 (1)
19	*N,N*-dimethyldodecanamide	1 (1.0)	5.5 (66)	1-dodecanol (98%), *N,N*-dimethyldodecylamine (2%)	94
20	*N,N*-diethyldodecanamide	1 (1.0)	36 (66)	1-dodecanol (27%), *N,N*-diethyldodecylamine (73%)	91
21	*N,N*-diethyldodecanamide	2 (1.0)	96 (66)	1-dodecanol (34%), *N,N*-diethyldodecylamine (66%)	85
22	*N,N*-dimethylcyclohexanecarboxamide	1 (1.0)	6 (66)	cyclohexylmethanol (99%), (dimethylamino)cyclohexylmethane (1%)	96
23	*N,N*-dimethylcyclohexanecarboxamide	2 (1.0)	65 (66)	cyclohexylmethanol (94%), (dimethylamino)cyclohexylmethane (6%)	62
24	*N,N*-diethylcyclohexanecarboxamide	1 (1.0)	24 (66)	cyclohexylmethanol (15%), (diethylamino)cyclohexylmethane (85%)	90
25	*N,N*-diethylcyclohexanecarboxamide	2 (1.0)	65 (66)	cyclohexylmethanol (42%), (diethylamino)cyclohexylmethane (58%)	81

[a] Reactions were 0.1 M in the amide. Workup involved addition of 2 mL of concentrated HCl, stirring 2 h, neutralization with base, and extraction with ether. Product ratios were determined by GC and corrected for detector response. [b] In THF unless specified otherwise. [c] Isolated, purified yields. [d] Yield by GC. [e] 1,4-Dioxane solvent. [f] No trace of alcohol by GC, IR, or NMR.

lactones (entries 11–14), although starting materials were consumed, the yields of allylic alcohol products were disappointingly low (0–48%) and contaminated with the saturated derivatives (entries 11 and 12). Presumably, the low yields reflect a combination of low rates of carbonyl attack coupled with competing conjugate addition of hydride to generate enolate anions that susequently undergo Claisen-type condensations. In fact, the only material recovered from the reduction of coumarin (entry 13) was a gelatineous mixture from which some starting material, but no alcohol products could be isolated. Such enolate condensations have also been noted with α,β-unsaturated systems using borohydride[11a] and trialkylborohydrides.[11b]

Reduction of Amides. The reduction of amides may proceed by two pathways (eq 2) to afford either amines by reductive removal of the carbonyl (path a) or alcohols via expulsion of the amine and reduction of the resulting exposed aldehyde (path b), and both choices have been observed with various reducing systems.[3]



(2)

With 1 and 2, the reactivity and course of reduction is greatly dependent on the type of amide and, apparently, on the steric bulk of N substituents. Results for a variety of primary, secondary, and tertiary amide examples are presented in Table III. Primary amides were reduced sluggishly to afford only moderate isolated yields of primary amines, but no alcohols (entries 1, 2). Surprisingly, secondary amides were quite resistant to reduction in refluxing THF or 1,4-dioxane even with extended reaction times (entries 5–7). In contrast, tetiary amides provided good to excellent yields of either alcohols or amines. The reduction course chosen appeared to depend critically on

(11) (a) Schechter, H.; Ley, D. E.; Roberson, E. B., Jr. *J. Am. Chem. Soc.* **1956**, *78*, 4984. (b) Fortunato, J.; Ganem, B. *J. Org. Chem.* **1976**, *41*, 2194.

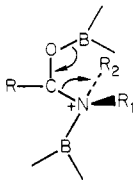
Table IV. Competitive Reduction of Amides by 1 in THF[a]

entry	amides (mmol)	mmol of 1	conditns, h (°C)	% amides remaining
1	*N,N*-diethylbenzamide (3.0) + *N,N*-diethyldodecanamide (3.0)	2.0	46 (25)	*N,N*-diethylbenzamide (36) *N,N*-diethyldodecanamide (89)
2	*N,N*-dimethyldodecanamide (3.0) + *N,N*-diethyldodecanamide (3.0)	2.0	46 (25)	*N,N*-dimethyldodecanamide (27) *N,N*-diethyldodecanamide (98)
3	acetanilide (5.0) + *N,N*-dimethyldecanamide (5.0)	20.0	16 (66)	acetanilide (86)[b] *N,N*-dimethyldecanamide (0)[c]

[a] Reactions were worked up by stirring with 2.5 mL of concentrated HCl for 1 h, followed by neutralization with base and extraction with ether. Amides remaining determined by GC and corrected for detector response. [b] Less than 1% ethylaniline and no trace of aniline detected by GC. [c] Decanol (91%) and *N,N*-dimethyldecanamine (1%) detected by GC.

the N substituents. Thus, *N,N*-dimethylamides (entries 8–10, 14, 18, 19, 22, 23) consistently afforded high predominances of the corresponding alcohols (94–99%) along with meager amounts of amines (1–6%). However, as the size of the N groups was increased, the amounts of alcohols produced fell with a concomitant rise in amine yields. Thus, for *N,N*-dimethyl-, *N,N*-diethyl-, and *N,N*-diisopropyldecanamides (entries 14–17), the relative yields of 1-decanol were 98%, 26–49%, and 5%, respectively, while the corresponding amounts of substituted decylamines produced rose from 2% for *N,N*-dimethyl to 95% for *N,N*-diisopropyl. Increasing the congestion of the carbonyl group also appears to enhance amine formation. For instance, *N,N*-diethyl-2,6-dichlorobenzamide gave amines exclusively (entry 13) while *N,N*-diethylbenzamide afforded predominately benzyl alcohol (entry 11). In addition, from Table III, the relative order of reductive reactivity appears to be *N,N*-dimethyl > *N,N*-diethyl > *N,N*-diisopropyl > primary amides > secondary amides. This suggested that selective conversions of one type of amide in the presence of others might be feasible. Table IV lists results from competition studies for three pairs of examples and illustrates that substantial selectivity is possible especially for the reduction of tertiary amides in the presence of secondary (entry 3) and *N,N*-dimethyl derivatives in the presence of *N,N*-diethylamides (entry 1). Since *N,N*-diisopropylamide reduction required extended times even in refluxing dioxane (100 °C, entry 17, Table III), other tertiary amides certainly may be reduced preferentially without damage to *N,N*-diisopropyl examples.

The mechanism of tertiary amide reductions presumably involves an initial nucleophilic attack by hydride at the carbonyl followed by either displacement by a second hydride to give an amine or carbon–nitrogen bond cleavage releasing an aldehyde that is subsequently reduced to an alcohol (eq 2). Apparently, this second cleavage reaction (path b) may require, or at least be enhanced by, complexation with a boron species (i.e. 3) to augment the leaving ability of the amine. As the N substituents become larger, such complexation evidently is resisted and hydride substitution (path a) favorably competes to afford the amine.



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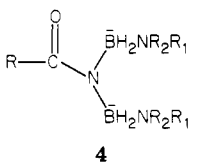

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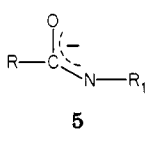

5

The acidic hydrogens of primary amides appear to react initially with 1 or 2 to generate an intermediate (i.e., 4) which slowly reacts further to reductively remove the carbonyl. In support of this, treatment of benzamide with 1 rapidly produces a white gelatinous precipitate that, if hydrolyzed with HCl, returns starting material. Such intermediates (4) have been implicated in reductions of primary amides with other hydride reagents.[12]

The reason for the inertness of secondary amides toward reduction is not obvious. Perhaps delocalization of the anion derived from removal of the acidic nitrogen proton (i.e., 5) prevents both attack at the carbonyl and the formation of a stable complex by a boron species with nitrogen so that both paths a and b are disfavored.

Reductions of Other Functional Groups. The reduction of a number of other functional groups was probed including aryl and alkyl halides, epoxide, nitrile, nitro, and sulfoxide, and the results are tabulated in Table V. As evident, although reduction of some of these groups occurred, none appear to be synthetically useful. Thus, while aryl iodides and bromides (entries 1–3) were dehalogenated, the yields were mediocre and inferior to results with other reagents. Curiously, with both alkyl iodides and epoxides (entries 5 and 7), the products received in good yields resulted from attack by the amine portion of the aminoborohydride rather than the hydride, indicating that the nitrogen retains considerable nucleophilicity. Phenylmethanenitrile afforded a deep red solution upon treatment with 1 but only starting material was returned upon hydrolysis. Evidently, α-proton abstraction competes and shuts down attack at the nitrile carbon. Benzonitrile (entry 9), which is devoid of α-hydrogens, was attacked and afforded a mixture of amine products in which benzylamine predominated (70%) but was contaminated (30%) by products resulting from condensation of benzylamine with imine intermediates. Reduction of nitrobenzene and benzyl phenyl sulfoxide gave complex mixtures that were not thoroughly investigated.

Summary and Conclusions. The aminoborohydrides 1 and 2 are effective reagents for the reductions of aldehydes, ketones, esters, and primary and tertiary, but not secondary, amides. The great rate differences exhibited by different amide types allows selective reductions between various types of these latter derivatives. Exploration continues with other aminoborohydrides including di- and triamino derivatives.

(12) Brown, H. C.; Narasimhan, S.; Choi, Y. Synthesis 1981, 441. Brown, H. C.; Narasimhan, S.; Choi, Y. *Ibid.* 1981, 996.

Table V. Reduction of Other Functional Groups with 1[a]

entry	compd	molar ratio 1/compd	solv	conditns, h (°C)	product(s) (rel yields)	% yield[b] (% st mat. remaining)
1	1-iodonaphthalene	2.0	dioxane	12 (101)	naphthalene	66
2	1-bromonaphthalene	2.0	dioxane	40 (101)	naphthalene	53 (2)
3	4-bromobiphenyl	2.0	dioxane	70 (101)	biphenyl	48 (1)
4	1-chloronaphthalene	2.0	dioxane	44 (101)	naphthalene	10 (83)
5	1-iodododecane	2.0	THF	26 (25)	*N,N*-dimethyldodecylamine	79
6	1,2-dodecene epoxide	1.0	THF	70 (25)	2-hydroxy-*N,N*-dimethyldecanamine	87[c]
7	phenylmethane nitrile	4.0	THF	19 (66)	2-phenylethylamine	0
8	benzonitrile	1.0	THF	24 (66)	benzylamine (70%), dibenzylamine (5%), 1,2-diamino-1,2-diphenylethane (25%)	46
9	nitrobenzene	1.0	THF	15 (66)	aniline (24%), azobenzene (44%)	(11)[d]
10	benzyl phenyl sulfoxide	1.0	THF	2 (66)	thiophenol, benzyl mercaptan, benzyl phenyl sulfide, and several others	*e*

[a] Reactions were 0.1 M in the compound. Worked up by stirring with 2–4 mL of concentrated HCl for 2–4 h, neutralized with base, and extracted with ether. Product ratios determined by GC and corrected for detector response. [b] Isolated. [c] A trace of 2-decanol detected by GC. [d] Mixture contained an unidentified component (ca. 21%). Ratio of products are approximate. [e] Yields and ratios not determined.

Experimental Section

Melting and boiling points are uncorrected. Infrared spectra were recorded on either a Perkin-Elmer Model 700 or a Perkin-Elmer Model 457 grating IR spectrophotometer. Proton magnetic resonance spectra were obtained on a Varian A-60A spectrometer employing Me_4Si as an internal reference. GC data were obtained on a Varian Model 3700 gas chromatograph coupled to either a Columbia Scientific Industries Model 38 or a Varian CDS 111 digital integrator. All GC analyses utilized either 10% carbowax 20M (column A) or SP 2250 (column B) packings. GC yields were determined by using internal standards and detector response factors. Elemental analyses were performed by Micro-Analysis Inc., Wilmington, DE.

All starting materials were commercial samples, purified by flash distillation or recrystallization prior to use, or synthesized via standard techniques. Dimethyl- and *tert*-butylamine–boranes were used as obtained commercially. THF was dried and purified by distillation from sodium/benzophenone.

Preparation of Reagents. Sodium (Dimethylamino)trihydroborate (1). All work was performed in a glovebox under dry argon. To NaH (24.0 g of 50%, 0.50 mol), which was washed and decanted three times with dry THF to remove the oil, in 100 mL of dry THF was added dropwise with stirring over 30 min dimethylamine–borane (23.6 g, 0.40 mol) in 200 mL of dry THF. The mixture was stirred for 1 h, diluted to 400 mL by the addition of dry THF, and filtered through a coarse sintered glass funnel. The clear solution was stored under argon and transferred via syringe techniques. Hydrogen evolution via hydrolysis was used to monitor the concentration of reagent prior to use: IR (THF) 2750 (s, CH_3), 2160 cm^{-1} (vs. BH); ^{11}B NMR (THF) 43.02 ppm (br s, BF_3 standard).

In an alterantive procedure, the final solution containing excess NaH was transfered to septum-sealed tubes and centrifuged and the reagent solution utilized via transfer from the tubes with syringes. This procedure was also employed for the preparation of **2** from *tert*-butylamine borane.

Reduction of Aldehydes and Ketones. The general procedure is presented for the reduction of benzaldehyde. For other examples, the ratios of reactant to **1** or **2**, reaction times, and temperatures are given in Table I.

A solution containing benzaldehyde (0.531 g, 5.0 mmol) and **1** (4.0 mL of a 1.24 M solution, 5.0 mmol) in 50 mL of dry THF was stirred at room temperature under Ar for 30 min, concentrated HCl (4 mL) added dropwise, and stirring continued for an additional hour. The solution was diluted with an equal volume of brine and extracted with three 50-mL portions of ether that was washed with saturated $NaHCO_3$, dried ($MgSO_4$), concentrated, and flash distilled to yield 0.485 g (90%) of benzyl alcohol that was homogeneous by GC (column B).

A similar reaction employing benzaldehyde (208 mg, 2 mmol), **1** (8 mL of a 1.0 M solution, 8 mmol), and undecane as an internal standard (312 mg, 2 mmol) in 12 mL of dry THF was stirred for 15 min at room temperature under Ar. Dilute HCl (15%, 10 mL) was added and the solution stirred for 4 h. An aliquot was removed, basified with 50% NaOH, and extracted with ether. Analysis of the ether extract by GC employing an authentic sample for sample for identification and corrected for detector response indicated a 90% yield of benzyl alcohol.

Reduction of Esters. The general procedure is illustrated for the reduction of ethyl decanoate. Ratios of reactant to **1** or **2**, reaction times, and temperatures are presented in Table II. A solution of ethyl decanoate (1.00 g, 5 mmol) and **1** (3.4 mL of a 1.0 M solution, 3.4 mmol) in 50 mL of dry THF was stirred at roo temperature under Ar, during which time aliquots were monitored by GC. After 14 h, 30 mL of 15% HCl was added dropwise and the solution stirred for an additional 4 h. The solution was diluted with an equal volume of brine and extracted three times with ether. The ether extract was washed with saturated $NaHCO_3$, dried ($MgSO_4$), concentrated, and flash distilled to yield 497 mg (63%) of *n*-decanol which was homogeneous by GC (column B).

Reduction of Amides. The general procedure is illustrated for the reduction of *N,N*-dimethylbenzamide. Ratios of reactants to **1** or **2**, reaction times, and temperatures are given in Table III. To a solution of *N,N*-dimethylbenzamide (746 mg, 5 mmol) in 50 mL of dry THF was added by syringe reagent **1** (5 mL of a 1.0 M solution, 5 mmol). The solution was stirred at room temperature under Ar for 45 h, 4 mL of concentrated HCl was added, and stirring was continued for 1.5 h. The solution was basified with 50% NaOH, diluted with an equal volume of brine, and extracted with three 50-mL portions of ether, and the ether was washed with $NaHCO_3$, dried ($MgSO_4$), concentrated, and distilled at reduced pressure (Kugelrohr apparatus) to yield 531 mg (98%) of a clear liquid, the composition of which was determined to be benzyl alcohol (99%) and *N,N*-dimethylbenzylamine (1%) by GC (column A).

Reduction of Amides: Competition Experiments. The general procedure is presented for the reduction of acetanilide and *N,N*-dimethyldecanamide. Ratios of reagents and reaction conditions for other competition experiments are given in Table IV. To a solution of acetanilide (676 mg, 5 mmol), *N,N*-dimethyldecanamide (997 mg, 5 mmol), and pentadecane (internal standard, 1.062 g, 5 mmol) in 50 mL of dry THF was added **1** (20 mL of a 1.0 M solution, 20 mol). The solution was refluxed under Ar for 16 h, 4 mL of concentrated HCl II was added, and the solution was stirred at room temperature for 3 h. The reaction was made basic with 10% NaOH, an aliquot was removed and analyzed by GC (column A), and and the results were corrected for detector response. Analysis revealed the presence of 86% acetanilide and 0% *N,N*-dimethyldodecanamide.

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Registry No. 1, 20596-52-5; 2, 90150-03-1; dimethylamine–borane, 1838-13-7; *tert*-butylamine–borane, 43795-48-8; benzaldehyde, 100-52-7; 2-undecanone, 112-12-9; acetophenone, 98-86-2; benzophenone, 119-61-9; 4-*tert*-butylcyclohexanone, 98-53-3; 3,3,5-trimethylcyclohexanone, 873-94-9; camphor, 76-22-2; isophorone, 78-59-1; α-ionone, 127-41-3; β-ionone, 79-77-6; benzyl alcohol, 100-51-6; 2-undecanol, 1653-30-1; 1-phenylethanol, 98-85-1; benzhydrol, 91-01-0; *trans*-4-*tert*-butylcyclohexanol, 21862-63-5; *cis*-3,3,5-trimethylcyclohexanol, 933-48-2; *trans*-3,3,5-trimethylcyclohexanol, 767-54-4; isoborneol, 124-76-5; isophorol, 470-99-5; α-ionol, 25312-34-9; 6-(2-butenylidene)-1,5,5-trimethylcyclohexene, 55497-53-5; ethyl decanoate, 110-38-3; methyl stearate, 112-61-8; methyl benzoate, 93-58-3; methyl cinnamate, 103-26-4; coumarin, 91-64-5; dihydrocoumarin, 119-84-6; benzyl benzoate, 120-51-4; decanol, 112-30-1; octadecanol, 112-92-5; cinnamyl alcohol, 104-54-1; 3-phenylpropanol, 122-97-4; 3-(*o*-hydroxyphenyl)-1-propanol, 1481-92-1; benzamide, 55-21-0; decanamide, 2319-29-1; acetanilide, 103-84-4; *N*-phenylbenzamide, 93-98-1; *N*-pentyldecanamide, 64891-15-2; *N,N*-dimethylbenzamide, 611-74-5; *N,N*-diethylbenzamide, 1696-17-9; 2,6-dichloro-*N,N*-diethylbenzamide, 10345-78-5; *N,N*-dimethyldecanamide, 14433-76-2; *N,N*-diethyldecanamide, 2602-61-1; *N,N*-diisopropyldecanamide, 57303-36-3; *N,N*-dimethyldodecanamide, 3007-53-2; *N,N*-diethyldodecanamide, 3352-87-2; *N,N*-dimethylcyclohexanecarboxamide, 17566-51-7; *N,N*-diethylcyclohexanecarboxamide, 5461-52-9; benzylamine, 100-46-9; decylamine, 2016-57-1; *N*-ethylaniline, 103-69-5; *N*-phenylbenzylamine, 103-32-2; *N,N*-diethylbenzylamine, 772-54-3; 2,6-dichloro-*N,N*-diethylbenzylamine, 90150-04-2; 2-chloro-*N,N*-diethylbenzylamine, 27958-80-1; *N,N*-diethyldecylamine, 6308-94-7; *N,N*-diisopropyldecylamine, 53137-37-4; *N,N*-diethyldodecylamine, 4271-27-6; cyclohexylmethanol, 100-49-2; (diethylamino)cyclohexylmethane, 90150-05-3; 1-iodonaphthalene, 90-14-2; 1-bromonaphthalene, 90-11-9; 4-bromobiphenyl, 92-66-0; 1-chloronaphthalene, 90-13-1; 1-iododecane, 4292-19-7; 1,2-dodecene epoxide, 2855-19-8; phenylmethanenitrile, 140-29-4; benzonitrile, 100-47-0; nitrobenzene, 98-95-3; benzyl phenyl sulfoxide, 833-82-9; naphthalene, 91-20-3; biphenyl, 92-52-4; *N,N*-dimethyldodecylamine, 112-18-5; 2-hydroxy-*N,N*-dimethyldecanamine, 20542-99-8; 1,2-diamino-1,2-diphenylethane, 5700-60-7; aniline, 62-53-3; azobenzene, 103-33-3; thiophenol, 108-98-5; benzylmercaptan, 100-53-8; benzyl phenyl sulfide, 831-91-4.

Dimethylaluminum Chloride Catalyzed Ene Reactions of Aldehydes. 2.[1] Stereochemistry and Scope

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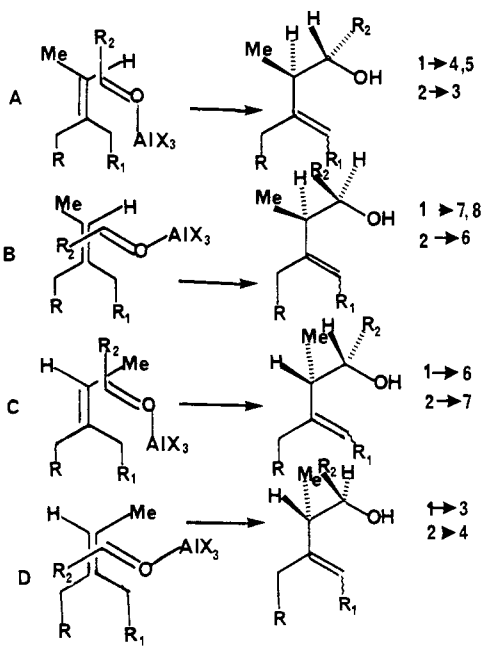
The dimethylaluminum chloride (Me_2AlCl) catalyzed ene reactions of aliphatic aldehydes with (*E*)- and (*Z*)-3-methyl-2-pentene (**1** and **2**) were examined. Complex mixtures of erythro and threo adducts and double-bond position isomers were obtained. Ene reaction of 2-phenylpropionaldehyde with methylenecyclohexane gives a 1.5:1 mixture of diastereomers. Geraniol, linalool, citral, geranylacetone, and 6-methyl-5-hepten-2-one are suitable substrates for Me_2AlCl-catalyzed ene reaction with formaldehyde.

We have recently reported that dimethylaluminum chloride (Me_2AlCl), in equivalent or greater amounts, is a uniquely useful catalyst for the ene reaction of aldehydes with alkenes.[1,3] Proton-initiated rearrangements do not occur since the alcohol–Lewis acid complex produced in the ene reaction reacts rapidly to give methane and a nonacidic aluminum alkoxide.[4] Using the Me_2AlCl as a catalyst, ene adducts can now be obtained in useful yield from aliphatic or aromatic aldehydes and alkenes containing a disubstituted vinylic carbon and from formaldehyde and nonnucleophilic mono- and 1,2-disubstituted alkenes. This extends the scope of Lewis acid catalyzed ene reactions of aldehydes that were previously limited to the reaction of formaldehyde with alkenes containing a disubstituted vinylic carbon and the reactions of reactive electron deficient aldehydes such as chloral or glyoxylate esters.

Uskokovic and Wovkulich have observed a high preference for the transfer of a hydrogen from the alkyl group syn to the vinylic hydrogen in the BF_3-catalyzed ene reaction of formaldehyde with (*E*)- and (*Z*)-ethylidene-2-methylcyclopentane.[5] We have observed similar selectivity

Scheme I



in the Me_2AlCl- and Me_3Al-catalyzed ene reactions of formaldehyde with (*E*)- and (*Z*)-3-methyl-2-pentene.[1] (See Table I.) The preferential abstraction of a hydrogen from the alkyl group syn to the vinylic hydrogen may be due to steric interaction of the Lewis acid, which is exo for steric reasons, with the substituent on the less substituted

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