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An oxime–carbapalladacycle complex covalently anchored to silica as an active and reusable heterogeneous catalyst for Suzuki cross-coupling in water

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Received (in Cambridge, UK) 27th November 2002, Accepted 20th January 2003
First published as an Advance Article on the web 3rd February 2003

A preformed oxime–carbapalladacycle complex covalently anchored onto mercaptopropyl modified silica is highly active (> 99%) for the Suzuki reaction of *p*-chloroacetophenone and phenylboronic acid in water; no leaching occurs and the same catalyst sample was reused eight times without decreased activity.

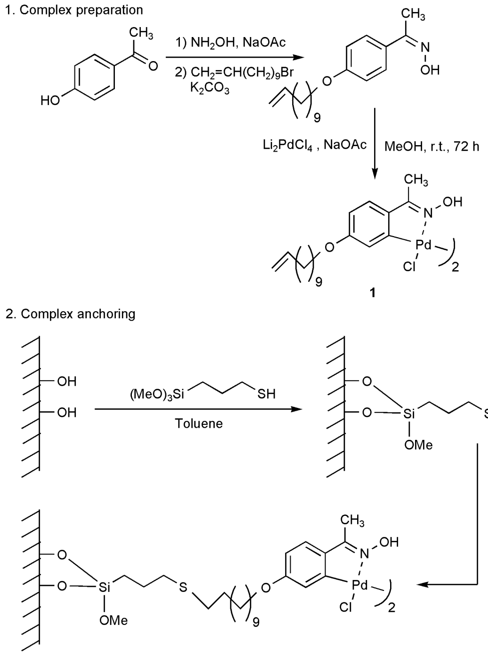
In recent years there has been an increasing interest in developing green processes in aqueous media.[1–3] While a considerable progress is being achieved, the vast majority of examples of catalytic reactions in aqueous medium still use homogeneous catalysis. It is clear that green chemistry not only requires the use of friendly solvents but also it is very convenient to convert homogeneous catalysis into heterogeneous catalysis in order to recover and reuse the catalyst. The Suzuki reaction is one of the most important Pd-catalysed C–C bond forming reactions and has a large potential commercial applicability.[4,5] One general strategy to transform a homogeneous into a heterogeneous process is to anchor the active site onto a large surface solid carrier provided that the anchoring methodology maintains the intrinsic activity and selectivity of the catalytic center.[6] In the present work we report the results obtained with an oxime–carbapalladacycle covalently anchored on a high surface silica as a heterogeneous catalyst for the Suzuki coupling of arylboronic acids and aryl halides.

Recently, it has been reported that a Pd complex analogous to **1** effects the Suzuki cross-coupling of aryl chlorides in water[7] as well as Ullman type, Heck, Sonogashira and other related C–C forming reactions in organic solvents.[7–10] Herein we report that by anchoring this complex on a high surface silica it is possible to perform the Suzuki reaction in water or water–organic solvent mixtures, and that the catalyst can be recovered and reused without noticeable loss of activity or leaching of the Pd from the solid to the liquid phase.

The preparation procedure followed to obtain the PdL@SiO_2 catalyst is indicated in Scheme 1.† Basically, it consists in preparing a Pd oxime–carbacycle complex having an ω-terminated C=C alkyl chain as substituent of the aromatic ring. The covalent bond between the mercaptopropyl functionalised silica and the Pd-complex was formed through a radical chain mechanism using AIBN as initiator in the absence of oxygen. Our strategy has the advantage of allowing a complete characterization (chemical analysis, UV, FAB-MS, IR and NMR spectroscopy) of each step of the complex preparation before the final binding of the solid, thus avoiding the excess of uncomplexed palladium or palladium oxide species on the solid surface.

The PdL@SiO_2 catalyst was characterised by chemical analysis and UV and IR spectroscopy. From the Pd, C and N analysis it is calculated that the loading of active complex in the solid was 0.34 mmol PdL g^{-1}. In the DR-UV-Vis spectrum of PdL@SiO_2 the most characteristic band is the absorption at 310 nm specific of the metal–ligand interaction that is present also in the complex in solution but is absent in the ligand (Fig. 1). IR spectroscopy also confirms the presence of the intact Pd-carbacycle complex on the silica surface (Fig. 2). In particular, two intense bands at 2950 and 2900 cm^{-1} corresponding to the stretching vibration of CH_2 of the tether were recorded together with the most characteristic absorption bands in the aromatic region. The covalent binding between the complex and the modified silica through the –SCH_2– linkage is indirectly inferred by the fact that exhaustive CH_2Cl_2 washings of the PdL@SiO_2 solid does not lead to a decrease of the signal intensity either of the DR-UV-Vis or the IR spectra. Also the leaching experiments (*vide infra*) indicate that the complex remains anchored on the solid surface.

To test the activity of PdL@SiO_2 as a heterogeneous Suzuki catalyst in water we selected the cross-coupling arylation of



Scheme 1 Anchoring procedure of the oxime carbapalladacycle onto the mercaptopropyl modified high surface silica.

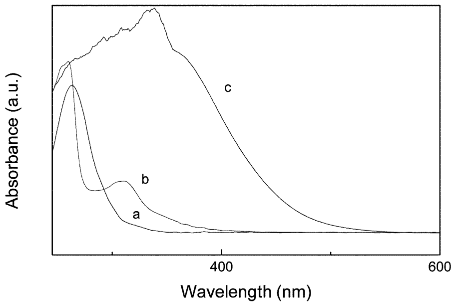


Fig. 1 UV-Vis spectra of the oxime ligand (a), oxime–carbapalladacycle compound **1** (b) and diffuse reflectance UV-Vis spectrum of PdL@SiO_2 (c).

DOI: 10.1039/b211742h

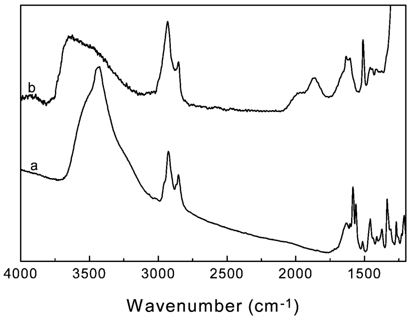


Fig. 2 Infrared spectra of oxime–carbapalladacycle (a) and PdL@SiO_2 (b).

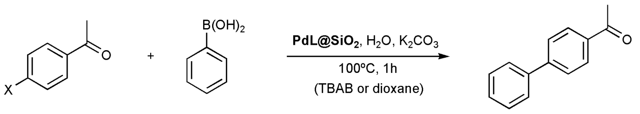
4-haloacetophenones and phenylboronic acid as the model reaction. Both reagents are soluble in water at the required concentrations and reaction temperature. To increase the solubility of the reaction product some assays were carried out using tetrabutylammonium bromide (TBAB, 0.5 equivalents) or the reaction was conducted in a mixture of dioxane–water (2 : 3). The results achieved are collected in Table 1.

Of note is that the presence of TBAB that has been considered crucial in homogeneous phase not only is not necessary when using PdL@SiO_2 as catalyst but it actually significantly decreases the activity of the catalyst (compare runs 1 and 3). A likely explanation of this negative influence of TBAB would be that Pd atom could exchange Cl^- by Br^-, the higher donicity of the latter increasing the softness of the active noble metal atom. Another feature from Table 1 is the fact that pure water is a more convenient solvent than dioxane–water mixtures. This observation is in agreement with the reported beneficial influence of solvent polarity on the activity of the Pd-carbacycle complex.[7] In fact, only when dioxane–water mixture is used as solvent was the presence of significant amounts of biphenyl arising from the phenylboronic homocoupling observed.

Although the reactions in Table 1 occur faster when *p*-bromoacetophenone is used as reagent, essentially complete conversions are also achieved with *p*-chloroacetophenone (compare runs 3 and 4).

When using a supported catalyst two points become crucial issues. The first is the possibility that some active metal migrates from the solid to the liquid phase and that this leached Pd would become responsible for a significant extent of the catalytic activity. To rule out the contribution of homogeneous catalysis in the results shown in Table 1, one reaction was carried out in the presence of the solid until the conversion was 22% and at that point the solid was filtered off at the reaction temperature. The liquid phase was then allowed to react, but no further conversion was observed (Fig. 3). This indicates that no active species were present in the supernatant. The second point was the deactivation and reusability of the PdL@SiO_2. To test this, a series of eight consecutive runs were carried out with the same PdL@SiO_2 sample, without a noticeable decrease in the activity (>99%, entry 5). This reusability demonstrates the high stability of heterogeneous catalyst. After using the catalyst, the solid was simply filtered off, washed with ethanol and ether and reused.

Table 1 Results of the Suzuki cross-coupling reaction of halobenzenes with phenylboronic acid in aqueous media



[b]Run	Conditions	X	*t*/h	Conversion (%)
1	Water/TBAB	Br	1	62
2	Water/TBAB	Br	48	67[a]
3	Water	Br	< 0.1	> 99
4	Water	Cl	0.25	91
5	Water[b]	Cl	2	> 99
6	Water–dioxane (3 : 2)	Cl	0.25	55[c]
7	Water–dioxane (3 : 2)	Cl	48	24[a,c]

[a] 0.65% of Pd was used. [b] Catalyst reused eight times. [c] Biphenyl was detected as byproduct.

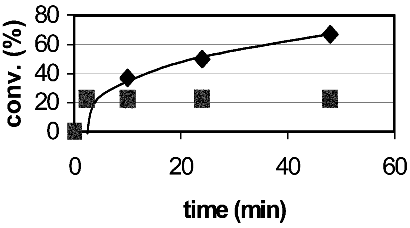


Fig. 3 Time conversion plot for the Suzuki reaction of *p*-bromoacetophenone and phenylboronic acid in water/TBAB in the presence of PdL@SiO_2 (◆) and after removal of the catalyst by filtration at reaction temperature (■).

In summary, the results presented above show that a silica supported Pd catalyst is an active and stable heterogeneous catalyst for the Suzuki reaction in water, making the whole process more efficient and environmentally friendly.

Financial support by the Spanish D.G.E.S. (MAT2000-1768-C02-01) is gratefully acknowledged. A. L. thanks the Spanish Ministry of Education for a post-graduated scholarship.

Notes and references

† Compound **1** was synthetized adding a methanolic solution (4 ml) of modified oxime (1.21 g, 4 mmol) and sodium acetate (0.33 g, 4 mmol) to a solution of Li_2PdCl_4 (1.05 g, 4 mmol) in methanol (8 ml). The mixture was stirred at room temperature for 72 h, filtered and after adding water (10 mL) the palladium carbacycle **1** precipitated as a yellow solid. To a solution of **1** in degassed chloroform, mercaptopropyl modified solid and AIBN were added under nitrogen atmosphere. The suspension was stirred magnetically at 80 °C under N_2 for 20 h. The solid was filtered off and Soxhlet extracted with dichloromethane for 24 h. After drying the solids (at 45 °C under 10^{-1} Torr for 2 h), the quantity of palladium was determined by quantitative atomic absorption spectroscopy. Suzuki reactions were carried out by stirring magnetically 4-bromo- or 4-chloroacetophenone (39.8 or 31.0 mg) and phenylboronic acid (36.6 mg. 1.5 equivalents) in water or water–dioxane in the presence of PdL@SiO_2 (38 mg) at reflux temperature. The course of the reaction was followed periodically by extracting aliquots of the aqueous phase with ethyl acetate and analysing the extract with GC using nitrobenzene as external standard.

1 S. Kobayashi and K. Manabe, *Pure Appl. Chem.*, 2000, **72**, 1373.
2 E. Kuntz, *Info Chim. Mag.*, 2000, **421**, 51.
3 N. A. Bumagin, *Tetrahedron*, 1997, **53**, 14437.
4 M. Beller and A. Zapf, *Top. Catal.*, 2002, **19**, 101.
5 J. G. De Vries and C. E. Tucker, *Top. Catal.*, 2002, **19**, 111.
6 A. Corma and H. Garcia, *Chem. Rev.*, 2002, **102**, 3879.
7 C. Najera, D. A. Alonso and M. C. Pacheco, *J. Org. Chem.*, 2002, **67**, 5588.
8 C. Najera and L. Botella, *Angew. Chem., Int. Ed*, 2002, **41**, 179.
9 C. Najera, M. C. Pacheco and D. A. Alonso, *Org. Lett.*, 2000, **2**, 1823.
10 C. Najera, D. A. Alonso and M. C. Pacheco, *Adv. Synth. Catal.*, 2002, **2**, 344.