NMR STUDY OF 2-ETHYLHEXYLLITHIUM AGGREGATE AND 2-ETHYLHEXYLLITHIUM/LITHIUM 2-ETHYL-1-HEXOXIDE MIXED AGGREGATES

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A ^{1}H, ^{13}C, and ^{6}Li NMR study of 2-ethylhexyllithium showed that 2-ethylhexyllithium exists solely as a hexamer in cyclopentane solution over the temperature range from 25 to –65 °C. Furthermore, 2-ethylhexyllithium and lithium 2-ethyl-1-hexoxide were shown to form mixed aggregates when the alkoxide was formed *in situ* by reacting 2-ethylhexyllithium with 2-ethyl-1-hexanol. A multinuclear, variable temperature NMR study of a sample with an O:Li ratio of 0.2 led to the identification of at least four such aggregates, one of which was found to be a hexamer with the composition $R_5(RO)Li_6$. Studies of samples with higher O:Li ratios, up to 0.8, showed additional mixed aggregates present. All solutions containing mixed aggregates were also shown to contain hydrocarbon soluble lithium hydride. A study of lithium 2-ethyl-1-hexoxide indicated that it aggregates in solution as well.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF ILLUSTRATIONS

Figure Page

CHAPTER I

INTRODUCTION

Alkyllithium Compounds

Organolithium compounds are important reagents for both organic and polymer chemistry.[1-3] A variety of these compounds are available commercially from a number of distributors. The production of organolithium compounds was over 550 tons/year in 1985, and is sure to have increased in the years since, making these compounds standard reagents in most synthetic labs. They find particular use in synthetic processes such as anionic polymerization,[4,5] the manufacture of pharmaceuticals,[6] and the production of fine chemicals. Their use is preferred over other reagents because they are more soluble than other potential reagents, and because they form metalated intermediates *in situ.*

A large body of data regarding structures and aggregation states of organolithium compounds has been accumulated through solid state structural studies,[7,8] theoretical calculations,[9] and NMR studies.[10-16] However, the solution state structures of these compounds are still not well understood.

The goal of this project was to determine the solution state structure of 2-ethylhexyllithium, and mixed alkyl/alkoxy aggregates formed *in situ.* This information is important for understanding the reactivity of these complexes, as well as potentially useful in the design of other similar compounds with specific characteristics tailored for specialized syntheses.

In hydrocarbon solution, alkyllithium compounds, commonly represented as RLi, exist as aggregates $(RLi)_n$ where n is the aggregation state. Dimer, trimer, tetramer, hexamer, octamer, and nonamer aggregates have all been observed.[10,13,17] A number of factors can affect the aggregation states of these compounds including: concentration, temperature, solvent, and the nature of the ligand. It is also not uncommon for multiple aggregates of the same compound to exist simultaneously in solution. The effects of changes in the aforementioned variables have been well documented.

When multiple aggregates are present in the same solution, increasing the concentration favors the formation of larger aggregates, as does lowering the temperature (for hydrocarbon solutions, the opposite is observed for coordinating solvents). The use of a non-coordinating solvent also tends to favor larger aggregates. For example, *t*-butyllithium exists as tetramers in cyclopentane,[18] a non-coordinating solvent, and as monomers in THF and dimers in diethyl ether,[19] both of which are coordinating solvents. The steric bulk of the ligand plays a key role in determining the aggregation state. Less bulky ligands form larger aggregates. For example, the straight chain alkyllithium compound n-propyllithium exists as hexamers, octamers, and nonamers in cylclopentane,[13] where as the more sterically hindered compound *t*-butyllithium exists as tetramers in the same solvent.

Most alkyllithium compounds exist as tetramers and hexamers in hydrocarbon solution. The structure of a tetramer is tetrahedral with the lithium atoms occupying the apices, and the alkyl groups sitting over each of the four triangular faces (see Figure 1). The alpha-carbon, the carbon atom directly bonded to lithium, is bridging three lithium atoms. The structure of the hexamer is octahedral. In this case, the six lithium atoms occupy the apices of an octahedron. The six alkyl groups sit over six of the eight triangular faces, bridging three lithium atoms as in the tetramer. The two empty triangular faces are believed to be opposite each other, possibly leading to non-random intra-aggregate fluxional exchange.

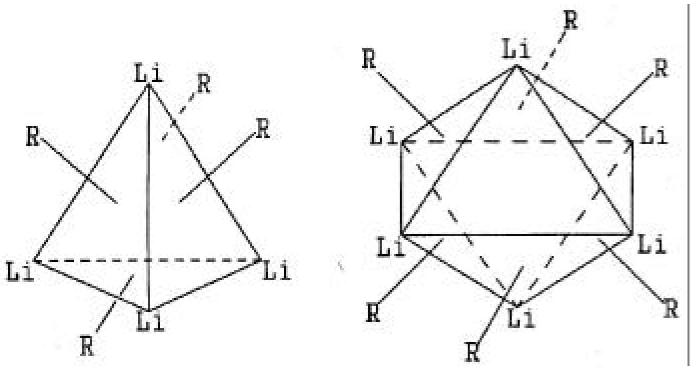

Figure 1 – Shapes for tetrameric (left) and hexameric (right) alkyllithium compounds.

Alkyllithium compounds undergo both inter- and intra-aggregate exchange. The study of intra-aggregate exchange has been primarily limited to tetrameric species because the rate of exchange in larger aggregates tends to be too fast on the NMR timescale to be studied effectively. Some research has been conducted in the area of intra-aggregate fluxional exchange in tetrameric alkyllithium compounds.[20-23] On the other hand, inter-aggregate exchange can be slowed or stopped in many cases even for large aggregates. This is accomplished by dropping the temperature. These processes must be considered when attempts are made to interpret data obtained via NMR spectroscopy.

NMR spectroscopy has been the method of choice for studying alkyllithium compounds.[10,16] In particular, this method allows a significant amount of information to be obtained about carbon-lithium bonding. Carbon-lithium coupling is observed in the ^{13}C NMR spectra of ^{6}Li enriched alkyllithium compounds, the magnitude of which has been used to assign aggregation states. Experimental data has shown the magnitude of coupling to be

$$J_{13C\text{-}6Li} = (17 \pm 2\ \text{Hz}) / n \qquad \text{[eq. 1]}$$

where n is the number of equivalently bonded ^{6}Li nuclei.[24,25] For fluxional aggregates, n is also the aggregation state.

Another method used to determine aggregation states is line-shape analysis.[26] This method examines the number and relative intensities of the peaks in the alpha-carbon multiplet in the ^{13}C NMR spectrum. The number of peaks is governed by the 2nI + 1 rule, where n is the number of equivalently bonded nuclei and I is the spin multiplicity of the bonded nuclei (I = 1 for ^{6}Li). For instance, the alpha-carbon multiplet of a fluxional hexamer will be a thirteen-line multiplet. The relative intensities of each of those lines are a function of the splitting. In the case of the hexamer, the relative intensities of the outermost peaks are so small that those lines are not observed in ^{13}C NMR spectrum due to signal-to-noise issues. Even so, the comparison of simulations of the alpha-carbon multiplet for several different aggregation states with experimental data can be quite definitive.

Some of the most commonly used alkyllithium compounds, such as n-butyllithium, are difficult to study because they do not show ^{13}C-^{6}Li coupling, presumably due to dynamic processes described above. Therefore, other systems, which can be studied effectively, are used as models for the straight chain compounds. Coupling between carbon and lithium has been observed for n-propyllithium, but for longer chains, n-butyl and longer, no coupling information has been obtained.

Alkyllithium/Lithium Alkoxide Mixed Aggregates

Alkyllithium compounds react with oxygen or alcohol to form alkoxides. Those reactions are as follows.

$$RLi + 1/2O_2 \Longrightarrow ROLi \qquad [eq. 2]$$

$$RLi + R'OH \Longrightarrow R'OLi + RH \qquad [eq. 3]$$

Alkyllithium compounds often contain alkoxides as impurities due to mishandling or exposure to air. The result is a change in reactivity of the complex. Presumably, the alkoxide ligands are incorporated into the alkyllithium aggregates according to equation 4.

$$aRLi + bR'OLi \longrightarrow R_a(R'O)_bLi_{a+b} \qquad [eq. 4]$$

Studies of alkyllithium/lithium alkoxide mixed aggregates have been conducted.[27-31] Samples containing these aggregates have been prepared *in situ* by reacting an alkyllithium compound with an alcohol in a controlled fashion as shown in equation 3. The mixed aggregates have been observed to be larger than the all alkyl aggregates. For example, n-propyllithium, a primary alkyllithium compound that exists as hexamers, octamers and nonamers in hydrocarbon solution, reacts with the corresponding alcohol to produce mixed aggregates, one of which is a dodecamer.[31] Also, *t*-butyllithium, a tetrameric species, reacts with the corresponding alcohol to produce *t*-butyllithium/lithium *t*-butoxide mixed aggregates which are both tetramers and hexamers.[30] The *t*-butyllithium/lithium *t*-butoxide mixed aggregates are of the form $R_n(RO)_{6-n}Li_6$, with n = 1,2 and $R_3(RO)Li_4$. In this case, the oxygen atom decreases the steric bulk of the ligand, which allows larger aggregates to form.

Lithium Hydride/Lithium Alkoxide Mixed Aggregates

Solutions containing alkyllithium/lithium alkoxide mixed aggregates have been observed to contain lithium hydride/lithium alkoxide mixed aggregates. This is due to the fact that the alkyl groups in the mixed aggregates more readily undergo beta-hydride elimination. These aggregates are larger than both the all alkyl and the alkyl/alkoxy mixed aggregates. For example, two mixed aggregates of lithium hydride/lithium t-butoxide have been observed and assigned as a decamer and dodecamer in hydrocarbon solvent, even though *t*-butyllithium is tetrameric and lithium *t*-butoxide is hexameric under the same conditions.[33] This class of compounds presents great interest because this is a relatively new way to prepare activated lithium hydride.

2-Ethylhexyllithium and its Mixed Aggregates

The compound 2-ethylhexyllithium was chosen as a model for straight chain systems. Straight chain systems contain multiple aggregates in solution, which are often undergoing rapid exchange. It was hoped that this compound would contain fewer aggregates, possibly only a single aggregate, and that the exchange processes would be slowed, thus allowing for the observation of ^{13}C-^{6}Li coupling.

This thesis presents the study of 2-ethylhexyllithium and mixed aggregates formed by adding 2-ethyl-1-hexanol to 2-ethylhexyllithium in cyclopentane solution. The amount of alcohol added is varied so that solutions containing different concentrations of alkoxide can be studied. For this investigation, the stoichiometric ratio between RLi and ROH is varied between 0 (no alcohol added) and 0.8.

Two lithium alkoxides are synthesized so that comparisons can be made with alkoxides formed *in situ.*

The effect of the chirality of the alkyl group used for this study is also investigated. A similar compound 2-methylbutyllithium, which also contains a chiral center, exhibited chiral properties in both the ^{6}Li NMR spectrum and the ^{13}C NMR spectrum.

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CHAPTER II

EXPERIMENTAL

Introduction

A former group member, Andrea Lay, synthesized the alkyllithium used for this project. The steps involved in that synthesis are included here for completeness. That compound, 2-ethylhexyllithium, was made using the following three steps:

$$\mathrm{RBr} + \mathrm{Mg} \longrightarrow \mathrm{RMgBr} \qquad \text{[eq. 1]}$$

$$2\mathrm{RMgBr} + \mathrm{HgCl_2} \longrightarrow \mathrm{R_2Hg} + 2\mathrm{MgCl_2} \qquad \text{[eq. 2]}$$

$$\mathrm{R_2Hg} + 2\mathrm{Li} \longrightarrow 2\mathrm{RLi} + \mathrm{Hg} \qquad \text{[eq. 3]}$$

Details of this type of synthesis can be found elsewhere.[1,2] Standard precautions were employed for handling of both oxygen sensitive and mercury containing compounds, some of which will be discussed later in detail as they relate to this work. The majority of this project focuses on the study of mixed complexes containing both alkyllithium and lithium alkoxide species. The synthesis of lithium alkoxide was accomplished by reacting the alkyllithium compound with an alcohol according to the following reaction:

$$\mathrm{RLi} + \mathrm{R'OH} \longrightarrow \mathrm{R'OLi} + \mathrm{RH} \qquad \text{[eq. 4]}$$

In this case, R and R' were both 2-ethylhexyl. If an excess of alcohol is used for the reaction in equation 4, it is presumed that the majority of the alkyllithium compound will be converted to lithium alkoxide and hydrocarbon because of its greater basicity. If, however, a less than stoichiometric amount of alcohol is reacted with the alkyllithium compound, the following reaction could take place between the remaining unreacted compound and the alkoxide:

$$\text{RLi} + \text{R'OLi} \Longrightarrow \text{R}_a(\text{R'O})_b\text{Li}_{a+b} \qquad \text{[eq. 5]}$$

The mixed species of interest for this study would be the products of the reaction in equation 5. Solutions potentially containing these aggregates were prepared experimentally by varying the amount of alcohol added in equation 4. The amounts of reactants used to prepare each sample are listed in Table 1.

Table 1 - Description of samples prepared for this study

O/Li	Sample ID	Amount of Alkyl Lithium 2-ethylhexyl lithium	Amount of Alcohol 2-ethylhexanol	Sample Volume (in mL)
0	RP001	0.168g (1.41 mmoles)	none used	0.7
0	RP007	0.168g (1.41 mmoles)	none used	0.7
0.2	RP003	0.168g (1.41 mmoles)	0.036g (0.28 mmoles)	0.7
0.2	RP020	0.738g (6.20 mmoles)	0.161g (1.24 mmoles)	3.2
0.4	RP002	0.168g (1.41 mmoles)	0.073g (0.56 mmoles)	0.7
0.6	RP004	0.168g (1.41 mmoles)	0.109g (0.84 mmoles)	0.7
0.8	RP005	0.168g (1.41 mmoles)	0.146g (1.12 mmoles)	0.7

These amounts were chosen for two reasons. First, since many of the properties of interest in this study are affected by concentration, all samples were prepared to be 2 F (2 M in monomeric RLi). And second, this concentration allows for comparison with other work done with similar compounds.

In addition, all compounds used for this project, which contained lithium, were prepared using 95.5% isotopically enriched ^{6}Li metal (U.S. Services). Both alkyllithium and lithium alkoxide compounds are air and water sensitive, so special precautions were taken to avoid contamination due to unwanted exposure to oxygenated species.

General Precautions

The majority of synthetic work required for this project was carried out either in an inert atmosphere glove box or on a high vacuum line. The work in the glove box was performed under an argon atmosphere. The glove box was equipped with a catalyst capable of removing oxygen and moisture from the atmosphere inside the box. The catalyst consisted of alternating layers of Alpha De-Ox oxygen removal catalyst and type 5A molecular sieves (Fisher Scientific). The catalyst was regenerated before each time the box was to be used, which helped ensure that the atmosphere inside was not contaminated due to saturation of the catalyst. While in use, the argon atmosphere inside was circulated through the catalyst. In general, the introduction of objects into the glove box capable of absorbing large amounts of moisture onto their surfaces was avoided. No wood or paper products were taken inside the glove box; and supplies such as glassware, trays, etc., were dried in an oven for at least two hours at 200 °C before being taken into the anti-chamber of the glove box.

The high vacuum line used for this work was capable of producing pressures as low as 1 x 10^{-6} torr, and was never used if the pressure was above 5 x 10^{-6} torr. Some of the glassware used had to be specially prepared by our glassblower. These and other pieces of glassware were attached to the vacuum line prior to use so that they could be checked for pinholes, which could jeopardize the integrity of the sample.

Storage of the Alkyl Lithium Compound

The alkyllithium compound used for this study was always stored in a refrigerator wrapped in aluminum foil. These precautions were taken to avoid thermal or photochemical decomposition. Our glassblower specially made the vessel, in which the compound was stored. It was capable of holding approximately 30 mL of solution, and was equipped with an inner high vacuum joint. The shape was a cylinder approximately 1.5 cm in diameter and 10 cm in length. The cylinder was connected to the inner high vacuum joint using a 10 cm extension of glass tubing with a diameter of less than 1 cm, which was chosen so that the vessel could easily be sealed.

Each time a new sample was to be prepared, a new vessel had to be made. Both vessels would then be taken into the glove box. The vessel containing the compound was opened by first scoring the neck, and then breaking it. The needed amount of compound was taken; and the remaining compound was transferred to the new vessel. A stopcock was then placed on the vessel. It was brought out of the glove box, degassed, flame sealed, and returned to storage. The amount of time the compound was out of storage was minimized, usually only a few hours.

Preparation of NMR Samples[3]

All glassware used for preparing NMR samples was dried in an oven for at least two hours. The glassware was allowed to cool in a desiccator, or in the anti-chamber of the glove box under a vacuum. These steps, as previously mentioned, were taken to minimize the amount of moisture absorbed onto the surface of the glassware. Once the supplies were placed in the anti-chamber, it was evacuated and then filled with argon from the atmosphere inside the glove box. The anti-chamber was then evacuated again. This process was repeated at least three times before the supplies were taken into the glove box. Finally, the anti-chamber was filled with argon to equilibrate the pressures inside the box and anti-chamber, and the inside door was opened. The supplies were then taken inside the glove box and the door was closed.

The following procedure, used to prepare samples containing mixed aggregates, was carried out inside the glove box. The stopcock, which was to be used on the NMR tube, was greased with suitable high vacuum grease, Apiezon H or N (M&I Materials LTD), H for joints that were not required to move and N for joints that must move, and placed out of the way. A 10 mL beaker was set on the balance. After the balance reading became constant, it was tared to zero. The vessel containing the RLi was opened and the desired amount of the compound was transferred to the beaker using a pipette. The same procedure was used to weigh the desired amount of ROH in a separate beaker. Next, approximately 0.35 mL or 1.5 mL of 10% d^{10}-cyclopentane in cyclopentane was added to each of the two beakers depending on the total volume of the solution needed. Sample volumes for 5mm and 10mm NMR tubes are 0.7 mL and 3.1 mL respectively. The solution of ROH was then transferred to the beaker containing the RLi. The ROH was added to the RLi to avoid highly localized concentrations of oxygen. This procedure was done drop by drop; and each drop was allowed to run down the side of the beaker. After each drop of ROH was added, the beaker was swirled for a few seconds. The reaction between RLi and ROH is highly exothermic; so, if the ROH were added too quickly, it could cause decomposition, which would lead to unwanted side-products, and or cause the solvent to evaporate. After all the ROH solution had been added, the sample was transferred to a NMR tube via pipette. The beaker was then washed with a small portion of solvent, which was also transferred to the NMR tube. The NMR tube had been marked at the desired volume. Enough solvent was then directly added to the NMR tube so that the total volume of the sample reached the marking. Next, a stopcock was placed on the NMR tube, and the sample was brought out of the glove box.

The sample was then placed on the high vacuum line. It was frozen by submerging it in a liquid nitrogen bath. Once frozen, the stopcock was opened, and the NMR tube was left under a vacuum for approximately seven minutes. The main manifold had been separated from the manifold being used by a U-trap submerged in liquid nitrogen. This precaution was taken to ensure that the solvent from the sample did not accidentally get drawn into the vacuum pump. After a few minutes, the stopcock was closed and the liquid nitrogen bath was removed slowly, allowing the sample to thaw. It is important that the sample be thawed slowly to avoid any sudden increases in sample volume, which could cause the NMR tube to rupture. This freeze-pump-thaw process was repeated at least three times on each sample. The sample was then flame sealed on the vacuum line.

Each sample was then wrapped in aluminum foil and stored in the refrigerator. Again, these last precautions were taken to avoid thermal or photochemical decomposition. Samples containing only the alkyllithium compound were prepared in a similar fashion, but without the addition of alcohol.

Synthesis of Lithium 2-ethyl-1-hexoxide

A comprehensive literature search was conducted for this compound. The registry number for lithium 2-ethyl-1-hexoxide is RN = 34689-96-8. Only the three following chemical abstracts references were found: 108:206131, 81:52099, and 76:5531. These three references refer to patents. In each, this compound was used as part of a hydrocarbon gelling system.

All glassware used for this procedure was dried in an oven at 200 °C, and then allowed to cool in a desiccator or under argon flow. The 2-ethyl-hexanol used for the procedure was dried over calcium hydride for one day. A fractional distillation was then used to obtain pure, dried alcohol from the mixture of alcohol and drying agent. Approximately 25 mL of 2-ethyl-hexanol was collected at 181 °C. Next, the solvent, cyclopentane, was dried over calcium hydride, and approximately 150 mL was distilled into a three-neck 500 mL round bottom flask, which had previously been flushed with argon. After adding the solvent, a stir bar was introduced to the flask and rubber septa were placed on the three necks. The septa were secured using wire, and the flask was taken into the glove box. Inside the glove box, 0.32 g (0.0533 moles) of enriched ^{6}Li was cut and added to the reaction flask. The flask was then brought out of the glove box, and a condenser and flow control device were attached.

Next, the system was flushed with argon for 20 minutes. A bubbler was attached to the top of the condenser to ensure that excessive pressure did not build up in the reaction flask. The system was then brought to reflux before proceeding. Next, 1.8 mL (0.0115 moles) of dried 2-ethyl-hexanol was injected into the reaction vessel through the rubber septum. The solution was allowed to reflux for 15 hours, during which time the solution turned yellow and a yellowish-white precipitate formed. The solution was transferred to a flask fitted with a high vacuum joint via a cannula. The flask was then attached to the high vacuum line. Another flask was attached to the line, and submerged in liquid nitrogen. With the manifold isolated, both stopcocks were opened. The solvent transferred to the empty flask leaving behind a dark yellow precipitate.

The flask was taken back into the glove box where an NMR sample of the solid in 10% d^{10}-cyclopentane was prepared in a 5 mm NMR tube. The sample was prepared by adding 0.04 g (0.30 mmoles) of the solid to 0.7 mL of cyclopentane. The original intent was to prepare a 2 F solution (0.2 g in 0.7 mL); however, this small amount of solid did not completely dissolve, so no more solid was added. The concentration of the solution was actually less than 0.4 F. No yield data was calculated for this synthesis. Lithium 2-ethyl-1-butoxide was synthesized using the same procedure outlined above.

NMR Spectrometer Details

All data was acquired on a Varian® VXR-300 spectrometer. Resonance frequencies were approximately 300 MHz for ^{1}H, 75 MHz for ^{13}C, and 44 MHz for ^{6}Li. Two probes were used for these experiments. One was a standard 5 mm tunable, multi-nuclear probe with observe, deuterium lock, and decoupler coils. The other was a tunable, 10 mm multi-nuclear probe, which was similar to the 5 mm probe, but without the deuterium lock coil. Instead, the lock coil was used as a second decoupler coil and tuned for ^{6}Li decoupling. This modification allowed for the simultaneous decoupling of ^{1}H and ^{6}Li nuclei, which was necessary for many experiments related to this research.

Samples were prepared in two different size NMR tubes, 5 mm and 10 mm. Both probes were used to acquire data on samples in 5 mm tubes; however, only the 10 mm probe was used for acquisitions on the sample in the 10 mm tube. Only one of the samples in this study was prepared in a 10 mm NMR tube. The larger tube was chosen because it offers a few advantages, the first of which is the fact that the 10 mm probe was intended for use in conjunction with samples in 10 mm tubes. As stated previously, the 10 mm probe's capability to decouple ^{6}Li made it crucial to this work; and while all experiments requiring lithium decoupling could be run on samples in 5 mm tubes, the probe was not designed for them. Another advantage was the increased signal-to-noise ratio resulting from the increase in sample volume (more compound at the same overall concentration as compared with a 5 mm tube).

The use of a 10 mm tube also had disadvantages, the biggest of which was the large amount of alkyllithium compound needed to prepare the sample. This was an important factor to consider for this and related projects because the synthesis of pure alkyllithium compounds can be difficult and quite time consuming. Another disadvantage, somewhat related to the first, was that if the sample tube was broken during preparation, which occurred more than once in this study with 5 mm tubes, a large amount of compound would be lost. In particular, it was much more difficult to flame seal the 10 mm tube.

Many of the experiments run for this study were performed at low temperatures (-10 to –70 °C). However, the variable temperature (VT) controller on our spectrometer did not register the actual temperature inside the probe correctly. While it did not register the temperature accurately, it did maintain a stable thermal environment. As a result, manual calibration of the temperature inside the probe had to be performed each time a low temperature experiment was to be run. A macro on the VXR-300 computer is capable of calculating the probe temperature by determining the distance between the two peaks in the proton spectrum of methanol. Each time the temperature of the probe was lowered, a standard methanol sample was used to calibrate the exact temperature in the probe.[4] The procedure was to allow the temperature in the probe to reach a constant value, and then insert the methanol sample. The methanol sample was then allowed to reach thermal equilibrium with the probe (approximately 15 minutes). Next, a proton spectrum was acquired, from which the exact temperature inside the probe could be ascertained. After the temperature was determined, the methanol sample was replaced with the sample of interest. It was then allowed to reach thermal equilibrium with the probe (approximately 15 minutes) before any data was acquired.

The probe was cooled using liquid nitrogen. Nitrogen gas was circulated through the probe for this procedure. It was cooled before entering the probe by passing it through a coil on the outside of the spectrometer that had been submersed in liquid nitrogen. The VT unit then controlled the exact temperature inside the probe using a heater to heat the gas to the correct temperature.

NMR Experiments

Various NMR experiments were run on the aforementioned samples including: ^{1}H, ^{13}C with lithium and/or proton decoupling, ^{6}Li with and without proton decoupling, ^{13}C inversion recovery experiments, heteronuclear two-dimensional ^{1}H, ^{13}C chemical shift correlation (HETCOR) with and without lithium decoupling, heteronuclear two-dimensional ^{1}H, ^{6}Li nuclear Overhauser experiments (HOESY), and ^{6}Li *J*-modulated ^{13}C spin echo[5] experiments. Most experiments were performed either at room temperature or at –11 °C. The details of each of those experiments follow.

For ^{1}H NMR experiments the following parameters represent typical values used for acquisitions. The spectral width was approximately 2000 Hz, acquisition time was usually 2 seconds, the pulse width was 1 μs (a flip angle of roughly 2.9°), and 16 transients were collected. Both probes were used to perform these experiments.

Typical values for ^{13}C NMR experiments were spectral widths of roughly 6500 Hz, acquisition times from 0.8 to 3 seconds, pulse widths of 4.9 μs (a flip angle of roughly 21.2°), and anywhere from 128 to 8000 transients were collected depending on the signal-to-noise needed. All ^{13}C NMR experiments were run with proton broadband decoupling. Many ^{13}C NMR experiments were also run with lithium decoupling. This was made possible by the specially configured 10 mm NMR probe. Details of many other experiments possible using this probe can be found elsewhere.[6] Again, the lock coil was replaced with a decoupler coil, which was tuned for ^{6}Li, to which a frequency synthesizer was connected to control the decoupling frequency. The frequency used to decouple lithium was determined by running a ^{6}Li NMR experiment, identifying the desired region in the spectrum to be decoupled, and using a computer macro (SETDMX) to calculate the exact value at which the frequency synthesizer must be set. This method determined the exact frequency of a particular point in the ^{6}Li NMR spectrum, and then the frequency synthesizer was manually set to that frequency. The decoupler frequency synthesizer was set to 43,140,772.7 Hz for all NMR experiments in this study.

The values of parameters for ^{6}Li NMR experiments were spectral widths of 500 Hz, acquisition times of 9.9 seconds, pulse widths of 10 µs (a flip angle of roughly 45.0°), from 1 to 16 transients, and a delay of 20 seconds between scans to allow the magnetization to return to its equilibrium position. These experiments were run in the 10 mm probe. Most experiments were run with proton broadband decoupling; however, a few experiments were run with gated decoupling to check for ^{1}H-^{6}Li coupling. In those cases, the decoupler was turned off during acquisition only. This allowed for the identification of the desired coupling, but also allowed NOE to build up during other times of the experiment, which increased the signal-to-noise ratio.

A set of ^{13}C inversion recovery NMR experiments were run to determine the T_1 times of two peaks in that spectrum. Those times were then used to determine optimal flip angles for the *J*-modulated spin echo experiments. For those experiments, the spectral width was 3910 Hz, the acquisition time was 2.332 seconds, the pulse width was 22 μs, 48 transients were collected, and an array of D2 times (0.01, 0.2, 0.3, 0.4, 1.0 seconds) were used. These experiments were run using the 10 mm probe.

Heteronuclear two-dimensional ^{1}H, ^{13}C chemical shift correlation (HETCOR) experiments were conducted as follows. Both the 5 mm and 10 mm probes were used for these experiments. Some of these experiments were run with lithium decoupling (HTCRLD), which required the use of the 10 mm probe. There were two reasons for doing this. First, since the peaks in the ^{13}C NMR spectrum, which were coupled to lithium, were broad, this method would lead to cross-peaks that were more focused. Second, the increased intensity of the peaks in the ^{13}C NMR spectrum would result in better signal-to-noise ratios. For experiments with lithium decoupling, the spectral widths were 2086 and 5202 Hz for ^{1}H (F1 dimension) and ^{13}C (F2 dimension), respectively. The ^{13}C pulse width was 10.2 μs, ^{1}H pulse (PP) was 30.5 μs, the number of increments was 64, and the number of transients was 128. The acquisition time was 1.993 seconds, and the delay was 2 seconds. For HETCOR experiments without lithium decoupling, the spectral widths were 1600 and 2937 Hz for ^{1}H (F1 dimension) and ^{13}C (F2 dimension), respectively. The ^{13}C pulse width was 22.3 μs, ^{1}H pulse (PP) was 30.5 μs, the number of increments was 32, and the number of transients was 128. The acquisition time was 1.492 seconds, and the delay was 0.5 seconds.

Heteronuclear two-dimensional ^{1}H, ^{6}Li nuclear Overhauser (HOESY) experimental parameters were: spectral widths of 1600 for ^{1}H (F1 dimension) and 120 Hz for ^{6}Li (F2 dimension), ^{6}Li 90° and 180° pulses of 20.0 and 40.0 μs, acquisition time of 1.33 seconds, 16 transients, a delay time of 3 seconds, a mixing time of 2 seconds, 128 increments, and a ^{1}H polarization transfer pulse (PP) of 19.4 μs. This experiment was performed using the 10 mm probe.

The parameters for the ^{6}Li *J*-modulated ^{13}C spin echo experiments were the following. The spectral width was approximately 6500 Hz, the ^{13}C 90° and 180° pulses were 20.8 and 41.6 μs, the acquisition time was 1.5 seconds, and an array of D2 times (0, 0.176, 0.216, and 0.324 seconds) were used. These experiments were performed using the 10 mm probe.

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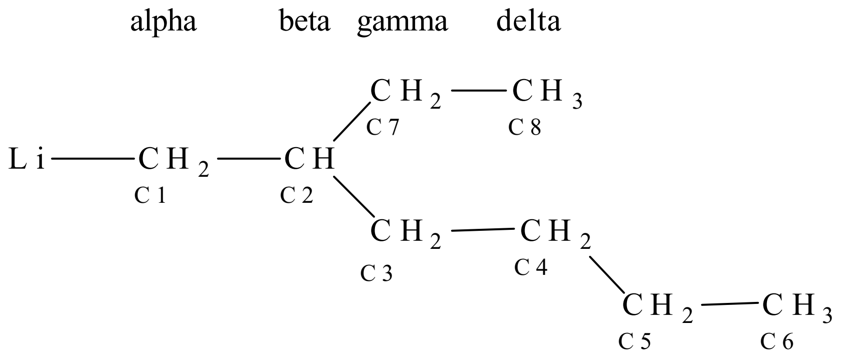
CHAPTER III

RESULTS AND DISCUSSION

2-Ethylhexyllithium

The first compound to be studied for this project was 2-ethylhexyllithium. This is a known compound.[1] A careful study and understanding of this compound's behavior in solution was paramount to future investigations of mixed species. This compound was chosen for this study for two reasons. First, it was thought that branching at the beta-carbon would produce sufficient steric bulk to hinder the formation of large aggregates in solution so often observed in straight chain systems. And second, there was a question of whether the chirality of this compound would have any effect on its properties. To investigate this second issue the results obtained here for 2-ethylhexyllithium, which contains a chiral center, were compared to those of its achiral analog, 2-ethylbutyllithium, and 2-methylbutyllithium both studied elsewhere.

Two samples were prepared for this study. The first was made shortly after the compound had been produced. The second was prepared two years later. The second sample was used to check for decomposition of the original compound before further samples were prepared from that stock. The results of a ^{13}C NMR experiment at room temperature (see Figure 2) on the second sample show nine major peaks, which are at identical chemical shifts as the first sample. These results indicate that no decomposition had occurred. The following is a basic representation of that compound.



Both the Greek and alphanumeric labels will be referred to throughout the discussion that follows. An identical scheme of labeling has been used to identify the carbon atoms in both the parent alkane and the corresponding lithium alkoxide. In the case of the alkane, a hydrogen atom replaces the lithium atom. For the lithium alkoxide, an oxygen atom is inserted between the lithium atom and the alpha-carbon.

The first step in analyzing the sample was to assign chemical shift values in the ^{13}C NMR spectrum (see Figure 2). The spectrum consists of nine major peaks. The large peak at 25.89 ppm is from the solvent, cyclopentane. This peak was used to reference all ^{13}C NMR experiments to TMS (trimethylsilane) by assigning it a value of 25.89 ppm. The other eight peaks are from the compound. Thomas *et al*[2] have outlined a method for assigning ^{13}C NMR spectra of alkyllithium compounds in hydrocarbon solvent based on chemical shift substituent relationships with their parent alkane. The results of those calculations for this compound are listed in Table 2 along with the assignment of peaks in the ^{13}C NMR spectrum for this compound. While those calculations did not lead to definite assignment of all peaks, those in conjunction with an APT experiment did lead to the unambiguous assignment of all peaks.

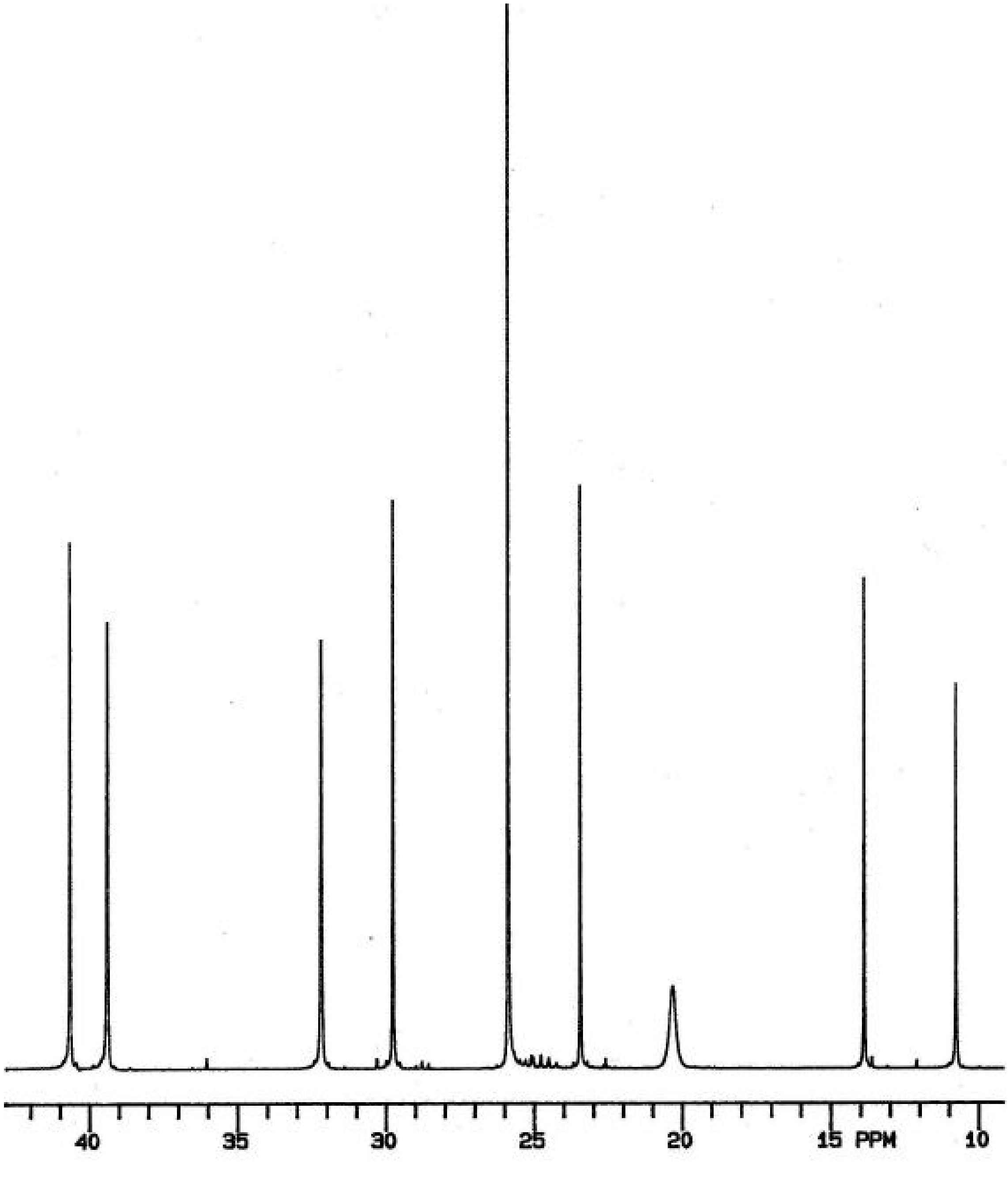


Figure 2 – ^{13}C NMR spectrum of 2-ethylhexyllithium at room temperature.

The quality of the data fit from the calculated values was excellent. The only ambiguity arose with the values of C2 and C3, whose calculated ranges overlapped. Since C2 had one proton attached to it and C3 had two, an APT NMR experiment could be used to make those assignments. Figure 3 shows the APT NMR experiment for this compound. The peak at 39.38 ppm is up indicative of a CH_2 group hence it was assigned to C3, and the peak at 40.65 ppm is down, indicative of a CH or CH_3 group (assigned to C2). Also, the substituent relationships in the aforementioned paper were only given for alpha, beta, gamma, and delta carbons; therefore, there was no basis for calculating the chemical shift values for C5 and C6. One reason for this, which is illustrated by the data presented in Table 2, is that the substituent effects decrease with increasing distance from the replaced atom. Therefore, the values for C5 and C6 were roughly the same for both compounds.

Table 2 - The assignment of ^{13}C NMR chemical shift values for 2-ethylhexyllithium based on theoretical calculations and an APT NMR experiment

	Chemical Shift of Parent Alkane[3]	Calculated Range of Chemical Shift for RLi	Results of APT	Assignment of ^{13}C Chemical Shifts for RLi
C1	19.3	19.9-20.0	(+)	20.3
C2	34.8	39.4-42.9	(-)	40.7
C3	36.7	37.4-45.8	(+)	39.4
C4	29.8	28.4-30.2	(+)	29.8
C5	23.4	no basis for calculation	(+)	23.5
C6	14.2	no basis for calculation	(-)	13.9
C7	29.8	30.6-38.0	(+)	32.2
C8	11.5	10.8-11.9	(-)	10.8

All values are in ppm

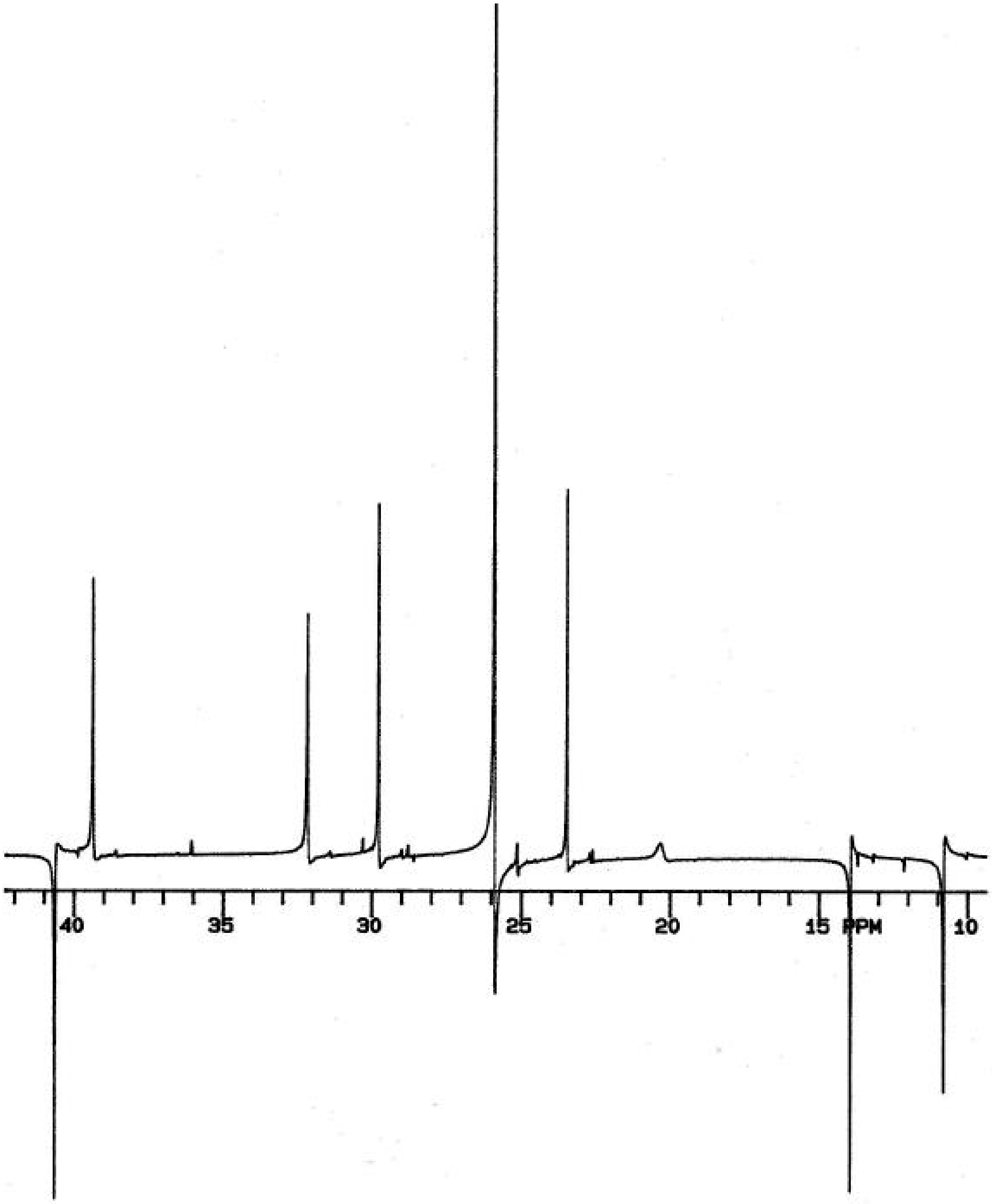


Figure 3 – APT (Attached Proton Test) for 2-ethylhexyllithium at room temperature.

The peak at 20.29 ppm, the alpha carbon, was of extreme interest for this study. It can easily be seen that the peak was broad at room temperature. This was presumed to be the result of unresolved ^{13}C-^{6}Li coupling, which splits the ^{13}C NMR signal according to the 2nI+1 rule, again, where n is the number of equivalent coupled nuclei, and I is the spin multiplicity of the coupled nuclei-in this case I = 1 for ^{6}Li. For example, for a hexamer n = 6 and the signal would be split into a thirteen line multiplet. The presence of carbon-lithium coupling was confirmed with the aid of a ^{6}Li decoupled ^{13}C NMR experiment. The ^{6}Li decoupler was turned on during acquisition and the broad peak in this region collapsed into a single narrow peak, thus confirming that the broadness was due to unresolved ^{13}C-^{6}Li coupling. Since such coupling is normally only observed for the alpha-carbon and since no other peaks showed this behavior, this experiment also confirms this peak as C1.

Alkyllithium compounds often undergo rapid inter- and intra-aggregate exchange on the NMR timescale, making it difficult to observe coupling due to line broadening. This phenomenon leads to a broad signal rather than a well-resolved multiplet. As a result, a series of low temperature experiments, to temperatures as low as –65 °C, were performed on the sample in hopes of slowing the exchange processes sufficiently to observe coupling.

While the coupling constant could be ascertained from the ^{13}C NMR spectrum at –11 °C, the multiplet was never sufficiently resolved to allow for line-shape analysis using a computer program, which is a common method for investigating such matters. At temperatures lower than –11 °C the signal became less resolved again. The observed coupling of 3.12 Hz was consistent with reported values for alkyllithium compounds known to be hexamers,[4] and a structurally similar compound, 2-ethylbutyllithium, investigated by a fellow group member, known to be solely hexameric in cyclopentane solution.[5] Based on this evidence, it was concluded that 2-ethylhexyllithium exists exclusively as a hexameric aggregate in cyclopentane solution. The alpha-carbon peak of this compound shifts upfield as much as 0.3 ppm as the temperature is lowered, however, no new species were formed. Therefore, this compound exists strictly as a hexamer at all temperatures investigated for this study.

The ^{1}H NMR spectrum of this sample at room temperature is shown in Figure 4. The peak at 1.51 ppm is from the solvent. The doublet at –0.81 ppm is from protons on the alpha carbon. It is the only signal that would produce a lone doublet because it is split only by the proton attached to C2. The fact that there was only one signal in this region supports the conclusion reached above that there was a single aggregate in solution. The multiplet at 0.90 ppm is actually two overlapping triplets. This assignment was made based on a HETCOR experiment (Figure 5). According to the HETCOR, this region in the proton spectrum shows correlations with C6 and C8, whose proton signals would be split into triplets by the protons attached to C5 and C7, respectively. The multiplet at 1.14 ppm correlates with C2. The broad multiplet from 1.20-1.40 ppm correlates to C3, C4, C5, and C7. Little effort was made to determine coupling constants of these peaks, as the data was somewhat convoluted. The assignments of all peaks in the ^{1}H NMR spectrum, including coupling constants and signal multiplicities where appropriate, are listed in Table 3.

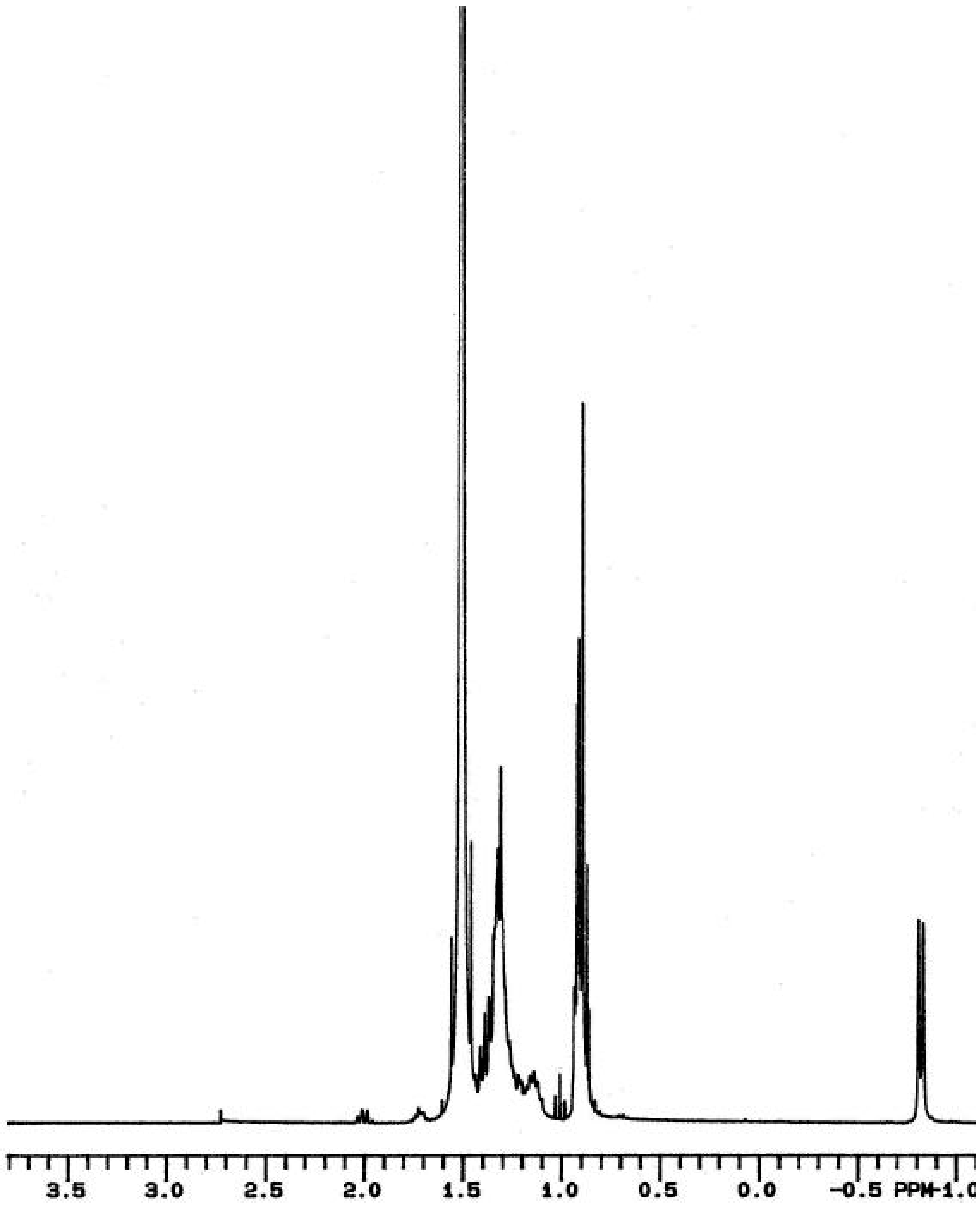


Figure 4 – ^{1}H NMR spectrum of 2-ethylhexyllithium at room temperature.

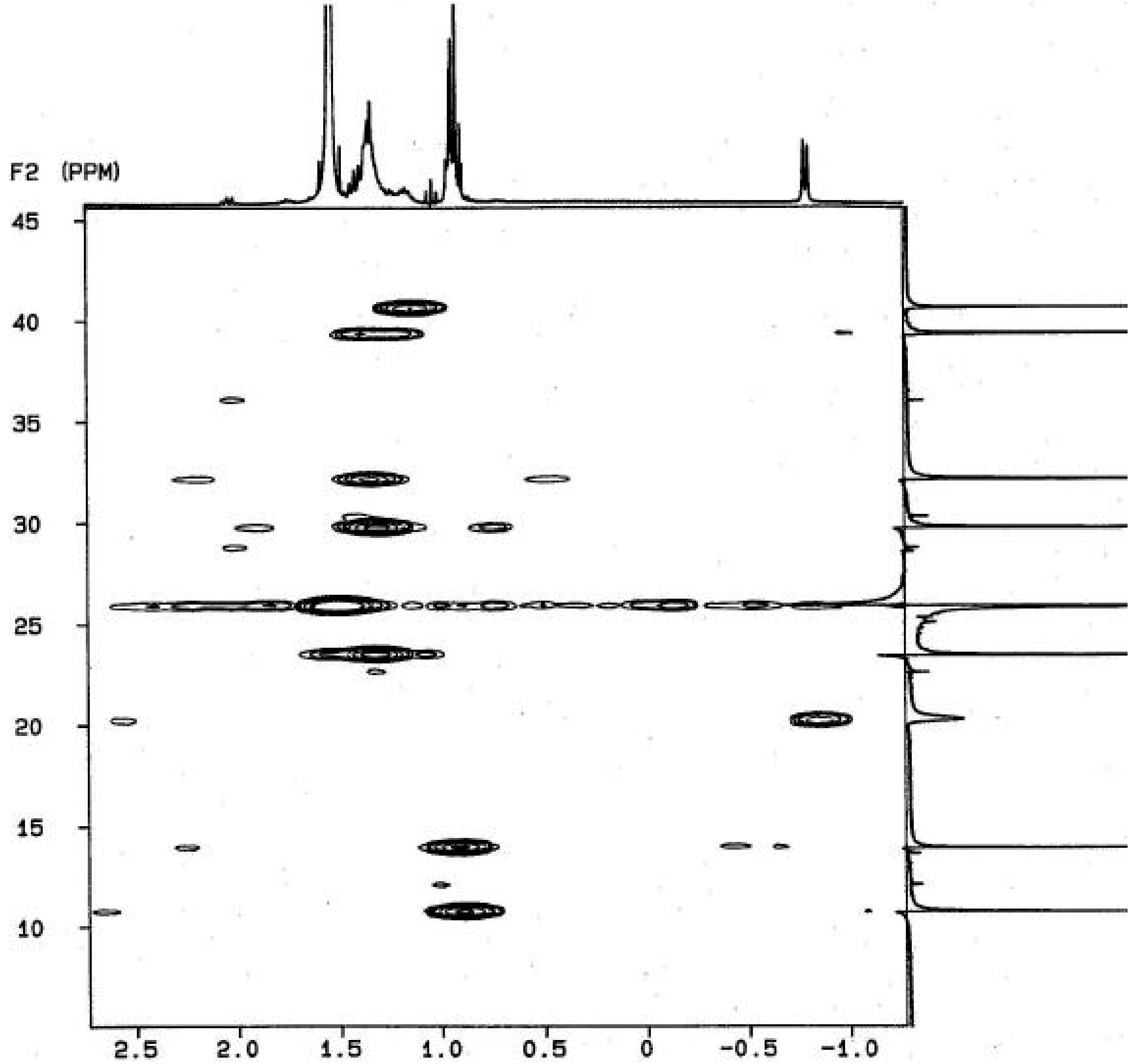


Figure 5 – ^{13}C-^{1}H HETCOR NMR experiment at room temperature for 2-ethylhexyllithium with carbon peaks in the F2 dimension (vertical) and proton peaks in the F1 dimension (horizontal).

Table 3 - The assignment of peaks in the ^{1}H NMR spectrum of 2-ethylhexyllithium including coupling constants and signal multiplicities

Protons Attached To:	Chemical Shift (ppm)	Multiplicity	Coupling Constant (Hz)
C1	-0.81	doublet	6.7
C2	1.14	multiplet	unresolved
C3	1.39	multiplet	unresolved
C4	1.32	multiplet	unresolved
C5	1.33	multiplet	unresolved
C6	0.91	triplet	7.3
C7	1.35	multiplet	unresolved
C8	0.89	triplet	7.3

The ^{6}Li NMR spectrum at room temperature (Figure 6) of 2-ethylhexyllithium shows a single peak at 0.87 ppm, indicating the presence of a single aggregate in solution. The spectrum was referenced using a sample of *t*-butyllithium. The peak in the spectrum of *t*-butyllithium was arbitrarily assigned to 0 ppm. All ^{6}Li NMR spectra acquired for this study were then referenced accordingly, assigning chemical shift values relative to *t*-butyllithium. Low temperature studies show only a single peak, again indicating the presence of a single aggregate at all temperatures.

As discussed previously, a series of variable temperature experiments were run on these samples. ^{13}C NMR data were acquired at –14.2 °C, -24.7 °C, -37.4 °C, -50.6 °C, and –65.1 °C. There were slight shifts in the resonance signals, but none shifted more than 1 ppm. ^{6}Li NMR data were acquired at -24.7 °C, -37.4 °C, -50.6 °C, and –65.1 °C. That data included both proton coupled and decoupled experiments. There was a single

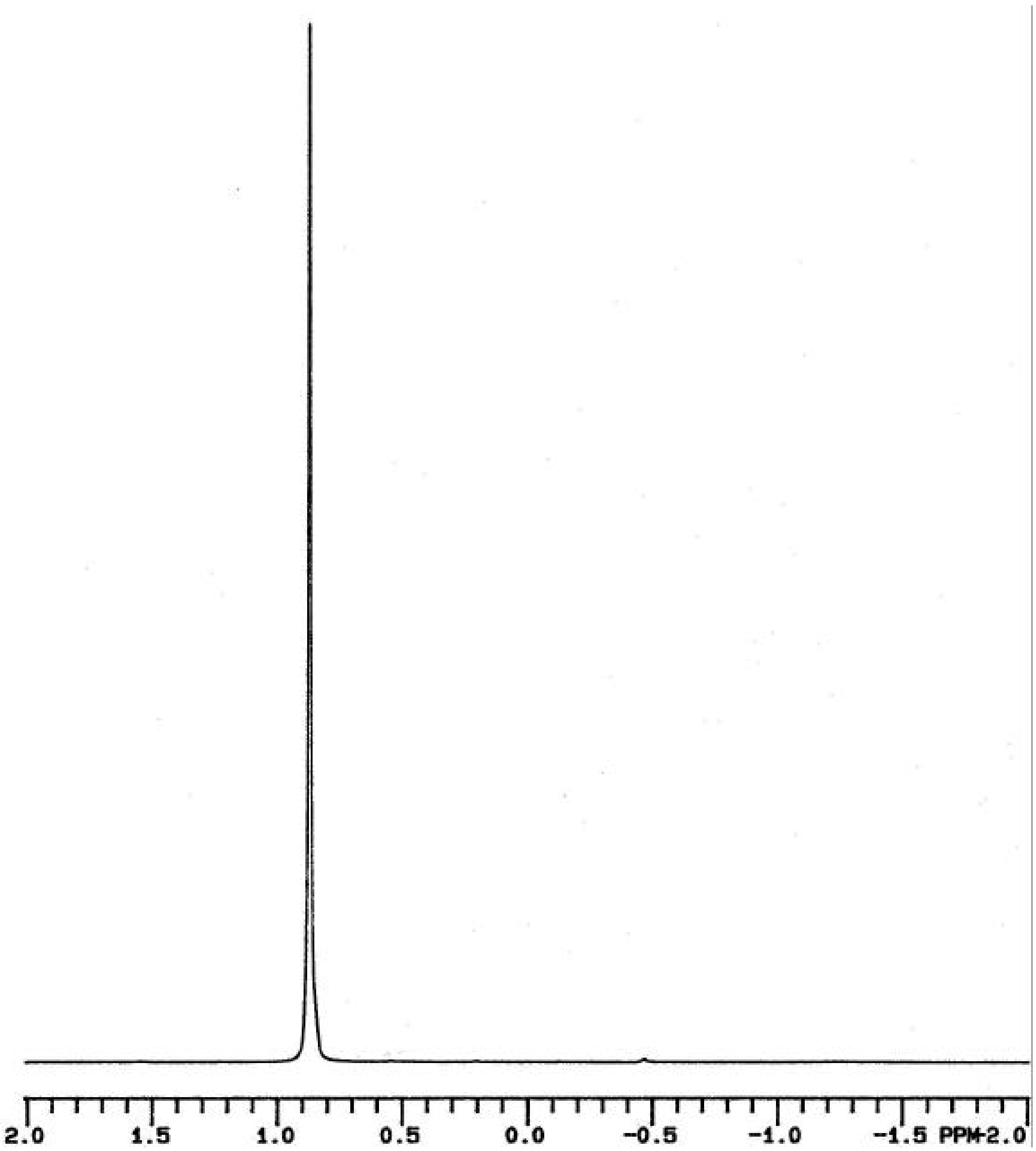


Figure 6 – ^{6}Li NMR spectrum of 2-ethylhexyllithium at room temperature.

peak at all temperatures, and the experiments without proton decoupling, which were used to check for the presence of lithium hydrides, showed no signs of ^{1}H-^{6}Li coupling.

The variable temperature experiments concluded the study of this compound. The key features of this investigation were the assignment of peaks in the ^{13}C, ^{1}H, and ^{6}Li NMR spectra, the assignment of the aggregation state (hexamer), the observation of any temperature dependence of the aforementioned resonance signals, and the lack of an observable effect of the chiral center at the beta position on the compounds properties. The final conclusion was based on comparison with studies of 2-methylbutyllithium[6] in which multiple peaks were observed in the ^{6}Li and ^{13}C NMR spectra due to its chirality. In that study, the peak separation in the ^{6}Li NMR spectrum was very small, on the order of 10^{-2} ppm. The ^{6}Li NMR spectrum acquired for this study for 2-ethylhexyllithium contained only a single peak; however, the small difference in chemical shift observed for 2-methylbutyllithium is roughly the same order of magnitude as the resolution of the NMR spectra obtained for this study. There was, however, a more pronounced effect in the ^{13}C NMR spectrum of 2-methylbutyllithium. In that spectrum, there were multiple peaks in the alpha-carbon region. Those peaks were confirmed to be the product of the chiral properties of the compound by comparison with results obtained for optically pure *R*-2-methylbutyllithium, in which a single alpha-carbon peak was observed. The alpha-carbon peak separation for racemic 2-ethylbutyllithium was approximately 1.2 ppm between the two outermost peaks. Multiple peaks were not observed in the alpha-carbon region for 2-ethylhexyllithium; therefore, it was concluded that the chirality of this compound had no observable effect on the structural attributes examined here. Having conducted a careful study of the alkyllithium compound, the next step was to study the lithium alkoxide compound.

Lithium 2-Ethyl-1-hexoxide

This compound was prepared independently as discussed in the experimental chapter of this work. There were two reasons for the synthesis of this compound. First, it was not known whether the compound was soluble in cyclopentane solution. Second, the data obtained from this compound could be used in conjunction with the data from the alkyllithium compound to serve as bookends so to speak, in the study of the mixed aggregates.

While it was only slightly soluble, enough compound went into solution to allow data to be acquired on the sample. The solubility of this compound was an issue that greatly affected the quality of the NMR experimental results. There was a large amount of solid dispersed in this sample, which made it difficult to shim the sample well. The lack of a homogeneous magnetic field lead to poor signal-to-noise ratios and line broadening. Having said that, some useful information was obtained from this sample.

The ^{13}C NMR spectrum at room temperature for this compound is shown in Figure 7. The spectrum consists of nine peaks, one of which is from the solvent, cyclopentane. While a detailed study of this compound's chemical shift values was not undertaken, some assignments were made. The peak at 67.9 ppm was assigned to the carbon alpha to oxygen (C1), and the peaks at 10.8 and 13.9 ppm were assigned to C8 and C6, respectively. The other chemical shift values were 23.9, 24.0, 29.9, 30.8, and

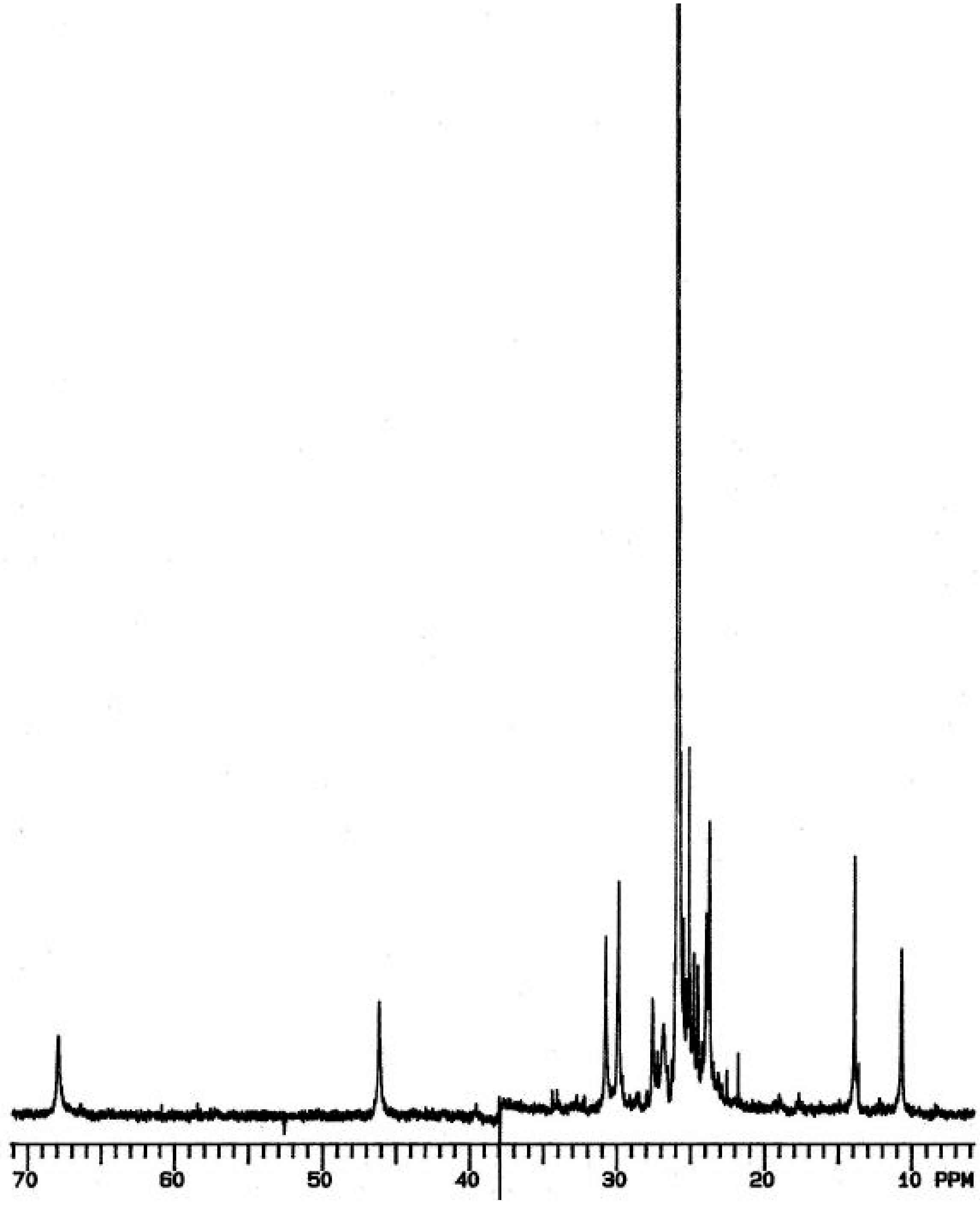


Figure 7 – ^{13}C NMR spectrum of lithium 2-ethyl-1-hexoxide at room temperature.

46.1 ppm. The real importance of this data was that the chemical shift values were obtained even though they were not fully assigned. This information was then used in the study of the mixed species containing both alkyl and alkoxy groups.

The ^{1}H NMR spectrum acquired at room temperature contains peaks in the same regions as the alkyllithium compound from 0.80-2.00 ppm. The differences arise with peaks at 3.58 and 3.68 ppm present in the spectrum of the alkoxide. These peaks are not present in the spectrum of the alkyllithium compound. They have been assigned to protons on the alpha-carbon of the alkoxide. Also, there is no peak at –0.81 ppm, which would correspond to the protons attached to the alpha-carbon of the alkyllithium compound. No further efforts were made to assign the remaining peaks in the proton spectrum of this compound.

The ^{6}Li NMR spectrum of this sample at room temperature is shown in Figure 8. It was initially believed that the multiple peaks in this spectrum were somehow related to the chirality of the compound. Its achiral analog, lithium 2-ethyl-1-butoxide, was then prepared to answer this question. The results of the ^{6}Li NMR experiment on that compound are identical to those obtained for this compound. Therefore, it was concluded that the peaks in the ^{6}Li NMR spectrum were not related to chirality.

Three possible explanations were proposed for the observed data: 1) there are multiple aggregates in solution, which has been observed for lithium menthoxide,[7] and/or 2) the lithium nuclei in the same aggregate are not all magnetically equivalent, or 3) the sample contains lithium based impurities. The third possibility seemed unlikely due to the similarities of data obtained for the two compounds. It is unlikely that the same

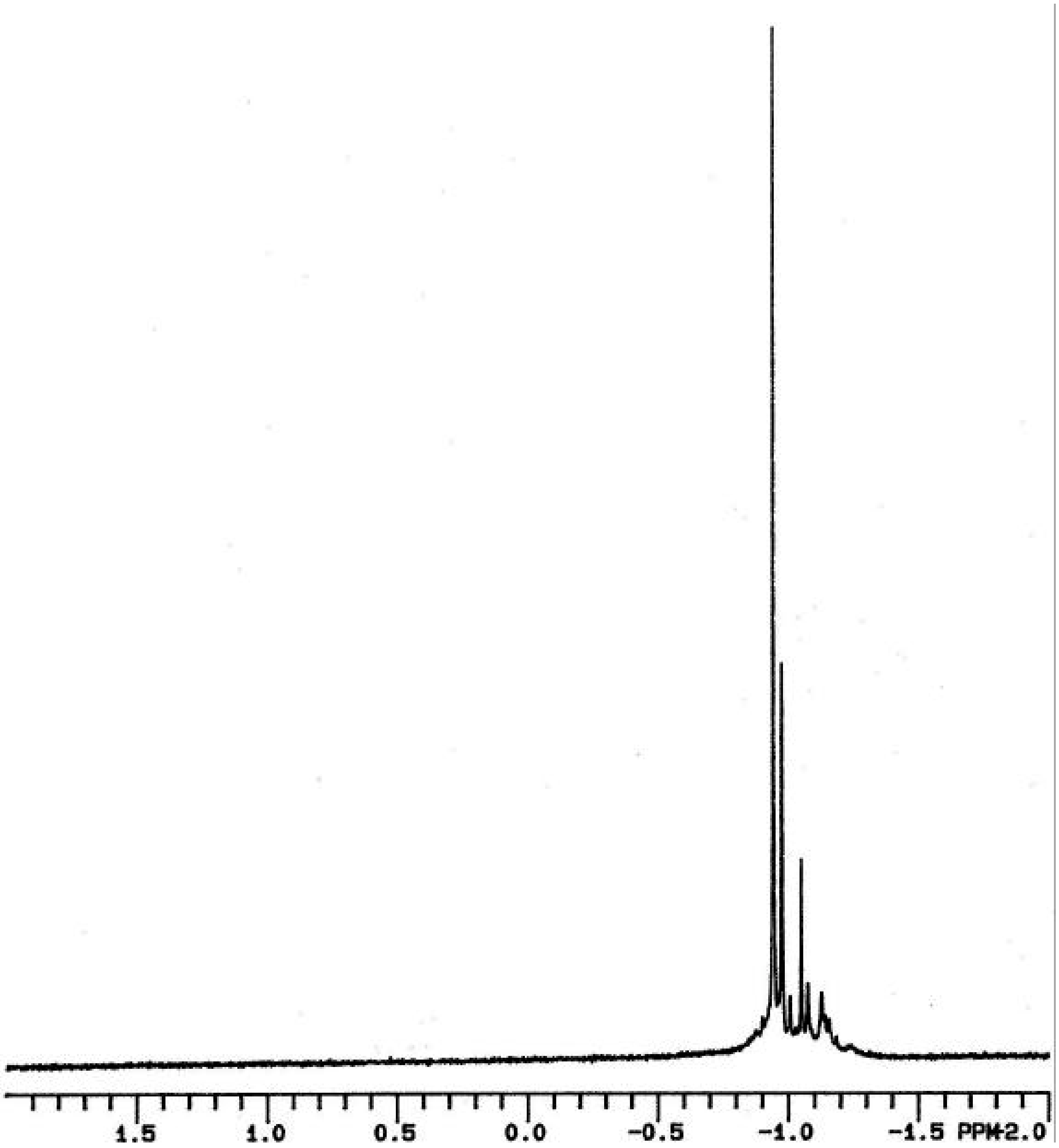


Figure 8 – ^{6}Li NMR spectrum of lithium 2-ethyl-1-hexoxide at room temperature.

contaminant would be present in the same relative amounts in two separate syntheses. The chemical shifts in this spectrum were noted, and no further effort was made to distinguish between the other two possible explanations.

Although little effort was put forth in this study relating to this compound, I believe its study could provide valuable insight into the aggregation states of the mixed species. If the replacement of alkyl groups in alkyllithium compounds by alkoxy groups decreases the steric bulk of the ligands in the aggregate sufficiently to allow for the formation of larger aggregates, then it seems reasonable to assume that the largest aggregate possible would be one in which all the bulkier alkyl groups have been replaced by the less bulky alkoxy groups. In this case, the aggregation state of the lithium alkoxide compound can be thought of as an upper limit on the size of the aggregates of the mixed species. One possible way to determine the aggregation state of this compound is through cryoscopic measurements.

Alkyllithium/Lithium Alkoxide Mixed Aggregates

0.2:1 Oxygen-to-Lithium Ratio

The study of this oxygen-to-lithium ratio represents the bulk of this investigation regarding the mixed aggregates. While other samples were prepared containing higher O:Li ratios, only basic experiments were run on them. Two samples at this approximate ratio were prepared-one in a 5mm NMR tube, and the other in a 10mm NMR tube.

Unless otherwise stated, all results reported here were obtained from experiments using the 10mm NMR sample tube.

The ^{13}C NMR spectrum of this sample at room temperature is shown in Figure 9. A detailed analysis of the peaks present in this spectrum was conducted, which led to the identification of three major species present in solution. Those species are the original alkyllithium compound, a lithium alkoxide, and 3-methylheptane. The alkane was a product of the reaction between the alkyllithium compound and alcohol used to produce the alkoxides, as outlined in the experimental chapter. It was identified using chemical shift data already reported (Table 2, p. 29). The other two species were confirmed using data obtained on each of those two compounds, as discussed earlier. Table 4 lists the assignments of peaks in the spectrum. These assignments were corroborated by general trends in the data obtained on samples with higher oxygen-to-lithium ratios. In that data, the peaks assigned to the alkyllithium compound slowly diminished, while the peaks assigned to the alkoxide intensified. The appearance of multiple broad peaks at approximately 20 ppm confirmed the presence of multiple types of carbon alpha to lithium. Again, the broadness of those peaks was assumed to be the result of carbon-lithium coupling. To confirm that assumption, a ^{13}C NMR experiment was run with both proton and ^{6}Li decoupling at -11 °C. A similar experiment was performed at room temperature; however, the peak remained broad, perhaps due to inter-aggregate exchange. At -11 °C, this process was slowed sufficiently, on the NMR timescale, to allow a decoupled spectrum to be obtained. The results of that experiment are shown in

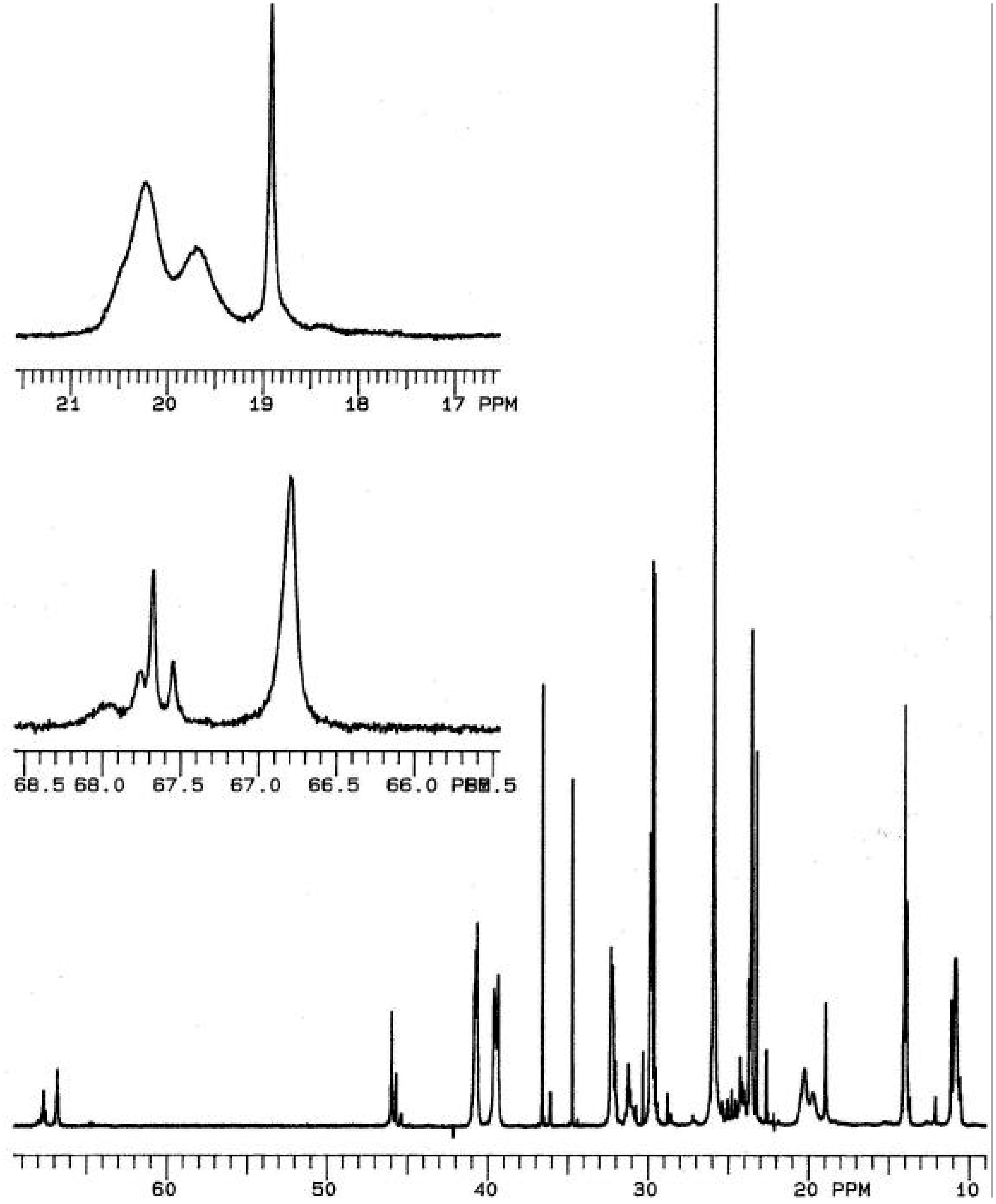


Figure 9 – ^{13}C NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at room temperature. Insets show expansion of alkoxide alpha-carbon region (bottom) and alkyl alpha-carbon region (top).

Table 4 - Assignment of peaks in the ^{13}C NMR spectrum of 0.2:1 O:Li sample (RP020)

Chemical Shift (ppm)	Alkyllithium Compound	Lithium Alkoxide Compound	3-methylheptane	Other Species
10.7		C8		
10.9	C8			
11.2			C8	
13.9		C6		
14.0	C6			
14.1			C6	
18.9			C1	
19.7	C1			
20.2	C1			
20.5	C1			
22.6				X
23.2			C5	
23.5	C5			
24.1		C5		
25.9				Solvent
27.1				X
28.7				X
29.8	C4	C4 & C7	C4	
30.1			C7	
31.2		C3		
32.2	C7			
34.8			C2	
36.1				X
36.5			C3	
39.4	C3			
40.8	C2			
45.9		C2		
66.8		C1		
67.54		C1		
67.68		C1		
67.75		C1		
67.78		C1		

Figure 10. They indicate the presence of multiple peaks in the ^{13}C NMR spectrum, which are coupled to lithium.

Only the alpha-carbon of the alkyllithium compound would exhibit carbon-lithium coupling. The ^{13}C NMR spectrum of the original alkyllithium compound has only one peak in this region. These results show that there are carbon atoms alpha to lithium that are in slightly different magnetic environments. The chemical shift values for all peaks exhibiting carbon-lithium coupling are: 18.60, 19.31, 19.49, 19.98, and 20.31 ppm. These additional peaks are the result of alkoxide ligands being incorporated into the all alkyl aggregates. This would result in a change in the magnetic environment of the alpha-carbon, and possibly lead to different aggregation states compared to the all alkyl aggregate. Other experimental evidence, which supports this conclusion, will be presented later.

At least five different types of carbon alpha to oxygen were identified (see Figure 9). Those peaks are at 66.80, 67.54, 67.67, 67.76, and 67.95 ppm. It is probably no coincidence that there are as many as six peaks from carbon atoms alpha to lithium assuming no peaks are overlapping. These results lead to the conclusion that there could be as many as six different types of aggregates in solution-one all alkyl aggregate and five aggregates containing both alkyl and alkoxy ligands.

The ^{13}C NMR spectrum of this sample at -11 °C (Figure 10) clearly indicates that there is a shift in equilibrium between aggregates as the temperature is lowered. The peak that appears at 66.80 ppm at room temperature (Figure 9) best exemplifies this shift. It decreases in intensity relative to other peaks in this region, and shifts upfield a distance of

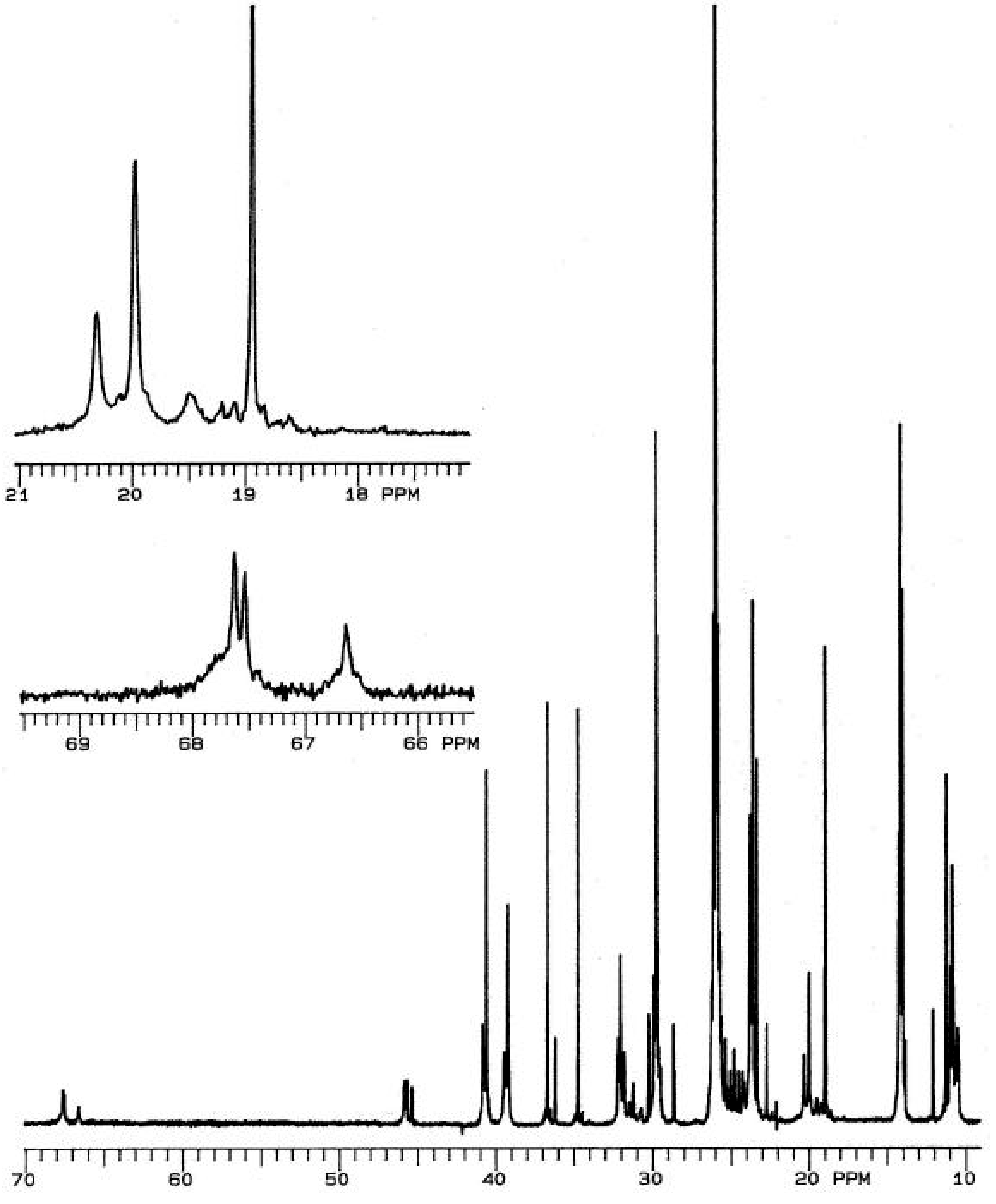


Figure 10 – ^{13}C NMR spectrum with ^{6}Li decoupling of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at –11 °C. Insets show expansion of alkoxide alpha-carbon region (bottom) and alkyl alpha-carbon region (top).

0.20 ppm at -11 °C. The shift upfield indicates that that species is exchanging with others further downfield in the spectrum, and that the change in temperature slows this process. The changes in intensity indicate shifts in the overall population of different species.

The ^{1}H NMR spectrum (Figure 11) shows new overlapping peaks in the region –0.8 to –0.9 ppm, which is the region assigned to protons attached to the alkyllithium alpha-carbon. In the ^{1}H NMR spectrum of the original alkyllithium compound, only a single doublet appeared in this region. In addition, there are multiple peaks in the region assigned to protons attached to the alpha-carbon of the alkoxide (3.4 to 3.6 ppm). Two doublets can be seen in this region, one at 3.38 ppm and the other at 3.57 ppm, and there is also a broad peak from 3.2 to 3.4 ppm. These two regions were the focal point of attempts to correlate peaks in the ^{13}C NMR spectrum with peaks in the ^{6}Li NMR spectrum using 2-D experiments. A detailed summary of those experiments will follow. No attempts were made to identify other peaks in this spectrum.

Another important feature of the ^{1}H NMR spectra that were obtained was the temperature dependence of some of the peaks. The peaks from protons attached to the alpha-carbon became somewhat more resolved at -11 °C. Instead of a single broad peak at approximately –0.85 ppm, at least two doublets at –0.83 and –0.87 ppm can be seen clearly with other smaller doublets overlapping. The peaks from protons on the alkoxide alpha-carbon also change with temperature. The peak at 3.57 ppm decreases in intensity while the peak at 3.38 ppm increases. These changes are possibly the result of a shift in equilibrium between aggregates.

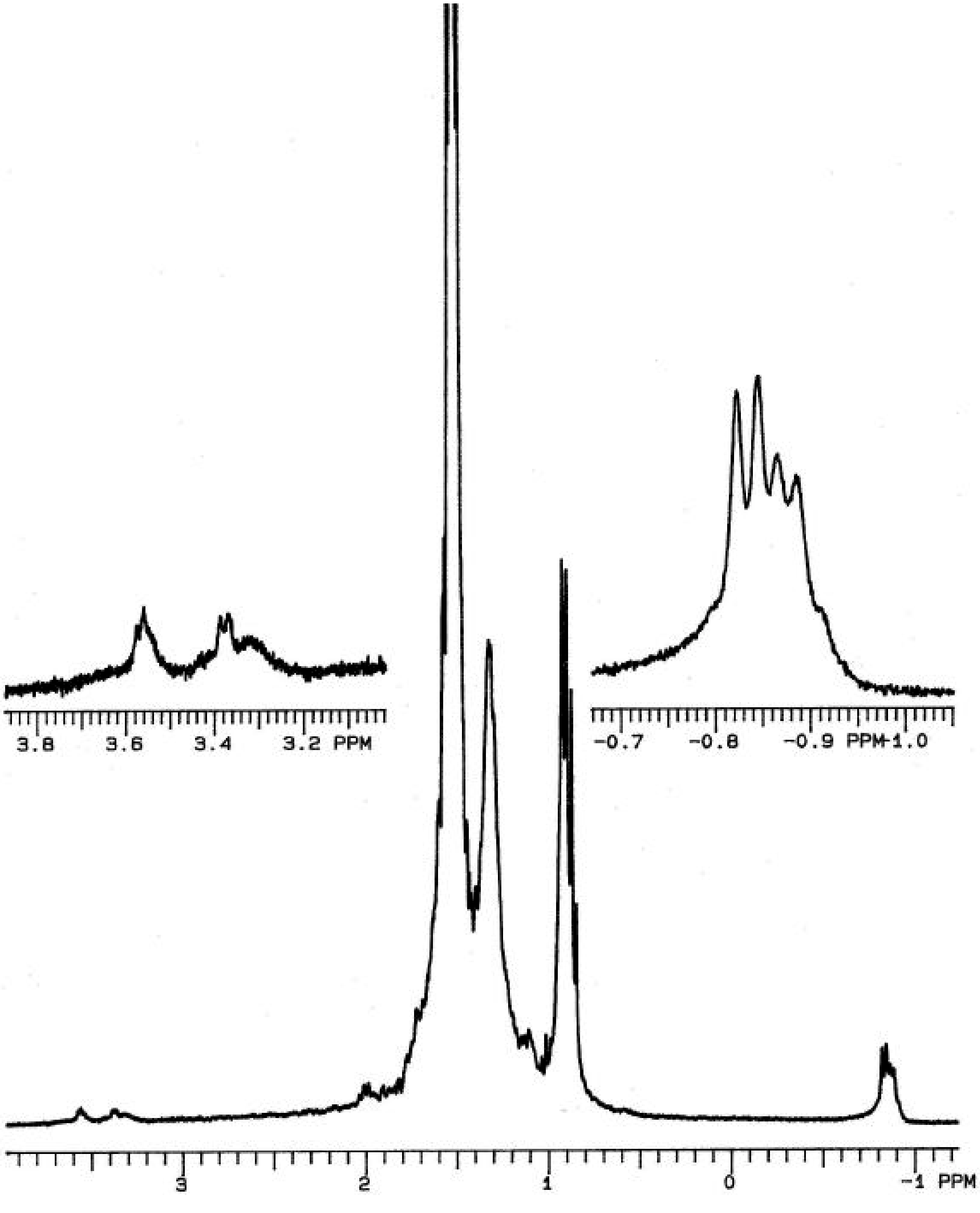


Figure 11 – ^{1}H NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at –11 °C. Insets show the expansion of the akoxide alpha-proton region (left) and the alkyl alpha-proton region (right).

The ^{6}Li NMR spectrum shows multiple new peaks upfield from that of the original alkyllithium compound at 0.87 ppm (see Figure 12). The chemical shift values are approximately 0.85, 0.45, 0.07, -0.11, -0.31, -0.48, -0.56, -0.65, and -0.74 ppm. Several of the peaks are broad due to inter-aggregate exchange as previously mentioned. Also shown in Figure 12 is the spectrum acquired at -13 °C. It is apparent that the exchange process has been slowed, resulting in sharper resonance signals. At this temperature, an additional signal at 0.24 ppm can be observed. There are also changes in relative peak intensities resulting from a shift in equilibrium between aggregates.

In similar experiments on the 5 mm sample, a multiplet centered at approximately –0.59 ppm can be seen (Figure 13). This appears to be a five-line multiplet. Experiments run without proton decoupling during data acquisition reveal that each peak is actually a doublet. This is interpreted as each of the five lithiums coupled to a single proton. Figure 14 shows an expansion of this series of peaks along with coupling constants and chemical shift differences between peaks. The resolution for this spectrum was calculated to be approximately 0.1 Hz per data point (NP = 2176, FN = 4K, and SW = 218.8). ^{6}Li-^{1}H coupling has only been observed when there is direct bonding between ^{6}Li and ^{1}H. These species were likely formed from lithium hydride elimination, and are perhaps aggregates containing alkoxide ligands and a single hydride ligand such as those identified elsewhere.[8] Lithium hydride elimination can occur either thermally or photochemically.[6] Lithium hydride species are also present in the 10 mm sample, but in much lower concentration. Greater care was taken in the preparation of that sample, which probably led to less heat being generated; hence less thermal decomposition. Since the

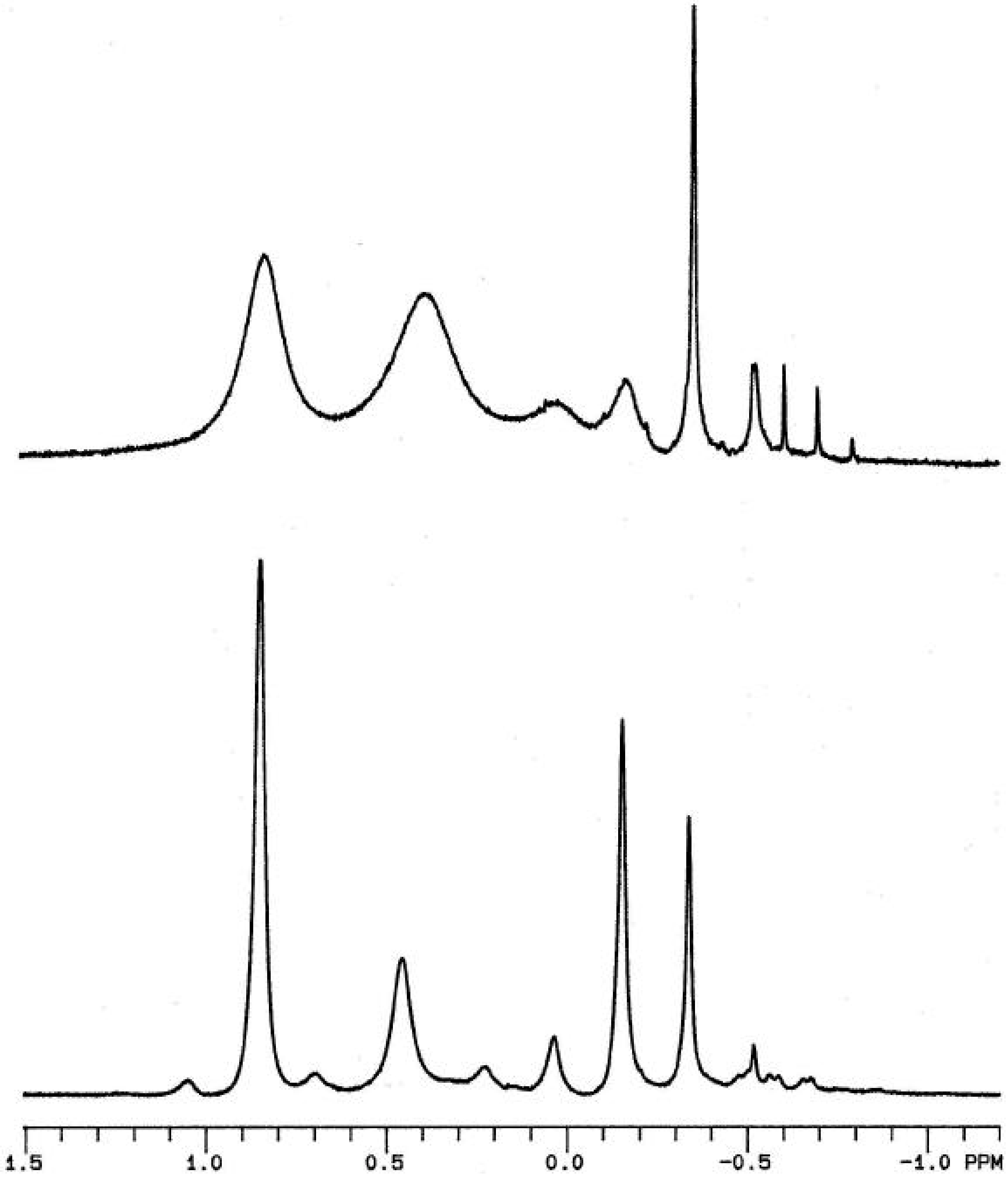


Figure 12 – ^{6}Li NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at room temperature (top, with ^{1}H decoupling) and –13 °C (bottom, without ^{1}H decoupling).

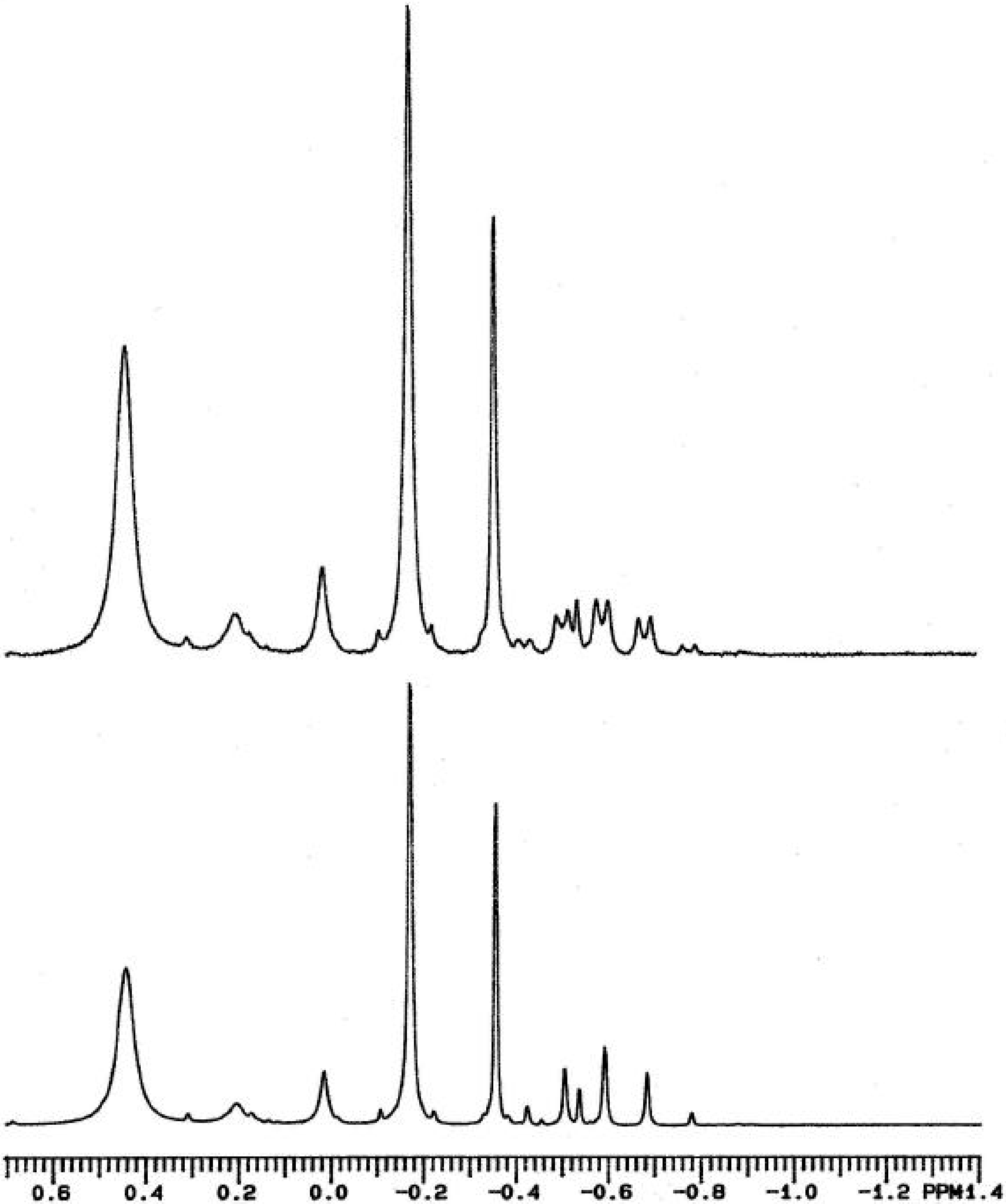


Figure 13 – ^{6}Li NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at –12 °C with ^{1}H decoupling (bottom) and without (top).

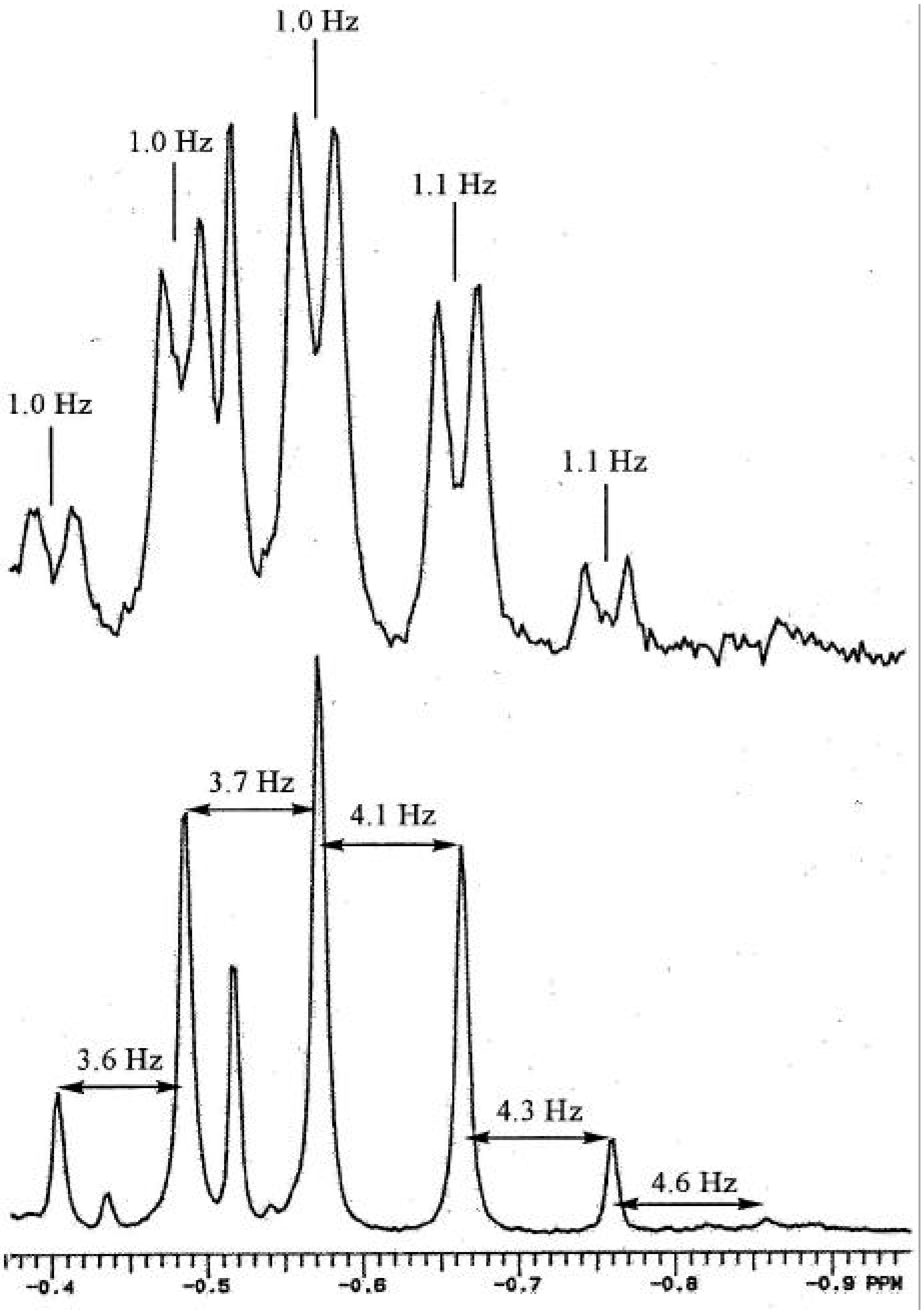


Figure 14 – Expansion of an unidentified multiplet in the ^{6}Li NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at –12 °C. The top spectrum (without ^{1}H decoupling) shows the peak splitting of doublets. The bottom spectrum (with ^{1}H decoupling) shows the difference in chemical shift between each of the peaks.

concentrations of those species are low in both samples (less than 6% of the total lithium nuclei), they were ignored in the analysis of the other aggregates.

The goal of the remainder of the investigation of this sample was to determine the aggregation states of species in solution. Two different approaches were used to that end. One way was to try to observe coupling, which has been shown in the past to obey the following equation.[9,10]

$$J_{13C\text{-}6Li} = (17 \pm 2) / n$$

where n is the number of equivalent lithium nuclei coupled to each carbon. Therefore, if the magnitude of the coupling can be determined for a particular aggregate, then some conclusions can be drawn about its aggregation state.

A nicely resolved multiplet would facilitate the determination of coupling constants; however, only the peak from the original alkyllithium compound was sufficiently resolved to allow that approach to be used. The observed coupling for that aggregate was 3.12 Hz. That information, obtained in a straightforward manner, served as an internal reference for future experiments to determine the coupling constants of other aggregates in solution via a more complicated method.

A series of ^{6}Li *J*-modulated ^{13}C spin echo experiments were run on the sample. This experiment is designed to refocus the magnetization of peaks in the ^{13}C NMR spectrum, which exhibit specific coupling. This approach is similar to using an attached proton test (ATP) to differentiate between carbon atoms with different numbers of hydrogen atoms attached. The first experiment was run using a delay of 0 seconds, which allowed all peaks to be refocused (see Figure 15, A). Then, the information already known for the original alkyllithium compound was used to set the delay to refocus what were presumably hexamers (D). The peak at 19.98 ppm assigned to the original hexamer was indeed refocused, and another peak at 20.31 ppm was also refocused (see Figure 15). There were two possible explanations for the peak at 20.31 ppm being refocused. First, it could simply be coupled to six lithiums. However, in addition to peaks being refocused at their observed *J* values, they are also refocused at integer multiples of *J*. For example, the peak from a carbon coupled to two lithiums (m = 2) will also be refocused at m = 4, 6, 8, etc, although at reduced intensity for each successive multiple. Therefore, the peak at 20.31 ppm, which was refocused for m = 6, could actually be coupled to two or three lithiums. These two possibilities were eliminated based on the results of experiments to test for m = 3 (B) and m = 4 (C). If it were coupled to two lithiums and it refocused with enough intensity to be observed for m = 6, then it would also show up in the test for m = 4, which it did not. Similarly, it did not refocus in the test for m = 3. While this does not prove conclusively that this aggregate is a hexamer, its observed coupling constant of approximately 3.12 Hz is consistent with a hexameric species.

The experiment designed to test for m = 3 shows a small peak at 20.10 ppm. This peak corresponds to a small peak barely visible in the same experiment with no delay. The signal-to-noise for this spectrum was poor, so no definite conclusion could be drawn. It could, however, be a sign that fluxional exchange for one of the aggregates in solution has been stopped. When that happens, the carbon atom would be bonded to three lithium

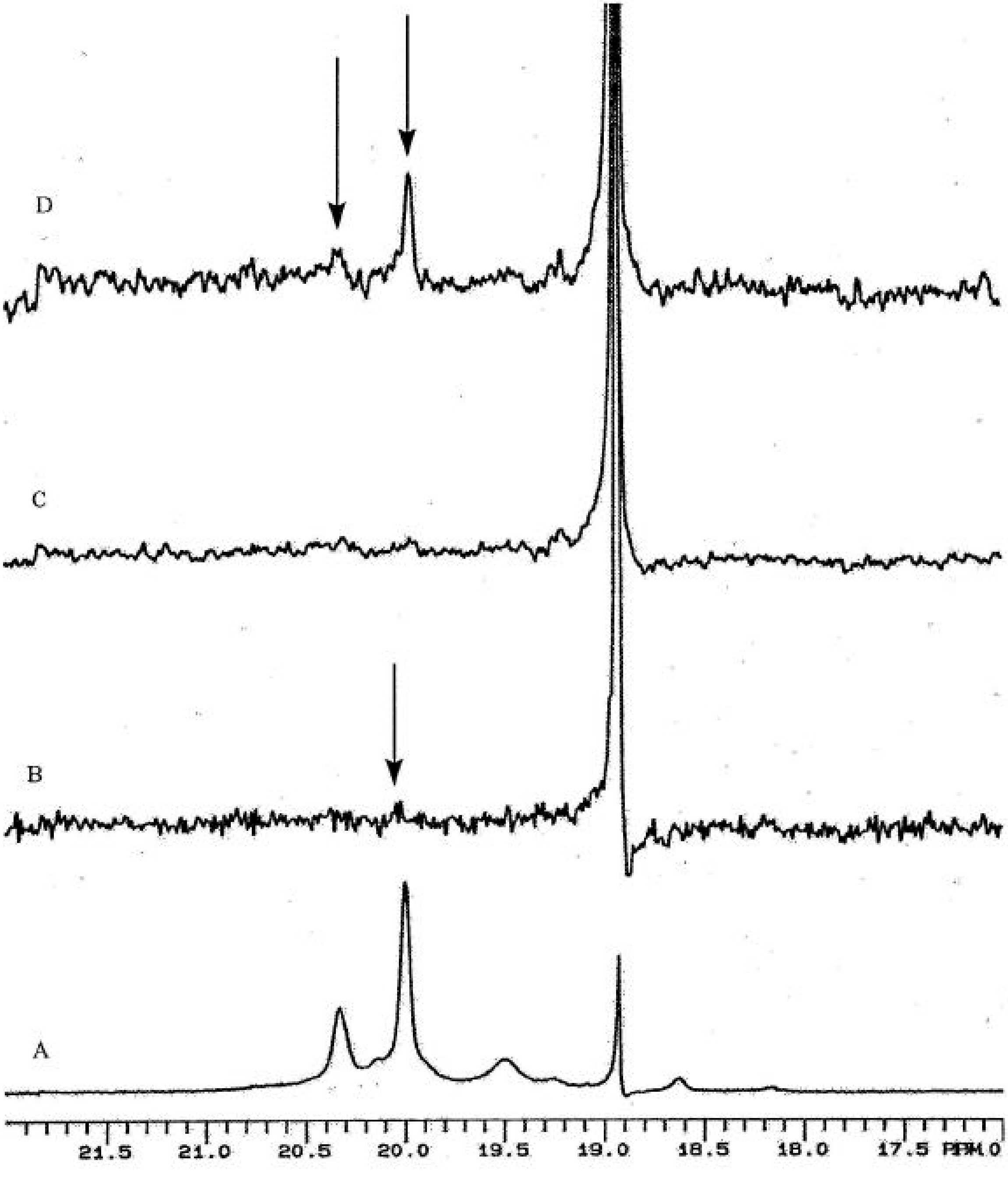


Figure 15 – ^{6}Li *J*-modulated ^{13}C spin echo experiments for a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at –11 °C. A) D2 = 0. B) D2 = 0.176 for m = 3 (trimer). C) D2 = 0.216 for m = 4 (tetramer). D) D2 = 0.324 for m = 6 (hexamer).

atoms. This experiment should be repeated to further investigate this matter. The test for m = 4 showed no peaks being refocused.

A set of experiments were run to obtain the T_1 times for peaks at 19.98 and 20.31 ppm. These values were then be used to optimize the ^{13}C flip angle for the ^{6}Li *J*-modulated ^{13}C spin echo experiments. The optimal flip angle, also known as the Ernst angle, is designed to balance signal detection with loss of longitudinal magnetization. A 90° flip angle allows for maximum signal detection; however, spin lattice relaxation times may be long resulting in long delays between transients. In some cases, it is more productive to use a smaller flip angle and acquire more transients, which ultimately result in signal-to-noise ratios similar to those obtained with a 90° pulse but in less time. In other words, the highest signal-to-noise ratios are achieved in the least amount of experimental time by using the Ernst angle. The Ernst angle is given by the following equation.

$$\cos a = \exp (-t_r / T_1)$$

where t_r is the repetition time between pulse and a is the Ernst angle.

The calculated T_1 times were 0.290 ± 0.004 s and 0.164 ± 0.012 s for the peaks at 19.98 and 20.31, respectively. Since these T_1 times were short, the Ernst angle turned out to be the standard 90° pulse. It is interesting to note that the T_1 time for the peak at 19.98 is longer than that of the peak at 20.31 ppm. This is interpreted as the aggregate at 19.98 ppm (the original alkyllithium hexamer) tumbling faster than the other aggregate (mixed alkyl/alkoxy aggregate). The mixed aggregate is probably tumbling less rapidly because the replacement of an R group by the longer OR group causes a small increase in the size of the complex.

The other approach employed to investigate aggregation states was to determine the composition of each aggregate. This method was based on the comparison of integral values in the ^{13}C NMR spectrum, which were used to determine the ratio of alkyl to alkoxy groups in a specific aggregate. In order to determine which peaks from the alkyl and alkoxy region were in the same aggregate, other experiments would have to be run. A ^{6}Li-^{13}C HETCOR would produce the needed correlations for the alkyl alpha-carbon region; however, that experiment was prohibitively long. It would also not show the correlation between peaks in the alkoxy alpha-carbon region. A less direct, but equally effective method was to correlate the ^{13}C alpha-carbon peaks in both the alkyl and alkoxy region, which had already been assigned, with the ^{1}H peaks using a ^{1}H-^{13}C 2D HETCOR experiment. The ^{1}H peaks were then correlated to the ^{6}Li peaks using a HOESY 2-D experiment. The results of those two experiments were then used to correlate ^{6}Li peaks directly to their counterparts in the ^{13}C NMR spectrum.

Two separate ^{1}H-^{13}C HETCOR experiments were performed: one with, and one without ^{6}Li decoupling. The experiment with lithium decoupling during data acquisition was used to correlate peaks in the alkyl alpha-carbon region. An expansion of the region of interest can be seen in Figure 16. It shows the correlation of the three most intense signals in the alpha-carbon region of the ^{13}C NMR spectrum with their corresponding signals in the ^{1}H NMR spectrum. The peaks in the proton spectrum at –0.83, -0.85, and

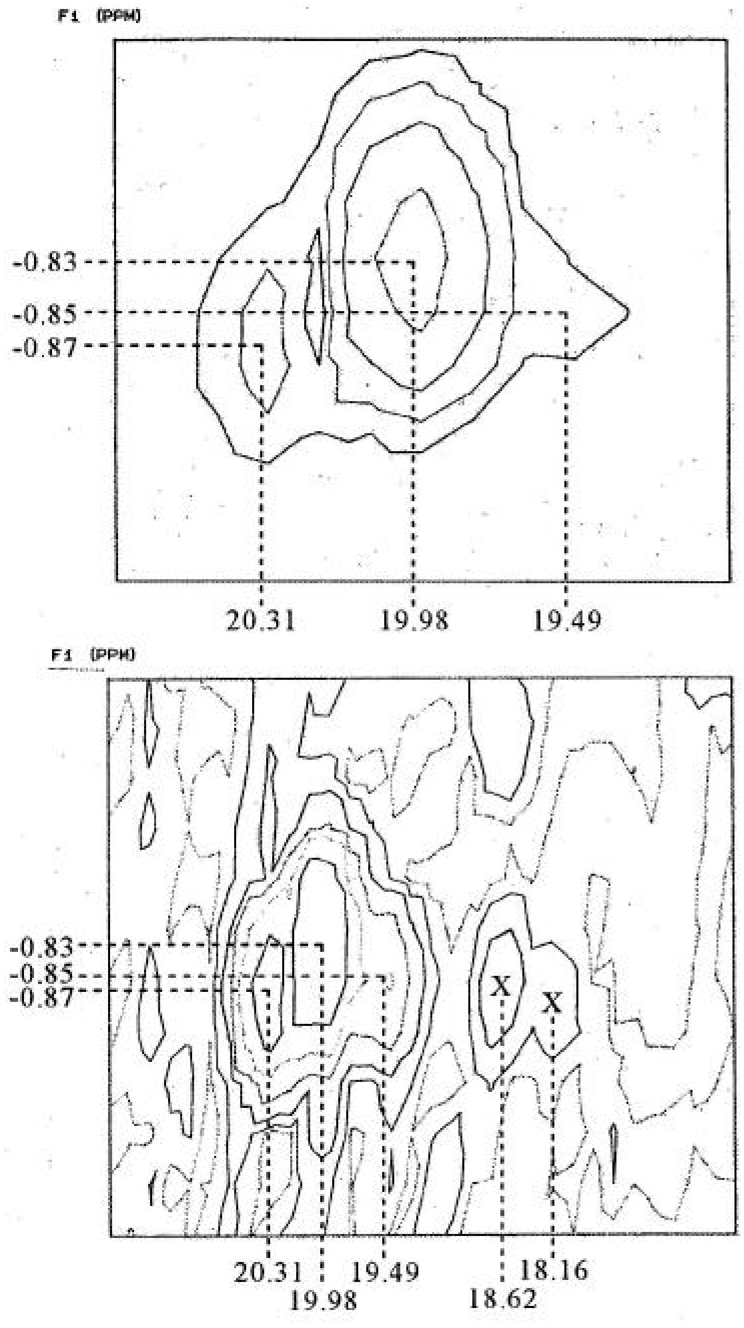


Figure 16 – Expansion of alkyl alpha-carbon region of ^{13}C-^{1}H HETCOR with ^{6}Li decoupling of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at –11 °C. The F1 dimension (vertical) shows the ^{1}H chemical shift values for cross peaks, and the F2 dimension (horizontal) shows the corresponding ^{13}C chemical shifts. The top spectrum was run with NT = 32, NI = 128, resulting in better resolution, and the bottom was run with NT = 128, NI = 64, resulting in better signal-to-noise.

–0.87 ppm are from protons attached to carbon atoms whose peaks are at 19.98, 19.49, and 20.31 ppm, respectively. Also shown in Figure 16 is approximately the same region from another experiment, which resulted in better signal-to-noise but less resolution. The number of increments was reduced (^{1}H dimension) and the number of transients was increased. This spectrum contains at least five cross-peaks in the alkyl alpha-carbon region, further bolstering the evidence for multiple aggregates in solution.

A standard ^{1}H-^{13}C 2D HETCOR experiment was used to correlate peaks in the alkoxy alpha-carbon region (see Figure 17). Two cross-peaks are clearly visible. The peak in the ^{13}C NMR spectrum at 66.63 ppm correlates with the peak at 3.57 ppm in the ^{1}H NMR spectrum. This correlation is unambiguous. The other cross peak seems to be a conglomeration of the remainder of ^{13}C peaks correlating with a broad range in the ^{1}H NMR spectrum. Therefore, no other unambiguous assignments could be made.

Having shown some connections between the ^{1}H and ^{13}C NMR spectra, the next step was to try to connect the ^{1}H NMR spectrum to the ^{6}Li NMR spectrum. This was accomplished using a 2-D heteronuclear NOESY (HOESY). This experiment detects through-space interactions between nuclei. The protons on the alpha-carbon of both the alkoxy and alkyl ligands were believed to be close enough in proximity to interact with the lithium nuclei. A full spectrum of this NMR experiment is shown in Figure 18.

A close examination of the alkyl alpha-carbon region shows four correlations (Figure 19). The peaks at 0.85, 0.45, -0.11, and –0.31 ppm in the ^{6}Li NMR spectrum correspond to peaks at –0.83, -0.83, -0.87, and –0.90 ppm in the ^{1}H NMR spectrum, respectively. A similar analysis of the alkoxy alpha-carbon region shows only two

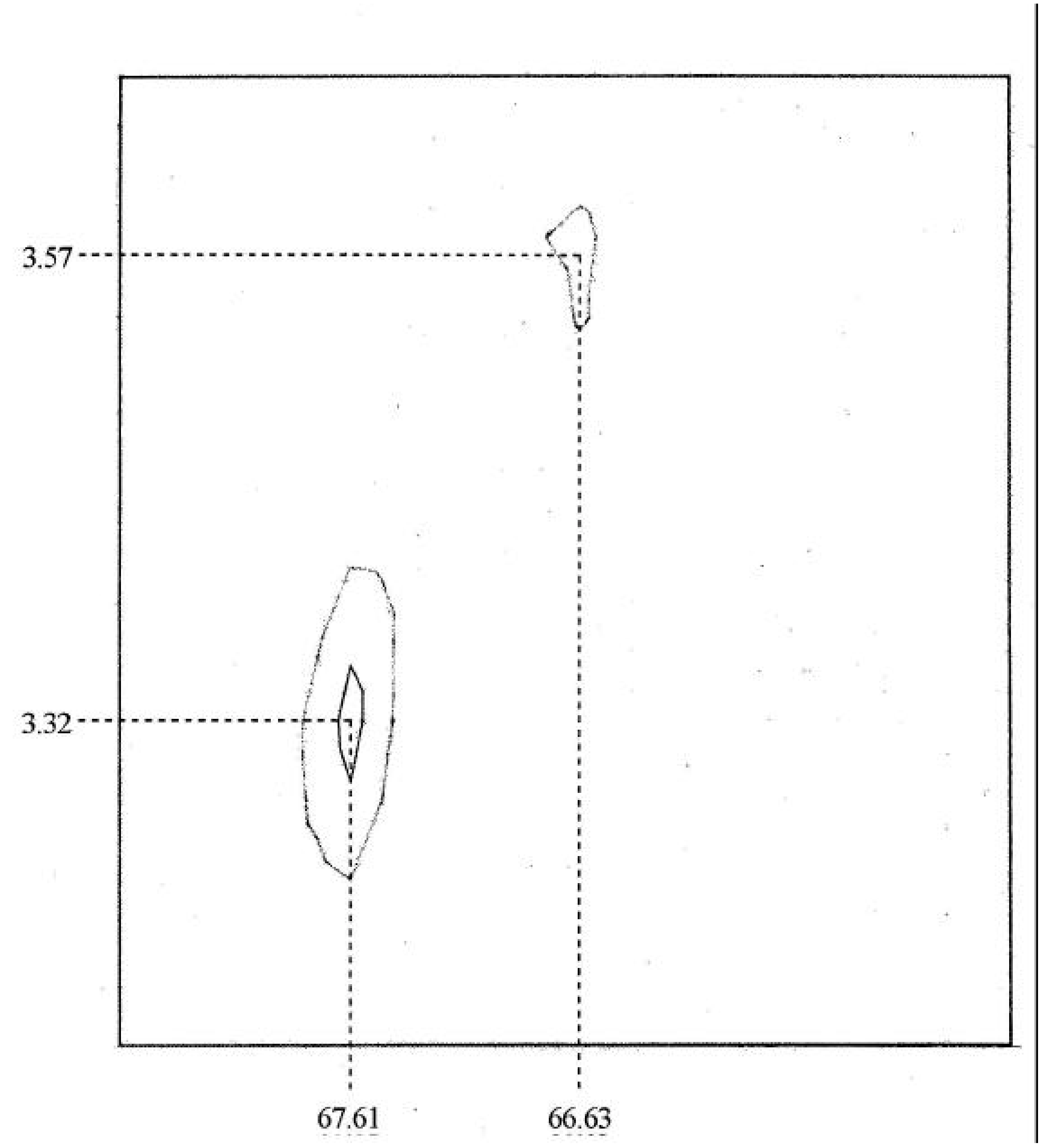


Figure 17 – Expansion of alkoxy alpha-carbon region of ^{13}C-^{1}H HETCOR, with ^{6}Li decoupling, of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at –11 °C. The ^{1}H (vertical) and ^{13}C (horizontal) chemical shift values for cross peaks are shown in ppm.

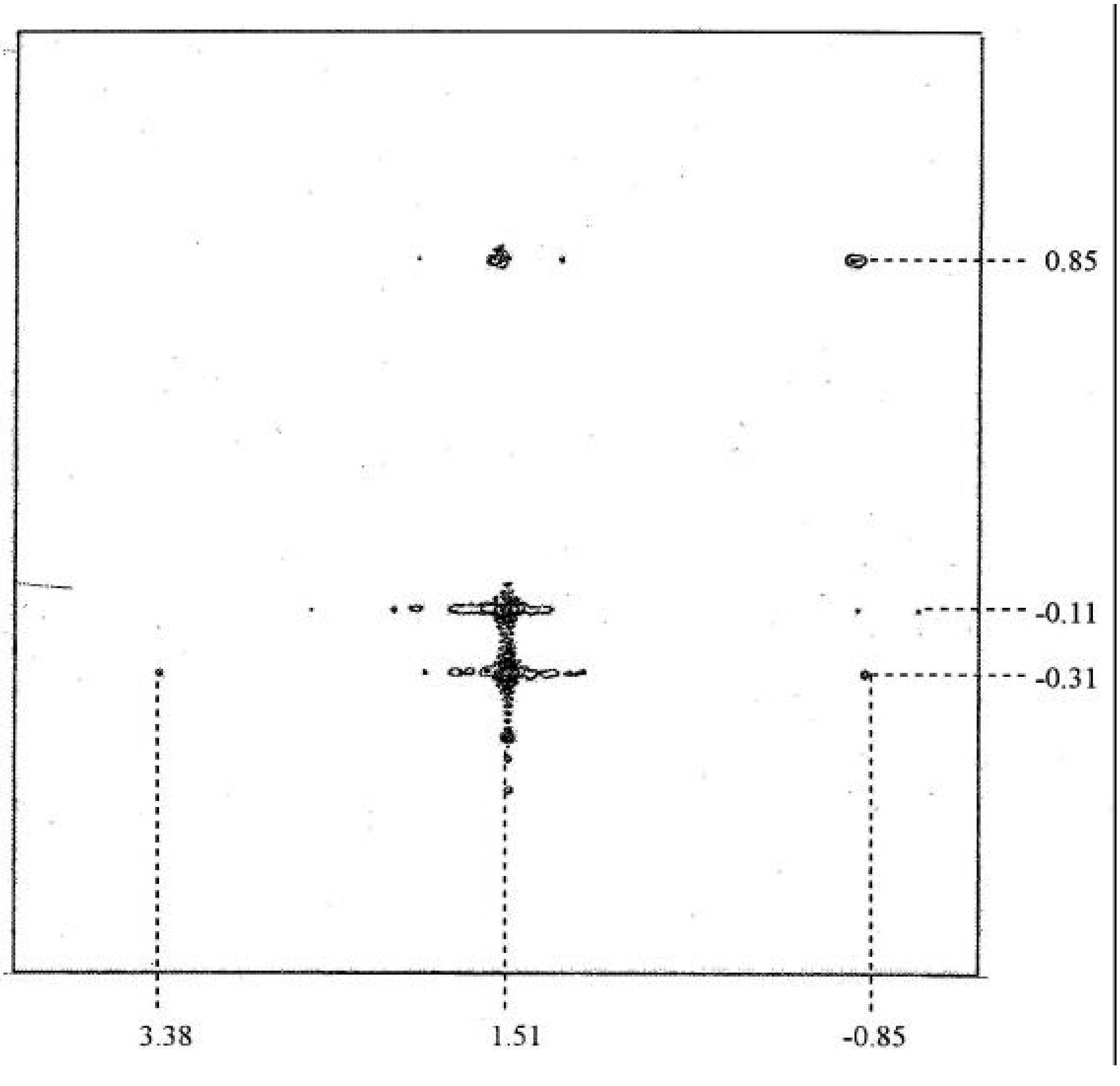


Figure 18 – ^1H-^6Li HOESY of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at –11 °C. The F1 dimension (horizontal) and F2 dimension (vertical) show the chemical shift values for ^1H and ^6Li, respectively, in ppm.

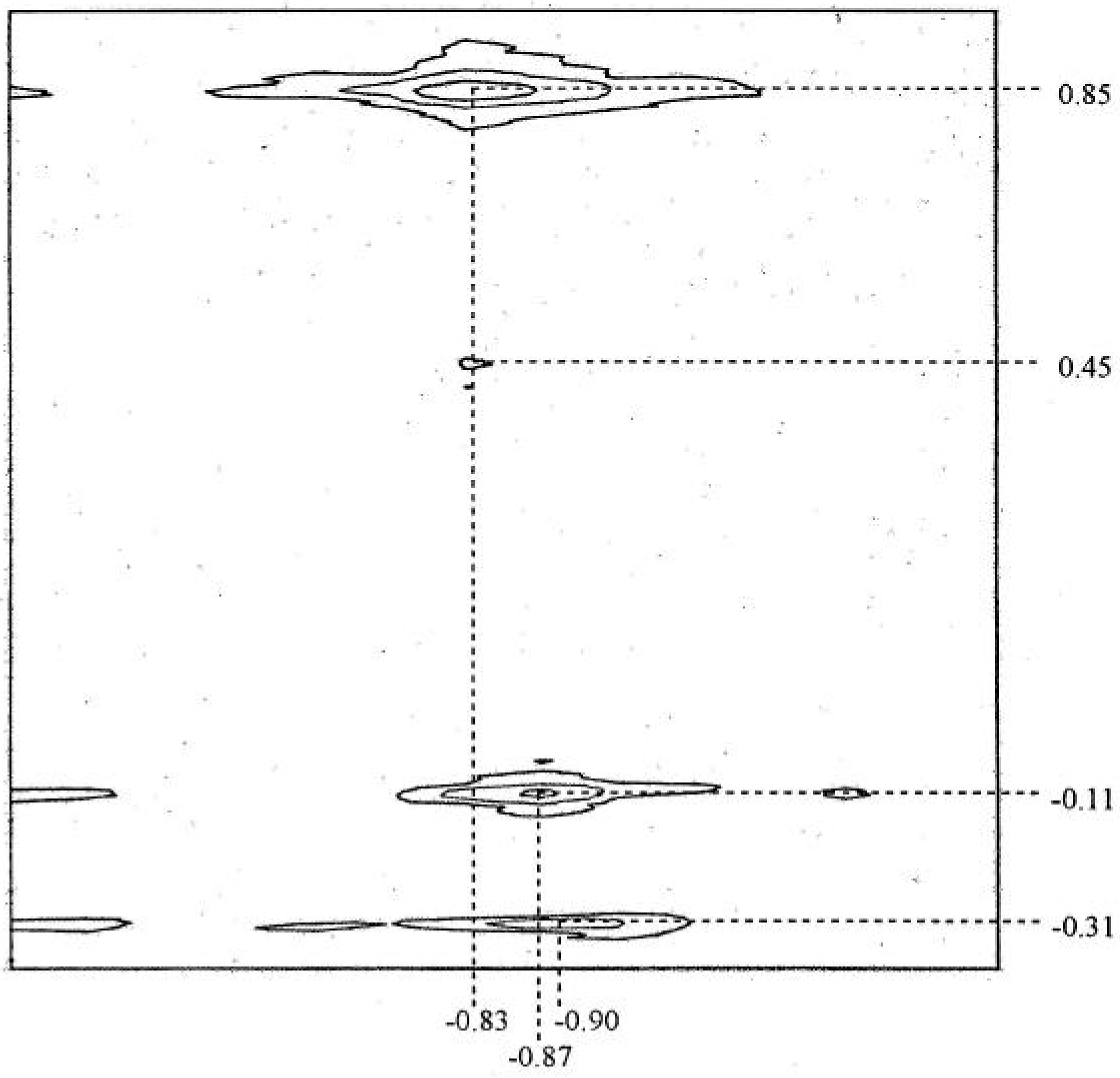


Figure 19 – Expansion of alkyl alpha-proton region of ^{1}H-^{6}Li HOESY of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.2:1 at –11 °C. The F1 dimension (horizontal) and F2 dimension (vertical) show the chemical shift values for ^{1}H and ^{6}Li, respectively, in ppm.

correlations. The peaks at -0.11 and –0.31 ppm correlate with peaks at 3.57 and 3.31 ppm, respectively. The other peaks, which should show some correlation, were too low in intensity to do such.

From this data, it was shown that the peak at -0.11 ppm in the ^{6}Li NMR spectrum correlated with peaks at 20.31 and 66.63 ppm in the ^{13}C NMR spectrum. While other connections could be made, no other aggregates were unambiguously determined. Since the alkyl and alkoxy alpha-carbon peaks from a single aggregate were now known, an integration of the ^{13}C NMR spectrum would give the approximate ratio between alkyl and alkoxy ligands in that aggregate.

The ^{13}C NMR experiment used to obtain integral values was run with both proton and ^{6}Li decoupling on during acquisition, but off at other times to prevent the buildup of NOE, which might affect peaks differently. A delay between transients equal to the acquisition time was also used to allow time for the NOE built up during acquisition to dissipate. The ratio of the aforementioned peaks was 5.1 to 1, alkyl to alkoxy. This result is consistent with what was expected based on the ^{6}Li *J*-modulated ^{13}C spin echo experiments. Based on those experiments, this aggregate was determined to be a hexamer. From this evidence it has been concluded that this aggregate is a hexamer with one alkoxy ligand and five alkyl ligands.

These methods proved fruitful for the determination of the aggregation state of one of the species in solution. It is my belief that similar analysis of samples with higher oxygen-to-lithium ratios will yield further information on other species in solution. As the alkoxide ligand concentration is increased, some of the low intensity peaks in this sample should intensify leading to better signal-to-noise ratios. The low intensities of some peaks greatly hampered efforts to study those species.

0.4:1 Oxygen-to-Lithium Ratio

The ^{13}C NMR spectrum for this sample, shown in Figure 20, contains the same peaks in the alkyl alpha-carbon region as the 0.2:1 O:Li sample, but with slightly different intensities. The chemical shift values are: 18.19, 18.60, 19.48, 20.00, and 20.29 ppm. The predominate alkyl species in this sample appears to be the hexameric mixed aggregate identified in the 0.2:1 O:Li sample at 20.31 ppm. While no experiments were run to positively identify the species as such, the peak is at approximately the same chemical shift (20.29 ppm). The majority of original alkyllithium compound appears to have been consumed at this point. Of the other smaller peaks associated with alkyl alpha-carbon atoms (18.19, 18.60, and 19.48 ppm), the peak at 18.19 ppm seems to have increased the most between the two samples. It is now roughly of the same intensity as the other small peaks, whereas in the first sample it was negligible.

The alkoxide alpha-carbon region of this sample also looks similar to the previous sample. The peaks are slightly more intense in this spectrum, as one would expect with a higher concentration of alkoxide ligand, but are at approximately the same chemical shifts. One major difference between the 0.2:1 and 0.4:1 O:Li samples is that there is a single peak at 66.63 ppm in the first, while there are two peaks in the second at 66.53 and 66.64 ppm. This would suggest that there is possibly another aggregate similar to the hexamer identified earlier.

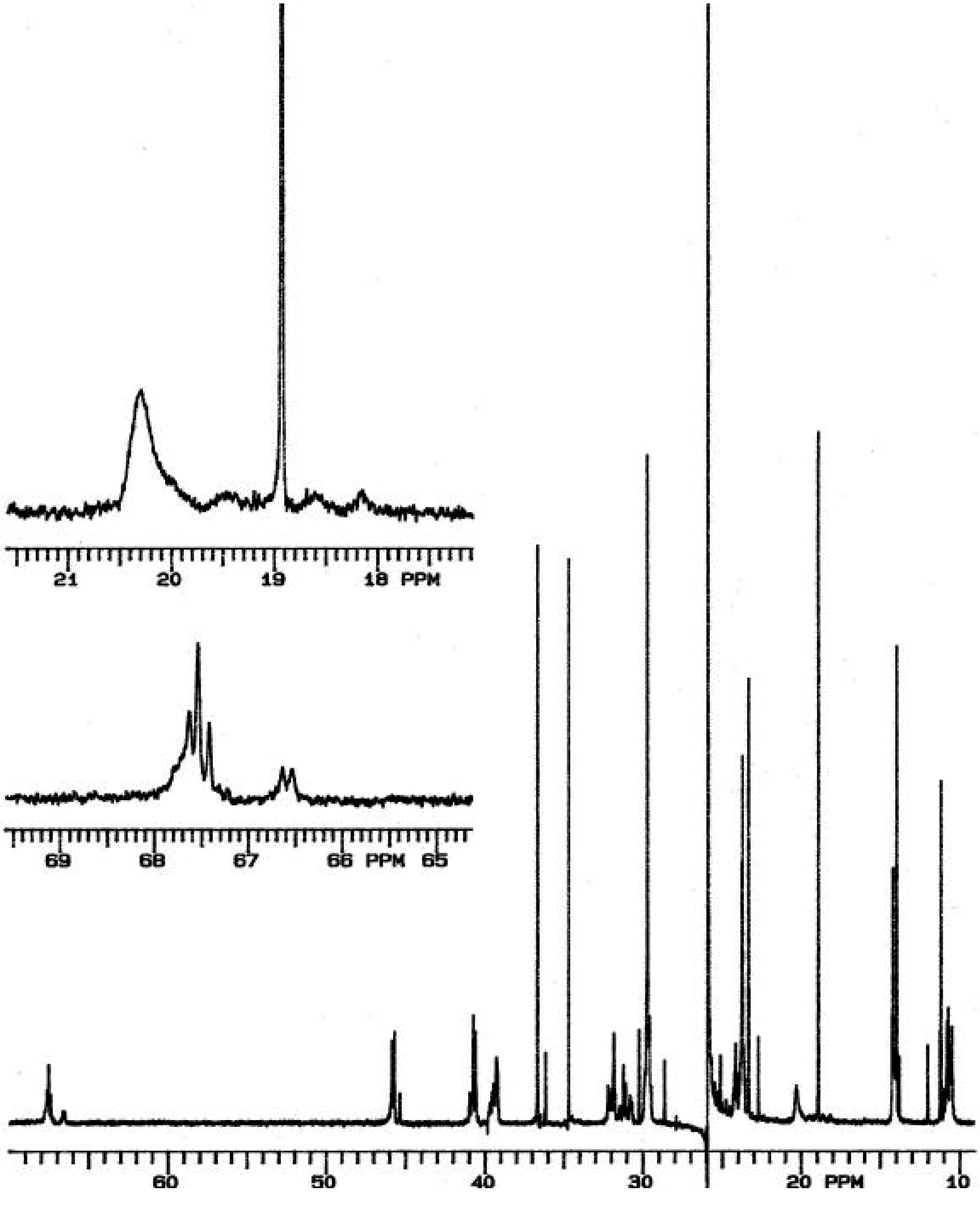


Figure 20 – ^{13}C NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.4:1 at –12 °C.

The peaks associated with 3-methylheptane become more pronounced in this sample, and even more so as the oxygen content is increased, because it is a byproduct of the synthesis of the alkoxide ligand. Although it was not attempted for this project, it may be possible to remove this compound by degassing the sample completely on the high vacuum line. In this case, it did not interfere with data analysis.

The ^{6}Li NMR spectrum is shown in Figure 21. The upfield peaks associated with the alkoxide containing species grew in intensity. This spectrum clearly shows that the original alkyllithium compound (0.85 ppm) has been almost entirely consumed. There are high concentrations of species, other than those already identified, present in this sample.

0.6:1 Oxygen-to-Lithium Ratio

The alkyl alpha-carbon region of this sample contains major peaks at 18.19 and 20.25 ppm (see Figure 22), as well as smaller peaks at 17.75, 18.55, and 19.89 ppm. A sample at this oxygen-to-lithium ratio is perhaps the best candidate to begin further study of this system for two reasons. First, the peak at 20.25 ppm should be the same hexameric mixed aggregate contained in the 0.2:1 and 0.4:1 O:Li samples already discussed and can be studied further. Second, the peak at 18.19 ppm, which has not been studied, exhibits fairly good signal-to-noise, which can be very advantageous when running some of the experiments described here.

The alkoxide alpha-carbon region shows multiple new peaks from 67.2 to 67.8 ppm. In addition to the three peaks clearly visible in the 0.2:1 O:Li sample at 67.42,

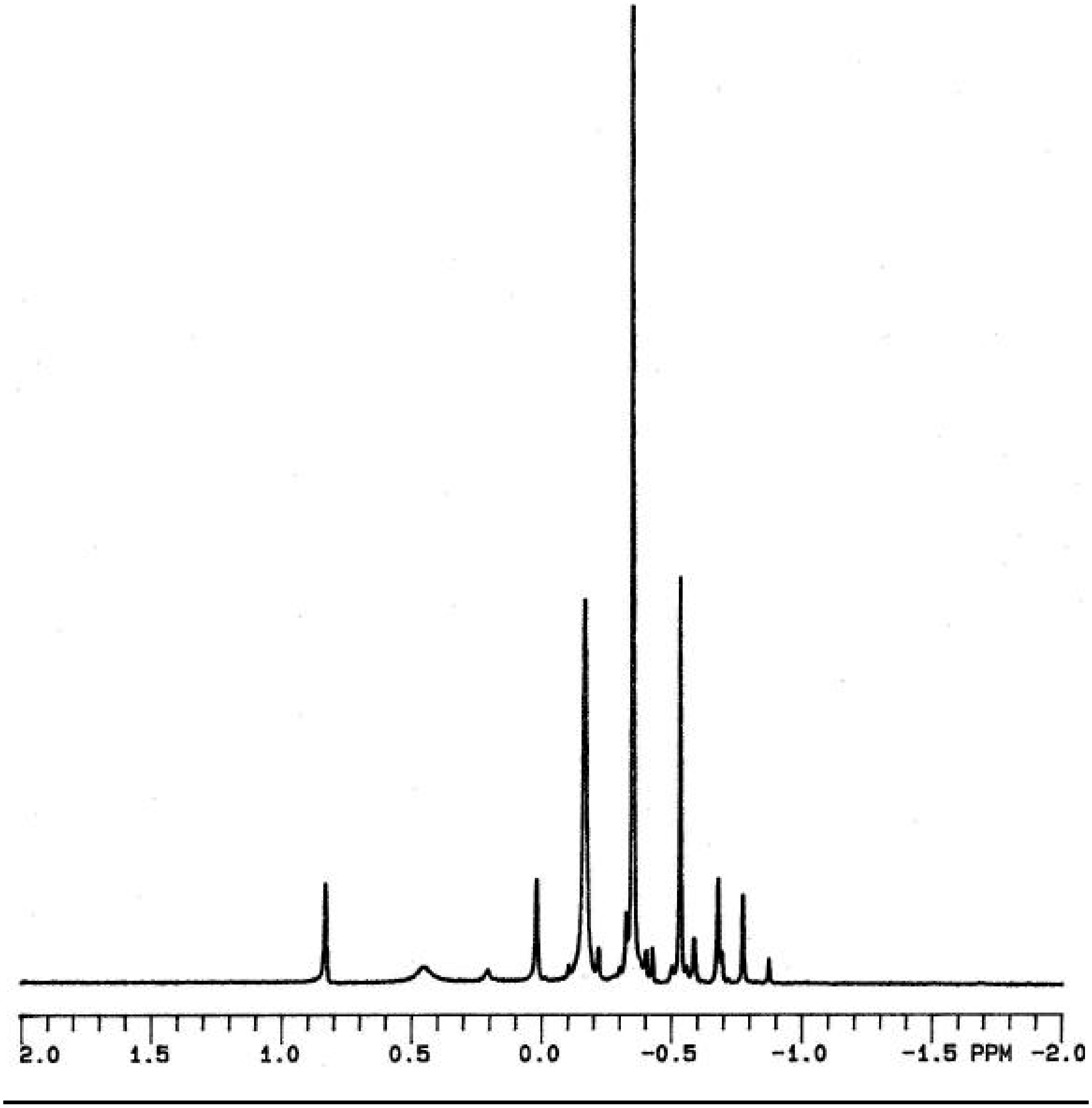


Figure 21 – ^{6}Li NMR spectrum, with proton decoupling, of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.4:1 at –12 °C.

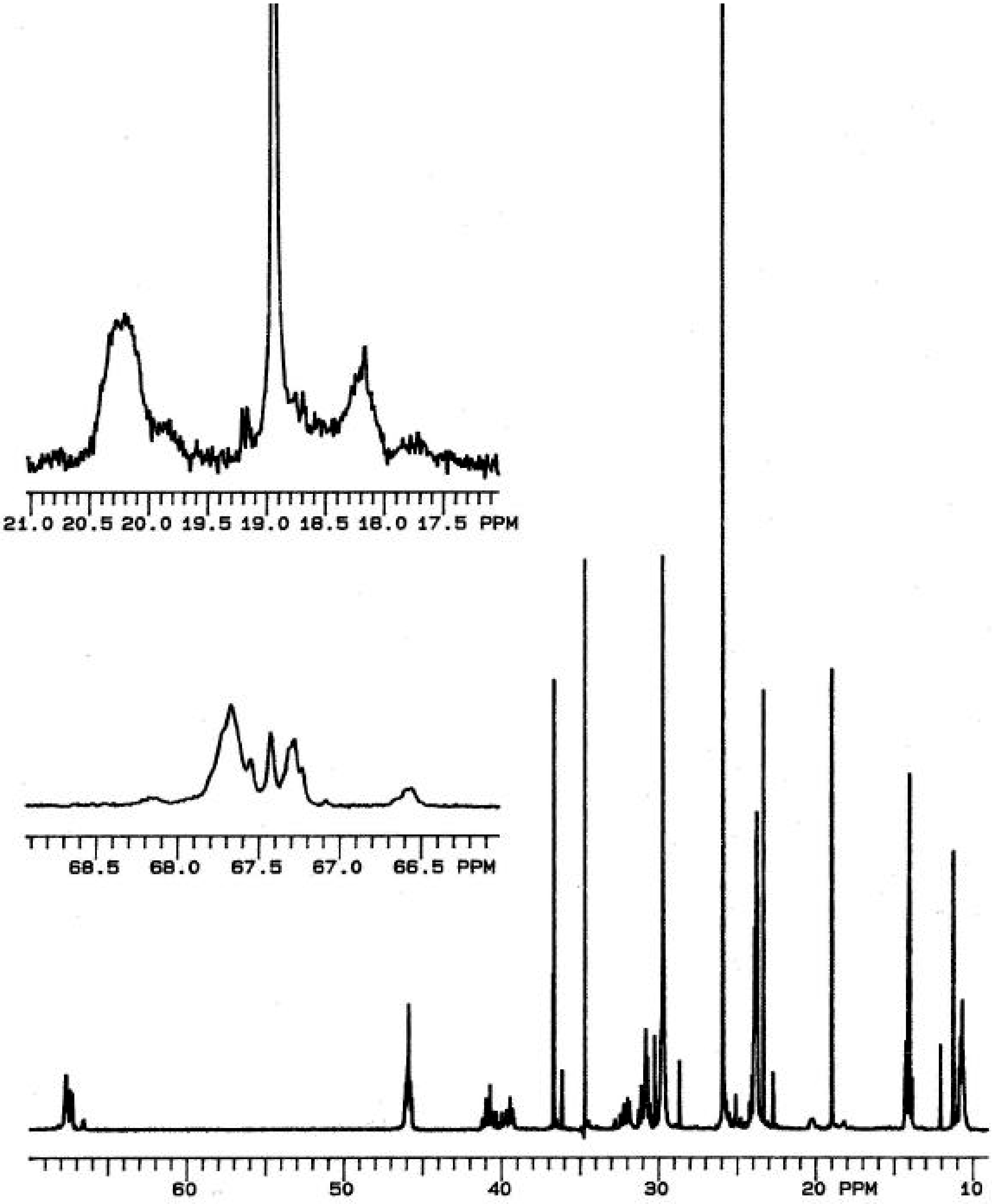


Figure 22 – ^{13}C NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.6:1 at –12 °C.

67.57, and 67.64 ppm, there are new peaks at 67.24, 67.29, 67.31, 67.68, and 67.73 ppm. Some of these peaks overlap, so there may be more.

The ^{6}Li NMR spectrum for this sample (Figure 23) is more complicated than that of the 0.4:1 O:Li sample. It contains many of the same peaks, however, it also contains many smaller peaks in between the others. The peak associated with the original alkyllithium compound is totally absent in this spectrum, which indicates that all remaining alkyl ligands are in aggregates containing alkoxide ligands. There is also increased hydride concentration in this sample.

0.8:1 Oxygen-to-Lithium Ratio

Virtually all the original alkyllithium compound has been consumed at this O:Li ratio. Only two small peaks remain in the alkyl alpha-carbon region of the ^{13}C NMR spectrum (Figure 24). Those peaks are at 18.52 and 19.44 ppm. There are also fewer peaks in the alkoxide alpha-carbon region indicating that overall fewer aggregates are present. The peak at 67.57 ppm is likely a mixed aggregate, and the peaks at 67.88, 67.94 and 67.98 ppm are probably all alkoxide aggregates.

The region of the ^{1}H NMR spectrum assigned to protons attached to the alkyl alpha-carbon atoms shows two very small peaks at –0.75 and –0.88 ppm. The low intensity of peaks in this region further indicates that most of the alkyllithium compound has been consumed. The region associated with protons on the alkoxide alpha-carbon atoms shows a large unresolved peak from 3.48 to 3.65 ppm. This is the result of the overlap of peaks from different species in solution.

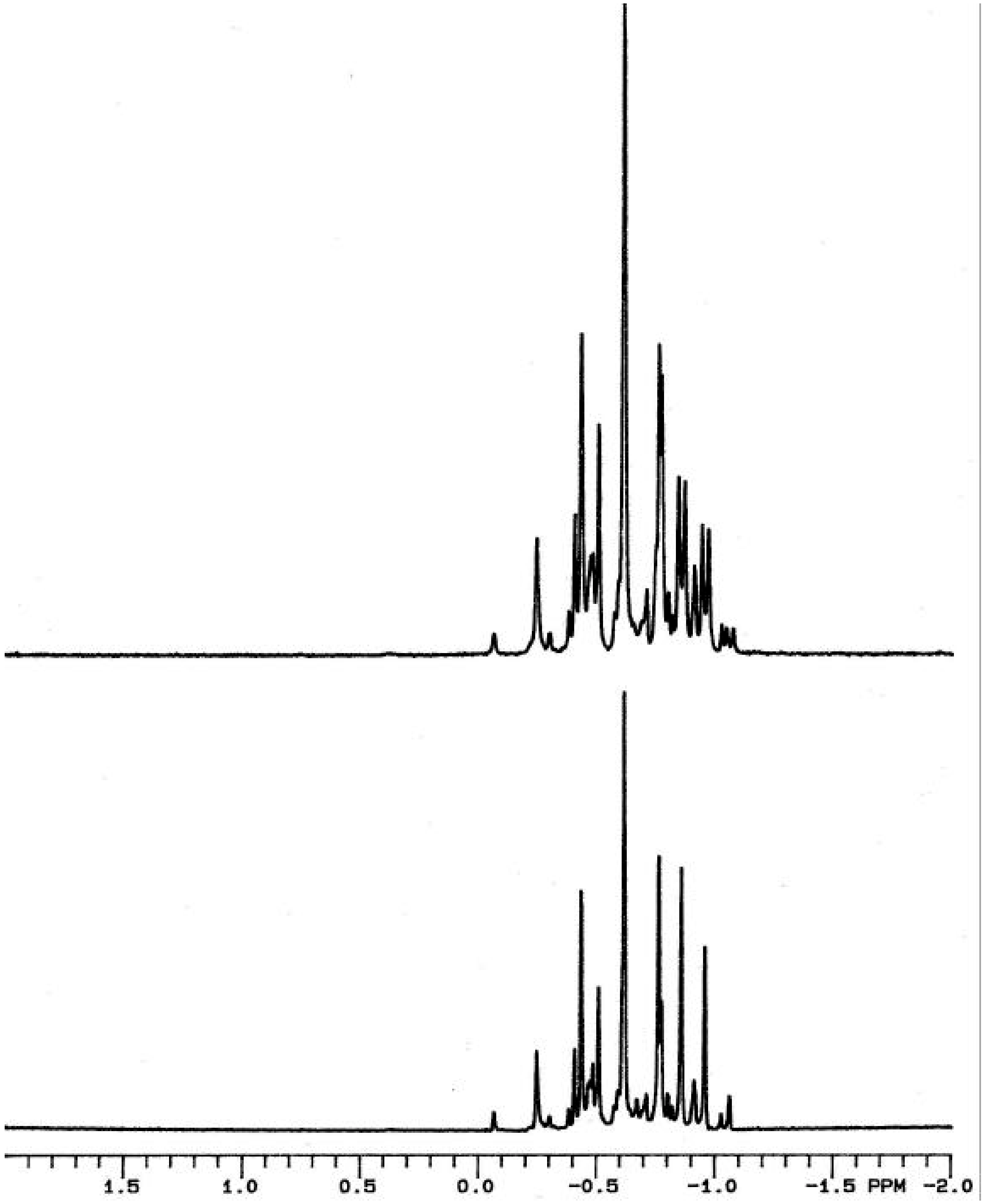


Figure 23 – ^{6}Li NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.6:1 at –12 °C with ^{1}H decoupling (bottom) and without (top).

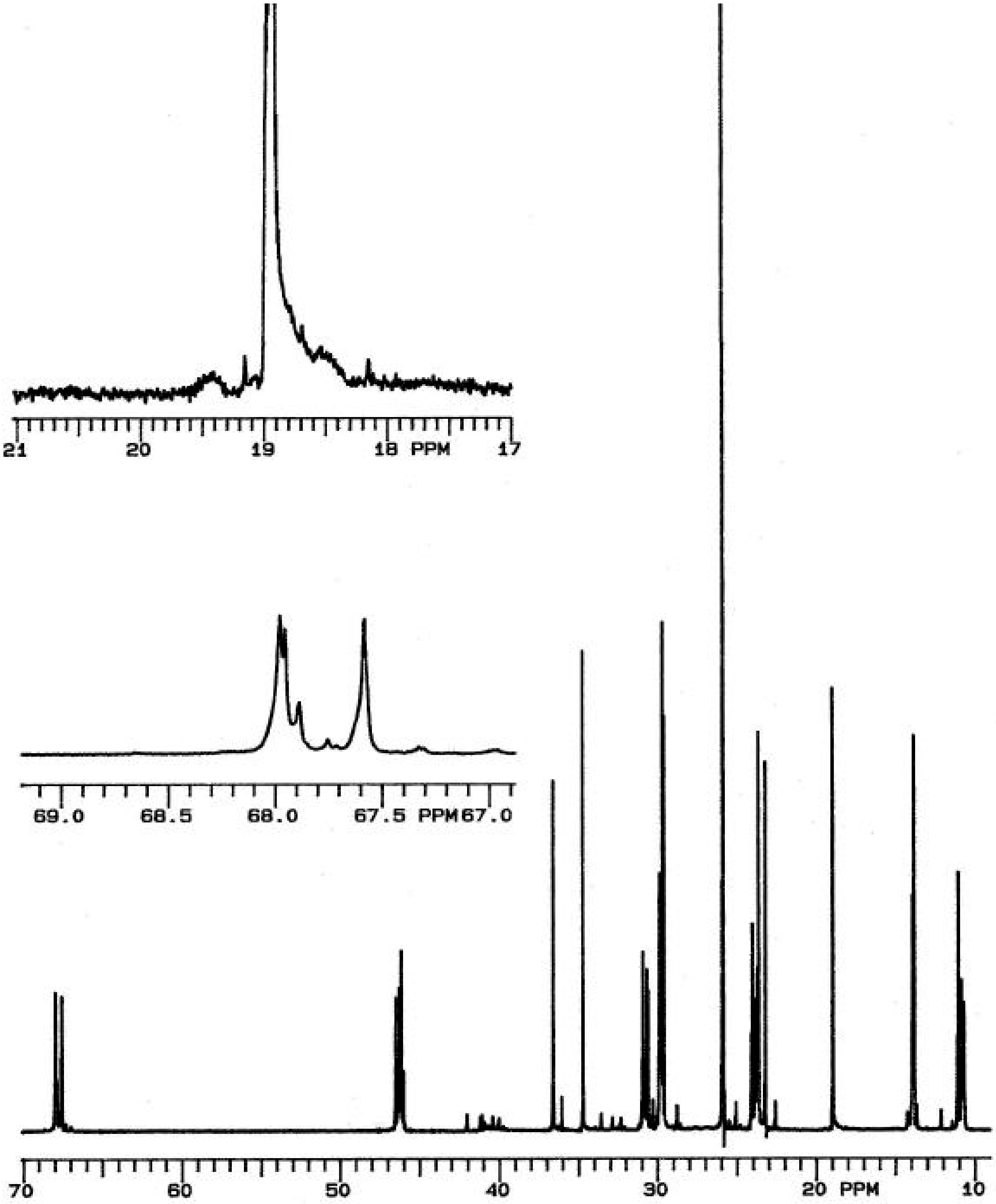


Figure 24 – ^{13}C NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.8:1 at room temperature.

The ^{6}Li NMR spectrum for this sample is shown in Figure 25. The major peaks are in the same region as peaks for the alkoxide that was synthesized independently. This spectrum also shows the presence of the hydride species referred to earlier. The multiplet centered at –0.59 ppm is believed to be this species, but no experimental evidence was collected to support that conclusion.

Conclusion

Three major questions have been answered by this study concerning 2-ethylhexyllithium. Branching at the beta-carbon in this compound has successfully limited the number of aggregates present in solution compared to straight chain alkyl groups such as n-propyllithium, which exists as hexamers, octamers, and nonamers in hydrocarbon solution.[11] It has been shown that 2-ethylhexyllithium exists as a single aggregate at all temperatures studied. Furthermore, based on the observed coupling the aggregation state of this compound has been assigned as six. Second, this study has shown that the optical activity of this compound has had no observable effect on any of the structural attributes examined here. Finally, it has been clearly demonstrated that 2-ethylhexyllithium and lithium 2-ethylhexoxide form mixed aggregates in solution, when the alkoxide is formed *in situ.*

Careful study of a sample with an oxygen-to-lithium ratio of 0.2:1 led to the determination of the aggregation state of one of the mixed aggregates. It was shown that two peaks in the ^{13}C NMR spectrum, one in the alkyl alpha-carbon region and one in the alkoxide alpha-carbon region, were from the same aggregate. This was determined

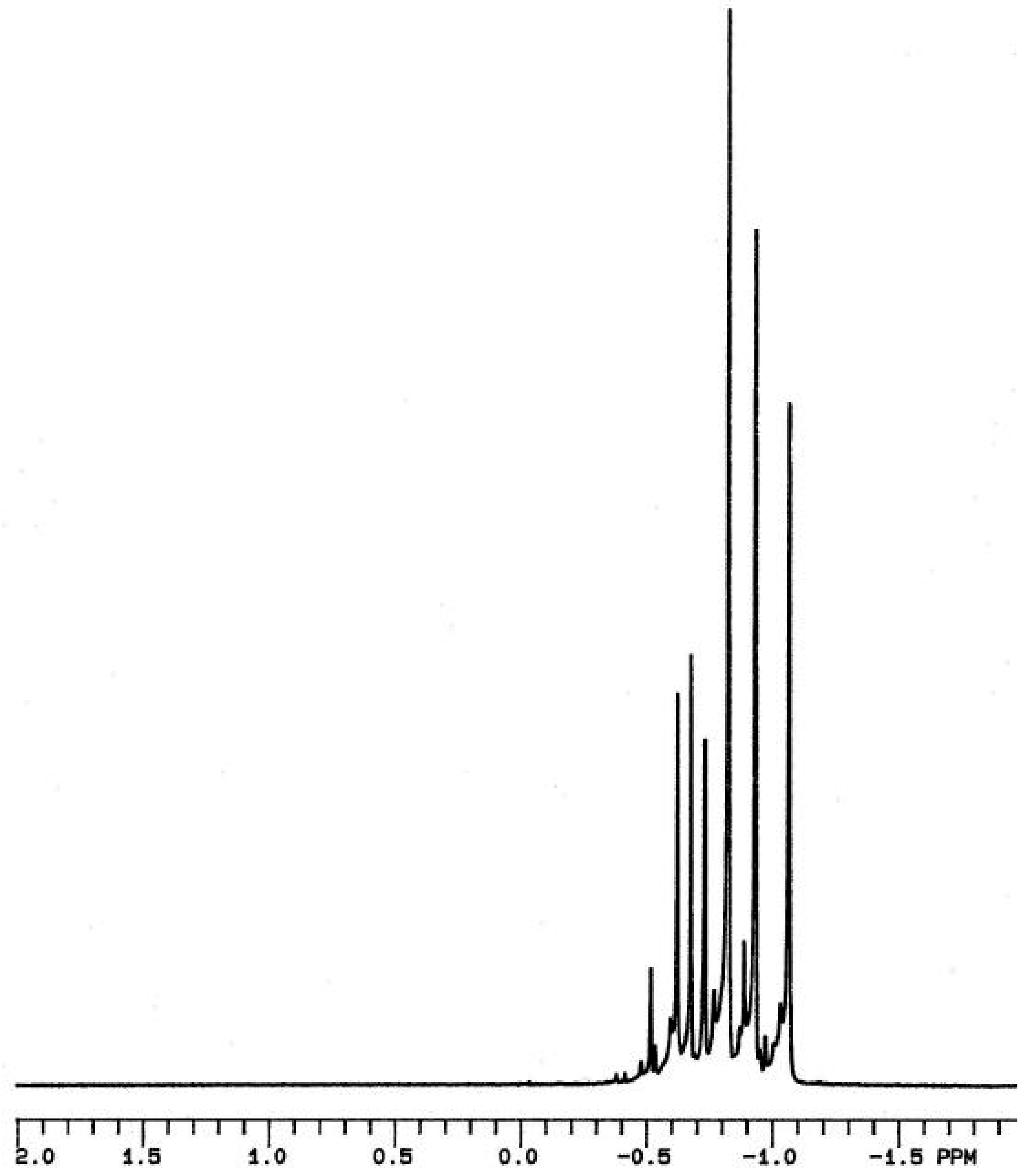


Figure 25 – ^{6}Li NMR spectrum of a mixture of 2-ethylhexyllithium and 2-ethyl-1-hexanol with O:Li = 0.8:1 at room temperature.

through data correlations between ^{1}H, ^{13}C, and ^{6}Li NMR spectra. The correlations between spectra were made using 2-D NMR experiments. The ^{1}H NMR spectrum was correlated with the ^{13}C NMR spectrum using HETCOR experiments, some with lithium decoupling. The ^{1}H NMR spectrum was then correlated with the ^{6}Li NMR spectrum using a HOESY experiment. After showing those correlations, the integral values for the two peaks, obtained through a gated decoupled ^{13}C NMR experiment, were compared, and shown to be in a ratio of five-to-one alkyl-to-alkoxide. That information and information obtained about the observed carbon-lithium coupling constant through a ^{6}Li *J*-modulated ^{13}C spin echo experiment led to the determination that that aggregate was a hexamer with five alkyl groups and one alkoxy group.

The aggregates already identified continued to be present in the sample with an oxygen-to-lithium ratio of 0.4:1. The hexameric mixed aggregate appears to be the most abundant species in this sample, and the original alkyllithium compound has decreased significantly. Other aggregates are present in this sample as well; however, no attempts were made to assign their aggregation states.

The sample with an oxygen-to-lithium ratio of 0.6:1 offers the most promise for future study. Two mixed aggregate peaks in the alkyl alpha-carbon region of the ^{13}C NMR spectrum are present with significant intensities. The increased signal-to-noise of those peaks may make it possible to obtain useful information regarding their carbon-lithium coupling constants through ^{6}Li *J*-modulated ^{13}C spin echo experiments. Their increased intensities would also shorten experimental times. One of the peaks is from the mixed aggregate already identified, so it could be used as an internal reference. The other is present in samples with lower oxygen-to-lithium ratios, but it is most abundant at this particular oxygen-to-lithium ratio.

The number of aggregates containing alkyl groups has decreased dramatically in the sample with an O:Li ratio of 0.8:1. Only two peaks remain visible in the alkyl alpha-carbon region of the ^{13}C NMR spectrum. This sample could provide valuable information as well. Because there are only two peaks in that region of the ^{13}C NMR spectrum, it may be fairly straightforward to determine their counterparts in the alkoxy alpha-carbon region, which is fairly well resolved. An analysis similar to the one carried out on the sample with an oxygen-to-lithium ratio of 0.2:1 could be used.

Finally, the compound 2-ethyl-1-hexoxide was shown to be slightly soluble in cyclopentane solution. The ^{6}Li NMR spectrum showed multiple peaks, which could be from different aggregates in solution or from lithium nuclei within the same aggregate that are not magnetically equivalent.

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