REVIEWS

Reduction of Organic Compounds by Alkoxyaluminohydrides

J. MÁLEK and M. ČERNÝ

Institute of Chemical Process Fundamentals, Czechoslovak Academy of Sciences, Praha-Suchdol

The introduction of alkoxy groups into lithium aluminohydride, sodium aluminohydride, and aluminum hydride usually results in modification of the steric requirements and thus of the reducing properties of the parent hydrides. The reactions of these alkoxyaluminohydrides with organic compounds are reviewed with special regard to selective reductions of functional groups in the presence of other reducible substituents, to partial reductions of esters, acid halides, amides, and nitriles to aldehydes, to stereospecific reductions of cyclic ketones and steroids and to hydrogenolytic reactions of these alkoxyhydrides in comparison with common metal hydrides.

Die Einführung von Alkoxygruppen in Lithiumalanat, Natriumalanat und Aluminiumhydrid verändert im allgemeinen die Raumerfüllung und somit die Reduktions-Eigenschaften dieser Hydride. In der vorliegenden Übersicht werden die Reaktionen der Alkoxyaluminohydride mit organischen Verbindungen besprochen. Besonders berücksichtigt sind hierbei selektive Reduktionen funktioneller Gruppen in Gegenwart anderer reduzierbarer Gruppen, partielle Reduktionen von Estern, Carbonsäurehalogeniden, Amiden und Nitrilen zu Aldehyden, stereospezifische Reduktionen von cyclischen Ketonen und Steroiden sowie Hydrogenolyse-Reaktionen mit Alkoxyaluminohydriden im Vergleich zu den mit einfachen Metallhydriden durchgeführten Reaktionen.

1. Introduction

Alkali metal aluminohydrides and alkali metal borohydrides display extremely different reactivities when applied as reducing agents. Since their discovery more than 20 years ago, considerable work has been devoted to modify the reducing ability of lithium aluminohydride as well as to increase that of sodium borohydride and to thus fill the gap between the most widely used representatives of these groups of metal hydrides. Whereas the reducing action of sodium borohydride, limited practically to aldehydes, ketones, and acid chlorides, could be greatly increased by the addition of certain metal salts and by the introduction of alkoxy groups into the hydride, modification of the powerful reducing capacity of lithium aluminohydride by the introduction of alkoxy substituents led to a series of lithium alkoxyaluminohydrides with different reactivity and selectivity. A wide variety of alkoxyhydrides with differentiated reactivities has similarly been derived from sodium aluminohydride and aluminohydride.

Of the great number of alkoxyaluminohydrides, especially the methoxy, ethoxy, and *t*-butoxy derivatives of lithium aluminohydride find regular application in synthetic organic chemistry. In many cases, the alkoxy derivatives of aluminohydride and sodium aluminohydride as well as the recently introduced 2-methoxyethoxy derivative of the latter are also utilized with success.

This review deals with the preparation and properties of these alkoxyaluminohydrides with regard to their selectivity and stereospecificity in reduction reactions. For comprehensive reviews including also other metal hydrides see Ref.[1].

2. Preparation of Alkoxyaluminohydrides

2.1. Lithium Alkoxyaluminohydrides

The reagents are conveniently prepared *in situ* by treating standardized solutions of lithium aluminohydride ($LiAlH_4$) in ether, tetrahydrofuran, or diglyme with a definite amount of the corresponding alkoxy compound, such as alcohol, ester, ketone, or phenol[2,3,4]. Of the great number of reagents prepared by this route only the most important are discussed further.

Addition of 3 molar equivalents of methanol to $LiAlH_4$ in tetrahydrofuran or diglyme leads to a stable solution of $LiAlH(OCH_3)_3$ which shows no tendency to disproportionate. Addition of a fourth mole of methanol yields $LiAl(OCH_3)_4$, which is precipitated from the solution. A different course of the methoxyhydride formation was observed in ether, in which addition of 3 equivalents of methanol leads to insoluble $LiAlH(OCH_3)_2$[2,3].

By treating $LiAlH_4$ in ether, tetrahydrofuran, or diglyme with 2 mol of ethanol, nearly pure $LiAlH_2(OC_2H_5)_2$ is formed; the reaction with 3 mol of ethanol affords a product which appears to be largely $LiAlH(OC_2H_5)_3$, accompanied, however, by significant amounts of the diethoxy and tetraethoxy derivatives [for the sake of simplicity, the formulae $LiAlH_2(OC_2H_5)_2$ and $LiAlH(OC_2H_5)_3$ will be used throughout this review for the adducts prepared by addition of 2 or 3 mol of ethanol, respectively, to $LiAlH_4$]. In both cases, ethanol can be replaced by the half amount of ethyl acetate[2-6].

Unlike 2-propanol, the adducts of which with $LiAlH_4$ always disproportionate to the insoluble tetra-*i*-propoxy derivative and to the parent hydride[3,7], *t*-butanol (3 mol) gives with $LiAlH_4$ in tetrahydrofuran as solvent stable solutions of $LiAlH(O—t\text{-}C_4H_9)_3$[2,3,8,9]; according to association measurements, this compound appears to be monomeric over a wide range of concentrations[10].

Sometimes, separate preparation and isolation of this hydride is recommended rather than the formation *in situ*[11]; isolated in pure form, $LiAlH(O—t\text{-}C_4H_9)_3$ can be sublimed under vacuum at 280° without decomposition[3].

Adducts with other hydroxy compounds are also formed. Thus, $LiAlH_4$ reacts with sterically hindered 2,6-di-*t*-butylphenol under evolution of only 2 equivalents of hydrogen; and 9,10-dihydro-9,10-ethano-9-anthrol liberates 3 equivalents of hydrogen and thus resembles *t*-butanol[12]. The complex hydride resulting from the reaction of $LiAlH_4$ with diethylene glycol monoethyl ether can be used for reductions at temperatures up to 200°[13].

Comparison of the I.R. spectra of different lithium alkoxyaluminohydrides

$LiAlH_{4-n}(OR)_n$ R = CH_3, C_2H_5, $t\text{-}C_4H_9$; n = 1-4

shows that monoalkoxyhydrides exhibit interactions of the form Al—O---Al, whereas dialkoxyhydrides show little tendency to form secondary valences. Bands associated with Al—H vibrations are found between 600 and 800 cm^{-1} as well as between 1500–1800 cm^{-1}. The spectra of $LiAl(OR)_4$ are much simpler than those of the less symmetric hydrogen-containing alkoxyaluminohydrides[14]. Comparison of the I.R. spectra of independently prepared $LiAlH(O—t\text{-}C_4H_9)_3$ (Al—H stretching band at 1760 cm^{-1} and no shoulder or weak band at 1860 cm^{-1}) and $AlH(O—t\text{-}C_4H_9)_2$ (Al—H stretching band at 1860 cm^{-1}) indicates that the equilibrium concentration of the latter hydride in the tetrahydrofuran solutions of the former is less than 1%[10]. This result contrasts with the earlier assumption that in solutions of $LiAlH(O—t\text{-}C_4H_9)_3$ an equilibrium exists according to Scheme A and that $AlH(O—t\text{-}C_4H_9)_2$ is thus the actual reducing species in reductions with $LiAlH(O—t\text{-}C_4H_9)_3$[15,16].

$$LiAlH(O—t\text{-}C_4H_9)_3 \rightleftharpoons AlH(O—t\text{-}C_4H_9)_2 + LiO—t\text{-}C_4H_9$$

Scheme A

Lithium mono-, di-, and tri-*t*-butoxy aluminohydrides all show similar N.M.R. spectra[17].

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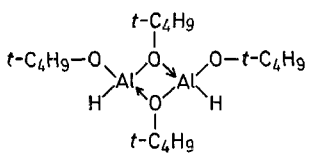
2.2. Alkoxyaluminohydrides

Depending on the ratio of reactants, slow addition of a calculated quantity of alcohol to AlH_3 in tetrahydrofuran affords alkoxyaluminohydrides of the type

$[(RO)_nAlH_{3-n}]_x$ R = CH_3, C_2H_5, i-C_3H_7, n-C_4H_9, t-C_4H_9; n = 1, 2, 3; $x \geqq 2$

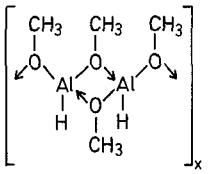
Ref.[10, 18, 19, 20].

The stability of $AlH_2(OR)$ towards disproportionation into AlH_3 and $AlH(OR)_2$ decreases with increased branching of the alkyl side chain at C-α; the degree of association (x) decreases in the same order. The stability of $AlH(OR)_2$ increases in the reverse order[18]. In tetrahydrofuran, $AlH(OR)_2$ exist as dimers (**1**), trimers, or insoluble polymers (**2**)[18].



$[AlH(O-t-C_4H_9)_2]_2$

1



$[AlH(OCH_3)_2]_x$

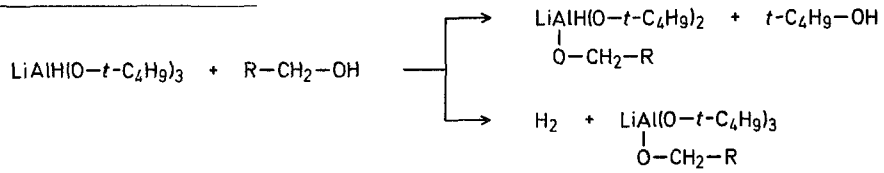
2

3. Reactions of Alkoxyaluminohydrides

3.1. Reactions with Active Hydrogen Compounds

$LiAlH(OCH_3)_3$[33] and $NaAlH_2(OC_2H_4OCH_3)_2$[34] react rapidly with alcohols, phenols, thiols, and primary amines under evolution of 1 and 2 mol of hydrogen, respectively. Benzyl alcohols containing electron-donor groups on the ring which facilitate formation of a resonance-stabilized carbonium ion readily undergo hydrogenolysis to the corresponding methyl derivatives when treated with $NaAlH_2(OC_2H_4OCH_3)_2$ in xylene at elevated temperatures (140°)[35–38]. Addition of equimolar amounts of methanol or water converts $NaAlH_2(OC_2H_4OCH_3)_2$ into half-methanolyzed or half-hydrolyzed hydrides of unknown structure which show markedly increased reducing power in comparison with that of the parent hydride (see Section 3.9.).

On the other hand, $LiAlH(O-t-C_4H_9)_3$ reacts only slowly with primary and secondary alcohols, and even more slowly with phenols and thiols; it is practically inert towards tertiary alcohols as well as primary amines[9,39]. According to Brown et al., the following reactions (Scheme **B**) take place simultaneously between this hydride and primary alcohols[9]:



Scheme **B**

2.3. Sodium Alkoxyaluminohydrides

For the preparation of sodium trialkoxyaluminohydrides, the synthesis from sodium hydride and trialkoxyaluminum has been recommended[21–25]; however, according to conductivity measurements, the composition of these hydrides is not homogeneous and does not correspond precisely to the formulae cited[22]. Sodium di- or tri-alkoxy and bis- or tris-[2-methoxyethoxy]-aluminohydrides were obtained by refluxing Na_3AlH_6 or $NaAlH_4$ with trialkoxyaluminum in tetrahydrofuran[26] or with tris-[2-methoxyethoxy]-aluminum in aromatic hydrocarbons[27], respectively. A series of sodium alkoxy-, aryloxy-, ω-alkoxyalkoxy-, and ω-dimethylamino-alkoxyaluminohydrides was synthesized by allowing metallic aluminum and sodium, both suspended in aromatic solvents, to react under hydrogen pressure and at elevated temperatures (160–190°) with aliphatic alcohols, phenols, methylphenols, xylenols, ω-alkoxyalkanols, or ω-dimethylaminoalkanols[28–32].

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Alkoxyaluminohydrides have also been used for partial reductions of some unsaturated primary alcohols. Thus in contrast to $LiAlH_4$, which reduces 1-hydroxyalk-2-ene-4,6-diynes (**3**, Scheme **C**) to allenenols (1-hydroxy-3,5,6-trienes, **4**) as main products and allenynols (1-hydroxyalka-3,4-dien-6-ynes, **5**) as minor products, the use of $LiAlH_2(OCH_3)_2$ or $LiAlH_2(OC_2H_5)_2$ affords improved yields of **5** together with **4** as a minor procut; the reaction using the $LiAlH_4$-butane-2,3-diol complex affords only **5**[40]:

$$R-C\equiv C-C\equiv C-CH=CH-CH_2-OH \longrightarrow$$

3

$$R-CH=C=CH-CH=CH-CH_2-CH_2-OH \quad + \quad R-C\equiv C-CH=C=CH-CH_2-CH_2-OH$$

4 **5**

R = H, C_2H_5, t-C_4H_9

Scheme **C**

The complex of $LiAlH_4$ with an α-D-glucofuranose derivative[41] proved similarly effective to dimenthoxyaluminohydride or lithium dimenthoxyaluminohydride[42] in the partial reduction of a triple bond in unsaturated primary alcohols and the elucidation of the configuration of the latter.

3.2. Reactions with Aldehydes and Ketones

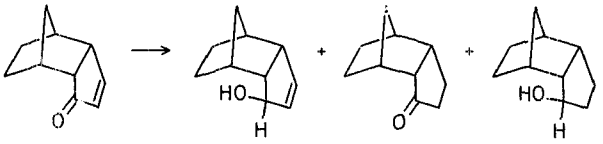
3.2.1. Reductions without Regard to Stereospecificity

Saturated aldehydes and ketones may be rapidly reduced with $NaAlH(OC_2H_5)_3$[22,25], $LiAlH(OCH_3)_3$[33,39], $LiAlH(O-t\text{-}C_4H_9)_3$[9,39], or $NaAlH_2(OC_2H_4OCH_3)_2$[43,44] to the corresponding alcohols. In the case of the latter hydride, however, the sterically hindered 2,4,6-trimethylacetophenone reacts predominatly in the enol form, yielding only ~10% of the carbinol[44]. Hydroxy-, alkoxy-, and amino-substituted aromatic aldehydes and ketones react with $NaAlH_2(OC_2H_4OCH_3)_2$ at a substantially higher rate than with $LiAlH_4$ and give substituted hydroxymethyl alcohols in high yields; at higher temperatures, these aldehydes and ketones, in which the position of the substituent on the ring allows the formation of a stabilized carbonium ion, readily undergo hydrogenolysis with $NaAlH_2(OC_2H_4OCH_3)_2$ giving substituted toluenes, diarylmethanes, or methylnaphthalenes in high yields[35–38].

2,4-Dihydroxydiphenylmethane[36]:
A 70% solution of sodium bis-[2-methoxyethoxy]-aluminohydride (12.1 g, 60 mmol) in xylene is added with stirring to a hot solution of 2,4-dihydroxybenzophenone (4.28 g, 20 mmol) in xylene (90 ml). Stirring and heating is continued. The initially formed light yellow precipitate dissolves to give a deep-red solution as the temperature reaches 143°. The reaction mixture is stirred for 1 hr at this temperature, then cooled with an ice bath, diluted with ether, and decomposed by the addition of 20% sulfuric acid. The organic layer is separated and the aqueous layer extracted with ether. The combined organic solutions are washed with water, shaken with solid sodium hydrogen carbonate, again washed with water, and dried with sodium sulfate. The solvents are distilled off and the residue is distilled in vacuo; yield: 3.3 g (82%); b.p. 162–163°/1 mm; m.p. 76–76.5°, from benzene.

α,β-Unsaturated carbonyl compounds are reduced by $NaAlH_2(OC_2H_4OCH_3)_2$ either to the unsaturated or saturated alcohols, depending on the reaction conditions, in 80–97% yields[43,44]. On the other hand, the behavior of both $LiAlH(OCH_3)_3$ and $LiAlH(O-t\text{-}C_4H_9)_3$ toward these compounds appears to be dependent on the structure of the carbonyl compound.

$LiAlH(OCH_3)_3$, previously reported to simultaneously reduce both the double bond and the carbonyl group in cinnamaldehyde[33], affords a 90% yield of the unsaturated alcohol in the reduction of 3-oxocyclopentene and reduces 5-oxo-*endo*-tricyclo-[5.2.1.$0^{2,6}$]dec-3-ene (5,6-dihydro-*endo*-dicyclopentadien-1-one, **6**) to yield approximately equal amounts of the unsaturated alcohol (**7**) and saturated ketone (**8**), along with minor amounts of alcohol **9**[45].



6 **7** **8** **9**

Scheme **D**

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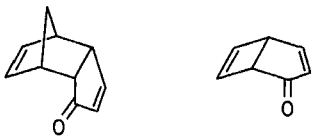
$LiAlH(O—t\text{-}C_4H_9)_3$, which only reduces the carbonyl function of cinnamaldehyde[9], gives the highest yield of **8** from reduction of **6** and a 89% yield of cyclopentanol (in comparison to 100% with $NaBH_4$) in the reduction of 3-oxocyclopentene[45]. On the other hand, this hydride effected selective saturation of the conjugated double bond of 5-oxo-*endo*-tricyclo[5.2.1.$0^{2,6}$]deca-3,8-diene (**10**)[46] and of 2-oxo-*cis*-bicyclo-[3.2.0]hepta-3,6-diene (**11**)[47]; the products, obtained in high yields,



10 **11**

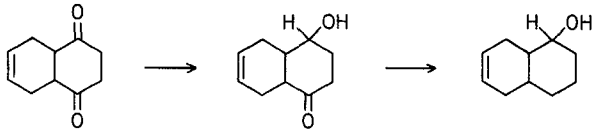
were the corresponding ketones with intact isolated double bond.

Table 1. Reduction of 5-Oxo-*endo*-tricyclo-[5.2.1.$0^{2,6}$]dec-3-ene (**6**) with Metal Hydrides[45] (Scheme **D**)

Hydride	Product composition, %		
	7	**8**	**9**
$LiAlH_4$ (ethyl ether)	67	12	21
$LiAlH_4$ (tetrahydrofuran)	0	67.2–100	0–32.8
$LiAlH(OCH_3)_3$	45	41	14
$LiAlH(O—t\text{-}C_4H_9)_3$	0	84.5	15.5
$NaBH_4$	0	0	100
AlH_3	64.3–86	7–32.7	1.5–19.2

In the reduction of mesityl oxide, $LiAlH_4$ is the preferred reagent and affords a better yield of the unsaturated alcohol as well as a cleaner product than does $LiAlH(O—t\text{-}C_4H_9)_3$[48].

$LiAlH(O—t\text{-}C_4H_9)_3$ was successfully used in the selective reduction of one carbonyl group in cyclic diketones (for this application in the steroid series see Section 3.3.). Thus, 1,4-dioxo-*cis-trans*-Δ^6-octalin (**12**) was reduced (Scheme E) to the ketol **13**, which after Wolff-Kishner reduction gave 1-hydroxy-Δ^6-octalin (**14**) in 64% yield (5–25% after reaction with $LiAlH_4$ and Wolff-Kishner reduction)[49].



12 **13** **14**

Scheme **E**

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3.2.2. Stereospecific Reductions of Monocyclic and Bicyclic Ketones

The results obtained to date on reductions of monocyclic and bicyclic ketones with alkoxyaluminohydrides (Tables 2 and 3) reveal that $LiAlH(OCH_3)_3$ is more stereoselective than either $LiAlH_4$, $LiAlH(OC_2H_5)_3$, or $LiAlH(O—t\text{-}C_4H_9)_3$. In comparison with $LiAlH_4$, $LiAlH(OCH_3)_3$ gives preferential attack from the less hindered side of the carbonyl plane in rigid ketone systems. Thus, bicyclic ketones such as norcamphor, camphor, isopinocamphone, and fenchone are reduced by $LiAlH(OCH_3)_3$ to the thermodynamically less stable of the two possible alcohols in high isomeric purity. In the less rigid monocyclic systems such as 2-methylcyclopentanone and 2-methylcyclohexanone, this hydride gives substantially less amounts of the more stable alcohol than does $LiAlH_4$ or $LiAlH(O—t\text{-}C_4H_9)_3$.

dl-endo-**Fenchyl Alcohol**[15]:

Lithium Trimethoxyaluminohydride in Tetrahydrofuran: In a 1000-ml flask, lithium aluminium hydride (15.2 g, 0.4 mol) is added to distilled tetrahydrofuran (750 ml). The mixture is stirred overnight, the solids are allowed to settle, and an aliquot of the clear solution is analyzed for dissolved hydride. A sufficient quantity of the clear solution is placed in a 1000-ml three-neck flask, fitted with condenser, stirrer, and addition funnel, to provide 0.3 mol of the reagent. The solution is cooled to 0° and methanol (36.6 ml, 28.8 g, 0.9 mol) is gradually added (exothermic reaction) as the hydrogen evolved is vented.

dl-endo-*Fenchyl Alcohol:* To the stirred solution of lithium trimethoxyaluminohydride prepared as described above, *dl*-fenchone (33 g, 0.25 mol) is added dropwise at such a rate that the temperature can be maintained at ~0°. The solution is stirred at 0° for 1 hr and the residual hydride is destroyed by water. The reaction mixture is transferred to a separatory funnel, ether is added, and the mixture is treated with a saturated solution of sodium potassium tartrate. The organic phase is separated, the aqueous layer is extracted with ether, and the combined ether extracts are dried with anhydrous magnesium sulfate. The solvents are removed using a rotatory evaporator and the residue is distilled in vacuo; yield: 30.7 g (80%); b.p. 43–45°/1 mm; isomeric purity: 97% (G.L.C. analysis); *p*-nitrobenzoate, m.p. 93–94.5°.

On the other hand, $LiAlH(OC_2H_5)_3$, $NaAlH_2(OC_2H_4OCH_3)_2$, and $LiAlH(O—t\text{-}C_4H_9)_3$ (the latter with some exceptions) reduce monocyclic and bicyclic ketones to two epimeric alcohols in a ratio close to that realized with $LiAlH_4$.

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In the case of 3,3,5-trimethylcyclohexanone (**15**), $LiAlH(O—t\text{-}C_4H_9)_3$ yields (in contrast to $LiAlH_4$) preferentially the more stable *trans*-alcohol resulting from the attack at the less hindered side of the C=O plane. Compared to $LiAlH_4$, the stereospecificity of $LiAlH(O—t\text{-}C_4H_9)_3$ observed in the reduction of 5-oxobicyclo[2.2.1]heptene (dehydronorcamphor) and 3-*exo*-dimethylaminomethyl-2-oxobicyclo[2.2.1]heptane is low.

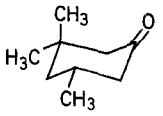
The failure of $LiAlH(O—t\text{-}C_4H_9)_3$ to give higher stereoselectivity (expected because of its larger steric requirements) was ascribed to different mechanisms involved in the reductions of hindered ketones with $LiAlH(O—t\text{-}C_4H_9)_3$ and $LiAlH(OCH_3)_3$[15,16]. In addition, the significantly different composition of products arising from the reduction of 2,4′-dioxodicyclohexylmethane by $LiAlH_4$, $LiAlH(OCH_3)_3$, and $LiAlH(O—t\text{-}C_4H_9)_3$ has led to the assumption that not $LiAlH(OCH_3)_3$ but $AlH(OCH_3)_2$, formed according to the Scheme **F**, was the actual reducing agent[50].

$$3\ CH_3OH + LiAlH_4 \longrightarrow AlH(OCH_3)_2 + CH_3C^{\ominus}Li^{\oplus} + 3\ H_2$$

Scheme **F**

The relatively high association recently found for solutions of $LiAlH(OCH_3)_3$ in tetrahydrofuran allows the assumption that molecular aggregation of this hydride, producing a reducing agent bulkier than monomeric $LiAlH(O—t\text{-}C_4H_9)_3$, may be responsible for the higher stereoselectivity of the former hydride[10].

The kinetic results obtained for the reaction of $LiAlH(O—t\text{-}C_4H_9)_3$ with monocyclic ketones[62] appear to rule out "product development control"[53] for the reduction of 3,3,5-trimethylcyclohexanone (**15**), 4-*t*-butylcyclohexanone (**16**), 3,5 dimethylcyclohexanone (**17**), and 3,3,5,5-tetramethylcyclohexanone (**18**);



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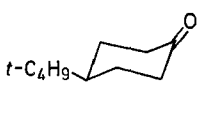

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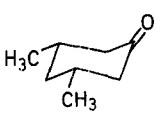

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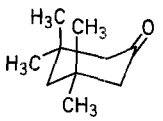

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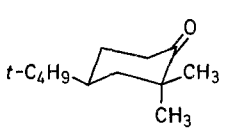

19

"steric approach control"[53] seems to be operative in the formation of the equatorial alcohol from **15**.

Table 2. Stereospecific Reduction of Monocyclic Ketones with Metal Hydrides

Ketone	Yield of *trans*-alcohol, %				
	LAH[a]	LTMA[a]	LTEA[a]	LTBA[a]	SDMA[a]
	76–79[c] 75[d]	56[c]	77[c]	72[c]	–
	74–76[c] 82[e,f] 64[g]	31[c] 37–39[h]	73[c]	70[c] 62–64[h] 64[i] 63.2[j]	67–74[k]
	98[g]	–	–	14[j]	–
	81[g] 81[b]	–	–	82.6[j] 84[m]	76–80[k]
	42[c]	36[c]	–	46[c]	36–40[k]
	90–91[n] 91–93[o] 92.5[p]	59[n]	–	90[n] 89.7[j] 91[q]	90–92[k]
	16–17[n]	47[n]	–	17[n] 11[q]	–
	94[n] 95[j]	84[n]	–	91[n] 100[j] 92[q]	–
	58–63[n] 52–54[t] 58[p] 53–62[u]	98[n] 75–92[t]	83[t]	96[n] 73–88[t] 93–95[v] 89[q] 87.8[j] 70[u]	55–59[w]

[a] LAH = $LiAlH_4$; LTMA = $LiAlH(OCH_3)_3$; LTEA = $LiAlH(OC_2H_5)_3$; LTBA = $LiAlH(O—t\text{-}C_4H_9)_3$; SDMA = $NaAlH_2(OC_2H_4OCH_3)_2$.

[b] Ref.[51]; the reduction with diisocampheylborane gives *cis*-alcohols in 92–94% purity.

[c] Ref.[15].

[d] Ref.[52].

[e] Ref.[53].

[f] Ref.[54].

[g] Ref.[55].

[h] Ref.[10]; the reduction with $AlH(O—t\text{-}C_4H_9)_2$ yielded 35–36% of *trans*-alcohol.

[i] Ref.[56].

[j] Ref.[57].

[k] Ref.[44].

[l] Ref.[58]; the reduction with $NaBH_4$ yielded 85% of *trans*-alcohol.

[m] Ref.[57].

[n] Ref.[59]; the reduction was also performed with $NaBH_4$, $NaBH(OCH_3)_3$, and $NaBH(O—i\text{-}C_3H_7)_3$.

[o] Ref.[60].

[p] Ref.[61].

[q] Ref.[62].

[r] Ref.[59]; the reduction was also performed with $NaBH_4$.

[s] Ref.[10]; the reduction with $AlH(O—t\text{-}C_4H_9)_2$ afforded 74–80% of *trans*-alcohol.

[t] Ref.[7].

[u] Ref.[16].

[v] Ref.[10].

[w] Ref.[63].

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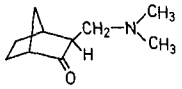
Table 3. Stereospecific Reduction of Bicyclic Ketones with Metal Hydrides

Ketone		LAH[a]	LTMA[a]	LTBA[a]
		Yield (%) of the predominating alcohol isomer		
	Norcamphor[b,c]	89[d] 90[e,f] 92[g]	98[d]	93[d] 92[g] 94–95[h]
	Camphor[i,j]	92[d] 90[k] 97[l]	99[d]	93[d] 94[h,m] 95[n,o]
	5-Oxobicyclo[2.2.1]hept-2-ene (Dehydronorcamphor)[b,g]	91		77
	Isopinocamphone[i,d]	89	98	84
	Fenchone[b,d]		97	
	7-Isopropylidene-5-oxobicyclo[2.2.1]hept-2-ene[b,g]	89		93
	7-Isopropylidene-2-oxobicyclo[2.2.1]heptane[b,g]	94		98
	2-*exo*-Dimethylaminomethyl-3-oxobicyclo[2.2.1]-heptane[p,q,r]	82		62
	3-Oxobicyclo[3.1.0]hexane[r,s,t,u]	89		88
	2-Oxobicyclo[3.2.1]octane[r,s,v]	90		92
	(−)-Cedran-2-one[w,x]	70	83	
	(−)-Isocedran-2-one[x,y]	93, 6	99	

[a] LAH = $LiAlH_4$; LTMA = $LiAlH(OCH_3)_3$; LTBA = $LiAlH(O—t\text{-}C_4H_9)_3$.
[b] Predominating isomer is *endo*.
[c] Ref.[15]; the reduction with $LiAlH(OC_2H_5)_3$ yielded 85% of *endo*-alcohol.
[d] Ref.[15].
[e] Ref.[64].
[f] Ref.[65].
[g] Ref.[66]; the reduction was also performed with $Al(O—i\text{-}C_3H_7)_3$.
[h] Ref.[10]; the reduction with $AlH(O—t\text{-}C_4H_9)_2$ yielded 90–93% of *endo*-alcohol.
[i] Predominating isomer is *exo*.
[j] The reduction with $NaAlH_2(OC_2H_4OCH_3)_2$ yielded 88–89% of *exo*-alcohol.
[k] Ref.[55].
[l] Ref.[67].
[m] Ref.[10]; the reduction with $AlH(O—t\text{-}C_4H_9)_2$ yielded 75–80% of *exo*-alcohol.
[n] Ref.[56].
[o] Ref.[57].
[p] Predominating isomer is 2-*exo*-dimethylaminomethyl-3-*endo*-hydroxybicyclo[2.2.1]heptane.
[q] Ref.[68]; also other 2-*exo*-dimethylaminomethyl derivatives were reduced.
[r] Reductions were also performed with $NaBH_4$.
[s] Predominating isomer is *cis*.
[t] Ref.[69].
[u] The reductions were also performed with $Al(O—i\text{-}C_3H_7)_3$.
[v] Ref.[70].
[w] Predominating isomer is (−)-cedran-2-ol, the isomer present in minor amount is (−)-neocedran-2-ol.
[x] Ref.[71].
[y] Predominating isomer is (−)-neoisocedran-2-ol, the isomer present in minor amount is (−)-isocedran-2-ol.

The isomer ratio in the reduction product of 2,2-dimethyl-4-*t*-butylcyclohexanone[57] (**19**) appears to be more determined by the eclipsing factor[72] than by steric approach factors. The relative rate constants determined for attack of compounds **15**–**19** from the axial and equatorial side using $LiAlH_4$, $LiAlH(OCH_3)_3$, and $LiAlH(O—t\text{-}C_4H_9)_3$, as well as $NaBH_4$ or $NaBH(O—i\text{-}C_3H_7)_3$, support the concept of "steric approach control" but suggest that "product development control" plays at best a minor role, especially in the reductions with aluminohydrides[59].

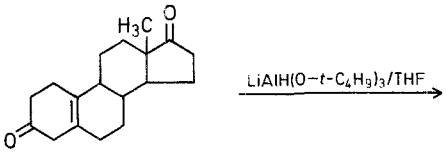
The results of kinetic studies of the reduction of *p,p'*-disubstituted benzophenones by $LiAlH(O—t\text{-}C_4H_9)_3$ show that in the transition state the C=O groups interact with a center carrying a significant negative charge; this eliminates the possibility of reduction by a neutral aluminohydride species and is consistent with hydride donation by an anion of the type $Al^{\ominus}(O—t\text{-}C_4H_9)_3H$[73].

For the reduction of ketones with optically active alkoxyaluminohydride complexes see a recent review on asymmetric synthesis[74].

3.3. Reactions with Steroids

The application of $LiAlH(O—t\text{-}C_4H_9)_3$ in the steroid series has made possible a number of reductions of high selectivity and stereospecificity not achieved with $LiAlH_4$ or $NaBH_4$[58,75,76,77].

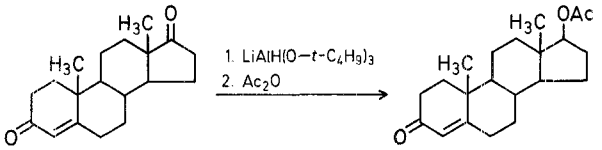
The differences in the rates of reduction of 3-, 7-, and 17-keto-steroids allow reduction to occur selectively at the C-3 carbonyl[76]. For example, the reduction of 3,17-dioxoestr-5(10)-ene (**20**; Scheme **G**) gives rise to two hydroxyketones **21** and **22** in a ratio of 15:1 (5:1 with $NaBH_4$)[78].



20 **21** **22**

Scheme **G**

The slow rate of reduction of α,β-unsaturated ketones made it possible to selectively reduce 17- and 7-keto groups in the presence of a conjugated 3-keto group. Thus, 3,17-dioxoandrost-4-ene (**23**) was converted into 17β-acetoxy-3-oxoandrost-4-ene (**24**; Scheme **H**) in 55% yield and 3β-acetoxy-7,17-dioxoandrost-5-ene into 3β,17β-diacetoxy-7-oxoandrost-5-ene in 66% yield[76].



23 **24**

Scheme **H**

In addition, an angular 10-formyl group could be partially reduced in the presence of a 3-keto group[79]; when $NaBH_4$ was used as the reducing agent, borate complexes were formed and the corresponding hydroxymethyl derivative could only be isolated after treatment with a mannitol/methanol/sulfuric acid mixture.

The high stereospecificity achieved with $LiAlH(O—t\text{-}C_4H_9)_3$ is illustrated by the almost quantitative yields of equatorial alcohols obtained from 3-keto-steroids[57,80–84] as well as the high or nearly quantitative yields of 3β-[76,80,81], 7β-[76], and 17β-hydroxy derivatives[76] obtained in the reductions of 3-, 7-, and 17-keto-steroids, respectively. In addition, 16-keto-steroids are selectively reduced to 16β-alcohols[85]. Thus, 3-oxocholest-4-ene and 3-oxocholest-5-ene afford 3β-hydroxycholest-4-ene[58,84,86] and 3β-hydroxycholest-5-ene[58,84], respectively. Both products are practically free of 3α-isomers (1%). Cholestan-3-one gives the nearly pure (98.5%) 3β-epimer[57,84].

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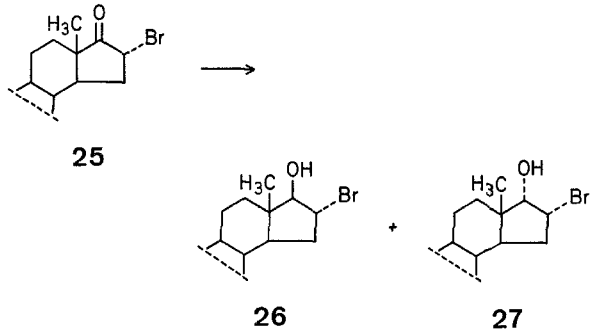
3β-Hydroxycholesten-4-ene[86]:

Dry *t*-butanol (12 g, 160 mmol) is added dropwise with stirring to a 0.5 *M* solution (100 ml) of lithium aluminohydride in ether. The white precipitate is allowed to settle, the ether decanted, and the solid *lithium tri-t-butoxyaluminohydride* dissolved in diglyme[2] (40 ml). To this solution is added at −40° to −50° a solution of 3-oxocholest-4-ene (15 g, 39 mmol; m.p. 79–80°) in ether/benzene (8:1, 200 ml, cooled to 0°). The mixture is allowed to stand at 0° overnight and is then hydrolyzed by treatment with ice, 5 *N* sodium hydroxide, and sodium potassium tartrate. The ethereal solution is dried and evaporated and the residue recrystallized from ethyl acetate; yield: 13 g (87%); m.p. 126–129°. The product is sufficiently pure and contains 1% of 3α-isomer. One more recrystallization from ethyl acetate affords the pure product in large needles; m.p. 131–132°; α_D: +46° (cf. Ref.[58]).

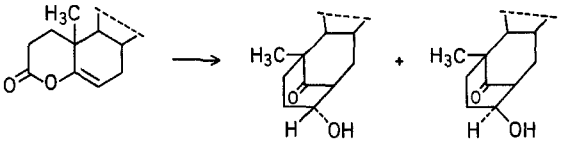
Similar results are observed when the keto-steroid is substituted by bromine in the 2α-, 2β-, 4α-, 4β-, and 16β-positions[75,76,87]. For example, the reduction of 2α-bromocholestan-3-one affords a crude product whose physical constants are almost identical with those of the pure 3β-alcohol[76]. Unlike $NaBH_4$, $LiAlH(O—t\text{-}C_4H_9)_3$ does not epimerize the bromine in the unstable 2β- or 16β-bromoketones[76]. Whereas during the reduction of 16α-bromo-17-keto-steroids (**25**) by other hydrides in a polar medium an inversion occurs at C-16, the reduction with $LiAlH(O—t\text{-}C_4H_9)_3$ in non-polar solvents gives rise to 16α-bromo-17-epimeric alcohols **26** and **27**[88] (Scheme **I**).



25 **26** **27**

Scheme **I**

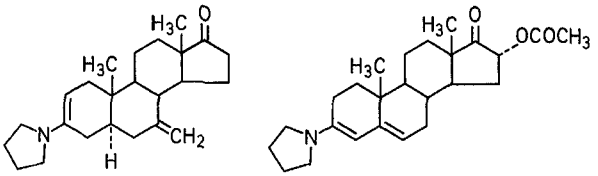
Apart from its stereospecifity, $LiAlH(O—t\text{-}C_4H_9)_3$ displays other advantages in comparison with $LiAlH_4$ or $NaBH_4$. Thus, when severe reaction conditions are required in order to reduce the keto group in conjugated ketones, the double bond is not attacked[76]. Reduction of keto groups proceeds without fission of acetoxy[76,82,85,89–92], benzoyloxy[93], or even formyloxy groups[89] at C-3, C-16, or C-17; and epoxide[76,94] as well as lactone rings[94] remain unaffected. Thus in contrast to $LiAlH_4$ or $NaBH_4$, $LiAlH(O—t\text{-}C_4H_9)_3$ proved unique in the cardenolide and bufadienolide series in selectively reducing the carbonyl or formyl groups and leaving intact the butenolide as well as hexadienolide rings[94]. Unlike $LiAlH_4$, which reduces a δ-enol lactone (**28**) to a diol, $LiAlH(O—t\text{-}C_4H_9)_3$ affords two ketols[95], **29** and **30** (Scheme **J**), in a ratio of 96:4.



28 **29** **30**

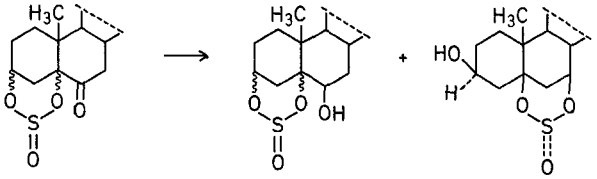
Scheme **J**

The 3-enamine grouping used to protect the 3-keto group in the reduction of 3,17-keto-steroids[85,96] (**31**, **32**) is not attacked by $LiAlH(O—t\text{-}C_4H_9)_3$; the same applies to the amide group in 20-acetylamino- or 18-benzoylamino-steroids[82,97].



31 **32**

The reduction of the cyclic sulfite mixture obtained from 3β,5-dihydroxy-5β-cholestan-6-one and containing compounds with axial SO- (**33a**; 9%) and equatorial SO-groups (**33b**; 91%) affords the 3,5-cyclic sulfite of 3β,5,6-trihydroxy-5β-cholestane with axial SO-groups (**34a**; 6%) and the 5,6-cyclic sulfite with equatorial SO-group (**35**; 57%).



3β, 5β series
33a S = O axial
33b S = O equatorial
3α, 5α series
33c S = O axial

3β, 5β series
34a S = O axial
3α, 5α series
34b S = O axial

35

Scheme **K**

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Reduction of the cyclic sulfite (**33c**) of 3α,5-dihydroxy-5α-cholestan-6-one proceeds without rearrangement, yielding the 6β-hydroxy-sulfite (**34b**)[98].

The partial reduction of 5α- and 5β-cyanocholestan-3-one ethylene ketal gives different results depending on the type of cyano derivative and hydride used. The highest yields (42%) of the 5α-formyl derivative were obtained with $LiAlH(OC_2H_5)_3$. In the case of the 5β-cyano derivative, $LiAlH_2(OC_2H_5)_2$ fails to react and the reduction with $LiAlH_3(OC_2H_5)$ gives rise to a 5β-aminomethyl derivative and a Schiff base in equal yields (32%)[99].

3.4. Reactions with Carboxylic Acids and Acid Anhydrides

Carboxylic acids and acid anhydrides are easily reduced to the corresponding alcohols and diols by $LiAlH(OCH_3)_3$[33,39,100] or more rapidly by $NaAlH_2(OC_2H_4OCH_3)_2$[43,101,102]. Using the latter hydride, excellent yields of the same products can also be obtained by reducing the sodium or bromomagnesium salts of carboxylic acids[103]. A certain selectivity is displayed by this hydride in the reduction of ketocarboxylic acids to diols[101,104] or latones[101]. Hydroxy-, alkoxy-, and amino-substituted aromatic carboxylic acids can easily be reduced with $NaAlH_2(OC_2H_4OCH_3)_2$ to give the corresponding hydroxymethyl derivatives in high yields. Under more severe conditions (80–145°), hydrogenolysis of the *o*- and *p*-substituted carboxylic acids takes place, affording high yields of the corresponding methylphenols, methylnaphthols, alkoxytoluenes, or toluidines[35–38].

$LiAlH(O{-}t\text{-}C_4H_9)_3$ does not attack carboxylic acids and thus offers a possibility of selectively reducing other substituents in the presence of a free carboxylic group[9,39,100]. On the other hand, cyclic acid anhydrides are reduced by this hydride to form lactones[39,105,106]. However, the use of $LiAlH_4$ at low temperatures (−55°)[107] and an even more versatile method using $NaBH_4$[108] have been recommended instead of the use of $LiAlH(O{-}t\text{-}C_4H_9)_3$ for lactone synthesis.

$NaAlH(OC_2H_5)_3$ reacts with acid anhydrides similarly to $LiAlH(OCH_3)_3$ or $NaAlH_2(OC_2H_4OCH_3)_2$[22,25].

3.5. Reactions with Esters and Lactones

Esters of aliphatic and aromatic carboxylic acids react relatively slowly with $NaAlH(OC_2H_5)_3$[22,25] in tetrahydrofuran at 0–65° and rapidly with $LiAlH(OCH_3)_3$[33,39,100] to form alcohols and diols. The reaction with $NaAlH_2(OC_2H_4OCH_3)_2$ in aromatic hydrocarbons at 80° is very rapid, giving excellent yields of the same products[43,101]. Using this hydride, aromatic allylic alcohols can be prepared by the reduction of conjugated esters (reverse addition at 20–30°) in high yields[43]. For this purpose, $LiAlH(OCH_3)_3$ has been suggested to be generally useful[109].

4-Hydroxybenzyl Alcohol[36]**:**

A hot solution of ethyl 4-hydroxybenzoate (6.08 g, 36.6 mmol) in benzene (80 ml) is added rapidly with stirring to a solution of sodium bis-[2-methoxyethoxy]-aluminohydride (16.7 g, 82.5 mmol) in benzene (80 ml). The reaction mixture is heated under reflux for 15 min, cooled with an ice bath, and decomposed with water (15 ml). The benzene layer is separated; the highly viscous aqueous layer is stirred with water (85 ml) for 1 hr, decomposed by passing gasous carbon dioxide through the mixture for 1 hr, and extracted with ether (3 × 200 ml). The organic layers are combined, dried with sodium sulfate, and evaporated under reduced pressure. The residue is recrystallized from water; yield: 3.2 g (70%); m.p. 109.5–110.5°.

A selective reduction of ethyl Vitamin-A-carboxylate is achieved with $NaAlH(C_2H_5)(OC_2H_5)_2$, which when used in $n\text{-}C_{6-8}$ aliphatic hydrocarbon solution does not affect the conjugated double bond system and gives Vitamin A in a yield of 95%[110,111].

Various 4-methylhexahydropyrazin-1-yl derivatives can be prepared in excellent yields by hydrogenolysis of 1-substituted 4-ethoxycarbonylhexahydropyrazines with $NaAlH_2(OC_2H_4OCH_3)_2$[112].

Although $LiAlH(OC_2H_5)_3$ can be used for the reduction of α-aminoesters to α-aminoaldehydes, $AlH(i\text{-}C_4H_9)_2$ appears to be the preferred reagent, giving higher product yields[113].

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$LiAlH(O—t\text{-}C_4H_9)_3$ does not react with alkyl esters of aromatic carboxylic acids and reduces alkyl esters of aliphatic carboxylic acids at a very slow rate[9,39,100]. A great difference between the transfer rates of the first and second hydride to phenyl esters led to the development of a new method for the conversion of carboxylic acids into the corresponding aldehydes via the phenyl esters[114] (Scheme **L**).

$$R{-}COOC_6H_5 + LiAlH(O{-}t\text{-}C_4H_9)_3 \xrightarrow{THF,\ 0^\circ} R{-}CHO + LiAl(OC_6H_5)(O{-}t\text{-}C_4H_9)_3$$

Scheme **L**

The highest aldehyde yields (~70%) are obtained by the reduction of phenyl esters of unsubstituted aliphatic, alicyclic, and araliphatic carboxylic acids. An exception is phenyl cyclopropanecarboxylate which, like phenyl benzoate, fails to give the corresponding aldehyde.

Alternatively, $NaAlH_2(OC_2H_4OCH_3)_2$ can be used for reduction of esters to aldehydes according to Scheme **M**[34].

$$2\ R^1{-}COOR^2 + NaAlH_2(O{-}CH_2{-}CH_2{-}OCH_3)_2 \xrightarrow{ether,\ -70^\circ} 2\ R^1{-}CHO + NaAl(OR^2)(O{-}CH_2{-}CH_2{-}OCH_3)_2$$

Scheme **M**

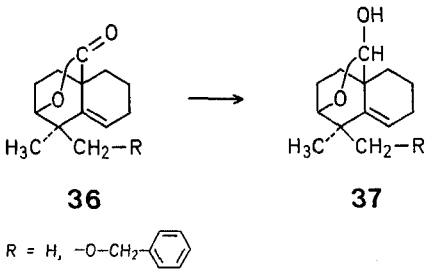
In this case, the highest aldehyde yields (80–90%) are obtained from methyl or 2-methoxyethyl esters of aliphatic carboxylic acids; the yields decrease with the lenght or branching of the R^2 substituent, *t*-butyl and phenyl esters being completely unreactive. Esters of arene- and aralkanecarboxylic acids give generally lower yields (30–50%).

The reactivities of both $LiAlH(O—t\text{-}C_4H_9)_3$[114] and $NaAlH_2(OC_2H_4OCH_3)_2$[34] are compared in in Table 4 with those of $AlH(i\text{-}C_4H_9)_2$[115] and $NaAlH_4$[116], recommended earlier for the aldehyde synthesis from esters.

Lactones are reduced by $LiAlH(OCH_3)_3$[33,39] or $NaAlH_2(OC_2H_4OCH_3)_2$[43,101] to the corresponding diols as rapidly as with $LiAlH_4$. On the other hand, the unusually slow reduction of lactones by $LiAlH(O—t\text{-}C_4H_9)_3$ to diols[9,39] can be utilized for the partial reduction of δ-lactones to lactols[117].

Whereas $LiAlH_4$ reduces both carbonyl groups in a δ-enollactone system[118], $LiAlH(O—t\text{-}C_4H_9)_3$ affords ketols[11,95,119] in high yields. In the latter case, the separate preparation and isolation of $LiAlH(O—t\text{-}C_4H_9)_3$ rather than its formation *in situ* is advisable because better yields and cleaner products are obtained[11].

Using $LiAlH(OC_2H_5)_3$, it is possible to reduce terpene lactones of the type **36** to the lactols, giving isochromanol derivatives (**37**) in 89–96% yields[120].



36 **37**

R = H, $-O-CH_2-C_6H_5$

Scheme **N**

3.6. Reactions with Carboxylic Acid Halides

Aliphatic and aromatic carboxylic acid chlorides are rapidly reduced by $LiAlH(OCH_3)_3$[33,39,100], $LiAlH(O—t\text{-}C_4H_9)_3$[9,39,100], $NaAlH(OC_2H_5)_3$[21,22,25], or $NaAlH_2(OC_2H_4OCH_3)_2$[43,101] to the corresponding alcohols in yields comparable to those obtained using $LiAlH_4$. These alkoxyhydrides can therefore find useful application in acid chloride reductions where the presence of other reducible substituents or conjugated double bonds makes the use of a more selective reagent necessary. Thus, cinnamyl alcohol[25,43,101,121] and ring-substituted cyclopropenyl carbinols[122] can be prepared in good yield from the corresponding unsaturated acid chlorides by reduction with $LiAlH(O—t\text{-}C_4H_9)_3$, $NaAlH(OC_2H_5)_3$, or $NaAlH_2(OC_2H_4OCH_3)_2$.

Of special interest is the partial reduction of carboxylic acid chlorides (reverse method) to the corresponding aldehydes by using one equivalent of $LiAlH(O—t\text{-}C_4H_9)_3$ in tetrahydrofuran or better in diglyme according to Scheme **O**.

$$R{-}C(=O){-}Cl + LiAlH(O{-}t\text{-}C_4H_9)_3 \xrightarrow{-70\ to\ -80^\circ} R{-}CHO + LiCl + Al(O{-}t\text{-}C_4H_9)_3$$

Scheme **O**

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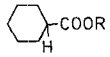
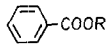
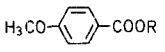
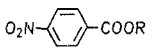
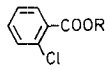
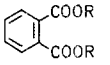
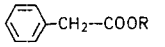
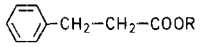
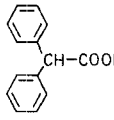
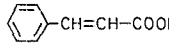
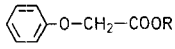
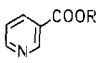
Table 4. Synthesis of Aldehydes by Partial Reduction of Carboxylic Acid Esters.

Ester	Yield (%) of the corresponding aldehydes[i]			
	LTBA[a,b,c]	SDMA[d,e,f]	ADB[a,g]	SAH[a,c,f,h]
$H_3C-COOR$	71 (4)[f,t]	92 (4)[j,k]		
$Cl-CH_2-COOR$	67 (0.5)[f]			
C_2H_5-COOR	77 (3)			
$n-C_3H_7-COOR$	63 (4)[f]		88[d]	81[m]
$i-C_3H_7-COOR$	71 (4)	88 (5)[m]	80[d]	
$H_3C-CH=CH-COOR$	33 (0.5)			
$t-C_4H_9-COOR$	67 (4)[f]	81 (5)[j]		
$Cl-CH_2-CH_2-CH_2-COOR$			78[d]	
$NC-(CH_2)_4-COOR$				25[m]
$n-C_5H_{11}-COOR$	71 (4)[f]	86 (7)[n]	85[m]	85[d]
$Cl-(CH_2)_4-CCl_2-COOR$				66[m]
$C_2H_5-O-(CH_2)_6-COOR$			82[d]	
$n-C_7H_{15}-COOR$		84 (8)[n]		
$n-C_9H_{19}-COOR$		82 (8)[n,o]		
$n-C_{11}H_{23}-COOR$			88[m]	76[m]
$H_2C=CH-(CH_2)_8-COOR$				60[m]
$n-C_{17}H_{35}-COOR$			50[m]	
$H_3C-(CH_2)_7-CH=CH-(CH_2)_7-COOR$		70 (24)[n,o]		66[d]
$ROOC-(CH_2)_8-COOR$			90[d]	74[d]
	70 (4)[f]			
	0[p]	38 (8)[n]	74[q]	48[m]
			70[m]	
			48[m]	
				43[d]
			86[r]	52[d]
	73 (1)	78 (8)[m,n]	86[q]	
				88[d]
		49 (36)[n,o]		
	60 (2)[f]			46[d]
	49 (0.25)[f]			
				81[m]

[a] LTBA = $LiAlH(O-t-C_4H_9)_3$; SDMA = $NaAlH_2(OC_2H_4OCH_3)_2$; ADB = $AlH(i-C_4H_9)_2$; SAH = $NaAlH_4$.

[b] For R = C_6H_5, reduction in tetrahydrofuran at 0°.

[c] Yields of 2,4-dinitrophenylhydrazones.

[d] For R = CH_3, unless stated otherwise.

[e] Reduction in ether at −70°.

[f] Reverse addition.

[g] Reduction in toluene, hexane, or ether at −70° (0.5–1 hr).

[h] Reduction in tetrahydrofuran or tetrahydrofuran/pyridine at −45° to −65° (aliphatic esters: 2–5 hr; aromatic esters: 5–7 hr).

[i] Numbers in parentheses denote reaction time (hr).

[j] Analytical yields.

[k] The reduction of the 2-methoxyethoxy ester gave a 87% yield (2 hr).

[l] Reduction of the 4-chlorophenyl ester gave 77% yield at −22° (8 hr).

[m] For R = C_2H_5.

[n] Yields of $NaHSO_3 \cdot R-CHO$ complexes.

[o] The reactivity was improved by grinding with added glass beads.

[p] Only benzyl alcohol (46%) was isolated after a reduction time of 4 hr.

[q] For R = $i-C_3H_7$.

[r] For R = $n-C_4H_9$.

p- And *m*-substituted aromatic aldehydes or dialdehydes are prepared by this method in 60–90% yield, *o*-substituted aldehydes in somewhat lower yields, and aliphatic or alicyclic aldehydes in yields of 37–60%[2,8,121,123–127]. As the conjugated double bond is not attacked in this procedure, a number of substituted cinnamaldehydes[128,129,130], or aliphatic unsaturated aldehydes and dialdehydes[121] can thus be obtained in good yield.

4-Nitrobenzaldehyde[2]:

Dry *t*-butanol (60 g, 0.80 mol) is added with stirring to a 0.5 *M* solution (500 ml) of lithium aluminohydride in ether. The white precipitate is allowed to settle, the ether decanted, and the solid *lithium tri-t-butoxyaluminohydride* dissolved in diglyme (200 ml). The solution is added over a period of 1 hr to a solution of 4-nitrobenzoyl chloride (45.3 g, 0.244 mol) in diglyme (100 ml) at −75° (Dry-Ice bath). The mixture is allowed to warm to room temperature over a period of 1 hr and is then poured onto crushed ice. The mixture is filtered, the solid on the filter pressed dry, and extracted several times with 95% ethanol. Evaporation of solvent yields 29.4 g (80%) of crude product; m.p. 103–104°. Recrystallization from aqueous ethanol gives the pure product in the form of light-brown crystals; yield: 25.4 g (69%); m.p. 104–105°.

Fluoroaldehydes can also be synthesized by the reduction of fluoroacyl fluorides with $LiAlH(O—t\text{-}C_4H_9)_3$; with other hydrides, hydrogenolysis of the C—F bond takes place[131].

The use of $NaAlH(O—t\text{-}C_4H_9)_3$ was recommended for the reduction of C_9–C_{18} acid chlorides to aliphatic aldehydes; in this case, however, the reduction to the aldehyde competes with the simultaneous formation of acid and alcohol[132].

3.7. Reactions with Carboxamides, Imides, and Lactams

Whereas $LiAlH(O—t\text{-}C_4H_9)_3$ is inert toward amides[39], $LiAlH(OCH_3)_3$[39] or $NaAlH_2(OC_2H_4OCH_3)_2$[133] reduce primary carboxamides to amines as readily as $LiAlH_4$ or AlH_3. Likewise, tertiary amides are reduced to the corresponding amines, the reaction surprisingly being faster with $LiAlH(OCH_3)_3$[39] or $NaAlH_2(OC_2H_4OCH_3)_2$[43,133] than with $LiAlH_4$.

In some cases, reductive cleavage to an alcohol and a secondary amine was observed; thus, the reduction of diphenylformamide with $NaAlH_2(OC_2H_4OCH_3)_2$ affords diphenylamine as the major product, together with the expected N-methyldiphenylamine[133].

One of the important reactions of tertiary amides is their partial reduction to aldehydes by metal hydrides. For this purpose, different routes have been earlier recommended, based on the partial reduction of the corresponding N-acylcarbazoles[134], N-acylimidazoles[135], 1-acylaziridines[136], 1-acyl-3,5-dimethylpyrazoles[137], or N-methylanilides[138,139,140] with $LiAlH_4$. Recently it has been shown[5,6,141,142] that dimethylamides of aliphatic, alicyclic, aromatic, and heterocyclic acids could be, with some exceptions, readily converted into the corresponding aldehydes in yields ranging from 60 to 90% using $LiAlH_2(OC_2H_5)_2$ or $LiAlH(OC_2H_5)_3$ in ether solution at 0°.

Cyclohexanecarboxaldehyde[6]:

A 1.25 *M* solution (300 ml) of lithium aluminohydride in ether is placed in a 1000-ml, three-necked flask equipped with condenser, mechanical stirrer, and dropping funnel. The flask is cooled by an ice bath. To the stirred solution is added ethyl acetate (49.6 g, 0.563 mol) over a period of 2 hr and the reaction mixture is stirred for 30 min at 0°. To the stirred slurry of *lithium triethoxyaluminohydride* thus prepared is added, with ice-cooling, N,N-dimethylcyclohexanecarboxamide (58.2 g, 0.375 mol) at such a rate that vigourous refluxing of the ether is avoided. The reaction mixture is stirred for 1 hr and then decomposed by the addition of 5 *N* sulfuric acid. The ether layer is separated and the aqueous layer extracted with ether (2 × 100 ml). The combined ether layers are washed with water, shaken with solid sodium hydrogen carbonate, washed again with water, and dried with sodium sulfate. The ether is distilled and the residue distilled in vacuo; yield: 32.8 g (78%; cf. also Ref.[5]); b.p. 74–78°/20 mm; n_D^{20}: 1.4499.

The hydrides $LiAlH_2(OC_2H_5)_2$ and $LiAlH(OC_2H_5)_3$ proved to be also suitable for the preparation of chloro- or thio-substituted aliphatic aldehydes or those containing isolated double bonds, which aldehydes are hardly accessible by the Rosenmund synthesis. *o*-Chloro-, *o*-methoxy-, and *p*-nitro-sub-

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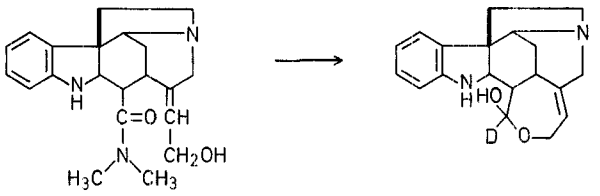
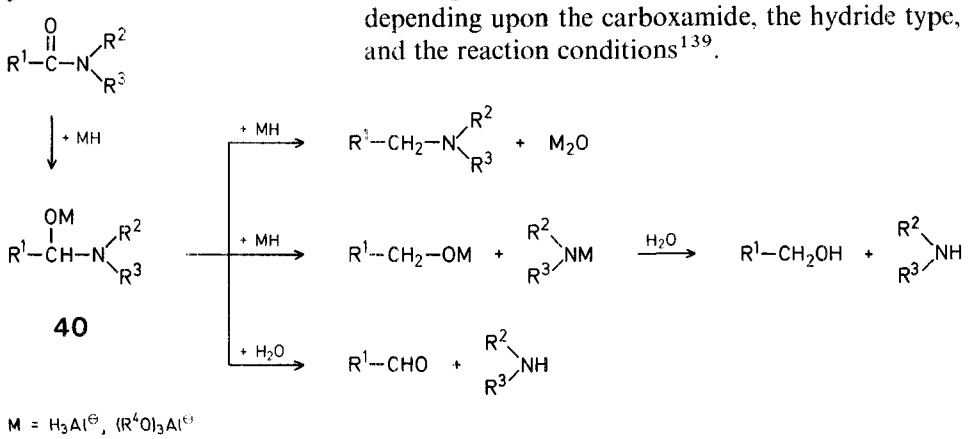
stituted benzaldehydes were also prepared in high yields[5,6]. Similarly, N,N-dimethyldifluoroacetamide was successfully reduced by $LiAlH_2(OC_2H_5)_2$ to difluoroacetaldehyde[143]. Using the same procedure, the N,N-dimethylamide of 18-hydroxy-2β,16α-cur-19-en-17-oic acid (**38**) could be reduced with $LiAlD_2(OC_2H_5)_2$ (Scheme **P**) affording 17-deuterio Wieland-Gumlich aldehyde (**39**) in 55% yield[144].



38 **39**

Scheme **P**

Results similar to those obtained using $LiAlH(OC_2H_5)_3$ in ether were observed in the reduction of N,N-dimethylbutanamide with $NaAlH(OC_2H_5)_3$ in tetrahydrofuran; somewhat lower yields of butanal were obtained by the reduction with $NaAlH(OCH_3)_3$[145].



M = $H_3Al^{\ominus}$, $(R^4O)_3Al^{\ominus}$

Scheme **Q**

On the other hand, both $LiAlH_2(OC_2H_5)_2$ and $LiAlH(OC_2H_5)_3$ fail to reduce conjugated dimethylamides to the corresponding conjugated aldehydes; thus, the reduction of N,N-dimethylcrotonamide affords no crotonaldehyde, and cinnamaldehyde is obtained in only 7–9% yield[6] from the reduction of N,N-dimethylcinnamamide. Similarly, the reduction of dimethylamides of β,γ- and γ,δ-unsaturated cyclopentenyl- and cyclohexenylacetic acids with $LiAlH_2(OC_2H_5)_2$ gives low yields of the unsaturated aldehydes[146] and thus in this case the reduction of the corresponding N-methylanilides is recommended.

Relatively low yields of butanal[6] (41%) and trimethoxyacetaldehyde[147] (45%) are obtained by reduction of the corresponding dimethylamides with $LiAlH_2(OCH_3)_2$.

In some cases, N-methylanilides were used instead of dimethylamides for the aldehyde synthesis; thus, $NaAlH_2(OC_2H_4OCH_3)_2$ reduces, as does $LiAlH_4$, N-methyl-N-phenylbenzamide to benzaldehyde or a mixture of benzyl alcohol and benzaldehyde, together with deacylated amine[133]. N-Methylanilides of N,N-disubstituted amino acids undergo a similar reaction on using $LiAlH(OC_2H_5)_3$ as the reducing agent; the yields of the corresponding aldehydes, however, in any case do not surpass those obtained with $AlH(i\text{-}C_4H_9)_2$[113].

Of all mechanisms proposed for the reaction between N,N-disubstituted carboxamides and metal hydrides, that of Weygand (Scheme **Q**) seems to best explain the formation of different products depending upon the carboxamide, the hydride type, and the reaction conditions[139].

According to this theory, a common single intermediate complex (**40**) is formed in the first step of the reaction; this intermediate can then react in three ways, affording either aldehyde plus secondary amine, alcohol plus secondary amine, or tertiary amine.

Lactams and imides are readily reduced by $NaAlH_2(OC_2H_4OCH_3)_2$ to the corresponding cyclic imines in high yields[133].

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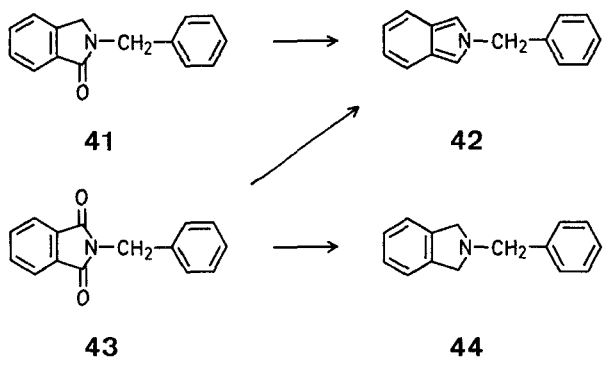
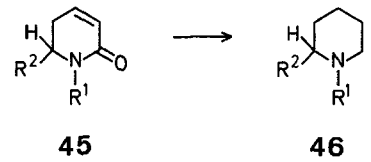
Treatment of N-benzylphthalimidine (**41**) or N-benzylphthalimide (**43**) with $NaAlH_2(OC_2H_4OCH_3)_2$ (Scheme **R**) affords N-benzylisoindole (**42**), whereas the reduction of the imide compound (**43**) with $LiAlH_4$ gives only N-benzylisoindoline (**44**)[148].



Scheme **R**

In a number of unsaturated lactams (**45**), the carbonyl group is simultaneously reduced (Scheme **S**) with the double bond, regardless of the hydride used. The highest yields (84%) of the corresponding substituted piperidines (**46**) are obtained with $LiAlH_3(OC_2H_5)$ and $LiAlH_4 \cdot 2\ AlCl_3$[149].



R^1 = $-C_6H_5$, $-CH_2-C_6H_5$

R^2 = CH_3, C_6H_5

Scheme **S**

3.8. Reactions with Nitriles

Aliphatic nitriles with relatively acidic hydrogens at C-α give only traces of aliphatic amines in the reduction using $NaAlH_2(OC_2H_4OCH_3)_2$[43,133]. Because of the low yield of amine and the large evolution of hydrogen observed when using $LiAlH_4$[100], $LiAlH_4$-$AlCl_3$ complex is recommended for the reduction of aliphatic nitriles to amines[150]. $LiAlH(OCH_3)_3$[100] or AlH_3[39] also appear promising for this use, whereas $LiAlH(O—t\text{-}C_4H_9)_3$ does not react with aliphatic and aromatic nitriles. A nitrile group directly bound to the aromatic ring is reduced to an amine group by $LiAlH(OCH_3)_3$[33,39] or $NaAlH_2(OC_2H_4OCH_3)_2$[36,43,133] as well as by AlH_3[39], $LiAlH_4$[151,152], or $NaAlH_4$[153]. In the series of the heterocyclic nitriles, 3,5-dicyano-1,4-dihydropyridine is obtained as the sole product in excellent yield by reduction of 3,5-dicyanopyridine with $NaAlH_2(OC_2H_4OCH_3)_2$; other hydrides give mixtures of products[154]. The reductions of 3-cyanofuran and 3-cyanothiophene with this hydride afford 3-formylfuran and 3-formylthiophene in yields surpassing those obtained by other available methods[155].

Of special interest is the partial reduction of nitriles, which makes widely varying structural types of aldehydes easily accessible. In contrast to $NaAlH(OC_2H_5)_3$, which is used with great success in the aromatic and heterocyclic series but gives unsatisfactory results in the conversion of aliphatic nitriles[21,22,25], $LiAlH(OC_2H_5)_3$ reduces not only aromatic but also aliphatic nitriles within one hour to the corresponding aldehydes in 68–96% yields. Normal addition of the nitrile (1 mol per mol of the reagent) to the hydride solution in ethyl ether at 0° was found most suitable[3,4,156]. The partial reduction fails in the case of phenylacetonitrile[4], *o*-phthalodinitrile, and 9-cyanofluorene[25]. A higher yield of cyclopropanealdehyde is obtained from the corresponding nitrile with $LiAlH(O—t\text{-}C_4H_9)_3$ than with $LiAlH(OC_2H_5)_3$[4].

3,3-Dimethylbutanal (Pivalaldehyde)[4]:

A solution (300 ml) of lithium aluminohydride (0.3 mol) in ether is placed in a 1000-ml flask equipped with condenser, stirrer, thermometer, and dropping funnel. A nitrogen atmosphere is maintained throughout the reaction. To the stirred solution, ethyl acetate (39.6 g, 0.45 mol) is added at 3–7° over a period of 30 min. Stirring is continued for 30 min. To the stirred slurry of *lithium triethoxyaluminohydride* thus prepared, trimethylacetonitrile (24.9 g, 0.3 mol) is added over a period of 5 min., whereby the temperature is raised to 10° and a highly viscous solution is formed. The reaction mixture is stirred at 0° for 1 hr, and then decomposed by the addition of 5 *N* sulfuric acid (300 ml). The ether layer is separated and the aqueous layer extracted with ether (3 × 50 ml). The combined ether layers are washed with saturated sodium hydrogen carbonate solution (once) and with water (8 × 50 ml). The ether layer is dried with sodium sulfate and distilled through a Todd fractionating column; yield: 25.8 g (74%); b.p. 70.0–72.5°/747 mm; n_D^{20}: 1.3794.

4-Methylbenzaldehyde[24]:

4-Methylbenzonitrile (5 g, 42 mmol) is added under a nitrogen atmosphere to a solution of sodium triethoxyaluminohydride (13 g, 70 mmol) in tetrahydrofuran (50 ml). The temperature raises to 40° and the mixture, which is protected from moisture, becomes brown-yellow. After 2 hr, the mixture is poured into dilute sulfuric acid at 0° and extracted thoroughly with ether. The ethereal extract is washed and dried with sodium sulfate. The ether is distilled and the residue repeatedly fractionated under normal pressure; yield: 3.7 g (72%); b.p. 200–202°; 2,4-dinitrophenylhydrazone, m.p. 236°.

3.9. Reactions with Alkyl and Aryl Halides

$LiAlH(OCH_3)_3$ shows greater reducing power than $LiAlH_4$ in the reaction with 4-bromotoluene, which affords toluene in 59% yield [$LiAlH(OCH_3)_3$] in comparison to 7% with $LiAlH_4$[157]. $NaAlH(OC_2H_5)_3$ was also found suitable for the reduction of aromatic halides. It reduces bromobenzene and iodobenzene to benzene in 41 and 96% yield, respectively, but fails to react with chlorobenzene[25].

The reducing power of $NaAlH_2(OC_2H_4OCH_3)_2$ toward aliphatic halides is almost the same as that of $LiAlH_4$. Similarly to the case with $LiAlH_4$, an

elimination reaction competes with the reduction of vicinal aliphatic or alicyclic dihalides to hydrocarbons. In comparison with $LiAlH_4$, however, substantially shorter reaction times and a smaller excess of the hydride can be used, and higher yields of hydrocarbons are obtained in the reduction of aromatic halides with $NaAlH_2(OC_2H_4OCH_3)_2$[28,43,158]. Moreover, if instead the half-methanolyzed hydride prepared *in situ* corresponding to the above reagent is used, practically quantitative yields of the dehalogenated hydrocarbons are obtained from 1-bromoheptane, bromobenzene, or benzyl chloride; and *m*-bromochlorobenzene and chlorobenzene are reduced within 1hr to chlorobenzene and benzene in 94 and 14% yields, respectively. The latter yields are not achieved with other hydrides. The half-hydrolyzed hydride can also be used in these reactions[159].

Using $NaAlH_2(OC_2H_4OCH_3)_2$, poly-(vinyl chloride) is dehalogenated to the fully saturated polymer in a yield higher than 95%; in this case, $LiAlH_4$ gives a lower yield and the product contains double bonds in the chain[160].

3.10. Reactions with Epoxides

Epoxides are reduced by $LiAlH(OCH_3)_3$ more slowly than by AlH_3 or $LiAlH_4$[20,33,39,100]. With $LiAlH(O—t\text{-}C_4H_9)_3$, the reduction is still slower and thus provides a means of selectively reducing aldehyde or ketone groups in the presence of the oxirane ring[9,39]. Nevertheless, if prolonged reaction times are used, high yields and high stereoselectivity are obtained in the reduction of epoxides using $LiAlH(O—t\text{-}C_4H_9)_3$[9,39]. Whereas in the reduction of styrene oxide with the latter reagent, only secondary alcohol is obtained, using $LiAlH(OCH_3)_3$, $LiAlH_4$, AlH_3, and $HAlCl_2$, the primary alcohol is formed in 1, 4, 24–26, and 95–99% yields, respectively[20,33,100]. A comparative study of the reactivities of alkoxyaluminohydrides H_2AlOR and $HAl(OR)_2$ ($R = CH_3$, $i\text{-}C_3H_7$, $t\text{-}C_4H_9$) and of hydridoaluminum halides H_2AlX and $HAlX_2$ (X = Cl, Br, J) towards 2-*t*-butyl-3,3-dimethyloxirane (*β*-diisobutylene oxide) and styrene oxide shows that the hydride reactivity incerases in the order

$$HAl(OR)_2 \approx H_2AlOR \approx AlH_3 < H_2AlX < HAlX_2$$

and can be correlated with increasing Lewis acidity of the reagents[19,20].

$NaAlH_2(OC_2H_4OCH_3)_2$ generally gives higher yields of secondary alcohols in the reductions of styrene oxide, propylene oxide, and 1-butene oxide than does $LiAlH_4$ or $LiBH_4$. In the case of aliphatic epoxides, however, the selectively formed propan-2-ol and butan-2-ol are accompanied by a small amount (1–5%) of ethanol and propan-1-ol, respectively, produced by a novel C—C bond cleavage[161].

3.11. Reactions with Quinones

In the reduction of *p*-benzoquinone, one equivalent of $LiAlH(OCH_3)_3$ is used for reduction and another for hydrogen evolution; thus, reduction to the hydroquinone stage takes place[33]. With $LiAlH(O\text{-}t\text{-}C_4H_9)_3$, however, no hydrogen is evolved, and side reactions are believed responsible for this course of the reaction[9]. In the reduction of anthraquinone with $LiAlH(OCH_3)_3$, a complicated stoichiometric relationship is noted, which is compatible with the observed formation of equal amounts of both 9,10-dihydroxyanthracene and 9.10-dihydroxy-9,10-dihydroanthracene[33].

3.12. Reactions with Nitro Compounds and Their Derivatives

Aliphatic nitro compounds are reduced by $LiAlH(OCH_3)_3$[33,39,100], $NaAlH(OC_2H_5)_3$[25], or $NaAlH_2(OC_2H_4OCH_3)_2$[43,162,163], as well as by $LiAlH_4$, to amines. Similarly to $LiAlH_4$, $LiAlH(OCH_3)_3$ reacts only slowly with nitrobenzene, azobenzene, or azoxybenzene[100], and $LiAlH(O—t\text{-}C_4H_9)_3$ fails to react with these compounds[9,100]. No attempts have so far been made to utilize the latter hydride for selective reductions in the presence of these groups. In one case, namely in the reduction of nitrobenzene to azobenzene, the use of $NaAlH(OC_2H_5)_3$ is also mentioned[25].

The reverse addition of nitroarenes to 2 equivalents of $NaAlH_2(OC_2H_4OCH_3)_2$ affords azo compounds in yields comparable with those obtained with $LiAlH_4$[28,163]. Using 1.5–1.8 equivalents of $NaAlH_2(OC_2H_4OCH_3)_2$, however, azoxy or hydrazo compounds are obtained[43,162,163]. In the reduction of halogenated nitroarenes with this hydride, iodine and bromine are always eliminated but chlorine is retained. The reduction of 2,2′-dinitrobiphenyl affords benzo[*c*]cinnoline in good yield[163].

3.13. Reactions with Other Nitrogen Compounds

Aldoximes and ketoximes are rapidly reduced by $NaAlH_2(OC_2H_4OCH_3)_2$ to amines in yields higher than or comparable to those obtained with $LiAlH_4$[36,43,133]. Although both $LiAlH(OCH_3)_3$ and $LiAlH(O—t\text{-}C_4H_9)_3$ evolve hydrogen with oximes, no reduction to amines is observed[39,100].

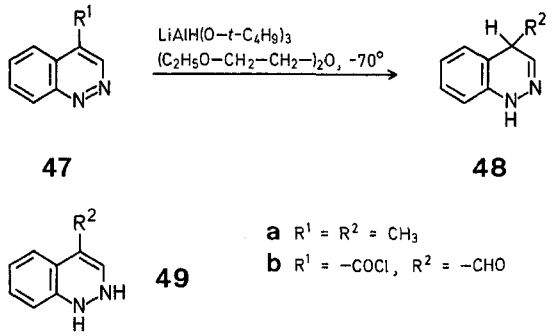
Phenyl isocyanate reacts with $LiAlH(OCH_3)_3$ as well as with $LiAlH_4$ or AlH_3 with formation of N-methylaniline, whereas with $LiAlH(O—t\text{-}C_4H_9)_3$ the reaction stops at the formanilide stage[39,100].

Pyridine N-oxide and its 3- or 4-methyl derivatives react with $NaAlH_2(OC_2H_4OCH_3)_2$ as with $LiAlH_4$ giving a mixture of piperidine, 1,2,5,6-tetrahydropyridine, and pyridine or their derivatives. Pyridine or substituted pyridines are the main products. In contrast to the reactions with these hydrides, AlH_3

affords mainly 1,2,5,6-tetrahydropyridine or its methyl derivatives[164]. Pyridine N-oxide is inert toward $LiAlH(O—t\text{-}C_4H_9)_3$[39].

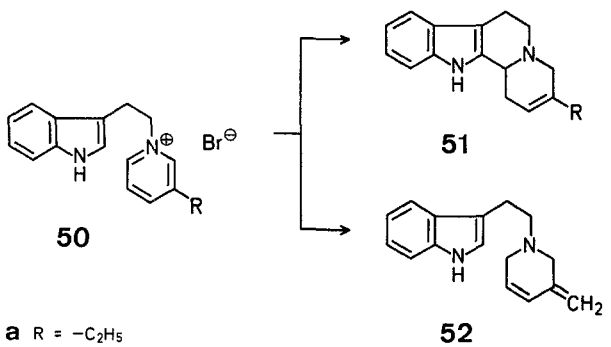
N-Alkoxypyridinium salts are reduced by $NaAlH_2(OC_2H_4OCH_3)_2$ to the same mixture of products as is obtained from pyridine N-oxide, but in this case piperidine is obtained as the main product in a yield higher than with $NaBH_4$[164].

Dihydrocinnoline derivatives which were obtained by the reduction of the corresponding cinnolines (**47**) with $LiAlH(O—t\text{-}C_4H_9)_3$ (Scheme **T**) and assigned the 1,2-dihydro structure (**49**)[165] have since been shown by N.M.R. spectrometry to have 1,4-dihydro structures (**48**)[166].



Scheme **T**

$LiAlH(O—t\text{-}C_4H_9)_3$ has also been successfully applied to the synthesis of indoloquinolizine derivatives from the corresponding pyridinium salts; reductive cyclization of 3-ethyl-1-[2-(3-indolyl)-ethyl]-pyridinium bromide (**50a**) in tetrahydrofuran (Scheme **U**) leads to the tetracyclic 3-ethyl-1,4,6,7,12, 12b-hexahydroindolo[2,3-*a*]quinolizine ("hydroflavopereirine", **51a**)[167]. On the other hand, the reduction of the corresponding 3-hydroxymethylpyridinium bromide (**50b**) affords a mixture of a diene (**52**; 17%) and an allylic alcohol (**51b**; 28%), whereas the acetoxy derivative (**50c**) affords diene **52** exclusively, in 30% yield[168].



Scheme **U**

[162] M. Kraus, K. Kochloefl, Collect. Czech. Chem. Commun. **34**, 1823 (1969).

[163] J. F. Corbett, Chem. Commun. **1968**, 1257.

3.14. Reactions with Sulfur Compounds

$LiAlH(OCH_3)_3$ reduces aliphatic and aromatic disulfides to mercaptans and sulfoxides to sulfides as rapidly as $LiAlH_4$; on the other hand, no reaction is observed with sulfides, sulfones, sulfonic acids, or tosylates[33,40]. $LiAlH(O—t\text{-}C_4H_9)_3$ reduces aromatic disulfides more slowly than $LiAlH(OCH_3)_3$ and only negligible formation of alkylmercaptans is noted in the reduction of alkyl sulfides. Because of inertness of $LiAlH(O—t\text{-}C_4H_9)_3$ toward other sulfur compounds, this hydride can be utilized for selective reductions in the presence of these groups[39,100].

3.15. Reactions with Hydrocarbons

An alkoxyhydride complex formed from $LiAlH_4$ and diethylene glycol monoethyl ether (carbitol) reduces acenaphthylene to acenaphthene in 97% yield and 9,9′-bifluorenylidene to 9,9′-bifluorenyl[13].

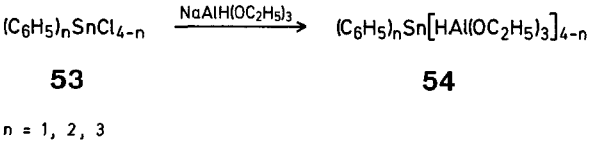
The reduction of methyltropylium perchlorate with $LiAlH(O—t\text{-}C_4H_9)_3$ affords, in contrast to $LiAlH_4$, $NaBH_4$ or $(C_6H_5)_2SnH_2$, a mixture of 1-, 2-, and 3-methyltropylidenes free of the 7-isomer[169].

3.16. Reactions with Organometallic Compounds

The reduction of phenyl-(1-phenylethyl)-phosphinyl chloride with $LiAlH(O—t\text{-}C_4H_9)_3$ affords two diastereoisomeric phenyl-(1-phenylethyl)-phosphine oxides[170].

A series of halogenosilanes was successfully reduced by $NaAlH_2(OC_2H_4OCH_3)_2$ in ethyl ether or aromatic hydrocarbons to silanes in yields comparable with those obtained with $LiAlH_4$[28,158]. In contrast to $LiAlH_4$, no side reactions in the reduction of alkoxychlorosilanes with $LiAlH(O—t\text{-}C_4H_9)_3$ to alkoxysilanes are observed; an exception has been noted in the case of ethoxychlorosilanes, where a partial replacement of the ethoxy groups by tertiary butoxy groups takes place[171].

In contrast to $LiAlH_4$, which reduces phenyltin halides (**53**) to phenyltin hydrides, $NaAlH(OC_2H_5)_3$ (Scheme **V**) replaces all chloro atoms in **53** by the hydride anion to give **54**[172].



Scheme **V**

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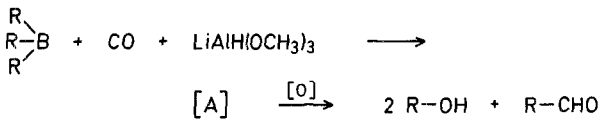
The acid chloride of (carboxycyclopentadienyl)-manganese tricarbonyl can be selectively reduced with $LiAlH(O—t\text{-}C_4H_9)_3$ to give the corresponding aldehyde in 68% yield[173].

$LiAlH_2(O—t\text{-}C_4H_9)_2$, $LiAlH_2(OC_6H_5)_2$, $LiAlH(O—t\text{-}C_4H_9)_3$, $NaAlH(O—t\text{-}C_4H_9)_3$, $AlH(O—t\text{-}C_4H_9)_2$, and $LiAlH(O—t\text{-}C_4H_9)_3—AlH_3$ form complexes with organometallic compounds or salts of metals such as iron, nickel, cobalt, titanium, or chromium. These complexes have been recommended as powerful catalysts to increase the rate of the homogeneous hydrogenation of olefins and diolefins with conjugated double bonds (by a factor of 10^2–10^3 in comparison with heterogeneous systems and by a factor of more than 10 compared with other homogeneous systems). Aromatic hydrocarbons are not hydrogenated in the presence of these complexes. The rate of hydrogenation using some of these catalysts is much higher than the rate of hydrocarbon isomerization[174,175,176].

A convenient route for the conversion of olefins into aldehydes is via olefin hydroboronation and carbonylation of the organoboranes in the presence of an equimolar amount of $LiAlH(OCH_3)_3$ (Scheme **W**). In the presence of this hydride, the latter reaction generally proceeds at a rapid rate at 0–25° and the oxidation of the intermediate product [A] (of unknown structure) with hydrogen peroxide produces aldehydes in 87–98% yields[177].



Scheme **W**

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