

# Heck Reaction Catalyzed by Nanosized Palladium on Chitosan in Ionic Liquids

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Palladium nanocolloids supported on chitosan behave as very efficient heterogeneous catalysts in the Heck reaction of aryl bromides and activated aryl chlorides in tetrabutylammonium bromide as solvent and tetrabutylammonium acetate as base. Only 15 min is required to convert bromobenzene or *p*-nitrochlorobenzene into cinnamates. The efficiency of this catalyst is due to the stabilization of Pd colloids by the solvent and to a very fast PdH neutralization by the base. In contrast, no reaction occurs when utilizing imidazolium-based ionic liquids. The stability of the catalyst allows an extensive recycle in the coupling of iodoaromatics with butyl acrylate.

The Heck reaction and related chemistry occupy a special place among basic types of palladium-catalyzed reactions.<sup>1–4</sup> This chemistry has been fueled by the discovery of a new generation of catalysts such as palladacycles and Pd–carbene complexes.<sup>5,6</sup> Nevertheless, several factors, such as the use of toxic, easily oxidable phosphines and the utilization of dangerous solvents such as DMF and volatile organic solvents (VOCs), have hampered a broad industrial application. In addition, a homogeneous Pd catalyst usually precipitated from the solution and recycling or recovery of the expensive catalyst was difficult. To overcome the latter drawback, polymer-supported Pd complexes<sup>7</sup> and Pd on carbon and Pd on different metal oxides<sup>8</sup> were used by several groups for activation of aryl iodides and bromides. The activation of cheaper aryl chlorides was

achieved by Fu and Choudary using expensive hindered phosphines and amines.<sup>9</sup> Recently, palladium nanoparticles of different origin have been utilized in the Heck arylation of unsubstituted acrylates and styrene with variable degrees of success, though, in some cases, the catalyst recycling was fruitless.<sup>10,11</sup> Among the various solvents utilized in the Heck reaction, in the last 10 years, imidazolium-based ionic liquids (ILs) have been utilized as “green solvents”.<sup>12</sup> However, under these reaction conditions, only aryl iodides reacted with high

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conversions, aryl bromides being practically unreactive or requiring elevated temperatures and high catalyst concentrations.<sup>13</sup> For this reason, to activate aryl bromides in these ILs, it was necessary to add phosphines as ligands.<sup>14</sup> Better results in activating aryl halides were obtained using tetrabutylammonium bromide (TBAB) as the IL.<sup>15</sup> In the past few years, we have demonstrated that very efficient Heck reactions, catalyzed by a Pd benzothiazole carbene complex, can be performed in TBAB as solvent using aryl iodides and bromides, activated aryl chlorides, and cheap inorganic bases without the addition of phosphines.<sup>6c,16</sup> In addition, in a search for a Pd-catalyzed regio- and stereoselective arylation of cinnamates<sup>17</sup> and methacrylates<sup>18</sup> in ILs, we found that, by dissolving Pd acetate in TBAB and using tetrabutylammonium acetate (TBAA) as base, the formed Pd nanoparticles<sup>19</sup> did catalyze efficiently

the reaction of aryl bromides. Under these conditions, and despite the protection of nanoparticles by TBAB with both electrostatic and steric effects, an extensive recycling of the catalyst proved to be difficult.

This paper reports that Pd nanoparticles supported on chitosan catalyze a very fast Heck reaction of aryl bromides and iodides and activated chlorides with a successful recycle of the catalyst for aryl iodides.

## Results and Discussion

Chitosan or poly[ $\beta$ -(1-4)-2-amino-2-deoxy-D-glucan] is a cheap natural polymer whose applications are numerous in biology, medicine, and food industries.<sup>20</sup> Nevertheless, chitosan has been little utilized as a support or supramolecular ligand for catalysts, even though its easy and clean elimination from the metal entity makes this biopolymer superior to inorganic metal oxides as supports. Few papers have been dedicated to the synthesis of Pd supported on chitosan,<sup>21</sup> and to our knowledge, none of these reported the Heck reaction in ILs catalyzed by nanosized Pd on chitosan. The catalyst was generated either by chemical means,<sup>17</sup> by reduction of Pd acetate by TBAA in TBAB as solvent and in the presence of chitosan, or by a sacrificial anode electrolysis, performed in a acetonitrile solution of TBAB, in the presence of chitosan under a nitrogen atmosphere.<sup>22</sup> The Pd concentration on chitosan was determined by atomic absorption spectroscopy (ETAAS). Cross-sectional transmission electron microscopy (TEM) characterization of the electrosynthesized Pd/chitosan nanocomposite revealed that it is a cortex-type catalyst (Figure 1).

The surface of the chitosan flakes is modified (up to a depth of few hundred nanometers) by the presence of well-dispersed Pd nanoparticles having an average core diameter of  $3.3 \pm 0.7$  nm (Figure 2).

An X-ray photoelectron spectrum of the Pd 3d region (Figure 3a) showed that two palladium oxidation states are present on the surface of the nanocomposite: Pd(0) and Pd(II), the latter being the most abundant one. Due to its position (BE of the  $3d_{5/2}$  peak falling at 337.1 eV), the Pd(II) doublet could be simultaneously attributed to PdO and to  $[\text{PdBr}_4]^{2-}$  species. However, in the absence of air exposure of the nanocomposite, the presence of PdO can be excluded.

These morphological and spectroscopic results are in perfect agreement with those obtained in previous studies, relevant to bare or polymer-supported Pd nanoclusters electrosynthesized under similar experimental conditions.<sup>22d</sup> It has already been demonstrated that the sacrificial anode process leads to core-shell Pd nanoparticles in which a metallic core is surrounded by a

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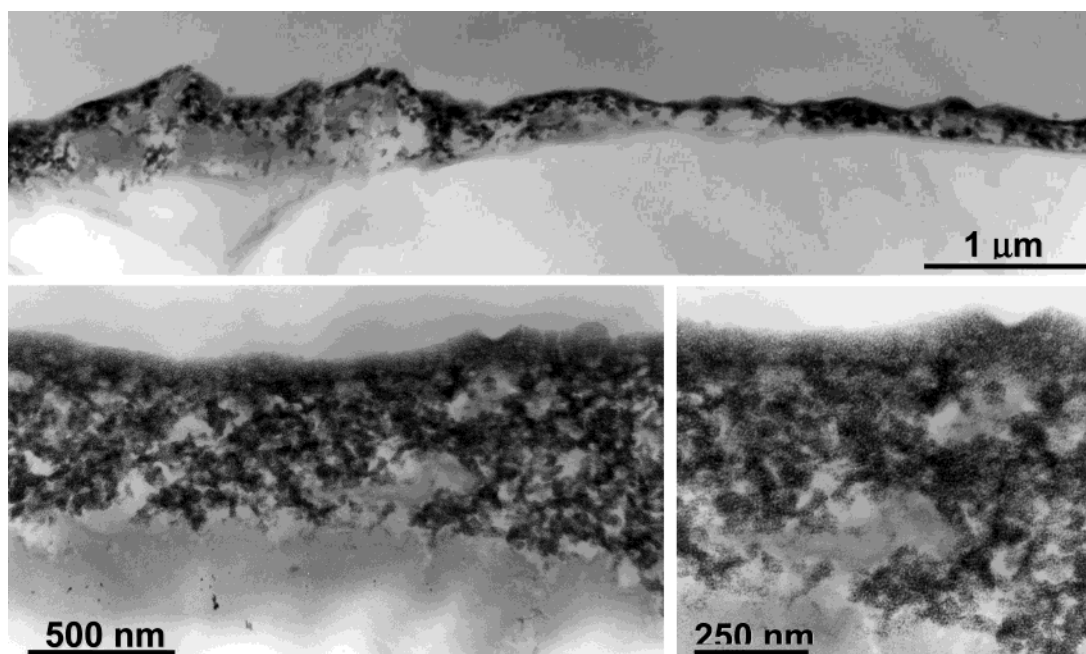
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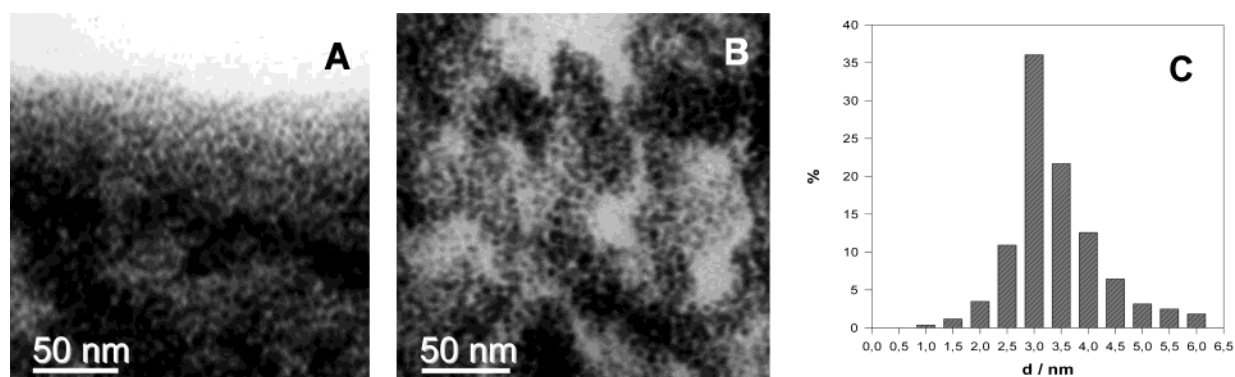
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**Figure 1.** Typical transmission electron microscopy (TEM) photographs of cross sections obtained from a Pd/chitosan flake.



**Figure 2.** TEM pictures showing palladium nanoparticles embedded in the outer part of the chitosan surface (A) or in the middle part (B) of the modified "cortex". The nanoparticles' core diameters are statistically identical in the two regions, and the overall size-distribution histogram is reported in part C.

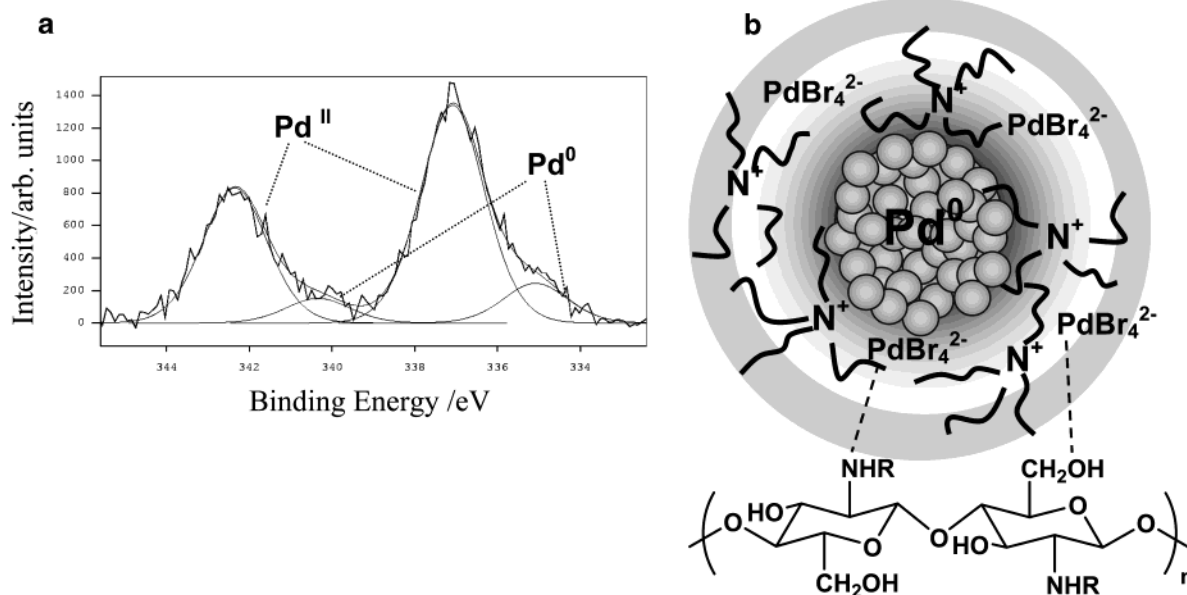
stabilizing shell composed of a tetrabutylammonium ion monolayer<sup>22</sup> surrounded by Br<sup>-</sup> and [PdBr<sub>4</sub>]<sup>2-</sup> species,<sup>22d</sup> which counterbalance the positive charges in the shell (Figure 3b).

A sample containing only  $4.2 \times 10^{-3}$  mmol of palladium does catalyze efficiently the reaction of bromobenzene (1.2 mmol) with butyl acrylate in TBAB as solvent and TBAA as base at 130 °C. Under these conditions, only 15 min is required to convert almost completely this halide into *trans*-butyl cinnamate with a TOF value (mol of product/((mol of catalyst) time)) of 1785 (Table 1, entry 1).

At the end of the reaction, after it is cooled to room temperature, the mixture solidifies and the reaction products are extracted with cyclohexane, leaving both the IL and catalyst, which can then be recycled. High reaction rates are observed for deactivated aryl bromides and activated aryl chlorides as *p*-chlorobenzophenone or *p*-nitrochlorobenzene (Table 1, entries 6 and 7). This was an interesting result, since it is known<sup>10m,p</sup> that while aryl iodides are converted by supported Pd catalysts, the deactivated aryl bromides are unreactive

and the activated ones require harsh reaction conditions and long reaction times.<sup>10k,q</sup> The presence of both TBAB and TBAA as base is essential to obtain high conversion rates. Indeed, in different ILs and with inorganic or organic bases (Table 2), the conversion rates decrease significantly and negligible conversions are observed if [bmim]BF<sub>4</sub> and [bmim]Br are used as solvents (Table 2, entries 4 and 6).<sup>13b,g,17</sup>

Since for industrial applications of the Heck olefination reaction both the lifetime of the heterogeneous catalyst and that of the IL should be high, we tested the recycle for the reaction of bromobenzene with butyl acrylate. However, after each cycle, the efficiency of the catalyst decreases with a concomitant leaching of palladium from the complex, probably due to the Hoffmann decomposition of TBAB at 130 °C, which destabilizes the nanocomposite. In contrast, since aryl iodides are more reactive than bromides, it is possible to decrease, for these substrates, the reaction temperature to 100 °C in order to eliminate the decomposition of this IL. At this temperature, despite the fact that the melting point of TBAB is 105 °C, the addition of the reagents



**Figure 3.** X-ray photoelectron spectrum of the Pd 3d high-resolution region relevant to a typical Pd/chitosan nanocomposite.

**Table 1.** Pd-NPs/Chitosan-Catalyzed Heck Couplings of Aryl Halides and *n*-Butyl Acrylate in TBAB as Solvent<sup>a</sup>

Entry	ArX	time	Conversion <sup>b</sup> %	Yields <sup>b</sup> %
1		15 min	>99	98
2 <sup>c</sup>		1.5 h	>99	94
3		15 min	98	89
4		15 min	97	85
5		15 min	>99	92
6		15 min	>99	90
7		45 min	97	85
8		24 h	<1	-
9 <sup>d</sup>		5 min	>99	95

<sup>a</sup> Reaction conditions: 1.2 mmol of aryl halide, 1.8 mmol of butyl acrylate, 2.4 mmol of TBAA, and 0.35 mol % of Pd-NPs/chitosan in 3 g of TBAB;  $T = 130\text{ }^{\circ}\text{C}$ . <sup>b</sup> Determined by GLC (internal standard diethylene glycol di-*n*-butyl ether). <sup>c</sup>  $T = 115\text{ }^{\circ}\text{C}$ . <sup>d</sup>  $T = 100\text{ }^{\circ}\text{C}$ .

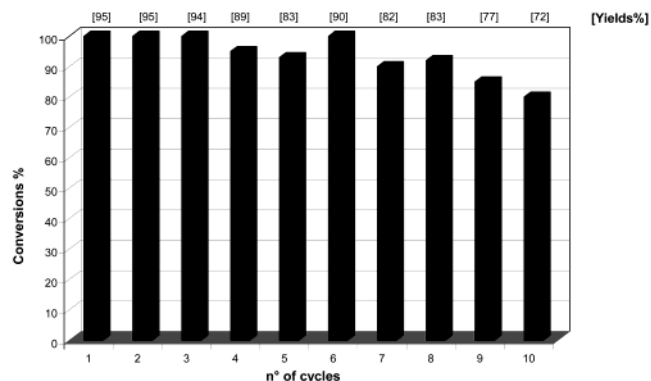
decreases the melting point, affording a liquid mixture. Therefore, the increased stability of both TBAB and catalyst does render the recycling process more convenient. Indeed, in only 3 g of TBAB and 35 mg of composite containing  $4.2 \times 10^{-3}$  mmol of palladium, after 11 cycles, each with an average conversion of 94%, 13.2 mmol of iodobenzene is processed with a total TON of around 2954 (Figure 4).<sup>23</sup>

From these results, the influence exerted by tetrabutylammonium salts on the reaction rates and catalyst

**Table 2.** Pd-NPs/Chitosan-Catalyzed Heck Arylation of *n*-Butyl Acrylate in ILs<sup>a</sup>

entry	solvent	base	time	conversion <sup>b</sup> (%)	yield <sup>b</sup> (%)
1	TBAB	TBAA	15 min	>99	95
2	TBAB	NaHCO <sub>3</sub>	2.5 h	75	62
3	TBAB	Bu <sub>3</sub> N	40 min	>99	95
4	[bmim]BF <sub>4</sub> <sup>c</sup>	TBAA	24 h	<1	-
5	[bupy]BF <sub>4</sub> <sup>d</sup>	TBAA	2.5 h	76	65
6	[bmim]Br <sup>e</sup>	TBAA	24 h	<1	-
7	TBPF <sup>f</sup>	TBAA	2.5 h	95	89

<sup>a</sup> Reaction conditions: 1.2 mmol of aryl halide, 1.8 mmol of butyl acrylate, 2.4 mmol of base, and 0.35 mol % of Pd-NPs/chitosan in 3 g of IL;  $T = 130\text{ }^{\circ}\text{C}$ . <sup>b</sup> Determined by GLC (internal standard diethylene glycol di-*n*-butyl ether). <sup>c</sup> [bmim]BF<sub>4</sub> = 1-butyl-3-methylimidazolium tetrafluoroborate. <sup>d</sup> [bupy]BF<sub>4</sub> = *N*-butylpyridinium tetrafluoroborate. <sup>e</sup> [bmim]Br = 1-butyl-3-methylimidazolium bromide. <sup>f</sup> TBPB = tetrabutylphosphonium bromide.



**Figure 4.** Recycle of the catalyst in the reaction of iodobenzene with butyl acrylate: GLC conversions and yields (internal standard diethylene glycol di-*n*-butyl ether).

stabilization emerges. Nevertheless, despite the observed beneficial effects exerted by quaternary ammonium salts on the Heck reaction,<sup>11,17,18</sup> the exact

(23) Negishi, E.-I.; Takahashi, T.; Akiyoshi, K. *Chem. Commun.* **1986**, 1338–1339.

nature of this influence cannot be ascribed to a single effect such as the high polarity or phase-transfer ability but, rather, to a superposition of several factors. For example, Reetz et al.<sup>22</sup> reported the stabilization of Pd nanoparticles by tetraalkylammonium cations. Furthermore, Negishi et al.<sup>23</sup> and Amatore and Jutand<sup>4</sup> demonstrated that Pd<sup>0</sup>(PPh<sub>3</sub>)<sub>2</sub>, the proposed catalyst in the Heck reaction, was unstable in the absence of halide or acetate ions, which transform this complex into a more catalytically active 16-electron anionic complex such as [Pd(PPh<sub>3</sub>)<sub>2</sub>X]<sup>-</sup>. The formation of Pd nanoparticles surrounded by a large tetraalkylammonium cation, imposing a Coulombic barrier for collision, should impede the formation of clusters growing further into metal particles. As a consequence, TBAB would extend the catalyst life. Stabilization of the catalytic systems by ammonium salts was also demonstrated by the extension of the lifetime of the Herrmann palladacycle.<sup>5a</sup> In addition, the ammonium cation could electrostatically assist the polarization or decomplexation of the bromide or iodide derived from oxidative addition with aryl halides, and this would render the Pd(II) complex more electrophilic for a fast olefin insertion. The results in Table 2 (entry 1) show the enhanced efficiency of tetrabutylammonium acetate in increasing the reaction rate in comparison with inorganic or different organic bases. The TBAA as base exerts several positive effects on the reaction. First, being very soluble in TBAB, it does reduce the Pd<sup>2+</sup> particles on chitosan to the catalytically active Pd(0) nanoparticles, thus enhancing the catalyst concentration.<sup>17,18</sup> Second, through a fast neutralization of the PdH, it allows the restoration of the active catalyst.<sup>24</sup> Furthermore, it does overcome the gradual catalyst deactivation, a problem commonly found in the Heck reaction, due to an increase of sodium

or ammonium halide concentrations,<sup>15c</sup> deriving from PdH neutralization by inorganic or organic bases as tertiary amines. Indeed, the neutralization of PdH by TBAA affords, besides acetic acid, tetrabutylammonium cation, which behaves as a sequestering agent for the bromide ion with the formation of TBAB. Actually, we do not have a convincing explanation for the lack of reactions in imidazolium ionic liquids. A probable one is the failure of these liquids to stabilize the nanosized Pd particles.

## Conclusions

Our results show that Pd supported on chitosan behaves as an efficient and recyclable catalyst, as well as the essential role of both the tetraalkylammonium salts in determining the catalyst life and the reaction rate of the C–C coupling process.

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**Supporting Information Available:** Text giving experimental details of the procedures used in this paper. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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(24) This fast neutralization of PdH might be due to the p*K*<sub>a</sub> value of acetate anion in TBAB. This value cannot be the same as that measured in water. This would not be surprising, since in this solvent the anion, being poorly solvated, should be a stronger base than in water.