

# Suzuki coupling reactions catalyzed by poly(*N*-ethyl-4-vinylpyridinium) bromide stabilized palladium nanoparticles in aqueous solution

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**Abstract.** In this work, it was investigated to use of poly(*N*-ethyl-4-vinylpyridinium) bromide stabilized palladium nanoparticles in the Suzuki reaction between phenylboronic acid and aryl halides in aqueous solution. The nanoparticles were isolated and re-used several times with low loss of activity.

**Keywords:** *nanomaterials, Pd, polymer, Suzuki reaction*

## 1. Introduction

The Suzuki coupling reaction between arylboronic acids and aryl halides is one of the most effective methods for the preparation of biaryl compounds [1, 2], which are an important class of organic compounds useful as precursors to pharmaceuticals, ligands, liquid crystals, and polymers. The classical conditions for performing these coupling reactions involve the use of various Pd/ligand complexes [3, 4] as catalysts in organic solvents. These catalysts include many different kinds of phosphine-based palladium catalysts as well as phosphine-free palladium catalysts. However, phosphine ligands may be toxic or expensive and one serious drawback in the use of homogeneous metal catalysts is that they often are difficult to separate from the reaction mixtures and recycle.

It is of interest to develop new catalysts that are environmentally benign and effective. Stabilized palladium nanoparticles have also been reported as catalysts for the Suzuki coupling reaction [5].

Noble metal colloidal particles have a characteristic large surface-to-volume ratio, and consequently large fractions of the metal atoms are accessible to reactant molecules and available for catalysis. However, unprotected metallic nanoparticles in solution are kinetically unstable with respect to aggregation to larger particles or bulk metal, and must therefore be stabilized by electrostatic or steric protection to keep them from agglomerating. This stabilization of nanoparticles in solution can be achieved by adding a stabilizer, for example surfactants, soluble polymers, quaternary ammonium salts, or polyoxoanions. Palladium nanoparticles stabilized with poly(*N*-vinyl-2-pyrrolidone) [6–8], poly(amidoamine) dendrimers [9, 10], polystyrene-*b*-poly(sodium acrylate) block copolymer [9], Keggin-type polyoxometalate [11], cyclodextrin [12], and poly(*N,N*-dihexylcarbodiimide) [13, 14], have been used to catalyze various Suzuki reactions in different solvents. Use of water as a reaction medium for transition-metal-catalyzed reactions is

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very attractive for organic synthesis because it is non-toxic, cheap and readily available. However, the reported catalytic activities of the recovered catalysts using water as solvent are too low for them to be reused for practical organic synthesis. Here we have investigated the use of the polycationic poly(*N*-ethyl-4-vinylpyridinium) bromide (pEVPBr) polymer as a stabilizer for palladium nanoparticles by studying the Suzuki reaction.

## 2. Experimental

### 2.1. Materials and methods

4-Vinylpyridine (>96%), iodobenzene (>99%), 1-bromo-4-methoxybenzene (>97%), chlorobenzene (>98%), and phenylboronic acid (>97%) were purchased from Fluka. Bromoethane (>98%), PdCl<sub>2</sub>, and all solvents were obtained from Shanghai Sinopharm Group Chemical Reagent Co., Ltd. All chemicals were used as received. pEVPBr was synthesized according to Marcilla *et al.* [15]. Pd nanoparticles were investigated by transmission electron microscopy (TEM) on a JEOL 2010 transmission electron microscope. The samples were prepared by placing a drop of the solution on carbon coated copper grids and allowed to dry in air. The particle size and size distribution were determined by manually measuring around 200 particles from enlarged TEM images using ImageJ. The

identity of synthesized compounds was confirmed by <sup>1</sup>H NMR.

### 2.2. Preparation of pEVPBr-stabilized Pd nanoparticles

An aqueous solution of H<sub>2</sub>PdCl<sub>4</sub> (5 mM) was prepared by adding HCl (6 ml, 0.2 M) to PdCl<sub>2</sub> (0.6 mmol) in water (114 ml). Ethanol (20 ml), water (10 ml) and pEVPBr (210 mg) were added to 20 ml of the H<sub>2</sub>PdCl<sub>4</sub> solution to yield a pEVPBr:Pd (monomeric unit:metal) ratio of 10:1. The solution was refluxed under air for 3 hours, turning dark brown. The solution was evaporated to dryness under vacuum at 60°C, and the residue re-dissolved in 5 ml of water for later use.

### 2.3. Suzuki coupling reactions

In a typical Suzuki coupling reaction experiment, iodobenzene (1 mmol), phenylboronic acid (1 mmol) and Na<sub>2</sub>CO<sub>3</sub> (3 mmol) were added to ethanol (aq., 30% v/v, 5 ml) in a 10 ml round-bottom flask. The mixture was vigorously stirred and heated to the temperature stated in Table 1, and 0.2 mol% of palladium in the form of pEVPBr-stabilized Pd nanoparticles were added. At the end of the reaction, the reaction mixture was extracted three times with petroleum ether (5 ml). The combined extrac-

**Table 1.** Product yields for Suzuki coupling reaction catalyzed by pEVPBr-Pd nanoparticles

Entry	R	X	Pd [mol%]	Temperature [°C]	Base	Time [h]	Yield [%]
1	H	I	0.20	90	Na <sub>2</sub> CO <sub>3</sub>	0.5	59
2	H	I	0.20	90	Na <sub>2</sub> CO <sub>3</sub>	1	76
3	H	I	0.20	90	Na <sub>2</sub> CO <sub>3</sub>	2	83
4	H	I	0.20	90	Na <sub>2</sub> CO <sub>3</sub>	4	90
5	H	I	0.20	90	Na <sub>2</sub> CO <sub>3</sub>	9	95
6	H	I	0.10	90	Na <sub>2</sub> CO <sub>3</sub>	9	89
7	H	I	0.05	90	Na <sub>2</sub> CO <sub>3</sub>	9	85
8 <sup>a</sup>	H	I	0.20	90	Et <sub>3</sub> N	9	96
9 <sup>b</sup>	H	I	0.20	90	Et <sub>3</sub> N	9	89
10 <sup>c</sup>	H	I	0.20	90	Et <sub>3</sub> N	9	82
11 <sup>d</sup>	H	I	0.20	90	Et <sub>3</sub> N	9	81
12	H	I	0.20	50	Na <sub>2</sub> CO <sub>3</sub>	9	63
13	H	I	0.20	50	Et <sub>3</sub> N	9	61
14	4-CH <sub>3</sub> O	Br	0.20	90	Na <sub>2</sub> CO <sub>3</sub>	9	68
15	H	Cl	0.20	90	Na <sub>2</sub> CO <sub>3</sub>	9	35

<sup>a</sup>the first run, <sup>b</sup>the second run, <sup>c</sup>the third run, <sup>d</sup>the fourth run

tion was washed with water and the organic phase was separated and concentrated with reduced pressure. The resulting crude was purified by column chromatography on silica gel to give final biphenyl product.

### 3. Results and discussion

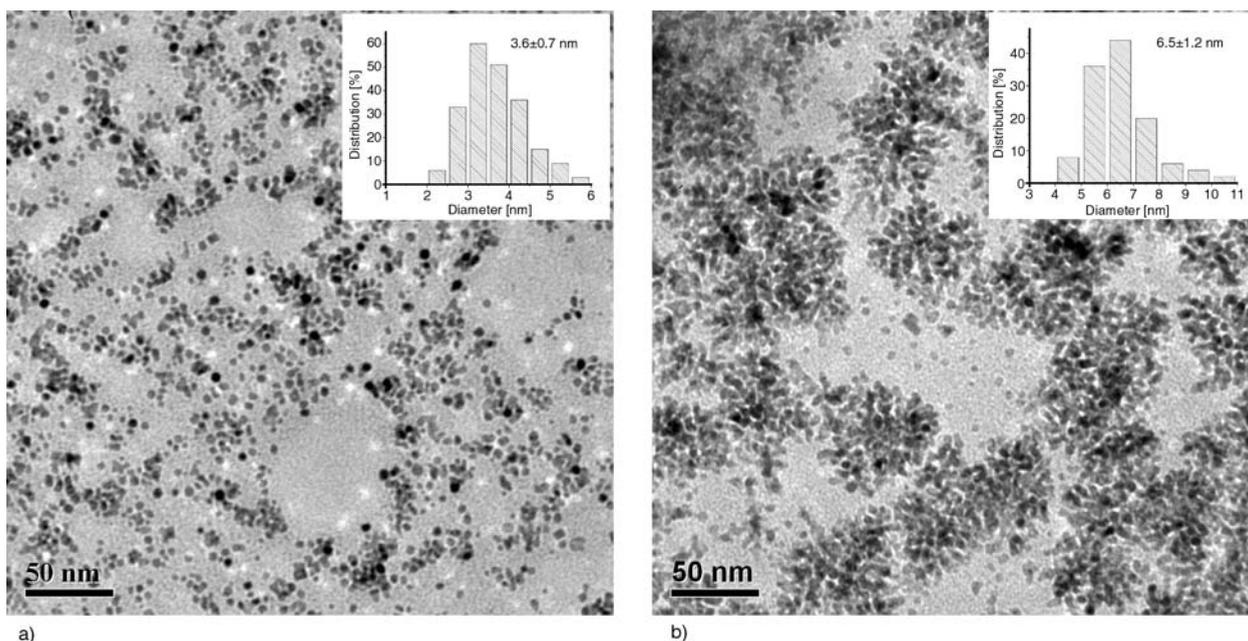
#### 3.1. Characterization of Pd nanoparticles

The Pd nanoparticles displayed good stability under storage, with no palladium black observed even after several months. A typical micrograph of the Pd nanoparticles is shown in Figure 1a. A relatively narrow size distribution, with an average diameter of  $3.6 \pm 0.7$  nm, was observed. Repeated recycling of the catalyst phase, as described below, led to aggregation, yielding larger clusters made up by particles with an average size of  $6.5 \pm 1.2$  nm (Figure 1b).

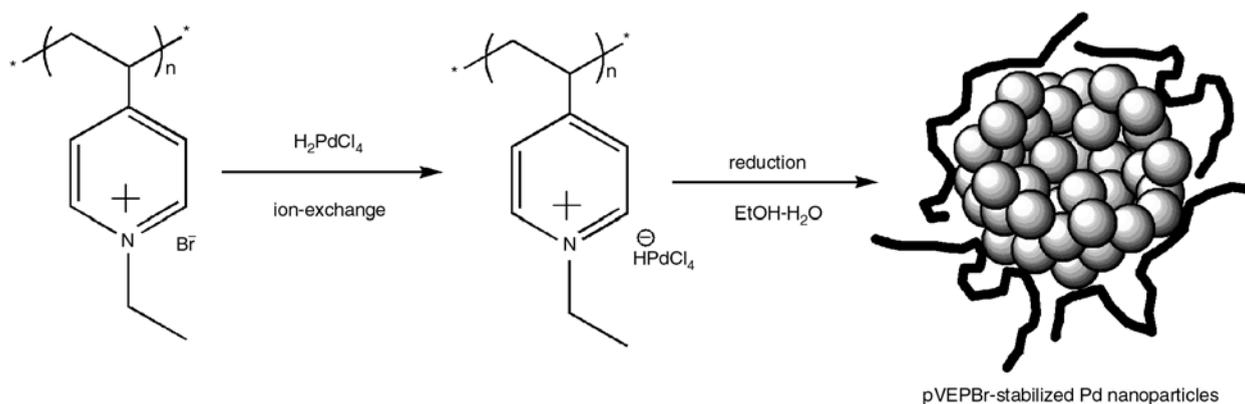
#### 3.2. Catalytic performance of Pd nanoparticles

The catalytic performance of the pEVPBr-stabilized Pd nanoparticles was evaluated by using the Suzuki coupling reaction in aqueous solution. The results shown in Table 1 reveal that pEVPBr-Pd is a highly active catalyst in the Suzuki reaction under relatively mild conditions. When 0.2 mol% of pEVPBr-Pd as catalyst in aqueous  $\text{Na}_2\text{CO}_3$  solution

was used to catalyze the reaction between iodobenzene and phenylboronic acid, the yields of biphenyl were 59, 76, 83, 90, and 95% after 0.5, 1, 2, 4, and 9 hours, respectively (entries 1–5). Next, the amount of pEVPBr-Pd and lower reaction temperatures were examined (entries 5, 6, 7, 12, 13). Although the reaction proceeded at  $50^\circ\text{C}$  (entries 12 and 13) or when 0.05 mol% of catalyst was used (entries 7), relatively longer reaction times were needed to get full conversion. In addition, 1-bromo-4-methoxybenzene and chlorobenzene were chosen as substrates to perform the Suzuki coupling reaction. However, the yields of using 1-bromo-4-methoxybenzene and chlorobenzene as reactant were lower than that of iodobenzene under the same reaction conditions (entries 14 and 15). Finally, we found that using triethylamine as base is also suitable under these conditions, and this base was used in the recycling experiments. After the reaction mixture was extracted with petroleum ether, the aqueous phase containing the catalyst was separated and ethanol (1.5 ml) was added together with new substrate and triethylamine, to recycle the palladium nanoparticles. After recycling, the Pd nanoparticles became larger than before the reaction; a typical micrograph of the Pd nanoparticles after recycling twice is shown in Figure 1b. Although the catalytic activity gradually diminished due to formation of Pd black, the catalyst can be recycled several times with acceptable yields (entries 8–11).



**Figure 1.** TEM images of pEVPBr-Pd nanoparticles before (a) and after recycling twice (b). The inset shows the particle size distribution



**Figure 2.** Formation scheme of Pd nanoparticles by using pVEPBr

pVEPBr is a kind of polymer with pyridium groups along a polymeric chain. When the polymer was used in the in situ synthesis of Pd nanoparticles, it can be speculate that the  $\text{HPdCl}_4^-$  anion was attached to pyridium units of the polymer chain by ion-exchanging and then the ‘metalized’ polymer was reduced with ethanol to produce the Pd nanoparticles (Figure 2). pVEPBr have been shown to be effective stabilizer for preparing narrowly dispersed Pd nanoparticles and for preventing agglomeration of colloidal Pd nanoparticles. Apart from the wide ranging adaptability of polymer, some additional advantages of polycationic pVEPBr polymer are obvious: as high molecular weight stabilizers, additional mechanisms of colloidal stabilization can be invoked, i.e., steric and electrosteric stabilization contributions are added to the standard stabilization by charge repulsion (electrostatic). We believe that the stability of the of the colloidal Pd nanoparticles arises from both eletrostatic and steric effects of pVEPBr.

#### 4. Conclusions

A simple method for preparing pVEPBr-stabilized Pd nanoparticles in aqueous solution has been described. The pVEPBr-stabilized Pd nanoparticles are quite stable and provide high catalytic activity in Suzuki coupling reactions under relatively mild conditions using low amounts of Pd in aqueous solution.

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