

## *N*-Heterocyclic carbene–palladium complex on polystyrene resin surface as polymer-supported catalyst and its application in Suzuki cross-coupling reaction

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**Abstract**—A poly(imidazoliummethyl styrene)-*surface grafted*-polystyrene resin was prepared by suspension polymerization. This was used as the polymer-supported carbene precursor for the palladium complex, which efficiently catalyzed the Suzuki cross-coupling of aryl halides and phenylboronic acid.

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Since *N*-heterocyclic carbenes were first introduced by Öfele and Wanzlick,<sup>1</sup> they have become universal ligands in organometallic and inorganic coordination chemistry. They exhibit a similar  $\sigma$ -donor and low  $\pi$ -acceptor ability as phosphine. Moreover, these NHCs have an excellent air and moisture stability, and have higher dissociation energies than other ligands, which have been quantified by theoretical calculations for different metals.<sup>2</sup> Therefore, they can efficiently bind to any transition metal in the low or high oxidation states.

Many successful demonstrations of homogeneous catalysis using the NHCs as a ligand for transition metals, particularly palladium,<sup>3</sup> have been reported. However, there are several problems with these homogeneous catalysis systems. These include the separation and recycling of the catalysts and contamination of the ligand residue in the final product. In order to avoid these problems, several types of heterogeneous catalysts have recently been developed by anchoring the Pd-adppp onto a PS-PEG,<sup>4a</sup> and a Pd-NHCs complex onto a Wang resin<sup>4b</sup> and PS-DVB.<sup>4c</sup> Recently, we also synthesized Pd-NHCs onto a Merrifield resin and demonstrated their excellent catalytic activity.<sup>4d</sup> However,

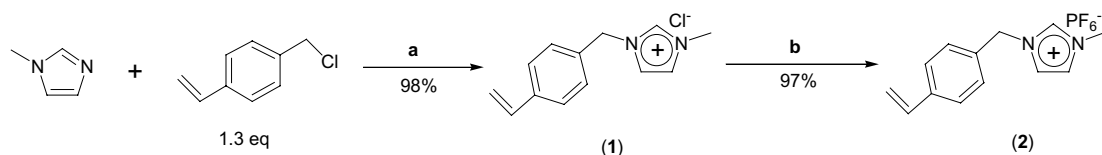
these polymer-supported catalysts have catalytic active sites in all the regions of the resin, including the interior, making it difficult for reagents to diffuse into the interior of the resin, thereby reducing the overall reaction rate. All chemical reactions can proceed more effectively if the catalytic active sites are located at the resin surface.<sup>5</sup>

This letter reports a method for preparing a novel polymer-support containing 1-methyl-3-(4-vinylbenzyl) imidazolium hexafluorophosphate group, [MVBIM][PF<sub>6</sub><sup>-</sup>], on the surface of the resin and demonstrate its efficacy as a polymer-supported NHC ligand for a Pd-catalyst in Suzuki cross-coupling in the aqueous phase. In order to prepare this support, a suspension polymerization system of styrene, DVB and a synthetic ionic liquid comonomer with a vinyl group, which is immiscible with styrene and water, was used.

As shown in Scheme 1, the ionic liquid monomer, [MVBIM][PF<sub>6</sub><sup>-</sup>], (**2**) was readily synthesized by the following procedure. 1-Methylimidazole was dissolved in CHCl<sub>3</sub>, and chloromethyl styrene (1.3 equiv) was added. After the mixture was stirred for 8 h at 50 °C, the resulting 1-methyl-3-(4-vinylbenzyl) imidazolium chloride, [MVBIM][Cl<sup>-</sup>], (**1**) was washed with EA. After evaporating the solvent, [MVBIM][Cl<sup>-</sup>] was dissolved in acetone, and NaPF<sub>6</sub> (1.2 equiv) was added with constant stirring. The reaction was then allowed to proceed for 2 days at room temperature. After evaporating the solvent, the final ionic liquid monomer (**2**) was extracted with MC from water. This ionic liquid monomer (**2**) was

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**Scheme 1.** Synthesis of the polymerizable ionic liquid monomer (2), [MVBIM][PF<sub>6</sub><sup>-</sup>]. Reagents and conditions: (a) CHCl<sub>3</sub>, 50 °C, 8 h; (b) NaPF<sub>6</sub> (1.2 equiv), acetone, 25 °C, 2 days.

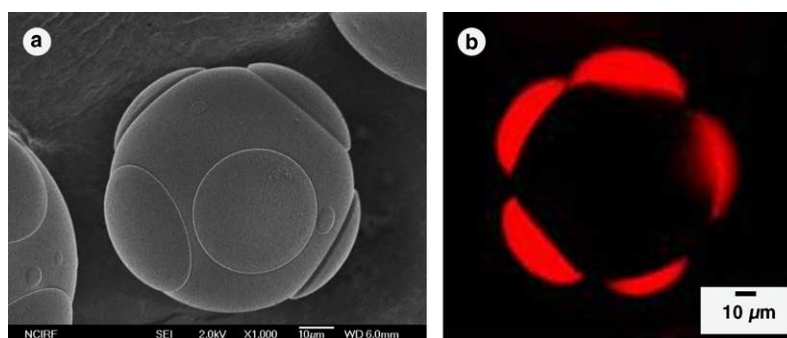
not only insoluble in the aqueous phase but also in the styrene phase. Therefore, this ionic liquid monomer (2) could be located at the interface between the aqueous phase and organic phase in the suspension polymerization system.

Poly(imidazoliummethyl styrene)-*sg*-polystyrene (PS) resin, where *sg* denotes surface grafted, was prepared by utilizing a conventional suspension polymerization system with a reactor and an overhead stirrer. The synthetic ionic liquid monomer (3.0, 5.0, and 7.0 g) was suspended in an aqueous phase, which consisted of water (150 mL) and PVA (0.75 g). An organic phase consisting of styrene (7.0 mL), DVB (0.7 mL, 50% in ethylvinylbenzene), and benzoyl peroxide (0.22 g), as an initiator, was added to the aqueous phase with constant stirring (250 rpm) under a nitrogen atmosphere. The mixture was then polymerized for 24 h at 80 °C. The resulting polymer resins were sieved and washed with H<sub>2</sub>O, MeOH, and MC. They were finally dried in vacuo overnight. As shown in Figure 1, all the resins are the bead type (diameter of 38–150 μm) with imidazolium group loading levels of 0.23–1.12 mmol/g,<sup>6</sup> which could be adjusted by changing the amount of the ionic liquid monomer, as shown in Table 1. The CLSM (Confocal Laser Scanning Microscope) image of the fluorescent dye, 5(6)-carboxytetramethyl rhodamine, adsorbed res-

ins<sup>7</sup> showed that all of the imidazolium groups were located on the surface of the resins.

In order to apply this poly(imidazoliummethyl styrene)-*sg*-PS resin to the reactions in the aqueous phase,<sup>8</sup> the swelling property in water and various organic solvents was measured.<sup>9</sup> As shown in Table 2, the difference in the swelling volume between the hydrophobic and hydrophilic solvents was quite low, which means that the new resin is amphiphilic compared to conventional polystyrene-based resins, and can be used in all the solvents, even in water.

The poly(imidazoliummethyl styrene)-*sg*-PS resin (0.23 mmol/g, entry 1 in Table 1) was used as a NHC ligand precursor for the Pd-catalyzed Suzuki cross-coupling. In order to form the complexes between the palladium and the imidazolium groups, a mixture of Pd(OAc)<sub>2</sub> and the resins was shaken in DMF/H<sub>2</sub>O for 2 h at 50 °C with Cs<sub>2</sub>CO<sub>3</sub>,<sup>10</sup> which played a role as a base for the deprotonation of the imidazolium groups. The loading levels of the immobilized palladium were measured by inductively coupled plasma-atomic emission spectrometry (ICP-AES). As shown in Scheme 2, the amount of Pd(OAc)<sub>2</sub> was varied to determine the optimal loading of immobilized palladium. It was observed that almost all of the imidazolium groups (0.23 mmol/g)



**Figure 1.** (a) SEM micrograph of the poly(imidazoliummethyl styrene)-*sg*-PS resin (entry 1 in Table 1). (b) CLSM image of the 5(6)-carboxytetramethyl rhodamine-adsorbed resin (entry 1 in Table 1).

**Table 1.** Suspension polymerization system for preparing the poly(imidazoliummethyl styrene)-*sg*-PS resin

Entry	Styrene (mL)	DVB (mL)	Ionic liquid monomer (g)	BPO (g)	PVA (g)	H <sub>2</sub> O (mL)	Loading capacities of imidazolium (mmol/g) <sup>a</sup>
1	7.0	0.7	3.0	0.22	0.75	150	0.23
2	7.0	0.7	5.0	0.22	0.75	150	0.53
3	7.0	0.7	7.0	0.22	0.75	150	1.12

<sup>a</sup> The loading capacities of imidazolium were determined by means of the nitrogen content from the elementary analysis.

**Table 2.** Swelling volume of the poly(imidazoliummethyl styrene)-*sg*-PS resin in various solvents

Entry	Loading capacities of imidazolium (mmol/g) <sup>a</sup>	Swelling volume in solvent (mL/g polymeric support) <sup>b</sup>					
		Dry	THF	MC	DMF	MeOH	H <sub>2</sub> O
1	0.23 <sup>c</sup>	3.0	6.8	6.0	5.2	4.0	3.6
2	0.53 <sup>d</sup>	3.0	6.0	6.0	5.2	4.0	3.6
3	1.12 <sup>e</sup>	3.0	5.6	5.2	9.2	4.4	3.6

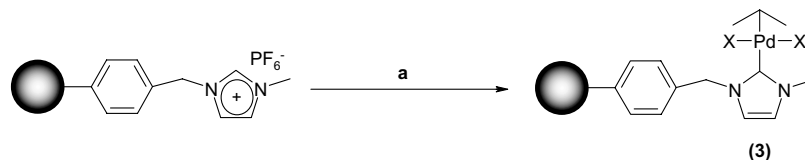
<sup>a</sup>The loading capacities of imidazolium were determined by means of the nitrogen content obtained from elementary analysis.

<sup>b</sup>The swelling volumes were measured by the protocol shown in Ref. 9.

<sup>c</sup>The bead prepared by suspension condition (entry 1 in Table 1).

<sup>d</sup>The bead prepared by suspension condition (entry 2 in Table 1).

<sup>e</sup>The bead prepared by suspension condition (entry 3 in Table 1).



**Scheme 2.** Preparation of the polymer-supported Pd–NHC complex (3). Reagents and conditions: (a) Pd(OAc)<sub>2</sub> (1, 2, and 4 equiv), Cs<sub>2</sub>CO<sub>3</sub> (5 equiv), water/DMF (1:1 v/v), 50 °C, 2 h.

**Table 3.** The loading levels of the immobilized Pd on the resins<sup>a</sup>

The amount of Pd(OAc) <sub>2</sub> (μmol)	23 (1 equiv)	46 (2 equiv)	92 (4 equiv)
Loading levels of Pd on the resins (mmol/g) <sup>b</sup>	0.017	0.03	0.11

<sup>a</sup> 100 mg of the resin was used. The initial loading capacity of imidazolium on the resins was 0.23 mmol/g (entry 1 in Table 1).

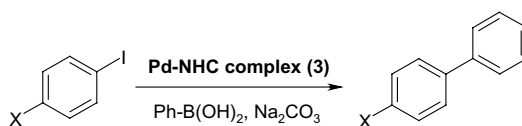
<sup>b</sup> The loading levels of Pd on the resins were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES).

on the resins participated in the formation of the Pd–NHC complex (0.11 mmol-Pd/g) when a 4-fold excess of Pd(OAc)<sub>2</sub> was used, as shown in Table 3.

The catalytic activity of the polymer-supported Pd–NHC complexes (3) with a palladium loading of 0.11 mmol/g was investigated for the Pd-catalyzed Suzuki cross-coupling of the aryl halides with phenylboronic acid. The coupling of iodobenzene (0.5 mmol)

and phenylboronic acid (0.6 mmol), as a model reaction, was performed using the polymer-supported Pd–NHC complexes (1.1 mol%) in an aqueous solution of Na<sub>2</sub>CO<sub>3</sub> (2.5 mmol).<sup>11</sup> Several reaction variables, such as reaction time and solvents, were examined and the results are summarized in Table 4.

Initially, the reaction in water and DMF showed better results than that in the aqueous phase only.<sup>4a</sup> Because

**Table 4.** Suzuki cross-coupling of Ph–I with Ph–B(OH)<sub>2</sub><sup>a</sup>

Entry	X	Solvent	Temp (°C)	Time (h)	Yield (%) <sup>b</sup>
1	H	Water	50	3	20
2	H	Water	50	12	36
3	H	Water/DMF	50	1	93
4	H	Water/DMF	50	12	96
5	CH <sub>3</sub>	Water/DMF	50	1	92
6	OCH <sub>3</sub>	Water/DMF	50	1	94
7 <sup>c</sup>	H	Water/DMF	50	1	83
8 <sup>d</sup>	H	Water/DMF	50	1	81

<sup>a</sup>All of the reactions were carried out with the mole ratio of Ph–I/Ph–B(OH)<sub>2</sub>/Na<sub>2</sub>CO<sub>3</sub>/Pd = 1:1.2:5.0:0.01. The imidazolium loading capacity of starting polymeric support was 0.23 mmol/g.

<sup>b</sup> Isolation yields were calculated from the mass of the biphenyl product after separation by column chromatography.

<sup>c</sup> The repeat experiment with the polymeric support catalyst of entry 3 under the same conditions (the second use).

<sup>d</sup> The repeat experiment with the polymeric support catalyst of entry 5 under the same conditions (the third use).

the starting iodobenzene and the biphenyl product had a poor solubility in water, the addition of DMF might solve these solubility problems and accelerate the reaction rate. In addition, the reaction rate was so fast that most of the iodobenzene had converted into biphenyl within 1 h at 50 °C. This result was quite unusual considering previous results obtained in a homogeneous catalysis and the other.<sup>4a,d</sup> This might be due to the fact that all of the catalytic active sites were located on the surface of the resins. Therefore, the reagents do not need to diffuse into the interior of the resins. Moreover, the local concentration of the reagents became high on the surface of the resins, which possibly promoted the very rapid reaction. However, the catalytic activity of the recovered catalyst decreased slightly in its second and the third use under the same reaction conditions.

In summary, a polymer-supported Pd–NHC complex, which is located on the surface of the resin beads, was prepared using a simple procedure. It was confirmed that the Pd–NHC complexes on the polymeric support catalyzed the Suzuki cross-coupling reaction quite effectively in the water/DMF phase with satisfactory yields and excellent purities. A more efficient polymer system for the Pd–NHC complex and its catalytic activity in the cross-coupling reactions are currently under investigation.

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- The loading capacity of the imidazolium groups on the resins was determined by means of the nitrogen content from elementary analysis.
- CLSM (Confocal Laser Scanning Microscope) image was visualized using the following procedure: Fluorescent dye, 5(6)-carboxytetramethyl rhodamine (34.5 μmol, 3 equiv), was dissolved in DMF (3 mL) and then added to the resin (0.23 mmol/g, 50 mg). After the mixture was shaken for 4 h at room temperature, the resins were washed with DMF, MeOH, and MeOH extensively. The resin beads were viewed through CLSM.
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- A typical procedure for measuring the swelling properties of the poly(imidazoliummethyl styrene)-*sg*-PS resin. The swelling volumes of the poly(imidazoliummethyl styrene)-*sg*-PS resin in various solvents were measured in a fritted column (ID 0.8 cm, length 20 cm). The resins (1.0 g) were swollen in a solvent at room temperature for 30 min, and then washed with a 10-fold volume of each solvent. The resin volume was measured after filtering out the solvent.
- A typical procedure for preparing the polymer-supported Pd–NHC complexes (**3**) on the poly(imidazolium methyl styrene)-*sg*-PS resin. A mixture of the poly(imidazolium-methyl styrene)-*sg*-PS resin (100 mg, 0.23 mmol/g) and Pd(OAc)<sub>2</sub> (1, 2, and 4 equiv) was suspended in DMF (2 mL). To this suspension, an aqueous solution (2 mL) of Cs<sub>2</sub>CO<sub>3</sub> (37 mg, 5 equiv) was added. The mixture was sonicated at room temperature for 30 min, and then agitated for 2 h at 50 °C in a shaking incubator. After filtration, the resins were washed vigorously with DMF (10 mL×5), distilled water (10 mL×5), and MeOH (10 mL×5), and dried under reduced pressure to give compound (**3**). In order to measure the amount of Pd loaded on the resins, the resins (50 mg) were treated with a mixture (5 mL) of hydrochloric acid and nitric acid (3:1, v/v) at 100 °C for 4 h. After the orange-colored solution was filtered, the resin beads were washed with distilled water (2.5 mL×6), and the filtrate and the washing solution were then combined to determine the amount of Pd by inductively coupled plasma-atomic emission spectrometry (ICP-AES). We tried to measure solid-state NMR of polymer-supported NHC–Pd complex. But, we could not detect any differences in the peaks before and after forming NHC–Pd complex. 200 MHz <sup>13</sup>C NMR (solid state); δ 41 (aliphatic polystyrene skeleton), 45 (NCH<sub>3</sub>), 128 (NCH, NCH, aromatic polystyrene skeleton), 146 (NCN, aromatic polystyrene skeleton).
- A typical procedure for Pd-catalyzed Suzuki cross-coupling in an aqueous phase. (Table 4) The polymer-supported Pd–NHC complex (**3**) (50 mg, 5.5 μmol Pd, 0.11 mmol-Pd/g) was suspended with DMF (2 mL). After a mixture of iodobenzene (57 μL, 0.5 mmol), phenylboronic acid (75 mg, 1.2 equiv), and Na<sub>2</sub>CO<sub>3</sub> (265 mg, 5 equiv) in distilled water (2 mL) was added, the reaction mixture was agitated in a shaking incubator at 50 °C for 1 or 12 h. The coupling reactions were performed under an air atmosphere. The reaction mixture was filtered and washed with distilled water (4 mL×5) and diethyl ether (4 mL×5). After the organic portion was separated and

dried over  $\text{MgSO}_4$  followed by evaporation under reduced pressure. The chemical identification of the product was performed by gas chromatography/mass spectroscopy (GC–MS) from the mass database library (WILEY 275), showing a good similarity (>95%) with the reported data.

After the biphenyl product had been isolated by column chromatography (eluent; *n*-hexane), the isolation yield was calculated from the mass of the product, and the purity of the isolated product was determined by GC (99.9% GC purity).