

Stereochemistry of Solvation of Benzylic Lithium Compounds: Structure and Dynamic Behavior

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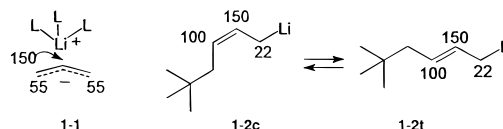
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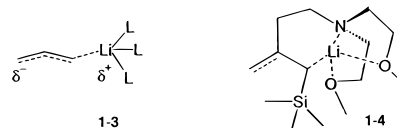
Abstract: Several *sec*-benzylic lithium compounds, both externally coordinated, [α -(trimethylsilyl)benzyl]-lithium·PMDTA (**12**) and *p*-*tert*-butyl- α -(dimethylethylsilyl)benzyl lithium·TMEDA (**13**), and internally coordinated, [α -[[[*cis*-2,5-bis(methoxymethyl)-1-pyrrolidiny]methyl]dimethylsilyl]-*p*-*tert*-butylbenzyl]lithium (**14**) and [α -[[[(*S*)-2-(methoxymethyl)-1-pyrrolidiny]methyl]dimethylsilyl]benzyl]lithium (**15**), have been prepared. Ring ^{13}C NMR shifts indicate that **12**–**15** have partially delocalized structures. Externally solvated allylic lithium compounds are found to be delocalized, and only some internally coordinated species are partially delocalized. Compound **15** exists as >95% of one stereoisomer of the two invertomers at C_α . This is in accord with a published ee of >98% in products of the reactions of **15** with aldehydes. All four compounds show evidence of one-bond ^{13}C – ^6Li spin coupling, ca. 3 Hz, which indicates a small detectable C–Li covalence. Averaging of the ^{13}C – ^6Li coupling of **12** with increasing temperature provides the dynamics of intermolecular C–Li bond exchange, with $\Delta H_{\text{ex}}^\ddagger = 9 \pm 0.5 \text{ kcal mol}^{-1}$. Carbon-13 NMR line shape changes due to geminal methyls, and ligand carbons gave similar rates of inversion at C_α in **13** (externally solvated) and **14** (internally solvated), $\Delta H_{\text{inv}}^\ddagger \approx 4.9 \pm 0.5 \text{ kcal mol}^{-1}$. By contrast, barriers to rotation around the ring– C_α bonds vary widely, depending on the mode of lithium coordination, $\Delta H_{\text{rot}}^\ddagger \approx 8 \pm 0.5$ to $19 \pm 1.0 \text{ kcal mol}^{-1}$. Some mechanisms for these processes are proposed.

Main group allylic¹ and benzylic¹ organometallic compounds have always been regarded as among the simplest delocalized carbanionic species, a concept which is largely qualitatively supported by the results of X-ray crystallographic,^{2,3} spectroscopic,^{4,5} and calculational studies.^{6,7} Solvated allylic lithium

compounds show ^{13}C NMR shifts that are to be expected of ion-pairs containing delocalized allylic anions,⁴ see **1-1**. By



contrast, unsolvated alkane-soluble allylic lithium compounds, most likely aggregated as, for example, **1-2**, show ^{13}C NMR shifts similar to those of alkenes.⁸ Therefore, they should be regarded as largely localized compounds. Species with structures between **1-1** and **1-2**, i.e., partially delocalized, **1-3**, with some detectable C, Li covalency have not been recognized until recently, and then only for compounds with attached pendant ligands, such as **1-4**.⁹ For such cases, we proposed that restricted



stereochemistry of internal coordination of lithium favored a

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structure in which lithium lies closer to the allyl plane⁹ when compared to the externally solvated species, in which lithium lies normal to this plane.^{2,4} Compounds such as **1-4** are the only allylic lithium compounds which exhibit one-bond ¹³C–⁶Li spin coupling constants. Their small values of 3–4 Hz⁹ contrast with the 15 Hz that was observed for many monomeric organolithium compounds.¹⁰ This argues for a small detectable C–Li covalency in **1-4** and similar compounds.⁹

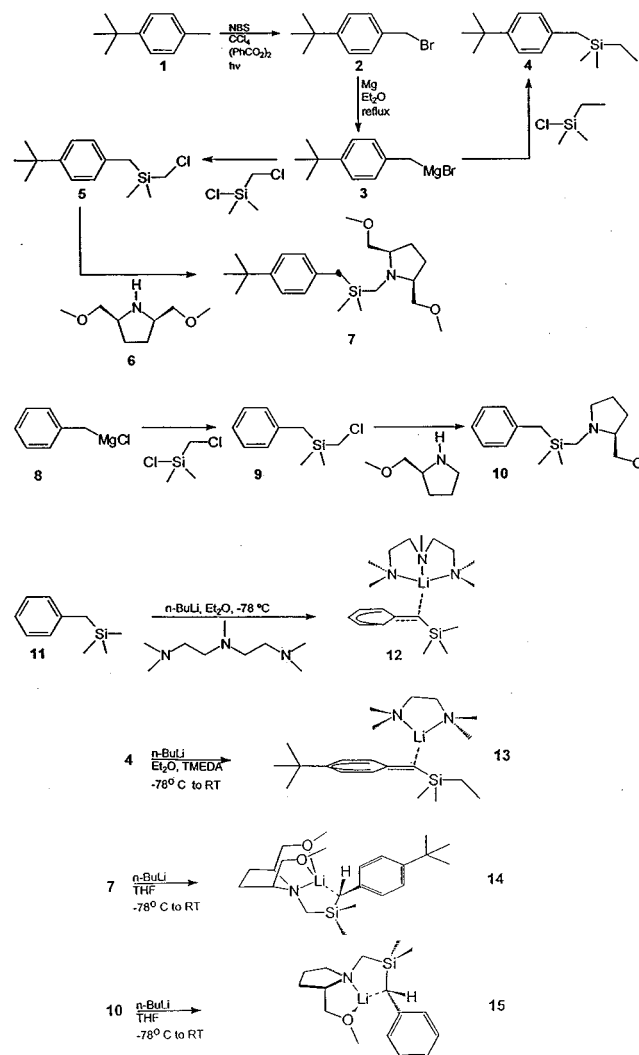
Analysis of the temperature-dependent ¹³C NMR line shapes of several ion-paired allylic lithium compounds¹¹ showed a rich diversity of dynamic behavior that included (1) transfer of coordinated lithium between faces of the allyl planes, (2) reorientation of coordinated lithium on one side of the allyl plane, (3) rotation about the allyl bonds, and (4) local reversible Li,N (of ligand) dissociation with inversion at nitrogen. Additionally in the case of the internally coordinated allylic lithium compounds, averaging of the ¹³C–⁷Li coupling constants was used to monitor the dynamics of bimolecular C–Li bond exchange.⁹

Effects similar to those described above have been observed for some benzylic lithium compounds.¹² However, as will be shown below, only the α -disubstituted benzylic lithium compounds exhibit properties expected of delocalized carbanions;^{13,14} only the α -monosubstituted species appear to be partially delocalized. Their behavior will be described below. In particular, we compare both the structures and dynamic behavior of externally and internally solvated compounds. Possible mechanisms responsible for these dynamic effects are suggested.

Results and Discussion

Synthesis. Starting materials required for subsequent metalation experiments were prepared as described by **1-10**, below. Two different silylations (chlorodimethylethylsilane and chloromethylchlorodimethylsilane) of benzylic Grignard **3** produced **4** and **5**, respectively. Amination of chloro compound **5** with *cis*-2,5-bis(methoxymethyl)pyrrolidine gave **7**, and a similar reaction using **9** (from Grignard **8**) with (*S*)-2-methoxymethylpyrrolidine¹⁵ provided enantiomerically pure **10** with ee > 98%. Compounds **4, 7, 10**, and **11** all smoothly underwent benzylic metalation at –78 °C in THF or diethyl ether using *n*-butyllithium-⁶Li for **7, 10**, and **11** and its ⁷Li isotopomer for **4**. The metalations of **4** and **11** were carried out in the presence

of external ligands. These interconversions are shown in reactions **11** → **12**, **4** → **13**, **7** → **14**, and **10** → **15**.



volatile components were removed under high vacuum from preparations **12-15** and replaced by THF-*d*₈ or diethyl ether-*d*₁₀. These samples, largely ca. 0.25 M, were retained for subsequent NMR study.

NMR Parameters. cursory inspection of the NMR data for **12-15** reveals that each of the spectra obtained at low-temperature represents a single molecular species, although rapid interconversion among several species giving rise to a single averaged spectrum cannot be neglected. The manner in which signal averaging takes place at higher temperatures implies that the same species or species distribution prevails throughout the temperature range investigated.

Table 1 lists the ¹³C NMR chemical shifts obtained at <180 K for compounds **12-15**. These shifts are drawn around the proposed structures. Compound **13** is drawn by analogy to the structure proposed for α -(trimethylsilyl)benzyl lithium·TMEDA based on HOESY (⁶Li{¹H}) measurements.¹⁶ These results are also consistent with Boche's X-ray crystallographic structure.^{3c}

The ¹³C NMR shifts for the α -secondary benzylic lithium compounds reported here and previously¹² are remarkably similar. Each spectrum shows alternating shifts that are qualitatively indicative of a conjugated anion. However, **12-15** cannot be regarded as incorporating benzylic anions. Based on

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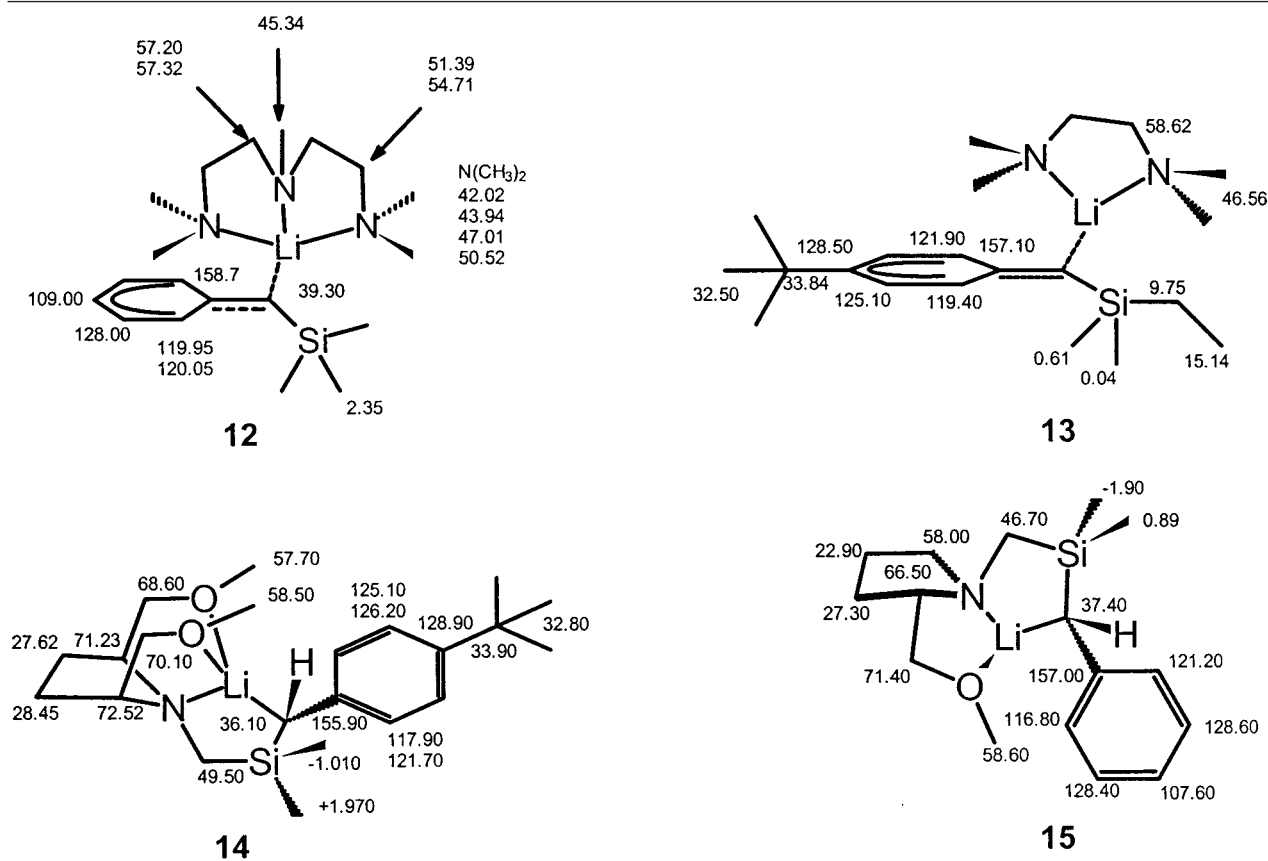
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Table 1. ^{13}C NMR Chemical Shifts with Structures of **12**–**15**

the well-known linearity of ^{13}C shift with π charge,¹⁴ the model system which exhibits shifts to be expected for a delocalized benzylic anion is α -methyl- α -neopentylbenzyl lithium·TMEDA.¹³ These ^{13}C shifts are, in δ units; α , 71; *ipso*, 131; *o*, 105; *m*, 128; and *p*, 87. Values similar to those just listed have been reported for cumylpotassium^{13a} and 7-phenyl-7-metallonorbornane ($M = \text{K}, \text{Cs}$), all in THF.¹⁸ Compared to these latter compounds the α -secondary benzylic lithium compounds **12**–**15** and those reported previously¹² must all be regarded as partially delocalized, to a similar extent. Consistent with this proposal is our observation of one bond $^{13}\text{C}_\alpha$ – ^6Li spin coupling of 3 to 4 Hz, as shown below. Such spin coupling implies a small detectable degree of C_α – Li covalence.

Below, the structure and dynamic behavior of **12**–**15** will be considered separately. We will show how the dynamics of inversion at C_α , of carbon lithium bond exchange, and of rotation around the ring benzyl carbon have been determined separately.

Down to 170 K, ^{13}C NMR of α -TMS-benzyl lithium·TMEDA gave no evidence for $^{13}\text{C}_\alpha$ – ^6Li or $^{13}\text{C}_\alpha$ – ^7Li spin coupling, nor did the TMEDA resonances show the type of fine structure indicative of slow ion–ion reorientation within an unsymmetrical ion-paired environment.^{11a,b} By contrast, the $^{13}\text{C}_\alpha$ NMR spectrum of α -TMS-benzyl lithium– ^6Li in the presence of an equivalent of pentamethyldiethylene triamine, **12**·PMDTA, in THF at 230 K consists of an equally spaced 1:1:1 triplet with splitting of 3.7 Hz due to one-bond $^{13}\text{C}_\alpha$ – ^6Li spin coupling. Note that the spin of ^6Li is 1. This pattern clearly indicates that compound **12** is a monomer, and intermolecular carbon–lithium bond exchange is slow relative to the NMR time scale at 230

K. One-bond ^{13}C – ^6Li coupling constants were also observed for **14** (3 Hz) and **15** (2.5 Hz). That the $^{13}\text{C}_\alpha$ resonance of **13** is selectively broadened at low temperature compared to the other resonances and narrows with increasing temperature clearly implicates $^{13}\text{C}_\alpha$ – ^7Li coupling. Its value should be 9.8 Hz based on the 3.7 Hz value for $^1J(^{13}\text{C}, ^6\text{Li})$ of **12**. Both compounds should have the same electronic structures, as evidenced by their ^{13}C ring shifts. They should therefore have similar ^{13}C – Li lithium coupling constants when corrected for the isotope. Lithium-7 quadrupole-induced relaxation rates increase with decreasing temperature and thus would be responsible for narrowing of the $^{13}\text{C}_\alpha$ resonance on cooling the sample of **13**· ^7Li ·TMEDA. Narrowing of this resonance with increasing temperature can only be due to intermolecular carbon–lithium bond exchange. That compound **12** exhibits $^{13}\text{C}_\alpha$ – ^6Li coupling whereas **13** does not suggests that tridentate coordination of PMDTA to **12** reduces the rate of carbon–lithium exchange when compared to that of **13**·TMEDA.

The one-bond ^{13}C – ^6Li coupling constants of 3–4 Hz reported herein and previously for secondary benzylic lithium compounds and for internally solvated monomeric allylic lithium compounds⁹ are much smaller than the ca. 16 Hz values reported for most monomeric organolithium compounds. Among a wide variety of solvated and unsolvated $(\text{RLi})_n$ species ($\text{R} = \text{alkyl}, \text{vinyl}, \text{aryl}, \text{alkynyl}$) studied under conditions of slow intermolecular C–Li exchange, the coupling constants $^1J(^{13}\text{C}, ^6\text{Li})$ fall into a remarkably simple and unexpected common pattern. The values depend only on the state of aggregation, n (1), not on the nature of the organic moiety.¹⁰ While this relationship is not well understood, it may be rationalized as follows:

$$^1J(^{13}\text{C}, ^6\text{Li}) = 16/n \quad (1)$$

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We assume that these one-bond coupling constants are largely due to the Fermi contact interaction¹⁹ and use the average energy and normalization approximations proposed by Karplus, Grant, and Lichtman²¹ in their treatment of one bond coupling constants.^{20,21} For a given state of aggregation, the $^1J(^{13}\text{C}, ^6\text{Li})$ values would be proportional to $\gamma^{13}\text{C}\gamma^6\text{Li}s^2Z^3$, where s^2 is the "s" character associated with the C–Li bond, Z is the effective nuclear charge on carbon, and Z^3 is a function of the C–Li covalence. For this coupling constant to be independent of the organic moiety, s^2Z^3 would have to be constant. Such an exact inverse relationship between "s" character and C–Li covalence is unexpected but not unreasonable from a qualitative point of view.^{22–24}

Externally solvated allylic and tertiary benzylic lithium^{13,18} compounds do not show $^{13}\text{C}_\alpha\text{--}^6\text{Li}$ or $^{13}\text{C}\text{--}^7\text{Li}$ spin coupling. Their ^{13}C shifts are consistent with delocalized carbanions within solvated ion-pairs. When compared to the 16 Hz $^1J(^{13}\text{C}\text{--}^6\text{Li})$ values observed for the many "common pattern" monomers, the much smaller coupling constants for secondary benzylic and internally solvated allylic lithium compounds suggest that their C–Li ionicities are somewhere between those of the "common pattern" species and the solvated ion-pairs. This is also supported by the ^{13}C shifts reported in this paper and previously.¹²

Free PMDTA, at 180 K, shows ^{13}C shifts, all in δ units, at 46.20 (N(CH₃)₂), 44.60 (NCH₃), 58.50 (CH₂), and 57.30 (CH₂). By comparison at 190 K, all carbons in contained PMDTA in the sample of **12** are magnetically nonequivalent; all the PMDTA resonances are of equal intensity, see Figure 1. This observation, together with the 1:1:1 triplet for the $^{13}\text{C}_\alpha$ resonance due to $^{13}\text{C}\text{--}^6\text{Li}$ coupling, implies that the PMDTA is tridentately coordinated to lithium and that the spectrum represents a single monomeric species. The pattern of the PMDTA ^{13}C NMR bears a close resemblance to the shifts of PMDTA complexed to monomeric mesityllithium·PMDTA^{10b} and to those of neopentyllithium·PMDTA.^{10c} In the latter case, PMDTA resonances, in δ units, at 43.00, 44.60, 47.50 and 49.80 (N(CH₃)₂), 45.00 (NCH₃), 51.50, 54.50 (CH₂), and 57.10 (both CH₂'s)^{10c} compare closely to 42.02, 43.94, 47.01, 50.52 (N(CH₃)₂), 45.34 (NCH₃), 51.39, 54.71 (CH₂), 57.2, and 57.32 (C¹H₂) that were obtained for compound **12**, see Figure 1. Apparently, the magnetic environment of PMDTA tridentately complexed to lithium in these three RLi monomers appears to be largely independent of the organic moiety.

Previous studies of ion–ion reorientation within allylic and benzylic lithium compounds did not resolve the dynamics of the different reorientational processes. Compounds **13** and **14**

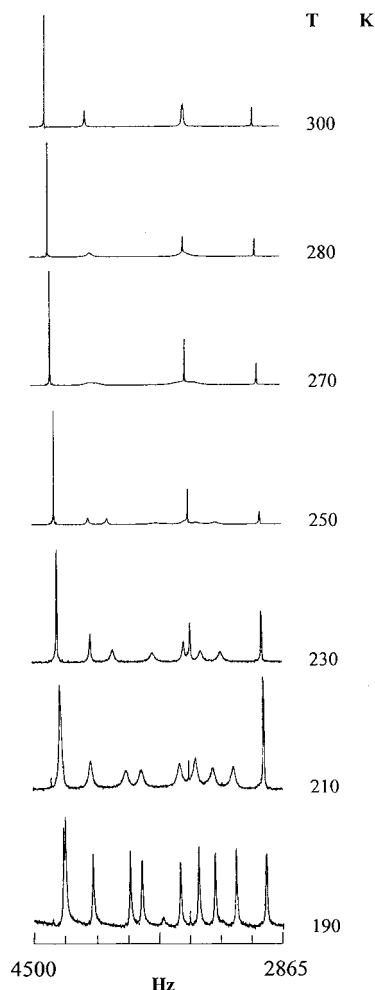


Figure 1. ^{13}C NMR spectra of **12**·PMDTA in diethyl ether-*d*₁₀, PMDTA portion, different temperatures, assignments from left (190 K spectrum), in δ units: 57.32, 57.2, 54.71, 51.39 (CH₂); 50.52, 47.01 (N(CH₃)₂); 45.34 (NCH₃); 43.94, 42.02 (N(CH₃)₂).

were prepared incorporating geminal silyl methyls in each. We hoped these geminal methyls would be magnetically nonequivalent due to the expected chiral environment within these species. The diastereotopicity could then be exploited to measure the rate of overall inversion in **13** and **14**, which is the result of transfer of coordinated lithium between two faces of the benzylic planes. Note that diastereotopic methylene hydrogens were observed by Hoffmann et al. in low-temperature NMR of α -hetero benzylic lithium compounds and were utilized to measure the rate of inversion at C _{α} .²⁵

At low temperature, the geminal silyl methyls of **13** and **14** are, as we predicted, nonequivalent in ^{13}C NMR. Each gives rise to an equal doublet (Table 1), indicating that at this temperature overall inversion is slow relative to the NMR time scale. The NMR of attached ligand in **14** also supports slow inversion at C _{α} , as all ligand carbons are magnetically nonequivalent. However, although benzylic inversion is slow in **13** at 180 K, as indicated by nonequivalent geminal silyl methyls, coordinated TMEDA must be undergoing other reorientational processes faster than benzylic inversion since the TMEDA ^{13}C NMR consists of just two peaks down to 160 K. NMR line shape analysis of the dynamics of inversion processes is treated further below.

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(23) Consistent with and in support of these results is the observation of one-bond $^{13}\text{C}_\alpha\text{--}^7\text{Li}$ spin coupling of 7.0 Hz in a benzylic lithium compound with the 2,6 positions bridged by CH₂(OCH₂CH₂)₄OCH₂, wherein internal encapsulation of lithium reduces the rate of intermolecular C–Li exchange: Ruhland, T.; Hoffmann, R. W.; Schade, S.; Boche, G. *Chem. Ber.* **1995**, 128, 551–556.

(24) A number of α -hetero and α , α -dihetero organolithium compounds (hetero = Te, Si, S, Se) show one bond $^{13}\text{C}\text{--}^7\text{Li}$ spin coupling of 8–21 Hz, less than the 42 Hz values observed for the common pattern organolithium compounds. (a) Reich, H. J.; Kulicke, K. J. *J. Am. Chem. Soc.* **1995**, 117, 6621–6622. (b) Reich, H. J.; Kulicke, K. J. *J. Am. Chem. Soc.* **1996**, 118, 273–274. (c) Reich, H. J.; Dykstra, R. R. *J. Am. Chem. Soc.* **1993**, 115, 7041–7042. (d) Reich, H. J.; Dykstra, R. R. *Angew. Chem., Int. Ed. Engl.* **1993**, 32, 1649–1650.

Compound **15**²⁶ is a special case due to the chirality at C₂ of the pyrrolidino ring. The compound was prepared starting from (S)-(+)-2-methoxymethylpyrrolidine, and it is unlikely that the stereochemistry at C₂ of pyrrolidine changed during transformation of **9** to **15**. Carbon-13 NMR of **15** in THF-*d*₈ solution was monitored down to 180 K. At this temperature, rotation around the Si-C_α bonds in similar solvated benzylic lithium compounds has been shown to be slow relative to the NMR time scale.¹² The two rotamers around the silicon benzyl bond, with lithium on opposite sides of the benzyl plane, would be diastereomeric and would be expected to give rise to different NMR spectra. However, at 180 K, **15** exhibited a single ¹³C NMR spectrum in which all carbons are nonequivalent and all resonances are of equal intensity. A second species was not detected. If present, its concentration would be less than 4% of the predominant stereoisomer. By 240 K and above, interconversion of the two possible stereoisomers would be fast relative to the NMR time scale. The observed NMR spectrum would be the weighted average of the two stereoisomeric spectra. The ratio of the two stereoisomers might be expected to vary with temperature. Yet aside from averaging of the ¹³C_α-⁶Li spin coupling and of the two ortho carbon resonances, the ¹³C NMR spectrum of **15** is unchanged between 180 and 300 K. This signifies the predominance of a single stereoisomer. Changes seen for C_α and the ortho carbon NMR reflect the dynamics of bimolecular C_αLi bond exchange and rotation around the ring-C_α respectively. This will be further described below.

Of the two structures that can be proposed for internally solvated monomeric **15**, the structure shown would minimize the steric interaction between phenyl and methoxymethyl compared to the species obtained by inverting the configuration at C_α in **15**, as was proposed by Chan.²⁶

The results described for **15** also explain the 98% ee reported by Chan²⁶ for the reaction product of **15** with benzaldehyde. Clearly, this is largely the result of the presence of one stereoisomer of **15** under their reaction conditions. The chemistry used to prepare **15** was also carried out with racemic 2-methoxymethylpyrrolidine, resulting in **15**•RAC. As expected, the ¹³C NMR spectra of **15** and **15**•RAC are identical.

Dynamic Behavior. With increasing temperature, compounds **12**–**15** exhibited interesting changes in the line shapes of their ¹³C NMR spectra. This is indicative of the operation of different dynamic effects. These effects are (1) bimolecular C_αLi bond exchange, (2) inversion at C_α, which is equivalent to transfer of coordinated lithium between opposite faces of the benzyl plane, and (3) rotation around the ring benzyl bond. The dynamics of each of these processes have been examined separately.

The dynamics of carbon–lithium bond exchange in **12** were investigated using the ¹³C_α NMR line shapes. With increasing temperature above 230 K, the 1:1:1 ¹³C_α triplet due to ¹³C–⁶Li scalar coupling progressively averages to a single line by 290 K. This is the result of increasingly faster bimolecular C_α–Li bond exchange. In terms of ¹³C_α NMR, the process is modeled for a system with ¹³C in natural abundance as shown in eq 2. Calculation of the ¹³C_α line shape as a function of the specific



rate of exchange is carried out as described previously.²⁷ Comparison of observed and calculated ¹³C_α NMR line shapes provided the *k*₁ values, which are the pseudo-first-order rate constants for bimolecular C_αLi exchange. Activation parameters obtained from the Eyring plot are listed in Table 2.

Table 2. Activation Parameters for Inversion, Benzylic Rotation, and C_αLi Bond Exchange for Benzylic Lithium Compounds in THF-*d*₈

compd	process	¹³ C resonance	Δ <i>H</i> [‡] (±0.5 kcal mol ⁻¹)	Δ <i>S</i> [‡] (±3 eu)
12	C _α Li exchange	C _α	9.4	-15
13	inversion	Si(CH ₃) ₂	5.1	-21
	benzyl rotation	<i>o</i> C's	14.2 ^a	5.6
14	inversion	Si(CH ₃) ₃	4.8	-24
		OCH ₃	4.3	-26
		NCH	3.9	-27
		OCH ₂	4.6	-24
	benzyl rotation	<i>o</i> C's	8.5	-14
15	benzyl rotation	<i>o</i> C's	19.2 ^a	23

^a ±1.0 kcal.mol⁻¹

The behavior of the ¹³C_α resonances of **14** and **15** qualitatively resembles that of **12**. However, the small coupling constants and reduced resolution do not permit acceptable analysis of the line shape changes.

We next consider NMR data indicative of inversion phenomena. Equal doublets observed at low temperature for the geminal methyl silyl groups in ¹³C NMR of **13** and **14** were ascribed to the chiral environment in these complexes. We initially proposed that averaging of the diastereotopicity would be the result of inversion alone and would thus separate and reveal the dynamics of inversion from all the other ion–ion reorientation processes. In fact, warming these two samples above 180 K does average the geminal methyl doublets to single lines at their respective centers. Comparison of observed and calculated line shapes yields the rate constants for inversion. The resulting activation parameters are listed in Table 2. It is interesting that, although the ligands for **13** (external) and **14** (internal) are different, the activation parameters for inversion at C_α are remarkably similar. Hoffmann and Ahlbrecht²⁵ have used a similar technique based on diastereotopicity of methylene hydrogens to monitor the dynamics of carbanionic inversion in several α-hetero, including α-SCH₂Ph and α-SO₂Ph, benzylic lithium compounds.²⁵ Where temperature-dependent data were used, their Δ*H*[‡] values were larger, ca. 7 kcal mol⁻¹, compared to those reported herein.

The effects described above with regard to the geminal methyl silyl ¹³C resonances of **13** and **14** do not apply to **15** since this compound largely exists as one enantiomer, >95%. Interconversion between the latter and a minor (<5%) stereoisomer would not be detected among the ¹³C NMR data.

Compound **14** was designed to incorporate a pendant bis-(2,5-methoxymethyl)pyrrolidino group, a more constrained version of the bis(2-methoxyethyl)amino moiety used before.¹² We previously showed that signal averaging effects seen for pendant ligands on allylic lithium compounds could be ascribed to several different effects, including inversion. At low temperature, 180 K, all carbons of the pendant ligand on **14** are magnetically nonequivalent. With increasing temperature, each set of 1:1 ¹³C doublets for the CH₃O, CH₂O, ring CH₂, and pyrrolidino CH carbons, respectively, progressively signal average to single lines at their respective centers. NMR line shape analysis of the collapsing doublets provides the rate constants and ultimately the activation parameters listed in Table 2. All the ligand line shapes for **14** give rise to closely similar activation parameters (Table 2). The dynamic process uncovered

(27) (a) Kaplan, J. I.; Fraenkel, G. *NMR of Chemically Exchanging Systems*; Academic Press: New York, 1980; Chapters 5 and 6. (b) Fraenkel, G. In *Techniques in Chemistry, Investigation of Rates and Mechanisms of Reactions*, 4th ed.; Bernasconi, D. F., Ed; Wiley-Interscience: New York, 1986; Part 2, pp 357–604.

(26) Lamothe, S.; Chan, T. H. *Tetrahedron Lett.* **1991**, 32, 1847–1850.

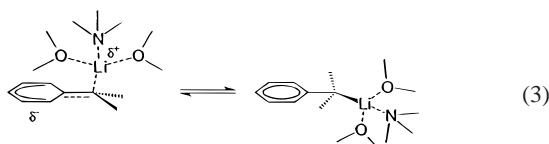
here is clearly almost entirely inversion at C_{α} , since the rates derived from the ligand NMR line shape changes are so similar to those from the geminal methyls on silicon. These latter changes can only be due to inversion. It is not unexpected that changes in the ligand ^{13}C NMR line shapes of **14** result mainly from inversion. The other reorientational motions, which include rotation of ligand-coordinated lithium on one side of the benzylic plane and fast reversible ligand lithium dissociation accompanied by inversion at lithium, are not easily available to the ligand in **14** due to its pendant and constrained nature. These other motions are expected to be faster than inversion in the case of lithium coordinated to an external ligand, such as TMEDA complexed to **13**.

As described above, **12** forms a 1:1 complex with PMDTA. This is evidenced by the nonequivalence of all PMDTA carbons at 190 K, Figure 1, and by the similarity of this spectrum to those of PMDTA complexed to mesityllithium^{10b} and to neopentylolithium.^{10c} The spectra of the latter samples above 190 K revealed the operation of two dynamic processes: (1) the rotation of the entire coordinated ligand with respect to the carbanionic moiety, and (2) fast reversible N,Li dissociation accompanied by inversion at nitrogen. These effects can be detected in Figure 1. However, the quality of the data do not allow an acceptable line shape analysis.

The slowest of the dynamic processes observed in NMR of **12–15** is rotation around the ring- C_{α} bond, as evidenced by signal averaging of the ortho carbon resonances in these compounds. All four compounds, **12–15**, exhibit nonequivalent ortho aromatic carbons at 220 K. There are also small ^{13}C shifts between the meta carbons. With increasing temperature, these 1:1 doublets signal-average to single lines at their respective centers, as do the meta carbon resonances. Due to the magnitudes of these internal shifts, acceptable line shape analysis could be carried out for **13**, **14**, and **15**, but not for **12**. Thus, the collapsing ortho carbon doublets were treated as equally populated half-spin-exchanging systems. Comparison of observed with calculated line shapes yields the rates of rotation. The resulting activation parameters for rotation around the ring benzyl bonds in **13**, **14**, and **15** are listed in Table 2.

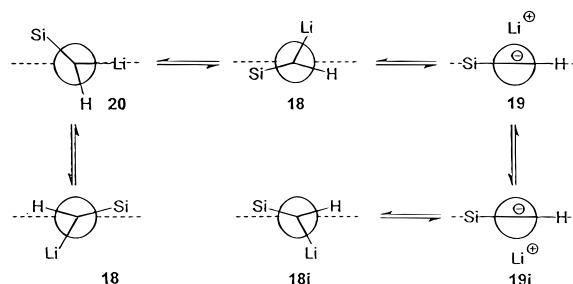
Though more localized than the tertiary benzylic lithium compounds,¹³ the secondary species reported above and previously¹² show substantial barriers around the ring- C_{α} bonds of 14–18 kcal mol⁻¹, respectively. The exception is compound **14**, with a barrier of only 8 kcal mol⁻¹.

These ring- C_{α} barriers to rotation depend significantly on the nature of ligand coordination to lithium.¹³ It has been suggested that development of the transition state for rotation involved an increase in C_{α} -Li covalence accompanied by some change in the nature of lithium ligand coordination,^{13a} see eq 3. With

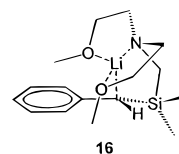


similar ground states, differences among the ring- C_{α} barriers of these secondary benzylic lithium compounds must be due more to energy changes of the transition states for rotation. The significantly lower barrier for **14** might be rationalized as being due to the constrained nature of the pendant 2,5-bis(methoxymethyl)pyrrolidino ligand, which renders its coordination to lithium particularly energetically favorable in the transition state for rotation.

Scheme 1

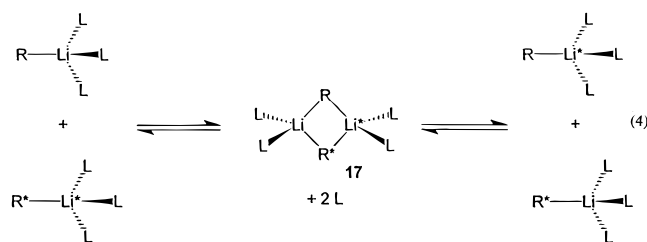


It is interesting that, although inversion and rotation in these compounds must involve very different mechanisms, the rate ratios, inversion/rotation, at 300 K are similar. Their values for **13**, **14**, and **16**¹² are 6.6, 5.0, and 10.9, respectively.



Conclusions. What follows will summarize what has been established in this work. Given that tertiary benzylic lithium and potassium compounds are suitable models for delocalized benzylic anions, we have found that a variety of α -secondary benzylic lithium compounds, **12–15**, have similar partially delocalized structures. This is evidenced by their ring ^{13}C NMR shifts and by the existence of a small, one-bond $^{13}\text{C}_{\alpha}$ - ^6Li spin coupling constant observed under conditions of slow intermolecular carbon, lithium bond exchange. By contrast, externally solvated allylic lithium compounds appear to be delocalized independently as to the extent of alkyl substitution. Only selected internally coordinated allylic lithium compounds displayed partial delocalization, due to the restricted stereochemistry of lithium coordination.⁹

Carbon-13 NMR line shape changes have been used to determine the dynamics of inversion at C_{α} , C-Li bond exchange, and rotation around the ring- C_{α} bonds. Line shape changes due to inversion and rotation are independent of concentration of the organolithium compounds; hence, these must be considered to be first-order processes. In contrast, bimolecular C-Li bond exchange necessarily requires a dimeric transition state that is most likely preceded by a dimeric intermediate. This is analogous to the many solvated RLi dimers described in the literature^{2–5} and shown in **17**. An abbreviated mechanism is outlined in eq 4.



A unified mechanism is proposed in Scheme 1 to account for both inversion and rotation phenomena in **12–15**, taking account of the first-order character of both of these processes. The circles diagram the projection along the ring- C_{α} bonds, to show the bonding arrangement around C_{α} . The dotted line represents the plane of the aromatic ring end-on. To account for inversion, we propose a very fast equilibrium between the

partially delocalized ground states, **18**, and a delocalized higher energy ion-pair, **19**. Rate-determining inversion is the result of transfer of coordinated lithium between two faces of the aromatic plane of the ion-pair, **19** \rightarrow **19i**. We have already observed inversion of ion-paired delocalized allylic lithium compounds with ΔH^\ddagger values of 6–8 kcal mol⁻¹.¹¹ In every equilibrium mixture known to contain similar concentrations of covalent and ion-paired delocalized forms, for example, neopentylallyl-lithium, interconversion of the two species was too fast to measure down to 160 K⁸ relative to the NMR time scale. Below this temperature, precipitation of the reagent precluded acquisition of usable NMR data. With respect to rotation around the ring C_α bonds, the proposed transition state has increased C_α–Li covalence compared to the ground state, **18**, and the C_α–Li bond lies in the aromatic plane. This is similar to the transition state for allyl rotation proposed by Schleyer.^{6a}

Because our internally solvated organolithium compounds are monomers with well-defined structures, their reactivity should be more selective and more easily understood compared to that of the more reactive externally solvated organolithium compounds. These compounds are aggregated to different degrees with variable solvation.

Experimental Section

NMR Samples. A dry 7-in., 5-mm-o.d. precision NMR tube with an attached female S 14/20 joint was fitted with a 2-mm straight bore stopcock adaptor, the latter with a male S 24/40 joint at each end. The assembly was gently flame-dried under vacuum and then filled with argon, and the open end was closed with a serum cap. Then, the RLi sample was syringed into the NMR tube and solvent carefully evaporated under moderate (0.1 Torr) vacuum. After removal of remaining solvent under high vacuum (vacuum line), deuterated solvent was vacuum-transferred into the RLi sample. The resulting sample was degassed using two freeze–thaw cycles and then sealed off frozen under high vacuum.

NMR Spectroscopy. NMR data were obtained using the Bruker AC-200 or Avance 300 instrument. The Avance 300 was used for all variable-temperature work.

***n*-Butyllithium-⁶Li.** Within the drybox, under argon atmosphere, a 250-mL three-neck round-bottom flask equipped with a condenser, an addition funnel, and a glass-coated magnetic stir bar was loaded with finely cut lithium-6 (1.5 g, 0.25 at. wt). The apparatus was closed off and removed from the box. Pentane (100 mL) was introduced, and then 1-chlorobutane (7.3 g, 79 mmol) was slowly added from the addition funnel. The mixture was left to stir overnight, which resulted in a large amount of purple precipitate. Equal volumes of supernatant were transferred by cannula into two centrifuge tubes (argon atmosphere) closed with serum caps. The tubes were centrifuged for 20 min and then cannulated into a Schlenk flask. Titration indicated a solution 0.6 M in *n*-butyllithium-⁶Li with just a trace (<0.1%) of alkoxide.

1-[[*p*-*tert*-Butylbenzyl]dimethylsilyl]methyl]-*cis*-2,5-bis(methoxymethyl)pyrrolidine (7**).** In a 10-mL round-bottom flask equipped with a reflux condenser, an argon inlet, and a magnetic stir bar, *cis*-2,5-bis(methoxymethyl)pyrrolidine (**6**) and *p*-*tert*-butyl- α -(chloromethyl)dimethylsilyl)toluene (**5**) (2.0 g, 10 mmol) were combined and heated at 80 °C overnight. The mixture was poured into an addition funnel and the flask rinsed first with water (10 mL) and then diethyl ether (25 mL). These rinsings were also added to the contents of the addition funnel. The ether layer was washed with aqueous saturated NaCl (10 mL) and then dried over anhydrous Na₂SO₄. The ether was removed by rotary evaporation and the residue purified by bulb-to-bulb distillation to yield the title product, 2.01 g, in 66% yield. ¹H NMR (CDCl₃, δ = 7.26 ppm): δ 7.23 (d, *J* = 12.3 Hz, 2H), 6.95 (d, *J* = 12.3 Hz, 2H), 3.33 (m, 2H), 3.32 (s, 6H), 3.13 (m, 2H), 2.78 (s, br, 2H), 2.34 (s, br, 2H), 2.11 (s, 2H), 1.88 (m, 2H), 1.61 (m, 2H), 1.30 (s, 9H), 0.06 (s, 6H). ¹³C NMR (CDCl₃, δ = 77.0 ppm): δ 146.68, 137.34, 127.95, 125.18, 34.39, 31.70, 7.50, 6.72, –3.83.

[α -[[[*cis*-2,5-Bis(methoxymethyl)-1-pyrrolidinyl]methyl]dimethylsilyl]-*p*-*tert*-butylbenzyl]lithium (14**).** A 35-mL Schlenk tube equipped with a magnetic stir bar and an argon inlet was flame-dried under vacuum and then flushed with argon. Freshly distilled THF (2 mL) and 1-[[*p*-*tert*-butylbenzyl]dimethylsilyl]methyl]-*cis*-2,5-bis(methoxymethyl)pyrrolidine (**7**) (0.206 g, 0.55 mmol) were introduced into the tube. After the solution was chilled to –78 °C with a dry ice–acetone bath, a solution of *n*-butyllithium-⁶Li (0.36 mL, 1.6 M in hexanes, 0.58 mmol) was introduced by syringe. The mixture was stirred for 2 h at –78 °C and then allowed to warm to room temperature and stirred for 4 h.

An NMR sample with a concentration of 0.25 M was prepared as previously described. ¹H NMR (THF-*d*₆, δ = 1.73): δ 0.658 (d, *J* = 8.5 Hz, 2H), 6.289 (d, *J* = 8.5 Hz, 2H), 3.67 (d, 2H), 3.61 (d, 2H), 3.11 (s, 6H), 2.59 (s, br, 2H), 2.18 (s, 2H), 1.78 (m, 4H), 1.36 (s, 1H), 0.01 (s, 6H). ¹³C NMR (THF-*d*₆, δ = 25.3): δ 154.9, 125.56, 124.71, 119.19, 73.20, 70.06, 59.18, 51.10, 34.53, 34.10, 32.83, 27.70, 0.95.

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Supporting Information Available: Derivation of the NMR line shape equations for C,Li exchange, calculated and observed NMR line shapes, Eyring plots, and experimental details concerning compounds **2**, **4**, **5**, **9**, **10**, **12**, **13**, and **15** (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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