Electronic Supplementary Material (ESI) for Physical Chemistry Chemical Physics.

Quantitative assessment of kosmotropicity of hydrated ionic liquids by nuclear magnetic resonance

Yohsuke Nikawa,[ab] Kyoko Fujita*[abc†] and Hiroyuki Ohno*[abc]

a. Department of Biotechnology, Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei, Tokyo 184-8588, Japan. E-mail: ohnoh@cc.tuat.ac.jp;

b. Functional Ionic Liquid Laboratories (FILL), Graduate School of Engineering, Tokyo University of Agriculture and Technology, Japan

c. Japan Science and Technology Agency (JST), Core Research for Evolutional Science and Technology (CREST), Chiyoda, Tokyo 102-0076, Japan

† Current affiliation: Department of Pathophysiology, Tokyo University of Pharmacy and Life Sciences, 1432-1 Horinouchi, Hachiouji, Tokyo 192-0392, Japan, E-mail: kyokof@toyaku.ac.jp

Supplementary Information

・ Condition of nuclear magnetic resonance measurement

Proton nuclear magnetic resonance (NMR) measurement were carried out to analyse the hydration state of ionic liquids (ILs) on JNM-ECX400 (JEOL, 400MHz) using NMR coaxial tube with deuterated solvent and a reference inserted into outer sample tube at room temperature, 25°C.

To avoid NMR reference mixing with NMR sample, SHIGEMI SC-010 coaxial tube was used for NMR measurement (inner tube, ID : 1.5 mm OD : 2.50 mm, outer tube, ID : 4.2 mm, OD : 4.965 mm).

The $CDCl_3$ purchased from Kanto Chemical was chosen as a deuterated solvent. The inner tube contains $CDCl_3$ with 0.03% TMS and the outer tube contains each sample. The resulting chemical shift values were determined using TMS as an external reference.

・ Differential scanning calorimetry measurement of hydrated cholinium thiocyanate

Hydrated ionic liquid (HyIL) prepared by adding a suitable amount of water showed an exothermic peak for cold crystallisation (CC) during the heating scan in differential scanning calorimetry (DSC) measurement.[1] CC is a thermal phase transition from amorphous ice to crystalline ice. Previous study suggested that CC may be related to the coordination state of cytochrome *c* in HyIL.

Hydrated cholinium thiocyanate (Hy[Ch][SCN]), which was prepared at different water content, was measured in DSC in order to confirm the presence or absence of CC. No peak for CC was observed regardless of water content.

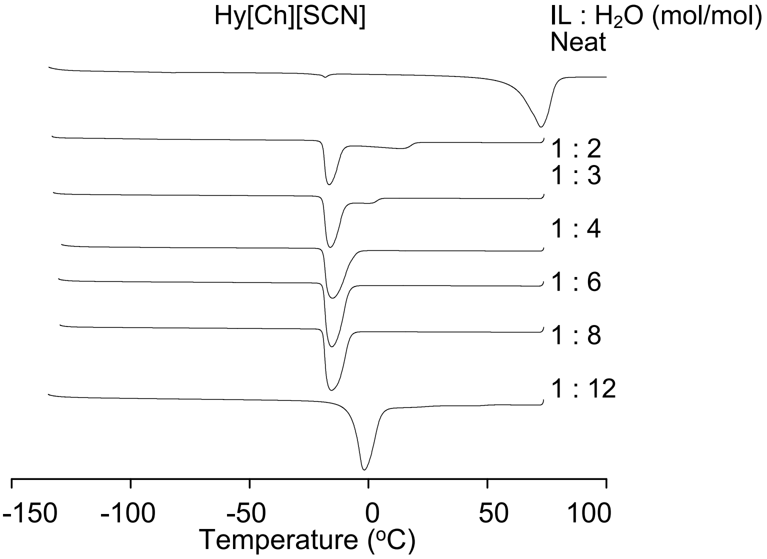


Fig. S1 DSC charts of Hy[Ch][SCN] at the different molar ratio of IL : H_2O.

・ The coordination state of cytochrome *c* in hydrated cholinium thiocyanate

Fig. S2 shows that UV spectra of cytochrome *c* in buffer and Hy[Ch][SCN]. Soret band is blue-shifted in Hy[Ch][SCN] compared to that in buffer. Charge transfer band indicates that the axial ligand are coordinated to the heme iron and is positioned at the 695 nm in native cytochrome *c*. Charge transfer band disappeared in Hy[Ch][SCN].

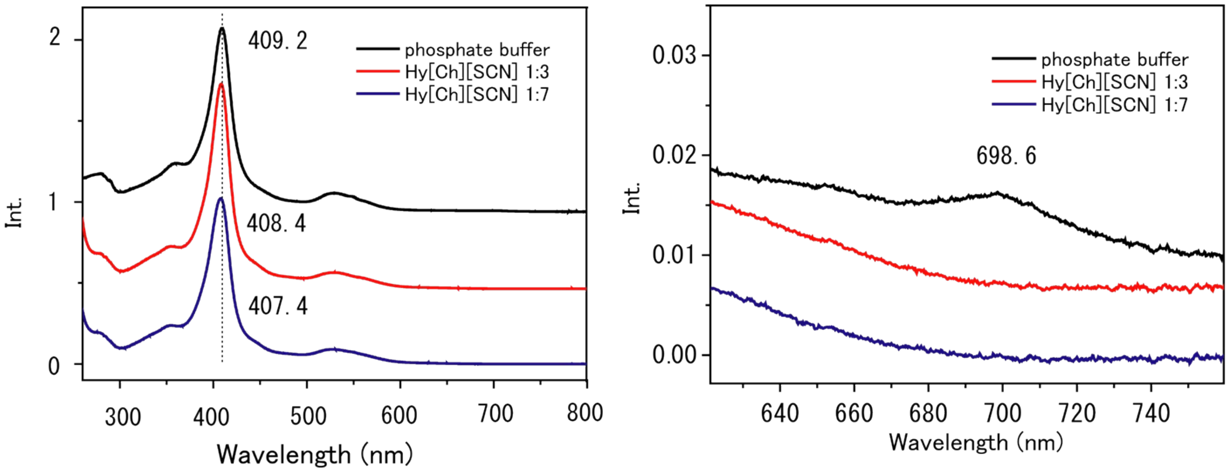


Fig. S2 UV spectra of cytochrome *c* in buffer and Hy[Ch][SCN] (left). UV spectra ranging from 620 to 760 (right).

・The effect of water content on the chemical exchange between cholinium dibutyl phosphate and water molecule

The exchangeable rate of proton is different by water content (Fig. S3). Cholinium dibutyl phosphate ([Ch][dBp]) has exchangeable proton in cholinium cation. At the molar ratio of [Ch][dBp] : H_2O = 1 : 3, the chemical exchange between hydroxyl group of cholinium cation and water molecule is rapid and these two peak merge. At the molar ratio of [Ch][dBp] : H_2O = 1 : 1, this chemical exchange becomes slowly and these two peak are able to be distinguishable.

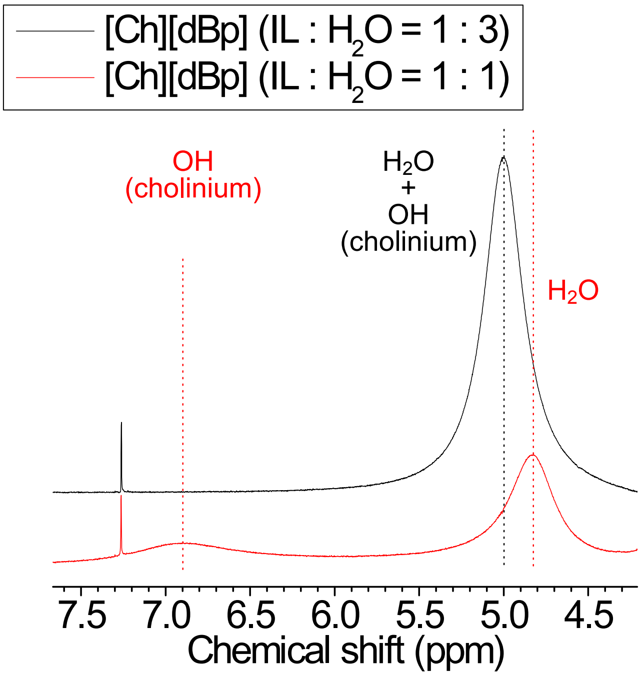


Fig S3. NMR spectrum of [Ch][dBp] at the molar ratio of [Ch][dBp] : H_2O = 1 : 3 (black) and [Ch][dBp] : H_2O = 1 : 1 (red).

・ The effect of ionic volume in aqueous solution on hydration state

In order to explain the interaction between ion and water, charge distribution on the ion is important. The size of ion relates to the charge density on its ion structure. In previous report, small ions, which are high charge density, associated with water molecules strongly and these ions are regarded as kosmotropes.[2] In contrast, in the case of large ions whose charge density is low, the interaction between these ions and water molecules is relatively weak. These ions are known as chaotropes.

The partial molar volume of each ion in previous reports show in Table S2.[3-9] These values are the partial molar volume of each ion at infinite diluted solution. Although these values are not equal to the volume of ion in HyIL which is concentrated solution, we could regard these values as an indicator of ionic volume.

The order of ionic volume is following :

$$[\text{citrate}]^{3-} > [\text{SCN}]^{-} > [\text{dHp}]^{-} > \text{Cl}^{-}$$

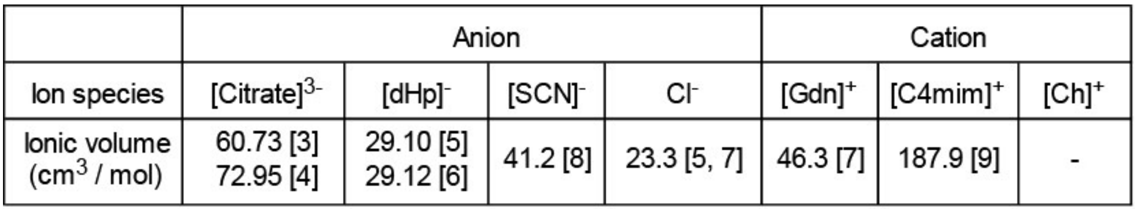
$$[\text{C4mim}]^{+} > [\text{Gdn}]^{+}$$

The kosmotropicity order of the ILs in this study could be predicted from previous report.[10-12]

$$[\text{citrate}]^{3-} > [\text{dHp}]^{-} > \text{Cl}^{-} > [\text{SCN}]^{-}$$

There is no correlation between ionic volume and predicted kosmotropicity. Thus, the effect of structure such as chemical group needs to be taken into account for understanding the interaction between ion and water.

Table. S1 The partial molar volume of ions at room temperature reported in previous study. References are indicated by numbers in square brackets.



	Anion				Cation		
Ion species	$[\text{Citrate}]^{3-}$	$[\text{dHp}]^{-}$	$[\text{SCN}]^{-}$	Cl^{-}	$[\text{Gdn}]^{+}$	$[\text{C4mim}]^{+}$	$[\text{Ch}]^{+}$
Ionic volume (cm^3 / mol)	60.73 [3] 72.95 [4]	29.10 [5] 29.12 [6]	41.2 [8]	23.3 [5, 7]	46.3 [7]	187.9 [9]	-

・ The relation between ion structure and viscosity of HyIL

The HyILs used in this study were divided into three classes. The type (1) is the HyILs which form weak hydrogen bond and the type (3) is the HyILs which form strong hydrogen bond. The type (2) is an intermediate between type (1) and type (3).

Viscosity is regarded as a macro scale mobility of liquid, and the strength of hydrogen bond is related to a micro scale mobility of molecule. The viscosity could be regarded as one of the indicator of kosmotropicity according to previous study.[2] In the case of concentrated solution such as HyIL, ion-ion interaction and ion-water interaction is strongly reflected in viscosity compared with water-water interaction. Purpose of this measurement is to estimate the ion-water interaction and kosmotropicity of IL.

The viscosity measurement was performed on a cone plate viscometer, LVDV-1+ (BROOKFIELD). The cone spindles used for this measurement were CPE-042 and CPE-052. The spindles were selected and used depending on the viscosity of HyIL appropriately.

The viscosity results in this study roughly agree with kosmotropicity (Table. S1). In HyILs classified as type (3) and type (2), the viscosity tends to be high. On the other hand, the viscosity of HyIL classified as (1) is relatively lower. Thus, ILs classified as type (3) and type (2) are strongly interacted with water compared to the type (1). The kosmotropicity order of the ILs in this study could be predicted from previous reports,

[Ch][dhC] > [Ch][dHp] > [C4mim][dHp] > [Ch][dBp] > [Ch][SCN] > [Gdn]Cl. [10-12]

Table. S2 The viscosity of each HyIL (molar ratio IL : H_2O = 1 : 3) at room temperature. The viscosity of HyIL except [Gdn]Cl was measured at 20 °C. The viscosity of [Gdn]Cl is calculated from the value in reference (25 °C). [13]

Class	(3)				(2)	(1)	
IL	[Ch][dhC]	PC	[Ch][dHp]	[C4mim][dHp]	[Ch][dBp]	[Ch][SCN]	[Gdn]Cl
viscosity (cP)	4331	2651	278.4	155.3	160	6.46	2.083 (25°C)

1. K. Fujita, Y. Nikawa and H. Ohno, *Chem. Commun.*, 2013, 49, 3257-3259.
2. K. D. Collins, *Biophy. J.*, 1997, 72, 65-75.
3. A. Salabat, L. Shamshiri, F. Sahrakar, *J. Mol. Liq.*, 2005, 118, 67-70.
4. A. Apelblat, E. Manzurola, *Fluid Phase Equilib.*, 1990, 60, 157-171.
5. F. J. Millero, *Chem. Rev.*, 1971, 71, 147-176.
6. A. G. Shankarwar, V. A. Shelke, and S. G. Shankarwar, *Adv. Appl. Sci. Res.*, 2011, 2,

426-430.

7. Y. Marcus, *J. Chem. Thermodynamics.*, 2012, 48, 70-74.
8. Y. Marcus, *Ion Properties.*, Marcel Dekker, New York, 1997.
9. V. D. Kiselev, I. I. Shakirova, and A. I. Konovalov, *Russ.Chem.Bull., Int.Ed.*, 2012, 61, 506-509.
10. K. Fujita, D. R. MacFarlane, M. Forsyth, M. Yoshizawa-Fujita, K. Murata, N. Nakamura and H. Ohno, *Biomacromolecules.* , 2007, 8, 2080–2086.
11. D. Constatinescu, H. Weingärtner and C. Herrmann, *Angew. Chem. Int. Ed.*, 2007, 46, 8887–8889.
12. H. Zhao, S. M. Campbell, L. Jackson, Z. Y. Song and O. Olubajo, *Tetrahedron: Asymmetry*, 2006, 17, 377–383.
13. K. Kawahara and C. Tanford, *J. Biol. Chem.*, 1966, 241, 3228-3232.