Formation of Anhydroglucose in Ionic Liquids by Microwave Heating
—Temperature and Chloride Ion Effects—

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It is found that the dehydration of glucose to anhydroglucose, such as 1,6-anhydro-β-D-glucopyranose and 1,6-anhydro-β-D-glucofuranose, proceeds very effectively in hydrophobic ionic liquids, for example ionic liquid *N,N*-diethyl-*N*-(2-methoxyethyl)-*N*-methylammonium bis(trifluoromethanesulfonyl)-amide, without any catalysts at high temperature. On the other hand, addition of a small amount of an ionic liquid with chloride anion reduces the yield of the anhydroglucose significantly.

Room-temperature ionic liquids have very unique properties, such as negligible vapor pressure, high thermal stability, and ionic conductivity. Recent work[1] has shown that ionic liquids 1-butyl-3-methylimidazolium chloride (Bmim-Cl) can dissolve cellulose at high temperature (over 80 °C). Very recently, Ohno's group[2,3] examined a series of ionic liquids, and found that 1-ethyl-3-methylimidazolium methylphosphate can dissolve cellulose under very mild heating conditions. It is possible to prepare a 10 wt % cellulose solution at 45 °C. These recent findings open a new path for lignocellulosic biomass treatment, for example the conversion into fuels and chemicals.

We have studied methods to produce anhydroglucose from lignocellulosic biomass and glucose, for example microwave heating of wood block,[4] supercritical water treatment of glucose,[5] and superheated steam treatment of glucose.[6] The above-mentioned properties of ionic liquids are attractive enough to examine the potential of ionic liquids as a solvent for formation of anhydroglucose. The anhydroglucose is known as a highly valuable chemical to produce hyperbranched polysaccharides.[7] A relatively high yield of anhydroglucose has been reported recently,[8] where the reaction was carried out in dimethylformamide with solid catalysts such as Amberlyst15. It has been reported[9] that ionic liquids can provide very good reaction environments for enzymatic acylation of anhydroglucose. Shoda et al.[10] also found that 1,6-anhydro sugars have been synthesized directly from the corresponding unprotected glycopyranose by using 2-chloro-1,3-dimethylimidazolium chloride as a dehydrative condensing agent. In the present study, we examined the formation of anhydroglucose by dehydration of glucose in ionic liquids without any catalysts, and found that ionic liquids can give very good reaction environments for anhydroglucose.

The reaction was carried out using a microwave heating reaction system (IDX, Green Motif Ib). Microwave frequency was 2.45 GHz and a maximum out put power was 300 W. Glucose (50 mg, Kanto Kagaku) was dispersed in 5 g of ionic liquid. *N,N*-Diethyl-*N*-(2-methoxyethyl)-*N*-methylammonium bis(trifluoromethanesulfonyl)amide (DEME-TFSA, Lot#061108-T-

01) was kindly donated by Nisshinbo Industries Inc. Ionic liquid butylmethylimidazolium bis(trifluoromethanesulfonyl)amide was purchased from Solvent Innovation GmbH (Bmim-TFSA(S), Lot#99/748) and Toyo Gosei Co., Ltd. (Bmim-TFSA(T), Lot#58C04J), respectively. *N,N,N*-Trimethyl-*N*-propylammonium bis(trifluoromethylsulfonyl)amide (TMPA-TFSA, Lot#906X7201) was purchased from Kanto Chemical Co., Ltd. Other ionic liquids ethylmethylimidazolium bis(trifluoromethanesulfonyl)amide (Emim-TFSA, Lot#99/710) and methyltrioctylammonium bis(trifluoromethanesulfonyl)amide (TOM-TFSA, Lot#99/733), were purchased from Solvent Innovation GmbH. The ionic liquids were dried at 60 °C under vacuum for 3 h before use. Reaction was carried out at 180 to 220 °C. The sample was purged with argon gas during the reaction. Reaction temperature was monitored by a K-type thermocouple. After desired reaction time elapsed, the sample was immediately cooled by airflow to terminate the reactions. Anhydroglucose produced in the ionic liquid was extracted with water, and analyzed by HPLC (Shimadzu HIC-6A, equipped with a refractive index detector and a Shodex SUGAR KS-801 column).

We have previously reported that the reaction of glucose in subcritical water can be described as a first-order reaction.[5] It was found that the same analysis can be applied to glucose reaction in ionic liquid. However, the reaction kinetics in ionic liquids is found to be quite different from that in the subcritical water. The reaction rates of glucose transformation in ionic liquids are significantly slower than that in subcritical water even at the same reaction temperature. Figure 1 shows an Arrhenius plot of glucose transformation rate constants in TMPA-TFSA. At 200 °C, the first-order rate constant is 0.16 min^{-1}. On the other hand, in subcritical water, the first-order rate constant was 3.0 min^{-1}. It is also clear from the figure that the activation energy for the ionic liquid is significantly higher than that in subcritical water. The activation energy for glucose transformation in TMPA-TFSA is 176 kJ mol^{-1}, while in subcritical water the activation energy is 60 kJ mol^{-1}. Recently the hydrolysis of lignocellulosic biomass[11] was examined in ionic liquid 1-ethyl-3-methylimidazolium chloride. The reported activation energy is 102 kJ mol^{-1}. Therefore, the activation barrier for the dehydration of glucose is significantly higher than that for the hydrolysis of lignocellulosic biomass.

Because the glucose transformation reaction is found to be slow below 200 °C in the ionic liquid TMPA-TFSA, we examined optimum reaction time and temperature conditions where a reasonable conversion of glucose can be obtained. We also pay attention to reuse of the ionic liquids without any decomposition after the high-temperature reactions. It was found that
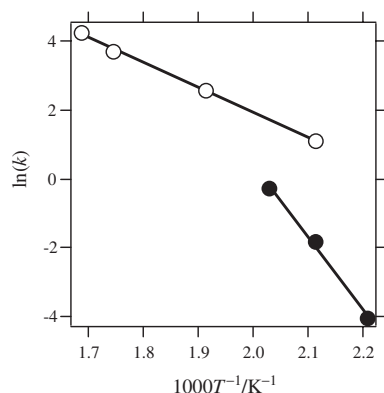
Figure 1. Temperature dependence of reaction rate for glucose transformation in subcritical water (open circle, pressure 25 MPa) and in ionic liquid (filled circle).
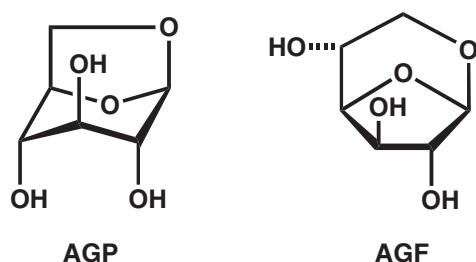

Figure 2. Chemical structure of 1,6-anhydro-β-D-glucopyranose (AGP) and 1,6-anhydro-β-D-glucofuranose (AGF).

when the reaction is performed at 200 °C for 17 min, there is no significant change in the UV–vis absorption spectra of the solvent, and the conversion of glucose is sufficient. While the reaction was performed at 220 °C, the color of the ionic liquid solution changed to dark brown, indicating decomposition of the solution. Therefore in the following experiments we examined the formation of anhydroglucose at 200 °C.

After the reactions in the ionic liquids, two anhydrosugars, 1,6-anhydro-β-D-glucopyranose (AGP) and 1,6-anhydro-β-D-glucofuranose (AGF) (Figure 2) were detected. In Table 1, the selectivity of AGP and AGF in several ionic liquids is summarized. The selectivity of AGP and AGF is 40 to 50% and 20 to 25%, respectively, in the ionic liquids TMPA-TFSA, DEME-TFSA, and Bmim-TFSA. The highest selectivity was obtained in Bmim-TFSA. However, in the ionic liquid Emim-TFSA, the yield was small despite the fact that there is no significant difference in the physicochemical properties between Bmim-TFSA and Emim-TFSA. The difference in the yield could be due to some impurities in the Emim-TFSA, because after washing with water, the selectivity of AGP increased significantly (Table 1). The conversion and the selectivity seem to be affected by impurities, especially, chloride ion. Therefore the effect of chloride ion was examined. The reaction of anhydrosugar formation was carried out in a mixed ionic liquid Bmim-TFSA + Bmim-Cl(0.5 wt %) at 200 °C for 10 min. In the pure Bmim-TFSA the yield of AGP was 30.3 mol %, while in the mixed ionic liquid, the yield decreased dramatically to 7.7 mol %. When the concentration of Bmim-Cl increased up to 1.5 wt %, no anhydroglucose

Table 1. Conversion X_A of glucose and selectivity of AGP and AGF, S_{AGP} and S_{AGF}, respectively, in ionic liquids[a]

Ionic liquids	X_A/mol %	S_{AGP}/mol %	S_{AGF}/mol %
DEME-TFSA	93.0	39.0	23.2
TMPA-TFSA	93.8	40.7	24.4
Emim-TFSA	42.7	19.3	21.2
Emim-TFSA[b]	97.0	49.4	28.1
Bmim-TFSA(S)	80.6	37.6	25.3
Bmim-TFSA(T)	96.9	54.5	25.5
TOM-TFSA	26.5	5.9	5.4

[a]Reaction conditions: 200 °C, 17 min. [b]Pretreatment with water washing.

was produced. Therefore it is clear that the chloride ion has a significant effect on the formation of AGP even at quite small concentration. It is known that the anion, which interacts with the hydroxy group in glucose most strongly is chloride ion.[12] We speculate that chloride ion interacts with OH in glucose then protons may be produced. These protons may react with the oxygen ring in AGP then decomposition of AGP may proceed. Therefore the yield of AGP significantly decreased by adding Bmim-Cl.

In summary, it was found that the dehydration of glucose to anhydroglucose proceeds very effectively in hydrophobic ionic liquids without any catalysts. On the other hand, addition of a small amount of 1-butyl-3methylimidazolium chloride reduced the yield of the anhydroglucose significantly.

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