Tetrahedron Letters 52 (2011) 5308–5310

Contents lists available at SciVerse ScienceDirect

Tetrahedron Letters

journal homepage: www.elsevier.com/locate/tetlet

Investigation of carbon-2 substituted imidazoles and their corresponding ionic liquids

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ARTICLE INFO

Article history:
Received 18 June 2011
Revised 29 July 2011
Accepted 1 August 2011
Available online 9 August 2011

Keywords:
Imidazole
Ionic liquid
Organic synthesis
Substituent

ABSTRACT

The functionality at the C-2 position of the imidazole ring plays a key role in defining the chemical properties of the imidazoles and their corresponding ionic liquids. Imidazoles **1**–**6** with different C-2 functionality were synthesized and their corresponding ionic liquids were systematically investigated. Based on their physical properties the six imidazoles can be divided into three groups. (1) The imidazoles **2** and **3** are capable of self-polymerization to form poly(ionic liquid)s, and they are characterized with a strong leaving group at the C-2 position. (2) The imidazoles **4** and **5** can form ionic liquids, but they are very sensitive to moisture. (3) The imidazoles **1** and **6** can form stable ionic liquids, and their stabilities were influenced by the electronic effects of the substituents at the C-2 position.

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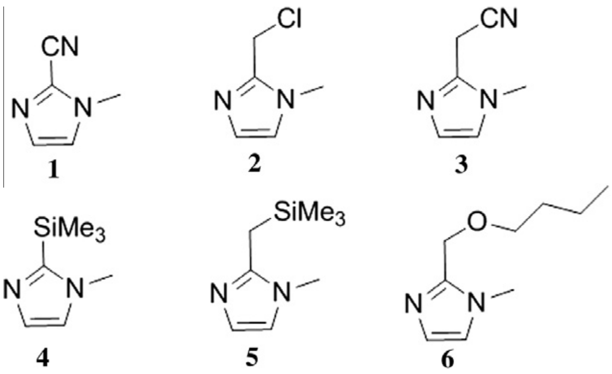
Since the first discovery by Walden in 1914, ambient temperature ionic liquids (ILs) have attracted considerable interest due to their favorable properties such as non-flammability, high chemical and thermal stability, negligible vapor pressure, and high ionic conductivity.[1] As a result, ionic liquids have been used in a wide range of applications such as organic synthesis,[2] nanostructure materials,[3] separation,[4] electrolytes for lithium-ion battery,[5] and electrochemical capacitors.[6] The discovery of air-stable ionic liquid based on 1-ethyl-3-methylimidazolium cation with BF_4^- has inspired researchers to focus more on these imidazolium ionic liquids.[7] Compared with the ionic liquids based on phosphonium, tetraalkylammonium, and pyridinium structures, imidazolium ionic liquids usually have the advantages of low viscosity and high ionic conductivity because of their highly delocalized charges.[6] The functionalization of imidazolium ionic liquids is mainly focused on the appendages at the N-1 and N-3 positions (Scheme 1).[8] For example, task-specific ionic liquids were synthesized by incorporating functional groups such as urea, thiourea, metal complexes, phosphine and silicate at the N-1 and N-3 positions, in order to tune their physical properties such as polarity, hydrophobicity/hydrophilicity, and miscibility with solvents.[9] However, so far few studies have focused on C-2 functionalized imidazolium ionic liquids. In fact, most of the imidazolium ionic liquids have one proton at the C-2 position and the acidity of this particular proton reduces the electrochemical window of the ionic liquids and thus limits their application in electric energy storage applications.[6,10] With a simple methyl substitution at the C-2 position, the chemical and electrochemical stability of the 1-butyl-2,3-dimethylimidazolium bis(trifluoromethylsulfonyl) imide ([bdmim]- TFSI) is greatly improved than its C2-H analog, [bmim]TFSI.[10] In this study, a series of C-2 substituted imidazoles (**1**–**6**, Scheme 2) were synthesized and used to prepare ionic liquids for the first time. Because of the different functional groups at the C-2 position, they show remarkable difference in their stability and reactivity, which will be discussed in detail later.



Scheme 1. The structures of imidazoles **1**–**6**.

The six C-2-modified 1-methylimidazoles **1**–**6** shown in Scheme 1 were synthesized via three different reactions. (1) A simple reaction between 1-methylimidazole and a cyanating reagent.

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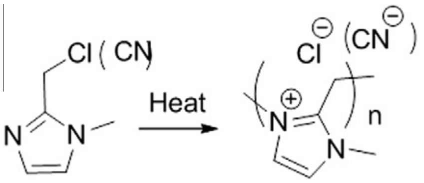
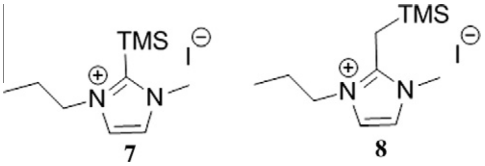
0040-4039/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.tetlet.2011.08.010



Scheme 2. Self-polymerization of **2** and **3**.



Scheme 3. Imidazolium iodides **7** and **8**.

Imidazole **1** was prepared by the reaction of 1-methylimidazole with 1-cyano-4-dimethylaminopyridinium bromide salt[11] in a one-step synthesis. (2) A reaction involving the formation of 2-hydroxymethyl-1-methylimidazole.[12] This category includes the compounds **2**, **3**, and **6**. Compound **2** was obtained quantitatively by the reaction of 2-hydroxymethyl-1-methylimidazole with thionyl chloride. Compound **3** was obtained by the nucleophilic reaction of **2** with sodium cyanide in DMSO solution at room temperature. For the synthesis of compound **6**, 2-(hydroxymethyl)-1-methylimidazole was deprotonated with excess NaOH before addition of 1-bromobutane. Catalytical amount of tetrabutylammonium bromide was used in the reaction as the phase transfer catalyst.[13] (3) A reaction involving lithiation by *n*-butyllithium at −78 °C followed by addition of trimethylsilyl chloride. Synthesis of the compounds **4** and **5**[14] falls into this category. The details of the synthesis and structure characterization of **1**–**6** were presented in the Supporting Information.

The stability of the imidazoles (hence imidazolium ionic liquid) largely depends on the C-2 functionality. The deprotonation of the C2-H imidazolium cations and decarboxylation in 1,3-dimethylimidazolium-2-carboxylates lead to the formation of *N*-heterocyclic carbene (NHC).[15] Another common side reaction that occurs with C2-H imidazolium cations is the Baylis–Hillman reaction.[16] The C-2 substitutes of the imidazoles in our work (Scheme 1) avoid the use of carboxylate groups and can prevent the carbene formation. The reactivities of these C-2 substituted imidazoles (**1**–**6**) and the stabilities of their corresponding ionic liquids are investigated. Based on their behaviors, these imidazoles can be divided into three groups: (1) the imidazoles **2** and **3** are capable of self-polymerization to generate poly(ionic liquid)s; (2) the imidazoles **4** and **5** can form ionic liquids, but are very moisture-sensitive and (3) the imidazoles **1** and **6** can lead to stable ionic liquids with properties tunable by the electronic effect of the substituents at the C-2 position.

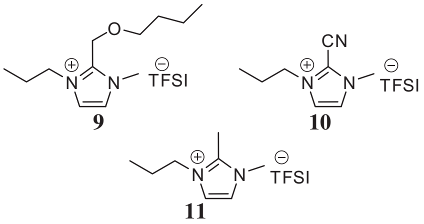
In group 1, upon heating both **2** and **3** underwent self-polymerization quickly (Scheme 2) because of the good leaving ability of the chloro and cyano groups, respectively. A similar self-reaction was utilized to synthesized the cyclic 1-butyl-2,3-trimethyleneimidazolium bis(trifluoro methanesulfonyl)imide ([b-3C-im][TSFI]).[17] In the case of **2** and **3**, the alkyl chain linkage is too short to self-alkylate to form a cyclic product. The self-polymerization of similar imidazoles with chloroalkyl substituents at the N-1 position has been reported,[18] and the advantage of such polymerization is that no inhibitor is required. The resulting poly(ionic liquids) can undergo metathesis with different anions (TFSI^-, N(CN)_2^-, and C(CN)_3^-) in order to tune their physical properties such as polarity, hydrophobicity, and miscibility with solvent. These poly(ionic liquids) can be used as surface coating agent for a variety of applications and also can be used as electrolytes for fuel cell, solar cell and lithium ion battery applications.[19]

In group 2 both **4** and **5** underwent hydrolysis quickly upon exposure to air and moisture because of their instability as 2-trimethylsilyl *N*-heterocyclic compounds. The C–Si bond cleaves under mild conditions because of the assisting role of the sp^2 N atom.[14] In order to avoid long reaction time and exposure to moisture, the alkylation of **4** and **5** were carried out with the highly reactive 1-iodopropane in anhydrous benzene under inert atmosphere. Compared with its original imidazole **4**, the reactivity of imidazolium iodide **7** (Scheme 3) toward moisture increased dramatically. In fact, upon exposure to air, all the TMS leaving groups in **7** were immediately replaced by protons. The imidazolium iodide **8** (Scheme 3) showed lower but still significant reactivity toward water, and slowly decomposed to the 1-propyl-2,3-dimethylimidazolium iodide. The ^{1}H NMR spectrum of the **8** still shows loss of TMS group (~33%, Supplementary Information).

In group 3 the reaction of both **1** and **6** with 1-bromopropane went smoothly in toluene with high yields. The resulting imidazolium bromide was stable toward water and can undergo metathesis with LiTFSI. The TFSI anion was chosen because its negative charge is highly delocalized and the corresponding ionic liquids have low melting points, as well as high chemical and electrochemical stability. The resulting stable ionic liquids are **9** and **10**, (Scheme 4), respectively. Their analog with a methyl substitution at the C-2 position (([bdmim][TFSI], IL **11**, Scheme 4) was also synthesized as a reference compound.

The thermal stability of IL **9**–**11** was studied by TGA under nitrogen atmosphere between RT and 700 °C at a heating rate of 10 °C/min. The bromide impurities in these ILs were negligible because during the synthesis, the ionic liquids were repeatedly washed with copious amount of water until the chloride test with 0.1 M AgNO_3 is negative. As shown in Figure 1, all the ionic liquids are thermally stable above 300 °C. Interestingly, TGA trace of **10** shows a small plateau between 500 and 750 °C, which was due to the carbon formation via the crossing linking of the CN functional group, as studied by our group previously.[20]

These C-2 substituted ionic liquids **9**–**11** showed enhanced chemical stability. Common methodologies to test the chemical



Scheme 4. Structures of ionic liquids **9**–**11**.

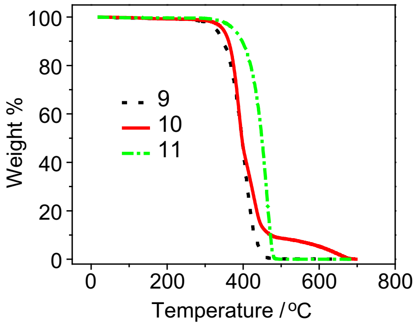
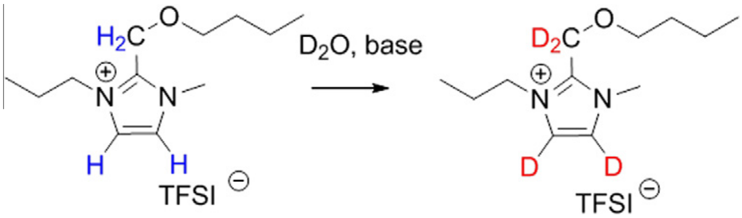


Figure 1. TGA traces of IL **9**–**11**.



Scheme 5. Deuterium exchange reaction of **9**.

stability include the deuterium exchange reaction and the methylation with methyl iodide after deprotonation with a strong base such as sodium hydride.[17b] Both reactions reflect the acidity of the protons at the possible reactive sites such as C-2, C-4, C-5, and $-CH_3$ on C-2.[21] We carried out deuterium exchange reactions in both neutral and strongly basic condition. The reaction was conducted in a NMR tube containing a mixture of 1 M ionic liquid in 0.5 mL CD_3OD. Since the C2-subsituted ionic liquids are less susceptible to exchange, it is not surprising that neither of the stable ionic liquids underwent any detectable deuterium exchange under neutral condition. To further test their stability, KOH powder (0.5 mmol) was added to the above solutions and the disappearance of the ^1H signal was followed as a function of reaction time. We observed an uneven deuteration on the three types of protons in IL **9** and **11**. The deuterium exchange occurred on the protons at C-4, and C-5, as well as in $-CH_3$ (or $-CH_2OCH_2CH_2CH_2CH_3$) at C-2, as shown in Scheme 5 using IL **9** as an example. Under the strong basic condition, both IL **9** and **11** underwent fast deuteration on the α-protons in the C-2 substituents ($-CH_3$ and $-CH_2OCH_2CH_2CH_2CH_3$). IL **9** showed significantly faster deuteration rate on the protons at the C-4 and C-5 positions, with 90% deuterated in approximately an hour (Fig. S12, Supporting Information). On the contrast, the deuteration of the protons at the C-4 and C-5 positions in IL **11** was much slower, with only 9% deuterated during the first hour. (Figure S1, Supporting Information) This suggests that the substitution of $-CH_2OCH_2CH_2CH_2CH_3$ at the C-2 position has strong electronic effects on the imidazolium ring so that the C$-$H bonds at the C-4 and C-5 positions are significantly weakened. No detectable deuteration was observed in IL **10**; instead, upon strong base addition (potassium hydroxide), a precipitation in deuterated methanol was obtained. As confirmed by ^1H NMR, the precipitation is the OH^- metathesis product of IL **10**. The $-CN$ substitution at the C-2 position significantly enhanced the stability of the protons at the C-4 and C-5 positions. As demonstrated in the above examples, the electronic effects of the substituents at the C-2 position played a key role in defining the reactivity of the ionic liquids.

In conclusion we have synthesized three different types of imidazoles and their ionic liquids. Depending on their C-2 substituents, the imidazoles can be used as monomers for polymerization, precursors for moisture-sensitive and air stable ionic liquids.

Acknowledgments

This research was supported by the U.S. Department of Energy's Office of Basic Energy Science, Division of Materials Sciences and Engineering, under contract with UT-Battelle, LLC. C.L. acknowledges Professor Robert C. Corcoran at University of Wyoming for helpful discussions.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2011.08.010.

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