

2016

## Spectroscopic Measurements of Ionic Association in Common Lithium Salts and Carbonate Electrolytes

Navid Chapman  
University of Rhode Island, [navid\\_chapman@uri.edu](mailto:navid_chapman@uri.edu)

Follow this and additional works at: <https://digitalcommons.uri.edu/theses>

---

### Recommended Citation

Chapman, Navid, "Spectroscopic Measurements of Ionic Association in Common Lithium Salts and Carbonate Electrolytes" (2016). *Open Access Master's Theses*. Paper 924.  
<https://digitalcommons.uri.edu/theses/924>

This Thesis is brought to you for free and open access by DigitalCommons@URI. It has been accepted for inclusion in Open Access Master's Theses by an authorized administrator of DigitalCommons@URI. For more information, please contact [digitalcommons@etal.uri.edu](mailto:digitalcommons@etal.uri.edu).

SPECTROSCOPIC MEASUREMENTS OF IONIC ASSOCIATION IN COMMON LITHIUM  
SALTS AND CARBONATE ELECTROLYTES

BY

NAVID CHAPMAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIRMENTS FOR THE  
DEGREE OF MASTER OF SCIENCE

IN

CHEMISTRY

UNIVERSITY OF RHODE ISLAND

2016

MASTER OF SCIENCE IN CHEMISTRY THESIS  
OF  
NAVID CHAPMAN

APPROVED:

THESIS COMMITTEE:

Major Professor Brett Lucht

William Euler

David Heskett

Nasser Zawia

DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND

2016

## Abstract

FTIR and NMR spectroscopy were used to investigate the structure and composition of lithium ion solvation spheres of single salt electrolyte solutions composed of common lithium salts (LiTFSI, LiPF<sub>6</sub>, LiBF<sub>4</sub>, and LiClO<sub>4</sub>) dissolved in aprotic polar linear and cyclic carbonate solvents (propylene carbonate (PC), dimethyl carbonate (DMC)). The coordination of the carbonyl oxygen of the solvents to the lithium ion is observed by FTIR spectroscopy. Determination of relative percent coordination of PC and DMC was used to calculate solvent coordination numbers in a range from 2 to 7. Solvent coordination was also monitored with <sup>13</sup>C NMR spectroscopy and agreement was found when comparing the two spectroscopic methods. Solvent coordination is dependent upon the magnitude of salt dissociation. LiTFSI, LiPF<sub>6</sub>, and LiClO<sub>4</sub> dissociated to approximately the same degree, while LiBF<sub>4</sub> had significantly less dissociation. Dissociation trends between salts were approximate under all solvent systems. The primary solvation sphere was determined to form contact ion pairs at low solvent to salt ratios (up to 4:1) and solvent separated ion pairs in dilute solutions up to (30:1). In dilute solutions, PC had preference over DMC for preferential solvation as expected by the magnitude of relative permittivity. This investigation was conducted in order to develop a fundamental understanding about the solution structure and aid as a tool for the ionic association evaluation of commonly used LIB electrolytes.

## ACKNOWLEDGMENTS

I would like to express my gratitude to Professor Brett L. Lucht for advising me throughout my graduate school career. I am grateful to have Professor Lucht as well as Professor Bill Euler, Professor, Sze Yang, Professor David Heskett, and Professor Arijit Bose to have taken the time out of their busy schedules to review my thesis. I am indebted to all the brilliant minds of the Lucht lab for providing constructive feedback and helping maintain our instrumentation. This work is an extension of the work by Dr. Daniel Seo and I appreciate his years of research that made this study possible. A very special thanks for Dr. Taeho Yoon and Dr. Cao Nguyen for their invaluable input. Thank you to Partha Datta, Oleg Kazakov, and Craig Hessler for sitting in on a mock-review committee for my defense preparation. I would like to also acknowledge the University of Rhode Island Chemistry department for providing the resources required for this work and providing me with a Teaching Assistantship every semester that funded my education. This material is based upon work supported by the U.S. Department of Energy Office of Basic Energy Sciences EPSCoR Implementation award (DE-SC0007074).

Finally, my deepest and most sincere appreciation goes to my exceptionally clever, beautiful, and caring wife Ming for believing in me throughout my graduate school career.

## **PREFACE**

This thesis is written in manuscript format and is prepared for submission to the Journal of Physical Chemistry C with authors Navid Chapman, Taeho Yoon, Cao Cuong Nguyen, and Brett L. Lucht.

## TABLE OF CONTENTS

<b>ABSTRACT.....</b>	<b>ii</b>
<b>ACKNOWLEDGEMENTS.....</b>	<b>iii</b>
<b>PREFACE.....</b>	<b>iv</b>
<b>TABLE OF CONTENTS.....</b>	<b>v</b>
<b>LIST OF TABLES.....</b>	<b>vi</b>
<b>LIST OF FIGURES.....</b>	<b>vii</b>
<b>CHAPTER 1.....</b>	<b>1</b>
MANUSCRIPT INTRODUCTION PAGE.....	1
INTRODUCTION.....	2
EXPERIMENTAL SECTION.....	4
RESULTS AND DISCUSSION.....	6
CONCLUSION.....	12
LIST OF REFERENCES.....	14
<b>BIBLIOGRAPHY.....</b>	<b>17</b>

## LIST OF TABLES

TABLE	PAGE
Table 1. Properties of Solvents.....	23

## LIST OF FIGURES

FIGURE	PAGE
Figure 1a. PC IR carbonyl band absorbance with coordination to LiTFSI.....	24
Figure 1b. PC IR carbonyl band absorbance with coordination to LiClO <sub>4</sub> .....	24
Figure 1c. PC IR carbonyl band absorbance with coordination to LiPF <sub>6</sub> .....	24
Figure 1d. PC IR carbonyl band absorbance with coordination to LiBF <sub>4</sub> .....	24
Figure 2a. DMC IR carbonyl band absorbance with coordination to LiTFSI.....	25
Figure 2b. DMC IR carbonyl band absorbance with coordination to LiClO <sub>4</sub> .....	25
Figure 2c. DMC IR carbonyl band absorbance with coordination to LiPF <sub>6</sub> .....	25
Figure 2d. DMC IR carbonyl band absorbance with coordination to LiBF <sub>4</sub> .....	25

Figure 3a. Proportion of coordinated solvent for single salt and solvent solutions with lithium salts LITFSI, LiPF <sub>6</sub> , LiClO <sub>4</sub> , and LiBF <sub>4</sub> in solvents PC	26
Figure 3b. Calculated solvation number for single salt and solvent solutions with lithium salts LITFSI, LiPF <sub>6</sub> , LiClO <sub>4</sub> , and LiBF <sub>4</sub> in solvents PC	26
Figure 4a. Proportion of coordinated solvent for single salt and solvent solutions with lithium salts LITFSI, LiPF <sub>6</sub> , LiClO <sub>4</sub> , and LiBF <sub>4</sub> in solvents DMC	27
Figure 4b. Calculated solvation number for single salt and solvent solutions with lithium salts LITFSI, LiPF <sub>6</sub> , LiClO <sub>4</sub> , and LiBF <sub>4</sub> in solvents DMC	27
Figure 5. PC <sup>13</sup> C-NMR carbonyl carbon resonance with coordination to LiTFSI	28
Figure 6. Demonstration of <sup>13</sup> C-NMR chemical shifts due to cation coordination in a solution of PC with LITFSI	29
Figure 7. Demonstration of correlation between IR and NMR observed effects from solvent coordination with a solution of LiBF <sub>4</sub> in PC at various concentrations	30

**MANUSCRIPT – I**

*Prepared for submission to Journal of Physical Chemistry C*

**Spectroscopic Measurements of Ionic Association in Common Lithium Salts  
and Carbonate Electrolytes**

Navid Chapman, Taeho Yoon, Cao Cuong Nguyen, and Brett L. Lucht

Chemistry, University of Rhode Island, Kingston, RI, USA

Corresponding Author: Brett L. Lucht, Ph.D.

Chemistry

University of Rhode Island

51 Lower College Rd.

Kingston, RI, 02881, USA

Email address: blucht@chm.uri.edu

## CHAPTER 1

### INTRODUCTION

Lithium Ion Batteries (LIBs) are of high interest in energy research due to the increased global need for energy storage sources for portable devices<sup>1-4</sup>. There is a lack of understanding about ion solvate structures of electrolytes. Further investigation is important because ion-solvent structure, salt concentration, and temperature, to a lesser extent, directly dictate the physical properties of electrolytes and the performance in electrochemical systems<sup>5</sup>. These fundamental physicochemical properties affect many aspects of performance such as voltage-current curves, electrochemical stability window, working temperature range, hydrolytic stability, and ionic conductivity, which is the overall result of effects from solvent migration and solvation structure<sup>1,3,4,6-12</sup>. Determining the solvation structure, and in turn preferential binding of one solvent over another, is also of interest because it dictates which solvent molecules would be preferentially reduced on the anode surface as an interfacial film dubbed the solid electrolyte interface (SEI). Understanding how co-solvents interact with lithium salts will allow for custom engineered electrochemical systems with optimal ionic mobility and SEI resistance<sup>13</sup>.

Binary mixtures of cyclic and linear carbonates were first implemented by Tarascon and Guyomard in order to balance the cyclic carbonates that possessed high permittivity, but high viscosity with linear carbonates that possessed low

viscosity, yet low permittivity<sup>14</sup>. Binary and ternary solvent mixtures are presently commonplace in electrolyte solutions, yet there is a lack of research in understanding the cooperative effects of these mixtures in relation to single solvent systems. Previous understandings suggest that solvent relative permittivity dictates solvation ability. Using  $\text{LiPF}_6$  as a salt, Seo et al. previously examined cation-solvent coordination via FTIR and NMR spectroscopy<sup>9</sup>. This study expands on Seo's work by examining solvation and ion pairing with several different salts. Spectroscopic instrumentation like FTIR, Raman, NMR can be used to indirectly observe solvent coordination by detecting changes in the local electronic environment that surrounds the solvation interactions of electrolyte components. Coordination of the solvent with the cation and the coordination of the solvent with the anion both allow for quantitative analysis of the magnitude of solvent coordination.

In this research, FTIR and NMR spectroscopy were used to investigate the molecular cation solvent interactions resulting from lithium salts dissolved in carbonate solvents. Four intermediately associated lithium salts ( $\text{LiTFSI}$ ,  $\text{LiPF}_6$ ,  $\text{LiBF}_4$ ,  $\text{LiClO}_4$ ) and two similar, but different types of commonly used carbonate solvents (Propylene carbonate (PC) and dimethyl carbonate (DMC)) were selected for this study<sup>15</sup>. The results suggest that the relative permittivity of the solvent is not as important in dictating the primary solvation sphere, that additional solvation effects along with salt dissociation play more significant roles than previously thought, and that solvation structure is a complicated system composed of many factors and cannot be easily defined.

## EXPERIMENTAL SECTION

PC was used as-received (MP Biomedicals). DMC was used as-received (Sigma-Aldrich, anhydrous). LiTFSI, LiPF<sub>6</sub>, LiBF<sub>4</sub>, and LiClO<sub>4</sub> were also used as-received (Sigma-Aldrich). The four lithium salts (LiTFSI, LiPF<sub>6</sub>, LiBF<sub>4</sub>, LiClO<sub>4</sub>) were chosen because they meet the minimal requirements for a lithium salt for usage in lithium ion batteries. These requirements are the ability to dissolve and dissociate in non-aqueous polar aprotic electrolyte solvents, have high ionic mobility, be non-reactive with electrolyte solvents, and relative stability against thermally induced reactions<sup>3,16,17</sup>. These four salts possess a balance of these requirements and dissociate relatively intermediately in relation to the full scale of lithium salts<sup>5,18</sup>. The solvent-to-salt ratios (30:1 to 4:1) have been selected to incorporate a full range of salt concentrations with the conventional concentration of ~1M in the middle<sup>3</sup>. Solutions were prepared in an airfree environment and analyzed shortly after creation at room temperature to minimize contamination of moisture, which is known to react with the dissociated anions and catalyze parasitic degradation reactions, and thermal effects which can occur at high and low temperatures<sup>3,19</sup>. Constant temperature was maintained because temperature has a small effect on ionic association, but at the same time, minimal in comparison with the effects of salt concentration<sup>5,20</sup>. These two solvents related in many properties such as both being aprotic polar solvents liquid at room temperature, low toxicity, and large lithium ion solubility, chemical and electrical stability, but they are also contrasting in a few properties; the

magnitude of  $\epsilon$  is  $\sim 8$  times higher for PC than it is for DMC, thus a large preferential solvation might be expected for PC.

Samples were prepared in an inert atmosphere ( $N_2$ ) glovebox ( $<1$  ppm of  $H_2O$ ) by adding the appropriate amount of each solvent to the salts in the vials and stirring until homogeneous solutions were obtained.

Fourier transform infrared (FTIR) measurements were conducted on a Bruker FT-IR Tensor 27 spectrometer fitted with a PIKE MIRacle germanium-crystal ATR accessory. The spectra were acquired in the attenuated total reflection (ATR) mode with  $4\text{ cm}^{-1}$  resolution with 128 total scans. All FTIR spectra were processed by OPUS software and deconvoluted with the combination of Gaussian and Lorentzian fitting function by SigmaPlot 11 software. To ensure confidence in the deconvolution, constraints of a consistent Gaussian to Lorentzian ratio was maintained on all curves in a single spectrum as well as maintaining the same full width half maximum ratio peak ratio for each functional group. The resulting peak areas were found by integrating the proposed line-fits with Mathematica 10 software.

$^{13}C$  NMR analyses were conducted on a Bruker Avance III 300 MHz NMR Spectrometer. Deuterated DMSO was sealed in a capillary tube and placed in an NMR tube with the solution samples. All NMR spectra were referenced to  $d_6$ -DMSO.

## RESULTS AND DISCUSSION

**FTIR Spectroscopy investigations on coordination.** In order to develop a fundamental understanding about the solution structure and ionic association of commonly used LIB electrolytes, FTIR spectra were acquired for solutions of aprotic polar cyclic and linear carbonate solvents (PC and DMC respectively) with common lithium salts (LiTFSI, LiPF<sub>6</sub>, LiBF<sub>4</sub>, and LiClO<sub>4</sub>) dissolved in them at varied solvent-to-salt ratios (30:1, 25:1, 20:1, 15:1, 10:1, 8:1, 7:1, 6:1, 5:1, and 4:1) to probe the cation inner solvation structure at different electrolyte compositions and proportions.

As seen in figure 1, Carbonate solvents possess a strong distinctive IR absorption at approximately 1700-1850 cm<sup>-1</sup> due a carbonyl band, C=O, stretching vibration. Figure 1 shows the change in the IR spectra of PC with various concentrations of dissolved salts. Upon introduction of a lithium salt to the solvent solution, a second absorption appears in this region. The second absorption results from coordination of the solvent molecule to the primary solvation sphere of the lithium cation. Coordination of the carbonyl oxygen with the lithium cation affects the local electronic environment which is manifested in an observable change in the stretching frequency of the carbon-oxygen double bond and can be observed as a shift of the absorption to lower wavelength. Coordination of the lithium cation with the electronegative carbonyl oxygen results in a decrease in the electron density of the carbonyl group, thus also a decrease in the force constant of the C=O stretch, which is observed here as a decrease of the carbonyl band absorption wavelength.<sup>8,9,12,21</sup> The FT-IR spectrum

of pure PC solvent has an absorption from the carbonyl band  $1805\text{ cm}^{-1}$  and a fermi resonance at  $1790\text{ cm}^{-1}$ . This coordination to the lithium cation results in a shift of the carbonyl stretching band and the corresponding fermi resonance to a lower wavelength, corresponding to a higher stretching frequency, which can be observed at  $1772\text{ cm}^{-1}$  and  $1752\text{ cm}^{-1}$  respectively.<sup>9</sup> The ratio of uncoordinated to coordinated peak intensity is directly correlated to the ratio of solvent-to-salt molecules. As the quantity of salt in solution is increased, a decrease in the peaks at  $1805\text{ cm}^{-1}$  and  $1790\text{ cm}^{-1}$  is observed and accompanied by the appearance of peaks at  $1772\text{ cm}^{-1}$  and  $1752\text{ cm}^{-1}$ . Likewise, the same effects are observed when salts are added to DMC, as seen in figure 2, where the absorption of the uncoordinated C=O stretch located at  $1755\text{ cm}^{-1}$  decreases with increasing salt concentration and a coordinated absorption peak appears at  $1724\text{ cm}^{-1}$ . The resolution between the uncoordinated and coordinated absorptions of both solvents is sufficient to provide meaningful deconvolution for quantitative species population analysis. The total integrated peak area of the coordinated and uncoordinated absorptions remain the same regardless of the quantity of salt added and thus, each band has equivalent IR sensitivity, thus the ratio of the area of the coordinated and uncoordinated peaks is directly proportional the population of coordinated and uncoordinated solvent. In the case of both solvents in figure 1 for PC and figure 2 for DMC, there is an isosbestic point between the two relative maxima, which provides evidence that there is an equilibrium between two species, the coordinated (in the solvation shell) and uncoordinated (bulk) solvent<sup>12</sup>.

As shown in *equation 1*,<sup>5,8,9</sup> comparing the ratio of the area of coordinated solvent,  $A_{CO}$ , to the total area, which is comprised of the uncoordinated area,  $A_{UC}$ , and  $A_{CO}$  will provide for the percentage of solvent coordination to the lithium cation. Multiplying this value by the number of solvent moles,  $n_{sol}$ , provides for the determination of the number of coordinated solvent molecules,  $n_{CO}$ . Further information in relation to the number of solvent molecules coordinated to a single lithium cation be found in equation 2 where  $n_{salt}$  is the moles of salt and  $N$  is the solvation number<sup>5,8,9</sup>.

$$\text{Equation 1} \quad n_{CO} = \frac{A_{CO}}{A_{CO}+A_{UC}} \times n_{sol}$$

$$\text{Equation 2} \quad N = \frac{A_{CO}}{A_{CO}+A_{UC}} \times \frac{n_{sol}}{n_{salt}} = \frac{n_{CO}}{n_{salt}}$$

	Molar Mass (g/mol)	Density (25°C)	$\epsilon_r$	$\mu$ (D)	$\eta$ /(mPas)	$t_{mp}/^\circ\text{C}$	$t_{bp}/^\circ\text{C}$
PC	102.09	1.2 g/cm <sup>3</sup>	64.92	16.5	2.53 (25°C)	-54.5	241.7
DMC	90.08	1.07 g/cm <sup>3</sup>	8.93	0.91	0.59 (20°C)	4.6	90.3

**Table 1: Properties of Solvents**<sup>16,22,23</sup>

The percentage of  $A_{CO}$ , to the total area ( $A_{CO} + A_{UC}$ ), and the correlating solvation number ( $N$ ) are presented in figure 3, for PC, and 4, for DMC, in solutions of various salt concentrations. As seen in figure 3, at a solvent to salt ratio of 4:1 with LiTFSI in PC (2.93 M), the solvation number,  $N$ , is  $\sim 3$  and approximately 3 PC molecules are coordinated to the  $\text{Li}^+$  cation. As the solvent to salt ratio increases and the solution becomes more dilute, more PC molecules coordinate to the  $\text{Li}^+$  cation, which is evidenced from  $N \sim 4$  at 8:1 ratio (1.47 M). Further dilution, 30:1 ratio (0.40 M) results in  $N=7$ , which is greater than the

typically expected coordination number between four and six.<sup>8,16,24,25</sup> The large N value obtained can be attributed to either the primary solvation sphere of the lithium cation being larger than previously determined or instrumental measurement error.

Comparison of the solvation ability in relation to the salts provides information for the degree of ion dissociation of the anion. As found in lithium salt aprotic polar solvent solutions, incomplete dissociation is common for the salts with a remaining population of neutral ion clusters.<sup>25</sup> Salts with higher populations of these uncharged ion pairs will have lower quantities of dissociated ions, require fewer solvent molecules to stabilize the ions in solution and thus the lower the solvation number, the less the salt dissociated.<sup>3,25</sup> According to the relative solvation numbers (figures 3 and 4) found in the varying salt concentrations and solvents; LiTFSI, LiPF<sub>6</sub>, and LiClO<sub>4</sub> all consistently dissociate approximately the same intermediate degree while LiBF<sub>4</sub> dissociates less.<sup>5,16,26-28</sup> In particular, LiBF<sub>4</sub> dissolved in DMC (figure 4) behaves quite differently. Even at the most dilute concentration (0.40M) with a solvent salt ratio of 30:1,  $N \sim 3$  and  $N \geq 4$  is never observed. As the salt concentration increases, the solvation number decreases to  $N \sim 2$ . This decrease in solvation number in this single solvent system is attributed to both the solvation ability of the solvent and the ionic association strength of the salt<sup>29</sup>. LiBF<sub>4</sub>, being the least disassociated salt, was expected to have a lower solvation number, as it would be stabilized with fewer solvent molecules<sup>3</sup>. The quantity of lithium available for solvent coordination is directly related to the magnitude of salt dissociation. At a solvent to salt ratio of 30:1, the

solvation number of LiBF<sub>4</sub> is twice as large in PC (figure 3) as the solvation number in DMC (figure 4). Since LiBF<sub>4</sub> dissociates less than the other three salts, it is expected that there will be more dissociated lithium available for coordination at all ratios for LiTFSI, LiPF<sub>6</sub>, and LiClO<sub>4</sub> than there was with LiBF<sub>4</sub>. This was found to be true as evidenced by the relatively smaller differences in solvation number with the less associated salts than found with LiBF<sub>4</sub>. Therefore, the significance of solvent relative permittivity in relation to solvation ability is inversely related to the quantity of dissociated ions in solution. However, this difference in solvation number between the two solvents decreases with decreasing solvent to salt ratio, which implies less influence of the solvent permittivity in concentrated electrolyte. Thus in agreement with Seo et al, relative permittivity isn't as important and solvent systems are more complicated than typically thought, especially in concentrated system.<sup>9</sup>

**NMR Spectroscopy investigations on coordination.** This change in the electronic environment of solvent's carbonyl carbon due to lithium cation coordination may also be detected via the use of <sup>13</sup>C-NMR spectroscopy as these solvents possess characteristic carbonyl resonances in <sup>13</sup>C-NMR 154.5ppm and 155.6ppm for PC and DMC respectively. Upon addition of the lithium salt to the pure solvent solution, ion-dipole coordination of the dissociated lithium cation effectively casts a deshielding effect and the carbonyl carbon experiences a downfield displacement<sup>21</sup>. By measuring the degree of the experienced chemical shift, it is possible to determine the degree of coordination of the solvent to cation as seen in figure 5 for LiTFSI dissolved in PC. FTIR spectroscopy measures the

relatively slow stretch of the carbonyl group, while the NMR measures the relatively rapid change in spin states, for this reason, it is possible to observe two distinct absorption via FTIR, while only one signal appears on the NMR spectrum. All chemical shift locations of single salt solutions have been plotted in figure 6a (for PC) and figure 6b (for DMC). Spectroscopic data from the NMR is useful for confirming FTIR peak area deconvolutions as linear relationships (figure 7) between the NMR weighted average shift directly correlates with the IR determined coordinated solvent percentage. Cross-method analysis and equation 2 allows for solubility comparison of the four different salts at various solvent-to-salt ratios dissolved in both linear and cyclic carbonate solvents.

## CONCLUSION

Two spectroscopic methods were utilized in an investigation to probe the solvation sphere of a lithium cation. The study was conducted with four lithium salts (LiTFSI, LiPF<sub>6</sub>, LiBF<sub>4</sub>, and LiClO<sub>4</sub>) and two common cyclic and linear carbonate solvents (PC and DMC) that used in lithium-ion battery systems. - Solutions were created in specific solvent-to-salt mole ratios and the quantities of coordinated and uncoordinated solvent were calculated based upon the relative areas of carbonyl IR stretching absorptions. For all systems, (LiTFSI, LiPF<sub>6</sub>, and LiClO<sub>4</sub>) were found to dissociate intermediately, while LiBF<sub>4</sub> dissociated less. At low ratios of salt to solvent, the solvation numbers were at their highest, up to ~7 in the most dissociative salts in PC (LiTFSI, LiPF<sub>6</sub>, and LiClO<sub>4</sub>) and up to ~3.5 with the less dissociative LiBF<sub>4</sub> in DMC. As the amount of solvent per salt decreased, the solvation numbers steadily decreased to ~3 in the most dissociative salts in PC and to ~2 for LiBF<sub>4</sub> in DMC. The solvation number was found to be dependent upon the degree of salt dissociation.

The results from IR were confirmed by comparison to the <sup>13</sup>C NMR resonance spectra of the same solutions. Upon Li<sup>+</sup> coordination, the <sup>13</sup>C resonance of the solvent's carbonyl carbon shifts in proportion to the quantity of salt in solution, and thus is an indicator of the degree of solvent coordination. Shifts in NMR form a linear relationship when plotted with the coordinated absorption relative peak area determined from the IR deconvolution.

At high concentrations, additional solvation effects may dominate and minimal preferential solvation may exist. Prediction of ion solvent preference with the dielectric constant appears to only be valid in dilute solutions.

## LIST OF REFERENCES

- (1) Bockris, J. O.; Reddy, A. K. N. *Modern Electrochemistry*, 2nd ed.; Kluwer Academic Publishers, 2004; Vol. 2B.
- (2) Lucht, B. L.; Markmaitree, T.; Yang, L. In *Encyclopedia of Inorganic Chemistry*; John Wiley & Sons, Ltd, 2006.
- (3) Xu, K. *Chem. Rev.* **2014**, *114* (23), 11503–11618.
- (4) U.S. Department of Energy March 2015.
- (5) Seo, D. M.; Borodin, O.; Han, S.-D.; Boyle, P. D.; Henderson, W. A. *J. Electrochem. Soc.* **2012**, *159* (9), A1489–A1500.
- (6) Aroca, R.; Nazri, M.; Nazri, G. A.; Camargo, A. J.; Trsic, M. *J. Solut. Chem.* **2000**, *29* (10), 1047–1060.
- (7) Burba, C. M.; Frech, R. *J. Phys. Chem. B* **2005**, *109* (31), 15161–15164.
- (8) Nie, M.; Abraham, D. P.; Seo, D. M.; Chen, Y.; Bose, A.; Lucht, B. L. *J. Phys. Chem. C* **2013**, *117* (48), 25381–25389.
- (9) Seo, D. M.; Reininger, S.; Kutcher, M.; Redmond, K.; Euler, W. B.; Lucht, B. *J. Phys. Chem. C* **2015**, *119* (25), 14038–14046.
- (10) Han, S.-D.; Yun, S.-H.; Borodin, O.; Seo, D. M.; Sommer, R. D.; Young, V. G.; Henderson, W. A. *J. Phys. Chem. C* **2015**, *119* (16), 8492–8500.
- (11) Takeuchi, M.; Kameda, Y.; Umebayashi, Y.; Ogawa, S.; Sonoda, T.; Ishiguro, S.; Fujita, M.; Sano, M. *J. Mol. Liq.* **2009**, *148* (2–3), 99–108.
- (12) Barthel, J.; Buchner, R.; Wismeth, E. *J. Solut. Chem.* **2000**, *29* (10), 937–954.

- (13) Xu, K.; Lam, Y.; Zhang, S. S.; Jow, T. R.; Curtis, T. B. *J. Phys. Chem. C* **2007**, *111* (20), 7411–7421.
- (14) Tarascon, J. M.; Guyomard, D. *Solid State Ion.* **1994**, *69* (3), 293–305.
- (15) Reichardt, C. *Solvents and Solvent Effects in Organic Chemistry*, 3rd ed.; WILEY-VCH, 2003.
- (16) Seo, D. M.; Borodin, O.; Han, S.-D.; Ly, Q.; Boyle, P. D.; Henderson, W. A. *J. Electrochem. Soc.* **2012**, *159* (5), A553–A565.
- (17) Takeuchi, M.; Matubayashi, N.; Kameda, Y.; Minofar, B.; Ishiguro, S.; Umebayashi, Y. *J. Phys. Chem. B* **2012**, *116* (22), 6476–6487.
- (18) Xu, K. *Chem. Rev.* **2004**, *104* (10), 4303–4418.
- (19) Kondo, K.; Sano, M.; Hiwara, A.; Omi, T.; Fujita, M.; Kuwae, A.; Iida, M.; Mogi, K.; Yokoyama, H. *J. Phys. Chem. B* **2000**, *104* (20), 5040–5044.
- (20) Campion, C. L.; Li, W.; Lucht, B. L. *J. Electrochem. Soc.* **2005**, *152* (12), A2327–A2334.
- (21) Soetens, J.-C.; Millot, C.; Maigret, B. *J. Phys. Chem. A* **1998**, *102* (7), 1055–1061.
- (22) Kameda, Y.; Umebayashi, Y.; Takeuchi, M.; Wahab, M. A.; Fukuda, S.; Ishiguro, S.; Sasaki, M.; Amo, Y.; Usuki, T. *J. Phys. Chem. B* **2007**, *111* (22), 6104–6109.
- (23) Yuan, K.; Bian, H.; Shen, Y.; Jiang, B.; Li, J.; Zhang, Y.; Chen, H.; Zheng, J. *J. Phys. Chem. B* **2014**, *118* (13), 3689–3695.

- (24) Bogle, X.; Vazquez, R.; Greenbaum, S.; Cresce, A. von W.; Xu, K. *J. Phys. Chem. Lett.* **2013**, *4* (10), 1664–1668.
- (25) Yanase, S.; Oi, T. *J. Nucl. Sci. Technol.* **2002**, *39* (10), 1060–1064.
- (26) Nishikawa, K.; Fukunaka, Y.; Sakka, T.; Ogata, Y. H.; Selman, J. R. *J. Electrochem. Soc.* **2006**, *153* (5), A830–A834.
- (27) Nishida, T.; Nishikawa, K.; Fukunaka, Y. *ECS Trans.* **2008**, *6* (18), 1–14.
- (28) Ue, M.; Mori, S. *J. Electrochem. Soc.* **1995**, *142* (8), 2577–2581.
- (29) Henderson, W. A. *J. Phys. Chem. B* **2006**, *110* (26), 13177–13183.

## BIBLIOGRAPHY

Aroca, R., M. Nazri, G. A. Nazri, A. J. Camargo, and M. Trsic. 2000. "Vibrational Spectra and Ion-Pair Properties of Lithium Hexafluorophosphate in Ethylene Carbonate Based Mixed-Solvent Systems for Lithium Batteries." *Journal of Solution Chemistry* 29 (10): 1047–60. doi:10.1023/A:1005151220893.

Barthel, J., R. Buchner, and E. Wismeth. 2000. "FTIR Spectroscopy of Ion Solvation of LiClO<sub>4</sub> and LiSCN in Acetonitrile, Benzonitrile, and Propylene Carbonate." *Journal of Solution Chemistry* 29 (10): 937–54. doi:10.1023/A:1005186701329.

Bockris, Jon O'M., and Amulya K. N. Reddy. 2004. *Modern Electrochemistry*. 2nd ed. Vol. 2B. Kluwer Academic Publishers.

Bogle, Xavier, Rafael Vazquez, Steven Greenbaum, Arthur von Wald Cresce, and Kang Xu. 2013. "Understanding Li<sup>+</sup>-Solvent Interaction in Nonaqueous Carbonate Electrolytes with 17O NMR." *The Journal of Physical Chemistry Letters* 4 (10): 1664–68. doi:10.1021/jz400661k.

Burba, Christopher M., and Roger Frech. 2005. "Spectroscopic Measurements of Ionic Association in Solutions of LiPF<sub>6</sub>." *The Journal of Physical Chemistry B* 109 (31): 15161–64. doi:10.1021/jp058045f.

Campion, Christopher L., Wentao Li, and Brett L. Lucht. 2005. "Thermal Decomposition of LiPF<sub>6</sub>-Based Electrolytes for Lithium-Ion Batteries." *Journal of The Electrochemical Society* 152 (12): A2327–34. doi:10.1149/1.2083267.

Han, Sang-Don, Sung-Hyun Yun, Oleg Borodin, Daniel M. Seo, Roger D. Sommer, Victor G. Young, and Wesley A. Henderson. 2015. "Solvate Structures and Computational/Spectroscopic Characterization of LiPF<sub>6</sub> Electrolytes." *The Journal of Physical Chemistry C* 119 (16): 8492–8500. doi:10.1021/acs.jpcc.5b00826.

Henderson, Wesley A. 2006. "Glyme–Lithium Salt Phase Behavior." *The Journal of Physical Chemistry B* 110 (26): 13177–83. doi:10.1021/jp061516t.

Kameda, Yasuo, Yasuhiro Umehayashi, Munetaka Takeuchi, Mohanmmad Abdul Wahab, Shuhei Fukuda, Shin-ichi Ishiguro, Motoya Sasaki, Yuko Amo, and Takeshi Usuki. 2007. "Solvation Structure of Li<sup>+</sup> in Concentrated LiPF<sub>6</sub>–Propylene Carbonate Solutions." *The Journal of Physical Chemistry B* 111 (22): 6104–9. doi:10.1021/jp072597b.

Kondo, Kazutaka, Mitsuru Sano, Akio Hiwara, Takehiko Omi, Miho Fujita, Akio Kuwae, Masayasu Iida, Koichi Mogi, and Haruhiko Yokoyama. 2000. "Conductivity and Solvation of Li<sup>+</sup> Ions of LiPF<sub>6</sub> in Propylene Carbonate

Solutions.” *The Journal of Physical Chemistry B* 104 (20): 5040–44.  
doi:10.1021/jp000142f.

Lucht, Brett L., Tippawan Markmaitree, and Li Yang. 2006. “Lithium–Ion Batteries.”  
In *Encyclopedia of Inorganic Chemistry*. John Wiley & Sons, Ltd.  
<http://onlinelibrary.wiley.com/doi/10.1002/0470862106.ia818/abstract>.

Nie, Mengyun, Daniel P. Abraham, Daniel M. Seo, Yanjing Chen, Arijit Bose, and  
Brett L. Lucht. 2013. “Role of Solution Structure in Solid Electrolyte  
Interphase Formation on Graphite with LiPF<sub>6</sub> in Propylene Carbonate.” *The  
Journal of Physical Chemistry C* 117 (48): 25381–89.  
doi:10.1021/jp409765w.

Nishida, Tetsuo, Kei Nishikawa, and Yasuhiro Fukunaka. 2008. “Diffusivity  
Measurement of LiPF<sub>6</sub>, LiTFSI, LiBF<sub>4</sub> in PC.” *ECS Transactions* 6 (18): 1–14.  
doi:10.1149/1.2831921.

Nishikawa, K., Y. Fukunaka, T. Sakka, Y. H. Ogata, and J. R. Selman. 2006.  
“Measurement of LiClO<sub>4</sub> Diffusion Coefficient in Propylene Carbonate by  
Moiré Pattern.” *Journal of The Electrochemical Society* 153 (5): A830–34.  
doi:10.1149/1.2178648.

Reichardt, Christian. 2003. *Solvents and Solvent Effects in Organic Chemistry*.  
3rd ed. WILEY-VCH.

Seo, Daniel M., Oleg Borodin, Sang-Don Han, Paul D. Boyle, and Wesley A.

Henderson. 2012. "Electrolyte Solvation and Ionic Association II. Acetonitrile-Lithium Salt Mixtures: Highly Dissociated Salts." *Journal of The Electrochemical Society* 159 (9): A1489–1500. doi:10.1149/2.035209jes.

Seo, Daniel M., Oleg Borodin, Sang-Don Han, Quang Ly, Paul D. Boyle, and Wesley

A. Henderson. 2012. "Electrolyte Solvation and Ionic Association." *Journal of The Electrochemical Society* 159 (5): A553–65. doi:10.1149/2.jes112264.

Seo, Daniel M., Stefanie Reininger, Mary Kutcher, Kaitlin Redmond, William B.

Euler, and Brett L. Lucht. 2015. "Role of Mixed Solvation and Ion Pairing in the Solution Structure of Lithium Ion Battery Electrolytes." *The Journal of Physical Chemistry C* 119 (25): 14038–46. doi:10.1021/acs.jpcc.5b03694.

Soetens, Jean-Christophe, Claude Millot, and Bernard Maigret. 1998. "Molecular

Dynamics Simulation of Li+BF4- in Ethylene Carbonate, Propylene Carbonate, and Dimethyl Carbonate Solvents." *The Journal of Physical Chemistry A* 102 (7): 1055–61. doi:10.1021/jp972457+.

Takeuchi, Munetaka, Yasuo Kameda, Yasuhiro Umebayashi, Sari Ogawa, Takaaki

Sonoda, Shin-ichi Ishiguro, Miho Fujita, and Mitsuru Sano. 2009. "Ion-ion Interactions of LiPF6 and LiBF4 in Propylene Carbonate Solutions." *Journal of Molecular Liquids* 148 (2–3): 99–108. doi:10.1016/j.molliq.2009.07.003.

Takeuchi, Munetaka, Nobuyuki Matubayasi, Yasuo Kameda, Babak Minofar, Shin-

ichi Ishiguro, and Yasuhiro Umebayashi. 2012. "Free-Energy and Structural Analysis of Ion Solvation and Contact Ion-Pair Formation of Li<sup>+</sup> with BF<sub>4</sub><sup>-</sup> and PF<sub>6</sub><sup>-</sup> in Water and Carbonate Solvents." *The Journal of Physical Chemistry B* 116 (22): 6476–87. doi:10.1021/jp3011487.

Tarascon, J. M., and D. Guyomard. 1994. "New Electrolyte Compositions Stable over the 0 to 5 V Voltage Range and Compatible with the Li<sub>1+x</sub>Mn<sub>2</sub>O<sub>4</sub>/carbon Li-Ion Cells." *Solid State Ionics* 69 (3): 293–305. doi:10.1016/0167-2738(94)90418-9.

Ue, Makoto, and Shoichiro Mori. 1995. "Mobility and Ionic Association of Lithium Salts in a Propylene Carbonate-Ethyl Methyl Carbonate Mixed Solvent." *Journal of The Electrochemical Society* 142 (8): 2577–81. doi:10.1149/1.2050056.

"Vehicle Technologies Office: 2014 Energy Storage R&D Progress Report." 2015.

U.S. Department of Energy.  
<http://energy.gov/eere/vehicles/downloads/vehicle-technologies-office-2014-energy-storage-rd-annual-report>. (Accessed February 12<sup>th</sup>, 2016)

Xu, Kang. 2004. "Nonaqueous Liquid Electrolytes for Lithium-Based Rechargeable Batteries." *Chemical Reviews* 104 (10): 4303–4418. doi:10.1021/cr030203g.

Xu, Kang. 2014. "Electrolytes and Interphases in Li-Ion Batteries and Beyond."

*Chemical Reviews* 114 (23): 11503–618. doi:10.1021/cr500003w.

Xu, Kang, Yiufai Lam, Sheng S. Zhang, T. Richard Jow, and Timothy B. Curtis. 2007.

"Solvation Sheath of Li<sup>+</sup> in Nonaqueous Electrolytes and Its Implication of Graphite/Electrolyte Interface Chemistry." *The Journal of Physical Chemistry C* 111 (20): 7411–21. doi:10.1021/jp068691u.

Yanase, Satoshi, and Takao Oi. 2002. "Solvation of Lithium Ion in Organic

Electrolyte Solutions and Its Isotope Reduced Partition Function Ratios Studied by Ab Initio Molecular Orbital Method." *Journal of Nuclear Science and Technology* 39 (10): 1060–64. doi:10.1080/18811248.2002.9715294.

Yuan, Kaijun, Hongtao Bian, Yuneng Shen, Bo Jiang, Jiebo Li, Yufan Zhang, Hailong

Chen, and Junrong Zheng. 2014. "Coordination Number of Li<sup>+</sup> in Nonaqueous Electrolyte Solutions Determined by Molecular Rotational Measurements." *The Journal of Physical Chemistry B* 118 (13): 3689–95. doi:10.1021/jp500877u.

	Molar Mass (g/mol)	Density (25°C)	$\epsilon_r$	$\mu$ (D)	DN	$\eta$ /(mPas)	$t_{mp}/^\circ\text{C}$	$T_{bp}/^\circ\text{C}$
PC	102.09	1.2 g/cm <sup>3</sup>	64.92	16.5	15.1	2.53 (25°C)	-54.5	241.7
DMC	90.08	1.07 g/cm <sup>3</sup>	8.93	0.91	15.1	0.59 (20°C)	4.6	90.3

Table 1: Properties of Solvents<sup>15,18,24,25</sup>

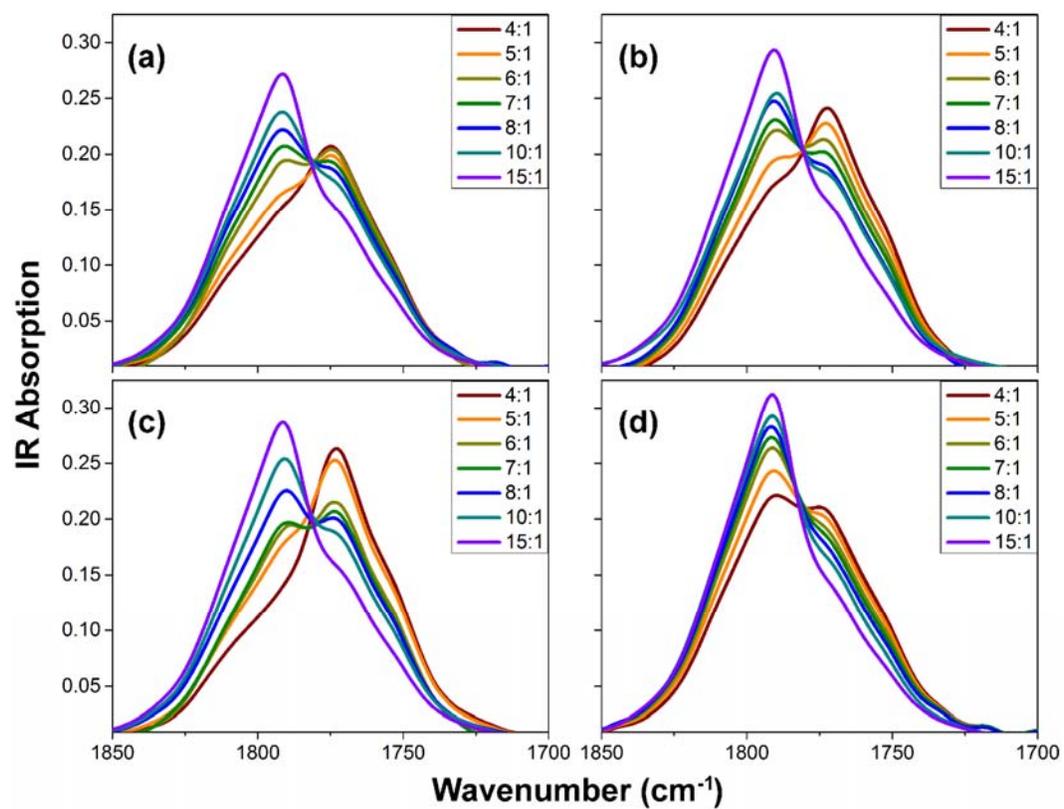


Figure 1 FTIR Propylene Carbonate (PC) carbonyl peak shifts relative to solvent:salt ratios with (a) LiTFSI (b) LiClO<sub>4</sub> (c) LiPF<sub>6</sub> (d) LiBF<sub>4</sub>. The isosbestic point at 1781cm<sup>-1</sup> provides evidence for equilibrium between the coordinated and uncoordinated species.

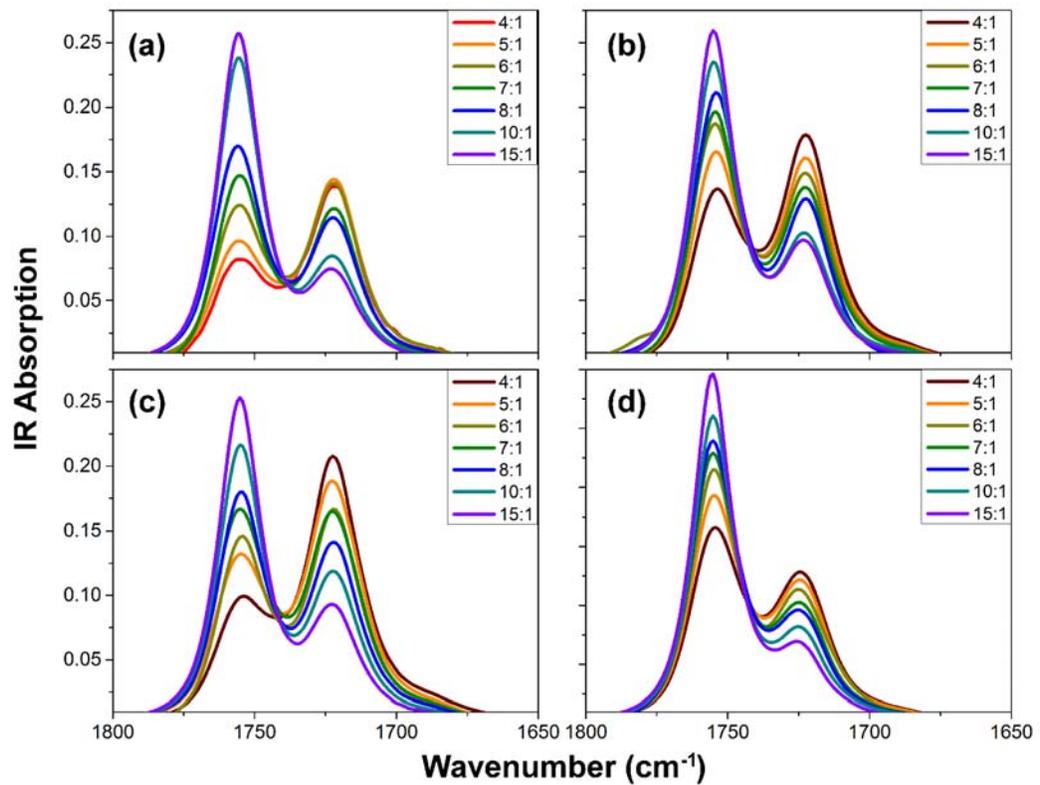


Figure 2 FTIR Dimethyl Carbonate (DMC) carbonyl peak shifts relative to solvent:salt ratios with (a) LiTFSI (b) LiClO<sub>4</sub> (c) LiPF<sub>6</sub> (d) LiBF<sub>4</sub>. The isosbestic point at 1738cm<sup>-1</sup> provides evidence for equilibrium between the coordinated and uncoordinated species.

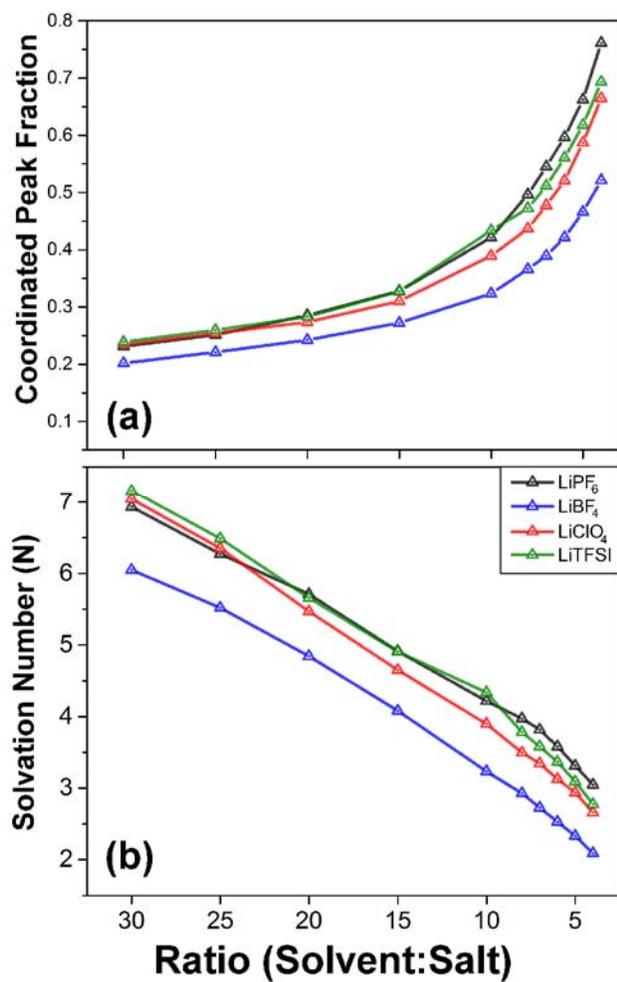


Figure 3 (a) Proportion of coordinated solvent fraction in LiPF<sub>6</sub>, LiBF<sub>4</sub>, LiClO<sub>4</sub>, and LiTFSI dissolved in PC at various solvent:salt ratios. (b) Calculated solvation number for LiPF<sub>6</sub>, LiBF<sub>4</sub>, LiClO<sub>4</sub>, and LiTFSI dissolved in PC at various solvent:salt ratios.

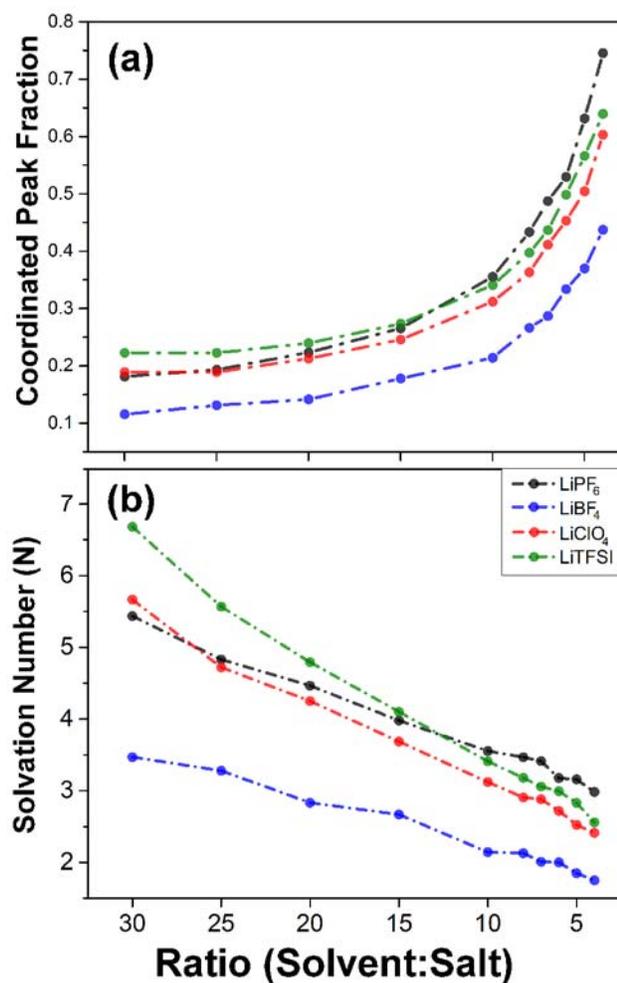


Figure 4 (a) Proportion of coordinated solvent fraction in LiPF<sub>6</sub>, LiBF<sub>4</sub>, LiClO<sub>4</sub>, and LiTFSI dissolved in DMC at various solvent:salt ratios. (b) Calculated solvation number for LiPF<sub>6</sub>, LiBF<sub>4</sub>, LiClO<sub>4</sub>, and LiTFSI dissolved in DMC at various solvent:salt ratios.

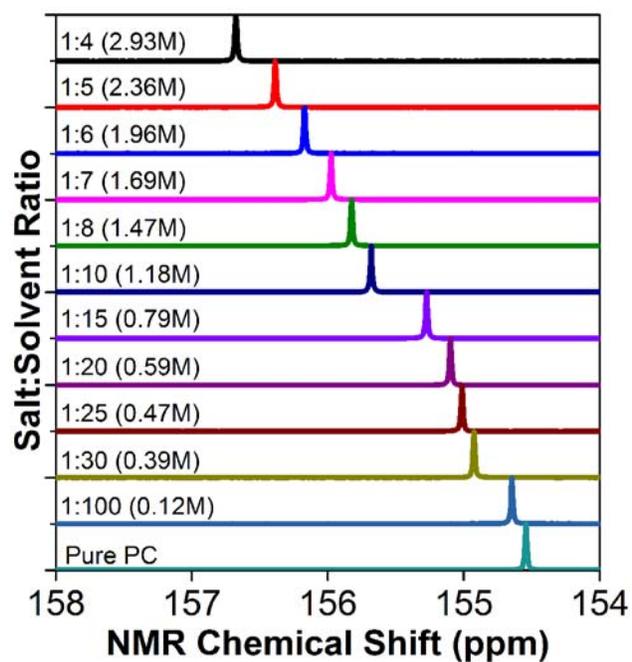


Figure 5 NMR  $^{13}\text{C}$  spectrum of the carbonyl carbon chemical shifts of PC solvent with various amounts of LiTFSI dissolved in. Solvent coordination to the lithium cation has a deshielding effect on the carbonyl carbon.

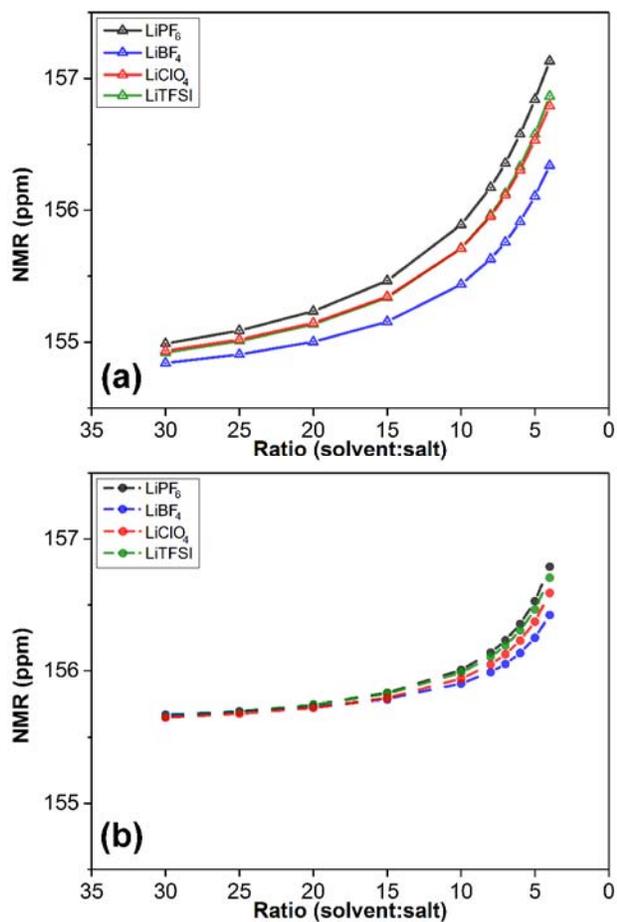


Figure 6 (a) NMR  $^{13}\text{C}$  spectrum of the carbonyl carbon chemical shifts of PC solvent with various amounts of salts;  $\text{LiPF}_6$ ,  $\text{LiBF}_4$ ,  $\text{LiClO}_4$ ,  $\text{LiTFSI}$  dissolved in single salt solutions. (b) NMR  $^{13}\text{C}$  spectrum of the carbonyl carbon chemical shifts of DMC solvent with various amounts of salts;  $\text{LiPF}_6$ ,  $\text{LiBF}_4$ ,  $\text{LiClO}_4$ ,  $\text{LiTFSI}$  dissolved in single salt solutions.

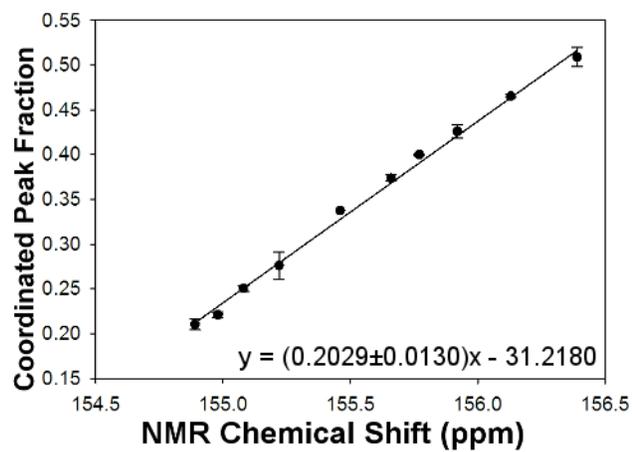


Figure 7 Plot of the FTIR solvent coordination percentage ( $\text{LiBF}_4$  dissolved in PC) against the  $^{13}\text{C}$ -NMR chemical shift. Agreement between the two spectroscopic methods increases confidence in the results.