Molecular Design of Polymerized Ionic Liquids

by

Gabriel Eduardo Sanoja

A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy in Chemical Engineering in the Graduate Division of the University of California, Berkeley

Committee in charge:

Professor Rachel A. Segalman, co-Chair
Professor Nitash P. Balsara, co-Chair
Professor Susan J. Muller
Professor Niren Murthy

Fall 2016
Abstract

Molecular Design of Polymerized Ionic Liquids

by

Gabriel Eduardo Sanoja

Doctor of Philosophy in Chemical Engineering

University of California, Berkeley

Professor Rachel A. Segalman, Co-Chair

Professor Nitash P. Balsara, Co-Chair

Polymerized ionic liquids are an emerging class of functional materials with ionic liquid moieties covalently attached to a polymer backbone. As such, they synergistically combine the structural hierarchy of polymers with the versatile physicochemical properties of ionic liquids. Unlike other ion-containing polymers that are typically constrained to high glass transition temperatures, polymerized ionic liquids can exhibit low glass transition temperatures due to weak electrostatic interactions even at high charge fractions. Promising applications relevant to electrochemical energy conversion and CO$_2$ capture and sequestration have been demonstrated for polymerized ionic liquids, but a molecular design strategy that allows for elucidation of their structure-property relationships is yet to be developed.

A combination of anionic polymerization, click chemistry, and ion metathesis allows for fine and independent control over polymer properties including the number of repeat units, fraction of ionic liquid moieties, composition, and architecture. This strategy has been exploited to elucidate the effect of lamellar domain spacing on the ionic conductivity of block copolymers based on hydrated protic polymerized ionic liquids. The conductivity relationship demonstrated in this study suggests that a mechanically robust material can be designed without compromising its ability to transport ions.

The vast set of ion pair combinations in polymerized liquids provides a unique opportunity to develop functional materials where properties can be controlled with subtle changes in molecular structure via ion metathesis. We illustrate the case of a polymerized ionic liquid that combines the low toxicity and macromolecular dimensions of poly(ethylene glycol) with the magnetic functionality of ion pairs containing iron(III). This material can yield novel theranostic agents with controlled residence time within the human body, and paramagnetic functionality to enhance $^1$H nuclei relaxation rate required for medical imaging.

Finally, the molecular design strategy is expanded to incorporate ion pairs based on metal-ligand coordination bonds between cations and imidazole moieties tethered to the polymer backbone. This illustrates a general approach for using chelating polymers with appropriate metal-ligand interactions to design high conductivity and tunable modulus polymer electrolytes.
To my father,
For always being the inspiration that I need
and not the one I always deserve
# Table of Contents

Table of Contents .......................................................................................................................... ii

Table of Tables .............................................................................................................................. iii

Table of Figures ............................................................................................................................. iii

Acknowledgements ....................................................................................................................... vi

Chapter 1. Introduction .................................................................................................................... 1
  1.1. Historical Background ........................................................................................................... 1
  1.2. Polymerized Ionic Liquids for Electrochemical Devices ..................................................... 4
  1.3. Polymerized Ionic Liquids as Functional Materials ........................................................... 5
  1.4. Motivation and Thesis Outline ............................................................................................ 6
  1.5. References ........................................................................................................................... 7

Chapter 2. Structure-Conductivity Relationships of Block Copolymer Membranes based on
Hydrated Protic Polymerized Ionic Liquids: Effect of Domain Spacing ............................................ 11
  2.1. Introduction ......................................................................................................................... 11
  2.2. Experimental Methods ......................................................................................................... 13
  2.3. Results and Discussion ......................................................................................................... 15
  2.4. Conclusions ......................................................................................................................... 25
  2.5. Acknowledgements ............................................................................................................. 25
  2.6. Appendix. $^1$H NMR, $^{13}$C NMR, GPC, conductivity data, and other information ... 25
  2.7. References ........................................................................................................................... 45

Chapter 3. Magnetic and Biocompatible Polymers as $^1$H Nuclei Relaxation Agents for
Magnetic Resonance Imaging ............................................................................................................ 50
  3.1. Introduction ......................................................................................................................... 50
  3.2. Experimental Methods ......................................................................................................... 51
  3.3. Results and Discussion ......................................................................................................... 54
  3.4. Conclusions ......................................................................................................................... 60
Table of Tables

Table 2.1. Properties of Block Copolymers Based on Protic Polymerized Ionic Liquids ........16
Table 4.1. Properties of Mixtures of PEO-stat-PHGE with Multivalent NTf2- Salts ............79

Table A 2.1. Properties of PS-b-PB as determined from 1H NMR ...............................31
Table A 2.2. Properties of PS-b-PH as determined from 1H NMR ...............................39
Table A 2.3. Calculation of Volume Fractions of Block Copolymers Based on Protic PILs ....41
Table A 2.4. Calculation of Lamellar Domain Spacing of Block Copolymers Based on Protic PILs .................................................................42
Table A 2.5. Calculation of the Ionic Conductivity of Block Copolymers based on Protic PILs 43
Table A 2.6. Calculation of Water Uptake of Block Copolymers Based on Protic PILs ....44

Table of Figures

Figure 1.1. Chemical Structures of Representative Cations and Anions used in Ionic Liquids .....2
Figure 2.1. Synthesis of Block Copolymers Based on Protic Polymerized Ionic Liquids ........17
Figure 2.2. SAXS Intensity Profiles of PS-b-PIL .............................................................19
Figure 2.3. Variation of Lamellar Domain Spacing for PS-b-PIL .................................20
Figure 2.4. WAXS Intensity Profiles for PS-b-PIL ....................................................22
Figure 2.5. Water Uptake and Ionic Conductivity of PS-\textit{b}-PIL ...........................................23
Figure 3.1. Synthesis of Magnetic and Biocompatible Polymer .................................................55
Figure 3.2. Toxicity of PEG-\textit{stat}-PIL and PEG .................................................................56
Figure 3.3. \textsuperscript{1}H NMR Magnetization of H\textsubscript{2}O and PEG-\textit{stat}-PIL ..................58
Figure 3.4. Relaxation Rate of Paramagnetic PEG-\textit{stat}-PIL ..................................................59
Figure 4.1. Synthesis of Multivalent Ion Conducting Polymers ................................................77
Figure 4.2. WAXS Intensity Profiles of Mixtures of PEO-\textit{stat}-PHGE with M(NTf\textsubscript{2})\textsubscript{z} Salts ....80
Figure 4.3. Ionic Conductivity of Mixtures of PEO-\textit{stat}-PHGE with M(NTf\textsubscript{2})\textsubscript{z} Salts ........81
Figure 4.4. VTF Renormalized Ionic Conductivity of Mixtures of PEO-\textit{stat}-PHGE with M(NTf\textsubscript{2})\textsubscript{z} Salts ............................83

Figure A 2.1. Gel Permeation Chromatography of PS-\textit{b}-PB calibrated against polystyrene standards .................................................................26
Figure A 2.2. \textsuperscript{1}H NMR of PS-\textit{b}-PB in CDCl\textsubscript{3} for SIL22.7 ..................................27
Figure A 2.3. \textsuperscript{1}H NMR of PS-\textit{b}-PB in CDCl\textsubscript{3} for SIL36.3 ...................................28
Figure A 2.4. \textsuperscript{1}H NMR of PS-\textit{b}-PB in CDCl\textsubscript{3} for SIL51.2 ..................................29
Figure A 2.5. \textsuperscript{1}H NMR of PS-\textit{b}-PB in CDCl\textsubscript{3} for SIL58.9 ..................................30
Figure A 2.6. \textsuperscript{1}H NMR of His-SH in CD\textsubscript{3}OD ..................................................32
Figure A 2.7. \textsuperscript{13}C NMR of His-SH in CD\textsubscript{3}OD ..................................................33
Figure A 2.8. Gel Permeation Chromatography of PS-\textit{b}-PH calibrated against polystyrene standards .................................................................................34
Figure A 2.9. \textsuperscript{1}H NMR of PS-\textit{b}-PH in DMF-d\textsubscript{7} for SIL22.7 ..................................35
Figure A 2.10. \textsuperscript{1}H NMR of PS-\textit{b}-PH in DMF-d\textsubscript{7} for SIL36.3 ..................................36
Figure A 2.11. \textsuperscript{1}H NMR of PS-\textit{b}-PH in DMF-d\textsubscript{7} for SIL51.2 ..................................37
Figure A 2.12. \textsuperscript{1}H NMR of PS-\textit{b}-PH in DMF-d\textsubscript{7} for SIL58.9 ..................................38
Figure A 3.1. \textsuperscript{1}H NMR of Im-SH in CDCl\textsubscript{3} .......................................................62
Figure A 3.2. Gel Permeation Chromatography of PEG-\textit{stat}-PAGE calibrated against poly(ethylene oxide) standards ........................................63
Figure A 3.3. \textsuperscript{1}H NMR of PEG-\textit{stat}-PAGE in CDCl\textsubscript{3} .......................................64
Figure A 3.4. \textsuperscript{1}H NMR of PEG-\textit{stat}-PIm in CD\textsubscript{3}OD .............................................65
Figure A 3.5. \textsuperscript{1}H NMR of PEG-\textit{stat}-PImBr in CD\textsubscript{3}OD ......................................66
Figure A 3.6. Inversion Recovery Spectra of H\textsubscript{2}O .........................................................67
Figure A 3.7. Inversion Recovery Spectra of PEG-stat-PlmBr

Figure A 3.8. Inversion Recovery Spectra of PEG-stat-PIL

Figure A 4.1. $^1$H NMR of His-SH in CD$_3$OD

Figure A 4.2. $^{13}$C NMR of His-SH in CD$_3$OD

Figure A 4.3. Gel Permeation Chromatography of PEO-stat-AGE calibrated against poly(ethylene oxide) standards.

Figure A 4.4. $^1$H NMR of PEO-stat-PAGE in CDCl$_3$

Figure A 4.5. $^1$H NMR of PEO-stat-PHGE in CD$_3$OD

Figure A 4.6. DSC of Mixtures of PEO-stat-PHGE with M(NTf$_2$)$_z$ Salts
Acknowledgements

The completion of a thesis evidently requires efforts beyond those of a graduate student. I would like to gratefully acknowledge my advisor, Professor Rachel Segalman, for providing support, encouragement, mentorship, and friendship over the past years. I would also like to thank my current and former labmates, in particular Nicole Schauser, Shubaditya Majumdar, Colin Bridges, Bhooshan Popere, Christopher Evans, Anastasia Patterson, Emily Davidson, Bryan Beckingham, Daniel Miller, Christina Rodriguez, Pepa Cotanda, Hilda Buss, Victor Ho, Boris Russ, Barbara Ekerdt, Shannon Yee, and Bryan Boudouris. They have provided strength within frustration, together with everlasting memories that go beyond science. A special recognition goes to Miguel Modestino who has been a teacher, labmate, and friend since the beginning of my scientific career. My collaborators Samir Mitragori, Jerry Hu, Jaya Nolt, Shamon Walker, and Douglas Vogus who have provided the expertise critical for the success of many experiments, and more importantly improve my science through enriching interactions. I would like to thank Nitash Balsara, Susan Muller, Clayton Radke, David Schaffer, and Niren Murthy for the advice and guidance they have provided as part of my thesis and qualifying exam committees. A very deep appreciation goes to Nathaniel Lynd, who has been effectively my co-advisor, and the work here would not have been possible without his support and encouragement. Faculty, post-docs, graduate students, and friends have been there in difficult times, and our discussions have helped me shape my perspectives of science: Bryan McCloskey, Jeffrey Reimer, Karen Winey, Glenn Fredrickson, Michael Chabinyc, Javier Read-de-Alaniz, Christopher Bates, Craig Hawker, Todd Squires, Matthew Helgeson, Ram Seshadri, Bradley Chmelka, Adam Weber, Ahmet Kusoglu, Nicolas Grosso, Marc Martin, Augusta Modestino, Nathan Haouzi, and The Number Six Club. Carlet Altamirano, member of the staff of the Department of Chemical and Biomolecular Engineering, has been invaluable in enabling this work. Finally, I would like to particularly thank Bradley Olsen who has provided inspiration, guidance, and support to help me keep a solid bearing throughout my undergraduate and graduate career.
Chapter 1. Introduction

Polymerized ionic liquids are an emerging class of functional materials with ionic liquid moieties covalently attached to a polymer backbone. As such, they synergistically combine the structural hierarchy of polymers with the versatile physicochemical properties of ionic liquids. Unlike other ion-containing polymers that are typically constrained to high glass transition temperatures, polymerized ionic liquids can exhibit low glass transition temperatures due to weak electrostatic interactions, while maintaining high charge densities. Previous research on polymerized ionic liquids has demonstrated promising technological applications in these systems, but a molecular design strategy that allows for elucidation of their structure-property relationships is yet to be developed. A combination of anionic polymerization, click chemistry, and simple ion exchange allows well-defined polymer structures to be explored, providing new avenues for elucidation of the structure-property relationships necessary to enable novel high-performance functional materials.

1.1. Historical Background

Early in the 20th century, Paul Walden identified triethylammonium nitrate as a pure low melting salt,1 a record of invention described the dissolution of cellulose using a molten pyridinium salt above 130 °C,2 and the development of nuclear energy motivated studies on low-melting chloroaluminates for nuclear fuel reprocessing.3 Among the cations based on quaternized nitrogens, those derived from imidazolium proved to be the best in terms of melting points and electrochemical stability.

Complementary to the aforementioned investigations, research on solid-state electrolytes based on poly(ethylene oxide) demonstrated that anions with delocalized charges stabilized by resonance can facilitate polymer segmental dynamics and effectively plasticize the polymer.4 The gold standard of such anions, bis(trifluoromethylsulfonyl)imide (i.e., NTf$_2$), has a negative charge on the nitrogen stabilized by resonance and the inductive effect from the extremely electron-withdrawing trifluoromethylsulfonyl groups. When combined with an imidazolium cation, such as 1-ethyl-3-methylimidazolium, the resulting ionic liquid, [emim][NTf$_2$],5 exhibits a melting temperature of -15 °C and an ionic conductivity comparable to that of the best organic electrolytes. The [emim][NTf$_2$] shows negligible decomposition and vapor pressure up to 400 °C. Interestingly, [emim][NTf$_2$] is not miscible with water (< 1000 ppm in equilibrium with liquid H$_2$O), and thus defies the traditional perception that relates polarity with hydrophilicity.

Ionic liquids are low-temperature molten salts composed entirely of ions. These salts are characterized by weak intermolecular interactions owing to the pairing of large, charge-delocalized, and asymmetric ions. The resulting steric hindrance and low lattice energy compromise long-range order and impair crystallization at low temperatures. Ionic liquids are composed of organic ions capable of experiencing unlimited structural modifications due to the simplicity associated with the synthesis of the corresponding cations and anions. Thus, appropriate molecular design can be used to develop ionic liquids that exhibit the desired properties for a given application. These include, among others, imidazolium, pyrrolidinium, and quaternary ammonium as cations and bis(trifluoromethanesulfonyl)imide, bis(fluorosulfonyl)imide, and hexafluorophosphate as anions (Figure 1.1).

The discovery of [emim][NTf$_2$] led to a reassessment of ions (e.g., quaternary
Figure 1.1. Chemical Structures of Representative Cations and Anions used in Ionic Liquids

From left to right, the cations (top row) imidazolium, pyrrolidinium, and ammonium; and anions (bottom row) bis(trifluoromethylsulfonyl)imide, hexafluorophosphate, and bis(fluoromethylsulfonyl)imide. $R_1$, $R_2$, $R_3$, and $R_4$ represent alkyl substituents.
ammoniums) which had been avoided due to the difficulty in crystallizing salts composed of large, charge-delocalized, and asymmetric ions. Beyond the ionic liquids based on chloroaluminates with controlled Lewis acidity for nuclear fuel reprocessing, many ionic liquids that were unreactive towards both Lewis and Brønsted acids and bases were developed. Therefore, ionic liquids were originally explored as environmentally benign solvents, which can be recycled with negligible use of volatile organic compounds. Most chemicals synthesized in ionic liquids can be purified by distillation or extracted with water or hydrophobic solvents.

The unique physicochemical properties of ionic liquids makes them critical materials for the development of a range of technologies. The emergence of ionic liquids has enabled processes that were not possible with conventional solvents. Metals and semiconductors that could only be deposited at potentials above that of water splitting can now be electroplated using electrochemically stable ionic liquids. Energy conversion and storage devices such as fuel cells, batteries, and supercapacitors might benefit from low vapor pressure, non-flammable, ionic liquid electrolytes. The exceptional amphiphilic solvent properties allow for preparation of cellulose solutions up to 25 wt %. This has major consequences on the textile industry, but also on the scalability of polysaccharides as a source of biofuels. Prior to the development of ionic liquids, the only known solvent for cellulose was an explosive organic compound. The negligible vapor pressure, non-flammability, electrochemical stability, high ionic conductivity, high chemical and thermal stability, and particularly the broad chemical diversity owing to a large number of cations and anions available that can form ionic liquids have led to a high concentration of research on these materials over the past decades.

The incorporation of ionic liquid moieties into a polymer was originally reported in 1973, when the free-radical polymerization of cationic vinyl monomers was being investigated. Vinylimidazolium and vinylpyridinium salts were particularly exciting due to the stability of a positive charge delocalized in an aromatic ring and covalently bonded to the polymer backbone. Nonetheless, it was not until 1998 that Hiroyuki Ohno coined the term polymerized ionic liquids: a polymeric form of an ionic liquid, where the cations of the ionic liquid are covalently attached to the monomers of the polymer chain and balanced by mobile anions. It is worth noting that although ionic liquids are in a liquid state at low temperatures, polymerized ionic liquids are generally solids. However, as opposed to other ion-containing polymers (e.g., polyacrylates and polysulfonates) that are typically constrained to high glass transition temperatures due to strong electrostatic interactions, polymerized ionic liquids can exhibit low glass transition temperatures at high charge fractions due to weak electrostatic interactions resulting from large, charge-delocalized, and asymmetric ion pairs.

Polymerized ionic liquids synergistically combine the structural hierarchy of polymers with the versatile physiochemical properties of ionic liquids. Initially, polymerized ionic liquids were envisioned uniquely for providing mechanical robustness to ionic liquids. However, this emerging class of ion-containing functional materials has recently become attractive for fundamental research in polymer science; as well as for applications ranging from energy conversion, carbon capture and sequestration, among others. Due to the ambiguity in the salts that qualify as ionic liquids, there is currently no widely accepted definition of polymerized ionic liquids. For the purposes of this thesis, we restrict our attention to ion-containing polymers based on moieties inspired in ionic liquids that have weak electrostatic interactions.
1.2. Polymerized Ionic Liquids for Electrochemical Devices

Global energy markets, which strongly rely on fossil fuels, have non-sustainable and detrimental effects on climate change. Thus, there are currently vigorous efforts in place to achieve major scientific breakthroughs, such as the large-scale replacement of internal-combustion-engine vehicles with zero or low emission alternatives that allow evolution towards an economy based on renewable resources and guarantee society an improved quality of life. For the successful transition to a more environmentally benign economy, it is critical to develop systems both to store the energy in power stations harnessing intermittent sources (e.g., solar) and to power electric or hybrid vehicles. Electrochemical systems such as batteries, fuel cells, and supercapacitors are promising for this purpose and ionic liquids might lead to major advances in their development. For example, the high thermal stability and low vapor pressure of ionic liquids electrolytes ensure safe operation of batteries by preventing thermal runaway and pressure build-up.\(^{25}\) If designed with protic cations, ionic liquids allow proton conductivity in the absence of water combined with thermal and electrochemical stability, which allows operational temperatures in fuel cells above 100 °C and opens new avenues for catalyst design to replace expensive and scarce platinum.\(^{26}\) The development of ionic liquid based electrochemical devices is still in its infancy and further progress is needed to ensure their full exploitation. The main challenges are choosing an ionic liquid that features wide electrochemical stability windows combined with high ionic conductivity, and designing electrode structures capable of assuring proper wettability by the ionic liquid.

Issues related with ionic liquids can be addressed to an extent with polymerized ionic liquids. The latter have also garnered significant amount of attention for electrochemical energy devices due to their broad range of properties arising from chemical diversity. Unlike ionic liquids where both cations and anions are mobile in a liquid phase, polymerized ionic liquids are generally single-ion conductors, because cations are covalently attached to the polymer chain. This can have a variety of implications in the operation of electrochemical systems as the inefficiencies arising from the electrolyte and electrode (i.e., kinetic, ohmic, and concentration overpotentials) will be affected.\(^{27}\)

The challenge in developing novel polymerized ionic liquids for electrochemical devices is that factors which traditionally enhance ionic conductivity have a detrimental effect on the mechanical properties.\(^{15}\) Block copolymers based on polymerized ionic liquids are promising materials as solid-state electrolytes or ion-conducting membranes because each block can be separately designed to provide complementary structural and transport properties. These materials self-assemble into various nanostructures on length scales of 10-100 nm which are determined by the volume fraction of each block and the strength of their phase segregation.\(^{28}\) The resulting morphology ultimately dictates the bulk mechanical and transport properties as it allows for synergy between the constituent blocks. The first block copolymer based on a polymerized ionic liquids was reported by Waymouth, Gast, and coworkers in 2004,\(^ {29-30}\) but recently there has been an increased interest in these materials.

The parameter space dictating the molecular structure of polymerized ionic liquid block copolymers is extensive, including chemistry of ionic liquid moieties, molecular weight, composition, and architecture. The meticulous selection of these parameters results in polymers where the conductivity and mechanical properties can be tailored in the solid-state; which has
been of significant interest in the development of solid-state electrolytes and membranes for electrochemical devices. For investigations on water-assisted ion transport (e.g., OH\(^{-}\)) for alkaline fuel cells, self-assembled polymerized ionic liquids block copolymers exhibit ionic conductivities that exceed that of amorphous polymerized ionic liquids (e.g., homopolymers or random copolymers) due to increased transport as a result of confinement in channels with length scales of 10-100 nm.\(^{31-32}\) Enhancements in ionic conductivity have been achieved by increasing the size of the conducting channel in lamellae nanostructured membranes, indicating that narrower domains may hinder ion transport.\(^{33}\) Similar effects arise from the inclusion of hydrophobic alkyl chains between the ion pairs and the polymer backbone or as substituents of the cations.\(^{34-35}\) For work focused on dry fluorinated anion transport (e.g., NTf\(_2\)) for lithium batteries, the morphology, long-range order, strength of phase segregation, and glass transition temperature have been demonstrated to have a significant impact on ion conductivity. A bicontinuous morphology (i.e., network) resulted in increased ionic conductivity relative to lamellae, while hexagonally packed cylindrical morphologies exhibited poor ion transport potentially due to increased defects and grain boundaries.\(^{36}\) Improving long-range order through processing conditions improves ionic conductivity.\(^{36-37}\) Faster segmental chain dynamics, and in turn higher ionic conductivity, was achieved through a lower glass transition temperature in the polymerized ionic liquid channel.\(^{38}\)

The substantial interest in polymerized ionic liquids as components in electrochemical energy devices offers opportunity for fundamental research in polymer science; as well as for applications in electrochemical systems beyond the conventional hydrogen fuel cells, and lithium ion batteries. Specifically, exploring a richer set of ionic liquid moieties and therefore properties of polymerized ionic liquids is promising. To date most polymerized ionic liquids are based on imidazolium, though there are many more cations in the ionic liquid family. Therefore, polymerized ionic liquids with different covalently attached cations are of interest. It is this vast set of ion pair combinations in ionic liquids that provides a unique opportunity to develop numerous functional materials based on polymerized ionic liquids where properties (e.g., ionic conductivity) can be controlled with subtle changes in molecular structure.

1.3. Polymerized Ionic Liquids as Functional Materials

Another grand engineering challenge to mitigate global warming is to develop carbon capture and sequestration technologies. Gas separation membranes based on polymerized ionic liquids are promising for this application because they synergistically combine the mechanical robustness of polymers with the negligible vapor pressure and carbon dioxide permeability intrinsic to ionic liquids,\(^ {39}\) such as those based on tetralkylammonium cations. Pioneering work by Shen et al. demonstrated that polymerized ionic liquids exhibit higher CO\(_2\) sorption capacity than the corresponding small molecule ionic liquids.\(^ {40}\) The earliest reports examined imidazolium based polymerized ionic liquids including poly[1-(4-vinylbenzyl)-3-butylimidazolium tetrafluoroborate] and its hexafluoroborate derivate. However, it was later recognized that the tetralkylammonium tetrafluoroborate polymerized ionic liquids exhibit higher CO\(_2\) sorption capacity than those based on imidazolium, although the underlying mechanism of gas permeation is yet to be elucidated.\(^ {21, 41}\) Although there have been demonstrations on the effect of structural variations on the ion pair (e.g., increasing the length of the N-alkyl substituent) on the CO\(_2\) permeability and selectivity, a complete understanding between molecular composition, macromolecular structure, and gas permeability is still required.
Due to their characteristic change in physicochemical properties such as solubility, hydrophilicity, and molecular volume induced by exchanges in the ion pair, polymerized ionic liquids have been exciting as smart materials that exhibit a response in the presence of an external stimuli. For example, Li et al. designed optical sensors based on volume changes of polymerized ionic liquids induced by ion exchange.\textsuperscript{42} In particular, photonic crystals were prepared from polymers based on imidazolium inverse opals capable of shrinking or expanding depending on the counter-anion, humidity, and solvent content. Changes in the characteristic size of the pores and walls of the photonic crystal translated into different optical responses and macroscopic colors. This effect can be exploited to develop novel optical anion and humidity sensors, or functional materials with electrooptical switchable wettability.\textsuperscript{43-44} The unlimited structural variations of ionic liquids, as well as nanostructures suitable for photonic crystals, turns polymerized ionic liquids into a power platform for novel stimuli-responsive materials.

An interesting application of polymerized ionic liquids results from their intrinsic electric and magnetic properties. Polymerized ionic liquids are based on ion pairs and therefore have a relatively high density of strong dipoles. This unique molecular structure makes them promising candidates for microwave absorption. Shen et al. investigated polymerized ionic liquids based on model imidazolium and tetralkylammonium cations with dielectric constants from 3.7 to 5.3 and dielectric loss factors from 0.18 to 0.37, which are significantly higher than those reported for conventional polar polymers. Interestingly, both the dielectric constant and dielectric loss factor of polymerized ionic liquids remain essentially constant in the frequency range of 10-10 GHz.\textsuperscript{45} The polymerized ionic liquid based on tetralkylammonium tetrafluoroborate exhibits the highest dielectric constant and dielectric loss factor reported to date. More recently, Dobbelin et al. demonstrated the synthesis of paramagnetic polymerized ionic liquids. The magnetic properties were incorporated with anions based on transition metals combined with conventional imidazolium and pyrrolidonium backbones.\textsuperscript{46} These materials present an interesting combination between the processability of polymers and the paramagnetic properties of the ion pair.

1.4. Motivation and Thesis Outline

Polymerized ionic liquids are broadening the chemistry, physicochemical properties and applications of conventional ion-conducting polymers. The introduction of novel anions and cations is producing a renaissance of the field of ionic polymers. Although an important number of polymers have already been synthesized, the potential for innovative ion-containing polymers with applications in electrochemical energy conversion, gas separation, or stimuli-responsive materials is extremely high due to the new types of ions which are being developed coming from the ionic liquid community and the recent advances in controlled and precise polymer chemistry. The development of a molecular design strategy that allows for elucidation of structure-property relationships is critical for addressing fundamental questions in polymer science, and enabling generation of high-performance functional materials.

In Chapter 2, the effect of domain spacing of the ionic conductivity of hydrated block copolymer membranes based on protic polymerized ionic liquids is investigated. The conductivity scaling relationship demonstrated in this study suggests that a mechanically robust membrane can be designed without compromising its ability to transport ions.

In Chapter 3, a polymerized ionic liquid that synergistically combines the low cytotoxicity and structural hierarchy of poly(ethylene glycol) with the magnetic functionality of
ion pairs containing iron(III) is presented. The material designed in this study can yield novel theranostic agents with controlled residence time within the human body, and paramagnetic functionality to enhance the $^1$H nuclei relaxation rate required for magnetic resonance imaging.

In Chapter 4, the molecular design strategy is expanded to develop solid-state electrolytes that transport multi-valent cations due to kinetically labile metal-coordination bonds between cations and imidazole moieties tethered to the polymer backbone. This study provides a general approach for using neutral polymers with appropriate ion-complex formation interactions to design high conductivity and tunable modulus polymer electrolytes.

1.5. References


2. Graenacher, C. Cellulose solution. 1934.


Reproduced with permission from Gabriel E. Sanoja, Bhooshan C. Popere, Bryan S. Beckham, Christopher M. Evans, Nathaniel A. Lynd, and Rachel A. Segalman. Macromolecules (2016), 49, 2216-2223. 2016 American Chemical Society

Elucidating the relationship between chemical structure, morphology, and ionic conductivity is essential for designing novel high-performance materials for electrochemical applications. In this work, the effect of lamellar domain spacing on ionic conductivity is investigated for a model system of hydrated block copolymer based on a protic polymerized ionic liquid. We present a molecular design strategy that allows for the synthesis of a well-defined series of narrowly dispersed PS-b-PIL with constant volume fraction of ionic liquid moieties ($f_{\text{IL}} \approx 0.39$) and with two types of mobile species: trifluoroacetate anions and protons. These materials self-assemble into ordered lamellar morphologies with variable domain spacing (ca. 20-70 nm) as demonstrated by small-angle X-ray scattering. PS-b-PIL polymers exhibit ionic conductivities above $10^{-4}$ S/cm at room temperature, which are independent of domain spacing consistent with their nearly identical water content. The conductivity scaling relationship demonstrated herein suggest that a mechanically robust membrane can be designed without compromising its ability to transport ions. In addition, PIL-based materials exhibit low water uptake ($\lambda \approx 10$) in comparison with many proton-conducting systems reported elsewhere. The low water content of the materials described herein makes them promising candidates for electrochemical devices operating in aqueous electrolytes at low current densities where moderate ion conduction and low product crossover are required.

2.1. Introduction

Ion-conducting polymers are key components in a variety of electrochemical systems, as they allow for ion transport across physically separated reaction sites. These materials are frequently used in energy storage and conversion devices such as solar-fuels generators, fuel cells, supercapacitors, and batteries where they serve as membranes or solid-state electrolytes with robust mechanical and transport properties. Given that the efficiency of an electrochemical device is intimately coupled to the polymer properties, efforts have been made in order to elucidate design rules for improved materials based on their structure-property relationships.

The challenge in developing novel ion-conducting polymers for electrochemical devices is that factors which traditionally enhance ionic conductivity (e.g., electrolyte uptake) have a detrimental effect on the mechanical and gas barrier (e.g., H$_2$ and O$_2$) properties. Block copolymers are promising materials as ion-conducting membranes because each block can be separately designed to provide complementary structural and transport properties. These materials self-assemble into various nanostructures on length scales of 10–100 nm which are determined by the volume fraction of each block, and the strength of their phase segregation. The resulting morphology ultimately dictates the bulk mechanical and transport properties as it allows for synergy between the constituent blocks.

Membranes based on blends of ionic liquids and block copolymers have been of interest due to their gas separation properties, high ionic conductivity, as well as thermal and electrochemical stability. In these blends, ionic liquids can be confined within one phase of
the block copolymer, and the self-assembly yields nanometer length scale ion-conducting channels embedded in a mechanically robust matrix. These materials are not suitable for electrochemical devices operating in aqueous electrolytes because leaching of the ionic liquid moieties significantly impacts the stability of the membrane. A strategy to improve the stability of ion-conducting membranes based on blends of ionic liquids and block copolymers is to covalently bind the ionic groups to the backbone resulting in a novel class of materials known as polymerized ionic liquids.13-16

Polymers based on imidazolium salts are particularly exciting due to the stability of a positive charge in an aromatic ring covalently bonded to the polymer backbone16. Investigations on polymerized ionic liquids have primarily focused on aprotic and quaternized imidazolium ions unable to participate in proton transport.17-19 However, carbon-linked imidazole moieties represent a promising chemistry for proton conducting PILs due to the amphoteric nature of the nitrogen atoms located in the aromatic ring. These materials would constitute the macromolecular version of imidazolium bis(trifluoromethylsulfonyl)imide, a small molecule protic ionic liquid known to facilitate long-range proton transport via Grotthuss mechanism.20-21 These protic PILs are particularly interesting for applications that require moderate proton conduction and low levels of gas permeation, such as solar driven water electrolysis devices.22

Block copolymers based on protic polymerized ionic liquids have not been thoroughly investigated due to the difficulties associated with their synthesis in a controlled, processable, and scalable manner.23 Conventional proton conducting membranes are inspired in Nafion and contain sulfonic acid groups that are characterized by their low synthetic tunability. Although proton conducting systems are important for many applications that require acidic electrolyte, there are limited examples of protic polymerized ionic liquids in the literature.24 We recently reported a novel block copolymer based on a protic polymerized ionic liquid that significantly uptakes less water than Nafion and sulfonated block copolymers.25 The low water content in these membranes is anticipated to translate into a stronger dependence of morphology and polymer dynamics on the physics governing proton conduction. Understanding in detail the conductivity scaling relationships in these materials will provide knowledge about important design criteria for ion-conducting membranes based on protic polymerized ionic liquids.

Structure-conductivity relationships have been investigated in blends of poly(styrene-block-ethylene oxide) (PS-b-PEO) and lithium bis(trifluoromethylsulfonyl)imide (LiNTf2) envisioned as solid-state electrolytes for lithium batteries. In this system, Li+ ions are coordinated by the oxygen atoms of the polymer backbone and consequently the transport is strongly coupled to the dynamics of the PEO chains.26 Moreover, the addition of LiNTf2 salt increases the PEO glass transition temperature (Tg) yielding a maximum in ionic conductivity due to the competition between ion concentration and polymer segmental motion.27 Hydrated and ionic liquid swollen sulfonated polymers, inspired by Nafion, have also been investigated as proton exchange membranes (PEMs) for fuel cells. In these materials, the sulfonic acid sites dissociate into tethered sulfonates and mobile protons that can be transported via water facilitated Grotthuss mechanism. Thus, water plays a key role in the structure-conductivity relationships of these materials. In particular, at high hydration levels, the ionic conductivity of sulfonated PEMs scales with the percent of conducting volume, while at low hydration levels, the conductivity is a more complicated function of sulfonate content, humidity, and morphology.28 Block copolymer membranes based on protic polymerized ionic liquids are
fundamentally different from both PS-\textit{b}-PEO/LiNTf$_2$ and sulfonated PEMs. These materials appear to transport protons via Grotthuss mechanism, exhibit lower $T_g$ upon protonation of the imidazole moieties (i.e., increasing ionic liquid concentration), and uptake less water than Nafion inspired block copolymers.$^{25,29}$ Therefore, a more important effect of morphology and polymer dynamics is expected on the physics governing ion conduction.

Herein, we report the development of a novel generation of block copolymers based on protic polymerized ionic liquid. We present a strategy based on a combination of sequential anionic polymerization and thiol-ene click chemistry that allows for control over the chemical structure of the block copolymer and guarantees scalability appropriate for extensive physical characterization. The system self-assembles into lamellar nanostructures, and exhibits an ionic conductivity above $10^{-4}$ S/cm that does not depend on domain spacing. The insight of this study on the structure-conductivity relationships of block copolymers based on protic polymerized ionic liquids allows us to elucidate rules for development of improved ion-conducting membranes for applications in electrochemical devices. In particular, within the domain spacing range investigated (ca. 20–70 nm) membranes with robust mechanical properties can be designed without compromising ionic conductivity.

2.2. Experimental Methods

Materials. All materials were used as received from Sigma-Aldrich unless otherwise noted. CDCl$_3$ and Methanol-d$_4$ were purchased from Cambridge Isotope Laboratories; and acetone, methanol, isopropyl alcohol, acetonitrile, and hexanes from BDH Chemicals. Cyclohexane and dimethylformamide were collected from a commercial J.C. Meyer dry solvent system and used immediately thereafter. Styrene was dried over CaH$_2$, degassed through three freeze-pump-thaw cycles, and further purified by distillation to a flame-dried receiving flask where it was stored at 0 °C until immediately before use. Butadiene was degassed through three freeze-pump-thaw cycles, and then vacuum transferred to a buret kept at 0 °C until immediately prior to use.

Synthesis of N-((2-(1H-Imidazol-4-yl)Ethyl)-4-Mercaptobutanamide (His-SH). The synthesis of His-SH was reported previously by Lundberg et al.$^{30}$ In a 250 mL round bottom flask equipped with a Teflon-coated stir bar and a condenser, 10.1 g (99.0 mmol) of $\gamma$-thiobutyrolactone, 10.0 g (90.0 mmol) of histamine and 150 mL of acetonitrile was added. The reaction mixture was heated to 95 °C using a heating mantle and the reaction was allowed to proceed for 12 h. The reaction was cooled to room temperature, and the resulting pale yellow solid isolated by filtration, and dried \textit{in vacuo}.

Synthesis of Polystyrene-\textit{block}-Polybutadiene (PS-\textit{b}-PB). Separate burets containing cyclohexane, and butadiene were connected to a thick-walled glass reactor fitted with Ace threads. The butadiene was connected by a flexible, stainless steel bellows so that the buret could be held in an ice bath until use. The reactor assembly was flame dried and then cycled between vacuum and positive nitrogen pressure (5 psig) three times. The reactor was finally charged with a nitrogen atmosphere and then isolated from the Schlenk line. Cyclohexane was added, and the temperature equilibrated at 0 °C. Based on the amount of purified butadiene (2.86 g, 52.9 mmol), a quantity of \textit{sec}-butyl lithium (0.52 mL, 1.4 M in cyclohexane, 0.728 mmol) was added through a gastight syringe. \textit{Caution!} \textit{sec}-butyl lithium is a pyrophoric and moisture-sensitive material and should be handled with appropriate care. Styrene (16.8 mL, 146.8 mmol) was added through a
gastight syringe and the reaction mixture turned orange due to the formation of the polystyryl lithium complex. The temperature was increased to 40 °C, and the polymerization was allowed to proceed for 4 h. After the consumption of styrene monomer, the temperature was decreased to 30 °C, tetramethylethylenediamine (TMEDA, 0.11 mL, 0.734 mmol) was added through a gastight syringe to bias the regiochemistry of the butadiene towards the 1,2 addition, and the reaction mixture turned dark red. Butadiene was poured in through the flexible bellows and the reaction mixture turned bright yellow due to the formation of polybutadienyl lithium chain ends. The reaction was allowed to proceed for 8 h. Finally, degassed and acidified isopropyl alcohol was added to terminate the polymerization. The resulting PS-\(\text{b-PB}\) was precipitated into an excess of methanol/isopropyl alcohol (50:50), and dried in vacuo.

Synthesis of Histamine functionalized Block Copolymer PS-\(\text{b-PH}\). In a 250 mL round bottom flask equipped with a Teflon-coated stir bar, PS-\(\text{b-PB}\) (2.00 g, 3.94 mmol of allyl groups), His-SH (1.05 g, 4.92 mmol), azobisisobutyronitrile (AIBN, 0.13 g, 0.79 mmol) and dimethylformamide (40 mL) were added and sealed with a septum. The solution was sparged with \(\text{N}_2\) (g) for 30 min and then allowed to react at 65 °C for 24 h. The resulting PS-\(\text{b-PH}\) was precipitated in isopropanol, isolated by filtration, washed with methanol (3x50 mL) and acetone (1x50 mL), and dried in vacuo overnight to yield a yellow solid.

Synthesis of Block Copolymer based on Protonated Ionic Liquid PS-\(\text{b-PIL}\). In a 20 mL vial equipped with a Teflon-coated stir bar, \(\text{P(S-b-H)}\) (1.50 g, 1.73 mmol of histamine groups), trifluoroacetic acid (TFA, 0.15 mL, 1.95 mmol) were dissolved in tetrahydrofuran (15 mL). The solution was stirred overnight and the resulting PS-\(\text{b-PIL}\) was collected by evaporation in vacuo.

Molecular Characterization. Gel Permeation Chromatography (GPC) was performed on a Waters instrument using a refractive index detector and Agilent PLgel 5 μm MiniMIX-D column. Tetrahydrofuran at 25 °C was used as the mobile phase with a flow rate of 1.0 mL/min. Polydispersity values (D) were determined against narrow PS standards (Agilent). \(^1\)H Nuclear Magnetic Resonance (NMR) spectra were collected on a Bruker Avance DMX 500 MHz. Block copolymer molecular weights (Mn) were determined using \(^1\)H NMR end-group analysis. Density of PS-\(\text{b-PIL}\) was measured with a helium AccuPyc II 1240 Pycnometer.

Morphological Characterization. Dry polymer samples were prepared by melt-pressing PS-\(\text{b-PIL}\) into 0.5 mm thick disks at 150 °C and annealing at 150 °C under a vacuum of 10\(^{-3}\) Torr for 24 h. The samples were hydrated by placing them in sealed holders containing Milli-Q water (T = 80 °C) and equipped with X-ray transparent Kapton windows. Small-angle X-ray scattering (SAXS) and wide-angle X-ray scattering (WAXS) were performed at beamline 7.3.3 of the Advanced Light Source (ALS) using X-rays of wavelength 1.240 Å focused on a 50 x 300 μm spot. Full two-dimensional scattering patterns were collected using a 2D Dectris Pilatus 2M charge-coupled device (CCD) detector (1475 x 1679 pixels). The scattering patterns were azimuthally integrated using Nika version 1.58.

Electrochemical Impedance Spectroscopy. Membranes were prepared by melt-pressing PS-\(\text{b-PIL}\) at 150 °C and annealing at 150 °C under a vacuum of 10\(^{-3}\) Torr for 24 h. These were equilibrated in Milli-Q water (T = 80 °C) until the pH of the solution was roughly equivalent to that of the Milli-Q water (5.7). In-plane Electrochemical Impedance Spectroscopy (EIS) was performed using a two-point probe BT-110 conductivity cell (Scribner), which was interfaced
with a Biologic VSP-300 potentiostat. The membranes were placed in a cell and immersed in Milli-Q water (V = 300 mL). A sinusoidal voltage with amplitude of 10 mV was applied in the frequency range of 0.1 Hz to 10 MHz. Nyquist plots of the imaginary versus real impedance were analyzed to determine the membrane resistance. Ionic conductivity was calculated using the equation: \( \sigma = \frac{L}{RWt} \), where \( \sigma \) is the ionic conductivity (S/cm), \( L \) is the distance between the platinum electrodes (0.350 cm), \( W \) is the width of the membrane, \( t \) is the thickness of the membrane, and \( R \) is the resistance.

**Water Uptake Measurements.** Membranes were prepared by melt-pressing PS-\( b \)-PIL at 150 \( ^\circ \)C and annealing at 150 \( ^\circ \)C under a vacuum of 10\(^{-3} \) Torr for 24 h in the presence of phosphorus pentoxide. The dry weights of the films were recorded immediately after removal from the vacuum oven. Hydrated membranes were prepared by equilibration in Milli-Q water (\( T = 80 \) \( ^\circ \)C) for 7 days. Water uptake (\( \lambda \)) was calculated using the equation: \( \lambda = \frac{m_{\text{wet}} - m_{\text{dry}}}{M_{\text{H}_2\text{O}}n_{\text{IL}}} \), where \( m_{\text{wet}} \) and \( m_{\text{dry}} \) are the weights of the hydrated and dried membranes, respectively; \( M_{\text{H}_2\text{O}} \) is the molecular weight of water (18.02 g/mol); and \( n_{\text{IL}} \) is the number of moles of ionic liquid moieties in the membrane as determined from \( ^1\text{H} \) NMR spectroscopy.

### 2.3. Results and Discussion

From a molecular design standpoint, it is critical to achieve systematic and independent control over block copolymer properties including the number of segments (\( N \)), volume fraction of ionic liquid (\( f_{\text{IL}} \)), and volume fraction of mechanical block (\( f_s \)) in order to tune nanostructure (e.g., spherical, cylindrical, gyroid, and lamellar) and bulk mechanical and transport properties. To investigate the effect of lamellar domain spacing on the ionic conductivity of block copolymers based on protic polymerized ionic liquids, a series of PS-\( b \)-PIL block copolymers with constant composition and morphology was synthesized. These materials are suitable as ion-conducting membranes because ion transport is confined to the PIL while the PS imparts mechanical robustness. Well-defined and narrowly dispersed PS-\( b \)-PIL polymers were obtained (\( D < 1.2 \)) with an approximately constant volume fraction of ionic liquid (\( f_{\text{IL}} \approx 0.39 \)). The properties of these copolymers are summarized in Table 2.1.

The strategy used to prepare block copolymers membranes based on protic PILs is illustrated in Figure 2.1. First, the histamine functionalized block copolymer (PS-\( b \)-PH) was synthesized using sequential anionic polymerization of styrene and butadiene, followed by thermally activated thiol-ene click chemistry of His-SH. PH was chosen as a PIL precursor due to the remarkable stability and ionic conductivity previously reported for the alkyl substituted N-vinylimidazolium analog,\(^{34} \) and the amphoteric nature of the nitrogen atoms located in the aromatic ring that facilitate long-range proton transport. Next, the resulting PS-\( b \)-PH was treated with TFA to generate proton conducting PS-\( b \)-PIL. The desired systematic and independent control over the number of segments, volume fraction of ionic liquid, and volume fraction of each block is respectively achieved by levering the monomer to initiator ratio, concentration of living chain-end polar modifier TMEDA, and the relative amounts of styrene and butadiene. Notice that PS-\( b \)-PIL contains two types of mobile charge carriers, trifluoroacetate anions and protons, and the contributions to the ionic current (i.e., transference number) from each of them will depend on the operating conditions of the electrochemical device.\(^5 \) The conductivities
Table 2.1. Properties of Block Copolymers Based on Protic Polymerized Ionic Liquids

<table>
<thead>
<tr>
<th>Polymer(^a)</th>
<th>(D(^b)</th>
<th>Mn (kg/mol)(^c)</th>
<th>(f_S(^d)</th>
<th>(f_{IL}(^e)</th>
<th>N(^f)</th>
<th>d (nm)(^g)</th>
<th>Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIL22.7</td>
<td>1.12</td>
<td>20.8</td>
<td>0.60</td>
<td>0.37</td>
<td>296</td>
<td>22.7</td>
<td>LAM</td>
</tr>
<tr>
<td>SIL37.0</td>
<td>1.13</td>
<td>42.5</td>
<td>0.58</td>
<td>0.39</td>
<td>605</td>
<td>37.0</td>
<td>LAM</td>
</tr>
<tr>
<td>SIL51.5</td>
<td>1.13</td>
<td>66.6</td>
<td>0.57</td>
<td>0.40</td>
<td>948</td>
<td>51.5</td>
<td>LAM</td>
</tr>
<tr>
<td>SIL63.5</td>
<td>1.11</td>
<td>85.3</td>
<td>0.56</td>
<td>0.41</td>
<td>1214</td>
<td>63.5</td>
<td>LAM</td>
</tr>
</tbody>
</table>

\(^a\)Polymers are labeled SILXX.X, where XX.X is the lamellar domain spacing in nm of PS-\(b\)-PIL equilibrated in water and at room temperature. 
\(^b\)Determined against narrow PS standards by GPC. 
\(^c\)Determined via \(^1\)H NMR spectroscopy end-group analysis. 
\(^d\)Determined using a polystyrene monomer volume of 0.165 nm\(^3\). 
\(^e\)Determined using a polybutadiene monomer volume of 0.111 nm\(^3\). 
\(^f\)Determined using a segment reference volume of 0.1 nm\(^3\). 
\(^g\)Determined from the primary scattering peak of the SAXS profiles of hydrated PS-\(b\)-PIL at room temperature.
Figure 2.1. Synthesis of Block Copolymers Based on Protic Polymerized Ionic Liquids
reported in this study correspond to the overall ionic conductivity of membranes equilibrated in Milli-Q water and includes components from each of the ions present in the PIL phase.

Block copolymers based on protic PILs self-assembled into ordered nanostructures with tunable domain sizes. The systematic and independent control over the volume fraction of IL and domain size is essential for understanding the relationship between morphology and ionic conductivity in these materials. Small-angle X-ray scattering (SAXS) was used to characterize the solid-state structure of PS-b-PIL block copolymers. Melt-pressed polymer samples were thermally annealed above $T_g$ (150 °C) under vacuum (10$^{-3}$ Torr) to aid the self-assembly process while avoiding degradation. Azimuthally integrated SAXS profiles of the hydrated polymers investigated (Figure 2.2) are consistent with lamellar (LAM) morphologies, as demonstrated by the location of higher order peaks at integer values of the primary scattering peak. The primary scattering peak at $q = q^*$ enables determination of the domain spacing $d = 2\pi/q^*$ (i.e., center-to-center distance between adjacent PS domains), which varies from 23 to 68 nm. Moreover, the absence of several reflections suggests a minor degree of long-range order in the materials. Control over nanostructure orientation and structural defects (e.g., grain boundaries, disclinations, and dislocations) has been demonstrated to play a crucial role in the optimization of the ionic conductivity of block copolymers.$^{37,38}$ The size scale of the defects is set by the domain spacing, and their energetics depend on the particular defect type as well as the inherent physical properties of the polymer. Nonetheless, defects may not be important if the conducting phase is well-connected (i.e., percolated) throughout the membrane and the nanostructure strongly segregated and isotropic. Further work is necessary to establish the extent to which long-range order affects the ionic conductivity of hydrated block copolymers based on PILs.

Additional insight on the nanostructure of the PS-b-PIL can be gained from the relationship between lamellar domain spacing and the number of volumetric repeat units of the block copolymers (Figure 2.3). Generally, the interfacial properties of block copolymer melts are determined by a free energy competition between the entropic stretching of the polymer chains and the surface tension between the blocks. In particular, the lamellar domain spacing ($d$) that minimizes the free energy theoretically scales as $d \sim N^{0.67}$ in the strong-segregation limit; although the general trend that $d$ increases with the strength of segregation remains true over the entire range of $\chi N$.$^{40-42}$ The scalings experimentally obtained from a least-square regression power-law fit are $d \sim N^{0.68}$ and $d \sim N^{0.74}$ for dry and hydrated PS-b-PIL copolymers, respectively. Thus, it is evident that although the variation of domain spacing with chain length in dry PS-b-PIL copolymers is in excellent agreement with theory, the swollen materials exhibit significantly higher chain stretching than that predicted in the strong-segregation regime of block copolymer melts. This discrepancy between theory and experiment has been previously reported on hydrated block copolymers containing phosphonium moieties,$^{43}$ and we attribute it to the selective nature of water for the PIL phase.$^{44-46}$ Chain stretching at the interface has been hypothesized to affect the bulk conductivity of block copolymers because segments near the center of the domains are in relaxed configuration and provide the conducted ions with a higher mobility.$^{47}$ However, chain stretching might not affect ionic conductivity if ion transport is decoupled from the polymer dynamics, or the fraction of segments with restricted mobility near the interface is negligible.
Figure 2.2. SAXS Intensity Profiles of PS-\(b\)-PIL

PS-\(b\)-PIL with varying number of segments (N) access lamellar morphologies with tunable domain spacing (d). Profiles are offset for clarity. SAXS data collected on hydrated PS-\(b\)-PIL membranes at 30 °C.
The scaling $d \sim N^{0.74}$ demonstrates significantly higher chain stretching than that predicted by strong segregation theory. Domain spacing ($d$) determined from the primary scattering peak of the SAXS profiles of hydrated PS-$b$-PIL at 30 °C (Table 2.1)
The formation of ion clusters within the PIL phase of the self-assembled PS-b-PIL was investigated using wide-angle X-ray scattering (WAXS). Azimuthally integrated WAXS profiles of the hydrated polymers (Figure 2.4) reveal phase segregation, as demonstrated by the presence of a scattering peak at 1.4 Å⁻¹. This scattering enables determination of a trifluoroacetate anion-to-anion distance of 4.5 Å, which is independent of domain spacing. This observation is consistent with previous reports on PILs.¹⁸,²⁹,⁴⁸ Yet the absence of an inter-cluster peak at low q suggests that either ion clusters are not present in the PIL phase, or there is not sufficient electronic contrast between the ion clusters and the surrounding media to scatter X-rays. The formation of ion clusters within conducting domains is ubiquitous in ion-conducting polymers due to the presence of charged species in a low dielectric constant media.⁴⁹-⁵³ Thus, we hypothesize that in PS-b-PIL membranes there are ion clusters embedded in hydrated ion-conducting channels that percolate through the membrane and could potentially influence the ionic conductivity. In particular, it has been argued that clusters impede ion motion because ions are required to move across ion-free regions in the channels as they are transported from one cluster to the next, and Manning counter-ion condensation is increased due to the proximity of fixed protonated charged moieties.⁵⁴ The effect of ion clusters on ionic conductivity is currently the topic of an exciting debate in the literature. However, given that the length scale associated with trifluoroacetate correlations remains constant, and that there are no significant differences in the WAXS profiles, we believe the effect of clusters on bulk ion transport to be decoupled from our study.

The ion-conducting system presented in this work is designed for electrochemical devices that operate under aqueous conditions. Given that the structural stability of polymer membranes is anticipated to deteriorate with increasing water uptake⁶ but recognizing that some hydration is necessary to facilitate proton transport, it is important to design materials with controllable water content. The presence of water is also anticipated to have a significant impact on the bulk transport properties as it can be absorbed by the PIL phase while excluded from the PS. This increases the volume fraction of the conducting phase and allows for greater segmental motion of PIL polymer chains, which can ultimately enhance ionic conductivity. Due to the critical role played by water in ion conduction, the structure-property relationships of hydrated block copolymer membranes were investigated. Four lamellar block copolymer samples, described in Table 2.1, were selected to assess the effect of humidity on morphology and ionic conductivity. The use of samples with constant morphology and volume fraction of ionic liquid moieties, allows for the direct elucidation of the effect of domain spacing on conductivity. The water uptake of the membranes was determined after equilibrating melt-pressed and dried polymer membranes in Milli-Q water (T = 80 °C) for 7 days, according to previously reported procedures²⁵,⁴³ (Figure 2.5). PS-b-PIL copolymers absorb 17 wt% water corresponding to 10 water molecules per ionic liquid group (λ) which is lower than that of traditional proton conducting membranes such as Nafion (λ = 20–25)⁵⁵ and most sulfonated block copolymers (λ = 8–40).² The low water uptake is consistent with the hydrophobicity of the ionic liquid in comparison to the systems referenced above. In this work, the hydrated state of the PS-b-PIL did not depend on chain length or domain spacing. This experimental observation is consistent with phase equilibrium and has been previously reported in bromide-conducting block copolymer membranes.⁴³ In particular, if the temperature, pressure, and composition of the PS-b-PIL copolymers were held constant during the water uptake measurements, then the water content of
Figure 2.4. WAXS Intensity Profiles for PS-\(b\)-PIL

PS-\(b\)-PIL exhibits a trifluoroacetate correlation peak at 1.4 Å\(^{-1}\). The absence of an intercluster peak at low q makes inconclusive the expected formation of ion clusters within the hydrated ion-conducting channels that percolate through PS-\(b\)-PIL membranes. Profiles are offset for clarity. WAXS data collected on hydrated PS-\(b\)-PIL membranes at 30 °C.
The water content ($\lambda$, ○) and conductivity ($\sigma$, ■) in PS-\textit{b}-PIL did not have a dependence on lamellar domain spacing or chain length in the range investigated. EIS data collected on hydrated PS-\textit{b}-PIL membranes at 30 °C.
the block copolymers studied must be the same across the series due to equality of chemical potentials in the limit of high molecular weight where the virial coefficients are weak functions of chain length. The systematic and independent control achieved over volume fraction of ionic liquid and domain spacing in these PS-\(b\)-PIL ion-conducting membranes can potentially translate into tunability of their bulk transport properties. Accordingly, it is important to understand the relationship between the ionic transport and domain spacing in PS-\(b\)-PIL membranes. The ionic conductivity of block copolymers based on protic PILs was investigated using Electrochemical Impedance Spectroscopy on hydrated membranes immersed in Milli-Q water. PS-\(b\)-PIL membranes show conductivities above \(10^{-4}\) S/cm at room temperature. The results are summarized in Figure 2.5 and demonstrate that the ionic conductivity of these materials did not depend on lamellar domain spacing (i.e., error bars represent 95% confidence intervals). This observation is consistent with studies on hydrated ion-conducting block copolymers. In particular, in PIL-based block copolymer membranes the ionic conductivity has been reported to change by less than an order of magnitude over a lamellar domain spacing range of 10–70 nm, and in sulfonated block copolymers the ionic conductivity plateaus at a domain spacing of 20 nm. The comparison with hydrated sulfonated block copolymers is particularly interesting due to the similarities in the mechanism that governs proton transport, and the potential application of these membranes in electrochemical devices such as fuel cells and solar-fuels generators. In these materials, a dependence of ionic conductivity on domain spacing is only observed below 20 nm due to an interplay between morphology, hydration, and transport. In particular, Park et al. studied sulfonated polystyrene-\(block\)-polymethylbutylene copolymers and demonstrated that decreasing the size of the conducting domains below 6 nm led to remarkable increases in proton conductivity and water uptake. Possible reasons for this enhancement include elimination of ionic clusters due to confinement effects and associated reduction in Manning counter-ion condensation. Additionally, Beers et al. investigated sulfonated polystyrene-\(block\)-polyethylene and revealed that disruption of the nanostructure induced by crystallization results in lower water uptake and proton conductivity. The dependence of ionic conductivity on domain spacing in sulfonated block copolymers is only observed in the low molecular regime and the plateau achieved around 20 nm is consistent with the results reported herein.

The conductivity scaling relationship demonstrated allows for the design of membranes with improved mechanical properties without compromising conductivity, as the modulus increases with molecular weight due to entanglement effects. While a priori this result might appear inconsequential, such knowledge is critical to enable the design of functional materials for electrochemical devices operated in aqueous electrolyte. A constant \(\lambda\) and fIL in the PS-\(b\)-PIL polymers investigated suggest that ion transport could rely more strongly on the overall volume fraction of ionic liquid or the water content. These situations correspond respectively to those reported for blends of block copolymers and ionic liquids, and sulfonated block copolymers. From a nanostructure standpoint, we had anticipated defects and interfacial chain stretching to have important effects on the bulk transport properties. However, in the domain spacing range investigated these effects might not be critical. In particular, the ionic conductivity could be unaffected by domain spacing as long as the conducting phase percolates throughout the membrane and the nanostructure is strongly segregated and isotropic. Moreover, if the number of segments near interfaces only constitutes a negligible percentage of the PIL phase, then the ion
mobility will be independent of chain length. Further work is necessary to establish the extent to which overall volume fraction of ionic liquid, water content, structural defects, and interfacial stretching dictate the structure-conductivity relationships of block copolymer membranes based on protic PILs in aqueous electrolyte.

2.4. Conclusions

We present a system of block copolymer membranes based on protic PILs that exhibit low water uptake ($\lambda \approx 10$) and ionic conductivity above $10^{-4}$ S/cm. The water content in these materials can afford membranes with improved structural properties that in principle mitigate the transport of uncharged molecules through hydrated channels (i.e. H$_2$ and O$_2$) without compromising ionic conductivity. The PS-$b$-PH copolymers presented here are readily transformed into a PIL with tethered protic ionic liquids, which can improve the stability of ion-conducting membranes by preventing ions from leaching to an aqueous electrolyte. The synthetic strategy used to prepare the PS-$b$-PIL copolymers allows for systematic and independent control over the overall volume fraction of ionic liquid and lamellar domain spacing as dictated by the polymer chain length. Thus, a well-defined series of block copolymers was studied to elucidate the effect of domain spacing on ion-conduction. We found that the ionic conductivity is independent of domain spacing. This suggests that other properties of the block copolymer (e.g., water content, and volume fraction of ionic liquid) might be the variables that dictate the ion transport in these materials. The ion-conducting membranes described herein have potential for electrochemical devices that operate at low current densities (e.g. solar-fuels generators) where moderate ion conduction and low product crossover are required. The insights gained by this work could facilitate the development of design rules for the next generation of high performance ion-conducting membranes.

2.5. Acknowledgements

We gratefully acknowledge Dr. Eric Schaible, Polite Stewart, and Chenhui Zhu for experimental assistance at the ALS. The authors also thank Prof. Nitash P. Balsara, Prof. Karen I. Winey, Prof. Andrew Herring, Dr. Adam Z. Weber, Dr. Pepa Cotanda, Dr. Daniel J. Miller, Dr. Miguel Modestino, and Christina Rodriguez for helpful discussions. Beamline 7.3.3 of the Advanced Light Source is supported by the Director of the Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. The synthesis and molecular characterization of PS-$b$-PIL was performed at the Joint Center for Artificial Photosynthesis, a DOE Energy innovation Hub, supported through the Office of Science of the U.S. Department of Energy under Award No. DE-SC0004993. The physical characterization of PS-$b$-PIL and data analysis was supported by the AFOSR MURI program under FA9550-12-1. The ionic conductivity and water uptake measurements were performed at the Materials Research Laboratory, a facility supported by the MRSEC Program of the National Science Foundation under Award No. DMR 1121053. Work by Bryan S. Beckingham and Nathaniel A. Lynd was supported by the California Energy Commission (CEC) under contract 500-11-23.

2.6. Appendix. $^1$H NMR, $^{13}$C NMR, GPC, conductivity data, and other information
Figure A 2.1. Gel Permeation Chromatography of PS-b-PB calibrated against polystyrene standards

The polydispersity ($D = M_w/M_n$) was lower than 1.2 in the block copolymers synthesized. This is consistent with the living nature of the sequential anionic polymerization of styrene and butadiene.
Figure A 2.2. $^1$H NMR of PS-$b$-PB in CDCl$_3$ for SIL22.7

End-group analysis yields the number of repeat units of styrene and butadiene.
Figure A 2.3. $^1$H NMR of PS-$b$-PB in CDCl$_3$ for SIL36.3

End-group analysis yields the number of repeat units of styrene and butadiene.
Figure A 2.4. $^1$H NMR of PS-$b$-PB in CDCl$_3$ for SIL51.2

End-group analysis yields the number of repeat units of styrene and butadiene.
Figure A 2.5. $^1$H NMR of PS-$b$-PB in CDCl$_3$ for SIL58.9

End-group analysis yields the number of repeat units of styrene and butadiene.
Table A 2.1. Properties of PS-\textit{b}-PB as determined from $^1$H NMR

<table>
<thead>
<tr>
<th>Polymer$^a$</th>
<th>N$_S$</th>
<th>N$_{B-1,2}$</th>
<th>N$_{B-1,4}$</th>
<th>1,2</th>
<th>M$_n$ (kg/mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB22.7</td>
<td>108</td>
<td>26</td>
<td>6</td>
<td>81.3</td>
<td>12.98</td>
</tr>
<tr>
<td>SB36.3</td>
<td>213</td>
<td>54</td>
<td>13</td>
<td>80.6</td>
<td>25.81</td>
</tr>
<tr>
<td>SB51.2</td>
<td>327</td>
<td>85</td>
<td>22</td>
<td>79.4</td>
<td>39.84</td>
</tr>
<tr>
<td>SB58.9</td>
<td>413</td>
<td>109</td>
<td>25</td>
<td>81.3</td>
<td>50.26</td>
</tr>
</tbody>
</table>

$^a$Polymers are labeled SBXX.X, where XX.X is the lamellar domain spacing of the PS-\textit{b}-PIL derived from the corresponding PS-\textit{b}-PB precursor.
Figure A 2.6. $^1$H NMR of His-SH in CD$_3$OD
Figure A 2.7. $^{13}$C NMR of His-SH in CD$_3$OD
Figure A 2.8. Gel Permeation Chromatography of PS-b-PH calibrated against polystyrene standards

The polydispersity ($D = M_w/M_n$) was lower than 1.2 in the block copolymers synthesized. The absence of a significant coupling peak demonstrates that no cross-linking occurs in the functionalization of PS-b-PB with His-SH vial thiol-ene click chemistry.
Figure A 2.9. $^1$H NMR of PS-$b$-PH in DMF-d$_7$ for SIL22.7

Integrals yield the conversion of 1,2 polybutadiene with His-SH.
Figure A 2.10. $^1$H NMR of PS-$b$-PH in DMF-d$_7$ for SIL36.3

Integrals yield the conversion of 1,2 polybutadiene with His-SH
Figure A 2.11. $^1$H NMR of PS-$b$-PH in DMF-d$_7$ for SIL51.2

Integrals yield the conversion of 1,2 polybutadiene with His-SH
Figure A 2.12. $^1$H NMR of PS-b-PH in DMF-d$_7$ for SIL58.9

Integrals yield the conversion of 1,2 polybutadiene with His-SH
Table A 2.2. Properties of PS-b-PH as determined from $^1$H NMR

<table>
<thead>
<tr>
<th>Polymer$^a$</th>
<th>% Conversion</th>
<th>$N_S$</th>
<th>$N_H$</th>
<th>$N_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SH22.7</td>
<td>93.9</td>
<td>108</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>SH36.3</td>
<td>95.2</td>
<td>213</td>
<td>51</td>
<td>16</td>
</tr>
<tr>
<td>SH51.2</td>
<td>97.50</td>
<td>327</td>
<td>83</td>
<td>24</td>
</tr>
<tr>
<td>SH58.9</td>
<td>98.0</td>
<td>413</td>
<td>107</td>
<td>27</td>
</tr>
</tbody>
</table>

$^a$Polymers are labeled SHXX.X, where XX.X is the lamellar domain spacing of the PS-b-PIL derived from the corresponding PS-b-PH precursor.
2.6.1 Elemental Analysis of PS-b-PIL

Elemental analysis of SIL22.7 yields: 74.15 % C, 7.01 % H, 2.84 % N, and 6.34 % F, as determined by Elemental Analysis, Inc. This result is consistent with that anticipated from $^1$H NMR: 72.39 % C, 6.98 % H, 4.84 % N, and 6.56 % F.

Elemental analysis of SIL58.9 yields: 72.71 % C, 7.08 % H, 3.01 % N, and 7.70 % F, as determined by Elemental Analysis, Inc. This result is consistent with that anticipated from $^1$H NMR: 70.64 % C, 6.89 % H, 5.27 % N, and 7.15 % F.
Table A 2.3. Calculation of Volume Fractions of Block Copolymers Based on Protonic PILs

<table>
<thead>
<tr>
<th>Polymer</th>
<th>$M_n$ (kg/mol)$^b$</th>
<th>$\nu$ (nm$^3$)$^c$</th>
<th>$\nu_S$ (nm$^3$)$^d$</th>
<th>$\nu_B$ (nm$^3$)$^e$</th>
<th>$f_{IL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIL22.7</td>
<td>20.8</td>
<td>29.6</td>
<td>17.82</td>
<td>0.888</td>
<td>0.37</td>
</tr>
<tr>
<td>SIL36.3</td>
<td>42.5</td>
<td>60.5</td>
<td>35.15</td>
<td>1.78</td>
<td>0.39</td>
</tr>
<tr>
<td>SIL51.2</td>
<td>66.6</td>
<td>94.8</td>
<td>53.96</td>
<td>2.66</td>
<td>0.40</td>
</tr>
<tr>
<td>SIL58.9</td>
<td>85.3</td>
<td>121.4</td>
<td>68.15</td>
<td>3.00</td>
<td>0.41</td>
</tr>
</tbody>
</table>

$^a$Polymers are labeled SILXX.X, where XX.X is the lamellar domain spacing in nm. $^b$Determined via $^1H$ NMR end-group analysis. $^c$Determined using a density of 1.167 g/cm$^3$ as measured with a helium AccuPyc II 1340 Pycnometer. $^d$Determined using a polystyrene monomer volume of 0.165 nm$^3$. $^e$Determined using a polybutadiene monomer volume of 0.111 nm$^3$.35
<table>
<thead>
<tr>
<th>Polymer&lt;sup&gt;a&lt;/sup&gt;</th>
<th>q (nm&lt;sup&gt;-1&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>d (nm)&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Morphology</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIL22.7</td>
<td>0.277</td>
<td>22.7</td>
<td>LAM</td>
</tr>
<tr>
<td>SIL36.3</td>
<td>0.173</td>
<td>36.3</td>
<td>LAM</td>
</tr>
<tr>
<td>SIL51.2</td>
<td>0.123</td>
<td>51.2</td>
<td>LAM</td>
</tr>
<tr>
<td>SIL58.9</td>
<td>0.107</td>
<td>58.9</td>
<td>LAM</td>
</tr>
</tbody>
</table>

<sup>a</sup>Polymer are labeled SILXX.X, where XX.X is the lamellar domain spacing in nm.  
<sup>b</sup>Determined from the primary scattering peak of the SAXS profiles.  
<sup>c</sup>Determined using the following equation: \( d = \frac{2\pi}{q} \).
Table A 2.5. Calculation of the Ionic Conductivity of Block Copolymers based on Proti PILs

<table>
<thead>
<tr>
<th>Polymer&lt;sup&gt;a&lt;/sup&gt;</th>
<th>L(cm)</th>
<th>t (μm)</th>
<th>W (cm)</th>
<th>R (kΩ)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>σ x 10^-4 (S/cm)&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIL22.7</td>
<td>0.350</td>
<td>165</td>
<td>1.30</td>
<td>56.7</td>
<td>2.90</td>
</tr>
<tr>
<td>SIL36.3</td>
<td>0.350</td>
<td>210</td>
<td>1.16</td>
<td>34.2</td>
<td>4.20</td>
</tr>
<tr>
<td>SIL51.2</td>
<td>0.350</td>
<td>197</td>
<td>1.30</td>
<td>42.9</td>
<td>3.20</td>
</tr>
<tr>
<td>SIL58.9</td>
<td>0.350</td>
<td>203</td>
<td>1.04</td>
<td>57.6</td>
<td>2.90</td>
</tr>
</tbody>
</table>

<sup>a</sup>Polymers are labeled SILXX.X, where XX.X is the lamellar domain spacing in nm. <sup>b</sup>Determined from the high x-intercept of a Nyquist plot (i.e., negative imaginary part of the complex impedance, -Z', versus the real part of the impedance, Z'). <sup>c</sup>Determined using the following equation: \( \sigma = \frac{1}{RWt} \).
### Table A.2.6. Calculation of Water Uptake of Block Copolymers Based on Protic PILs

<table>
<thead>
<tr>
<th>Polymer&lt;sup&gt;a&lt;/sup&gt;</th>
<th>(m_{\text{dry}}) (mg)</th>
<th>(m_{\text{wet}}) (mg)</th>
<th>(m_{\text{water}}) (mg)</th>
<th>(%_{\text{water}})</th>
<th>(n_{\text{water}} \times 10^{-5}) (mol)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>(n_{\text{IL}} \times 10^{-5}) (mol)&lt;sup&gt;c&lt;/sup&gt;</th>
<th>(\lambda)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIL22.7</td>
<td>71.5</td>
<td>87.3</td>
<td>15.8</td>
<td>18.1</td>
<td>87.8</td>
<td>8.43</td>
<td>10</td>
</tr>
<tr>
<td>SIL36.3</td>
<td>67.4</td>
<td>81.7</td>
<td>14.3</td>
<td>17.5</td>
<td>79.4</td>
<td>7.95</td>
<td>10</td>
</tr>
<tr>
<td>SIL51.2</td>
<td>72.6</td>
<td>87.9</td>
<td>15.3</td>
<td>17.4</td>
<td>84.9</td>
<td>8.57</td>
<td>10</td>
</tr>
<tr>
<td>SIL58.9</td>
<td>58</td>
<td>69.7</td>
<td>11.7</td>
<td>16.8</td>
<td>64.9</td>
<td>6.84</td>
<td>9</td>
</tr>
</tbody>
</table>

<sup>a</sup>Polymers are labeled SILXX.X, where XX.X is the lamellar domain spacing in nm. <sup>b</sup>Determined from the molecular weight of water 18.02 g/mol. <sup>c</sup>Determined from the mass fraction (45 wt%) and the molecular weight 381.41 g/mol of ionic moieties.
2.7.  References


Chapter 3. Magnetic and Biocompatible Polymers as \( ^1 \text{H} \) Nuclei Relaxation Agents for Magnetic Resonance Imaging


Magnetic and biocompatible polymers are essential for applications ranging from medical diagnostics to therapeutics. These materials can yield novel theranostic agents with controlled residence time within the human body, and paramagnetic functionality to enhance the \( ^1 \text{H} \) nuclei relaxation rate required for magnetic resonance imaging (MRI). Herein, we present a novel statistical copolymers, PEG-stat-PIL, that synergistically combines the low toxicity and structural hierarchy of poly(ethylene glycol) (PEG) with the magnetic functionality of a polymerized ionic liquid based on trichlorobromoferrate(III) anions and tethered imidazolium cations \((x_{IL} = 0.09)\). PEG-stat-PIL exhibits a \( ^1 \text{H} \) relaxivity \((r_1 \approx 2.42 \text{ L.mmol}^{-1}.\text{s}^{-1} \text{ at } 37^\circ \text{C})\) comparable with clinically relevant contrast agents based on paramagnetic metal complexes; and a cytotoxicity similar to that of PEG at concentrations below 0.5 mg.mL\(^{-1}\). The magnetic and biocompatible nature of PEG-stat-PIL afford sufficient contrast enhancement in water demonstrating the material to be promising for novel theranostic agents; as it can be imaged by MRI while used for localized targeting.

3.1. Introduction

Polymerized Ionic Liquids (PILs) are an emerging class of functional materials with ionic liquid moieties covalently attached to a polymer backbone.\(^1\) As such, they synergistically combine the structural hierarchy of polymers with the versatile physicochemical properties of ionic liquids. PILs have been of interest for gas separation\(^2\) and electrochemical energy conversion\(^3\) due to the CO\(_2\) solubility, ionic conductivity, and thermal and electrochemical stability intrinsic to ionic liquids.\(^4\) However, the ability to incorporate functionality through ionic liquid chemistry while retaining polymer properties turns PILs into a powerful platform for developing novel functional materials.

Polymers based on imidazolium salts are a particularly exciting due to the stability of a positive charge delocalized in an aromatic ring which is covalently bonded to the polymer backbone and electrostatically associated with an anion.\(^5\) Investigations on PILs have primarily focused on imidazolium bis(trifluoromethylsulfonyl)imide moieties and their response in the presence of an external electric field.\(^6-9\) However, imidazolium trichlorobromoferrate(III) moieties \((\text{ImFeCl}_3\text{Br})\) represent a promising chemistry for magnetic PILs due to the paramagnetic nature of the iron(III) atoms contained in the anion. These materials would constitute the macromolecular analogue of 1-butyl-3-methylimidazolium trichlorobromoferrate(III) \(([\text{bmim}][\text{FeCl}_3\text{Br}])\), a paramagnetic room temperature magnetic ionic liquid in which a fraction of the magnetic moments intrinsic to the iron(III) align in the direction of an external magnetic field for all practical field strengths.\(^10\) These magnetic PILs are particularly exciting for applications that require spin coupling with \( ^1 \text{H} \) nuclei, such as contrast agents for MRI.

Although magnetic polymers are important for applications ranging from medical therapeutics, magnetorheological fluids,\(^11\) and organic electronics;\(^12\) there are limited examples
of magnetic PILs reported in the literature. In particular, cross-linked poly(1-vinyl-3-butylimidazolium tetrachloroferrate(III)) was used as a recyclable heterogeneous catalyst for Friedel-Crafts alkylation of toluene with benzyl chloride making the material attractive for environmentally friendly chemical processes. More recently, magnetic polymers have been investigated as novel functional materials for thermosets, and latexes and coatings. Nonetheless, applications exploiting the spin coupling of magnetic PILs with $^1$H nuclei in aqueous solutions, such as MRI contrast agents, are yet to be demonstrated.

The development of MRI contrast agents requires a fundamental understanding of nuclear relaxation rates in aqueous solutions of stable nontoxic materials. From a biological standpoint, it is also essential to achieve control over the blood circulation time, magnetic environment within tissue, and cytotoxicity. Traditional materials are based on paramagnetic metal complexes (e.g., gadolinium) or iron oxide nanoparticles with unknown toxicity, distribution, stability, and excretability. Magnetic and biocompatible PILs are promising theranostic agents for MRI because they combine the intrinsic mesoscopic structure of polymers with the low toxicity and spin necessary to affect the $^1$H nuclei spin-lattice relaxation rate and thus enhance magnetic contrast. These materials, when in solution, adopt an ensemble of configurations on length scales of 10-100 nm determined by the size and architecture of the polymer chain. The resulting hydrodynamic volume and fraction of magnetic ionic liquid moieties dictate the material residence time of the within the human body, magnetism, and toxicity.

Herein, we report the development of a novel magnetic and biocompatible statistical copolymer, PEG-stat-PIL, based on a poly(ethylene glycol) backbone and a polymerized ionic liquid containing ImFeCl$_3$Br moieties. We present a molecular design strategy based on a combination of epoxide ring opening polymerization, thiol-ene click chemistry, and simple ion exchange that allows for control over the chemical structure of the polymer and guarantees scalability. PEG-stat-PIL significantly impacts the magnetic environment experienced by the $^1$H nuclei of water, as revealed by a decrease over an order of magnitude in the spin-lattice relaxation time in aqueous polymer solution. The $^1$H relaxivity ($r_1$) is 2.42 L.mmol$^{-1}$.s$^{-1}$ which is comparable to that reported for paramagnetic metal complexes used in clinical settings. Cytotoxicity assays on breast epithelial cells MCF-10a and hemolysis of red blood cells isolated from BALB/c mice demonstrate a low toxicity of PEG-stat-PIL, comparable to that of PEG, at concentrations below 0.5 mg.mL$^{-1}$. The structure-property relationships elucidated herein demonstrate that PEG-stat-PIL is suitable as a $T_1$-weighted MRI contrast agent. The magnetic and biocompatible nature of this material, within the concentration range determined, is promising for development of novel theranostic agents based on polymers conjugated to drugs, proteins, and antibodies that exhibit controlled residence time within the human body; and magnetic functionality for imaging.

3.2. Experimental Methods

Materials. All materials were used as received from Sigma-Aldrich unless otherwise noted. CDCl$_3$ and D$_2$O were purchased from Cambridge Isotope Laboratories; acetonitrile, hexanes, methanol, and isopropyl alcohol from BDH Chemicals; and allyl glycicyl ether (AGE) from TCI America. Tetrahydrofuran (THF) was collected from a commercial J. C. Meyer dry solvent system and used immediately thereafter. AGE was dried over butyl magnesium chloride,
degassed through three freeze-pump-thaw cycles, and further purified by distillation to a flame-dried receiving flask. Ethylene oxide (EO) was degassed through three freeze-pump-thaw cycles, and then vacuum transferred to a flame-dried buret kept at 0 °C until immediately prior to use. Potassium naphthalenide was prepared from potassium metal and naphthalene in dry THF and allowed to stir with a glass-coated stir bar for 24 h at room temperature before use.

**Synthesis of N-(3-(1H-Imidazol-1-yl)propyl)4-mercaptobutanamide (Im-SH).** The synthesis of Im-SH was adapted from Lundberg et al. In a 250 mL round-bottom flask equipped with a Teflon-coated stir bar and a condenser, 10.0 (79.9 mmol) of 1-(3-aminopropyl)imidazole, 8.2 (80.2 mmol) of γ-thiobutyrolactone, and 135 mL of acetonitrile were added. The reaction mixture was heated to 95 °C using a heating mantle, and the reaction was allowed to proceed for 12 h. The reaction was cooled to room temperature, and the resulting pale yellow liquid isolated by evaporation in vacuo.

**Synthesis of Poly(ethylene oxide-stat-allyl glycidyl ethyl) (PEG-stat-PAGE).** The copolymerization of EO and AGE was adapted from Lee et al. Separate burets containing THF and EO were connected to a thick-walled glass reactor fitted with Ace threads. The EO was connected by a flexible, stainless steel bellows so that the buret could be held in an ice bath until use. The reactor assembly was flame dried and then cycled between vacuum and positive argon pressure (5 psig) three times. The reactor was finally charged with an argon atmosphere and then isolated from the Schlenk line. THF was added, and the temperature equilibrated at 0 °C. Based on the amount of purified EO (5.08 g, 115 mmol), a quantity of benzyl alcohol (21 μL, 0.203 mmol) was added through a gastight syringe. Potassium naphthalenide (0.3 M in THF) was added through a gastight syringe to titrate the benzyl alcohol until a pale green endpoint. EO was added by lifting the cold buret and allowing monomer to drain in the reactor while AGE (1.12 g, 9.8 mmol) was simultaneously added via gastight syringe. The temperature was increased to 40 °C, and the polymerization was allowed to proceed for 24 h. After incomplete conversion of EO and AGE monomers, degassed and acidified isopropyl alcohol was added to terminate the polymerization. The resulting PEG-stat-PAGE was precipitated into an excess of hexanes, and dried in vacuo.

**Synthesis of Imidazole Functionalized Statistical Copolymer (PEG-stat-PIm).** In a 50 mL Schlenk flask equipped with a Teflon-coated stir bar, PEG-stat-PAGE (1.00 g, 1.84 mmol of allyl groups), Im-SH (2.09 g, 9.19 mmol), 2,2-dimethoxy-2-phenylacetophenone (DMPA, 0.08 g, 0.31 mmol) and THF (18 mL) were added. The solution was degassed through three freeze-pump-thaw cycles and then allowed to react for 2 h under UV irradiation (λ = 365 nm). The resulting PEG-stat-PIm was concentrated by rotary evaporation, dissolved in water, purified by dialysis (7 x 1 L), and lyophilized in vacuo for 8 h to yield a white rubbery solid.

**Quaternization of PEG-stat-PIm with 1-Bromoethane (PEG-stat-PImBr).** In a 250 mL round-bottom flask equipped with a Teflon-coated stir bar, PEG-stat-PIm (1.00 g, 1.97 mmol of Im groups), bromoethane (0.43 g, 3.95 mmol), and a solvent mixture of THF and methanol (1:1, 20 mL) were added. The reaction was heated to 70 °C using a heating mantle and allowed to proceed for 24 h. The resulting PEG-stat-PImBr was cooled to room temperature, concentrated by rotary evaporation, stabilized with 3,5-di-tert-4-butylhydroxytoluene (BHT, 2.8 mg), precipitated in hexanes, decanted, and dried in vacuo.
Synthesis of Statistical Copolymer Based on a Magnetic Polymerized Ionic Liquid (PEG-stat-PIL). The synthesis of PEG-stat-PIL was adapted from Döbbelin et al. In a 20 mL vial equipped with a Teflon-coated stir bar, PEG-stat-PImBr (200 mg, 0.235 mmol of Br) and iron(III) chloride (FeCl$_3$, 38 mg, 0.235 mmol) were dissolved in methanol (2.5 mL). The solution was stirred overnight, and the resulting PEG-stat-PIL was collected by evaporation in vacuo.

Molecular Characterization. Gel permeation chromatography (GPC) was performed on a Waters instrument using a refractive index detector and Agilent PL gel 5 μm MiniMIX-D column. THF at 35 °C was used as the mobile phase with a flow rate of 1.0 mL.min$^{-1}$. Polydispersity index (Đ) was determined against PEG narrow standards (Agilent). $^1$H NMR spectra were collected on a Bruker Avance DMX 500 MHz. Copolymers molecular weights ($M_n$) were determined using $^1$H NMR end-group analysis.

Spin-Lattice Relaxation Time ($T_1$) of PEG-stat-PIL with a $^1$H NMR Inversion Recovery Pulse Sequence. $^1$H NMR spectra were collected on a Bruker Avance DMX 500 MHz. The pulse sequence begins with a recycle delay ($\tau$) that is sufficiently long to ensure that all magnetization returns to equilibrium (i.e., pure $z$-magnetization). A $\pi$ pulse is applied which inverts the magnetization. The recovery delay follows to allow varying degrees of $T_1$ relaxation (depending on the value of the recovery delay time). The final $\pi/2$ pulse then converts any $z$-magnetization into observable transverse magnetization, which is detected during the acquisition period immediately following the final pulse. Notice that if the recovery delay time is very short, the pulse sequence is equivalent to a recycle delay of $3\tau/2$, and the detected signal has full, negative intensity. On the other hand, if the recycle delay is very long, full $T_1$ relaxation occurs between $\pi$ and $\pi/2$ pulses, and the detected signal has full positive intensity. $T_1$ can be determined by repeating the experiment with several different recovery delay values, processing the results identically, and plotting peak intensity with respect to recovery delay time. The resulting curve can be fit to the following expression with time constant $T_1$:  

$$ M(\tau) = M_o \left(1 - 2exp\left(-\frac{\tau}{T_1}\right)\right) $$

Where $M(\tau)$ is the nuclear spin magnetization, $M_o$ is the nuclear spin magnetization at thermal equilibrium, and $T_1$ is the spin-lattice relaxation time.

Cytotoxicity of PEG-stat-PIL on Breast Epithelial Cells MCF-10a. MCF-10a cells (ATCC) were cultured in MEGM complete media (excluding GA-1000) supplemented with 100 ng.mL$^{-1}$ cholera toxin in an incubator at 37 °C and 5% CO$_2$. For cell viability assays, MCF-10a cells were seeded at a density of 7500 cells per well in a 96-well plate. After incubating overnight, media was aspirated and varying amounts of PEG or PEG-stat-PIL of the same degree of polymerization were added. Following 2 days of incubation with the polymers, media was replaced with MTT reagent (0.5 mg.mL$^{-1}$). After incubating for 4 h, media was aspirated and replaced with DMSO, and plates were shaken for 30 min. Absorbance values at 570 nm were used to determine cell viability.

Hemolysis of PEG-stat-PIL on Red Blood Cells. Red blood cells were isolated from mouse. Whole blood was collected using cardiac puncture after euthanizing healthy female
BALB/c mice with an overdose of carbon dioxide, and further stored in tubes coated with heparin to prevent coagulation. The whole blood was diluted (1:20) in citrate buffer (pH = 7.4, 0.109 M) followed by centrifugation at 100 g for 5 min. The resulting red blood cells were washed (3x) by removing the supernatant and re-suspending in the same original volume of citrate buffer.

For the hemolysis study, 200 μL of the re-suspended red blood cells were mixed with 100 μL of each sample. PEG-stat-PIL and PEG were initially dissolved in PBS buffer at 10 mg.mL\(^{-1}\) and diluted in citrate buffer to yield final concentrations of 1, 0.1, and 0.01 mg.mL\(^{-1}\) in the cell solution. A solution of Triton X-100 (0.1 %) was used as the positive control to induce complete hemolysis and a solution of PBS and citrate buffer (1:9) was used as a negative control. Samples were rotated at 37 °C for 1 h to induce lysis and then centrifuged at 200 g for 5 min. The absorbance of the supernatant was measured at 540 nm to determine the degree of hemolysis.

3.3. Results and Discussion

The development of MRI contrast agents requires control over the blood circulation time, magnetic environment within tissue, and cytotoxicity. These properties are ultimately dictated by the hydrodynamic volume and magnetism of the contrast agent; which can be tuned in polymers through the number of segments (N), fraction of magnetic ionic liquid moieties (x_{IL}), and architecture of the chain. Herein, a combination of anionic ring opening copolymerization of epoxides,\(^{23, 25-26}\) thiol-ene click chemistry,\(^{27}\) and simple PIL ion exchange is used to achieve fine and independent control over N, x_{IL}, and architecture through the monomer to initiator ratio, the relative amounts of monomers, and the degree of branching of the initiator. The incorporation of an ionic liquid anion based on iron(III), a transition metal with partially filled d-orbitals, provides the material with the required spin to affect the \(^1\)H nuclear relaxation rate in aqueous solution and generate contrast. The strategy presented herein can be adopted for the development of polymers with functionality beyond magnetism by simple ion exchange. It is this vast set of ion pair combinations in ionic liquids that provides a unique opportunity to develop PILs with numerous applications where properties can be controlled with subtle changes in molecular structure.

To demonstrate a novel magnetic and biocompatible polymer MRI contrast agent, PEG-stat-PIL, was prepared following the scheme presented in Figure 3.1. First, the imidazole functionalized copolymer (PEG-stat-PIm) was synthesized using ring opening anionic copolymerization of EO and AGE, followed by UV activated thiol-ene click chemistry of Im-SH. PIm was chosen as a PIL precursor due to the remarkable stability previously reported for the alkyl-substituted N-vinylimidazolium bromide that results from nucleophilic substitution with ethyl bromide.\(^{28}\) Next, the resulting PEG-stat-PImBr was treated with FeCl\(_3\) to generate PEG-stat-PIL. This material responds to an external magnetic field due to the paramagnetic properties intrinsic to ionic liquids containing anions based on iron(III). Well-defined and narrowly dispersed PEG-stat-PIL was obtained (M\(_n\) = 40 kDa, D < 1.1) with mole fraction of ionic liquid (x_{IL} = 0.09), as determined using a combination of Gel Permeation Chromatography (GPC) and \(^1\)H Nuclear Magnetic Resonance (NMR).

The poly(ethylene glycol) backbone, a key component in a variety of polymer-based drug delivery therapies,\(^{29}\) provides PEG-stat-PIL with the low toxicity necessary for MRI. Given the trade-off between magnetic contrast and toxicity of a contrast agent, it is important to understand cytotoxicity in solutions of PEG-stat-PIL. The toxicity of PEG-stat-PIL was investigated with
Figure 3.1. Synthesis of Magnetic and Biocompatible Polymer
Figure 3.2. Toxicity of PEG-stat-PIL and PEG

(a) On breast epithelial cell line MCF-10a after incubation for 48 h, and (b) red blood cells from BLB/c mice after incubation for 1 h. At concentrations below 0.5 mg.mL\(^{-1}\), PEG-stat-PIL is biocompatible as it does not influence cellular proliferation of breast epithelial cells nor induce lysis of red blood cells. Cell viability assays performed at 37 °C. Error bars represent 95% confidence intervals.
cell viability assays on human breast epithelial cell line MCF-10a and hemolysis of red blood cells isolated from BALB/c mice. The results are summarized in Figure 3.2 and demonstrate that PEG-stat-PIL exhibits a similar toxicity to PEG at concentrations below 0.5 mg.mL\(^{-1}\) (i.e., 0.5 mM FeCl\(_3\)Br\(^{-}\)). Notice that PEG is the gold standard polymer for therapeutics due to its influence on the pharmacokinetic properties of drugs and drug carriers. Therefore, the demonstrated magnetic and biocompatible PEG-stat-PIL, within the concentration range determined, could be a critical component of novel theranostic agents based on polymers conjugated to drugs, proteins, and antibodies that exhibit controlled blood circulation times; and magnetic functionality for imaging. Evidently, the acute and chronic toxicity of a MRI contrast agent is related in part to its stability in vivo and tissue clearance behavior. The transition-metal ions and ligands are relatively toxic at doses required for changes in the spin-lattice relaxation time. Thus, the dissociation of the FeCl\(_3\)Br\(^{-}\) moieties cannot occur to any significant degree prior excretion. Further work is necessary to establish the in vivo stability and excretion of PEG-stat-PIL, yet we anticipate tunability over these macroscopic properties as a consequence of the structural control over the number of segments, fraction of magnetic ionic liquid moieties, and polymer architecture.

PEG-stat-PIL exhibits a paramagnetic response under the influence of an external magnetic field. The incorporation of iron(III) with partially filled d-orbitals provides PEG-stat-PIL with the spin necessary to affect the magnetic environment experienced by the \(^1\)H nuclei of water, and generate contrast for MRI. Given that contrast enhancement arises due to changes in the spin-lattice relaxation time (\(T_1\)) of the \(^1\)H nuclei of water, it is important to understand changes in \(^1\)H relaxation in aqueous solutions of PEG-stat-PIL. The spin-lattice \(^1\)H relaxation time of PEG-stat-PIL was investigated using an inversion recovery NMR pulse sequence. The resulting exponential curves, with time constant \(T_1\),\(^{24}\) are presented in Figure 3.3 and demonstrate that addition of paramagnetic PEG-stat-PIL causes a decrease in the spin-lattice relaxation time of \(^1\)H water nuclei from 14.00 to 5.93 s at a physiologically relevant concentration of 0.5 mg.mL\(^{-1}\) (i.e., 0.5 mM FeCl\(_3\)Br\(^{-}\)). Notice that only a fraction of the effect of PEG-stat-PIL on \(T_1\) is attributed to the presence of an anion containing iron(III) as the precursor PEG-stat-PImBr only changes \(T_1\) from 14.00 to 12.05 s at a similar concentration of 0.5 mg.mL\(^{-1}\) (i.e., 0.6 mM Br\(^{-}\)) (Supporting Information). This observation is consistent with the standard theory (i.e., fast exchange model) describing solvent nuclear relaxation times in the presence of dissolved paramagnetic substances.\(^{30-32}\) The large and fluctuating local magnetic field in the vicinity of a paramagnetic ImFeCl\(_3\)Br center provides an additional relaxation pathway for \(^1\)H nuclei. Due to the short-range spatial nature of these fields, the change in \(T_1\) will be dictated by random translational diffusion of solvent molecules and the ionic liquid moieties as well as intermolecular interactions that bring the solvent molecules near the iron(III). Nonetheless, as opposed to aqueous solutions of inorganic salts based on iron(III), the Brownian motion contributions to the paramagnetic relaxation rate are anticipated to be related to the dynamics of polymers in solution under an external magnetic field. Further work is necessary to elucidate the differences in nuclear relaxation mechanism between PILs and inorganic salts, yet the reported order of magnitude decrease in \(T_1\) demonstrates PEG-stat-PIL to be promising as a \(T_1\)-weighted MRI contrast agent.

The magnetic and biocompatible PIL exhibits an efficiency to enhance \(^1\)H nuclei relaxation rates of water comparable to that of clinically relevant extracellular contrast agents.
PEG-stat-PIL significantly influences the magnetic environment of $^1$H nuclei of H$_2$O. The spin-lattice relaxation times ($T_1$) experimentally obtained from a least-squares regression exponential fit are $14.00 \pm 0.72$ s, and $5.93 \pm 1.54$ s for H$_2$O, and PEG-stat-PIL, respectively. The intensity corresponds to $^1$H nuclei in H$_2$O (4.79 ppm). $^1$H NMR data collected on O$_2$-free H$_2$O and D$_2$O (1:4), polymer concentration of 0.5 mg.mL$^{-1}$, and temperature of 37 °C. Errors for $T_1$ represent 95% confidence intervals.

Figure 3.3. $^1$H NMR Magnetization of H$_2$O and PEG-stat-PIL
Figure 3.4. Relaxation Rate of Paramagnetic PEG-stat-PIL

PEG-stat-PIL enhances the $^1$H nuclei relaxation rates of water with an efficiency comparable to that of most clinically relevant extracellular contrast agents even at low concentration. The relaxivity obtained from a least-squares regression linear fit is $2.42 \pm 0.25 \text{ L.mmol}^{-1}\text{s}^{-1}$ ($R^2 = 0.99$). Relaxation rate determined on O$_2$-free H$_2$O and D$_2$O (1:4), and temperature of 37°C. Error bars represent 95% confidence intervals.
even at low concentrations, as illustrated in Figure 3.4. Generally, relaxation chemistry can be considered within a fast exchange model which assumes all \(^1\)H nuclei that contribute to the NMR intensity to have unhindered and similar access to the paramagnetic center on a time scale less than the \(T_1\) relaxation time of \(^1\)H nuclei in water.\(^{30-32}\) Evidently, this is a strong approximation in biological tissues based on concentrated colloidal solutions containing proteins, carbohydrates, nucleic acids, and salts. Nonetheless, the fast exchange model constitutes a good starting point to explain basic phenomena involving MRI contrast agents in solution. In this framework, the relaxation rate of the \(^1\)H nuclei of water is given by Equation 1

\[
\frac{1}{T_1} = \frac{1}{T_{1,o}} + r_1 c \quad (3.1)
\]

where \(T_{1,o}\) is the spin-lattice relaxation time in the absence of PEG-stat-PIL, \(r_1\) is the specific relaxivity of the paramagnetic agent, and \(c\) is the concentration. The relaxivity experimentally obtained from a least-squares regression linear fit is 2.42 L.mmol\(^{-1}\).s\(^{-1}\) and is similar to most contrast agents based on paramagnetic metal complexes (3-5 L.mmol\(^{-1}\).s\(^{-1}\)).\(^{21}\) This translates into sufficient enhancement of spin-lattice relaxation rate for imaging, though this is strongly dependent on the pre-contrast solution relaxation rate. Notice that even though it is unclear whether \(T_{1,o}\) should be that corresponding to water or a solution of precursor PEG-stat-PILmBr, the relaxivity is insensitive to the pre-contrast relaxation rate due to the large differences between \(T_1\) and \(T_{1,o}\). The nearly equivalent relaxivities between PEG-stat-PIL and paramagnetic metal complexes might mistakenly lead to conclude that the same \(T_1\)-weighted magnetic contrast would be achieved. However, this is not the case because it is the relaxation rate \((T_1^{-1})\) and not relaxation time that is additive and proportional to the concentration of paramagnetic agent.

The relationship between toxicity, \(^1\)H relaxation rate, an concentration allow us to elucidate a maximum nontoxic dose that generates contrast in a clinical setting of 0.5 \(\mu\)mol.kg\(^{-1}\), which is significantly lower than the standard for MRI contrast agents used in clinical settings (30-100 \(\mu\)mol.kg\(^{-1}\)). Further work is necessary to optimize this value, yet we anticipate tunability as a consequence of the rational molecular design strategy implemented. The material presented herein is fundamentally different from those traditionally adopted in the development of MRI contrast agents based on metal complexes and inorganic nanoparticles, as magnetic functionality at the monomer level is synergistically combined with the structural hierarchy intrinsic to polymers.

3.4. Conclusions

We present a novel magnetic and biocompatible statistical copolymer that can afford novel theranostic agents based on polymer conjugates with controlled residence time within the human body, and complementary functionality for MRI imaging. The molecular design strategy used to prepare this material allows for the synthesis of a well-defined and narrowly dispersed polymerized ionic liquid that synergistically combines the monomer magnetic functionality of the ionic liquid moieties with the structural hierarchy and biocompatibility of the polymer backbone. The systematic and independent tunability over the number of segments, fraction of ionic liquid moieties, and architecture allows for control over the hydrodynamic volume and content of paramagnetic iron(III). These parameters ultimately dictate the residence time within the human body, magnetic environment within tissue, and cytotoxicity; which are essential features of MRI contrast agents. Cytotoxicity assays on MCF-10a and hemolysis on red blood
cells isolated from BALB/c mice demonstrate PEG-stat-PIL to have similar toxicity to PEG at concentrations below 0.5 mg.mL⁻¹. PEG-stat-PIL significantly influences the magnetic environment experienced by the ¹H nuclei of water, as revealed by an order of magnitude decrease in the spin-lattice relaxation time. Moreover, it exhibits a ¹H relaxivity comparable with clinically pertinent MRI contrast agents based on paramagnetic metal complexes. The interplay between toxicity, ¹H relaxation rate, and concentration presented herein can be optimized with the presented molecular design strategy to afford novel theranostics based on polymers conjugated to drugs, proteins, and antibodies that can be imaged by MRI while used for localized targeting.

3.5. Acknowledgements

We gratefully acknowledge Dr. Shamon Walker for experimental assistance. The authors also thank Prof. Craig Hawker for helpful discussions. This work was primarily supported by the AFOSR MURI program under FA9550-12-1. The characterization of the material presented herein was performed at the Materials Research Laboratory, a facility supported by the MRSEC Program of the National Science Foundation, under Award DMR 1121053.

3.6. Appendix. ¹H NMR, GPC, and Inversion Recovery Data
Figure A 3.1. $^1$H NMR of Im-SH in CDCl$_3$
The polydispersity ($Đ = M_w/M_n$) was lower than 1.1 in the statistical copolymer synthesized. This is consistent with the living nature of the anionic copolymerization of ethylene oxide and allyl glycidyl ether.
Figure A 3.3. $^1$H NMR of PEG-stat-PAGE in CDCl$_3$

End-group analysis yields the number of repeat units of ethylene oxide and allyl glycidyl ether, PEG$_{369}$-stat-PAGE$_{38}$
Figure A 3.4. $^1$H NMR of PEG-stat-PIm in CD$_3$OD

Disappearance of the allyl groups from PEG-stat-PAGE and appearance of imidazole aromatic peaks confirms complete conversion of the thiol-ene click reaction
Figure A 3.5. $^1$H NMR of PEG-stat-PImBr in CD$_3$OD

Change in chemical shift of the aromatic protons confirms quaternization of PEG-stat-PIm. Integrals yield the number of repeat units of ethylene oxide and imidazolium bromide PEG$_{386}$-stat-PImBr$_{38}$. This is consistent with conservation of moles based on the end-group analysis of PEG-stat-PAGE.
Figure A 3.6. Inversion Recovery Spectra of H$_2$O

$^1$H NMR data collected on O$_2$-free H$_2$O and D$_2$O (1:4), and temperature of 37 $^\circ$C
Figure A 3.7. Inversion Recovery Spectra of PEG-\textit{stat}-PImBr

$^1$H NMR data collected on O$_2$-free H$_2$O and D$_2$O (1:4), polymer concentration of 0.5 mg.mL$^{-1}$, and temperature of 37 °C
Figure A 3.8. Inversion Recovery Spectra of PEG-

$^{1}H$ NMR data collected on O$_2$-free H$_2$O and D$_2$O (1:4), polymer concentration of 0.5 mg.mL$^{-1}$, and temperature of 37 °C
3.7. References


Chapter 4. Multivalent Ion Transport in Polymers via Metal-Ligand Coordination


Multivalent ion conducting polymers are critical for electrochemical devices with improved volumetric energy densities. These materials currently face transport limitations that prevent optimal device performance. Herein, we present a novel statistical copolymer, PEO-stat-PHGE, that synergistically combines the structural hierarchy of poly(ethylene oxide) with the Lewis basicity of tethered histamine ligands (xHGE = 0.17) required to solvate a series of Li+, Zn2+, Ni2+, Co2+ and Fe3+ bis(trifluoromethylsulfonyl)imide salts. Mixtures of PEO-stat-PHGE with divalent salts exhibit a nanostructure in which ion-enriched regions alternate with some periodicity with ion-deficient regions, and an ionic conductivity that scales with the glass transition temperature. Variations in nanostructure and ionic conductivity are evidenced for cations of variable valency suggesting that novel renormalization schemes that account for differences in solvation site connectivity are required to attain a universal scaling relationship for multivalent ion transport in polymers via metal-ligand coordination.

4.1. Introduction

Li+ batteries have improved dramatically over the past decades but as their limit in terms of energy density is approached, alternative electrochemical reduction-oxidation couples will be required. To date, candidates include Li-air,1 Li-S,2 Zn-air,3 Al-air, Mg-air, Mg2+, among others.4 Multivalent metals promise to significantly improve the volumetric energy density of batteries, which is critical in devices with packing restrictions such as vehicles and portable electronics. These materials are generally less scarce than lithium, do not pose important safety concerns when exposed to air, and are less susceptible to dendrite growth and failure. However, current transport limitations of multivalent ions in both the electrolyte and the solid electrolyte interface severely detriment device performance. Herein, we molecularly design multivalent ion conducting polymer electrolytes based on metal-ligand interactions and illustrate engineering rules for novel high conductivity and tunable modulus materials.

Polymer electrolytes are promising not only from a safety standpoint, but also because their electrochemical stability in the presence of pyrophoric electrodes that operate at high voltage affords batteries with enhanced energy densities. These materials conduct ions due to a combination of polymer segmental dynamics and ion solvation site connectivity,5-6 as demonstrated extensively in mixtures of Li+ salts with poly(ethylene oxide),7-8 polyethers,9 polyesters,10-12 among others.13-16 Although the physical laws governing transport multivalent ions Li+ are anticipated to be similar to that of Li+, polymer electrolytes have proven ineffective for this purpose and still remain limited.17

Polymer electrolytes rely on the solvation of ions with dynamic bonds that reversibly break and form on timescales that allow for ion motion. Dynamic bonds can exhibit very distinct timescales of reversible breakage and formation (i.e., bond lifetime) depending on whether they are reversible covalent (e.g., Diels-Alder) or non-covalent (e.g., hydrogen bonds, π-π stacking, and metal-ligand coordination). Among the latter, metal-ligand coordination bonds are particularly attractive, as a broad range of parameters including the chemistry of the cation, anion, and ligand can be tuned to provide the appropriate bond energy required for a desirable
material property. Although bonds formed between metals and ligands are often more labile than covalent bonds, this does not translate into weak mechanics as these dynamic chemical crosslinks provide the material with remarkable strength.\textsuperscript{18} For example, metal-ligand coordination bonds have been explored recently for the development of materials that self-heal upon damaged either spontaneously or with the aid of a stimulus.\textsuperscript{19} While significant progress has been made in the area of self-healing polymers using metal-ligand coordination, ion transport in these materials remains unexplored.

Polymers based on imidazole and histidine moieties are particularly exciting due the remarkable ability of these ligands to coordinate multivalent ions with well-defined geometry.\textsuperscript{20} Investigations on these materials have primarily focused on quaternized imidazolium\textsuperscript{21-24} and histammonium\textsuperscript{25-27} ions unable to transport multivalent ions. However, imidazole and histidine moieties represent a promising chemistry for multivalent ion conducting polymers due to the Lewis basicity of the nitrogen atom located in an aromatic ring covalently bonded to the polymer backbone. These materials constitute macromolecular analogues of chelating ionic liquids known to solubilize multivalent ions in battery electrolytes.\textsuperscript{28} Thus, these so-called polymerized ionic liquids are interesting for applications that require multivalent ion conduction such as batteries with electrochemical reduction-oxidation couples beyond Li\textsuperscript{+}.

Herein, we design novel solid-state polymerized ionic liquid electrolytes based on a poly(ethylene oxide) backbone, histamine ligand moieties, and bis(trifluoromethylsulfonyl)imide salts. We present a molecular design strategy based on a combination of ring opening anionic polymerization, thiol-ene click chemistry, and metal-ligand coordination that allows exquisite control over the chemical structure and guarantees scalability appropriate for elucidating structure-property relationships. The system exhibits a nanostructure in which ion-rich regions alternate with some periodicity with ion-poor region, and an ionic conductivity that scales with the glass transition temperature for a series of cations of fixed valency. Further renormalization schemes are required to account for differences in solvation site connectivity and attain a universal conductivity scaling relationship for multivalent ion transport in polymer electrolytes via metal-ligand coordination.

### 4.2. Experimental Methods

**Materials.** All materials were used as received from Sigma-Aldrich unless otherwise noted. CDCl\textsubscript{3} and methanol-d\textsubscript{4} were purchased from Cambridge Isotope Laboratories; acetonitrile, hexanes, methanol, and isopropyl alcohol from BDH Chemicals; and allyl glycidyl ether (AGE) from TCI America. Tetrahydrofuran (THF) was collected from a commercial J. C. Meyer dry solvent system and used immediately thereafter. AGE was dried over butyl magnesium chloride, degassed through three freeze-pump-thaw cycles, and then vacuum transferred to a flame-dried buret kept at 0 \textdegree C until immediately prior to use. Potassium naphthalenide was prepared from potassium metal and naphthalene in dry THF and allowed to stir with a glass-coated stir bar for 24 h at room temperature before use.

**Synthesis of N-(2-(1H-Imidazol-4-yl)ethyl)-4-mercaptobutanamide (His-SH).** The synthesis of His-SH was reported previously by Lundberg et al.\textsuperscript{29} In a 250 mL round-bottom flask equipped with a Teflon-coated stir bar and a condenser, 10.1 (99.0 mmol) of γ-
thiobutyrolactone, 10.0 g (90.0 mmol) of histamine, and 150 mL of acetonitrile were added. The reaction mixture was heated to 95 °C using a heating mantle, and the reaction was allowed to proceed for 12 h. The reaction was cooled to room temperature, and the resulting pale yellow solid was isolated by filtration and dried in vacuo.

Synthesis of Poly[(ethylene oxide)-stat-(allyl glycidyl ether)] (PEO-stat-PAGE). The copolymerization of EO and AGE was adapted from Lee et al.30 Separate burets containing THF and EO were connected to a thick-walled glass reactor fitted with Ace threads. The EO was connected by flexible stainless steel bellows so that the buret could be held in an ice bath until use. The reactor assembly was flame dried and then cycled between vacuum and positive argon pressure (5 psig) three times. The reactor was finally charged with an argon atmosphere and then isolated from the Schlenk line. THF was added, and the temperature equilibrated at 0 °C. Based on the amount of purified EO (22.77 g, 517 mmol), a quantity of benzyl alcohol (166 μL, 1.60 mmol) was added through a gastight syringe. Potassium naphthalenide (0.3 M in THF) was added through a gastight syringe to titrate the benzyl alcohol until a pale green endpoint. EO was added by lifting the cold buret and allowing monomer to drain in the reactor while AGE (15 mL, 127 mmol) was simultaneously added via gastight syringe. The temperature was increased to 40 °C, and the polymerization allowed to proceed for 24 h. After complete conversion of EO and AGE, degassed and acidified isopropyl alcohol was added to terminate the polymerization. The resulting PEO-stat-PAGE was precipitated into an excess of hexanes, and dried for 48 h at 55 °C in vacuo. PEO-stat-PAGE was immediately transferred to a glovebox maintained in an inert nitrogen atmosphere to mitigate moisture uptake.

Synthesis of Histamine Functionalized Copolymer (PEO-stat-PHGE). In a 100 mL round-bottom flask equipped with a Teflon-coated stir bar, PEO-stat-PAGE (2.50 g, 7.48 mmol of allyl groups), His-SH (4.00 g, 18.75 mmol, 2,2-dimethoxy-2-phenylacetophenone (DMPA, 0.38 g, 1.48 mmol), and methanol (75 mL) were added. The solution was degassed sparging with nitrogen for 30 min and then allowed to react for 2 h under UV irradiation (λ = 365 nm). The resulting PEO-stat–PHGE was concentrated by rotary evaporation, purified by dialysis (4 x 4 L), and dried for 48 h at 55 °C in vacuo to yield a rubbery solid. PEO-stat-PHGE was immediately transferred to a glovebox maintained in an inert nitrogen atmosphere to mitigate moisture uptake.

Preparation of Mixtures of Copolymers with Multivalent Salts (PEO-stat–PAGE/M(NTf₂)₂ and PEO-stat–PHGE/M(NTf₂)₂). In a nitrogen atmosphere, stock solutions prepared in anhydrous methanol of polymer (500 μL, 20 wt%, 0.30 mmol of allyl groups or 0.19 mmol of histamine) and 1 M bis(trifluoromethylsulfonyl)imide salts of lithium (1 equiv), cobalt, nickel, zinc (0.5 equiv), and iron (0.33 equiv) were mixed in 5 mL vials. The resulting mixtures of PEO-stat–PAGE/M(NTf₂)₂ and PEO-stat–PHGE/M(NTf₂)₂ were stored in a glovebox to mitigate moisture uptake.

Molecular Characterization. Gel Permeation Chromatography (GPC) was performed on a Waters instrument using a refractive index detector and Agilent PL gel 5 μm MiniMIX-D column. THF at 35 °C was used as the mobile phase with a flow rate of 1.0 mL.min⁻¹. Polydispersity index (Đ) was determined against PEO standards (Agilent).¹H NMR spectra were collected on a Bruker Avance DMX 500 MHz. Copolymers molecular weights (Mₙ) were determined using ¹H NMR end-group analysis.
Thermal Characterization. Polymer samples were prepared in an inert nitrogen atmosphere by casting PEO-stat-PAGE/M(NTf₂)₂ and PEO-stat-PHGE/M(NTf₂)₂ into standard aluminum pans, and drying for 8 h at 55 °C in vacuo. The samples were sealed, and characterized with a Perkin Elmer DSC 8000 to determine the glass transition temperature (T_g) and melting temperature (T_m) on second heating at 20 °C.min⁻¹ using the onset method.

Morphological Characterization. Polymer samples were prepared in an inert atmosphere by casting PEO-stat–PAGE/M(NTf₂)₂ and PEO-stat–PHGE/M(NTf₂)₂ into ¼” disks bottom-coated with X-ray transparent Kapton film, and drying for 8 h at 55 °C in vacuo. The samples were covered with Kapton and sealed in air-tight holders prior transport to the X-ray source. Wide-angle X-ray scattering (WAXS) was performed at beamline 7.3.3 of the Advanced Light Source (ALS) using X-rays of wavelength 1.240 Å focused on a 50 x 300 μm spot. Full two-dimensional scattering patterns were collected using a 2D Dectris Pilatus 2M charge-coupled device (CCD) detector (1475 x 1679 pixels). The scattering patterns were azimuthally integrated using Nika version 1.58.

Electrochemical Impedance Spectroscopy. Polymer samples were prepared in an inert atmosphere by casting PEO-stat–PAGE/M(NTf₂)₂ and PEO-stat–PHGE/M(NTf₂)₂ into ¼” circular indium tin oxide (ITO) substrates top-coated with a 150 μm Kapton spacer, and drying for 8 h at 55 °C in vacuo. The samples were sealed with an ITO substrate, and characterized with a Biologic SP-200 potentiostat. A sinusoidal voltage with amplitude 100 mV was applied in the frequency range 1 Hz-10 MHz.

4.3. Results and Discussion

The development of novel multivalent ion conducting polymers requires control over the polymer segmental dynamics and ion solvation site connectivity. These properties are ultimately dictated by the glass transition temperature and the nature, distribution, and structure of ion solvation sites; which even if strongly dependent on monomer, ligand, and ion structure can still be tuned in mixtures of salts and polymers through the number of segments (N), fraction of ligand moieties (x_HGE), and architecture of the chain. Herein, a combination of anionic ring opening copolymerization of epoxides, thiol-ene click chemistry, and metal-ligand coordination is used to achieve control over N, x_HGE, and architecture through the monomer to initiator ratio, the relative amounts of monomers, and the degree of branching of the initiator. The incorporation of ligands based on histamine, a Lewis base, provides the material with the kinetically labile bonds necessary to conduct multivalent ions. The strategy presented herein can be adopted for the development of polymers with functionality beyond multivalent ion transport.

To demonstrate multivalent ion transport in polymers via kinetically labile metal-ligand coordination, PEO-stat-PHGE/M(NTf₂)₂, was prepared following the scheme presented in Figure 4.1. First, the histamine functionalized copolymer (PEO-stat-PHGE) was synthesized using epoxide ring opening copolymerization of ethylene oxide (EO) and allyl glycidyl ether (AGE), followed by UV activated thiol-ene click chemistry of N-(2-(1H-Imidazol-4-yl)ethyl)4-mercaptopbutanamide (His-SH). PHGE was chosen due to the Lewis basicity of the nitrogen atoms located in the aromatic ring that facilitate multivalent ion transport. Next, the resulting
Figure 4.1. Synthesis of Multivalent Ion Conducting Polymers
PEO-stat-PHGE was treated with bis(trifluoromethylsulfonyl)imide (NTf₂⁻) salts based on Li⁺, Ni²⁺, Zn²⁺, Co²⁺, and Fe³⁺ to generate PEO-stat-PHGE/M(NTf₂)ₓ. These materials constitute the multivalent ion conducting Lewis acid-base analogues of proton and hydroxide conducting polymers based on Brønsted acid-base chemistry. Moreover, the weak electrostatic interactions resulting from large, charge-delocalized, and asymmetric NTf⁻ ions resemble that of chelating ionic liquids; yielding low glass transition temperatures compared to conventional ion-containing polymers (e.g., polycrlylates). Well-defined and narrowly dispersed PEO-stat-PHGE/M(NTf₂)ₓ were synthesized (Δ < 1.2) with a constant mole fraction of histamine moieties (x_{HGE} = 0.17). The properties and thermal transitions of mixtures of copolymers with NTf₂⁻ salts are summarized in Table 4.1.

Investigations on mixtures of ether-based polymers with lithium salts suggest that solvation site connectivity is essential for ion transport.⁵⁻⁶ Given that the physical laws governing multivalent ion conduction are anticipated to be similar to that of Li⁺, it is critical to understand the nature, distribution, and structure of ion solvation sites in polymers based on metal-ligand coordination bonds. To elucidate the effect of solvation site connectivity on ion transport; the nanostructure of PEO-stat-PHGE/M(NTf₂)ₓ was investigated. Polymers with metal-ligand coordination bonds resulting from Lewis acid-base chemistry of histamine with Co²⁺, Zn²⁺, and Ni²⁺ exhibit ion clusters at the nanometer length scale due to association of multiple ion solvation sites. Azimuthally integrated wide-angle X-ray scattering (WAXS) profiles of the PEO-stat-PHGE/M(NTf₂)ₓ (Figure 4.2) reveal periodic alternation of ion deficient and enriched regions, as demonstrated by the scattering peak at 1.35 Å⁻¹. This scattering peak enables determination of a NTf₂⁻ anion-to-anion distance of 4.65 Å, which is independent of the chemistry of the divergent cation. Although, the formation of ion clusters is ubiquitous in ion-containing polymers due to the presence of charged species in low dielectric constant media,³⁹⁻⁴⁰ structural differences dependent on ion valency are evident from the presented data. The absence of clustering in mixtures of PEO-stat-PHGE with Li⁺ and Fe³⁺ salts is indicative of weak electrostatic interactions insufficient to overcome the entropic penalties associated with ion aggregation. The role of ion clusters and solvation site connectivity on ionic conductivity is currently an exciting topic in the literature, as the lack of connectivity (i.e., percolation) of ion clusters hinders ion motion due to limited transport across insulating regions. The nanostructure and connectivity in the series of PEO-stat-PHGE/M(NTf₂)ₓ mixtures investigated depend strongly on the equilibrium constant and metal-ligand coordination environment, which are unknown in polymers with multiple ligands due to entropic penalties associated with chain stretching upon binding.⁴¹ The insight obtained by WAXS is restricted to the evident structural differences and similarities related to ion valency, as an infinite set of electron density distributions would yield the observed scattering patterns. Further experimental and theoretical work, including extended X-ray absorption spectroscopy (EXAFS) and molecular dynamics, is necessary for a comprehensive characterization of ion solvation site connectivity in these materials.

Polymers resulting from mixtures of PEO-stat-PHGE with M(NTf₂)ₓ salts containing Li⁺, Ni²⁺, Co²⁺, Zn²⁺, and Fe³⁺ (i.e., equimolar amounts of NTf₂⁻ to histamine moieties) exhibit an ionic conductivity in an absolute temperature scale similar to that of the neutral precursor (Figure 4.3). A priori this observation is vexing as the conductivity is expected to significantly increase with the concentration of ions, yet it is important to notice that the transport of charged species
Table 4.1. Properties of Mixtures of PEO-\textit{stat}-PHGE with Multivalent NTf$_2^+$ Salts

<table>
<thead>
<tr>
<th>Polymer</th>
<th>[HGE]:[M]$^a$</th>
<th>$T_g$ [°C]$^b$</th>
<th>$d$ [Å]$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEO-\textit{stat}-PHGE</td>
<td>-</td>
<td>-14</td>
<td>-</td>
</tr>
<tr>
<td>+Li$^+$</td>
<td>1</td>
<td>11</td>
<td>-</td>
</tr>
<tr>
<td>+Ni$^{2+}$</td>
<td>2</td>
<td>24</td>
<td>4.59</td>
</tr>
<tr>
<td>+Co$^{2+}$</td>
<td>2</td>
<td>6</td>
<td>4.62</td>
</tr>
<tr>
<td>+Zn$^{2+}$</td>
<td>2</td>
<td>12</td>
<td>4.90</td>
</tr>
<tr>
<td>+Fe$^{3+}$</td>
<td>3</td>
<td>11</td>
<td>-</td>
</tr>
</tbody>
</table>

$^a$Stoichiometry of multivalent cations to histamine ligand moieties. $^b$Determined from DSC (Figure A 4.6) using the onset method. $^c$Determined from the scattering peak of the WAXS profiles of PEO-\textit{stat}-PHGE/M(NTf$_2$)$_z$ at 40 °C.
Figure 4.2. WAXS Intensity Profiles of Mixtures of PEO-stat-PHGE with M(NTf$_2$)$_2$ Salts

PEO-stat-PHGE/M(NTf$_2$)$_2$ exhibits a NTf$_2^-$ correlation peak at 1.35 Å$^{-1}$ for Co$^{2+}$, Zn$^{2+}$, and Ni$^{2+}$. The absence of this peak for Li$^+$ and Fe$^{3+}$ suggests differences in the nanostructure and ion solvation site connectivity associated with ion valency. Profiles are offset for clarity. WAXS data collected on PEO-stat-PHGE at 40 °C.
The ionic conductivity of mixtures of PEO-stat-PHGE and salts is similar to that of the neutral precursor. This observation is vexing as the ionic conductivity is expected to increase with the concentration of ions.
through polymers is strongly coupled to the chain dynamics; which is affected by the addition of M(NTf₂)₂ salts.

To illustrate the impact of metal-ligand coordination on multivalent ion transport in polymers, the temperature dependence of the ionic conductivity was rescaled by the glass transition temperature (T_g). This normalization scheme; pioneered by Vogel, Tamman, Fulcher, and Hess (i.e., VTF);⁴²⁻⁴⁴ is critical to decouple the contribution from chain dynamics on macroscopic properties such as the ionic conductivity. Noteworthy, the T_g of PEO-stat-PHGE increases and broadens upon addition of M(NTf₂)₂ salts, as the hydrogen bonding local packing of the histamine precursor is disrupted by weak electrostatic interactions resulting from asymmetric, charge-delocalized, and large ions. This is consistent with previous studies on mixtures of PEO with LiNTf₂, where Li⁺ ions are coordinated by the electron donating oxygen atoms of the polymer backbone. Upon addition of LiNTf₂, the T_g of PEO increases yielding a maximum in ionic conductivity due to the competition between ion concentration and polymer segmental motion.⁴⁵ The ionic conductivity VTF renormalization of PEO-stat-PHGE/M(NTf₂)₂ is presented in Figure 4.4 and reveals a universal scaling for the divalent Ni²⁺, Co²⁺, and Zn²⁺ ions but discrepancies among ions with different valency. Although the salt concentrations in the polymers vary with cation valency due to the equimolar stoichiometry between histamine and NTf₂⁻ anions, these differences are not sufficient to account for the non-universal VTF renormalization given that the ionic conductivity of PEO-stat-PHGE/Fe(NTf₂)₃ is higher than that of PEO-stat-PHGE/M(NTf₂)₂ even with a lower number of ions. Given that the physical laws governing multivalent ion transport through polymers are anticipated to be analogous to that of Li⁺, the observed differences are attributed to differences in the nature, distribution, and structure of ion solvation sites, as indirectly supported by WAXS. Again, further experimental and theoretical work is necessary to elucidate and quantify this effect; including molecular dynamics simulations to develop molecular insight for connectivity and its dependence on fraction of ligand moieties in the polymer chain; and extended X-ray absorption spectroscopy (EXAFS) to determine the energy, distribution, and structure of complexes in polymers based on metal-ligand coordination bonds.

4.4. Conclusions

We present a novel multivalent ion conducting statistical copolymer based on metal-ligand coordination, PEO-stat-PHGE, that can afford solid-state electrolytes for next generation batteries with high volumetric energy density. The molecular design strategy used to prepare PEO-stat-PHGE allows for the synthesis of a well-defined and narrowly dispersed material that synergistically combines the structural hierarchy of polymers with the Lewis basicity of the ligand moieties required for ion solvation and multivalent ion conduction. The tunability over the number of segments, fraction of ligand moieties, and architecture allows for control over the glass transition temperature, and equilibrium constant of the metal-ligand complexes. These parameters ultimately dictate the segmental dynamics and ion solvation site connectivity; which are essential features of ion conducting polymer electrolytes. Mixtures of PEO-stat-PHGE with NTf₂ salts of Ni²⁺, Zn²⁺, and Co²⁺ cations exhibit ion clusters at the nanometer length scale, that are absent in Li⁺ and Fe³⁺. These structural differences presumably account for an ionic conductivity that scales with the glass transition temperature for a series of divalent Ni²⁺, Co²⁺, and Zn²⁺ ions and with convoluted effects dependent on ion valency. Further investigations are required to account for differences in solvation site connectivity and attain a universal structure-
Figure 4.4. VTF Renormalized Ionic Conductivity of Mixtures of PEO-stat-PHGE with M(NTf₂)₂ Salts

The ionic conductivity scales with the glass transition temperature for Co²⁺, Zn²⁺, and Ni²⁺ but exhibits discrepancies associated with ion valency presumably due to ion solvation site connectivity.
property relationship for multivalent ion transport in polymer electrolytes via metal-ligand coordination.

4.5. Acknowledgements

G.E.S gratefully acknowledges the AFOSR MURI program under FA9550-12-1 for financial support; and N.S.S the Fannie and John Hertz Foundation for a graduate fellowship. We thank Dr. Chenhui Zhu for experimental assistance at the Advanced Light Source. The authors also thank Prof. Christopher Bates for helpful discussions. The synthesis and molecular characterization of the materials presented herein were primarily conducted at the UCSB Materials Research Laboratory, a facility supported by the MRSEC Program of the National Science Foundation under Award DMR 1121053. Beamline 7.3.3 of the ALS is supported by the Director of the Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract DE-AC02-05CH11231.

4.6. Appendix. $^1$H NMR, GPC, and DSC data
Figure A 4.1. $^1$H NMR of His-SH in CD$_3$OD
Figure A 4.2. $^{13}$C NMR of His-SH in CD$_3$OD
Figure A 4.3. Gel Permeation Chromatography of PEO-stat-AGE calibrated against poly(ethylene oxide) standards.

The polydispersity (Đ) was lower than 1.2 in the statistical copolymer synthesized. This is consistent with the living nature of the copolymerization of EO and AGE.
Figure A 4.4. $^1$H NMR of PEO-stat-PAGE in CDCl$_3$

End-group analysis yields the number of repeat units of ethylene oxide and allyl glycidyl ether, PEO$_{331}$-stat-PAGE$_{68}$. 
Figure A 4.5. $^1$H NMR of PEO-stat-PHGE in CD$_3$OD

Disappearance of the allyl groups from PEO-stat-PHGE and appearance of histamine aromatic peaks confirm complete conversion of the thiol-ene click reaction.
Figure A 4.6. DSC of Mixtures of PEO-stat-PHGE with M(NTf$_2$)$_2$ Salts

$T_g$ broadens and increases upon addition of M(NTf$_2$)$_2$ salts, as the hydrogen bonding local packing of the histamine precursor is disrupted by weak electrostatic interactions resulting from asymmetric, charge-delocalized ions.
4.7. References


42. Fulcher, G. S., Analysis of Recent Measurements of the Viscosity of Glasses. *Journal of the American Ceramic Society* 1925, 8 (6), 339-355.


Chapter 5. Conclusions and Outlook

Polymerized ionic liquids are broadening the chemistry, physicochemical properties and applications of conventional ion-conducting polymers. The introduction of novel anions and cations is producing a renaissance of the field of ion-containing polymers. Although an important number of polymers have already been synthesized, the potential for innovative ion-containing polymers with applications in electrochemical energy conversion, carbon capture and sequestration, water purification, medical therapeutics, and urban infrastructure is extremely high due to the new ions developed by the ionic liquid community and recent advances in controlled and precise polymer chemistry and manufacturing. The design strategy for polymerized ionic liquids presented herein provides fine and independent control over molecular properties including the number of segments, fraction and chemistry of ionic liquid moieties, and architecture of the polymer chain. Consequently, it opens new avenues to address fundamental questions in polymer science, as well as to enable generation of high-performance functional materials.

The molecular design of polymerized ionic liquids allows for a comprehensive understanding of the relationship between molecular structure, mesoscale morphology, and local dynamics on macroscopic material properties. Polymerized ionic liquids were originally envisioned for providing mechanical robustness to ionic liquid electrolytes for electrochemical systems and therefore only a restricted set of ion pairs and macroscopic properties have been explored. Synthetic efforts are required to expand the set of cations, anions, and backbones that can be incorporated into polymerized ionic liquids; as demonstrated herein with tethered histamine ligands capable of forming chelates with multivalent ions electrostatically balanced by large, charge-delocalized, asymmetric bis(trifluoromethanesulfonylelimide anions. The interplay between electrostatic, metal-ligand, and polymer excluded volume interactions can be optimized to develop materials capable of conducting ions while exhibiting robust mechanical self-healing properties. However, advanced characterization techniques ubiquitous in organometallic chemistry (e.g., EXAFS) together with continuum and mesoscale theory (e.g., molecular dynamics) are still required to decouple the effects of ion solvation site connectivity on macroscopic material properties. This problem is tightly related to the thermodynamics of metal-polymer ligands which is significantly different from that of small molecules due to chain connectivity, as extensively investigated in chemical glycobiology to control cellular response. The interconnection between the thermodynamics governing multivalent ion conduction in polymer electrolytes and cell-ligand interactions in chemical glycobiology is another demonstration of the novel routes provided by polymerized ionic liquids to address fundamental questions in polymer science while providing design rules to develop high-performance functional materials.

The ability to incorporate functionality at the monomer level by simple ion exchange, as demonstrated with paramagnetic trichlorobromoferrate(III) anions, can be exploited to engineer polymerized ionic liquids with multiple mobile ions that exhibit orthogonal, reconfigurable, and gradient macroscopic properties. The spatiotemporal stability of these materials is governed by transport phenomena and can be tuned with a variety of external force fields (e.g., electric and magnetic). From a fundamental standpoint, insights on the physical laws governing ion transport in polymers can be attained by complementing images of ion concentration profiles obtained with non-destructive and non-invasive techniques (e.g., MRI and interferometry) with continuum
and mesoscale modeling. If designed properly, polymerized ionic liquids are promising to program functionality in 3-D for accessing unprecedented macroscopic viscoelastic, dielectric, magnetic, and optical properties.

Polymerized ionic liquids optimized with a combination of synthesis, advanced structural characterization, and theory can also be designed to be smart and stimuli-responsive. Spatiotemporal control over macroscopic properties can be achieved using electromagnetic radiation (e.g., light or UV) to afford large permanent or temporary changes in functionality. Integrating the polymerized ionic liquid design with stimuli-responsiveness has important implications for existing applications that demand precise tunability of material properties and enable new technologies not yet accessible with state-of-the-art polymers. Dynamic control over functional material properties including stiffness, ionic and electronic conductivity, chemical composition and associated gradients, and mesoscale assembly portends considerable utility for applications spanning 3-D printing, membranes, confined reaction media, and patterning.

The fundamental insights arising from stimuli-responsive polymerized ionic liquids are anticipated to augur technological breakthroughs across disparate disciplines. For instance, complex 3D structures can be constructed through a combination of direct printing, light patterning, programmed mechanical properties, and solvent swelling. These structures could contain arbitrary, rewritable, and intricate conducting pathways with spatially-controlled dynamics for use in membrane separation technologies. Polymer architectures based on stimuli-responsive polymerized ionic liquids, such as block copolymers, can be morphologically modulated by triggering changes in polarizability with light, creating new opportunities in 2D patterning for lithography. The outstanding solubility of ionic liquid moieties for catalyzing reactions and sequestering greenhouse gases can be married with the unparalleled structural control of stimuli-responsive, light-writable polymerized ionic liquids to develop confined nanoreactors with enhanced chemical kinetics.

Polymerized ionic liquids are thus a fascinating class of materials with structural control at length scales ranging from molecular, mesoscopic, and macroscopic. The tunability of these materials represents a complex interdisciplinary challenge with major relevance to chemical and biomolecular engineering. The presented molecular design strategy of polymerized ionic liquids provides a valuable foundation for the application of these functional polymers to problems in energy, biotechnology, and materials science.

5.1. References