

Peculiar Concentration Dependence of H/D Exchange Reaction in 1-Butyl-3-methylimidazolium Tetrafluoroborate-D₂O Mixtures

Souichi Ohta¹, Akio Shimizu¹, Yusuke Imai², Hiroshi Abe², Naohiro Hatano³, Yukihiro Yoshimura^{3*}

¹Department of Environmental Engineering for Symbiosis, Soka University, Tokyo, Japan

²Department of Materials Science and Engineering, National Defense Academy, Yokosuka, Japan

³Department of Applied Chemistry, National Defense Academy, Yokosuka, Japan

*E-mail: muki@nda.ac.jp

Received June 7, 2011; revised August 4, 2011; accepted September 5, 2011

Abstract

We have investigated the H/D exchange reaction between heavy water and an ionic liquid, 1-butyl-3-methylimidazolium tetrafluoroborate ([bmim][BF₄]), throughout the whole concentration region as a function of D₂O mol% at room temperature. We expected that the extent of the H/D reaction would increase linearly with increasing content of D₂O, but the results show an extended N-shaped behavior having a small maximum at around 40 mol% and the reaction becomes very slow at a specific concentration around 80 mol%. We found that this non-linear concentration dependence correlates with the *pD* dependence of the solutions.

Keywords: H/D Exchange Reaction, *pD*, NMR, Ionic Liquid

1. Introduction

Room temperature Ionic liquids (RTILs) shows versatility of their properties by interchanging cations and anions [1,2]. Typical ionic liquids are composed of a large bulky, asymmetric organic cation containing nitrogen (e.g. imidazole, pyrrole, piperidine and pyridine) and a wide variety of anions ranging from simple halides to more complex organic species. The liquid structure of ionic liquids results from a balance between geometric factors and long-range electrostatic forces is a key to prevent crystallization.

When mixing water into RTILs, the following unique features were so far reported to occur in the RTILs-water mixtures. Firstly, a nearly-free hydrogen bonded band (NFHB) of water molecules which are not associated into the hydrogen-bonded water network structure is observed up to the water-rich region (~80 mol% H₂O) in the Raman spectra of 1-butyl-3-methylimidazolium tetrafluoroborate, [bmim][BF₄]-water mixtures [3,4]. The NFHB waters are probably very weakly interacting *via* H-bonding with the BF₄ anions. In previous studies, we found that the NFHB is preserved even at 77 K and the NFHB water survives, not forming the hydrogen bond network among themselves as in pure H₂O liquid, when making the glassy water-ionic liquid solutions [5,6].

More surprisingly, even at water-rich conditions, H₂O ice crystals and the solitary water co-exist in the solutions. These facts imply that the nearly-free hydrogen bonded state of water molecule is fairly stable once formed in the RTIL.

Another notable feature is the unique spatial heterogeneity resulting from their inherent polar/nonpolar phase separation [7-9]. The pure 1-alkyl-3-methylimidazolium based RTILs with various alkyl chain lengths show nano-phase separation (a nano-structural organization) [8]. There is also a nano-structuring of the mixtures of [bmim][BF₄] [10] and/or 1-octyl-3-methylimidazolium nitrate [omim][NO₃] [11] with water, but no macroscopic phase separation occurs. We presume that the nano-phase separation existing in the RTIL may be enhanced by the presence of NFHB water molecules [5].

The final one is that the H/D exchange reaction in which HDO is generated by the rapid exchange of D between D₂O and the C-H at position 2 of the 1-butyl-3-methylimidazolium (denoted as [bmim]) ring occurs [12,13]. Now a protein H/D exchange method in deuterium solvents using NMR spectroscopy can provide the direct information on the detailed structure, dynamics, folding and local fluctuations [14,15]. Actually, whether the hydrogens are buried or at the solvent-exposed surface is quantitatively predictable from the exchange rates

for hydrogens [16]. By applying this useful method to the RTIL-D₂O mixture, the H/D exchange reaction rate in hydrophilic 1-butyl-3-methylimidazolium chloride ([bmim][Cl]) at 50°C has been studied in detail by Nakahara *et al.* [13]. They found a slowdown of H/D exchange reaction rate in the water-poor conditions at D₂O below 7 M (~30 mol% D₂O), reflecting that solitary water as a single molecule without self-associated state is deactivated in the region where the solitary water is bound strongly by the solvent ions (Cl⁻) as the water-water contact is negligible compared to water in water-rich conditions. Thus the results can be understood in terms of change in the solvation dynamics in the system depending on the water concentration.

As stated above, the properties of RTILs vary depending on the combination of the cation and the anion. Importantly, the solubilities of water in RTILs highly depend on the nature of the anion. If we use the RTIL containing hydrophilic anion, the contamination of water from the atmosphere might be inevitable more or less [4]. Therefore, a detailed understanding of the behavior of RTILs-water mixtures is important, e.g., for the application uses of these substances. We point out that there is a limitation of the solubility of [bmim][Cl] in water (about 48 mol% at room temperature), but [bmim][BF₄] is soluble in water at any concentration. In this situation, the H/D exchange reaction between heavy water and [bmim][BF₄] is intriguing. We expect that the deuterated water effect might be different and this is the motivation for the current work. We have investigated the NMR spectral changes as a function of water concentration in [bmim][BF₄]-D₂O mixtures at room temperature. Here we show a peculiar concentration dependence of the H/D exchange reaction in the mixed solution.

2. Experimental

As an ionic liquid, we used 1-butyl-3-methylimidazolium tetrafluoroborate [bmim][BF₄] (Kanto Chemical Co., Cl⁻ < 0.005%, Br⁻ < 0.005%, F⁻ < 0.01%, Na⁺ < 0.002%, Li⁺ < 0.002%, H₂O < 0.02%). The concentration of water contained in the [bmim][BF₄] as-received sample was doubly checked to be 130 - 150 ppm on the basis of the Karl-Fisher titration method. All mixtures of different concentration ($x = 10, 20, 30, 40, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 98, 99$ and 99.5 mol% D₂O) were prepared by mixing out the required amounts of [bmim][BF₄] and D₂O (99.9% D, Cambridge Isotope Laboratories). The sample preparations were done in a dry box to avoid atmospheric H₂O and CO₂. The purity of the ionic liquid was doubly confirmed on the basis of ¹H and ¹⁹F NMR spectra.

As NMR is highly sensitive to the inter- and intra-

molecular interactions, it can be used as a probe for the present purpose. ¹H and ¹⁹F NMR spectra of samples of [bmim][BF₄] mixed with D₂O were measured using a JEOL ECA500 (operating at 500 and 470 MHz, respectively) at room temperature (23.3°C). Spectra widths of ¹H and ¹⁹F were 9384 and 83333 Hz respectively. The digital resolutions were 0.14 Hz for ¹H and 1.27 Hz for ¹⁹F spectra. To avoid a mixing of the sample solution and the NMR lock solvent, we used double tubes for the H/D measurements. The NMR lock solvent was kept in a 4 mm diameter inner glass tube and this tube was inserted in a 5 mm diameter glass tube of the sample solution. The mixture of CDCl₃ containing 1 v/v% tetramethylsilane (TMS) and D₂O containing about 1 v/v% trifluoroacetic acid (TFA) was used as the NMR lock solvent for ¹H and ¹⁹F NMR spectral measurements, respectively. The peaks of TMS (0 ppm) and TFA (0 ppm) were used as the external chemical shift standards of ¹H and ¹⁹F NMR spectra, respectively. But when we use the double tubes, the magnetic susceptibility corrections are necessary to determine the accurate chemical shift. Thus, we used a single tube for the chemical shift measurements. 5 or 100 L of 0.2 M 3-trimethylsilyl-propane sulfonic acid sodium salt (DSS) was added to the each 1 mL samples, and the peak of the DSS (0 ppm) was used as the internal chemical shift standard of the ¹H NMR spectra.

To detect the H/D exchange reaction, ¹H NMR spectroscopy was used to monitor the deuteration ratio (isotope exchange) in the [bmim][BF₄]-D₂O mixtures. A hydrolysis of the BF₄⁻ ion in water is sometimes known to occur [17,18]. We checked an extent of the hydrolysis by the ¹⁹F NMR spectra and the *pD*. The *pD*s of each mixed solutions after the equilibration conditions were determined with a pH meter, model F-51 from Horiba co. ltd. Values of *pD* were obtained by adding 0.40 to the reading of the *pH* meter [19].

3. Results and Discussion

Firstly, we show a typical example of the NMR spectrum of [bmim][BF₄]-D₂O mixed solution ($x = 90$) in **Figure 1**. The chemical structure of [bmim] along with the numbering of each carbon in imidazolium ring is shown schematically in the inset of **Figure 1**. All the fundamental peaks corresponding to [bmim] cation at room temperature were reported by Holbrey and Seddon [20]. Our results are basically in agreement with their results. The numbers (①~⑧) in Figure 1 correspond to the skeleton atoms for the [bmim] cation in the inset of Figure 1. A notable feature in the spectrum is the peak ② from the exchange between the proton attached to C(2) (hereafter denoted as C(2)-H) and D₂O [12]. The

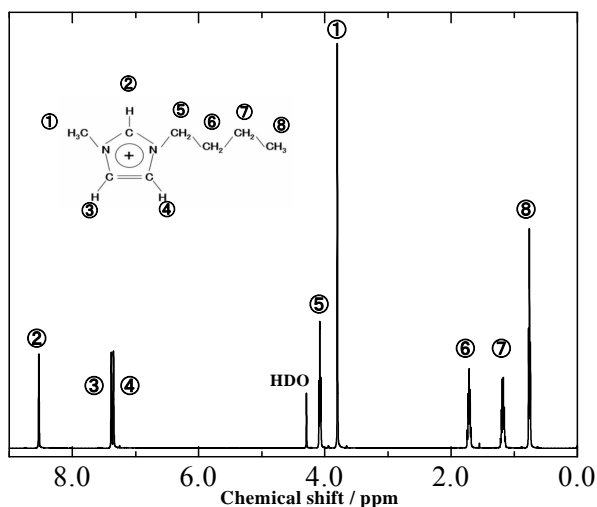


Figure 1. Representative ^1H NMR spectrum of [bmim][BF₄]-D₂O mixtures ($x = 90$ mol%) at 500 MHz obtained after a deuterium exchange for the C(2)-H proton at 23.3°C. ^1H NMR chemical shifts δ relative to TMS internal standard are shown. The exchange for deuterium of the C(2)-H of imidazolium cation in D₂O were determined by monitoring the decay of the C(2)-H proton (②) and the deuterium exchange results in the disappearance of the signal due to the C(2)-H proton and the appearance of that due to HDO. The inset shows a chemical structure and the numbering of the skeleton atoms for the [bmim] cation.

intensity increased along with the deuterium exchange after the mixture was made. An extent of the H/D reaction with time evolution (0 - 42 days) covering a whole range of the water concentration x is shown using a relative intensity ratio ($I_{\text{HDO}}/(I_{\text{C(2)-H}} + I_{\text{HDO}})$) of the ^1H signals of HDO and of C(2)-H in [bmim] in **Figure 2**. We followed the H/D reaction up to 42 days and found that the time require for reaching the apparent equilibrium state is at most 1 month.

At the equilibrium state, we expected that the extent of the H/D reaction would increase linearly with increasing content of D₂O. However, the change in the $I_{\text{HDO}}/(I_{\text{C(2)-H}} + I_{\text{HDO}})$ with x shows an extended N-shaped behaviour having a small maximum at about $x = 40$. It is intriguing that at a specific concentration region of around 80 mol%, the H/D exchange reaction hardly proceeds even if the samples left for 42 days. Notably, we found that even if the temperature of the mixture at $x = 80.0$ was raised to 75°C, the exchange reaction rate (⊙ as shown in Figure 2) was still slow. For a comparison, the value at $x = 40.9$ is also shown in the same figure. Then, the $I_{\text{HDO}}/(I_{\text{C(2)-H}} + I_{\text{HDO}})$ again increases steeply with further increase in the water concentration toward $x = \sim 100$. Thus, contrary to the case of the [bmim][Cl]-D₂O mixtures, one can say that the slow-down of H/D exchange reaction moves to more “water-rich” conditions.

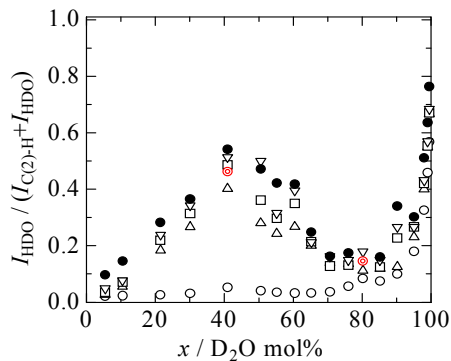


Figure 2. The intensity ratio of the $I_{\text{HDO}}/(I_{\text{C(2)-H}} + I_{\text{HDO}})$ for [bmim][BF₄]-D₂O mixed solution against the D₂O concentration x . The extent of a deuterium exchange is examined with time evolution from 0 - 42 days. The symbols show the data depicted. ○: 0 day, △: 14 days, □: 23 days, ▽: 29 days, ●: 42 days, ⊙: heated for 2 hours at 75°C immediately after the sample preparations.

On the other hand, the changes in the chemical shift of HDO with x are shown in **Figure 3**. The chemical shift of HDO increases from 3.0 ppm ($x = 20.0$) to 4.8 ppm ($x = 100$, *i.e.*, pure D₂O) with increasing water concentration. Normally, the higher-frequency shift is ascribed to the enhancement of hydrogen bonding between water molecules in the water structure [21]. Here we quote that if a relatively hydrophobic co-solvent such as *t*-butyl alcohol (*t*-BuOH) is added to water, the chemical shift of water shows a maximum value at about 92 - 94 mol% water in the water-rich region, which is envisaged by the hydrophobic hydration concept [22,23] in which *t*-BuOH molecules form hydrogen bonded clusters and the enhancement of water-water hydrogen bonding is promoted by the dissolved *t*-BuOH [24]. In contrast, all of the proton signals due from the [bmim] cation (①~⑧) on the deuterium exchange showed hardly any variation in the chemical shifts up to *ca.* $x = 90$, though there were clear even small downfield shifts above $x = 90$. Additionally, the values of all of the signals for the mixed solutions remained unchanged with time decay from the sample preparation. The results imply that there is no indication of the specific cluster formation in the [bmim][BF₄]-D₂O mixtures, such as that proposed for the *t*-BuOH-water mixtures. Therefore, the peculiar concentration dependence of H/D exchange reaction together with the time evolution is not originated from the structural change relating to the chemical shifts.

Next, we presumed that the rate of H/D exchange reaction might be affected by the solution pD . Then, in order to see more about the peculiar concentration dependence of H/D exchange, we performed pD measurements. The results of pD are displayed in **Figure 4**. Interestingly, the change in the $I_{\text{HDO}}/(I_{\text{C(2)-H}} + I_{\text{HDO}})$ and the

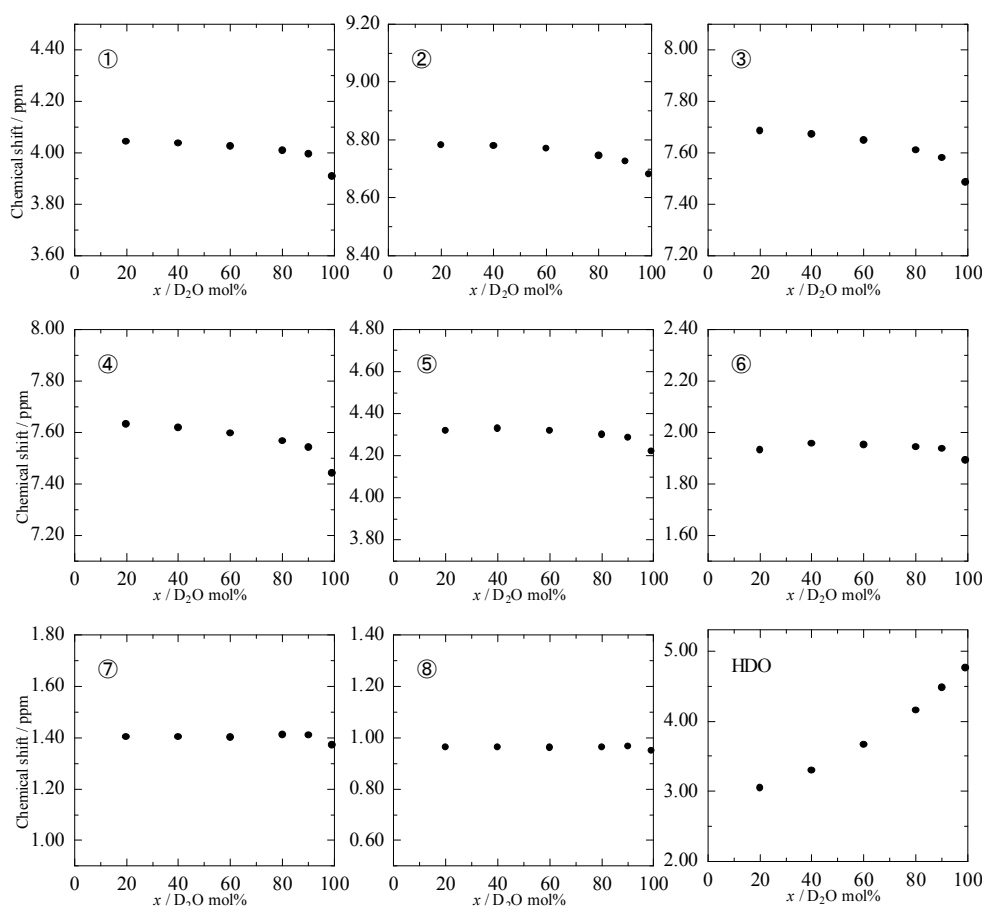


Figure 3. Chemical shifts of respective protons in [bmim] cation and HDO as a function of water concentration x . The chemical shifts correspond to the deviations from the position of the reference (DSS).

pD with x is well correlated. This correlation indicates that the H/D reaction dynamics of [bmim] in D_2O along with the minimum at $x = 80$ is, at least partly, connected to the solution pD .

To understand the pDs in [bmim][BF_4]- D_2O mixtures, the following information is instructive. There have been indications [25-27] that hydrolysis of BF_4 anion in RTILs sometimes occurs to form HF etc., though to our best knowledge there seems to have been no full-detailed study covering whole range of water concentration. The ^{19}F NMR spectra of the RTIL-rich phase measured by us do not show any peaks corresponding to decomposition products of the anion, pointing to the absence of significant hydrolysis in this phase, but those of the water-rich phase after $x = \sim 75$ indicated that the decomposition of the BF_4 anion proceeds with increasing x . At apparent equilibrium conditions (*i.e.*, after 42 days sample at room temperature), the ^{19}F NMR measurements indicated that about 4% of the BF_4 anions hydrolyze at $x = 85$ mol% in the mixed solution.

As already mentioned, the C(2)-position of [bmim]

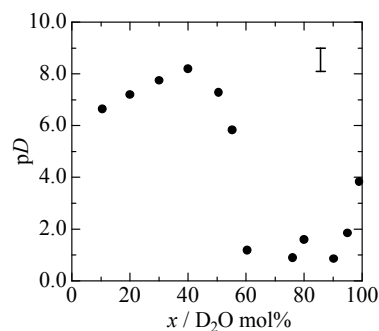


Figure 4. Concentration dependence for the pD of [bmim][BF_4]- D_2O mixed solutions. The values for the mixed solutions after 42 days from the sample preparation are plotted.

cation is relatively acidic. The problem here is how acidic. Amyes *et al.* [28] investigated the carbon acid pK_a values of imidazolium cations in aqueous solution. The reported pK_a value for the imidazolium cation is 23.8 and that for the 1,3-dimethylimidazolium cation is 23.0. These are intermediate values between the pK_a s of acetone (19.3) and ethyl acetate (25.6). This acidity some-

times leads to undesired side reactions for the purpose of using imidazolium ionic liquids as solvents under certain reaction conditions [29]. Handy and Okello [30] reported that by replacing the H with a CH₃ group the exchange became slow, though it was detectable even in the presence of a very mild base.

Considering the aforementioned results in the literatures, we presumed that the rate of H/D exchange reaction might be affected by the solution *pD*. To confirm this expectation, we performed the additional experiments using the buffered solutions. The mixed solutions of *x* = 10, 20, 40, 80, 90 and 99 mol% were adjusted to certain *pDs* (= 11 - 12) by NaOD. As might be expected, the rate of exchange in the presence of strong base at higher *x* regions was found to accelerate where the reaction of the starting materials were complete quickly after mixing, done in five minutes, as shown in **Figure 5**.

It is interesting to refer that this results are basically in agreement with the results on the hydrolysis of imidazole-2-ylidenes (imidazole-derived carbenes) under strongly alkaline solutions (*pH* = 12 - 13) studied by Hollóczki, *et al.* [31]. On the other hand, in a lower D₂O concentration region, little effect of the base on the rate of H/D exchange reaction could be detected. This is reasonable because an extent of the H/D reaction is already almost completed. We also confirmed that there were no significant acid and/or base catalysis *pD* effects on the chemical shifts at given concentrations (data not shown).

4. Conclusions

In summary, we have demonstrated the H/D exchange reaction of D₂O in [bmim][BF₄] throughout the whole concentration range (*x* = 0 - 100) at room temperature. We found that there is no linear increase in the extent of the H/D reaction with D₂O concentration. The results show an extended N-shaped behavior having a small maximum at around 40 mol% and the reaction does hardly occur at a specific concentration region of ~80 mol%. This is, at least partly, ascribed to the hydrolysis of BF₄ anion in this concentration region. We should keep this in mind and be cautious of the H/D exchange reaction, e.g., for the application use of [bmim][BF₄] in water. Although we find the good correlation between the H/D exchange reaction and the solution *pD*, to give a clear-cut answer for whether the peculiar concentration dependence of H/D exchange occurred at a specific concentration solely depend on the *pD* or not is more difficult task. The interaction between D₂O water and the RTIL is probably anisotropic because of the inherent heterogeneity existing in the RTILs in nano-scale order that operates at a molecular level in such systems. We suppose that it may be also connected to the existence of

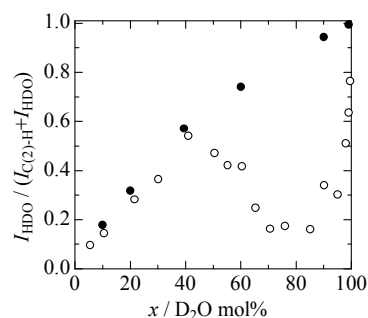


Figure 5. The intensity ratio ($I_{\text{HDO}}/(I_{\text{C(2)-H}} + I_{\text{HDO}})$) of the H/D exchange reaction in buffered solutions at a basic condition (adjusted to *pD* = 11 - 12) against the D₂O concentration *x*. For a comparison, the values for the mixed solutions without the addition of the base (open circle symbols) after 42 days left from the sample preparation are plotted in the same figure.

solitary water molecules in [bmim][BF₄] along with the spatial heterogeneity. Further quantitative understanding of the detailed interactions existing in the system at molecular level would require e.g., a still more precise modelling of structures of [bmim]-[BF₄], [bmim]-water, [BF₄]-water, water-water interactions. MD simulation and small angle x-ray scattering studies would help greatly, but this is beyond the present study. We believe that the present findings denote for the fundamental importance of the substances.

5. Acknowledgements

We are grateful to Dr. T. Takekiyo for experimental assistance and Ms. K. Yamazaki for help with the manuscript.

6. References

- [1] T. Welton, "Ionic Liquids in Synthesis," Wiley-VCH, Weinheim, 2002.
- [2] R. D. Rogers, K. R. Seddon and S. Volkov, "Green Industrial Applications of Ionic Liquids," *NATO Science Series*, Springer, New York, 2002.
- [3] Y. Jeon, J. Sung, D. Kim, C. Seo, H. Cheong, Y. Ouchi, R. Ozawa and H. Hamaguchi, "Structural Change of 1-Butyl-3-methylimidazolium Tetrafluoroborate + Water Mixtures Studied by Infrared Vibrational Spectroscopy," *The Journal of Physical Chemistry B*, Vol. 112, No. 3, 2008, pp. 923-928. doi:10.1021/jp0746650
- [4] L. Cammarata, S. G. Kazarian, P. A. Salter and T. Welton, "Molecular States of Water in Room Temperature Ionic Liquids," *Physical Chemistry Chemical Physics*, Vol. 3, 2001, pp. 5192-5200. doi:10.1039/b106900d
- [5] Y. Yoshimura, T. Goto, H. Abe and Y. Imai, "Existence of Nearly-Free Hydrogen Bonds in an Ionic Liquid,

- N,N*-Diethyl-*N*-methyl-*N*-(2-methoxyethyl) Ammonium Tetrafluoroborate-Water at 77 K,” *The Journal of Physical Chemistry B*, Vol. 113, No. 23, 2009, pp. 8091-8095. doi:10.1021/jp902125f
- [6] Y. Yoshimura, H. Kimura, C. Okamoto, T. Miyashita, Y. Imai and H. Abe, “Glass Transition Behaviour of Ionic Liquid, 1-Butyl-3-methylimidazolium Tetrafluoroborate-H₂O Mixed Solutions,” *The Journal of Chemical Thermodynamics*, Vol. 43, No. 3, 2011, pp. 410-412. doi:10.1016/j.jct.2010.10.010
- [7] H. Jin, X. Li and M. Maroncelli, “Heterogeneous Solute Dynamics in Room Temperature Ionic Liquids,” *The Journal of Physical Chemistry B*, Vol. 111, 2007, pp. 13473-13478. doi:10.1021/jp077226+
- [8] A. Paul, P. Kumar and A. Samanta, “How Transparent Are the Imidazolium Ionic Liquids? A Case Study with 1-Methyl-3-butylimidazolium Hexafluorophosphate, [bmim][PF₆],” *Chemical Physics Letters*, Vol. 402, No. 4-6, 2005, pp. 375-379. doi:10.1016/j.cplett.2004.12.060
- [9] Z. Hu and C. Margulis, “Heterogeneity in a Room-Temperature Ionic Liquid: Persistent Local Environments and the Red-Edge Effect,” *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 103, No. 4, 2006, pp. 831-836. doi:10.1073/pnas.0507364103
- [10] M. Moreno, F. Castiglione, A. Mele, C. Pasqui and G. Raos, “Interaction of Water with the Model Ionic Liquid [bmim][BF₄]: Molecular Dynamics Simulations and Comparison with NMR Data,” *The Journal of Physical Chemistry B*, Vol. 112, No. 26, 2008, pp. 7826-7836. doi:10.1021/jp800383g
- [11] W. Jiang, Y. Wang and G. A. Voth, “Molecular Dynamics Simulation of Nanostructural Organization in Ionic Liquid/Water Mixtures,” *The Journal of Physical Chemistry B*, Vol. 111, No. 18, 2007, pp. 4812-4818. doi:10.1021/jp067142i
- [12] M. Nakakoshi, S. Ishihara, H. Utsumi, H. Seki, Y. Koga and K. Nishikawa, “Anomalous Dynamic Behavior of Ions and Water Molecules in Dilute Aqueous Solution of 1-Butyl-3-methylimidazolium Bromide Studied by NMR,” *Chemical Physics Letters*, Vol. 427, No. 1-3, 2006, pp. 87-90. doi:10.1016/j.cplett.2006.06.052
- [13] Y. Yasaka, C. Wakai, N. Matubayashi and M. Nakahara, “Slowdown of H/D Exchange Reaction Rate and Water Dynamics in Ionic Liquids: Deactivation of Solitary Water Solvated by Small Anions in 1-Butyl-3-methylimidazolium Chloride,” *The Journal of Physical Chemistry A*, Vol. 111, No. 4, 2007, pp. 541-543. doi:10.1021/jp0673720
- [14] H. Maity, W. Kilim, J. N. Rumbley and S. W. Englander, “Protein Hydrogen Exchange Mechanism: Local Fluctuations,” *Protein Science*, Vol. 12, No. 1, 2003, pp. 153-160. doi:10.1110/ps.0225803
- [15] C. K. Woodward and B. D. Hilton, “Hydrogen Exchange Kinetics and Internal Motions in Proteins and Nucleic Acids,” *Annual Review of Biophysics & Bioengineering*, Vol. 8, 1979, pp. 99-127.
- [16] Y. Bai, J. S. Milne, L. Mayne and S. W. Englander, “Primary Structure Effects on Peptide Group Hydrogen Exchange,” *Proteins: Structure, Function, and Bioinformatics*, Vol. 17, No. 1, 1993, pp. 75-86. doi:10.1002/prot.340170110
- [17] C. A. Wamser, “Equilibria in the System Boron Trifluoride-Water at 25°,” *Journal of the American Chemical Society*, Vol. 73, No. 1, 1951, pp. 409-416. doi:10.1021/ja01145a134
- [18] M. Anbar and S. Guttmann, “The Isotopic Exchange of Fluoroboric Acid with Hydrofluoric Acid,” *The Journal of Physical Chemistry*, Vol. 64, No. 12, 1960, pp. 1896-1899. doi:10.1021/j100841a021
- [19] P. K. Glasoe and F. A. Long, “Use of Glass Electrodes to Measure Acidities in Deuterium Oxide,” *The Journal of Physical Chemistry*, Vol. 64, No. 1, 1960, pp. 188-190. doi:10.1021/j100830a521
- [20] J. D. Holbrey and K. R. Seddon, “The Phase Behaviour of 1-Alkyl-3-methylimidazolium Tetrafluoroborates; Ionic Liquids and Ionic Liquid Crystals,” *Journal of the Chemical Society, Dalton Transactions*, No. 13, 1999, pp. 2133-2140. doi:10.1039/a902818h
- [21] J. A. Pople, W. G. Schneider and H. J. Bernstein, “High-Resolution Nuclear Magnetic Resonance,” McGraw-Hill, New York, 1959.
- [22] F. Franks, “Water, A Comprehensive Treatise,” Plenum Press, New York, 1972.
- [23] J. M. Harvey, S. E. Jackson and M. C. R. Symons, “Interactions in Water-Alcohol Mixtures Studied by NMR and Infrared Spectroscopy,” *Chemical Physics Letters*, 1977, Vol. 47, No. 3, pp. 440-441. doi:10.1016/0009-2614(77)85011-2
- [24] P. K. Kipkemboi, P. C. Kiprono and A. J. Easteal, “Proton Nuclear Magnetic Resonance Study of Water + *t*-Butyl Alcohol, Water + *t*-Butylamine and Water + *t*-Butyl Alcohol + *t*-Butylamine Mixtures,” *Bulletin of the Chemical Society of Ethiopia*, Vol. 16, 2002, pp. 187-198.
- [25] J. G. Huddleston, A. E. Visser, W. M. Reichert, H. D. Willauer, G. A. Broker and R. D. Rogers, “Characterization and Comparison of Hydrophilic and Hydrophobic Room Temperature Ionic Liquids Incorporating the Imidazolium Cation,” *Green Chemistry*, Vol. 3, No. 4, 2001, pp. 156-164. doi:10.1039/b103275p
- [26] M. Tseng, Y. Liang and Y. Chu, “Synthesis of Fused Tetrahydro- β -carbolinequinoxalinones in 1-*n*-Butyl-2,3-dimethylimidazolium Bis(trifluoromethylsulfonyl)imide ([bdmim][Tf₂N]) and 1-*n*-Butyl-2,3-dimethylimidazolium Perfluorobutylsulfonate ([bdmim][PFBuSO₃]) Ionic Liquids,” *Tetrahedron Letters*, Vol. 46, No. 36, 2005, pp. 6131-6136. doi:10.1016/j.tetlet.2005.06.153
- [27] M. G. Freire, C. M. S. S. Neves, I. M. Marrucho, J. A. P. Coutinho and A. M. Fernandes, “Hydrolysis of Tetrafluoroborate and Hexafluorophosphate Counter Ions in Imidazolium-Based Ionic Liquids,” *The Journal of Physical Chemistry A*, Vol. 114, No. 11, 2010, pp. 3744-3749. doi:10.1021/jp903292n

- [28] T. L. Amyes, S. T. Diver, J. P. Richard, F. M. Rivas and K. Toth, "Formation and Stability of N-Heterocyclic Carbenes in Water: The Carbon Acid pK_a of Imidazolium Cations in Aqueous Solution," *Journal of the American Chemical Society*, Vol. 126, No. 13, 2004, pp. 4366-4374. [doi:10.1021/ja039890j](https://doi.org/10.1021/ja039890j)
- [29] J. Dupont and J. Spencer, "On the Noninnocent Nature of 1,3-Dialkylimidazolium Ionic Liquids," *Angewandte Chemie International Edition*, Vol. 43, No. 40, 2004, pp. 5296-5297. [doi:10.1002/anie.200460431](https://doi.org/10.1002/anie.200460431)
- [30] S. T. Handy and M. Okello, "The 2-Position of Imidazolium Ionic Liquids: Substitution and Exchange," *The Journal of Organic Chemistry*, Vol. 70, No. 5, 2005, pp. 1915-1918. [doi:10.1021/jo0480850](https://doi.org/10.1021/jo0480850)
- [31] O. Hollóczki, P. Terleczyk, D. Szieberth, G. Mourgas, D. Gudat and L. Nyulászi, "Hydrolysis of Imidazole-2-ylidenes," *Journal of the American Chemical Society*, Vol. 133, No. 4, 2011, pp. 780-789. [doi:10.1021/ja103578y](https://doi.org/10.1021/ja103578y)