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# $^{7}$Li/$^{31}$P NMR Studies of Lithiated Arylacetonitriles in THF−HMPA Solution: Characterization of HMPA-Solvated Monomers, Dimers, and Separated Ion Pairs

**Paul R. Carlier*,† and Cedric W.-S. Lo**

*Contribution from the Department of Chemistry, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong*

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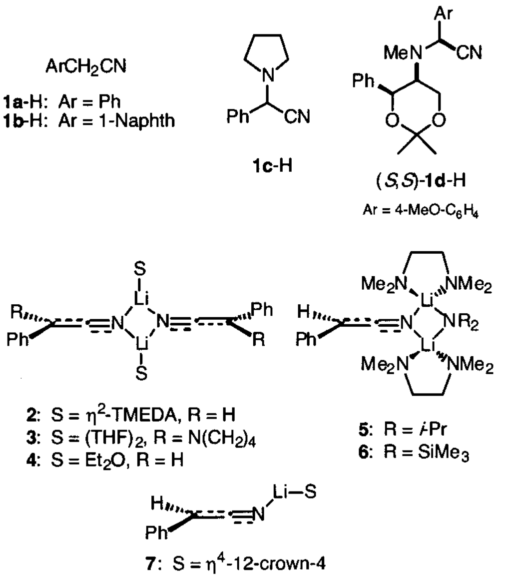
**Abstract:** The structures of lithiated phenylacetonitrile and 1-naphthylacetonitrile were studied in THF and HMPA−THF solution. In pure THF, $^{7}$Li NMR line width studies suggest that these species exist as contact ion pairs; HMPA titration studies confirm this conclusion. In the presence of 0.25−2 equiv of HMPA, HMPA-solvated monomeric and dimeric contact ion pairs are detected by $^{31}$P and $^{7}$Li NMR spectroscopy. Finally, at 4−6 equiv of added HMPA, $^{7}$Li NMR spectra provide direct evidence for the formation of HMPA-solvated separated ion pairs.

Lithiated nitriles are useful in organic synthesis,[1] and considerable effort has been spent to determine the structure of these reagents. The first X-ray crystallographic determination of a lithiated nitrile established N-lithiated dimer structure **2** for the TMEDA solvate of lithiated phenylacetonitrile **1a**-Li (Chart 1).[2]

**Chart 1.** Nitriles and Lithiated Nitriles Discussed



Subsequent X-ray studies have revealed this structural motif to be quite common: the THF solvate of lithiated α-amino nitrile **1c**-Li adopts analogous structure **3**,[3] and the mixed aggregate of **1a**-Li and LDA adopts heterodimeric structure **5**.[4] Only recently have N-lithiated monomers been reported in the solid state (e.g., **7**, Chart 1).[5] In solution, the most conclusive structural determinations of lithiated nitriles have relied upon multinuclear NMR.[6] Observation of $^{6}$Li−$^{15}$N scalar coupling in 100% isotopically enriched lithiated nitriles establishes both the location of the lithium and the aggregation state, and excellent agreement between solid-state and solution-state structures has been found. In this way, dimer **2** and analogous diethyl ether solvate **4** were characterized, and the structure of a **1a**-Li/LiHMDS mixed aggregate **(6)** was established, all in toluene solution. Thus far, monomeric lithiated nitriles have not been unambiguously identified in solution by NMR. In this paper, we address the structure of lithiated arylacetonitriles in THF and THF−HMPA solution, solvents in which these compounds have found wide synthetic application. Using $^{7}$Li and $^{31}$P NMR spectroscopy, we provide evidence for the formation of THF-solvated contact ion pairs, HMPA-solvated monomeric and dimeric contact ion pairs, and HMPA-solvated separated ion pairs (Chart 2).

Our previous efforts to determine the structure of [$^{6}$Li,$^{15}$N]-**1a**-Li in THF solution by $^{6}$Li, $^{15}$N, and $^{13}$C NMR were unsuccessful. Down to the freezing point of the solvent (−110 °C), no $^{6}$Li−$^{15}$N or $^{6}$Li−$^{13}$C scalar coupling could be detected at 0.1 M in 2:1 THF/pentane or 2:1 THF/toluene.[6] Similarly, Enders reported that Li−N scalar coupling could not be detected in NMR studies of [$^{6}$Li,$^{15}$N]**1d**-Li at 0.5 M in THF at −110 °C.[3] One possible explanation for these failures is that **1a**-Li and **1d**-Li exist in THF as contact ion pairs (e.g., **M$_0$**, **D$_0$**, Chart

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* Corresponding author. E-mail: pcarlier@vt.edu.

† Present address: Department of Chemistry, Virginia Tech, Blacksburg, VA 24061.

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10.1021/ja002318x CCC: $19.00

**Chart 2.** Basic Structural Types for Contact and Separated Ion Pairs

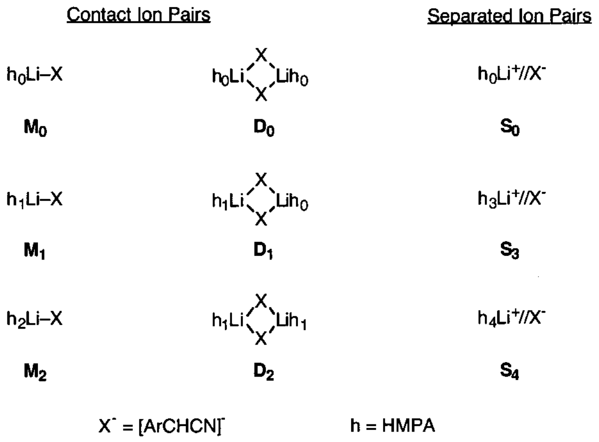

**Table 1.** $^{6}$Li and $^{7}$Li NMR Line Width Data at −100 °C[a]

| entry | compound | $\nu_{1/2}$, Hz ($\delta_{Li}$) $^{6}$Li NMR | $\nu_{1/2}$, Hz ($\delta_{Li}$) $^{7}$Li NMR | solvent |
|---|---|---|---|---|
| 1 | **1a**-Li | 1.3 (−0.35)[b] | 8.9 (−0.38) | 2:1 THF/pentane |
| 2 | **1a**-Li | 1.5 (−0.52)[b] | 5.6 (−0.59) | 2:1 THF/toluene |
| 3 | **1a**-Li | nd[c] | 7.9 (−0.61) | 20:1 THF/hexane |
| 4 | **1b**-Li | nd | 5.8 (−0.65) | 20:1 THF/hexane |
| 5 | LiHMDS | nd | 24.5 (−0.15) | 20:1 THF/hexane |
| 6 | LiCl | nd | 0.7 (0.0) | $CD_3OD$ |

[a] At 0.1 M in the indicated solvent, except for LiCl (0.3 M). Spectra were externally referenced and acquired unlocked; chemical shifts are reproducible to within ±0.1 ppm. Reported $^{7}$Li NMR $\nu_{1/2}$ values are the average of at least two experiments: variation in $\nu_{1/2}$ is ±1 Hz, except for LiCl (±0.3 Hz). [b] Data from ref 6. nd, not detectable.

2) and that THF facilitates rapid chemical exchange, resulting in loss of scalar coupling. Rapid associative chemical exchange was at least partly responsible for difficulty encountered in resolving $^{6}$Li−$^{13}$C scalar coupling in monomeric benzyllithiums.[7] However, an alternative explanation for the loss of scalar coupling is that **1a**-Li and **1d**-Li exist in THF as separated ion pairs (**S$_0$**, Chart 2).

## Results

To distinguish between these two possibilities for lithiated phenylacetonitrile **1a**-Li, we initially focused on the magnitude of $^{7}$Li NMR line widths. Whereas $^{6}$Li nuclei in the slow exchange limit generally give sharp NMR signals, $^{7}$Li nuclei typically give very broad resonances, due to rapid $T_1$ relaxation engendered by the 58-fold larger quadrupole moment of $^{7}$Li. However, the high symmetry of tetrahedrally solvated, separated lithium cations produces characteristically sharp $^{7}$Li NMR resonances, due to the low electric field gradient at the Li nucleus. Salient examples of separated ion pairs in THF that display sharp $^{7}$Li NMR line widths include fluorenyllithium ($\nu_{1/2}$ = 1.1 Hz) and trityllithium ($\nu_{1/2}$ = 3 Hz).[8] It may therefore be possible to distinguish between monomeric contact ion pairs **M$_0$** and solvent-separated ion pairs **S$_0$** on the basis of $^{7}$Li NMR line widths. Thus, $^{7}$Li NMR spectra of **1a**-Li were obtained at −100 °C, under the conditions that previously gave sharp $^{6}$Li resonances.

As can be seen in Table 1, in both cases (2:1 THF/pentane and 2:1 THF/toluene), the $^{7}$Li NMR line widths (8.9 and 5.6 Hz, entries 1 and 2) are significantly larger than previously observed for $^{6}$Li. Lithiated nitriles **1a**-Li and **1b**-Li were then examined at −100 °C in 20:1 THF/hexane. Again the line widths (7.9 and 5.8 Hz; entries 3 and 4) are substantially higher than has been reported for separated ion pairs in THF and are significantly greater than the LiCl in methanol reference ($\nu_{1/2}$ = 0.7 Hz), which is known to exist as a solvent-separated ion pair. For a point of comparison, the $^{7}$Li NMR line width of LiHMDS was determined and found to be quite broad (24.5 Hz), consistent with the monomeric contact ion pair structure determined by $^{6}$Li/$^{15}$N NMR under these conditions.[9] Thus, on the basis of these line width data, it would appear that lithiated arylacetonitriles **1a**-Li and **1b**-Li do not exist in THF as separated ion pairs **S$_0$**, but rather as contact ion pairs. Wartski and Corset had previously reached the same conclusion for **1a**-Li on the basis of IR and Raman studies.[10,11]

To confirm these conclusions, we then applied the HMPA titration protocol developed by Reich for characterizing lithium ion pairs.[8] Species that exist as separated ion pairs in THF ("THF-separable ion pairs") have been shown to possess a number of common characteristics. Of greatest relevance to this study are the following two observations. First, THF-separable lithium ion pairs readily accept sequential solvation of **S$_0$** by HMPA, forming **S$_1$**, **S$_2$**, **S$_3$**, and **S$_4$**.[12] Consequently, free HMPA does not appear in the $^{31}$P NMR spectra of THF-separable lithium ion pairs until at least 4 equiv of HMPA has been added.[8] Second, at −125 °C, the slow exchange limit for HMPA coordination is often attained, and observation of 2-bond $^{31}$P−$^{7}$Li scalar coupling then allows individual solvates to be identified on the basis of the $^{7}$Li NMR signal multiplicity. In the presence of 3 equiv of HMPA, THF-separable ion pairs normally give a clean quartet in the $^{7}$Li NMR spectrum, consistent with formation of separated ion pair **S$_3$** as the dominant species. Thus, $^{7}$Li and $^{31}$P NMR spectra of **1a**-Li were obtained in the presence of increasing amounts of HMPA at −125 °C in 20:1 THF/hexane (Figure 1).

The appearance of free HMPA ($\delta$ 26.1 ppm) in the $^{31}$P NMR spectra of **1a**-Li at 2 equiv of added HMPA is most striking and is characteristic of a contact ion pair with a strong donor ligand (Figure 1C). Reich previously observed the onset of free HMPA at 2 equiv of HMPA in the titrations of LiCl, LiSMe, and PhLi, all of which are contact ion pairs in pure THF.[8] The $^{7}$Li NMR spectra at 3 equiv of added HMPA also support the existence of **1a**-Li as a contact ion pair in pure THF. Instead of forming **S$_3$** as a single dominant species, at least three species appear to be present (Figure 1D, vide infra). The HMPA titration protocol was then performed on lithiated 1-naphthylacetontrile **1b**-Li, and identical results were obtained (see Supporting Information). Thus, on the basis of their $^{31}$P NMR spectra in the presence of 1−2 equiv of HMPA, and their $^{7}$Li NMR spectra in the presence of 3 equiv of HMPA, **1a**-Li and **1b**-Li are not THF-separable ion pairs, but are rather *contact ion pairs* in pure THF. Accordingly, we attribute our previous failure to observe scalar coupling in [$^{6}$Li,$^{15}$N]**1a**-Li[6] to rapid chemical exchange.

With the existence of **1a**-Li and **1b**-Li as contact ion pairs in pure THF now firmly established, we turn to the identification of individual HMPA solvates formed during the titration. The $^{7}$Li NMR spectra of **1a**-Li and **1b**-Li at 1 equiv of added HMPA

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(12) In Reich's nomenclature, **S$_0$**...**S$_4$** are designated as Lih$_0^+$...Lih$_4^+$.

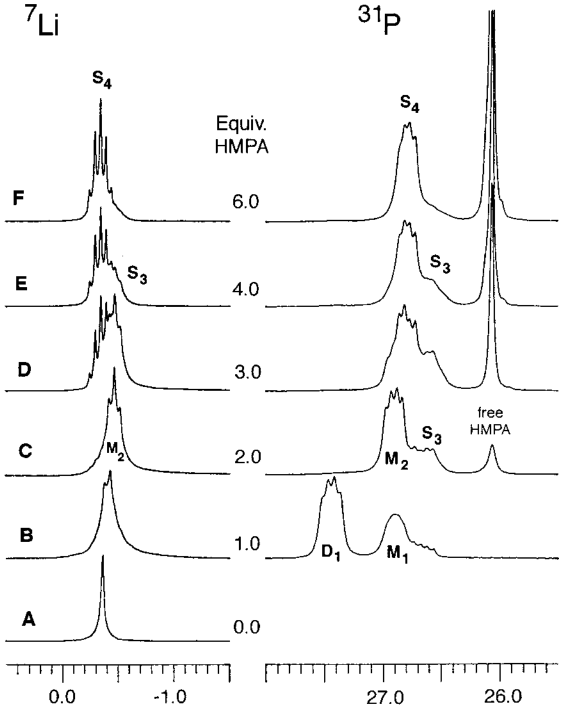


**Figure 1.** $^7$Li (155.25 MHz) and $^{31}$P (161.72 MHz) NMR spectra of 0.10 M **1a**-Li in 20:1 THF/hexane at −125 °C as a function of added HMPA. The $^7$Li and $^{31}$P NMR spectra are plotted at the same frequency scale (equivalent Hz/cm).

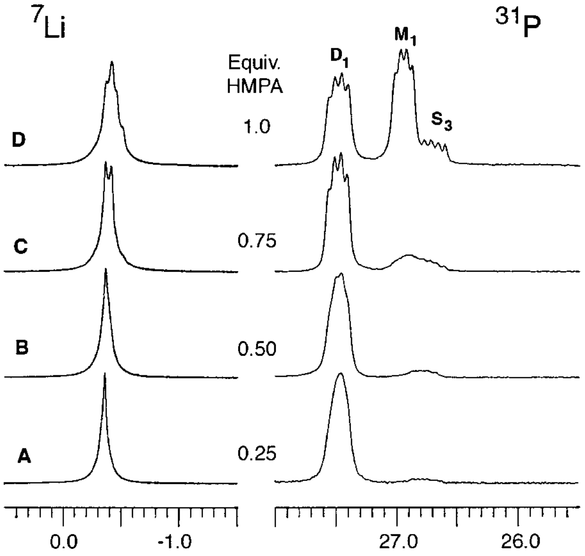


**Figure 2.** $^7$Li and $^{31}$P NMR spectra of 0.10 M **1a**-Li in 20:1 THF/hexane at −125 °C in the presence of 0.25−1.0 equiv of HMPA.

are characterized by broad signals and poorly resolved $^{31}$P−$^7$Li coupling (Figure 1B and Supporting Information). Spectra obtained at −135 °C in 3:2 THF/Et$_2$O had the same appearance and did not offer improved resolution. To address the aggregation and solvation states of **1a**-Li at low amounts of added HMPA, titrations with 0.25−1.0 equiv of HMPA were performed (Figure 2).

As can be seen, the $^7$Li NMR spectra display only one broad resonance under these conditions, revealing no useful structural information. Fortunately, the $^{31}$P NMR spectra again prove informative. At 1 equiv of added HMPA, the $^{31}$P NMR spectrum clearly shows three types of bound HMPA at δ 27.5, 27.0, and 26.7 ppm (Figure 2D). In each peak, coupling to one $^7$Li nucleus ($I = {}^3/_2$) is evidenced by the characteristic 1:1:1:1 quartet pattern.

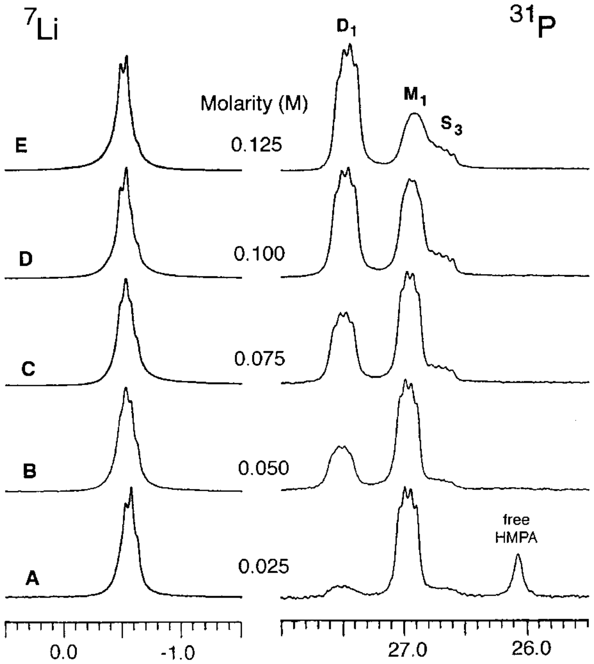


**Figure 3.** Concentration dependence of $^7$Li and $^{31}$P NMR spectra of **1a**-Li in 20:1 THF/hexane at −125 °C in the presence of 1 equiv of HMPA.

As the amount of added HMPA is decreased, the signals at δ 27.0 and 26.7 ppm shrink relative to the one at δ 27.5 ppm. The dominance of the δ 27.5 ppm peak at 0.5 and 0.25 equiv of added HMPA (Figure 2B and A), and its complete disappearance at 2 equiv of added HMPA (Figure 1C), strongly suggest that it corresponds to mono-HMPA solvated dimer **D$_1$**. We further propose that the peak at δ 27.0 ppm corresponds to mono-HMPA solvated monomer **M$_1$**, as suggested by experiments that keep the amount of added HMPA fixed at 1 equiv but vary the concentration of **1a**-Li from 0.125 to 0.025 M (Figure 3).

The change in relative intensities of the peaks at δ 27.5 and 27.0 ppm upon dilution strongly suggests that they correspond to species of different aggregation states. As expected, when the concentration of **1a**-Li is lowered, the peak attributed to **D$_1$** (δ 27.5 ppm) decreases significantly, and the peak at δ 27.0 ppm, attributed to **M$_1$**, increases. That the changes seen in Figure 3 are not solely due to accompanying changes in the HMPA concentration can be seen by comparing Figures 2A and 3A. In each case, the HMPA concentration is 0.025 M, but the concentrations of **1a**-Li differ. At [**1a**-Li] = 0.1 M (Figure 2A), the primary HMPA solvate is **D$_1$**, but at [**1a**-Li] = 0.025 M (Figure 3A), the primary HMPA solvate is **M$_1$**.

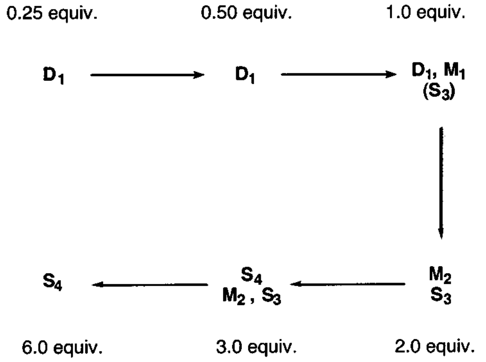
Upon addition of 2 equiv of HMPA, the $^7$Li NMR spectra show a triplet at δ −0.47 ppm, which suggests two bound HMPA per lithium (Figure 1C). We propose that this peak corresponds to disolvated monomer **M$_2$** and that the major $^{31}$P NMR resonance at δ 26.9 ppm is also due to **M$_2$** (i.e., **M$_1$** and **M$_2$** are accidentally equivalent by $^{31}$P NMR). This proposal is supported by the following observations. First, Reich reported that LiCl and LiSMe, compounds which like **1a**-Li show free HMPA in the $^{31}$P NMR spectrum at 2 equiv of added HMPA, also form significant amounts of **M$_2$** under these conditions.[8] Second, that the triplet at δ −0.47 ppm in the $^7$Li NMR spectrum is *not* due to separated ion pair **S$_2$** is supported by the complexity of the $^7$Li NMR spectrum at 3 equiv of added HMPA. As discussed previously, bis-HMPA-solvated separated ion pairs **S$_2$** readily accept additional HMPA solvation, forming tris-

**Table 2.** $^{7}$Li and $^{31}$P NMR Data for HMPA-Solvated Ion Pairs[a]

| solvate | lithiated nitrile | $^{7}$Li $\delta$ (mult, $J$) | $^{31}$P $\delta$ (mult, $J$) |
|---|---|---|---|
| $\mathbf{D_1}$[b] | **1a**-Li | −0.45 (br) | 27.5 (q, 7.9) |
| | **1b**-Li | −0.40 (br) | 27.5 (q, 8.3) |
| $\mathbf{M_1}$[b,c] | **1a**-Li | −0.45 (br) | 27.0 (q, 7.3) |
| | **1b**-Li | −0.40 (br) | 26.95 (br q) |
| $\mathbf{M_2}$[c] | **1a**-Li | −0.47 (t, 8.0) | 27.0 (q, 8.0) |
| | **1b**-Li | −0.47 (t, 7.6) | 26.95 (q, 7.6) |
| $\mathbf{S_3}$ | **1a**-Li | −0.45 (br) | 26.7 (q, 9.1) |
| | **1b**-Li | not resolved | 26.75 (q, 8.7) |
| $\mathbf{S_4}$ | **1a**-Li | −0.34 (qn, 7.6) | 26.8 (q, 7.6) |
| | **1b**-Li | −0.41 (qn, 7.4) | 26.8 (q, 7.4) |

[a] At −125 °C, $[\mathrm{Li}]_{\mathrm{total}} = 0.1$ M in 20:1 THF/hexane. Spectra were externally referenced and acquired unlocked; chemical shifts are reproducible to within ±0.1 ppm. Free HMPA appears at 26.1 ± 0.1 ppm. All coupling constants $J$ are reported in hertz; t = triplet, q = quartet, qn = quintet, and br = broad. [b] Solvates $\mathbf{D_1}$ and $\mathbf{M_1}$ cannot be distinguished by $^{7}$Li NMR. [c] Solvates $\mathbf{M_1}$ and $\mathbf{M_2}$ cannot be distinguished by $^{31}$P NMR.

**Chart 3.** Observed HMPA Solvates of **1a**-Li and **1b**-Li at 0.10 M, as a Function of Added HMPA[a]



[a] Where more than one solvate is listed, abundance decreases from top to bottom; solvates listed in parentheses are minor.

HMPA-solvated separated ion pair $\mathbf{S_3}$ as the dominant species at 3 equiv of added HMPA. Third, that the major species is monomer $\mathbf{M_2}$ and not tetrasolvated dimer $\mathbf{D_4}$ is supported by experiments that show no significant change in the $^{7}$Li or $^{31}$P NMR spectra of **1a**-Li in the presence of 2 equiv of HMPA upon dilution from 0.125 to 0.025 M (see Supporting Information).

Finally, the addition of 3−6 equiv of HMPA clearly causes the formation of separated ion pairs. At 6 equiv of added HMPA, tetrakis-HMPA-solvated separated ion $\mathbf{S_4}$ is the dominant species, as indicated by the characteristic quintet in the $^{7}$Li NMR spectrum ($\delta$ −0.34 ppm, $J = 7.6$ Hz) and the partially resolved quartet in the $^{31}$P NMR spectrum at 26.8 ppm (Figure 1F). At 4 equiv of added HMPA, a mixture of $\mathbf{S_4}$ and tris-HMPA-solvated separated ion pair $\mathbf{S_3}$ is seen in the $^{7}$Li and $^{31}$P NMR spectra. The $^{7}$Li and $^{31}$P NMR chemical shifts assigned to $\mathbf{S_4}$ and $\mathbf{S_3}$ are consistent with many previously characterized separated lithium ion pairs.[8] At 3 equiv of added HMPA, the $^{7}$Li NMR spectra demonstrate the presence of monomer $\mathbf{M_2}$ and separated ion pair $\mathbf{S_4}$; examination of the $^{31}$P NMR spectra also indicates the presence of $\mathbf{S_3}$. On the basis of the $^{31}$P NMR spectra, $\mathbf{S_3}$ appears in the titration as early as 1 equiv of added HMPA (Figure 1B). By way of comparison, Reich previously observed the formation of traces of $\mathbf{S_3}$ from LiSMe at 1 equiv of added HMPA and from LiCl and LiSeMe at 2 equiv of added HMPA.[8] The assignments of resonances in the $^{7}$Li and $^{31}$P NMR spectra to HMPA-solvated ion pairs $\mathbf{D_1}$, $\mathbf{M_1}$/$\mathbf{M_2}$, $\mathbf{S_3}$, and $\mathbf{S_4}$ are supported by performing the same experiments on **1b**-Li. Very similar behavior was seen (see the Supporting Information); a summary of the $^{7}$Li and $^{31}$P NMR data for the proposed HMPA solvates derived from **1a**-Li and **1b**-Li is given in Table 2.

## Discussion

The formation of separated ion pairs from **1a**-Li in THF−HMPA solution was proposed previously on the basis of vibrational spectroscopy[10] and from **1a**-Na in DMSO on the basis of $^{13}$C NMR spectroscopy.[13] Separated ion pairs have also been invoked to explain a preference for 1,4-addition of **1a**-Li to benzylidene acetone in HMPA−THF solution.[10,14] However, we believe that the NMR studies presented here provide the most compelling evidence to date for the formation of metalated nitrile-derived separated ion pairs. The $^{7}$Li/$^{31}$P NMR spectra of **1a**-Li in HMPA−THF solution were investigated previously by other workers.[10] At −120 °C, in the presence of 4 equiv of HMPA ([**1a**-Li] = 0.25 M), a "poorly resolved triplet" at $\delta$ −0.35 ppm was reported in the $^{7}$Li NMR spectrum; the $^{31}$P NMR spectrum displayed free HMPA at $\delta$ 24.65 ppm and a "poorly resolved quintet" at $\delta$ 25.33 ppm. Although these authors concluded that the major species under these conditions was a bis-HMPA solvate, we note that they had difficulty attaining the slow-exchange domain. On the basis of our studies, we believe that the "poorly resolved "triplet" at $\delta$ −0.35 ppm in the $^{7}$Li NMR spectrum is actually a quintet and corresponds to tetrakis-HMPA-solvated separated ion pair $\mathbf{S_4}$. The somewhat lower $^{31}$P chemical shift values reported by these authors for bound and free HMPA are likely a consequence of a different external referencing method.[15]

A summary of the effect of added HMPA on the population of the various HMPA solvates is presented in Chart 3.

Two things should be noted about this summary. First, Chart 3 only describes the population of HMPA solvates; any HMPA-free ion pairs that may be present at low amounts of added HMPA are not listed. Second, bis-HMPA-solvated dimeric contact ion pair $\mathbf{D_2}$ is conspicuously absent. Because an unambiguous NMR signature for $\mathbf{D_2}$ was not found, we believe that it is either concident with $\mathbf{M_1}$/$\mathbf{M_2}$ in the NMR spectra or that coordination of a second HMPA molecule to $\mathbf{D_1}$ results in dissociation to two molecules of $\mathbf{M_1}$. A similar explanation was provided by Reich for the absence of $\mathbf{D_2}$ in the HMPA titration of LiCl.[8]

The dominance of solvate $\mathbf{D_1}$ at 0.25 and 0.5 equiv of added HMPA might lead one to speculate that **1a**-Li and **1b**-Li exist in pure THF at 0.10 M as dimers $\mathbf{D_0}$. However, we do not believe this to be the case. It must be emphasized that the HMPA titration data presented here do not allow any conclusion to be drawn regarding the aggregation states of **1a**-Li and **1b**-Li *in pure THF*. Indeed, unambiguous NMR determination of aggregation states of these species in pure THF will not be possible until $^{6}$Li−$^{15}$N or $^{6}$Li−$^{13}$C scalar coupling can be observed.[16] Observation of scalar coupling will also unambiguously establish

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(15) The external reference used by the authors of ref 10 was pure $H_3PO_4$; the $^{31}$P NMR spectra in the present work were referenced to 1 M $PPh_3$ in THF at −100 °C.

(16) Our continuing attempts to observe scalar coupling in lithiated arylacetonitriles in THF have not been successful. Since the gyromagnetic moment of $^{7}$Li is 2.64-fold larger than that of $^{6}$Li, $^{7}$L−-$^{15}$N coupling constants will be correspondingly larger than those of $^{6}$Li−$^{15}$N and should be easier to resolve, as is often the case for Li−P coupling.[8] However, our examinations of [$^{15}$N]**1b**-Li at 0.10−0.025 M and down to −135 °C (3:2 THF/$Et_2O$) did not reveal coupling in the $^{7}$Li or $^{15}$N NMR spectra (Lo, C. W−S.; Carlier, P. R., unpublished).

the mode of metalation (N-lithiated,[2−6] C-lithiated,[17] or N,C-bridged[11,18]), and for this reason, the contact ion pairs depicted in Chart 2 have been drawn in a way that does not specify Li−N or Li−C connectivity. Returning to the aggregation states of the contact ion pairs in pure THF, reported freezing point depression measurements are consistent with predominantly *monomeric* aggregation states for **1a**-Li[19] and **1d**-Li[3] in THF, although average molecularity determinations based on colligative measurements are known to be susceptible to errors in both execution and interpretation.[20] Additional supporting evidence for the existence of **1a**-Li as a monomer in THF was provided by Streitwieser's observation that the p$K_A$ of **1a**-H in THF is invariant over a 20-fold concentration range.[21] IR studies in THF also support the predominance of a monomeric contact ion pair for **1a**-Li in THF at 0.25 M.[10,11] Finally, our previous observation[6] that **1a**-Li undergoes mixed aggregation with LiHMDS in TMEDA/toluene but not in THF suggests that **1a**-Li is a monomer in THF. On the basis of these observations, we cautiously propose that **1a**-Li exists as monomer $\mathbf{M_0}$ at 0.1 M in THF and that addition of small amounts of HMPA (0.25−0.5 equiv) *induces dimerization* to $\mathbf{D_1}$. Jackman previously reported that addition of HMPA causes aggregation of dimeric lithium phenolates to the corresponding tetramers.[22]

Above 0.5 equiv of added HMPA, monomer $\mathbf{M_1}$ and separated ion pair $\mathbf{S_3}$ begin to appear, suggesting deaggregation of $\mathbf{D_1}$. As would be expected from their formulations, the relative populations of the $\mathbf{D_1}$ and $\mathbf{M_1}$ solvates are quite sensitive to both the amount of added HMPA (see Figure 2C,D) and lithium ion concentration (see Figure 3). We therefore attribute the observed variability in peak height for these solvates in nominal 1-equiv HMPA/0.1 M experiments (see Figure 1B, 2D, and 3D) to slight differences in the amounts of added HMPA and lithium ion concentrations actually realized. Deaggregation is complete at 2 equiv of added HMPA, at which point the major species are bis-HMPA solvated monomer $\mathbf{M_2}$ and separated ion pair $\mathbf{S_3}$. Bis-HMPA solvated monomer $\mathbf{M_2}$ persists at 3 equiv of added HMPA, but at 6 equiv of added HMPA, both $\mathbf{M_2}$ and tris-HMPA separated ion pair $\mathbf{S_3}$ vanish to give tetrakis-HMPA-solvated separated ion pair $\mathbf{S_4}$ as the only visible lithiated species.

## Conclusion

On the basis of $^7$Li NMR line widths and HMPA titration studies, we have established that **1a**-Li and **1b**-Li exist in THF as contact ion pairs, a result that agrees with Wartski and Corset's earlier conclusions for **1a**-Li based on IR and Raman spectroscopy.[10,11] Furthermore, we have provided direct $^7$Li and $^{31}$P NMR evidence for the formation of tetrakis-HMPA-solvated separated ion pairs $\mathbf{S_4}$ from **1a**-Li and **1b**-Li in HMPA−THF solution. These compounds can thus be classified as "HMPA-separable contact ion pairs". All in all, the titrations of **1a**-Li and **1b**-Li proceed quite similarly to those previously reported by Reich for LiSMe and LiCl,[8] which highlights the fact that lithium salt aggregation and ease of ionization are not strongly correlated to the basicity of the counterion.

## Experimental Section

**Sample Preparation for $^7$Li and $^{31}$P NMR Experiments.** Volumetric flasks and NMR tubes were dried in an oven (120 °C) overnight. NMR samples were prepared on a vacuum line under argon using a combination of drybox and syringe techniques. THF, diethyl ether, pentane, and hexane were vacuum distilled from blue or purple solutions containing sodium benzophenone ketyl; the hydrocarbon stills contained 1% tetraglyme to dissolve the ketyl. Toluene was distilled from Na at atmospheric pressure and repeatedly degassed on the vacuum line. HMPA was distilled from $CaH_2$ under reduced pressure and stored over molecular sieves. Nitriles **1a**-H and **1b**-H were purchased from Aldrich. LiHMDS was prepared on a vacuum line according to the published procedure for [$^6$Li$^{15}$N]LiHMDS,[23] using freshly titrated commercial *n*-BuLi and normal hexamethyldisilazane. This reagent was recrystallized twice and stored and dispensed in a nitrogen-filled drybox. Lithiated nitriles were prepared in situ by combination of the nitriles and LiHMDS in THF solution. Previous multinuclear NMR studies using [$^{15}$N]**1a**-H and [$^6$Li,$^{15}$N]LiHMDS in THF solution[6] demonstrated that combination of these reagents gave clean conversion to **1a**-Li and that **1a**-Li does not complex the formed hexamethyldisilazane. Briefly, stock solutions of LiHMDS (0.3 M) and the nitrile of interest (0.3 M, 1:1 molar ratio) were transferred via a syringe into a septum-capped NMR tube under argon at −78 °C. Additional solvent and/or HMPA was then added to achieve the desired final lithium ion concentration (typically 0.10 M) and a total volume of 750 $\mu$L in each case. Silicone grease was placed on the septa tops to seal punctures, and NMR tubes were stored at −78 °C when not in the NMR probe. Identical Wilmad 7-in. 528-PP tubes were used for all samples and external references. Duplicate tubes were prepared for each experiment (nitrile/solvent/HMPA combination); experiments were performed at least twice. HMPA titration studies (e.g., Figures 1−3) represent a series of sample tubes, each of which contains a different number of equivalents of HMPA. $^7$Li and $^{31}$P NMR spectra that are presented side by side are derived from the same tube.

**Procedure for Low-Temperature $^7$Li/$^{31}$P NMR Studies.** Low-temperature NMR studies were performed on a spectrometer modified to use liquid nitrogen boil-off as the spinning and sample lift gas. Spectra were referenced externally at −100 °C, 0.3 M LiCl in $CD_3OD$ for $^7$Li (0.00 ppm) and 1 M $PPh_3$ in THF for $^{31}$P (−6.00 ppm). Shimming was performed on the $^7$Li external reference sample at −100 °C, by maximizing the $^2$H lock signal of $CD_3OD$. $^7$Li (155.25 MHz) and $^{31}$P NMR (161.72 MHz) spectra were then obtained with the spectrometer *unlocked*. Spectral drift was minimal (less than 0.1 ppm) after 15-min equilibration at the desired temperature; however, spectra were periodically re-referenced during a typical 6-h series of NMR experiments. Digital resolution was 0.5 Hz for $^7$Li NMR spectra and 0.6 Hz for $^{31}$P NMR spectra. In general, satisfactory signal-to-noise ratios were obtained by collecting 32 transients for $^7$Li NMR spectra and 64 transients for $^{31}$P NMR spectra. For $^7$Li line width studies, line broadening (BF) was set to 0 Hz and the reported $\nu_{1/2}$ values are the average of at least two experiments; run-to-run variation in $\nu_{1/2}$ was ±1 Hz, except for LiCl (±0.3 Hz).

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**Supporting Information Available:** $^7$Li and $^{31}$P NMR spectra of the HMPA titration of lithiated 1-naphthylacetonitrile **1b**-Li; spectra of **1a**-Li in the presence of 2 equiv of HMPA as a function of lithium ion concentration (PDF). This information is available free of charge via the Internet at http://pubs.acs.org.

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