Heterogeneous Catalysis

Metal Sulfonate Polymers as Catalysts for the Heterogeneous Acylation of Aromatic Derivatives

Vincent Morizur,[a] Daphné Hector,[a] Sandra Olivero,[a] Jean Roger Desmurs,[b] and Elisabet Duñach*[a]

Abstract: A series of metal sulfonate salts attached to a poly(ether ether ketone) (PEEK) polymer were prepared by ultrasonic activation and then examined as heterogeneous catalysts in the Friedel–Crafts acylation of aromatic derivatives.

Introduction

The availability of active catalysts that are easy to recycle constitutes an important challenge in the field of catalysis. In this context, the development of heterogeneous catalysis is of great importance, as this type of reaction system facilitates the separation of the catalyst from the product by simple filtration.[1]

We are interested in catalysis by using protic and Lewis acids that are supported on a polymer framework. In the area of heterogeneous protic and Lewis acid catalysis, porous materials such as natural and synthetic zeolites or sulfonic perfluorinated polymers such as Nafion have shown their efficiency and specificity in several catalytic processes.[2] Herein, we report the preparation of new polymeric materials in the form of metal salts and their use as catalysts in the Friedel–Crafts acylation of aromatic derivatives.

The Friedel–Crafts acylation is an essential transformation for the C–H functionalization of aromatic compounds and is highly valued in the chemical industry for the preparation of intermediates for applications such as pharmaceuticals, paint additives, flavors, plasticizers, and dyes.[3] Strong Lewis acids, mainly derived from metal sulfonates such as triflates ($CF_3SO_3^-$) and triflimides [$(CF_3SO_2)_2N^-$], have previously shown their high catalytic activity in these reactions.[4] Thus, we propose that functionalized polymers grafted with sulfonic acid groups can be used in the same sense. In related examples, adsorbed Al^{III} triflate on polystyrene[5] and Yb^{III} perfluoroctanesulfonate on Amberlyst A21[6] have been reported as efficient catalysts for acylation reactions.

[a] *Institut de Chimie de Nice UMR 7272, Université Nice Sophia Antipolis,*
    Faculté des Sciences,
    Parc Valrose, 06108 Nice cedex 2, France
    E-mail: dunach@unice.fr
    http://icn.unice.fr
[b] *CDP-Innovation, G2C Business Center,*
    63 Rue André Bollier, 69307 Lyon, France
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Results and Discussion

1. Preparation of a Polymeric Sulfonic Acid Catalyst

The commercially available polymer PEEK [poly(ether ether ketone), **1**] was chosen for functionalization.[7] This polymer is known for its high thermal and mechanical stability as well as its chemical resistance.[8] In addition, there are many available options for its functionalization to afford various controllable functional groups on a relatively polar skeleton. Despite its stability, the carbonyl group of polymer **1** has been converted into a thioacetal[9] and an imine.[10] The electrophilic aromatic substitution of **1** has also been reported by using a chloromethyl derivative,[11] a sulfonic acid, or a sulfonyl chloride.[12] However, these functionalization processes have involved polymer reticulation, and to the best of our knowledge, no catalytic processes using PEEK derivatives have been described in the literature.

We assembled a chlorosulfonation protocol that enabled the preparation of chlorosulfonated polymer **2** in an almost quantitative yield by controlling the reaction conditions and without the need for reticulation (Scheme 1). This sulfonation occurred exclusively at the diether aromatic unit, and its monofunctionalization was achieved in 97–100 % yield. The amount of dichlorosulfonation could be quantified by ^{1}H NMR analysis and the integration of the signal at $\delta = 8.20$ ppm, which corresponds to the proton of the disulfonated aromatic unit. This signal at $\delta = 8.20$ ppm was absent from the ^{1}H NMR spectrum of polymer **2**.
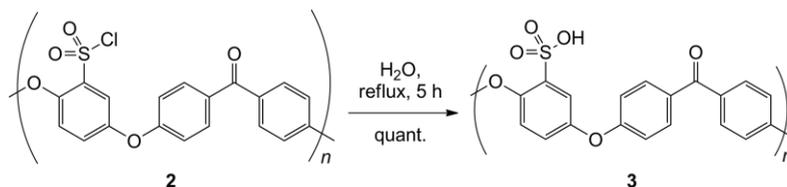

Scheme 1. Preparation of chlorosulfonated polymer **2** (DMF = *N,N*-dimethylformamide).

The hydrolysis of **2** in water at reflux allowed for the quantitative preparation of the sulfonic acid polymer **3** as a yellow powder (Scheme 2). Polymer **3** is insoluble in most organic sol-

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Scheme 2. Preparation of sulfonic acid polymer **3**.

vents, and partially soluble in dimethyl sulfoxide (DMSO), ethanol, and water.

2. Preparation of Lewis Acid Polymer Catalysts

Polymer **3** was used for the preparation of a series of polymer metal salts, namely, those of In^{3+}, Bi^{3+}, Cu^{2+}, Sm^{3+}, and Gd^{3+}. The salts were prepared by carrying out a redox reaction between sulfonic acid **3** and the corresponding metal with ultrasonic activation (35 kHz, 70 W, Sonometer UIP1000 hd Hielsher)[13] in an aqueous solution (Scheme 3). The yields obtained for the five polymers **4a**–**4e** were almost quantitative, as indicated in Table 1.
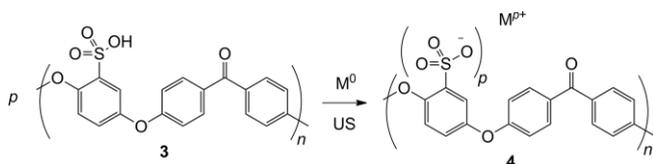
Scheme 3. Ultrasonic (US) preparation of polymer metal salts.

Table 1. Preparation of polymeric metal salts by ultrasonic activation.

M^0	Time [h]	Product	Yield [%]
In	12	In^{3+} (**4a**)	92
Bi	18	Bi^{3+} (**4b**)	97
Cu	18	Cu^{2+} (**4c**)	95
Sm	12	Sm^{3+} (**4d**)	98
Gd	14	Gd^{3+} (**4e**)	98

The functionalized polymers **4a**–**4e** were insoluble in water, and thus, they were isolated by filtration, rinsed with water, and further dried under vacuum. These polymers were slightly soluble in DMSO and insoluble in most organic solvents.

3. Acylation Reactions Catalysed by Polymer-Supported Lewis Acids

Polymers **3** and **4a**–**4e** were then examined as protic and Lewis acid heterogeneous catalysts, respectively, of the Friedel–Crafts acylation reaction of aromatic derivatives **5**. 1,3-Dimethoxybenzene (**5a**) was chosen as the model compound for these studies. The acylations were performed in nitromethane at reflux with 10 mol-% of the catalyst (metal content) in the presence of acyl chloride as the acylating agent (Scheme 4).
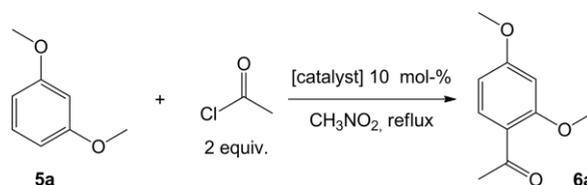
Scheme 4. Acylation of 1,3-dimethoxybenzene (**5a**).

The amount of acylated product **6a** was monitored by GC analysis using dodecane as an internal standard. The kinetic evolution of the reaction with the different polymeric catalysts is illustrated in Figure 1.
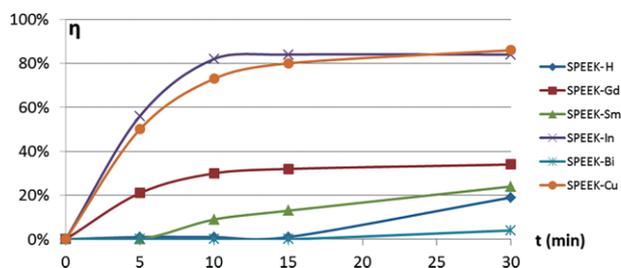

Figure 1. Kinetic evolution of the acylation of **5a** with polymers **3** and **4a**–**4e** (10 mol-%) in nitromethane at reflux [SPEEK = sulfonated poly(ether ether ketone)].
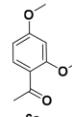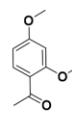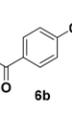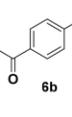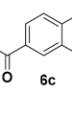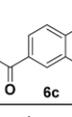
Indium(III) and copper(II) derivatives **4a** and **4c**, respectively, were determined to be the most active catalysts. A yield of 82 % for **6a** was attained in only 10 min by using the In^{III}-based polymer. Protic polymer **3** was less efficient and demonstrated the similar low catalytic activity that was observed with the Bi^{III}-, Sm^{III}-, and Gd^{III}-based polymers (Figure 1).

In the acylation of other aromatic compounds such as anisole (**5b**) and 1,2-dimethoxybenzene (**5c**), the In^{III}-based catalyst **4a** offered better results than those afforded by Cu^{II} polymer, **4c**. These results are summarized in Table 2.

Thus, In^{III}-based polymer **4a** was used as the catalyst for the acylation of various other (hetero)aromatic substrates. The results are summarised in Table 3. For the series of activated compounds that were examined, the yields of products **6a**–**6j** were generally good, in particular those produced by the anisole and thiophene derivatives.

The catalytic activity of this newly prepared catalyst was also compared to that of the corresponding metal tosylates $[M(OTs)_n]$, mesylates $[M(OMs)_n]$, and triflates $[M(OTf)_n]$ under homogeneous catalytic conditions.[14] Figure 2 shows the kinetic evolution of the acylation of 1,3-dimethoxybenzene (**5a**) with different In^{III} catalytic systems.

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Table 2. Comparison of the catalytic activity of polymers **4a** and **4c**.[a]

Entry	Catalyst	Substrate	Time [h]	Product	Yield of **6** (%)
1	In³⁺ (**4a**)	**5a**	0.25	**6a**	82
2	Cu²⁺ (**4c**)	**5a**	0.5	**6a**	84
3	In³⁺ (**4a**)	**5b**	1	**6b**	97
4	Cu²⁺ (**4c**)	**5b**	2	**6b**	40
5	In³⁺ (**4a**)	**5c**	2	**6c**	80
6	Cu²⁺ (**4c**)	**5c**	2	**6c**	55

[a] Reagents and conditions: in refluxing nitromethane, catalyst (metal based, 10 mol-%), and acyl chloride (2 equiv.). For details, see Supporting Information.
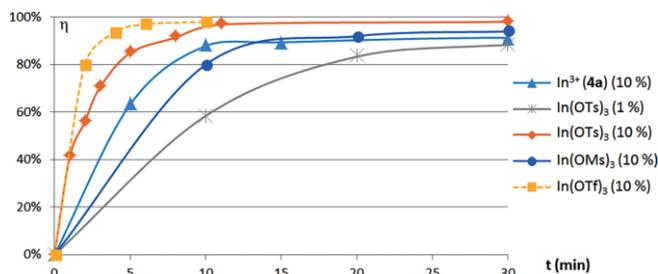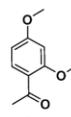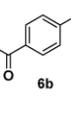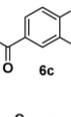

Figure 2. Acylation of 1,3-dimethoxybenzene (**5a**) by different In^III sulfonate salts under the conditions described in Table 2.

As expected, the most active catalyst was In(OTf)₃, which allowed for the quantitative acylation of **5a** in less than 5 min. In(OTf)₃ was also slightly more active than the corresponding polymer **4a**. The kinetics of the acylation of **5a** under In(OTs)₃ catalysis and homogeneous conditions is comparable to that of polymer **4a** under heterogeneous conditions.

Next, the possibility to recycle the catalyst by simple filtration was examined for the reaction of polymer **4a** and substrate **5a** under the conditions reported in Table 2. Each run was examined after 10 min. After five catalytic cycles, there was no significant loss in the catalytic activity of the polymer, and the yields of **6a** were maintained between 75 and 85 %. Finally, the stability of the catalyst was also studied by thermogravimetric

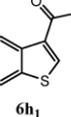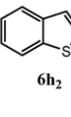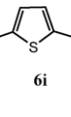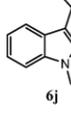Table 3. Acylation of (hetero)aromatic derivatives catalyzed by **4a**.[a]

Entry	Substrat	Time	Product	Yield of **6** (%)
1	**5a**	15 min	**6a**	82
2	**5b**	1 h	**6b**	96
3	**5c**	2 h	**6c**	80
4	**5d**	1 h	**6d**	35
5	**5e**	20 min	**6e**	80
6	**5f**	40 min	**6f₁** / **6f₂** : 80 / 20	96
7	**5g**	3 h 30	**6g₁** / **6g₂** : 77 / 23	49
8	**5h**	10 min	**6h₁** / **6h₂** : 60 / 40	96
9	**5i**	10 min	**6i**	94
10	**5j**	2 h 30	**6j**	84

[a] Reagents and conditions: in refluxing nitromethane, catalyst (metal-based, 10 mol-%), and acyl chloride (2 equiv.). For details, see Supporting Information.

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analysis (TGA), which indicated a thermal stability of **4a** of up to 250 °C (see Supporting Information).

Conclusions

Supported protic and Lewis acid catalysts were prepared by starting from the commercially available aromatic PEEK polymer. Its sulfonation allowed for the preparation of a protic sulfonic acid catalyst, which was further transformed into a series of metal sulfonate salts by ultrasonic activation. These supported Lewis acids were obtained in almost quantitative yields.

The efficiency of these polymers as heterogeneous catalysts was examined in the Friedel–Crafts acylation of activated aromatic compounds. These studies showed that In^{III} sulfonate polymer **4a** was the most active catalyst of the series. The catalytic activity of this polymeric catalyst was also compared to that of the corresponding nonpolymeric analogues. The In^{III} polymer catalyst **4a** could be recycled for use in five runs without the loss of its catalytic activity.

Experimental Section

Preparation of 2: To a suspension of PEEK (**1**, 10.0 g, 34.7 mmol) in dry CH_2Cl_2 (350 mL) was added chlorosulfonic acid (18.5 mL, 278 mmol). The resulting suspension was stirred at room temperature for 15 h. The supernatant was separated, and thionyl chloride (76 mL, 1.04 mol) and dry N,N-dimethyformamide (11 mL, 174 mmol) were added to the remaining gel. The resulting red slurry was stirred at room temperature for 2 h and then further diluted by the slow addition of dry THF (200 mL). The upper layer of the resulting two-phase system was separated and added dropwise to 2-propanol (500 mL) that was stirred. The resulting precipitate was removed by filtration, washed with acetonitrile (2 × 250 mL), and dried under vacuum to give polymer **2** (13.2 g, 34.1 mmol, 98 % yield) as a white solid. ^1H NMR (200 MHz, [D_6]DMSO): δ = 7.94–7.68 (m, 4 H), 7.51 (d, J = 2.9 Hz, 1 H), 7.33–6.92 (m, 6 H) ppm. IR: $\tilde{\nu}$ = 1654, 1597, 1473, 1375, 1257, 1217, 1159, 927, 764 cm^{-1}.

Preparation of 3: A stirred suspension of **2** (10.0 g, 25.9 mmol) in water (250 mL) was heated at reflux for 15 h. The solution was concentrated under vacuum, and the resulting solid was crushed, washed with acetonitrile (2 × 500 mL), removed by filtration, and dried under vacuum to give polymer **3** (9.5 g, 25.8 mmol, 99 % yield) as a yellow solid. ^1H NMR (200 MHz, [D_6]DMSO): δ = 7.94–7.66 (m, 4 H), 7.51 (d, J = 2.9 Hz, 1 H), 7.32–6.94 (m, 6 H) ppm. IR: $\tilde{\nu}$ = 3371, 1638, 1596, 1471, 1220, 1159, 1023, 929, 859 cm^{-1}.

General Procedure for Preparation of 4: Polymer **3** (368 g/mol, 2.7 mmol) was added to water (30 mL, 0.092 M), and the corresponding metal (0.32 equiv. for a trivalent metal and 0.48 equiv. for a divalent metal) was added to the solution. The mixture was placed under ultrasonic activation (35 kHz, 70 W, Sonometer UIP1000 hd Hielsher) at room temperature. Upon complete consumption of the metal, the solution was filtered, and the precipitate was washed with water (2 × 10 mL) and dried under vacuum overnight (1 × 10^{-2} mbar). The filtrate contained no metal residue.

General Procedure for Acylation Reaction: To a Schlenk flask were added dry nitromethane (20 mL), 1,3-dimethoxybenzene or the aromatic derivative (2 mmol), the catalyst (metal- or proton-based, 10 mol-%), and acetyl chloride (4 mmol). The resulting solution was heated at reflux, and the progress of the reaction was followed by gas chromatography. Extraction with diethyl ether and purification by column chromatography (AcOEt/Et$_2$O, 90:10) afforded the corresponding product. The acylated derivatives are known compounds, and the ^1H and ^{13}C NMR spectroscopic and MS data were in agreement with the literature data.

[1] B. Clapham, T. S. Reger, K. D. Janda, *Tetrahedron* **2001**, *57*, 4637–4662.
[2] G. Sartori, R. Maggi, *Chem. Rev.* **2011**, *111*, 181–214.
[3] J.-R. Desmurs, S. Ratton, *The Roots of Organic Development*, Elsevier Science B. V., Amsterdam, **1996**.
[4] a) S. Antoniotti, S. Poulain-Martini, E. Duñach, *Synlett* **2010**, 2973–2988; b) M. Kawamura, D.-M. Cui, S. Shimada, *Tetrahedron* **2006**, *62*, 9201–9209; c) S. Antoniotti, V. Dalla, E. Duñach, *Angew. Chem. Int. Ed.* **2010**, *49*, 7860–7888; *Angew. Chem.* **2010**, *122*, 8032; d) J. R. Desmurs, M. Labrouillère, C. Le Roux, H. Gaspard, A. Laporterie, J. Dubac, *Tetrahedron Lett.* **1997**, *38*, 8871–8874; e) S. Kobayashi, I. Komoto, J.-I. Matsuo, *Adv. Synth. Catal.* **2001**, *343*, 71–74; f) J. Ross, J. Xiao, *Green Chem.* **2002**, *4*, 129–133.
[5] K. P. Borujeni, A. R. Massah, *React. Funct. Polym.* **2006**, *66*, 1126–1131.
[6] W.-B. Yi, C. Cai, *J. Fluorine Chem.* **2008**, *129*, 524–528.
[7] a) W. H. Bonner Jr., US3065205, **1962**; b) J. B. Rose, GB1414422A, **1975**; J. B. Rose, P. A. Staniland, EP1879A1, **1979**.
[8] a) D. P. Jones, D. C. Leach, D. R. Moore, *Polymer*, **1985**, *26*, 1385–1393 (August 1985, conference issue); b) A. Jonas, R. Legras, *Polymer* **1991**, *32*, 2691–2706; c) S. D. Hudson, D. D. Davis, A. J. Lavinger, *Macromolecules* **1992**, *25*, 1759–1765.
[9] H. M. Colquhoun, F. P. V. Paoloni, M. G. B. Drew, P. Hodge, *Chem. Commun.* **2007**, 3365–3367.
[10] I. Manolakis, P. Cross, H. M. Colquhoun, *Macromolecules* **2011**, *44*, 7864–7867.
[11] X. Yan, G. He, X. Wu, J. Benziger, *J. Membr. Sci.* **2013**, *429*, 13–22.
[12] a) M. L. Di Vona, D. Marani, C. D'Ottavi, M. Trombetta, E. Traversa, I. Beurroies, P. Knauth, S. Licoccia, *Chem. Mater.* **2006**, *18*, 69–75; b) X. Zhao, Q. Zhang, L. Xue, Q. Shi, K. Tao, *J. Appl. Polym. Sci.* **2013**, *130*, 1058–1063; c) S. Kaliaguine, S. D. Mikhailenko, K. P. Wang, P. Xing, G. Robertson, M. Guiver, *Catal. Today* **2003**, *82*, 213–222; d) W. Zhang, V. Gogel, K. A. Friedrich, J. Kerres, *J. Power Sources* **2006**, *155*, 3–12.
[13] a) N. Legrave, A. Couhert, S. Olivero, J.-R. Desmurs, E. Duñach, *Eur. J. Org. Chem.* **2012**, 901–904; b) J. R. Desmurs, E. C. I. Duñach, S. Olivero, S. Antoniotti, WO2012010752A1, **2012**.
[14] V. Morizur, J. Szafranek, D. Bonhomme, S. Olivero, J. R. Desmurs, E. Duñach, *Tetrahedron* **2015**, *71*, 6813–6817.