Effect of tetrabutylphosphonium cation on the physico-chemical properties of amino-acid ionic liquids†

Junko Kagimoto, Kenta Fukumoto and Hiroyuki Ohno*

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Tetraalkylphosphonium-based amino-acid ionic liquids show lower viscosities and higher decomposition temperatures (>300 °C) than previously reported ammonium-based amino-acid ionic liquids.

Ionic liquids (ILs) are organic molten salts that have attracted much attention due to their potential for use in green chemistry and various unique characteristics such as an extremely low vapour pressure.[1] The ILs that melt at room temperature or below are potential electrolyte solution substituents. Many ILs have been prepared with anions containing fluorine such as bis(trifluoromethanesulfonyl)imide (Tf_2N), triflate (OTf) and tetrafluoroborate (BF_4). The electron-attracting properties of fluorine leads to delocalization of negative charge and the resulting weakening in the electrostatic forces help to lower the melting temperature. These ILs show excellent solution properties, but they are generally expensive and not environmentally friendly materials. Accordingly, ILs having halogen-free anions are strongly expected to be developed.[2] Many biologically relevant ions can be considered, and many have already been studied including amino acids as anions,[3] amino acids as cations,[4] sugars, sugar derivatives,[5] or lactic acid.[6] These ILs are also expected to be high-quality liquids having chiral centers,[7] biodegradable characteristics,[8] and high biocompatibility.

We have reported ILs having amino-acid anions, hereafter AAILs.[3] AAILs are not only halogen-free but also designer ILs. The solubility of organic molecules and thermal properties such as glass transition temperature depend on the side chains of the amino-acid anions.

In spite of excellent properties of previously synthesized AAILs, viscosity and thermal stability require further improvement. For example, AAILs containing 1-ethyl-3-methylimidazolium as a cation ([emim][amino acid]) were obtained as liquids at room temperature, but they were not stable to 250 °C and had a narrow electrochemical potential window due to the presence of a proton at the 2-position on the imidazolium ring. The hydrogen bonding at the 2-position of the imidazolium cation ring with its amino-acid anions caused the AAILs to have a relatively high viscosity. However, introduction of a methyl group at the 2-position was not good for the properties of the ILs. In the present paper, we report novel amino-acid ILs using a variety of cations to find AAILs with a lower viscosity and better thermal properties.

Tetraalkylammonium, pyrrolidinium and pyridinium cations were used to prepare AAILs. They are generally known as excellent cations to form ILs.[9] Then we used phosphonium cations, which form salts with good chemical[10] and thermal stability,[11] and also have a lower toxicity[12] than ammonium salts.

As a model experiment, salts were formed by mixing L-alanine (L-Ala) with the cations shown in Fig. 1. The preparation of these salts was the same as that reported previously.[3] The corresponding cation hydroxide aqueous solution was prepared with an anion exchange column, and then neutralized with L-alanine. In case of butylpyridinium hydroxide ($[Py_4][OH]$), no reaction product was obtained after mixing with L-alanine due to decomposition of $[Py_4]^+$, and no characterization of this salt was carried out. In contrast, tetrabutylphosphonium hydroxide ([TBP][OH]) was quite stable and corresponding salts could be obtained easily by mixing with acids. Phosphonium-based amino-acid salts were prepared by mixing amino acid with this [TBP][OH] aqueous solution. The [TBP][OH],[13] a gift from Hokko Chem. Ind. Co. Ltd., was used without further purification. All L-alanine salts prepared were dried under vacuum for 24 h at 70 °C. For all salts examined here, the water content was less than 0.2 wt% according to the Karl Fischer (MKC-510N; KEM) test. Table 1 summarizes the thermal properties of the obtained L-alanine salts. DSC measurements revealed that the tetrabutylammonium salts and pyrrolidinium salts were solids, having melting points exceeding 70 °C, but the asymmetric tetraalkylammonium (*e.g.* N_{2226}) salt was liquid having a glass transition temperature of −40 °C. Some ammonium-based amino-acid salts became liquid at room temperature; however, their decomposition temperatures (T_{decomp}) of 150–170 °C were about 50 °C lower than that of

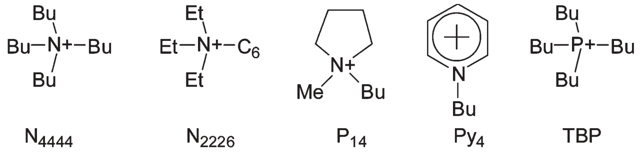

Fig. 1 Cations used to prepare IL with L-Ala.

Table 1 Thermal properties of various alanine-salts

Cation	T_g/°C	T_m/°C	T_{decomp}/°C
emim[a]	−57	ND	212
N_{4444}	ND	76	162
N_{2226}	−40	ND	150
P_{14}	−64	77	176
TBP	−70	ND	286

ND: not detected. [a] Data cited from ref. 3.

Department of Biotechnology, Tokyo University of Agriculture and Technology, Koganei, Tokyo, 184-8588, Japan.
E-mail: ohnoh@cc.tuat.ac.jp; Fax: +81-42-388-7024;
Tel: +81-42-388-7024

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imidazolium-based amino-acid ionic liquids. Thus, we found it difficult to make ILs with low viscosity and high decomposition temperature using ammonium cations.

The tetrabutylphosphonium-based amino-acid ILs ([TBP][Ala]) had a lower glass transition temperature (T_g) than that of [emim][Ala]. This encouraging finding led us to examine the characteristics of the other 19 natural amino acids. Amino acids became liquid at room temperature after neutralization with [TBP][OH]. All [TBP][amino acid] were miscible with water and various organic solvent, such as methanol and acetonitrile. Crude products were therefore washed with acetonitrile–methanol mixed solvent to remove free amino acid (see ESI†). The [TBP][His] showed only a melting point (T_m) at 85.9 °C, 11 salts showed only a glass transition temperature, and 8 salts showed both a melting point and a glass transition temperature (Table 2). Phosphonium-based ILs generally had high melting points. For example, [TBP][Tf_2N][11] is solid at room temperature (T_m = 86 °C). The melting points of six ILs made from one of Gly, Phe, Leu, Pro, Arg and Val were about 80–50 °C lower than that of [TBP][Tf_2N], and the four ILs from Gly, Phe, Pro and Val, were liquids at and below room temperature. It should be noted here that some of the TBP salts were supercooled. These were semi-stable supercooled liquids, but some of them crystallized when stored in a refrigerator for months. Butyl and longer alkyl chains are effective for suppressing crystallization of the corresponding salts due to configurational rotations.

The thermal stability of [TBP][amino acid] was generally better than that of [emim][amino acid]. In particular, the decomposition temperature (T_{decomp}, onset) of [emim][amino acid] was around 220 °C,[3] while T_{decomp} of several types of [TBP][amino acid] was above 300 °C. Fig. 2 shows the thermal gravimetric results of [emim][Leu] and [TBP][Leu]. We attribute the high decomposition temperatures of [TBP][amino acid] to its cation structure; that is, the phosphonium cation is more stable than the imidazolium cation because of the proton at the 2-position of imidazolium cations. Some 2-alkyl-substituted imidazolium cations gave better thermal stability but worse solution properties.

Table 2 Thermal properties of phosphonium type amino-acid ionic liquids

Ionic liquid	T_m/°C	T_g/°C	T_{decomp}/°C	η/cP (at 25 °C)	T_g (of emim salt[3])
[TBP][Ala]	ND	−70.2	286	344	−57
[TBP][Met]	ND	−63.5	217	371	−57
[TBP][Gly]	13.6	−63.7	293	415	−65
[TBP][Leu]	30.0	−63.4	292	389	−51
[TBP][Ile]	ND	−60.7	294	605	−52
[TBP][Ser]	ND	−59.9	243	902	−49
[TBP][Val]	26.0	−59.1	286	423	−52
[TBP][Lys]	ND	−58.8	277	779	−47
[TBP][Pro]	25.4	−57.5	314	851	−48
[TBP][Thr]	ND	−56.1	223	965	−40
[TBP][Phe]	8.1	−53.1	288	927	−36
[TBP][Arg]	30.7	−36.0	286	[a]	−18
[TBP][Trp]	ND	−25.6	316	[a]	−31
[TBP][Gln]	ND	−25.0	311	[a]	6
[TBP][Glu]	101.7	−23.3	319	[a]	−12
[TBP][Cys]	ND	−20.7	190	3029	−19
[TBP][Asp]	ND	−7.6	246	7437 (50 °C)	5
[TBP][Tyr]	ND	−6.5	294	[a]	−23
[TBP][Asn]	83.0	−3.9	224	[a]	−16
[TBP][His]	85.9	ND	299	[a]	−24

ND: not detected. [a] Solid or glass at 25 °C.

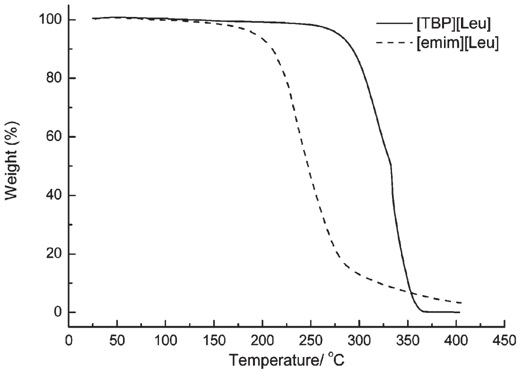

Fig. 2 Thermal gravimetric analysis of [emim][Leu] and [TBP][Leu].

Fig. 3 shows the comparison of the T_g values of a series of [emim][amino acid] with that of [TBP][amino acid]. The points below the dotted line mean that T_g of [TBP][amino acid] is lower than that of [emim][amino acid]. As seen in this figure, 16 out of 20 phosphonium-based amino acids had a lower T_g value than that of [emim][amino acid]. The T_g value of most [TBP][amino acid]s were about 10 °C lower than that of [emim][amino acid]. We attribute this tendency of T_g to cation structure; in particular, the emim cation has protons at the 2, 4 and 5 positions that contribute to hydrogen bonding. On the other hand, the TBP cation has a flexible alkyl chain. The effect of amino-acid side chain structures on the T_g of [TBP][amino acid] was similar to that of [emim][amino acid]. The [TBP][amino acid]s with functional carboxyl and amido groups showed high T_g values due to the additional interaction force among ions. The effect of amino-acid side-chain structure on the properties of [TBP][amino acid] is the same as that discussed for the [emim][amino acid] system. Additionally, the viscosity of [TBP][amino acid] was lower than that of [emim][amino acid]. Hydrogen bonding should increase the solution viscosity as well as increase the T_g value. Especially in the present case, amino acids were used as anions without any chemical modification. Most of these amino-acid anions contain functional groups such as not only amino group, but also carboxyl, hydroxy, and so on. This may open a new possibility of application through introduction of further functions on the anions.

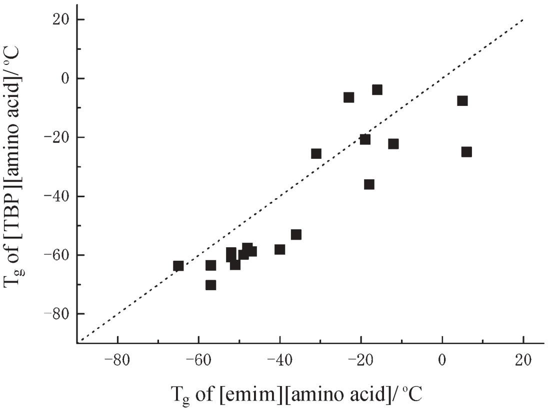

Fig. 3 Comparison of T_g of amino-acid ionic liquids having two different cations.

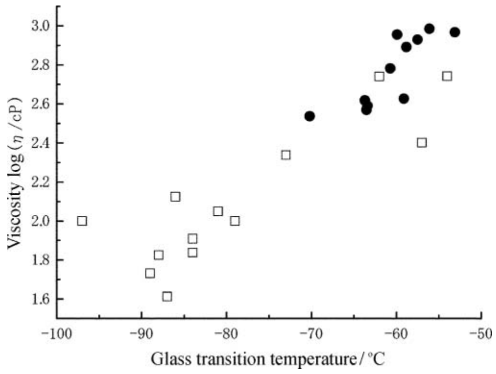

Fig. 4 Relation between viscosity (25 °C) and glass transition temperature (T_g) of amino-acid ionic liquids (●, [TBP][amino acid]s; □, other ionic liquids[14]).

There are many ways for the ions to form hydrogen bonds. There are clear trends that indicate that hydrogen bonding effectively raises the T_g value. For example, T_g for [TBP][Gly] was −63.7 °C. On the other hand, T_g of [TBP][Lys] having amino group was −58.8 °C and [TBP][Ser] containing hydroxy group had T_g of −59.9 °C. In contrast, the T_g value of [TBP][Asp] having carboxyl group was −7.6 °C. Thus, the introduction of the carboxyl group elevated the T_m value considerably, and its effect was much more than that of the amino and hydroxy groups. When ions have another possibility to participate in ion–ion interaction through hydrogen bonding as well as electrostatic force, their solution properties are obviously worse than those having no functional group.

Although [emim][Gly] had the lowest viscosity (486 cP at 25 °C)[3] among the [emim][amino acid], the five [TBP][amino acid]s, containing Ala, Met, Leu, Gly or Val, had even lower viscosity than [emim][Gly]. Fig. 4 shows the relation between T_g and viscosity (at 25 °C) for [TBP][amino acid]s and other imidazolium-type ionic liquids prepared in our laboratory.[14] All [TBP][amino acid]s have a linear relationship between viscosity and T_g. Thus, for these ionic liquids, the side-chain structure did not affect the general relationship between T_g and viscosity. The introduction of a functional group, such as a hydrogen-bonding donor or acceptor, on ions can raise the viscosity due to the increase in the interaction; however, there still remains the possibility of lowering the T_g value by another route to suppress the crystallization of salts containing some functional groups.

ILs having phosphonium cation are generally thought to show good chemical and thermal stabilities, but they had higher melting points and higher viscosities than ammonium salts such as imidazolium salts. For example, [TBP][Tf$_2$N] and [TBP][BF$_4$] are solid at room temperature and the viscosity of [trihexyl(tetradecyl)phosphonium][Tf$_2$N] is 450 cP at 25 °C, whereas that of [emim][Tf$_2$N] is 34 cP.[15] This tendency was seen for most ILs. However, the tetrabutylphosphonium cation seemed to be better only for the amino acids. The results obtained here show that the combination of phosphonium cation and amino-acid anion results in an IL with excellent properties.

In conclusion, we analyzed 20 ILs made by coupling the *n*-tetrabutylphosphonium cation with amino-acid anions. Of these, 15 salts were liquid at room temperature. As they were also halogen-free and had relatively high decomposition temperatures, they are expected to be used for various applications.

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