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Novel method for catalyst immobilization using an ionic polymer: a case study using recyclable ytterbium triflate

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Abstract—A series of ionic polymers prepared by quarternization of cross-linked poly(4-vinylpyridine/styrene) (P/S) resins with several alkylating agents, including short-length PEG mesylate were used as polymeric supports to immobilize $Yb(OTf)_3$. The efficacy of the polymer-bound catalyst was examined in a Mannich-type reaction.

The development of recyclable catalysts continues to be one of the most active areas in applied organic synthesis, and in particular organometallic research in light of ever-growing environmental and economic concerns.[1] Several methods for the efficient recycling of catalysts have been studied in the last two decades; among these, the immobilization of catalysts on solid supports has gained special prominence, as this tact allows precious catalysts to be separated from the reaction mixture by simple filtration for reuse.[2] Metal-based catalysts have been immobilized onto solid supports by ligand–metal interaction or complexation, however, these procedures may change the structure and activity of the original catalyst. Furthermore, immobilization based on ligand exchange or complexation requires tailoring of the support for each individual catalyst.

In a biphasic reaction system, an ionic liquid provides a general method for immobilization of metal catalysts by way of the strong interaction between the metal and the ion.[3] Ionic polymers (or ionic resins) with easily accessible ionic regions within the polymer matrix can act as catalyst supports in the same manner as ionic liquids. Polymer-supported quarternary ammonium salts have found application in organic chemistry as phase transfer catalysts for asymmetric amino acid synthesis[4] and enhanced nucleophilic substitution reactions.[5] While two reports have described the preparation and use of ionic-immobilized metal catalysts OsO_4^{2-} and $[Rh(CO)_2I_2]^-$ via ion exchange between the metal complex anion and halide of the ionic polymer.[6,7] Regardless of the type of ionic polymer, ion exchange processes will eventually provide a polymer–metal ion pair as well as a removable ion pair species as the by-product. These applications notwithstanding, most useful metal catalysts exist not in cation or anion form but in a neutral form, and therefore cannot be immobilized by the ion exchange process.

Herein, we report a novel family of ionic polymers as a useful and effective class of solid supports for the immobilization of neutral metal catalysts, as exemplified by $Yb(OTf)_3$. Rare-earth metal(III) triflates ($RE(OTf)_3$) including lanthanide(III) triflates ($Ln(OTf)_3$) have been employed as mild Lewis acids in many organic transformations.[8] Several methods for immobilization of ytterbium(III) triflate ($Yb(OTf)_3$) and other $RE(OTf)_3$ have been developed. Especially relevant to our work is the immobilization of scandium(III) triflate ($Sc(OTf)_3$) on styrene-based polymers by a microencapsulation technique[9] and the immobilization of $Yb(OTf)_3$ by an ion exchange process on several resins such as amberlyst.[10]

A series of cross-linked poly(4-vinylpyridine/styrene) copolymers (^{x}P/S, where superscript x denotes pyridine content), ^{30}P/S (**1a**), ^{50}P/S (**1b**), ^{70}P/S (**1c**), ^{90}P/S (**1d**) and ^{100}P/S (**1e**) with 1% 1,4-bis(4-vinylphenoxy)butane[11] as a cross-linker were synthesized as resin beads by aqueous suspension polymerization initiated

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Keywords: Ionic polymer; Catalyst immobilization; ytterbium triflate.

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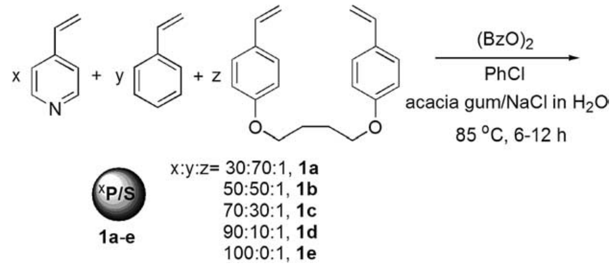
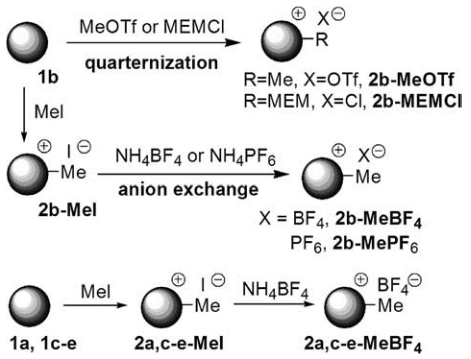


Scheme 1. The preparation of P/S resins. Nitrogen (pyridine) content (mmol/g) is tabulated in Supporting Information.



Scheme 2. Preparation of ionic polymers from ^{x}P/S resin.

by benzoyl peroxide (Scheme 1). To investigate the effect of anions on the properties of these ionic polymers, ^{50}P/S (**1b**) resin was quarternized with iodomethane, methyl triflate and methoxyethoxy-methyl chloride (MEMCl) to give corresponding ionic polymers [^{50}P/S-R][X] (Scheme 2). The reactive iodide anion of **2b-MeI** was substituted with two inert anions such as BF_4^- and PF_6^-. Additionally, four [^{x}P/S-Me][BF$_4$] resins **2a-MeBF$_4$** and **2c–e-MeBF$_4$** were prepared in the same manner to study the effect of pyridinium salt content.

The swelling of a resin in common organic solvents is a critical determinant of access to regions for immobilization and catalytic activity.[12] The swelling of the neutral base polymers and quaternized ionic polymers prepared in this series was determined by the syringe method in several organic solvents and water.[13] The ionic polymers exhibited overall good swelling and was dramatically affected by the type of counterpart anions and pyridinium salt content.

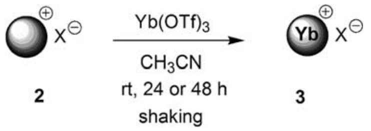
Immobilization of Yb(OTf)$_3$ within the ionic polymer was achieved by shaking a suspension of the ionic polymer and Yb(OTf)$_3$ in acetonitrile for 24 or 48 h at room temperature. Catalyst loading was determined gravimetrically by resin weight gain, and verified by quantitation of residual Yb(OTf)$_3$ in the filtrate after immobilization (Table 1). Ytterbium triflate was immobilized onto the ionic polymer within a range of 0.15–0.20 mmol/g, except for the [^{50}P/S-Me][OTf] (**3b-MeOTf**) resin.

We note that in contrast to a typical ion exchange process, that can provide a distinct polymer–metal ion pair, for the case at hand, polymer–metal ion pairing is not likely, although, clearly ion-exchange between the triflate of Yb(OTf)$_3$ and the polymer will occur. We postulate that the metal catalyst is likely to be captured not by an ionic interaction between the polymer and metal, but by metal ion (cations as well as anions of the ionic polymer) interaction as seen with metal-immobilized ionic liquids.

Of paramount importance in the development of an immobilized catalyst is the stability of the immobilization chemistry. Yb(OTf)$_3$ immobilized within ionic polymer could plausibly be released by an exchange process with substrate and/or product molecules, as well as with solvent. Seven common organic solvents were tested to examine the possibility and extent of catalyst leaching from [^{50}P/S-Me][BF$_4$](Yb) (**3b-MeBF$_4$**) resin. The degree of leaching of Yb(OTf)$_3$ was qualitatively estimated by comparison of IR spectra before and after solvent exposure.[14] No catalyst leaching was observed in CH_2Cl_2, THF, methanol, acetonitrile and even in 10% pyridine/acetonitrile (v/v). Not surprisingly, however, when 10% [bmim][BF$_4$] (a representative ionic liquid)/acetonitrile (v/v) was used, most of the Yb(OTf)$_3$ was removed from the ionic polymer.

The catalytic activity and reusability of these resins was investigated in a model reaction, namely a well established Mannich-type reaction of imine **4** and vinyl silyl-ether **5** (Table 2).[15] The [^{50}P/S-MEM][Cl](Yb) resin (**3b-MEMCl**) was recycled 10 times and showed decreased activity only after the seventh recycle. For

Table 1. Immobilization and loading amounts of Yb(OTf)$_3$[a]



Resin	3b-MeOTf[b]	3b-MEMCl[b]	3b-MeBF$_4$[b]	3b-MePF$_6$[b]	3a-MeBF$_4$[c]	3b-MeBF$_4$[c]	3c-MeBF$_4$[c]	3d-MeBF$_4$[c]	3e-MeBF$_4$[c]
Loading[d]	0.04	0.20	0.15	0.17	0.19	0.19	0.19	0.17	0.15
N/Yb[e]	73.0	14.9	19.6	15.1	11.0	17.0	18.4	25.7	30.8

[a] Determined by weight increase.

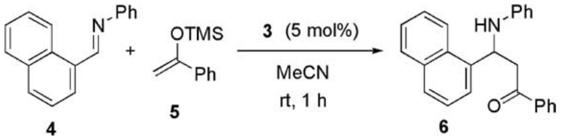
[b] 24 h.

[c] 48 h.

[d] mmol/g.

[e] The ratio of nitrogen to ytterbium.

Table 2. β-Aminoketone synthesis using [^{x}P/S-R][X](Yb) resins[a]



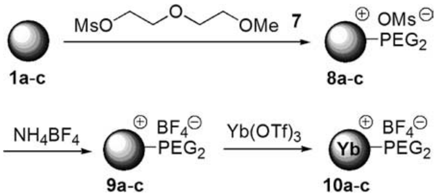
Run	1	2	3	4	5	6	7	8	9	10
3b-MEMCl	95	95	97	99	98	99	99	81	68	51
3b-MeOTf	98	98	88	10	0	—	—	—	—	—
3b-MeBF$_4$	99	82	6	—	—	—	—	—	—	—
3b-MePF$_6$	98	99	92	45	5	0	—	—	—	—
3a-MeBF$_4$[b]	99	91	31	0	—	—	—	—	—	—
3b-MeBF$_4$[b]	99	99	88	49	14	0	—	—	—	—
3c-MeBF$_4$[b]	99	99	92	34	5	—	—	—	—	—
3d-MeBF$_4$[b]	99	98	75	9	0	—	—	—	—	—
3e-MeBF$_4$[b]	99	91	22	2	—	—	—	—	—	—

[a] All reactions were carried out on a 0.1 mmol scale, and all data within the table is % conversion of **6** as determined by HPLC.

[b] Prepared for 48 h.

all other resins a sharp decrease in activity was noted after 2–5 recycles, regardless of the anionic species and the pyridinium salt content. Intriguingly, no change in the appearance of the resins and IR spectra before and after use was observed, indicating that Yb(OTf)$_3$ was retained in the resin. In addition, filtrates from reactions using resin **3b-MeBF$_4$** (Table 2, sixth entry) were analyzed for ytterbium by ICP-AES to quantitate catalyst retention. A small amount (<3%) of the immobilized ytterbium (probably located near or on the surface of the resin) was leached from the resin after the first use; however, no ytterbium was detected in the filtrates after 2–6 recycles. A further validation that virtually all of the initial loading of ytterbium was retained in the resin after the sixth recycle (catalytic activity was zero) was obtained by quantitative recovery of the ytterbium by washing the used resin with a 10% [bmim][BF$_4$]/acetonitrile solution followed by a ICP-AES analysis. This result suggests that the reduced activity is not due to catalyst leaching. In total these results suggest that the loss of catalytic activity is likely due to local rearrangement of polymer backbone surrounding the catalyst, leading to sterically hindered conformations that impede substrates access to catalyst.

To improve catalyst recyclability via attenuation of local aggregation in the polymer backbone, a second generation series of ionic polymers was prepared with decreased N/Yb ratios. As shown in Table 1, the loading and the N/Yb ratio of the [^{50}P/S-MEM][Cl] resin, **3b-MEMCl**, was slightly better than other resins (**3b-MeBF$_4$**, **MePF$_6$**, **MeOTf**). We speculate this could be due to additional binding between the oxygen atoms in the MEM functional group and metal. The relatively flexible MEM chain may also prevent local aggregation of polymer backbone surrounding the catalyst. Because the benzylic carbon bond between MEM and pyridine might be unstable under acidic conditions, a short-length PEG mesylate **7** containing two ethylene glycol units was also developed and used for quarternization of three ^{x}P/S (x = 30, 50, 70) resins **1a**–**c** to give [^{x}P/S-PEG$_2$][OMs] resins **8a**–**c** (Scheme 3).



Scheme 3. Preparation of [^{x}P/S-PEG$_2$][X] and immobilization of Yb(OTf)$_3$.

The mesylate anion in these resins was replaced with inert tetrafluoroborate to give the corresponding [^{x}P/S-PEG$_2$][BF$_4$] resins **9a**–**c**. Immobilization was performed in the same manner as shown in Table 1 to give [^{x}P/S-PEG$_2$][BF$_4$](Yb) resins **10a**–**c**. As expected, the short-length PEGylation of ^{x}P/S resins allowed more efficient immobilization of Yb(OTf)$_3$ and lower N/Yb ratio (Table 3). Again, the catalyst was retained within the resin in most organic solvents but was readily extracted in a solution of 10% [bmim][BF$_4$]/acetonitrile (v/v) solution.

The catalytic activity and reusability of these resins was investigated using the same model Mannich-type reaction as shown in Table 2. Excitingly, two resins [^{30,50}P/S-PEG$_2$][BF$_4$](Yb) resins (**10a** and **10b**) showed no loss of activity and were recycled 10 times without significant loss of catalytic efficiency (Table 4). The IR spectra of these resins showed no change before and after use in this model reaction.

In conclusion, a novel method for immobilization of a homogeneous neutral metal catalyst was developed

Table 3. Loading amount of Yb(OTf)$_3$[a]

Resin	**10a**	**10b**	**10c**
loading[b]	0.43	0.49	0.38
N/Yb[c]	2.4	3.4	5.3

[a] Determined by weight increase.

[b] mmol/g.

[c] The ratio of nitrogen to ytterbium.

Table 4. β-Aminoketone synthesis using [^{x}P/S-PEG$_2$][X](Yb) resins[a]

Run	1	2	3	4	5	6	7	8	9	10
10a	98	99	99	99	99	99	99	99	99	99
10b	99	99	99	99	99	99	99	99	99	99
10c	99	99	99	99	85	22	0	—	—	—

[a] All reactions were carried out on a 0.1 mmol scale for 1 h, and all data within the table is % conversion of **6** as determined by HPLC.

using the strong interaction between metal and ions within an ionic polymer. Short PEG-modified P/S ionic polymers resulted in higher immobilization capacity and enhanced stability. As the mechanism of immobilization is independent of ligand–metal interactions or complexation, and is not an ion exchange process as in the case of amberlyst resin, ionic polymers will likely find widespread use as a generally applicable solid support for various homogeneous metal catalysts. Further studies of these resins for immobilization of other metal catalysts are underway in our laboratory.

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tetlet.2004.12.013. The supplementary data is available online with the paper in ScienceDirect.

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