Solutions of Lithium Tetrahydrido Aluminates in Ethers: a $^7$Li and $^{27}$Al NMR Study

Heinrich Nöth*, Robert Rurländer, and Peter Wolfgardt
Institute of Inorganic Chemistry, University of Munich, Meiserstraße 1, D-8000 Munich 2

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Solutions of LiAlH$_4$ in tetrahydrofuran (THF), glycoldimethylether (monoglyme), diglycoldimethylether (diglyme) and triglycoldimethylether (triglyme) as well as solutions of LiAIH$_4$/THF in toluene have been investigated by $^7$Li and $^{27}$Al NMR. It was found that $^{27}$Al is nearly independent of the solvent as is $^1J$(AlH). However, the line width of the $^{27}$Al NMR signal shows strong solvent influences and, in addition, concentration and temperature dependences. Intermolecular hydride exchange becomes rapid in solutions of monoglyme and triglyme at room temperature. This can also be shown by the H/D exchange between LiAIH$_4$ and L$^1$AIH$_4$. $^7$Li NMR data indicate that Li is hexacoordinated in the series of glycoldimethylethers, and LiAIH$_4$ in diglyme seems to be the system in which the AlH$_4$ moiety is least affected by ion pair or triple ion formation.

A better understanding of reductions by simple and complex metal hydrides may result from a more detailed knowledge of their solutions in aprotic solvents. In spite of the widespread use of these materials astonishingly little is known about the various species which are present in their solutions, e.g. the extent of dissociation and association, ion pair formation, etc.

Early studies on LiAIH$_4$ in diethyl ether have recognized the association of this complex hydride [1], and this was fully confirmed in more recent investigations under more rigorous conditions [2]. The suggestion [3] that the solvent, e.g. THF, coordinates not only with the Li ion but also with the Al atom of LiAIH$_4$ was clearly disputed by $^{27}$Al NMR data. Hermanek et al. [4] and Wolfgardt [5] have shown that $^{27}$Al of MAI$_4$ is nearly independent of the solvent used. However, the cation has a significant effect on the line width [4, 5]. And it has been demonstrated that the line width of the $^{27}$Al NMR signal of a LiAIH$_4$ solution in diethyl ether is both temperature and concentration dependent [6]. In addition it is also strongly influenced by the solvent [4, 5, 7]. It decreases as one changes from diethyl ether to tetrahydrofuran (THF) and to diglycoldimethylether (diglyme). This is in consonance with the expected order of solvation of the Li cation.

$^{27}$Al possesses a nuclear spin of $I = 5/2$, and its sensitivity is 0.207 relative to $^1$H. The local field gradient interacts with the quadrupole moment of Al, $Q = 0.149 \cdot 10^{-24}$ cm$^2$, and this allows an efficient magnetic relaxation mechanism. Under the limits of fast motion [8] the quadrupole relaxation is the predominant relaxation mechanism which determines the line width. High symmetry, e.g. the nearly perfect octahedral symmetry of [Al(OH$_2$)]$^+$ results in very narrow lines, $\sim 3$ cps for this ion [9]. Small lines are also observed for the tetrahedrally coordinated tetrahaloaluminates [10]. Deviations from the ideal symmetry results in considerable line broadening, and, therefore, it is to be expected that the line width of $^{27}$Al and of $^1$Li ($I = 1$, sensitivity 0.294, quadrupole moment $-4.2 \cdot 10^{-26}$ cm$^2$) [8] will be intimately associated with the solution state of LiAIH$_4$.

Since association and dissociation are equilibrium phenomena, and since LiAIH$_4$ in solutions is associated, it was expected that an NMR study of LiAIH$_4$ in various ethers would give information about the species present in solution.

Tetrahydrofuran Solutions of LiAIH$_4$

The chemical shift $^\delta^{27}$Al of LiAIH$_4$ in THF is concentration independent in the range 0.02–6 M. Its value is $98.8 \pm 0.2$ ppm (lit. 97.7 [4], 100 [5]), and the 1:4:6:4:1 – quintet structure is readily recognized, $^1J$(AlH) = 175.5 $\pm$ 1.3 cps (lit. 172 [4], 175 [5]). However, the $^{27}$Al line width proved to be concentration dependent, cf. Fig. 1. There is a drastic decrease in the line width for a saturated solution (5 M) on dilution to 2.5 M; and this may, in part, be due to the viscosity of the 5 M solution.
In spite of the rather wide lines, the splitting of the signal due to Al–H coupling is still clearly observable, and $\delta^{27}\text{Al}$ certainly suggests no solvation of AlH$_4^-$ . Similar to LiAlH$_4$ solutions in diethyl-ether [6] an increase of the line width is observed at higher dilution as shown by the shallow minimum of the curve in Fig. 1.

![Fig. 1. Concentration dependence of the line width of $^{27}\text{Al}$ and $^7\text{Li}$ NMR signal for LiAlH$_4$ solutions in THF at room temperature [10].](image)

The $^7\text{Li}$ NMR signal of the LiAlH$_4$ solutions in THF consists of a single line, and its line width remains the same on $^1\text{H}$ broad band decoupling. This excludes any Li···H···Al interactions even at high concentration consistent with the assumption that Li$^+$ is completely solvated by THF. However, $\delta^7\text{Li}$ changes monotonically by 0.115 ppm to lower field as the 5 M solution is diluted to 0.08 M. On further dilution an increase of the line width is observed. Its minimum is found at higher concentrations as that for the $^{27}\text{Al}$ NMR signal.

Temperature affects both chemical shift and line width of the $^{27}\text{Al}$ NMR signal. Only one solution, 0.16 M in LiAlH$_4$, has been investigated. The shift difference is small, since the $^{27}\text{Al}$ signal moves only from 99.6 ppm at $-30^\circ\text{C}$ to 98.5 ppm at $+60^\circ\text{C}$. The coupling constant remains unaffected. Fig. 2 shows that the change in line width with temperature varies about linearly only between $-30^\circ\text{C}$ and $30^\circ\text{C}$, and a similar though opposite behaviour is observed for the $^7\text{Li}$ line width which increases at higher temperature and remains constant at low temperatures while the signal moves slightly to higher frequencies as the temperature increases.

![Fig. 2. Temperature dependence of the line width of the $^7\text{Li}$ and $^{27}\text{Al}$ NMR signals of a 0.16 M LiAlH$_4$ solution in THF.](image)

Both, the increase in line width with increasing temperature as well as the frequency shift of the $^7\text{Li}$ signal is in consonance with an equilibrium (1) which is shifted to the right hand side at higher temperature.

$$\text{Li}(\text{THF})_n^+ \rightleftharpoons \text{Li}(\text{THF})_{n-\text{m}}^+ + \text{mTHF} \quad (1)$$

**Monoglyme Solutions of LiAlH$_4$**

Glycoldimethylether (monoglyme) represents a bidentate ether and it solvates lithium ions more strongly than ether.

As observed for THF solutions, no significant change of $\delta^{27}\text{Al}$ for LiAlH$_4$ in the concentration range 2.0–0.016 M was found: $\delta^{27}\text{Al}$ 100.9 $\pm$ 0.3 ppm (lit. 100 [4], 101 [5]). Characteristic, however, is the absence of hyperfine splitting at concentrations $>1.1$ M ($20^\circ\text{C}$). At 1 M (see Fig. 3) the expected quintet structure of the signal has emerged, $J(\text{AlH}) = 174.2 \pm 0.2$ cps (lit. 172 [4], 170 [5]) and sharpens as the solution becomes more dilute. The line width of the proton coupled and decoupled $^{27}\text{Al}$ NMR signals are the same for 0.5 M and more dilute solutions. At higher concentrations there is considerable broadening in the proton coupled spectrum, but also a definite increase of the line width for the proton decoupled signal. Fig. 4 shows the results.

In contrast to $\delta^{27}\text{Al}$ we observe a significant low field shift of the $^7\text{Li}$ NMR signal on dilution: $-0.84$ ppm for a 2 M, $-0.60$ ppm for a 0.125 M and $-0.47$ for
a 0.031 M solution. Interestingly, the $^7$Li line width broadens as the solution becomes less concentrated.

The temperature dependence of chemical shifts and line width has been studied for a 0.125 M solution over the temperature range $-30$ to $+70$ °C. The $^{27}$Al NMR signal moves to lower frequencies (from 101.2 to 100.5 ppm) under these conditions without any change in $^1J$(AlH). Surprisingly, an increase in the line width of the $^{27}$Al NMR signal is observed as one progresses from $-30$ °C (25 cps) to $35$ °C (39 cps), followed by a decrease on further raising the temperature (31 cps at $70$ °C) (see Fig. 5). This is an unexpected behaviour as compared with other systems.

Changes in line width of the $^7$Li NMR signal are not very pronounced, and since differences in the line width in coupled and proton broadband decoupled spectra are only marginal, any covalent Li–H–Al interaction can be excluded. However, the line width is definitely smaller at $-30$ °C than at $30$ °C. In addition, the change in $\delta^7$Li is quite drastic, $-1.16$ ppm at $-30$ °C, $0.86$ ppm at $0$ °C, $-0.54$ ppm at $30$ °C and $-0.32$ ppm at $70$ °C, representing 0.9 ppm over a 100 °C temperature range.
This behaviour can be qualitatively understood by a shift towards a highly solvated Li$^+$ and a decrease in exchange rate of the solute with decreasing temperature.

\[ \text{(1)} \]

This type of exchange is slow at low temperature where Li$^+$ is optimally solvated. Under these conditions $^7$Li is highly shielded and the line width small due to high symmetry at this atom. As the temperature is raised the average coordination number for Li decreases, leading to a deshielding of the Li nucleus, reduction of symmetry and favouring the solvent/solvate exchange process.

**Diglyme Solutions of LiAlH$_4$**

The solubility of LiAlH$_4$ in diglycoldimethylether (diglyme) at a given temperature is less than in monoglyme [11]. Saturation at room temperature was reached at 0.83 M. Therefore only a limited concentration range - 0.83-0.013 M - could be investigated. No change of $\delta^{27}$Al was observed ($\delta^{27}$Al 100.6 ± 0.2 ppm; lit. [5] 101) as well as of $^1J$(AlH) (174.0 ± 0.7 cps, lit. 175 [5], 175.2 ± 1.2 cps [12]). The quintet structure of the $^{27}$Al NMR signal due to the Al–H coupling is extremely well resolved as a consequence of the small line width (13 cps) even for a saturated solution. This signal broadens on dilution as shown in Figure 6.

In contrast, the line width of the $^7$Li NMR signal is fairly small at high concentrations and decreases on dilution until a minimum is reached for a 0.1 M solution. Further dilution causes considerable line broadening. Again, no significant change in line width is observed on $^1$H broadband decoupling. No direct correlation exists with the change in the $\delta^7$Li value on dilution which is accompanied by a steady low field shift from —0.98 ppm to —0.82 ppm in the concentration range studied.

The temperature dependence of chemical shifts and line widths has been studied for a 0.41 and a 0.15 M solution. Both show the same trend, e.g. a 1.2 ppm high field shift of the $^{27}$Al NMR signal in the temperature range —30 to +60 °C (101.4 to 100.2 ppm), constancy of $^1J$(AlH) (174.2 cps) and an increase in the line width as shown in Fig. 7. The change in chemical shift as well as its value for $^7$Li are identical for both solutions.

**Triglyme Solutions of LiAlH$_4$**

The concentration range studied for triglycoldimethylether was limited to 0.39-0.013 M due to the

Fig. 6. Concentration dependence of the $^{27}$Al and $^7$Li line width of a LiAlH$_4$ solution in diglyme at 303 K. The change in chemical shift for the $^7$Li signal is also represented.

Fig. 7. Temperature dependence of chemical shift and the line width for the $^7$Li and $^{27}$Al NMR signal as observed on 0.41 and 0.15 M solutions of LiAlH$_4$ in diglyme.

In analogy to the monoglyme solution the $^7$Li signal shifts to higher frequencies (low field) as the temperature is raised, the difference between the two solutions is the smaller line width for the more dilute solution which increases less at higher temperatures.

These data are in consonance with an equilibrium of type (1).

**Triglyme Solutions of LiAlH$_4$**

The concentration range studied for triglycoldimethylether was limited to 0.39-0.013 M due to the
restricted solubility of LiAlH₄ [11]. δ²⁷Al was found to be 101 ppm, independent of concentration at 303 K, ¹J(AlH) = 173 ± 0.4 cps. Fig. 8 demonstrates the behaviour of these rather dilute solutions which reminds to that of LiAlH₄ in monoglyme at much higher concentrations. The line width of the ²⁷Al NMR signal passes through a minimum at 0.2 M solutions. In contrast, the ⁷Li line width increases steadily with dilution (from 2 to 6 cps) while the change in chemical shift is rather small, (δ⁷Li —0.79 ppm at 0.39 M, —0.74 at 0.195 M, —0.66 ppm at 0.05 M, —0.63 ppm at 0.0125 M).

The effect of temperature on the line width was investigated for 0.39 and 0.04 M solutions. δ²⁷Al changes only slightly in both cases. The signal moves 1.5 ppm over a temperature range of 120 °C to high field. Figure 8 represents the change in δ and line width with temperature for the 0.39 M solution.

A decrease in the line width is noted with increasing temperature for the proton decoupled signal until it passes through a minimum at ~10 °C. Further increases in temperature results in a steady line broadening, and at 18 °C the quintet coalesces. At 90 °C there is only a difference of 9 cps between the line width of the two types of spectra.

In contrast, the line width of the ²⁷Al NMR signal shows a steady increase for the 0.04 M solution with decreasing temperature. This leads to a vanishing of the structured quintet at ~70 °C. The reasons for the breakdown of the fine structure for the two examples is different. It is the temperature dependent quadrupole broadening of the signal in the dilute solution which prevents the observation of the quintet structure at low temperature while intermolecular hydride exchange is responsible for the coalescence of the signal in the 0.39 M solution at room temperature.

The ⁷Li NMR signal of LiAlH₄ in triglyme changes with temperature in a similar manner as for the other glycol ethers: A deshielding results with increasing temperature, however, the ⁷Li line width is not strongly affected.

**Diglyme and Triglyme Solutions of LiAlD₄ and LiAlH₄/LiAlD₄**

Hefmanek et al. [4] showed that LiAlD₄ solutions have the same chemical shifts in diglyme as LiAlH₄. They could not detect any fine structure due to Al-D coupling. Our ²⁷Al NMR spectra in diglyme and triglyme both show an isotope shift of the ²⁷Al NMR signal as well as a fine structure resulting from spin-spin coupling. The isotope shift found for LiAlD₄ in these solutions is 0.4 ppm (to lower frequence) – see Figure 10a. The Al-D coupling leads to a nonet, and the intensities found for the lines are in good agreement with the calculated ratio 1:4:10:16:19:16:10:4:1. Due to higher resolution of the signal in diglyme the value of 26.4 ± (0.4) cps for ¹J(Al-H) is most likely the better value than the 25 ± 1.1 cps found in triglyme. Using 175.5 cps for ¹J(Al-H) and the magnetogyric ratios for ¹H and ²H one may expect 27.9 cps for ¹J(Al-D).

The intermolecular hydride exchange was demonstrated by the interaction of LiAlH₄ with LiAlD₄. Under the concentration conditions for rapid
Fig. 10. $^{27}$Al NMR spectra of LiAlD$_4$ and LiAlH$_4$/LiAlD$_4$ solutions (0.6 M) in diglyme at 303 K, the mixture being heated to 60 °C for 17 hours. a) LiAlD$_4$; b) LiAlH$_4$: LiAlD$_4$ = 1:3; c) LiAlH$_4$: LiAlD$_4$ = 1:1; d) LiAlH$_4$: LiAlD$_4$ = 3:1.
hydride exchange of LiAlH₄ in triglyme we observed rapid H/D scrambling in LiAlH₄/LiAlD₄ mixtures, and only a rather broad signal resulted. At more dilute solutions a LiAlH₄ quintet was recorded superimposed on a quartet whose middle lines were split into a triplet by Al–D coupling as expected for the presence of LiAlH₃D.

More information provide the ²⁷Al NMR spectra of such solutions in diglyme as a result of the smaller line width. Since H/D exchange is slow on the NMR time scale we heated the mixture to 60 °C, and equilibrium was achieved in ~100 min. The spectra did not change on keeping the solutions for 17 h at this temperature. Figures 10b–d show the results.

Inspection of Fig. 10d reveals a quintet stemming from LiAlH₄, the presence of LiAlH₃D as a quartet split into triplets of equal intensity due to a single Al–D bond. Moreover LiAlH₂D₂ is also recognised as a triplet superimposed on the LiAlH₄ ²⁷Al NMR signal, each line split into a quintet (ratio 1:2:3:2:1). The presence of LiAlHD₃, a ²⁷Al doublet each split into a septet (1:3:6:7:6:3:1) can be deduced only from the intensity distribution. The presence of LiAlD₄, however, cannot be recognised.

As the ratio of LiAlD₄ increases the proportions of LiAlH₂D₂ and LiAlHD₃ increase respectively in accord with the equilibria

\[
\text{LiAlH}_4 + \text{LiAlD}_4 = \text{LiAlH}_3\text{D} + \text{LiAlH}_2\text{D}_2.
\]

This is indicated by the disappearance of the outer signals of LiAlH₄ for the LiAlH₄ : LiAlD₄ = 1:3 reactions. Fig. 10b indicates the explanation of the experimental spectrum. It should be mentioned that the outermost signals of LiAlH₄ are observed only at higher amplification since its concentration is very low. Moreover it also appears that ³J(Al–H) decreases slightly with increasing D content in AlH₄₋ₓDₓ⁺ and the same holds for ³J(Al–D) with increasing H content; however since the signals for the various species overlap, no reliable values can be given inspite of a resolution of 0.3 Hz per data point.

Attempts to deduce equilibrium constants from the data failed to give satisfying results; however an analysis of the signal heights approaches values expected for statistical scrambling.

Solutions of LiAlH₄ in Other Solvents

A number of ²⁷Al NMR spectra in different solvents have been recorded. No change in the chemical shift ²⁷Al was observed for LiAlH₄ solutions in toluene/THF (LiAlH₄ : THF 1:2) comprising a concentration range from 3.9 to 0.03 M. We believe that the rather high viscosity is at least in part responsible for the enormous line width of 950 cps observed for the ²⁷Al NMR signal at the most concentrated solution; however, an intermolecular hydride exchange may be a contributing factor. No fine structure of this signal was observed at any concentration. However, a steady decrease of the line width results on dilution by recording the ²⁷Al NMR spectrum proton broadband decoupled. Nevertheless the line width never reached a point where one could expect a fine structure in the undecoupled spectrum although the line broadening which we observed at concentrations lower than 0.12 M may be an indication that a quintet structure might arise at even lower concentrations.

Considering the LiAlH₄ : THF-ratio it is of no surprise to find the ⁷Li NMR signal at higher frequencies as compared to a THF solution. At high concentrations this signal is found nearer to tetracoordinated Li and it moves 'downfield' on dilution. The final values observed are 0.96 ppm for the concentration range 0.5–0.03 M. The line width is not very much affected, and, importantly, there is no line sharpening on proton broadband decoupling. Fig. 11 summarizes the observed data.

The following results were obtained in the CW mode, and proton decoupling has not been possible under these circumstances. Spectra with unresolved fine structure will therefore not provide sensible line

Fig. 11. Concentration dependence of chemical shifts and line width for LiAlH₄ in toluene/THF.
Table I. Chemical shifts $\delta^{27}$Al, and line width for some
tetrahydridoaluminate in various solvents ($c = 0.2$ to
0.5 M).

<table>
<thead>
<tr>
<th>Solvent</th>
<th>$\delta^{27}$Al [ppm]</th>
<th>$\gamma$(AlH) $h(1/2)$ [cps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiAlH$_4$</td>
<td>Tetrahydro-</td>
<td>&quot;390&quot;</td>
</tr>
<tr>
<td></td>
<td>pyran</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2-Methyl-</td>
<td>&quot;460&quot;</td>
</tr>
<tr>
<td>NaAlH$_4$</td>
<td>Tetrahydro-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>furan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Monoglyme</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>Diglyme</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>Benzene</td>
<td>205</td>
</tr>
<tr>
<td>(C$_4$H$_9$)$_4$NaAlH$_4$</td>
<td>Diglyme</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Diglyme</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>Benzene</td>
<td>210</td>
</tr>
</tbody>
</table>

width. Some results for NaAlH$_4$ and tetrabutyl-
ammoniumtetrahydridoaluminate are included in
Table I.

Discussion

Inspection of the data presented in this study clearly indicate that solutions of LiAlH$_4$ in ethers vary
with the nature of the ether. The conclusions drawn by Hefmanek et al. [4] are fully confirmed except
for the interpretation of the unresolved signals in diethylether.

$^1$Li chemical shifts not only depend on the solvent used but also on the nature of the counter ion [8]. In
this study the influence of the solvent, concentration and temperature on $\delta^7$Li and the line width can be
explained in terms of an equilibrium of type (1) and its rate of approach.

Since we are dealing here with only one species,
LiAlH$_4$, $\delta^7$Li should reflect the charge density at
this ion and therefore the mean coordination by the ethers. A better shielding would indicate a higher
mean coordination number. According to our data
(see also Table II) the following 'solvation' power
follows: diethylether $< THF <$ triglyme $< dighyme = monoglyme$.

Since it has been shown that 4 molecules of THF coordinate with LiAlH$_4$ [13] the $\delta^7$Li value for ether solutions of LiAlH$_4$ suggests the same coordination.

Since these ethers do not associate with AlH$_4^-$
tetra coordinated Li cations are indicated. The
considerable high field shift of the $^7$Li NMR signal in monoglyme and diglyme is in consonance with
hexacoordinated lithium, and this requires of course
3 molecules of monoglyme or two molecules of
diglyme, these ethers acting as di- and tridentate
ligands, respectively. From this point of view one
can readily understand the $^7$Li chemical shift for
the triglyme solution. Two molecules of this ether
are required for hexacoordinating Li$^+$ but none of
these can exert its maximal dentacity. This, most
likely, will result in a reduced stability of the
complex formed.

As can be learned from the data in Table II there
is a correlation between $\delta^7$Li and the line width of
the $^{27}$Al NMR signal. A better shielded Li cor-
responds to a smaller $^{27}$Al line width. Therefore,
solvation of the Li ion plays an important though
certainly not the only role. One may expect that the
dielectric constant of the solvent will also be of
importance. However, the dielectric constants of
the ethers investigated do not differ greatly and
they are fairly small. Ion pairs and triple ions are
therefore the dominant species present in solution
in the concentration range investigated. The in-
fluence of hexacoordinated Li$^+$ on AlH$_4^-$ is most
likely less pronounced on solvent separated ion pairs
or triple ions than with Li$^+$ at coordination less
than 6. Thus triglyme and THF as solvents are
dissimilar for the shielding of Li but comparable in
its influence of the $^{27}$Al line width. This width is
about four times as large as for monoglyme. Since
$^1$H broad band decoupling has no influence on the
$^7$Li line width it seems that the interaction of the
Li-cations and AlH$_4^-$ anions in the ion pair and triple
ions present in these solutions [13] is less efficient in
these solvents than in the diglyme allowing a more
rapid quadrupol relaxation.

Intermolecular hydride exchange occurs also, as
observed readily at higher concentrations of LiAlH$_4$
in monoglyme, while much lower concentrations are
necessary in triglyme ($\sim 0.3$ M at 303 K) and
diethylether ($\sim 0.15$ M) [6]. This process is accelerated
with increasing temperature but is still slow on the

Table II. Chemical shift and line width for $^{27}$Al and
$^7$Li at comparable concentrations at 243 K.

<table>
<thead>
<tr>
<th>Ether</th>
<th>THF</th>
<th>Mono-</th>
<th>Di-</th>
<th>Tri-</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{27}$Al [ppm]</td>
<td>103.3</td>
<td>99.6</td>
<td>101.2</td>
<td>101.5</td>
</tr>
<tr>
<td>$h(1/2)$Al</td>
<td>400</td>
<td>88</td>
<td>25</td>
<td>17</td>
</tr>
<tr>
<td>$^{27}$Li [ppm]</td>
<td>0.3</td>
<td>0.2</td>
<td>1.13</td>
<td>-1.13</td>
</tr>
<tr>
<td>$h(1/2)$Li</td>
<td>4</td>
<td>1.5</td>
<td>1.6</td>
<td>2</td>
</tr>
<tr>
<td>c M/l</td>
<td>0.06</td>
<td>0.16</td>
<td>0.125</td>
<td>0.15</td>
</tr>
</tbody>
</table>
NMR time scale for a 0.41 M LiAlH$_4$ solution in diglyme. Hydride exchange according to (2) between two negatively charged species would certainly not be a favored process. However, one should bear in mind that this is not an exchange between free anions but rather an exchange in the realm of triple ions, where the cation/anion interaction reduces the effective charge at the anion, and therefore makes the exchange according to (2) more feasible.

Taking this process into account and the formation of triple ions the temperature dependence of the line width observed for $^{27}$Al can be understood, since line narrowing will result with increasing temperature due to the temperature dependence of $T_1$ and line broadening due to triple ion formation and hydride exchange, the latter becoming more prominent with increasing concentration and temperature.

It follows from this study that diglyme is the solvent of choice if properties resulting from a rather undisturbed AlH$_4^-$ are to be investigated.

### Experimental Part

Commercial grade LiAlH$_4$ was recrystallized from ether or diglyme before use and desolvated in a high vacuum system. Solutions were prepared using purified ethers, freshly distilled from LiAlH$_4$. Stock solutions were prepared and analyzed for Li, Al and H$^\circ$.

The chemical shifts refer to Al(OH$_2$)$_6^{2+}$, 1 M aqueous solution of Al(NO$_3$)$_3$, and to Li(OH$_2$)$_6^{+}$ in an 1 M LiCl solution. A minimum quantity of C$_{6}$D$_{6}$ was added to the solutions as lock and for optimizing field homogeneity. As expected, no NOE was observed both for $^{27}$Al and $^7$Li. The conditions for recording the spectra are given in the following sequence: Number of scans (NS), pulse angle (PW in $\mu$s), sweep width (cps), offset (cps), resolution R (cps per data point). The frequencies used were 52.14 MHz for $^{27}$Al and 77.779 MHz for $^7$Li using a BRUKER WP 200 multinuclei FT-NMR spectrometer and 10 mm tubes. CW experiments were carried out using a VARIAN HA 100 instrument and a $^{14}$N probe head. To match the resonance frequency of $^{27}$Al the field strength had to be reduced.

We thank Deutsche Forschungsgemeinschaft for granting the purchase of a BRUKER WP 200 NMR spectrometer. In addition we greatfully acknowledge the financial support of this study by the Fonds der Chemischen Industrie and Metallgesellschaft AG, Frankfurt.
[10] Measurements of $^{27}\text{Al}$ at concentrations smaller than 0.02 M are not only time demanding but result also, in our case, in a rapid increase of the baseline due to the Al content of the glass. This leads to ambiguous results at low concentrations ($10^{-3}-10^{-5}$ M).