Catalysis

DOI: 10.1002/anie.200803567

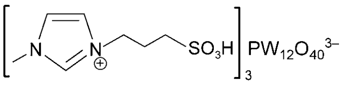
Heteropolyanion-Based Ionic Liquids: Reaction-Induced Self-Separation Catalysts for Esterification[**]

Yan Leng, Jun Wang,[*] Dunru Zhu, Xiaoqian Ren, Hanqing Ge, and Lei Shen

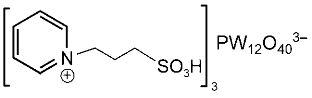
Organic esters are important intermediates in chemical and pharmaceutical industries, and they are mostly produced by acid-catalyzed esterification reactions.[1] Various mineral acids, such as H_2SO_4, HF, and H_3PO_4, have been used as catalysts for esterification. However, these acids are extremely corrosive and contaminative and need to be neutralized at the end of the reaction. Furthermore, it is very difficult to separate and reuse the mineral acid catalysts.[2] To overcome the above-mentioned problems, the use of heterogeneous catalysts such as resins,[3] supported mineral acids,[4] heteropolyacids,[5] and zeolites[6] has attracted much attention. However, these catalysts have disadvantages as well, for example, the tendency to deactivation, operation loss, and high mass transfer resistance, which limit their practical application in esterification.

In view of both the advantages and disadvantages of homogeneous and heterogeneous catalysts, and to improve catalyst recovery, multiphase systems, such as phase-transfer catalysis,[7–9] thermoregulated phase-transfer catalysis,[10] and liquid–liquid biphasic catalysis,[11] have been studied. Ionic liquids (ILs) have been revealed as green reaction media owing to their negligible volatility, excellent thermal stability, remarkable solubility, and the variety of structures available.[12,13] Many acid-catalyzed organic reactions based on ILs have been reported, among which esterifications are a hot topic.[14–17] By using ILs, especially Brønsted acidic ILs, as catalysts, the esterification system is homogeneous at the early stage of the reaction, and at the end it often forms a liquid–liquid biphase.[18] Consequently, ILs can be reused by decantation of the ester usually in the upper level of the resulting mixture. Davis and co-workers observed temperature-controlled liquid–solid separation by using an alkane sulfonic acid IL as solvent/catalyst for esterification.[14] Other advantages of ILs for esterification are the high conversion rate and selectivity. However, these results are not entirely satisfactory because the present systems still suffer from the high content of ILs (20–300 mol%) needed in the reaction media, relatively long reaction times, and the need of removing water by-product from the reaction system. Heteropolyacids (HPAs) and their salts have been extensively investigated as solid acid catalysts.[19] The combination of organic cations with heteropolyanions (or polyoxometalate (POM) anions) can cause the formation of HPA salts, which may be a kind of novel IL material. In fact, only a few examples of these IL compounds (e.g., $[(n\text{-}C_4H_9)_4N]_2M_6O_{19}$, $[C_n\text{mim}]_3PW_{12}O_{40}$, $[(n\text{-}C_4H_9)_4N]_4S_2M_{18}O_{62}$ (M = Mo, W; $n = 2$, 5; mim = methylimidazolium)) have thus far been described,[20–22] and they were used as electrochemicals rather than as catalysts. These considerations prompted us to design new heteropolyanion-based ILs containing the acidic functional group as "task-specific" catalysts for esterification reactions.

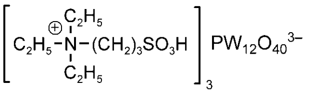
We synthesized a series of HPA salts containing organic cations—$[\text{MIMPS}]_3PW_{12}O_{40}$, $[\text{PyPS}]_3PW_{12}O_{40}$, and $[\text{TEAPS}]_3PW_{12}O_{40}$—and investigated their catalytic behavior in various esterification reactions. These new compounds were fully characterized by FT-IR, ^1H and ^{13}C NMR spectroscopy, ESIMS, and melting-point determination (see the Supporting Information). The results demonstrate that they contain three organic cations and an inorganic heteropolyanion. These compounds are not conventional ILs because their melting points are above 100 °C. Their solid nature could be due to the extended hydrogen bonding networks between the anion and cation (IR data, Supporting Information). The use of propane sulfonate (PS) functionalized ILs for the esterification reaction is considered to be an effective approach.[14] Furthermore, the heteropolyanion existing in the compounds gives them high melting points, which coincidently meets the requirements of a solid catalyst. They not only served as highly efficient and reusable catalysts but also circumvented the above-mentioned limitations of conventional ILs for



$[\text{MIMPS}]_3PW_{12}O_{40}$



$[\text{PyPS}]_3PW_{12}O_{40}$



$[\text{TEAPS}]_3PW_{12}O_{40}$

---

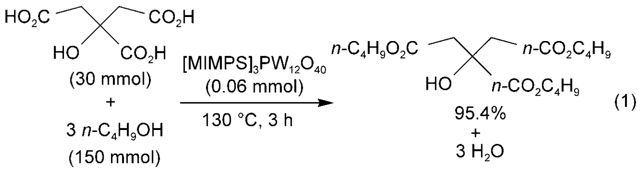
[*] Y. Leng, Prof. Dr. J. Wang, D.-R. Zhu, Dr. X.-Q. Ren, H.-Q. Ge, L. Shen
State Key Laboratory of Materials-Oriented Chemical Engineering
College of Chemistry and Chemical Engineering
Nanjing University of Technology, Nanjing 210009 (China)
Fax: (+86) 25-8317-2261
E-mail: junwang@njut.edu.cn

[**] We thank the National Natural Science Foundation of China (grant nos. 20476046, 20771059) and the "Qinglan" Project of Jiangsu Province for Young Researchers.

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/anie.200803567.

esterification. They could be used as homogeneous catalysts for many esterification reactions because of their good solubility in reaction media, and, moreover, at the end of the reaction, the catalysts precipitated and could be recycled without any regeneration being required, just like a heterogeneous system. Thus, these catalysts combine the advantages of homogeneous and heterogeneous catalysis.

The esterification of citric acid with *n*-butanol [Eq. (1)] was first carried out using $[MIMPS]_3PW_{12}O_{40}$ as the catalyst



(1)

(Table 1, entry 1). To our surprise, a yield of 95.4% and a selectivity of 98% for tributyl citrate were obtained at 130°C for 3 h, and, more notably, during the reaction process, switching from homogeneous to heterogeneous catalysis was clearly observed. At the beginning of the reaction, the catalyst itself was dissolved completely in the medium to form a homogeneous mixture (Figure 1 a,b), but near the completion of the reaction, the system became turbid (Figure 1 c), and the catalyst precipitated at the end of the reaction (Figure 1 d). This unusual behavior stimulated us to investigate further other esterification reactions with this catalyst. Similarly, the progression from a monophase catalysis to a biphase separation was observed also in the syntheses of dibutyl succinate, butyl lactate, and dibutyl oxalate, and excellent catalytic activities and selectivities were obtained as well (Table 1, entries 2–4, 6, 8, and 9; each reaction temperature is optimal for that reaction). These findings manifest a solid–liquid–solid phase-separation catalytic procedure, which is induced and controlled by the reaction, so we refer to this catalyst as a "reaction-induced self-separation catalyst". The outstanding feature of the catalyst is its excellent solubility in water or strong polar solvents but nonmiscibility with apolar esters. In above reaction systems, the solid catalyst $[MIMPS]_3PW_{12}O_{40}$ can be dissolved completely in polycarboxylic acids at reaction temperature or in polyols at room temperature, but it is insoluble in the product (ester). Thus, it is homogeneous at the early stage of the esterification reaction. With the consumption of the polycarboxylic acids or polyols, the system becomes heterogeneous, inducing a spontaneous self-separation of the catalyst. So at the end of reaction, the solid catalyst could be easily recovered by simple filtration. In contrast, in the formation of butyl acetate, butyl laurate, and dodecyl acetate, the reactions were heterogeneous (liquid–solid biphasic) for the entire reaction (Table 1, entries 5, 7, and 10) because of the insolubility of the catalyst in monocarboxylic acids or alcohols. However, high yields were also obtained in these heterogeneous systems possibly because of the pseudoliquid phase behavior of the HPA salt.[23] In each case, this novel catalyst for esterification not only shows very high catalytic activity but also can be recovered very conveniently.

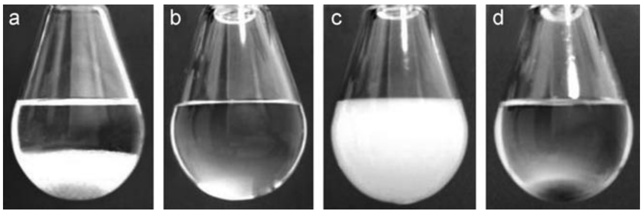


Figure 1. Photographs of the esterification of citric acid with *n*-butanol over $[MIMPS]_3PW_{12}O_{40}$. a) $[MIMPS]_3PW_{12}O_{40}$ (light brown solid at bottom), citric acid (white solid in the middle), and alcohol (liquid in the upper level) before mixing; b) homogeneous mixture during the reaction; c) heterogeneous mixture near completion of the reaction; d) at the end of the reaction; the catalyst has precipitated.

Table 1: Results of various esterification reactions over the $[MIMPS]_3PW_{12}O_{40}$ catalyst.[a]

Entry	Carboxylic acid (A)	Alcohol (B)	Reaction conditions					
			T [°C]	*t* [h]	n_A:n_B[b]	Phenomenon	Yield [%][c]	Sel. [%][c]
1	citric acid	*n*-butanol	130	3	1:5	phase separation	95.4	98
2	succinic acid	*n*-butanol	130	3	1:4	phase separation	98.6	100
3	lactic acid	*n*-butanol	110	2	1:3	phase separation	85.5	100
4	mandelic acid	*n*-butanol	120	3	1:4	phase separation	95.2	98
5	lauric acid	*n*-butanol	110	2	1:1.2	heterogeneous	91.4	100
6	oxalic acid	*n*-butanol	120	4	1:3	phase separation	74.4	98
7	acetic acid	*n*-butanol	110	1.5	1:1.2	heterogeneous	94.5	100
8	acetic acid	glycerol	100	3	8:1	phase separation	81.2	89
9	acetic acid	ethylene glycol	110	3	2.4:1	phase separation	87.9	98
10	acetic acid	dodecanol	110	2	1:1.2	heterogeneous	94.6	100

[a] Reaction conditions: catalyst $[MIMPS]_3PW_{12}O_{40}$ 0.20 g (0.06 mmol). [b] n_A:n_B: molar ratio of carboxylic acid to alcohol. [c] Yield or selectivity for the ester (entries 1–7 and entry 10 based on carboxylic acid (30 mmol), entries 8 and 9 based on alcohol (30 mmol)).

From the observations in Table 1, we were interested to know whether compounds similar to $[MIMPS]_3PW_{12}O_{40}$ also behaved as reaction-induced self-separation catalysts. Thus, we investigated the catalytic performance of $[TEAPS]_3PW_{12}O_{40}$ and $[PyPS]_3PW_{12}O_{40}$ for the esterification of citric acid with *n*-butanol (Table 2, entries 2 and 3). As expected, $[TEAPS]_3PW_{12}O_{40}$ and $[PyPS]_3PW_{12}O_{40}$ also acted as very active reaction-induced self-separation catalysts. However, their catalytic activities were slightly lower than that of $[MIMPS]_3PW_{12}O_{40}$. To determine whether the incorpora-

Table 2: Comparison of various catalysts for the esterification of citric acid with *n*-butanol.[a]

Entry	Catalyst	Phenomenon	Yield [%][b]	Sel. [%][b]
1	without catalyst	–	62.5	95
2	$[TEAPS]_3PW_{12}O_{40}$	phase separation	89.2	98
3	$[PyPS]_3PW_{12}O_{40}$	phase separation	91.5	98
4	$[MIM]_3PW_{12}O_{40}$	heterogeneous	73.8	98
5	$[TEA]_3PW_{12}O_{40}$	heterogeneous	68.3	98
6	$[Py]_3PW_{12}O_{40}$	heterogeneous	69.6	98
7	$[MIMPS]_3SiW_{12}O_{40}$	phase separation	89.3	98
8	$[MIMPS]_3PMo_{12}O_{40}$	phase separation	97.6	98
9	$[MIMPS]HSO_4$	homogeneous	76.2	98
10	$H_3PW_{12}O_{40}$	homogeneous	96.8	98

[a] Reaction conditions: catalyst (0.06 mmol), citric acid (30 mmol), molar ratio of citric acid to *n*-butanol 1:5, 130 °C for 3 h. [b] Yield or selectivity of tributyl citrate (based on citric acid).

tion of the acidic PS functional group in the organic cations of ILs is indispensible to achieve a high yield of esterification and to realize the reaction-induced phase-separation catalysis system, the same reaction was carried out on the three counterpart catalysts without PS: $[TEA]_3PW_{12}O_{40}$, $[MIM]_3PW_{12}O_{40}$, and $[Py]_3PW_{12}O_{40}$. Entries 4–6 in Table 2 show that the counterparts without PS were insoluble in the reactants and/or products, and the yields were only slightly higher than that of the control experiment (without catalyst; Table 2, entry 1), but much lower than those obtained using the PS-functionalized catalysts. The catalytic activities were in the order of $[MIM]_3PW_{12}O_{40} > [Py]_3PW_{12}O_{40} > [TEA]_3PW_{12}O_{40}$, which is in accordance with that of the PS-bearing catalysts. Therefore, the PS group in ILs is responsible for both the high catalytic activity and the reaction-induced phase separation.

The influence of various inorganic anions in the IL catalysts with the same MIMPS cation on the esterification of citric acid with *n*-butanol is shown in Table 2, entries 7–9. It can be seen that the two catalysts with $SiW_{12}O_{40}$ and $PMo_{12}O_{40}$ heteropolyanions demonstrated the reaction-induced phase-separation catalysis with high activities. However, when $[MIMPS]HSO_4$ was used as the catalyst, a homogeneous system resulted which gave a low yield. Although pure HPA catalyst $H_3PW_{12}O_{40}$ gave a very high yield of 96.8 %, its good solubility throughout the reaction makes its isolation from the reaction mixture difficult.

From the results reported herein, we think that it is the functional group PS in the IL catalysts rather than the heteropolyanion that provides the acid site responsible for the high activity in esterification. However, heteropolyanions are able to endow the IL catalyst with high melting points, which is responsible for the solid–liquid–solid phase transformation and catalyst separation.

As it is very convenient to recover the catalyst at the end of the reaction, the solid catalyst left could be readily reused for the next run. Therefore, the recycled $[MIMPS]_3PW_{12}O_{40}$ catalyst without any regeneration steps was investigated in the esterification of citric acid with *n*-butanol. As shown in Table 3, $[MIMPS]_3PW_{12}O_{40}$ exhibited a 95.4 % yield of tributyl citrate for the first run, and the catalytic activity slowly decreased with repeated use. At the fourth reaction run, 80.2 wt % of the catalyst was recovered and 84.5 % yield was obtained. In a control experiment, 0.16 g (0.2 g × 80.2 %, the same amount as that of the fourth run) fresh catalyst was used, and 89.6 % yield of tributyl citrate was obtained. This result indicates a slight decrease in the catalytic activity of the recovered catalyst.

Table 3: Catalytic recycling of the $[MIMPS]_3PW_{12}O_{40}$ catalyst for the esterification of citric acid with *n*-butanol.[a]

Run	Yield [%][b]	Sel. [%][b]
1	95.4	98
2	91.6	98
3	86.5	98
4	84.5	98

[a] Reaction conditions: catalyst 0.20 g (0.06 mmol), citric acid (30 mmol), molar ratio of citric acid to *n*-butanol 1:5, 130 °C for 3 h. [b] Yield or selectivity of tributyl citrate (based on citric acid).

The FTIR spectra for fresh $[MIMPS]_3PW_{12}O_{40}$ and recycled samples are compared in Figure S4 in the Supporting Information. It is revealed from the observation of four featured peaks of the Keggin anion at 1080, 978, 893, and 810 cm^{-1} that the Keggin structure of the heteropolyanion in fresh catalyst is well retained after the protons in the HPAs are substituted by the large organic cation. There were also three characteristic peaks at 1230, 1170 (S=O), and 621 cm^{-1} (imidazole ring) for the cation. Moreover, the IR spectrum for the recycled sample that was repeatedly used for four times was consistent with that of the fresh one, indicating good structural stability of the catalyst. However, the peak intensities decreased to some extent, which might be indicative of the slight deactivation of the recovered catalyst.

In summary, a series of nonconventional IL compounds in the solid state at room temperature composed of propane sulfonate functionalized organic cations and heteropolyanions were synthesized. They were used as "reaction-induced self-separation catalysts" for various esterification reactions with one of the reactants being polycarboxylic acid or polyol. The good solubility in the polycarboxylic acid or polyol, nonmiscibility with ester product, and high melting points of the heteropolyanion-based IL catalysts result in the switching from homogeneous to heterogeneous catalysis, which makes the recovery and catalytic reuse of this kind of catalyst very convenient. On the basis of the findings of this work, the exploration of the catalysts in other reactions and altering the composition of the catalysts is in progress.

Experimental Section

General preparation of the catalysts: High-melting-point ionic liquid catalyst $[MIMPS]_3PW_{12}O_{40}$ was synthesized as follows: Methylimidazole (0.11 mol) and 1,3-propane sulfone (0.10 mol) were dissolved in toluene (20 mL) and stirred for 24 h at 50 °C under a nitrogen atmosphere. A white precipitate (MIMPS) formed, which was filtered, washed with diethyl ether three times, then dried in a vacuum. MIMPS (0.06 mol) was added to an aqueous solution of $H_3PW_{12}O_{40}$ (0.02 mol), and then the mixture was stirred at room temperature for 24 h. Water was removed in vacuum to give the product as a solid, which was characterized by FTIR, ^1H and ^{13}C NMR spectroscopy, ESIMS, and melting-point determination.

$[TEAPS]_3PW_{12}O_{40}$, $[PyPS]_3PW_{12}O_{40}$, $[MIMPS]_3SiW_{12}O_{40}$, $[MIMPS]_3PMo_{12}O_{40}$, $[TEA]_3PW_{12}O_{40}$, $[MIM]_3PW_{12}O_{40}$, and $[Py]_3PW_{12}O_{40}$ were prepared accordingly.

Typical procedure for esterification: Citric acid (30 mmol), *n*-butanol (150 mmol), and $[MIMPS]_3PW_{12}O_{40}$ (0.06 mmol) were added to a flask with a water segregator. The reaction was heated under reflux at 130 °C with vigorous stirring for 3 h. After the reaction, tributyl citrate was detected by liquid chromatography (LC), and the compositions of the isolated other esters were detected by gas chromatography (GC) (Table 1, entries 2–10). If there was no *n*-butanol in the reaction, toluene was added as a water-carrying agent.

The conditions for other cases of reactions are listed in Table 1.

Received: July 22, 2008
Revised: October 21, 2008

Keywords: biphasic catalysis · heterogeneous catalysis · homogeneous catalysis · ionic liquids · phase-transfer catalysis

---

[1] R. C. Larock, *Comprehensive Organic Transformations*, VCH, New York, **1999**.

[2] P. Mäki-Arvela, T. Salmi, M. Sundell, K. Ekman, R. Peltonen, J. Lehtonen, *Appl. Catal. A* **1999**, *184*, 25 – 32.

[3] A. Heidekum, M. A. Harmer, W. F. Hoelderich, *J. Catal.* **1999**, *181*, 217 – 222.

[4] I. J. Dijs, H. L. F. van Ochten, C. A. van Walree, J. W. Geus, L. W. Jenneskens, *J. Mol. Catal. A* **2002**, *188*, 209 – 224.

[5] I. V. Kozhevnikov, *Chem. Rev.* **1998**, *98*, 171 – 198.

[6] R. A. Sheldon, R. S. Downing, *Appl. Catal. A* **1999**, *189*, 163 – 183.

[7] T. Ooi, K. Maruoka, *Angew. Chem.* **2007**, *119*, 4300 – 4345; *Angew. Chem. Int. Ed.* **2007**, *46*, 4222 – 4266.

[8] Z. Xi, N. Zhou, Y. Sun, K. Li, *Science* **2001**, *292*, 1139 – 1141.

[9] V. K. Dioumaev, R. M. Bullock, *Nature* **2000**, *424*, 530 – 532.

[10] Special issue (Ed.: J. A. Gladysz), *Chem. Rev.* **2002**, *102*, 3215 – 3216.

[11] S. Sunitha, S. Kanjilal, P. S. Reddy, B. N. Rachapudi, *Tetrahedron Lett.* **2007**, *48*, 6962 – 6965.

[12] E. D. Bates, R. D. Mayton, I. Ntai, J. H. Davis, Jr., *J. Am. Chem. Soc.* **2002**, *124*, 926 – 927.

[13] A. E. Visser, J. D. Holbrey, R. D. Rogers, *Chem. Commun.* **2001**, 2484 – 2485.

[14] A. C. Cole, J. L. Jensen, I. Ntai, K. L. T. Tran, K. J. Weaver, D. C. Forbes, J. H. Davis, Jr., *J. Am. Chem. Soc.* **2002**, *124*, 5962 – 5963.

[15] J. McNulty, S. Cheekoori, J. J. Nair, V. Larichev, A. Capretta, A. J. Robertson, *Tetrahedron Lett.* **2005**, *46*, 3641 – 3644.

[16] C. E. Song, D. Jung, S. Y. Choung, E. J. Roh, S. Lee, *Angew. Chem.* **2004**, *116*, 6309 – 6311; *Angew. Chem. Int. Ed.* **2004**, *43*, 6183 – 6185.

[17] J. Gui, X. Cong, D. Liu, X. Zhang, Z. Hu, Z. Sun, *Catal. Commun.* **2004**, *5*, 473 – 477.

[18] C. Xie, H. Li, L. Li, S. Yu, F. Liu, *J. Hazard. Mater.* **2008**, *151*, 847 – 850.

[19] L. C. W. Baker, D. C. Glick, *Chem. Rev.* **1998**, *98*, 3 – 49.

[20] A. B. Bourlinos, K. Raman, R. Herrera, Q. Zhang, L. A. Archer, E. P. Giannelis, *J. Am. Chem. Soc.* **2004**, *126*, 15358 – 15359.

[21] P. G. Rickert, M. R. Antonio, M. A. Firestone, K. A. Kubatko, T. Szreder, J. F. Wishart, M. L. Dietz, *J. Phys. Chem. B* **2007**, *111*, 4685 – 4692.

[22] P. G. Rickert, M. R. Antonio, M. A. Firestone, K. A. Kubatko, T. Szreder, J. F. Wishart, M. L. Dietz, *Dalton Trans.* **2007**, 529 – 531.

[23] M. Misono, *Chem. Commun.* **2001**, 1141 – 1152.