Nitration of Toluene and Chlorobenzene with HNO₃/Ac₂O Catalyzed by Caprolactam-based Brønsted Acidic Ionic Liquids

Xiufang QI, Guangbin CHENG,* Chunxu LU and Desheng QIAN

School of Chemical Engeering,
Nanjing University of Science & Technology,
Nanjing, 210094, China
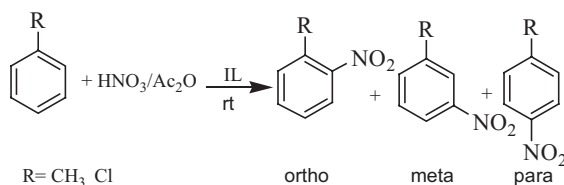*E-mail: gcheng@mail.njust.edu.cn*

Abstract: Several new caprolactam-based Brønsted acidic ionic liquids [Caprolactam]X (X⁻ = pTSO⁻, BSO⁻, BF₄⁻, NO₃⁻) with relatively lower cost and lower toxicity were synthesized and for the first time used in catalyzing organic reaction. They showed good catalytic activity in the nitration of toluene and chlorobenzene with HNO₃/Ac₂O under mild conditions. Among them, [Caprolactam]pTSO was the best one probably because of its better affinity to aromatics than the others. [Caprolactam]pTSO catalyzed the nitration of toluene with achieving a high yield (99.7%, calculated by quantitative GC) and better para-selectivity (ortho/para=1.03) than the traditional mixed acid methodology. And the catalyst can be recycled for four times.

Keywords: nitration, caprolactam-based Brønsted acidic ionic liquids, HNO₃/Ac₂O, aromatics, catalyze

Introduction

Nitration of aromatics is a fundamental reaction of great industrial importance, which provides energetic materials and key organic intermediates. Traditionally, this reaction is carried out in the presence of mixtures of concentrated or fuming nitric acid with sulfuric acid, which inevitably leads to yielding a mass of acid waste and causing serious environment problem. Therefore, various nitration approaches have been explored to avoid the problems of the traditional mixed acid method [1].

Over the past few years room temperature ionic liquids (ILs) have gained recognition as environmentally benign alternatives to volatile organic solvents and have been used for many reactions [2] as solvents and/or catalysts because of their peculiar physicochemical properties (Those are, a wide liquid range of about 300 °C, negligible vapor pressure, high thermal stability, and good solvating ability for a wide range of substrates and catalysts, high polarity, and excellent and variable Lewis/Brønsted acidity.). In most of the reactions employing ILs as solvents and/or catalysts, the reaction rates were enhanced and the outcomes were improved. The nitration of aromatics in ILs have also been gained attention of both academic and industrial researchers. A lot of work has been done to investigate the use of ILs for nitration and some success has been achieved and reported [3-6]. However, in the issued articles, most of the ILs used for nitration reactions are imidazolium-based, such as [emim][X] (X=OTf$^-$, CF$_3$COO$^-$, and NO$_3^-$) [3], [bmim]BF$_4$, [bmim]PF$_6$, and [bdmim]BF$_4$ [4], and [(CH$_2$)nSO$_3$Hmim]TfO (n=3, 4) [5].

In respect that imidazolium-based ILs have the main disadvantages of relatively higher cost and toxicity [7] in general chemical applications, we made an effort to seek new Brønsted acidic ILs with lower cost and lower toxicity. Youquan Deng et al. [8] reported the physicochemical properties of lactam-based Brønsted acidic ILs. These ILs are relatively cheaper, easily available in large amounts from industry and more environmentally friendly in comparison to imidazolium-based ILs. Moreover, the additional carbonyl groups in the lactam might lead to specific functions when these lactam-based ILs are used as media or solvents. Therefore, we chose [Caprolactam]BF$_4$ (H_0=-0.22) and [Caprolactam]NO$_3$ (H_0=2.08), which Brønsted acidity are relatively stronger, and applied them to nitration of simple aromatics. This was the first time for this type of ILs used in catalyzing organic reaction. Considering that addition of large aromatic head groups to the molecular of ILs may increase the solvating ability of ILs to aromatics, we synthesized two new caprolactam-based Brønsted acidic ILs, [Caprolactam]pTSO and [Caprolactam]BSO with p-toluenesulfonic acid (pTSA) and benzenesulfonic acid(BSA) as conjugated acid respectively according to the method of Ref. [8] and confirmed by ^{1}H NMR and Ms spectra.

$$X^- = \quad pTSO^-, \quad BSO^-, \quad BF_4^-, \quad NO_3^-$$
$$\qquad\qquad (1) \qquad (2) \qquad (3) \qquad (4)$$

Scheme 1. Preparation of caprolactam-based ILs.

Scheme 2. Nitration of aromatics with HNO$_3$/Ac$_2$O crystalized by ILs.

At first we attempted to use the caprolactam-based ionic liquids as catalysts and solvents in the nitration of aromatics with diluted nitric acid (67%) in which case water would be the only by-product. A series of reactions were processed with a 1:1 molar ratio of nitric acid to toluene at different temperature with varied dosage of ILs. However, the results suggested that there was nearly no reaction happening when the ratio of IL to toluene was 1:1; and the best result was obtained with a calculated yield (from GC, 37.4%) and a ratio of ortho/para (1.1:1) showing better para-selectivity than the traditional method (ortho/para = 1.97) when reacting at 55 °C with 20 mol% of IL1 for 24 h. The results indicated that the reaction was very slow when using nitric acid (67%) as the nitrating reagent.

Eventually, considering that HNO$_3$/Ac$_2$O system is a stronger nitrating agent than HNO$_3$ (67%) we chose HNO$_3$/Ac$_2$O system to investigate the catalytic activity of caprolactam-based ILs for nitration as a further try. Luckily good results were achieved and we reported them in this paper.

Materials and Methods

Materials: All reagents used in this study were analytically pure and used without further purification except for toluene and chlorobenzene which were dried over 4 Å molecular shieves.

Preparation and characterization of caprolactam-based ionic liquids: The preparation of caprolactam-based ILs was illustrated in Scheme 1. The ILs were prepared according to the method in Ref. [7]. Deionized water (10 ml) is added to a 50 ml flask containing 11.32 g of caprolactam (0.1 mol) and stirred. Then, the solution of acid (pTSA·H$_2$O, BSA, HBF$_4$, HNO$_3$, 0.1 mol) and deionized water (10 ml) was dropped slowly into the flask within ca 30 min in an ice bath. The reaction lasted for another 6 h at room temperature. Water was removed under reduced pressure and washed with benzene and toluene or ethyl ether for several times to deliminate unionized substances, then further dried at 65 °C under 10 mm Hg for 5 h.

^{1}H NMR spectra were recorded on a Bruker Advanced Digital 300 MHz NMR spectrometer and mass spectra were recorded on a Finnigan TSQ Quantun Ultra AM spectrometer. IR spectra were recorded on a Bruker EQUINOX55 IR spectrometer, melting points were measured on a XT4 micro-melting point instrument made by Beijing Keyi Dianguang Instrument Plant.

All of the caprolactam-based ILs were prepared with high yields of 85-92%. They are moisture stable. Among of them, [Caprolactam]pTSO is a white solid with a melting point of 69 °C and a yield of 85%; [Caprolactam]BSO is a yellow liquid of high viscosity with a yield of 90%; [Caprolactam]BF$_4$ is a colorless liquid with good fluidity and a yield of 87%; [Caprolactam]NO$_3$ a white solid with a melting point of 30 °C and a yield of 92%. All of them are easily soluble in water and have good moisture absorption.

The data of ^{1}H NMR and MS spectra of the four ILs were shown as following. The data were similar with those reported in Ref. [7]. In the ^{1}H NMR (CDCl$_3$) spectra, there are two active hydrogen in the range of δ 6.80-16.24 ppm respectively, indicating that they all formed N-protonated caprolactam cations.

[Caprolactam]pTSO: ^{1}H NMR (CDCl$_3$): δ1.73-1.83(m, 6H), 2.38 (s, 3H), 2.68(t, J=4.3, 2H), 3.46(s, 2H), 7.22(d, J=7.5, 2H), 7.76(d, J=7.7, 2H), 9.92(s, 1H), 10.91(s,1H). ^{1}H NMR (D$_2$O): 1.61-1.77(m, 6H), 2.41(s, 3H), 2.49(t, J=3.6, 2H), 3.26(t, J=4.6, 2H), 7.38(d, J=7.9, 2H), 7.71(d, J=7.9, 2H). MS(ESI): m/z 114.12 (Cation), calculated for cation (C$_6$H$_{12}$NO) 114.09.

[Caprolactam]BSO: ^{1}H NMR (CDCl$_3$): δ1.74-1.85(m, 6H), 2.65(d, J=9.1, 2H), 3.43(s, 2H), 6.80(s, 1H), 7.45(s, 3H), 7.90(d, J=5.9, 2H), 10.03(s, 1H); ^{1}H NMR: (D$_2$O): δ1.47-1.63(m, 6H), 2.33(t, J=5.3, 2H), 3.11(t, J=4.5, 2H), 7.44(t, J=7.7, 3H), 7.68(d, J=7.6, 2H). MS(ESI): m/z 114.13 (Cation), calculated for cation (C$_6$H$_{12}$NO) 114.09.

[Caprolactam]BF$_4$: ^{1}H NMR (CDCl$_3$): δ1.74-1.88(m, 6H), 2.71-2.76(q, J=5.6, 2H), 3.52-3.57(t, J=7.1, 2H), 3.46(s, 2H), 8.49(s, 1H), 9.79(s,1H). ^{1}H NMR (D$_2$O): 1.37-1.58(m, 6H), 2.29-2.33(t, J=5.7, 2H), 3.05-3.09(t, J=5.0, 2H). MS(ESI): m/z 114.09 (Cation), calculated for cation (C$_6$H$_{12}$NO) 114.09.

[Caprolactam]NO$_3$: ^{1}H NMR (CDCl$_3$): δ1.64-1.84(m, 6H), 2.62-2.65(t, J=5.6, 2H), 3.40-3.43(t, J=4.5, 2H), 8.54(s, 1H), 16.24(s, 1H); ^{1}H NMR: (D$_2$O): δ1.35-1.54(m, 6H), 2.25-2.29(t, J=5.7, 2H), 3.01-3.04(t, J=5.0, 2H). MS(ESI): m/z 114.10 (Cation), calculated for cation (C$_6$H$_{12}$NO) 114.09.

Using pyridine as IR probe molecule, pyridine and ILs mixed in a given ratio (1:1 by molar) and then spread into KBr liquid films, the Brønsted acidities of these ILs were determined by IR spectrometer. According to Ref. [9] and Ref. [10], the presence of a band near 1450 cm^{-1} is indicative of pyridine coordinated to Lewis acid sites; whilst a band near 1540 cm^{-1} is an indication

of the formation of pyridinium ions resulting from the presence of Brønsted acidic sites. From each probe IR spectra of these ILs, a band is observed at approximately or near 1540 cm^{-1}, confirming that Brønsted acidic sites are all present in the ILs synthesized. While no band near 1450 cm^{-1} is observed, suggesting the absence of Lewis acidity in these ILs. The wave number of the band corresponding to coordination at Brønsted acidic sites increases from 1541.59 cm^{-1} for [Caprolactam]BSO to 1543.69 cm^{-1} for [Caprolactam]pTSO, 1544.61 cm^{-1} for [Caprolactam]NO$_3$ and 1549.39 cm^{-1} for [Caprolactam]BF$_4$, indicating that the Brønsted acidity increases in the order [Caprolactam]BSO < Caprolactam]pTSO < [Caprolactam]NO$_3$ < [Caprolactam]BF$_4$.

Nitration of aromatics with HNO$_3$/Ac$_2$O catalyzed by IL: In a typical experiment, acetic anhydride (28 mmol) was dropped slowly into the stirred mixture of the IL (dosages indicated in Table 1) and nitric acid (67%, 10 mmol) under N$_2$ atmosphere in an ice-water bath, followed by addition of the substrate (10 mmol). Then the reaction mixture was warmed to room temperature. 2 h later the reaction was quenched by addition of water (5 mL), and the internal standard, nitrobenzene (0.2 mL) was added, followed by extraction with hexane (10 mL×3). The two phases formed were separated by simple decantation from each other and the organic extracts were combined and washed with saturated solution of sodium bicarbonate, water and brine, dried with Na$_2$SO$_4$, and then analyzed by GC with a FID detector. The recovered IL was dried at 65 °C under reduced pressure for 5 h and employed for further use.

Quantitative gas chromatography analysis: The analysis of product mixtures was carried out using an Agilent Technologies 6820 Gas Chromatography with an OV101 column (30 m×0.25 mm) and a FID detector. The GC conditions used for analysis were as follows: oven temperature was 160 °C for nitrotoluenes and 120 °C for nitrochlorobenzenes; both the injection and detection temperatures were 250 °C.

Results and Discussion

A series of experiments had been conducted to investigate the catalytic activity of the ILs synthesized for HNO$_3$/Ac$_2$O nitration of toluene and chlorobenzene and the main results were listed in Table 1.

Table 1. Reaction conditions and results of nitration of simple aromatics with HNO₃/Ac₂O catalyzed by ILs

Entry	R	IL	Dosage of IL (mol%)	Yield (%)[a]	Product distribution (%)			Ortho/ para
					ortho	meta	para	
1	CH_3	1	5	93.7	50.8	4.2	45.0	1.13
2	CH_3	1	10	99.7	48.3	5.1	46.7	1.03
3	CH_3	1	15	91.0	50.9	4.2	44.9	1.13
4	CH_3	1	20	92.9	51.5	4.0	44.5	1.16
5	CH_3	1	25	71.5	49.7	4.4	46.2	1.07
6	CH_3	1	30	74.4	50.3	4.4	45.3	1.11
7	CH_3	2	5	89.2	50.5	4.5	45.0	1.12
8	CH_3	2	10	92.1	48.7	5.0	46.3	1.05
9	CH_3	3	5	83.5	51.7	4.1	44.2	1.17
10	CH_3	3	10	95.8	50.9	4.2	44.9	1.13
11	CH_3	4	5	81.2	51.5	4.0	44.5	1.16
12	CH_3	4	10	84.3	51.4	4.0	44.6	1.15
13	Cl	1	5	43.4	17.8	0.3	81.8	0.21
14	Cl	1	10	43.8	18.8	0.4	80.8	0.22
15	Cl	1	15	36.7	18.8	0.4	80.8	0.23
16	Cl	1	20	37.1	21.4	0.6	78.0	0.27
17	Cl	none	0	7.9	21.4	trace	78.5	0.27
18	CH_3	none	0	17.4	56.5	4.7	38.8	1.46

[a] Calculated from quantitative GC.

Using IL1 as an example, the effect of the dosage of IL was tested on the nitration of toluene with IL-HNO₃/Ac₂O and the results are shown in Table 1, Entry 1-6. It can be observed that the yields of nitration products increased first and then decreased when the amount of IL1 was raised (Entry 1-6). To some extent, this is owing to the solvating effect of ionic liquid. When the dosage of IL increased to some degree the concentration of reaction substrates were diluted. The similar trend can be observed from the HNO₃/Ac₂O nitration of chlorobenzene (Entry 17-20) though the yields were relatively lower because chlorobenzene is deactive aromatic compound. No dinitrated products were detected in the nitration of toluene and chlorobenzene. As can be seen from the table, all the ionic liquids have shown good catalytic activity for the nitration of toluene with HNO₃/Ac₂O and among of them [Caprolactam]- pTSO was the best one with the highest yield of 99.7% (Entry 2, from GC) and the best para- selectivity with an ortho/para =1.03. The improvement of para-selectivity

(compared with the traditional nitric and sulfuric mixed acid methodology, ortho/para = 1.67) may be ascribed to the presence of IL offering ionic environment around the substrate toluene thus being advanced to the polarization of the substrate. [Caprolactam]pTSO showed better catalytic activity than the others, probably due to the strong Brønsted acidity and the pTSO⁻ in its molecule which made it have better affinity to toluene than the other ILs. However, the yield with IL3 [Caprolactam]BF₄ was also high (95.8%, Entry 10) since IL3 has stronger Brønsted acidity. It can be drawn that the acidity and affinity to aromatics of ILs have important roles on their catalytic activity in nitration. Stronger acidity and better affinity may lead to better catalytic activity.

Recycling of IL1 for HNO₃/Ac₂O nitration of toluene had been studied and the results were listed in Table 2. Though the yield decreased and ortho/para ratio increased after each recycling because of the loss of IL in the process of disposing, the IL still had good catalytic activity when it reused for the 4th time. And the MS spectra showed there was no NO₃⁻ in the recovered IL and IL1 was stable under the reaction conditions.
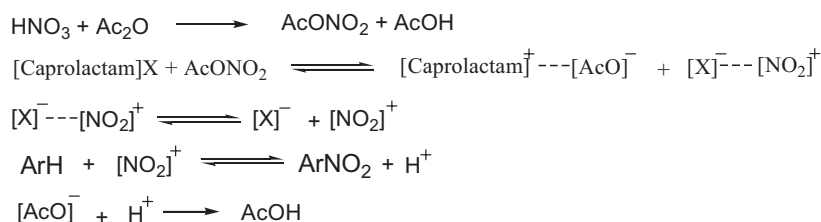
Table 2.   Recycling of IL1 in the HNO₃/Ac₂O nitration of toluene[a]

Run	Yield (%)[b]	Product distribution (%)			Ortho/Para
		Ortho	Meta	Para	
1	99.7	48.3	5.1	46.7	1.03
2	96.3	48.4	5.0	46.6	1.04
3	95.8	49.8	4.6	45.6	1.09
4	93.4	50.7	4.1	45.2	1.12

[a]   IL1: 10 mol%;
[b]   Calculated from quantitative GC.

From the reaction results and the ionic property of the ILs, nitration of simple aromatics with HNO₃/Ac₂O catalyzed by caprolactam-based ILs may be via a possible pathway showed in Scheme 3.

$$HNO_3 + Ac_2O \longrightarrow AcONO_2 + AcOH$$

$$[Caprolactam]X + AcONO_2 \rightleftharpoons [Caprolactam]^+ \text{---} [AcO]^- + [X]^- \text{---} [NO_2]^+$$

$$[X]^- \text{---} [NO_2]^+ \rightleftharpoons [X]^- + [NO_2]^+$$

$$ArH + [NO_2]^+ \rightleftharpoons ArNO_2 + H^+$$

$$[AcO]^- + H^+ \longrightarrow AcOH$$

Scheme 3. A possible pathway for nitration of simple aromatics with HNO₃/Ac₂O catalyzed by ILs.

Conclusion

In conclusion, caprolactam-based Brønsted acidic ionic liquids have catalytic activity in the nitration of simple aromatics with HNO_3/Ac_2O. And among them, [Caprolactam]pTSO is the best one probably because of its better affinity to aromatics than the others. The reaction was carried out in one phase at room temperature without volatile chlorinate organic solvents and it is quick and effective. The main by-product is acetic acid, which can be recycled by simple distillation or distillation under reduced pressure. Since caprolactam-based ILs are of lower cost and lower toxicity than traditional imidazolium-based ILs, they are more environmentally benign and economically practical. In a word, it is a promising and green way using ILs as catalysts and solvents for nitration of aromatic compounds and there is still a long way to go.

References

[1]   see for example: (a) Suzuki H.,.Tatsumi A, Suzuki H.M., Maeda K., A novel non-acidic method for the preparation of 2,2,2-trifluoro-1-(3-nitrophenyl)ethanone and 1-nitro-3- trifluoromethylbenzene, versatile starting materials for trifluoromethyl-containing aromatic compounds, *Synthesis*, **1995**, 1353; Suzuki H., Mori T., Ozone-mediated nitration of chloro- and bromo-benzenes and some methyl derivatives with nitrogen dioxide. High *ortho*-directing trends of the chlorine and bromine substituents, *J. Chem. Soc. Perkin Trans. 2*, **1994**, 479; Suzuki H., Mori T, Maeda K., Ozone-mediated reaction of polychlorobenzenes and some related halogeno compounds with nitrogen dioxides: A novel non-acid methodology for the selective mononitration of moderately deactivated aromatic systems, *Synthesis*, **1994**, 841; Suzuki H., Tomaru J., Murashima T., Iron (III)-catalysed nitration of non-activated and moderately activated arenas with nitrogen dioxide-molecular oxygen under neutral conditions, *J. Chem. Soc., Perkin Trans.* 1, **1996**, 2385; (b) Barrett A.G.M., Braddock D.C., Ducray R., Mckinnell R.M., Waller F.J., Lanthanide triflate and triflide catalyzed atom economic nitration of fluoro arenes, *Synlett.*, **2000**, *57*; Waller F.J., Barrett A.G.M., Braddock D.C., Ramprasad D., Lanthanide(III) triflates as recyclable catalysts for atom economic aromatic nitration, *Chem. Commun.*, **1997**, 613; (c) Delaude L., Laszlo P., Smith K., Heightened selectivity in aromatic nitrations and chlorinations by the use of sokid supports and catalysts, *Acc. Chem. Res.*, **1993**, *26*, 607; Gigante B., Prazeres A.O., Marcelo-Curto M.J., Mild and selective nitration by claycop, *J. Org. Chem.*, **1995**, *60*, 3445; Kwok T.J., Jayasuriya K., Damavarapu R., Brodman B. W., Applicat ion of H-ZSM-5 zeolite for regioselective mononitration of toluene, *J. Org. Chem.*, **1994**, *59*, 4939; Vessena D., Kogelbauer A., Prins R., Potential routes for the

nitration of toluene and nitrotoluene with solid acids, *Catal. Today*, **2000**, *60*, 275; Dagade S.P., Waghmode S.B., Kadam V.S., Dongare M.K., Vapor phase nitration of toluene using dilute nitric acid and molecular modeling studies over beta zeolite, *Appl. Catal., A*, **2002**, *226*, 49; Peng X., Suzuki H., Lu C., Zeolite-assisted nitration of neat toluene and chlorobenzene with a nitrogen dioxide/molecular oxygen system, Remarkableenhancement of *para*-selectivity, *Tetrahedron Letters*, **2001**, *42*, 4357.

[2] see for example: (a) Sheldon R., Catalytic reactions in ionic liquids, *Chem. Commun.*, **2001**, 2399; (b) Dupont J., Souza R.F., Suarez P.A.Z., Ionic liquid (Molten salt) phase organometallic catalysis, *Chem. Rev.*, **2002**, *102*, 3667; (c) Cole A.C., Jensen J.L., Ntai I., Tran K.L.T., Weaver K. J., Novel Brønsted acidic ionic liquids and their use as dual solvent-catalysts, *J. Am. Chem. Soc.*, **2002**, *124*, 5962; (d) Gui J.Z., Ban J.Y., Cong X.H., Zhang X.T., Sun Z.L., Selective alkylation of phenol with *tert*-butyl alcohol catalyzed by Brønsted acidic imidazolium salts, *J. Mol. Catal. A*, **2005**, *225*, 27; (e) Joseph T., Sahoo S., Halligudi S.B., Brønsted acidic ionic liquids, A green, efficient and reusable catalyst system and reaction medium for Fischer esterification. *ibid. A*, **2005**, *234*, 107; (f) Angueira E.J., White M.G., Arene carbonylation in acidic, chloro aluminate ionic liquids, *ibid.*, **2005**, *227*, 51; (g) Li D. M., Shi F., Peng J.J, Guo S., Deng Y.Q., Application of functional ionic liquids possessing two adjacent acid sites for acetalization of aldehydes, *J. Org. Chem.*, **2004**, *69*, 3582.

[3] Laali K. K., Gettwert V. J., Electrophilic nitration of aromatics in ionic liquid solvents, *J. Org. Chem.*, **2001**, *66*, 35.

[4] Smith K., Liu S.F., El-Hiti G.A., Regioselective mononitration of simple aromatic compounds under mild conditions in ionic liquids, *Ind. Eng. Chem. Res.*, **2005**, *44*, 8611.

[5] Qiao K., Yokoyama C., Nitration of aromatic compounds with nitric acid catalyzed by ionic liquids, *Chem. Lett.*, **2004**, *33*, 808.

[6] (a) Dal E., Lancaster N.L., Acetyl nitrate nitrations in [bmpy][N(Tf)$_2$] and [bmpy][OTf] and the recycling of ionic liquids, *Org. Biomol. Chem.*, **2005**, *3*, 682, (b) Lancaster N.L., Llopis-Mestre V., Aromatic nitrations in ionic liquids: the importance of cation choice, *Chem. Commun.*, **2003**, 2812.

[7] Swatloski R., Holbrey J., Memon S., Caldwell G., Caldwell K., Rogers R., Using Caenorhabditis elegans to probe toxicity of 1-alkyl-3-methylimidazolium chloride based ionic liquids, *Chem. Commun.*, **2004**, 668.

[8] Du Z.Y., Li Z.P., Guo S., Zhong J., Zhu L.Y., Deng Y.Q., Investigation of physicochemical properties of lactam-based Brønsted acidic ionic liquids, *J. Phys. Chem., B*, **2005**, *109*, 19542.

[9] Yang Y.L., Kou Y., Determination of the Lewis acidity of ionic liquids by means of an IR spectroscopic probe, *Chem. Commun.*, **2004**, 226.

[10] Parry E.P., An infrared of pyridine adsorbed on acidic solids, characterization of surface acidity, *J. Catal.*, **1963**, *2*, 371.