

REPORT DOCUMENTATION PAGE

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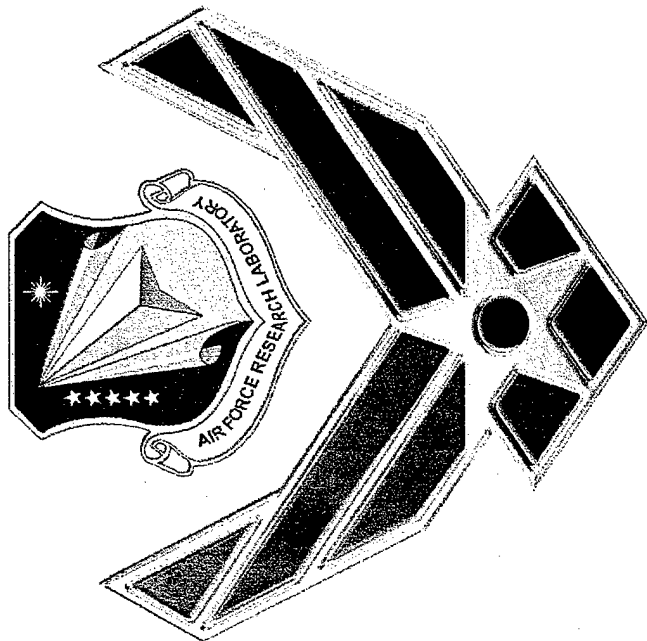
SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2003-066**
Greg Drake¹; Tom Hawkins¹; Kerri Tollison²; Leslie Hall¹; Adam Brand¹; Milton McKay¹; Aswani
Vij²; Ismail Ismail²; Greg Warmoth²; Sarah Sabowski²; Greg Kaplan¹, "Research in Ionic Liquids"
¹ (AFRL/PRSP); ² (ERC, Inc.)

JANNAF PDCS Conference
(Charlottesville, VA, 22-27 Mar 2003) (Deadline: 24 Mar 2003)

(Statement ^A ~~C~~)

Research in Ionic Liquids

March 2003

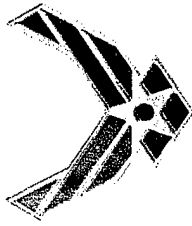


**Greg Drake, Tommy Hawkins, Kerri Tollison*,
Leslie Hall, Adam Brand, Milton McKay,
Aswani Vij, Ismail Ismail*, Greg Warmoth*,
Sarah Sabowski*, Greg Kaplan
AFRL/PRSP and *ERC, Inc.**

Air Force Research Laboratory

Edwards Air Force Base, CA 93524-7680

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Ionic Liquids

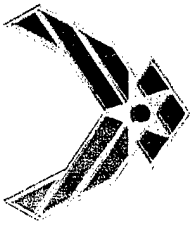


Ionic Liquids- one of the new focal points for HEDM research. Why are we here today? HEDM research effort has shifted away from cryogenic/matrix isolation and now is pointing into synthetic endeavors

Ionic liquids have been around a very long time (100 years), and recently they have really taken off. But in this “take off” most researchers are looking for applications in the use of ionic liquids. Few people are looking at ionic liquids for the “why” these materials are low melting and how this unusual class of compounds might be more useful for other applications.

Most of the rapidly growing international community has adopted the definition of an ionic liquid being a salt which melts less than 100°C¹⁻³, with most melting at or below ambient working conditions (STP). All are low melting salts. Our research at AFRL has been working on designing, synthesizing, and fully characterizing new low melting salts many of which are ionic liquids.

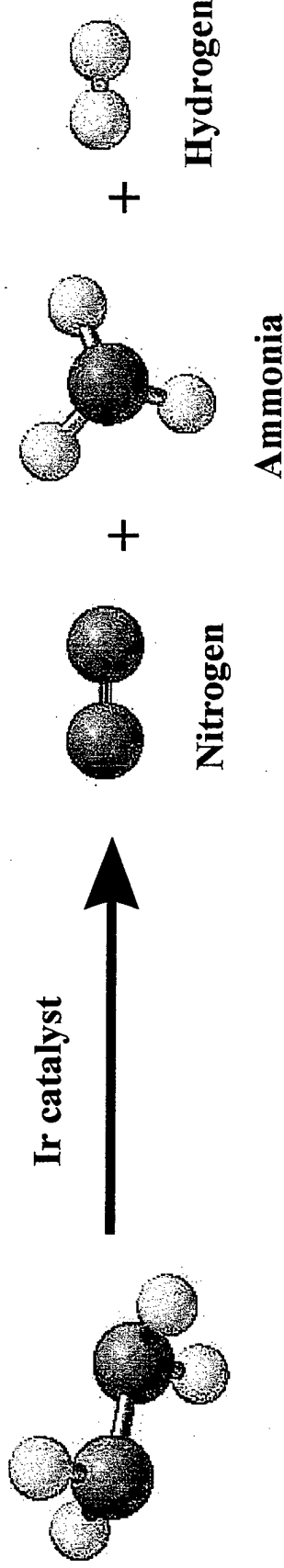
1. P. Wasserscheid; T. Welton *Ionic Liquids in Synthesis* Wiley-VCH Verlag, GmbH & Co. Weinheim, Federal Republic of Germany, 2003, pg 1.
2. Zhao, H. ; S.V. Malhotra *Aldrichimica Acta* 2002, 35, 3, 75.
3. W. Keim ; P. Wasserscheid *Angew. Chem. Int. Ed. Engl.* 2000, 39, 3772.



Ionic Liquids



State of the art is hydrazine, N_2H_4 , which is used in many satellite systems



Advantages: Tried and true for several decades, relatively cool burning for hardware.

Disadvantages: Hydrazine is extremely toxic (carcinogenic), has a high vapor pressure, a high melting point ($1^\circ C$), and results in workers using self contained suits.

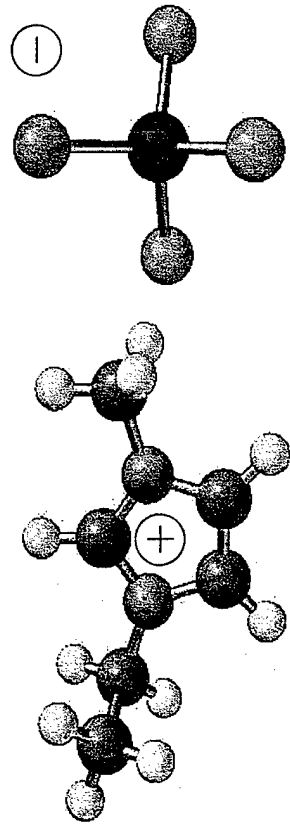
Our approach at AFRL has been investigating new low melting salts as they have inherent advantages including higher densities and negligible vapor pressures.



Ionic Liquids

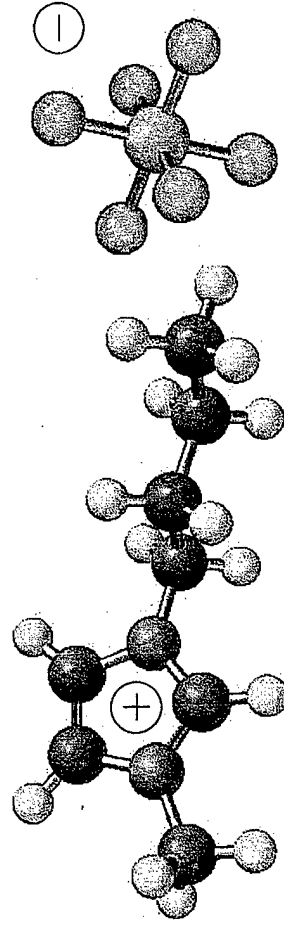


Ionic liquids research was really opened up by the pioneering work of John Wilkes, Charles Hussey and others under USAF research looking for new battery electrolytes. Dealt heavily with aluminum halide anions early on.

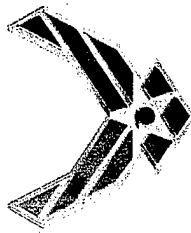


1-ethyl-3-methylimidazolium tetrachloroaluminate

Later, water stable ionic liquids were synthesized by Wilkes and coworkers which opened up the currently rapidly expanding field that we see today.

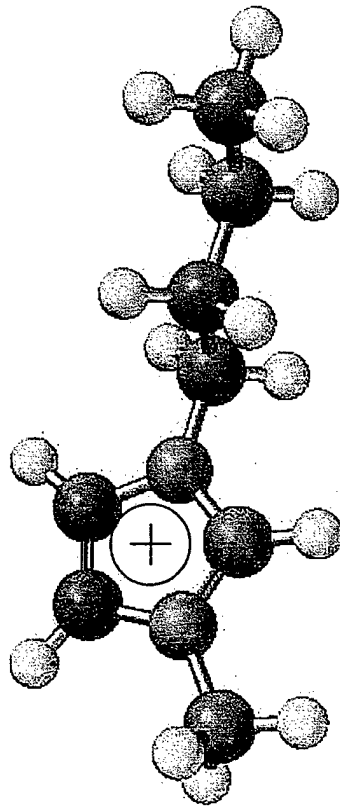


1-butyl-3-methylimidazolium hexafluorophosphate

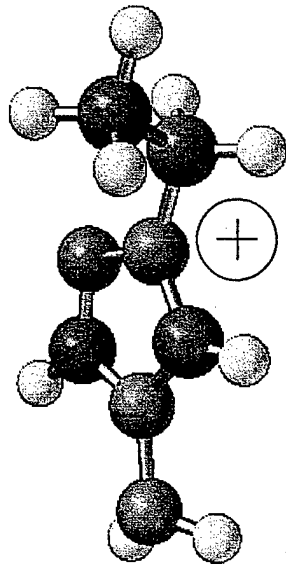


Ionic Liquids

Most ionic liquids are based upon imidazolium rings and “heavy” or “dead” anions. We felt that we could use the shape of the cation and the poor fit idea to make much more interesting salts in a simple manner.

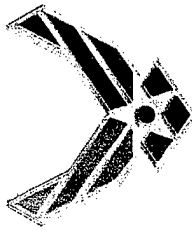


1-n-butyl-3-methyl imidazolium
cation

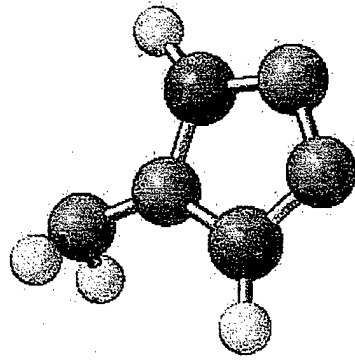


1-ethyl-4-amino-1,2,4-
triazolium cation

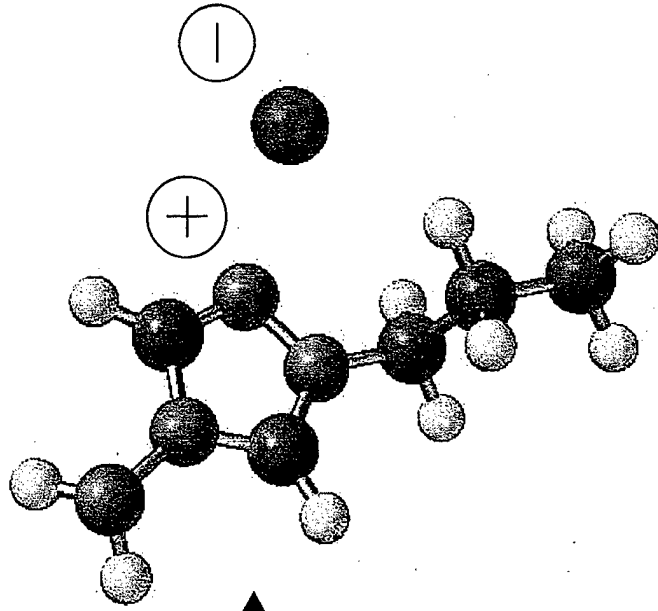
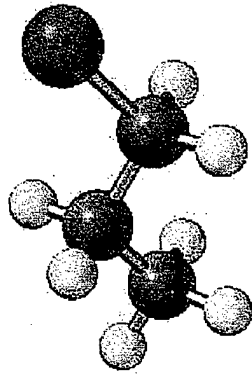
AFRL ionic liquids have similar shapes and physical properties, BUT higher ΔH_f , higher density, and better oxygen balances.



Ionic Liquids



+ XS



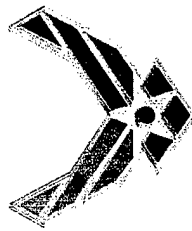
4-amino-1,2,4-triazole

N-propyl bromide

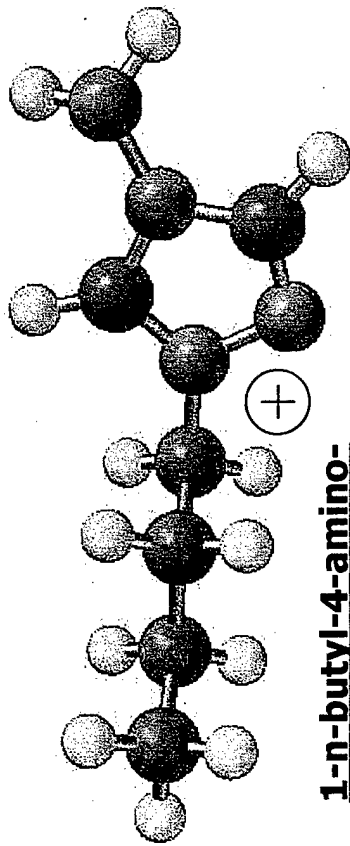
**Synthesis is from commercial materials
High yield simple isolation has been known
in literature for quite sometime.**

1-n-propyl-4-amino-
1,2,4-triazolium bromide
(yield >95% very pure)

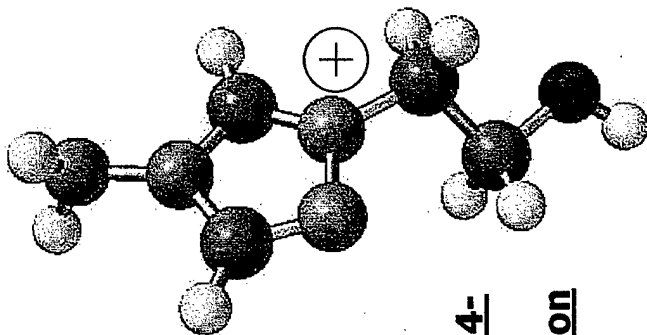
Scriven; Keay; Goe; Astleford J. Org. Chem. 1989, 54, 731.



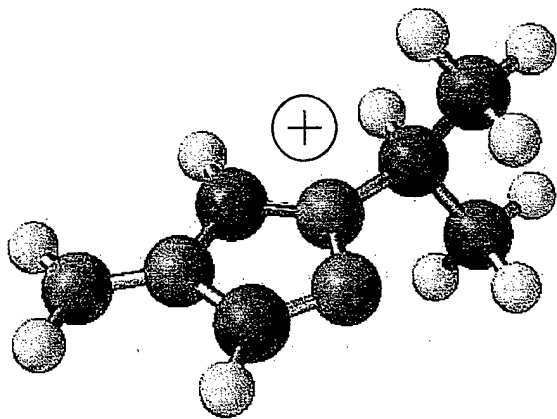
Ionic Liquids



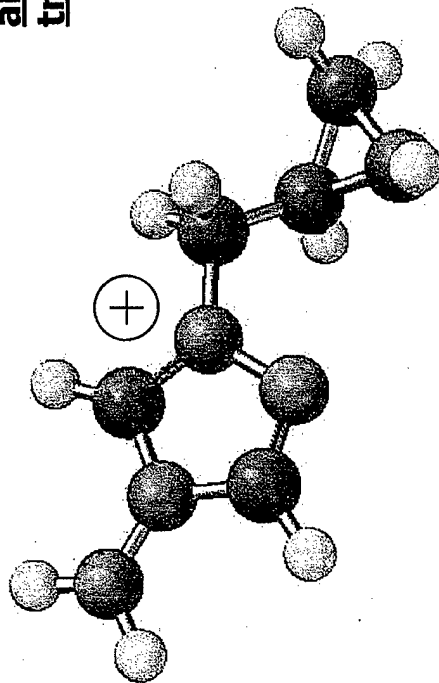
1-n-butyl-4-amino-1,2,4-triazolium cation



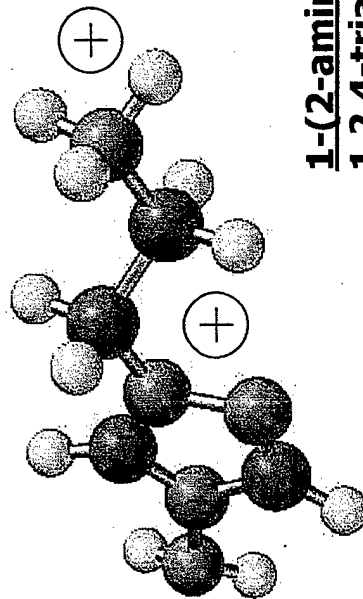
1-(2-ethanol)-4-amino-1,2,4-triazolium cation



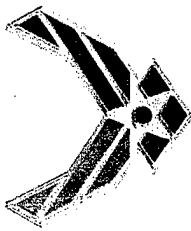
1-isopropyl-4-amino-1,2,4-triazolium cation



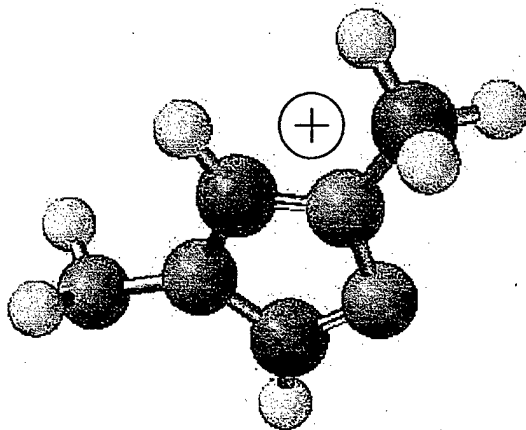
1-methylcyclopropyl-4-amino-1,2,4-triazolium cation



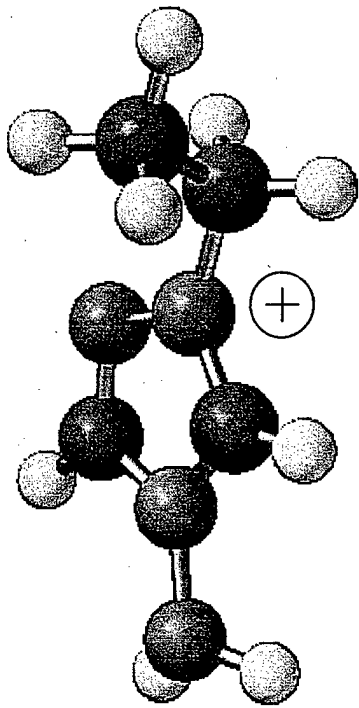
1-(2-aminoethyl)-4-amino-1,2,4-triazolium dication



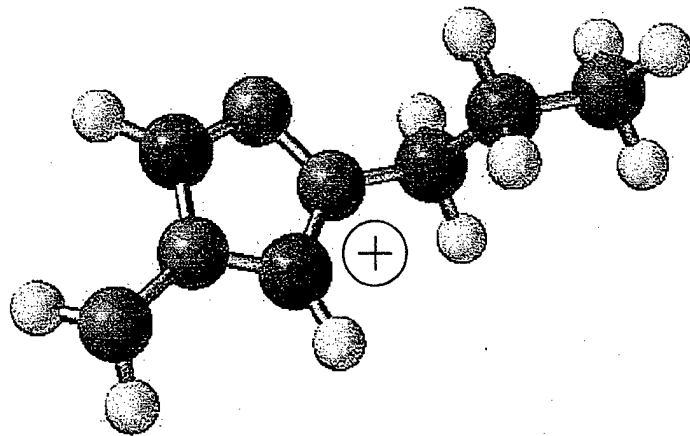
Ionic Liquids



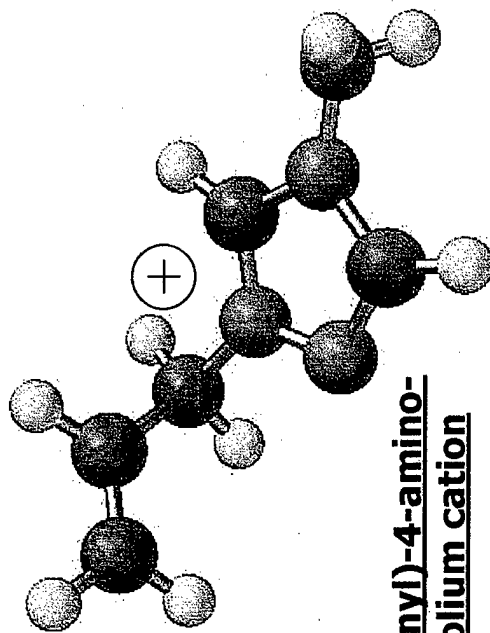
**1-methyl-4-amino-
1,2,4-triazolium cation**



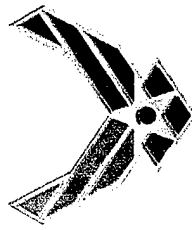
**1-ethyl-4-amino-
1,2,4-triazolium cation**



**1-n-propyl-4-amino-
1,2,4-triazolium cation**



**1-(2-propenyl)-4-amino-
1,2,4-triazolium cation**

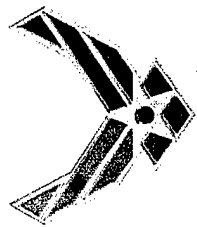


Ionic Liquids



Physical property trends of 1-n-alkyl substituted-4-amino-1,2,4-triazolium bromide salts roughly follow some trends but not all. Substituted 4-amino-1,2,4-triazolium bromide salts have increasing melting points with increasing molecular weights, decomposition onsets that are relatively low, and densities which follow the expected decreasing trend with increasing alkyl chain length.

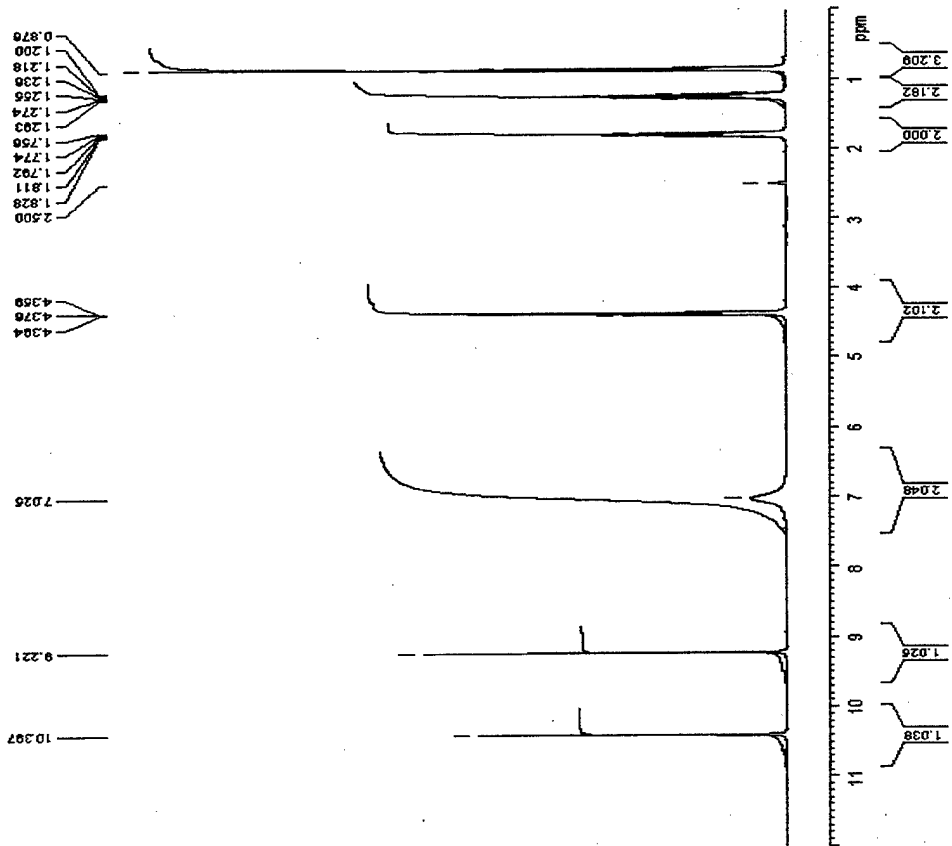
Substituted 4AT salts	m.p. (°C)	dec. onset (°C)	density (g/cm ³)
1-ethyl	63°	110	1.69
1-n-propyl	60°	120	1.56
1-isopropyl	90°	110	1.60
1-butyl	48°	130	1.46
1-n-pentyl	54°	130	1.37
1-n-hexyl	76°	120	1.34
1-n-heptyl	94°	120	1.30
1-n-octyl	80°	135	1.27
1-n-nonyl	81°	140	1.26
1-n-decyl	90°	135	1.23



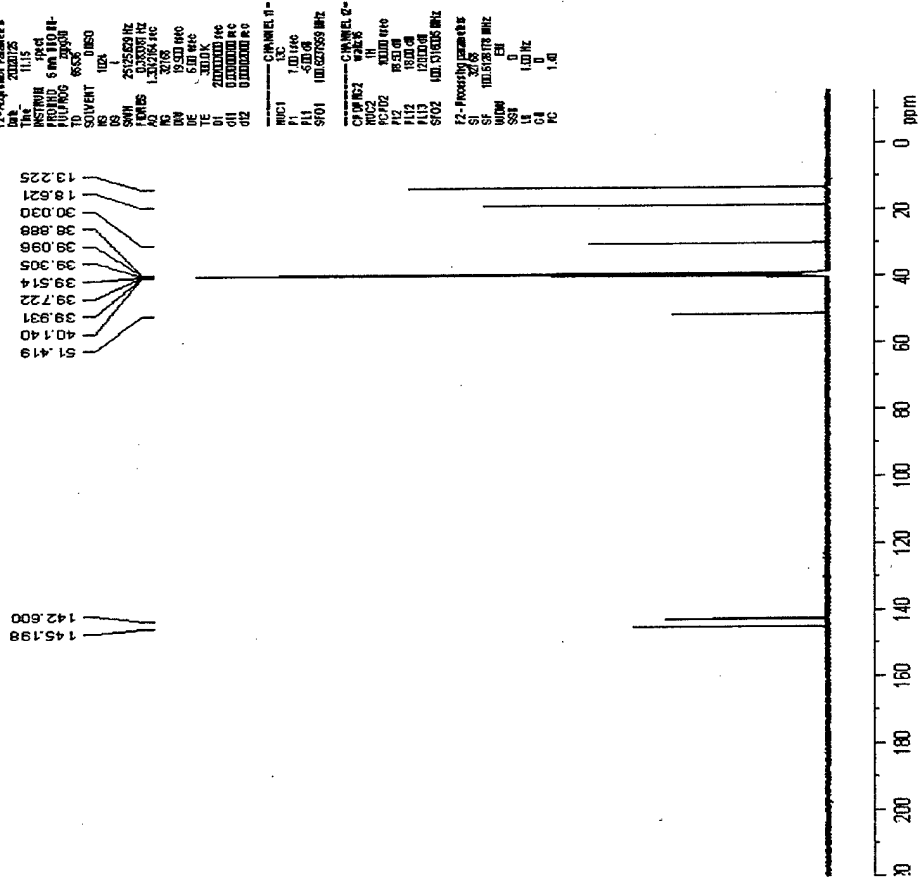
Ionic Liquids



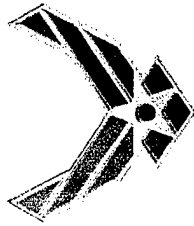
proton of 1-n-butyl 4-amino-1,2,4-triazolium bromide solid in d6-DMSO



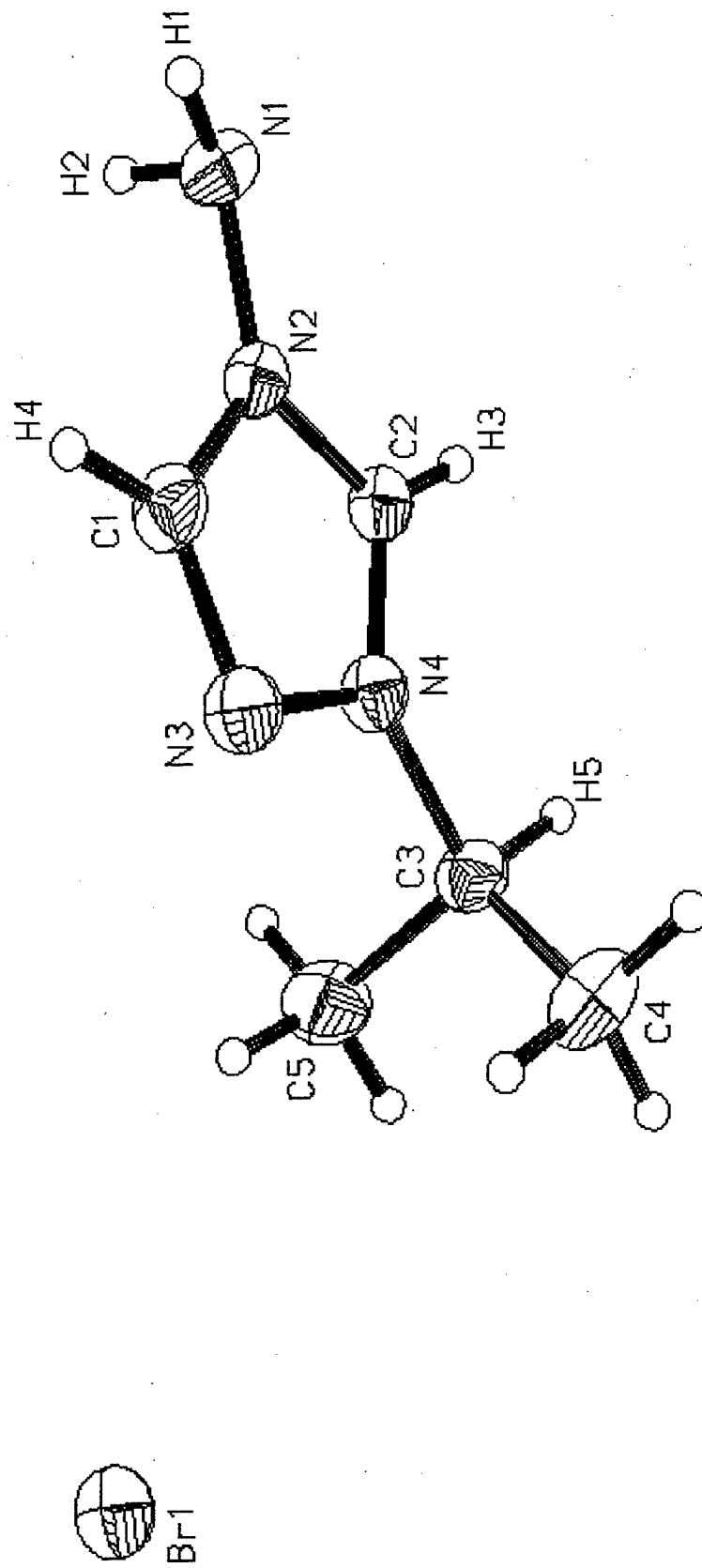
carbon of 1-n-butyl-4-amino-1,2,4-triazolium bromide solid in d6-DMSO



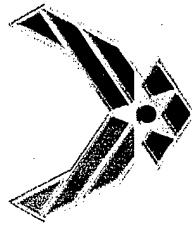
¹H(left) and ¹³C nmr spectra of 1-butyl-4-amino-1,2,4-triazolium bromide.



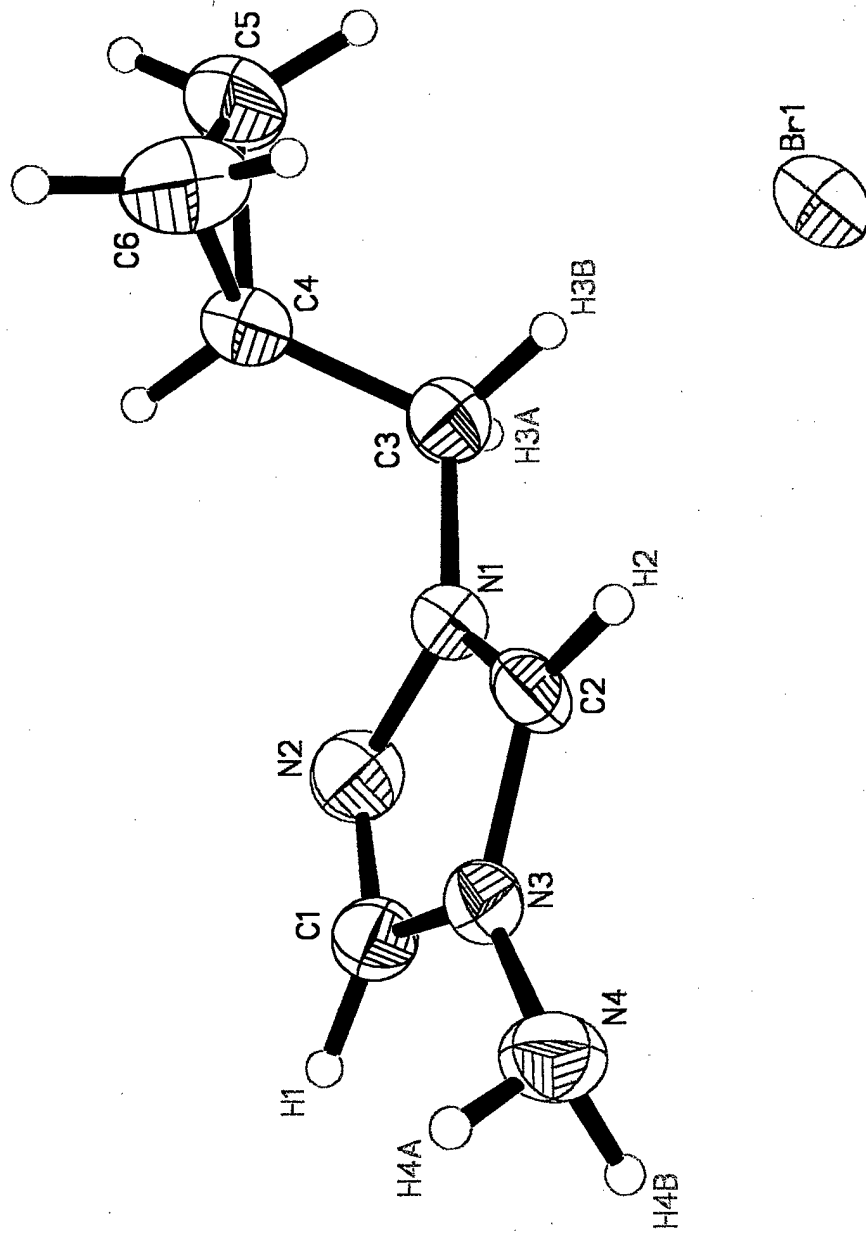
Ionic Liquids



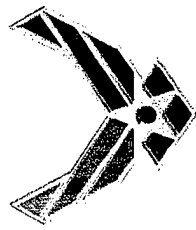
Single crystal x-ray diffraction study ORTEP view of 1-isopropyl-4-amino-1,2,4-triazolium bromide.



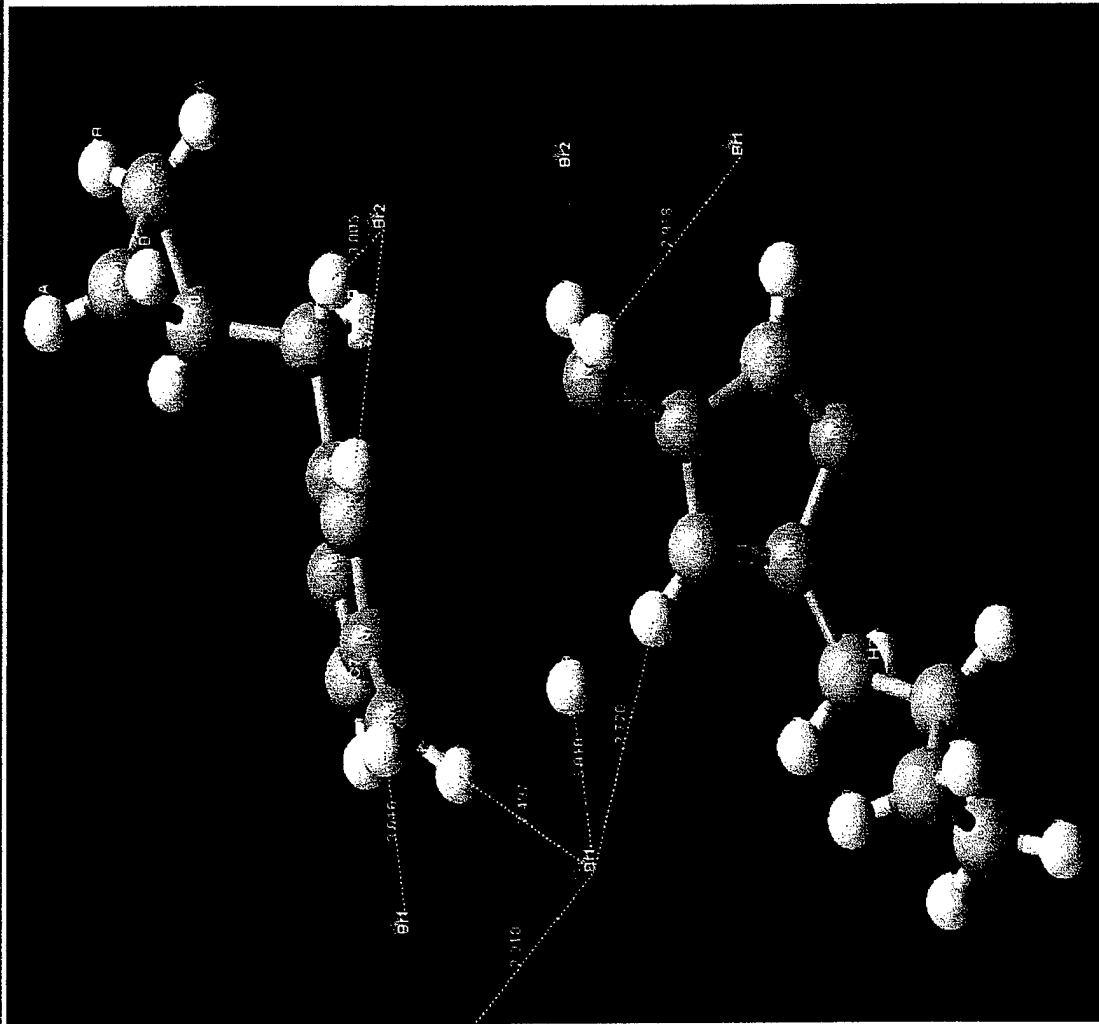
Ionic Liquids



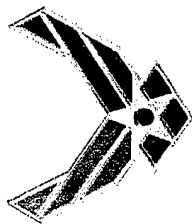
Single crystal x-ray diffraction study ORTEP view of 1-cyclopropylmethyl-4-amino-1,2,4-triazolium bromide(Dr. A. Vij and Lt L. Hall)



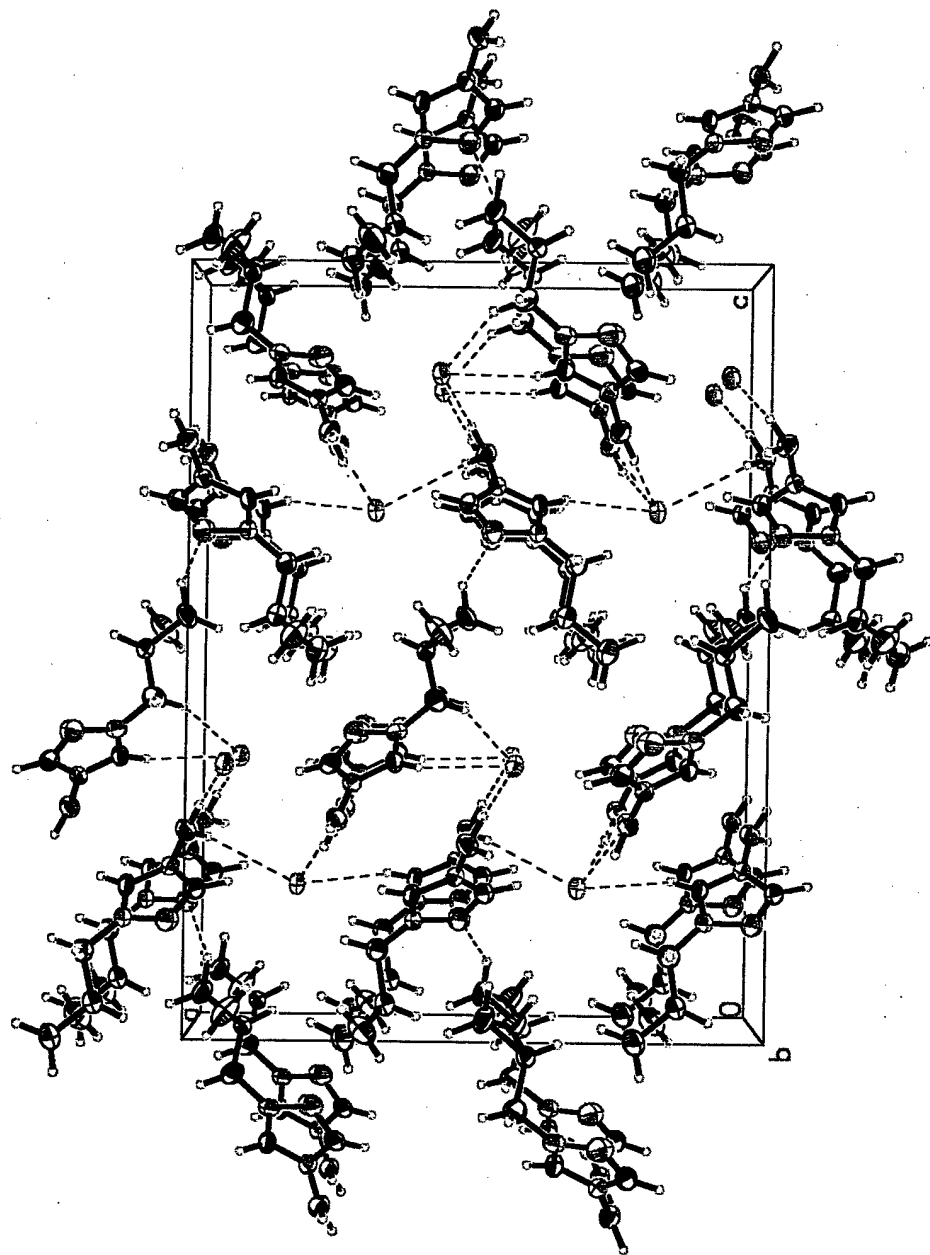
Ionic Liquids



Br--H-N interactions in 1-cyclopropylmethyl-4-amino-1,2,4-triazolium bromide



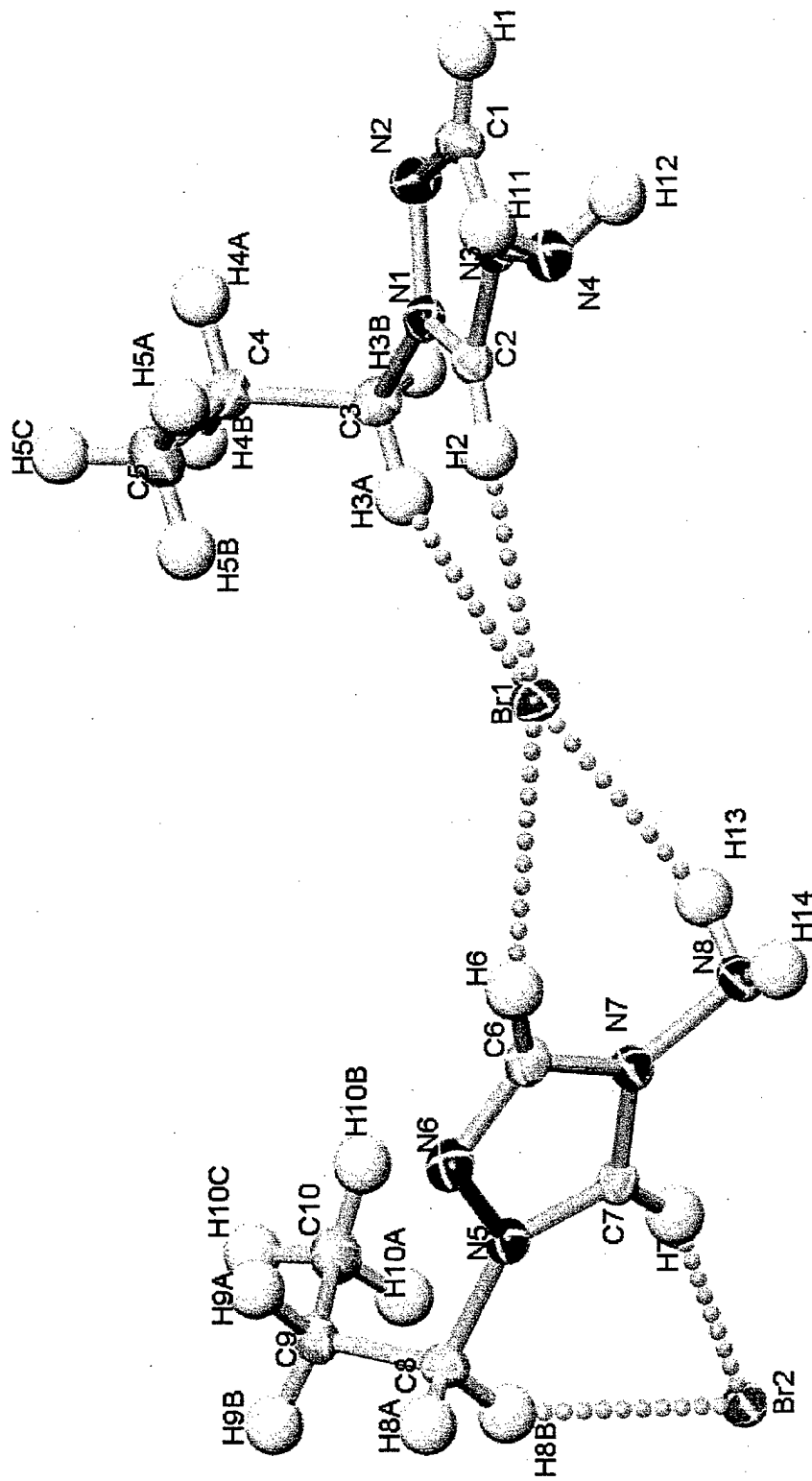
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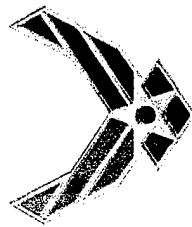
Packing in unit cell of 1-cyclopropylmethyl-4-amino-1,2,4-triazolium bromide



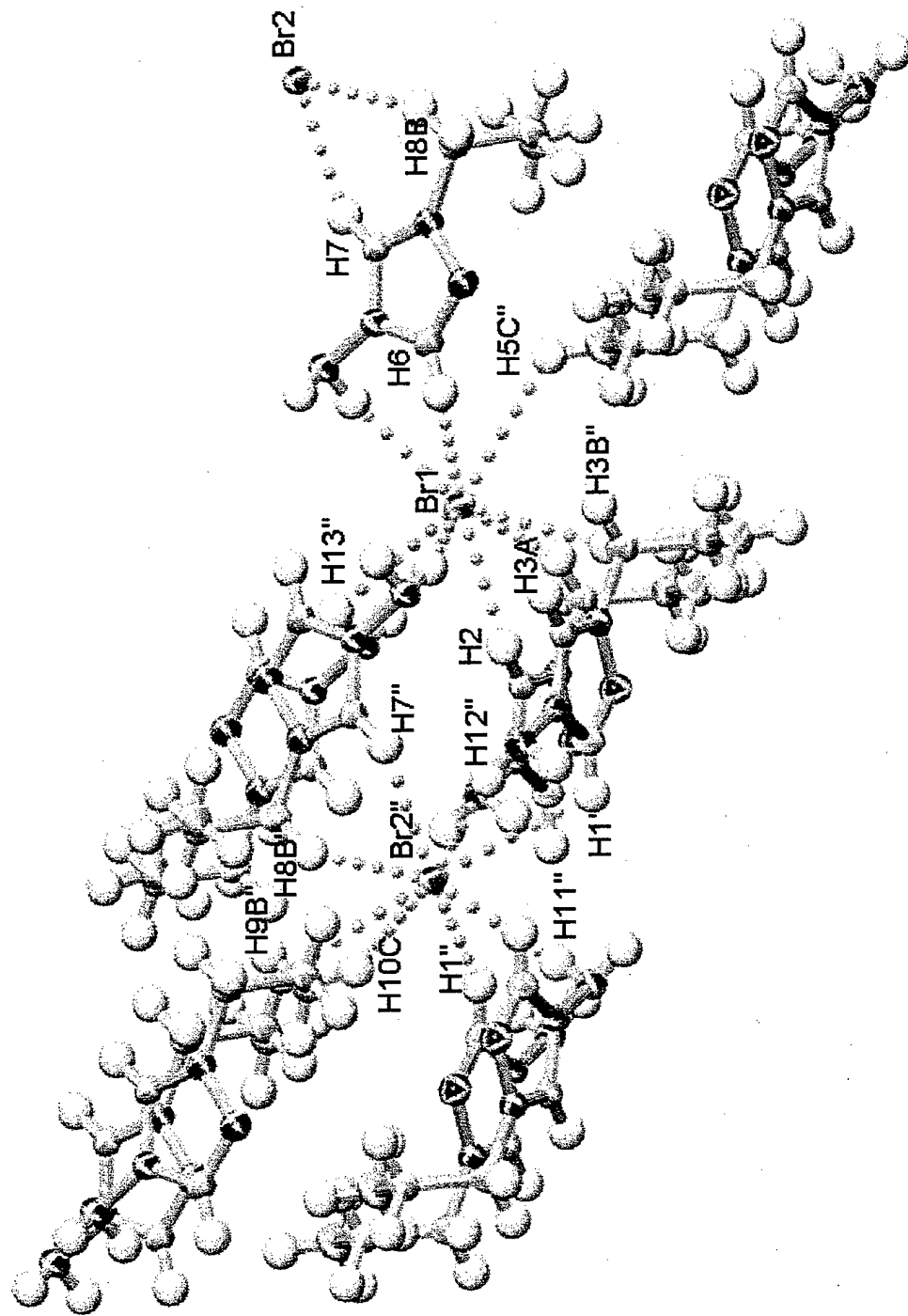
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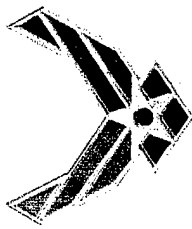
Single crystal x-ray diffraction study of 1-n-propyl-4-amino-1,2,4-triazolium bromide showing significant hydrogen bond contacts.



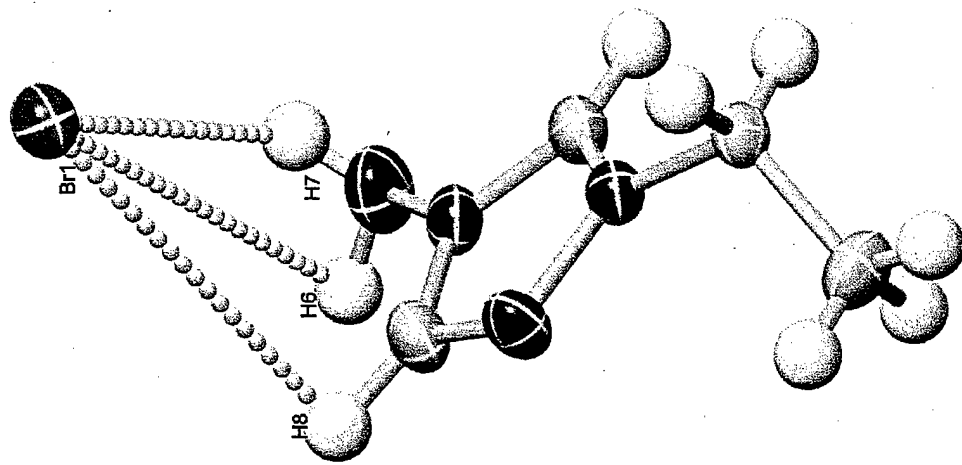
Ionic Liquids



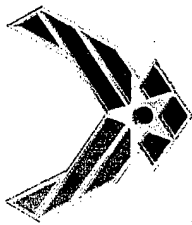
Extensive hydrogen bonding in 1-n-propyl-4-amino-1,2,4-triazolium bromide



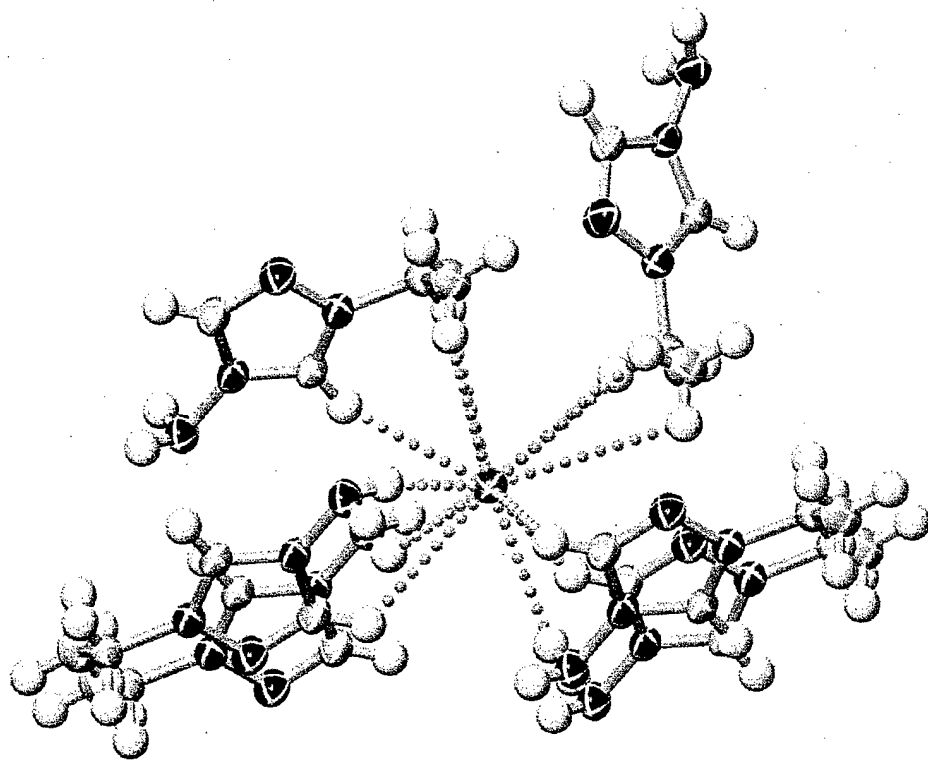
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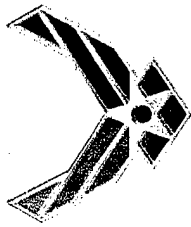
Single crystal x-ray diffraction study of 1-ethyl-4-amino-1,2,4-triazolium bromide



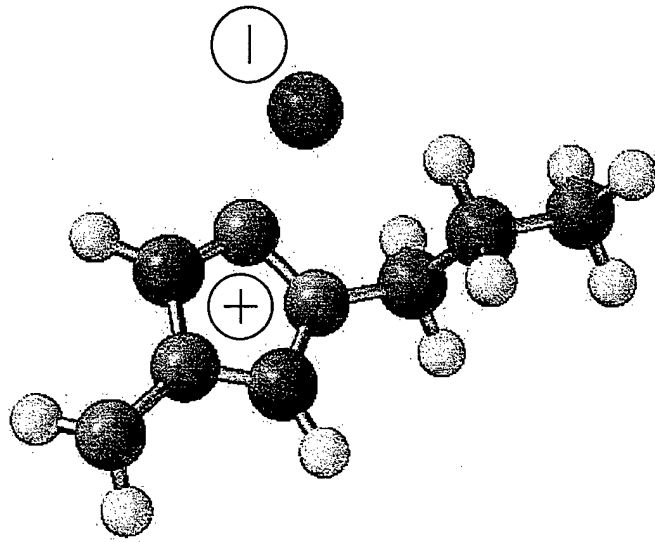
Ionic Liquids



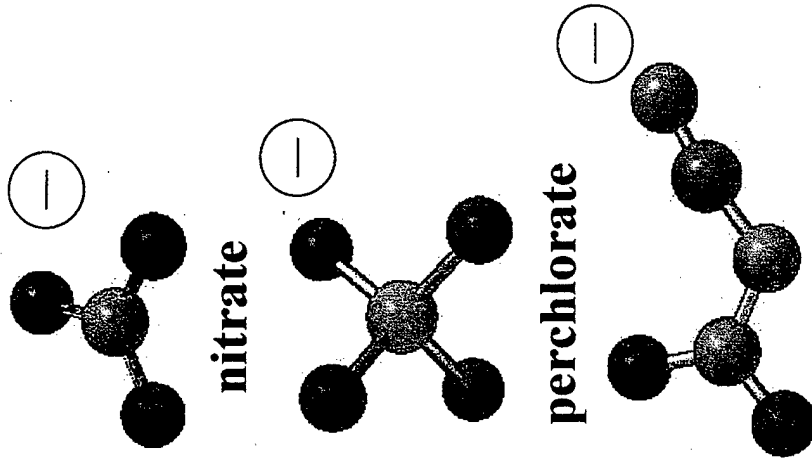
Extensive hydrogen bonding in crystalline 1-ethyl-4-amino-1,2,4-triazolium bromide



Ionic Liquids

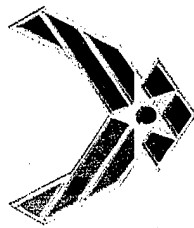


- AgBr



nitrocyanimide

Synthesis is straight-forward and high yield with simple filtration to remove silver halide to give high purity ionic liquid. We have synthesized a large family of new salts based on this methodology.



Ionic Liquids



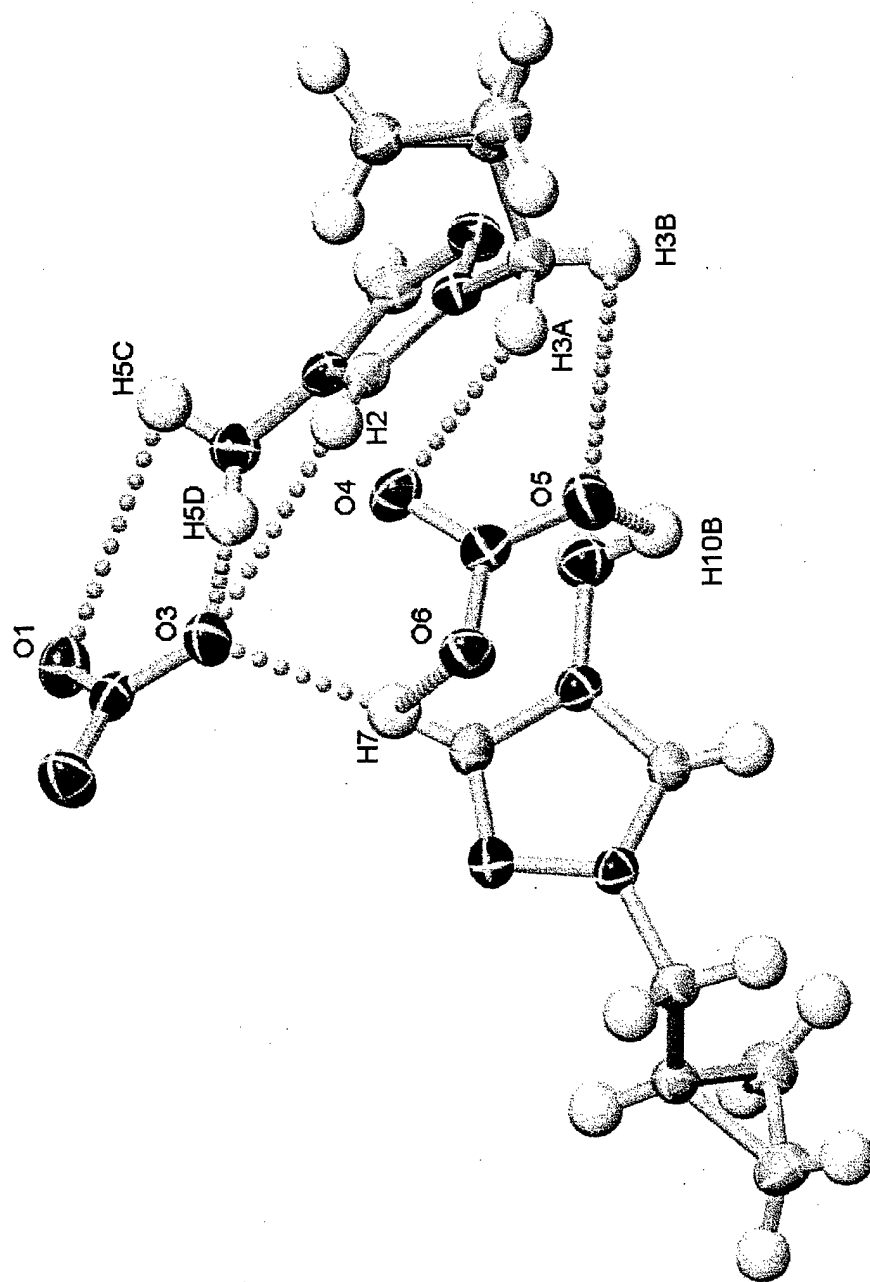
We have studied many but not all of the cation systems and have found some intriguing physical properties. The nitrate salts are much more thermally stable than their halide precursors and are extremely interesting.

1-substituted-4-amino-1,2,4-triazolium nitrate salts

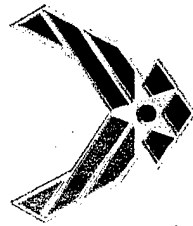
<u>Salt</u>	<u>melting point(°C)</u>	<u>decomp onset(°C)</u>	<u>density(g/cm³, est.)</u>
1-methyl	54	185	1.57
1-ethyl	5	185	1.39
1-n-propyl	34	190	1.35
1-n-butyl	-10	190	1.31
1-(2-ethanol)	10	180	1.48
1-methylcyclopropyl	56	190	1.36
1-(2-propenyl)	10	165	1.23



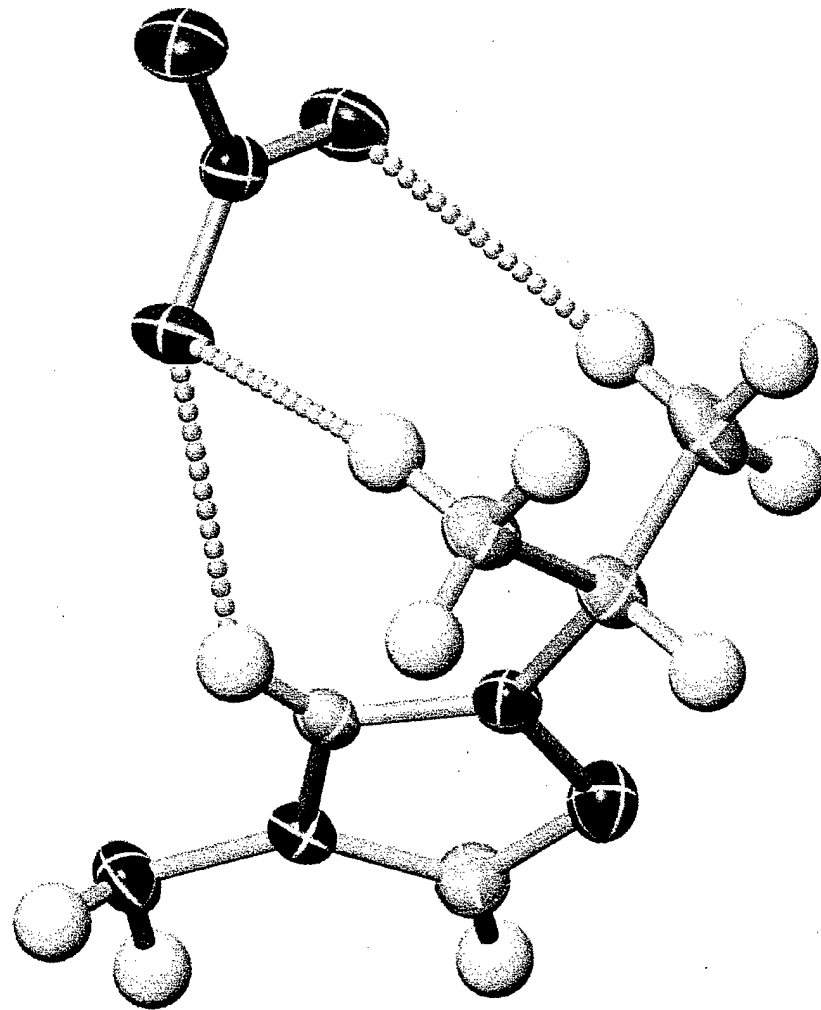
Ionic Liquids



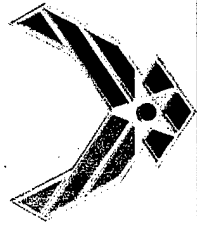
Single crystal x-ray diffraction study of 1-methylcyclopropyl-4-amino-1,2,4-triazolium nitrate showing extensive hydrogen bonding between the cation and the anion.



Ionic Liquids



Single crystal x-ray diffraction structure of 1-isopropyl-4-amino-1,2,4-triazolium nitrate



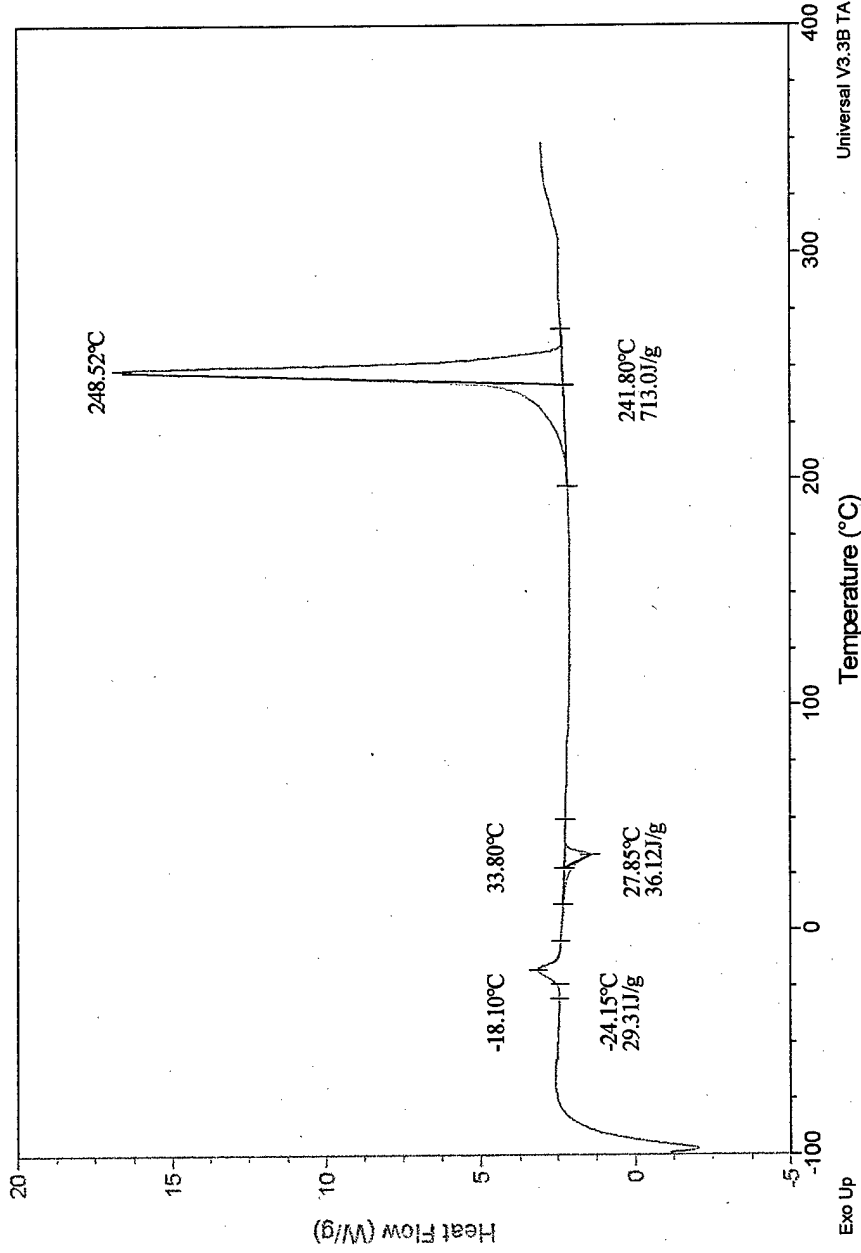
Ionic Liquids



Sample: 1-PROPYL-4-AT NITRATE
Size: 1.9000 mg
Method: greg
Comment: 10C/min/10ml/minhermeticalpans

DSC

File: C:\...Files from old DSC\4at propyl no3
Operator: DRAKE
Run Date: 16-Jan-02 23:04



DSC of 1-n-propyl-4-amino-1,2,4-triazolium nitrate



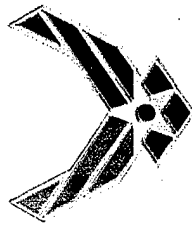
Ionic Liquids



The perchlorate salts are even more thermally stable than the nitrate salts and are interesting as well.

1-substituted-4-amino-1,2,4-triazolium perchlorate salts

<u>Salt</u>	<u>melting point(°C)</u>	<u>decomp onset(°C)</u>	<u>density(g/cm³, est.)</u>
1-methyl	83	250	1.62(1.59m)
1-ethyl	5	195	1.54
1-n-propyl	0	190	1.49
1-n-butyl	39	240	1.44
1-(2-ethanol)	10	175	1.63
1-methylcyclopropyl	5	150	1.49
1-(2-propenyl)	-11	185	1.31



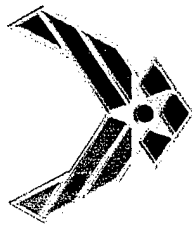
Ionic Liquids



The nitrocyamide salts are similar to the nitrate salts, are the least viscous, and have the lowest melting points.

1-substituted-4-amino-1,2,4-triazolium nitrocyamide salts

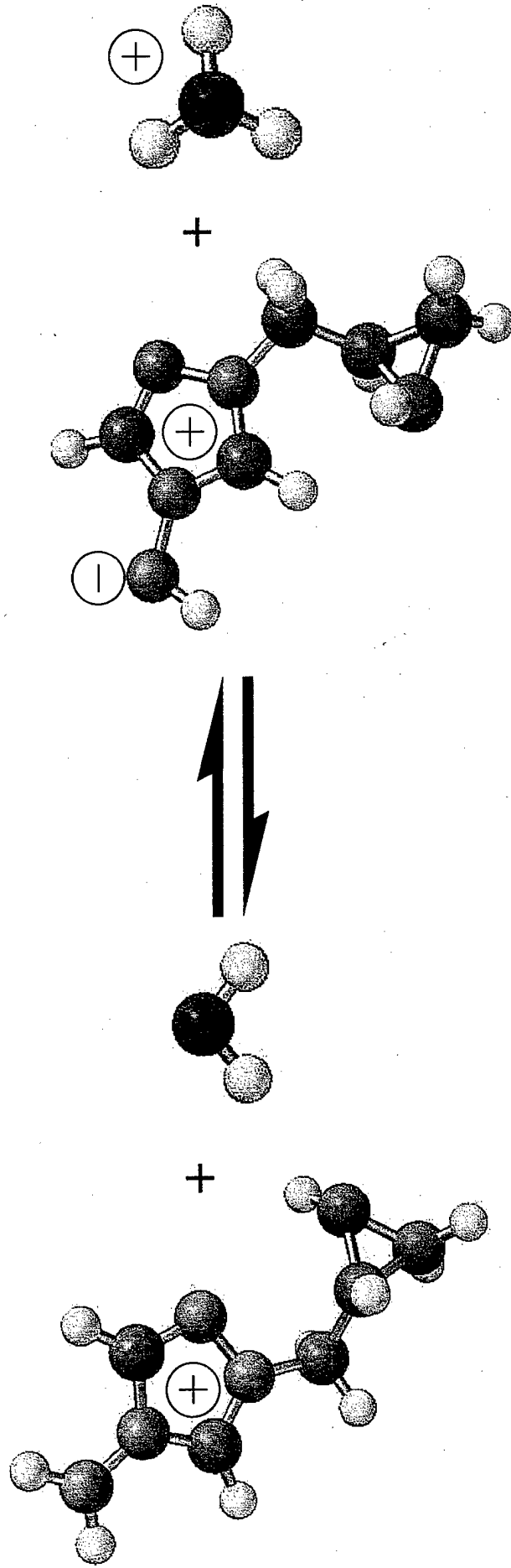
<u>Salt</u>	<u>melting point(°C)</u>	<u>decomp onset(°C)</u>	<u>density(g/cm³, est.)</u>
1-methyl	11	180	1.39
1-ethyl	10	175	1.37
1-n-propyl	5	185	1.33
1-n-butyl	< 0 ?	175	1.30
1-(2-ethanol)	< 0 ?	175	1.43
1-methylcyclopropyl	-10	195	1.35
1-(2-propenyl)	-11	185	1.23



Ionic Liquids



The new cations are weakly acidic in nature, aqueous solutions have a pH of around 5 which suggests the following equilibrium involving a zwitterionic 1-alkyl-4-amido-1,2,4-triazolium species. We have not tried to isolate this species yet to see if it exists. But similar chemistry has been observed with the acidic parent heterocycle 4-amino-1,2,4-triazole. This equilibrium could be one possible way for the ionic liquids to “come apart”.





Ionic Liquids

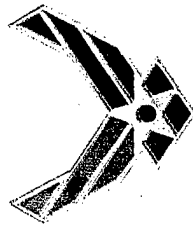


Summary and Conclusions

A large new class of low melting salts which are a member of the well known set materials identified as ionic liquids has been synthesized and well characterized. Using asymmetric cation shapes and poor cation-anion fit, an analogue system to the well known 1,3-dialkyl substituted imidazolium cation family, based upon 1-substituted-4-amino-1,2,4-triazolium cations and well known oxy- ions (NO_3^- , ClO_4^- , $\text{N}(\text{NO}_2)(\text{CN})^-$) has been explored. Facile synthesis routes from commercially available materials coupled with high yield and purity reactions make these new materials very exciting.

Several single crystal x-ray diffraction studies of several structures have been carried out proving the expected structure as well as revealing extensive hydrogen bonding in the solid state.

Thermal stabilities of the new low melting salts was as expected with the nitrate and nitrocyamide salts having roughly similar thermal stabilities with perchlorate salts being the most stable of all. This can be explained by the relative base strengths of the corresponding oxy-anion.



Ionic Liquids



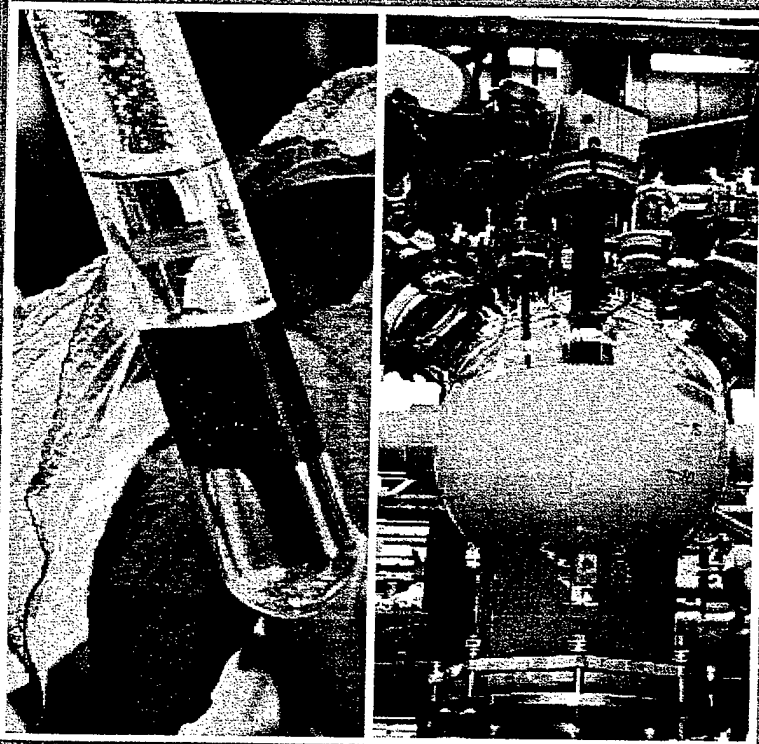
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1

Introduction

John S. Wilkes

Ionic liquids may be viewed as a new and remarkable class of solvents, or as a type of materials that have a long and useful history. In fact, ionic liquids are both, depending on your point of view. It is absolutely clear though, that whatever "ionic liquids" are, there has been an explosion of interest in them. Entries in Chemical Abstracts for the term "ionic liquids" were steady at about twenty per year through 1995, but had grown to over 300 in 2001. The increased interest is clearly due to the realization that these materials, formerly used for specialized electrochemical applications, may have greater utility as reaction solvents.

For purposes of discussion in this volume we will define ionic liquids as salts with a melting temperature below the boiling point of water. That is an arbitrary definition based on temperature, and says little about the composition of the materials themselves, except that they are completely ionic. In reality, most ionic liquids in the literature that meet our present definition are also liquids at room temperature. The melting temperature of many ionic liquids can be problematic, since they are notorious glass-forming materials. It is a common experience to work with a new ionic liquid for weeks or months to find one day that it has crystallized unexpectedly. The essential feature that ionic liquids possess is one shared with traditional molten salts: a very wide liquidus range. The liquidus range is the span of temperatures between the melting point and boiling point. No molecular solvent, except perhaps some liquid polymers, can match the liquidus range of ionic liquids or molten salts. Ionic liquids differ from molten salts in just where the liquidus range is in the scale of temperature.

There are many synonyms used for ionic liquids, which can complicate a literature search. "Molten salts" is the most common and most broadly applied term for ionic compounds in the liquid state. Unfortunately, the term "ionic liquid" was also used to mean "molten salt" long before there was much literature on low-melting salts. It may seem that the difference between ionic liquids and molten salts is just a matter of degree (literally); however the practical differences are sufficient to justify a separately identified niche for the salts that are liquid around room temperature. That is, in practice the ionic liquids may usually be handled like ordinary solvents. There are also some fundamental features of ionic liquids, such as strong

A note from the editors

This book has been arranged in several chapters that have been prepared by different authors, and the reader can expect to find changes in style and emphasis as they go through it. We hope that, in choosing authors who are at the forefront of their particular specialism, this variety is a strength of the book. The book is intended to be didactic, with examples from the literature used to illustrate and explain. Therefore, not all chapters will give a comprehensive coverage of the literature in the area. Indeed, with the explosion of interest in some applications of ionic liquids comprehensive coverage of the literature would not be possible in a book of this length. Finally, there is a point when one has to stop and for us that was the end of 2001. We hope that no offence is caused to anyone whose work has not been included. None is intended.

Acknowledgements

We would like to sincerely thank everyone who has been involved in the publication of this book. All of our authors have done a great job in preparing their chapters and it has been a pleasure to read their contributions as they have come in to us. When embarking on this project we were both regaled with stories of books that never saw the light of day because of missed deadlines and the general tardiness of contributors. All of our colleagues have met their commitments in the most timely and enthusiastic manner. We are truly grateful for them making our task so painless. We would also like to thank the production team at VCH-Wiley, particularly Dr. Karen Kriese.

Finally, in a project like this, someone must take responsibility for any errors that have crept in. Ultimately we are the editors and this responsibility is ours. So we apologise unreservedly for any mistakes that have found their way into the book.

P. Wasserscheid, T. Welton
August, 2002

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TETRAHEDRON
LETTERS

Novel organic ionic liquids (OILs) incorporating cations derived from the antifungal drug miconazole.

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Abstract

The imidazole-ring containing antifungal drug miconazole reacts with a variety of alkyl iodides to form imidazolium cations. After anion metathesis with NaPF₆, organic ionic liquids (OILs) are obtained. These new ionic liquids are believed to be the first to be derived from a bioactive molecule. One of the new OILs also exhibits lyotropic liquid crystalline behavior while inducing the gelation of benzene. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: ionic liquids; liquid crystals; antifungals; imidazoles

Organic ionic liquids (OILs), may be defined as materials which incorporate at least one organic ion in an ion pair which is liquid at temperatures of ~150°C or lower [1-3]. Because of a number of useful properties which they possess, OILs are of interest for development in several areas, including catalysis, electrochemistry and as solvents for "green" chemistry [2-4]. Most of the OILs described to date are combinations of a 1-butyl-3-methylimidazolium [bmim]⁺, 1-ethyl-3-methylimidazolium [emim]⁺ or *N*-butylpyridinium cation and a charge-diffused inorganic anion [4].

In connection with an ongoing project involving the use of azolium ions as carbene ligand precursors, we have prepared several novel imidazolium cations derived from drugs and natural products [5]. The side chains of these cations are structurally complex and functionally diverse compared to those commonly used in OILs. As an adjunct to our carbene work, we deemed it worthwhile to determine if these or related imidazolium ions might be utilized as the cation component of OILs. We now report the initial results of one of these studies, in which

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Ionic Liquids—New “Solutions” for Transition Metal Catalysis

Peter Wasserscheid* and Wilhelm Keim

Ionic liquids are salts that are liquid at low temperature (<100°C) which represent a new class of solvents with nonmolecular, ionic character. Even though the first representative has been known since 1914, ionic liquids have only been investigated as solvents for transition metal catalysis in the past ten years. Publications to date show that replacing an organic solvent by an ionic liquid can lead to remarkable

improvements in well-known processes. Ionic liquids form biphasic systems with many organic product mixtures. This gives rise to the possibility of a multiphase reaction procedure with easy isolation and recovery of homogeneous catalysts. In addition, ionic liquids have practically no vapor pressure which facilitates product separation by distillation. There are also indications that switching from a nor-

mal organic solvent to an ionic liquid can lead to novel and unusual chemical reactivity. This opens up a wide field for future investigations into this new class of solvents in catalytic applications.

Keywords: biphasic catalysis · homogeneous catalysis · ionic liquids · solvent effects

1. Introduction

In general, an ionic liquid is a liquid that consists only of ions. However, this term includes an additional special definition to distinguish it from the classical definition of a molten salt.^[1] While a molten salt is generally thought to refer to a high-melting, highly viscous and very corrosive medium, ionic liquids are already liquid at low temperatures (<100°C) and have relatively low viscosity. The apparently somewhat arbitrary line drawn between molten salts and ionic liquids at a melt temperature of 100°C can be justified by the abrupt improvement in the range of applications for liquid salts below this temperature. Even though some examples are known in which high-temperature salt melts have been successfully used as reaction media for synthetic applications,^[2] only a liquid range below 100°C can enable the versatile substitution of conventional, organic solvents by ionic liquids.

The development of ionic liquids goes back to 1914. First research efforts dealt with the synthesis of ethylammonium nitrate.^[3] This salt is liquid at room temperature but usually contains a small amount of water (200–600 ppm).^[4]

The first ionic liquids with chloroaluminate ions were developed in 1948 by Hurley and Wier at the Rice Institute in

Texas as bath solutions for electroplating aluminum.^[5] However, these systems were not studied further until the late 1970s when the groups of Osteryoung and Wilkes rediscovered them. For the first time, they succeeded in preparing room-temperature liquid chloroaluminate melts.^[6] Research and development concentrated mainly on electrochemical applications at this time.

As early as 1967, a publication by Swain et al described the use of tetra-*n*-hexylammonium benzoate as a solvent for kinetic and electrochemical investigations.^[7] Even though the liquid salt was a hemihydrate at room temperature, this research work had a pioneering significance because it already contained a quantitative determination of the ionization strength of the ionic medium.

In the early 1980s the groups of Seddon and Hussey began to use chloroaluminate melts as nonaqueous, polar solvents for the investigation of transition metal complexes. The investigations generally started with the electrochemical aspects of the relevant transition metal complexes;^[8] spectroscopic and complex chemistry experiments followed.^[9] It is specially thanks to Seddon's work that ionic liquids became more familiar to a broad public.

The first publications in which ionic liquids were described as new reaction media and catalysts for organic synthesis appeared at the end of the 1980s. Acidic ionic liquids with chloroaluminate ions proved to be effective Friedel-Crafts catalysts;^[10] phosphonium halide melts were used successfully in nucleophilic aromatic substitution reactions.^[11]

The use of ionic liquids as solvents for homogeneous transition metal catalysts was described for the first time in

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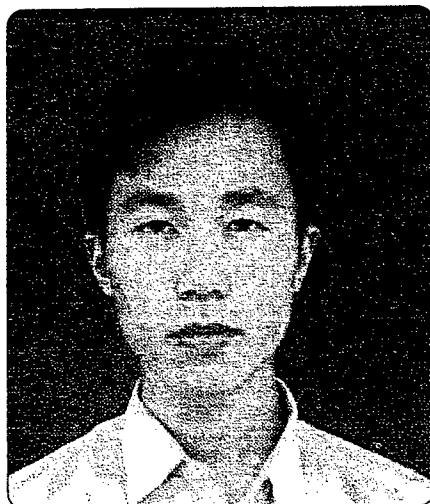
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Outline

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3. Transition-Metal-Mediated Catalyses
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 - 3.2. Oxidation
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 - 4.1. Diels–Alder Reaction
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6. Summary
7. References and Notes

1. Introduction

An ionic liquid (IL) is a liquid consisting of ions only, but this definition is different from the classic definition of a molten salt.¹ The latter is a high-melting, highly viscous, and highly corrosive liquid, while an ionic liquid is liquid at a much lower temperature (< 100 °C) and has a lower viscosity. Currently, a major drive is underway in industry and academia to substitute more environmentally friendly technologies for traditional ones in which damaging and volatile organic solvents are heavily used. Ionic liquids are considered as environmentally friendly substitutes for volatile organic solvents, not only because of their low vapor pressures, but, more



importantly, also because of their ability to act as catalysts. Moreover, ionic liquids possess several other attractive properties, including chemical and thermal stability, nonflammability, high ionic conductivity, and a wide electrochemical potential window.

Ambient-temperature, alkyipyridinium (RPy⁺) chloroaluminate based ionic liquids were first reported in the early 1950s.² However, the report by Wilkes and co-workers^{3a} of 1,3-dialkylimidazolium-based chloroaluminate ionic liquids, that possess favorable physical and electrochemical properties, provided the impetus for a dramatic increase in activity in this area.^{3b} Ionic liquids usually consist of inorganic anions and nitrogen-containing organic cations, and their chemical and physical properties can be finely tuned for a range of applications by varying the cations or anions.⁴ For example, varying the anion X in [EMIM][X] changes the melting point of the ionic liquid in the range of –14 to 87 °C.⁵ The fact that they can now be produced with melting points at or below room temperature (as low as –96 °C) has been an important reason why ionic liquids have been explored in many applications.¹



Recent reviews have surveyed the behavior of halogenoaluminate(III) ionic liquids in many reactions including dimerization, polymerization, and multiphase hydrogenation.⁶ Since halogenoaluminate(III)-type ionic liquids are sensitive to moisture, their applications in chemical reactions have been limited. Stable, room-temperature ionic liquids (RTILs) have been studied in many chemical processes, for example, bio-processing operations,⁷ as electrolytes in electrochemistry,^{8,9} in gas separations such as the capturing of CO₂,¹⁰ in liquid–liquid extractions,^{11,12} and as heat-transfer fluids.¹³ However, since most studies have employed ionic liquids as green solvents or catalysts for organic synthesis, this review will summarize recent research on the applications of RTILs in organic reactions.

2. Composition of Ionic Liquids

The most commonly used cations in room-temperature ionic liquids are alkylammonium, alkylphosphonium, *N,N'*-dialkylimidazolium ([RR'IM]), and *N*-alkylpyridinium ([RPy]) cations (Figure 1).⁵ The most commonly utilized alkyl chains are methyl, ethyl, butyl, hexyl, octyl, and decyl. The most commonly investigated IL anions are shown in Table 1.^{4,14–22}