ORGANIC
LETTERS

2006
Vol. 8, No. 6
1237−1240

New N-Heterocyclic Carbene Palladium Complex/Ionic Liquid Matrix Immobilized on Silica: Application as Recoverable Catalyst for the Heck Reaction

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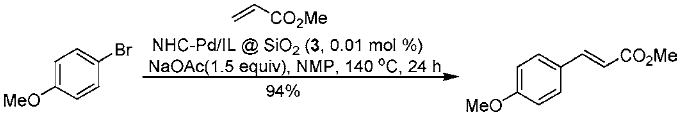
Received January 16, 2006

ABSTRACT



A new concept of simultaneous covalent anchoring of a N-heterocyclic carbene palladium/ionic liquid matrix on the silica surface and the application of the resulting catalyst in the Heck reaction of a variety of different haloarenes is described. The catalyst shows high thermal stability (up to 280 °C) and could be recovered and reused for four reaction cycles, giving a total TON ≅ 36 600. Furthermore, TEM coupled with EDX analysis indicate the formation of Pd nanoparticles within the immobilized IL layer.

The palladium-catalyzed arylation of olefins, universally referred to as the “Heck reaction”, has received increasing attention in the past decade because it is a selective method for the formation of new C−C bonds in a single operational step.[1] Although the Heck reaction has mostly been catalyzed by palladium complexes with phosphine ligands in homogeneous solution,[2] recently, the N-heterocyclic carbene (NHC) ligands have emerged as an alternative to phosphines as ligands for this transformation.[3]

However, homogeneous catalysts have been of somewhat limited use, mainly because of the difficulty of separation from the reaction product that in turn may lead to economical/environmental problems especially in the case of expensive or toxic metal catalysts. Therefore, the development of polymer-supported and insoluble transition-metal complexes has attracted a great deal of attention to address this issue.[4] Along this line, several polymer-supported NHC−Pd catalysts by immobilization of the corresponding homogeneous complexes on Wang resin,[5] Merrifield resin,[6a] and polystyrene[6b] have been developed to combine the advantages of both homogeneous and heterogeneous catalysts in a number of cross-coupling reactions. However, the polymer backbones in these catalysts are very expensive and most of them suffer

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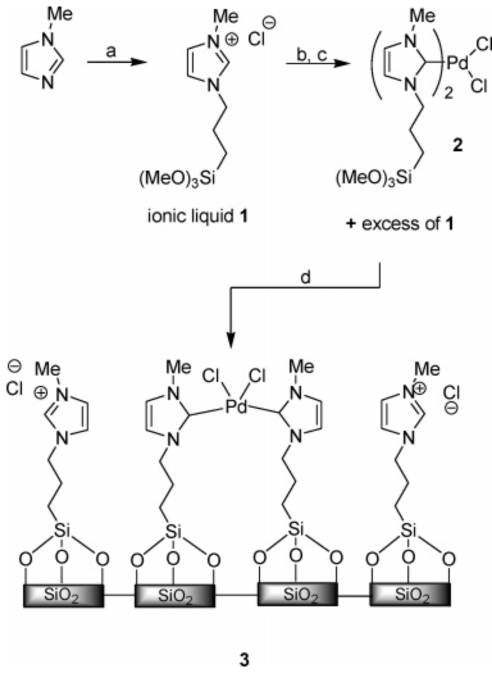
10.1021/ol060129z CCC: $33.50

from the drawback that many of their catalytic active sites are in the interior of the support. Therefore, they are, in general, less accessible for the substrates so that it is often necessary to use a high loading of these palladium-based catalysts in a typical reaction. On the other hand, ionic liquids (ILs) as environmentally acceptable solvents for organic reactions have also attracted attention in recent years because they have a very low vapor pressure and can be used to replace organic solvents. Among them, imidazolium-based ionic liquids have been extensively utilized as reaction media for a number of palladium-catalyzed coupling reactions that in fact act as in situ imidazole carbene ligands with transition metals.[7] However, ionic liquids are very expensive, and therefore, for many practical applications, it is more desirable to minimize the amount of ILs in reaction processes on the basis of economic criteria. Very recently, Mehnert and coworkers reported a new, interesting method for the *noncovalent* immobilization of a homogeneous phosphine−Rh^+ complex/[bmim][BF_4] solution onto the surface of silica modified with a monolayer of ionic liquid.[8] The catalyst was then successfully used for hydrogenation and hydroformylation of olefins.[8] However, it has been shown that the metal complex can leach from the surface because the adsorbed [bmim][BF_4], which served as the reaction phase, is partially dissolved in the organic phase and therefore restricted long-period catalyst recovery. A possible strategy to circumvent the aforementioned drawbacks could be based on the simultaneous covalent immobilization of the metal complex/ionic liquid matrix onto high-surface inorganic solids such as silica. Along the line of this hypothesis, herein we wish to disclose a new concept for in situ generation of Pd−NHC complexes in an imidazolium-type ionic liquid matrix (which is prefunctionalized with a trimethoxysilylpropyl group) and then simultaneous grafting of the whole system on the surface of silica. The preparation procedure for this new concept is shown in Scheme 1.

Scheme 1[a]



[a] (a) $(MeO)_3Si(CH_2)_3Cl$, toluene, reflux, 24 h. (b) $Pd(OAc)_2$, 50−60 °C Ar, 8 h. (c) 100 °C, 4 h. (d) SiO_2, $CHCl_3$, reflux, Ar, 24 h.

The ionic liquid matrix *N*-3-(3-trimethoxysilylpropyl)-3-methyl imidazolium chloride (**1**) was first synthesized by the reaction of *N*-methylimidazole with the corresponding (3-chloropropyl)trimethoxysilane in refluxing toluene.[9] Then, a sub-stoichiometric amount of $Pd(OAc)_2$ was allowed to react under an inert atmosphere with an excess of **1** at 50−60 °C for 8 h and then at 100 °C for 4 h to afford a clear, pale green-yellow solution (Figure 1, Supporting Information). In situ ^{13}C NMR analysis of this solution showed two peaks at 160 and 161 ppm concerning two regioisomers of **2**, which clearly supports the formation of a NHC−Pd complex.[5,7d] The resulting solution was then diluted with dry $CHCl_3$ and further reacted with SiO_2 under reflux for 24 h to form the corresponding *covalently* anchored NHC−Pd/IL matrix system **3**.[9] FT-IR spectroscopy of **3** showed a new broad absorption band at 1537 cm^{-1} (C═C stretching) along with bands at 1956, 2982 (for aliphatic C−H stretching), and 3171 cm^{-1} (unsaturated C−H stretching), respectively. This clearly indicates the successful covalent attachment of the above-mentioned matrix onto the silica surface (Figure 2, Supporting Information). TGA/DTG analysis of **3** shows a weight loss due to the desorption of water below 100 °C followed by a second small weight loss centered at 150 °C which is owing to the loss of inner water molecules as well as the loss of MeOH upon further condensation of unreacted methoxy groups. This is finally followed by a set of weight losses centered at 280 °C corresponding to the elimination of the surface-bound organic groups (Figure 3, Supporting Information). This indicates that catalyst **3** is thermally stable up to 280 °C.

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(4) For more recent leading references on heterogeneous palladium-catalyzed Heck reaction, see: (a) Crudden, C. M.; Sateesh, M.; Lewis, R. *J. Am. Chem. Soc.* **2005**, *127*, 10045. (b) Liang, L.; Zhang, L. X.; Shi, J. L.; Yan, J. N. *Appl. Catal. A* **2005**, *283*, 85. (c) Okumura, K.; Nota, K.; Yoshida, K.; Niwa, M. *J. Catal.* **2005**, *231*, 245. (d) Shimizu, K. I.; Koizumi, S.; Hatamachi, T.; Yoshida, H.; Komai, S.; Kodama, T.; Kitayama, Y. *J. Catal.* **2004**, *228*, 141. (e) Prökl, S. S.; Kleist, W.; Gruber, M. A.; Köhler, K. *Angew. Chem., Int. Ed.* **2004**, *43*, 1881. (f) Mandal, S.; Roy, D.; Chaudhari, R. V.; Sastry, M. *Chem. Mater.* **2004**, *16*, 3714. (g) Horniakova, J.; Raja, T.; Kubota, Y.; Sugi, Y. *J. Mol. Catal. A: Chem.* **2004**, *217*, 73. (h) Srivastava, R.; Venkatathri, N.; Ratnasamy, P. *Tetrahedron Lett.* **2003**, *44*, 3649. Choudary, B. M.; Mahdi, S.; Chowdari, N. S. *J. Am. Chem. Soc.* **2002**, *124*, 14127. (i) Köhler, K.; Heidenreich, R. G.; Krauter, J. G. E.; Piestsch, J. *Chem.−Eur. J.* **2002**, *8*, 622. (j) Mori, K.; Yamaguchi, K.; Hara, T.; Mizugaki, T.; Ebitani, K.; Kaneda, K. *J. Am. Chem. Soc.* **2002**, *124*, 11572.

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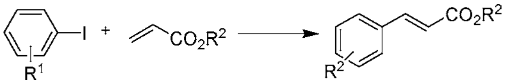
(9) See Supporting Information for details.

The catalytic activity of **3** was tested in the palladium-catalyzed arylation of olefins with different types of aryl halides under two different reaction conditions. Not unexpectedly, various types of substituted iodobenzenes were found to have high activity using electron-poor olefins such as methyl, ethyl, and butyl acrylate (1.1−2.5 equiv), a mixture of K_2CO_3/Et_3N (1.1 equiv each),[10] in the presence of **3** (0.05 mol %) in DMF at 100 °C (condition A), producing the corresponding cinnamic acid alkyl esters in excellent yields (Table 1).

Table 1. Heck Cross-Coupling Reaction of Iodobenzenes with Acrylates in the Presence of Silica-Supported NHC−Pd/IL **3**

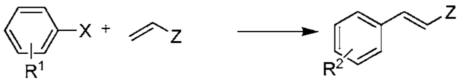


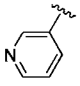
entry	R^1	R^2	time (h)	yield[a,b,c] (%)
1	H	Me	5	95[d]
2	H	Et	6	79
3	H	*n*-Bu	3	95
4	4-F	Me	4	94[d]
5	4-F	Et	5	91
6	4-F	*n*-Bu	4	89
7	4-MeO	Me	8	98[d]
8	4-MeO	*n*-Bu	7	92
9	H	Me	18	[e]
10	2-F	Me	18	9[f]

[a] Isolated product. [b] The molar ratios of iodobenzenes/acrylates/K_2CO_3/Et_3N/**3** are 1:1.1:1.1:1.1:0.0005. [c] The reaction was carried out in DMF under an Ar atmosphere at 100 °C. [d] The reaction was performed in the presence of 2.5 equiv of methyl acrylate. [e] Bromobenzene was used as substrate. [f] 2-Fluorobromobenzene was used as substrate.

However, bromobenzene was unreactive and 2-fluorobromobenzene only resulted in a low 9% yield, respectively, under similar reaction conditions (Table 1, entries 9 and 10). Interestingly, we found that by changing the base to NaOAc (1.5 equiv), changing the solvent to *N*-methylpyrolidinone (NMP), and increasing the reaction temperature to 140 °C the coupling reaction of bromobenzene with methyl acrylate went to completion within 24 h in the presence of as little as 0.01 mol % of **3**, affording *E*-cinnamate in excellent yield (condition B, Table 2, entry 1). To examine the scope of this method, the Heck reaction was reinvestigated with various types of iodo- and bromobenzenes coupled with different acrylates as well as styrene under the same reaction conditions (Table 2).

Table 2. Heck Cross-Coupling Reaction of Haloarenes with Olefins in the Presence of Silica-Supported NHC−Pd/IL **3**



entry	R^1	Z	X	time (h)	yield[a, b, c] (%)
1	H	CO_2Me	Br	24	90[d]
2	H	CO_2Me	I	8	93[d]
3	H	CO_2Et	I	9	91
4	H	CO_2Bu	I	9	95[e]
5	4-F	CO_2Me	I	4	95[d]
6	4-F	CO_2Et	I	6	99
7	4-F	CO_2Bu	I	4	94[e]
8	4-MeO	CO_2Me	I	10	96[d]
9	4-MeO	CO_2Bu	I	10	92
10	4-COMe	CO_2Me	Br	5	98[d]
11	4-CHO	CO_2Me	Br	2	92[d]
12	2-F	CO_2Me	Br	18	81[d]
13	4-Me	CO_2Me	Br	24	89[d]
14	4-MeO	CO_2Me	Br	24	94
15	4-MeO	CO_2Bu	Br	24	91[e]
16	H	Ph	Br	28	90[c, f]
17		CO_2Me	Br	30	78
18	4-CHO	CO_2Me	Cl	48	-

[a] Isolated product. [b] The molar ratios of iodobenzenes/olefins/NaOAc/**3** are 1:1.1:1.5:0.0001 unless otherwise stated. [c] The reaction was carried out in NMP under an Ar atmosphere at 140 °C. [d] The reaction was performed in the presence of 2.5 equiv of methyl acrylate. [e] 1 equiv of olefin was used. [f] A mixture of products was formed.

As shown in Table 2, all aryl iodides were rapidly converted to the corresponding Heck products with excellent yields, regardless of the electronic nature of the substituents (Table 2, entries 2−9). The coupling reaction of both electron-deficient and electron-rich aryl bromides with olefins also proceeded smoothly to furnish the Heck products with excellent yields (Table 2, entries 10−17). Especially, heteroaromatic substrates such as 3-bromopyridine and highly deactivated substrates such as 4-bromoanisole underwent the coupling reaction with good to excellent yields (Table 2, entries 14, 15, and 17). Unfortunately, our studies showed that this catalytic system in its present form is not suitable for the Heck reaction of chloroarenes even upon increasing the catalyst loading (Table 2, entry 18).

For practical applications of heterogeneous systems, the lifetime of the catalyst and its level of reusability are very important factors. To clarify this issue, we established a set of experiments using the recycled catalyst. Owing to very low catalyst loading (0.01 mol %), we performed the reaction of unactivated bromobenzene with methyl acrylate on a 30 mmol scale. After the completion of the first reaction to afford the corresponding methyl cinnamate in 95% yield, the catalyst was recovered by filtration, successively rinsed with distilled water (to remove excess of base), EtOH, and ether, and finally dried at 100 °C for 5 h. A new reaction was then performed with fresh solvent and reactants under the same conditions. Gratifyingly, the supported NHC−Pd/IL system could be reused four times with an average of 91.5% chemical yield in this way with virtually no considerable loss of activity (Scheme 2). This extremely high catalytic activity is clearly reflected by a high total turnover number up to 36 600 for this reaction.

To determine whether the catalyst is actually functioning in a heterogeneous manner or whether it is merely a reservoir

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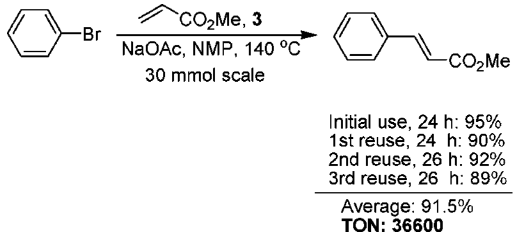
(10) It has been shown that sometimes a mixed base of carbonate and triethylamine increases the rate of the Heck reaction: Zhao, F.; Bhanage, B. M.; Shirai, M.; Arai, M. *Chem.−Eur. J.* **2000**, *6*, 843.

Scheme 2



for more active soluble palladium species, we performed a hot filtration test[11] after the reaction of bromobenzene with methyl acrylate initiates and before the substrates are consumed. The hot filtrates were then transformed to another Schlenk flask containing NaOAc (1.5 equiv) in NMP at 140 °C. Interestingly, upon the further heating of catalyst-free solution for 10 h, no considerable progress (∼7% by NMR analysis) was observed. Moreover, using atomic absorption spectroscopy of the same reaction solution at the midpoint of completion, we detected no palladium species. On the basis of these observations, we may conclude that the observed catalysis is truly heterogeneous in nature.

Quite recently, Dupont et al. made an interesting observation concerning the role and size evolution of Pd nanoparticles in an ionic liquid in the Heck reaction by performing a transmission electron microscopy (TEM) analysis before and after the coupling reaction.[12] To gain better insight into how our catalytic system changes during the reaction on a molecular level, we have also studied the catalyst evolution by means of TEM and energy-dispersive X-ray analysis (EDX). Interestingly, inspection of the TEM images of a sample of catalyst **3** after recovery from the cross-coupling reaction of bromobenzene with methyl acrylate clearly indicates the involvement of Pd nanoparticles with an irregular shape and wide-range size distribution (10−40 nm) confined inside the irregular pores of amorphous SiO_2 (Figures 4 and 5, Supporting Information). Furthermore, the recovered catalyst was analyzed at the nanoparticle level by EDX to ascertain whether palladium particles present inside the IL layer are directly attached to the silica surface. On the basis of the results of the EDX spectra, palladium seems to be present only in the imidazolium region (Figure 6, Supporting Information). Therefore, we concluded that the palladium particles were surrounded by the IL layer on the surface of silica.

In conclusion, we have described a new concept for simultaneous immobilization of a new NHC−Pd/IL matrix on silica. This system was effectively applied to the Heck reaction with a wide variety of iodo- and bromoarenes. The catalyst shows high thermal stability (up to 280 °C) and could be recovered and reused for four reaction cycles, giving a total TON ≅ 36 600. Furthermore, TEM coupled with EDX analysis indicate the formation of Pd nanoparticles within the immobilized IL layer. Further investigations aimed at developing this new concept are currently underway in our laboratories.

Acknowledgment. This work was supported by the Fonds des Chemischen Industrie. B.K. thanks the Alexander von Humboldt Foundation for a fellowship. We also acknowledge Prof. Hölderich (BET, FT-IR and TGA analysis), Prof. Simon, and Prof. Mayer for TEM, all from RWTH Aachen University.

Supporting Information Available: Experimental procedures, ^{1}H and ^{13}C NMR for new compounds, copy of NMR spectra, TGA, and FT-IR for **3**, EDX spectra, and TEM images of catalyst **3** after recovery. This material is available free of charge via the Internet at http://pubs.acs.org.

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