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Pd nanoparticles embedded in sponge-like porous silica as a Suzuki–Miyaura catalyst: Similarities and differences with homogeneous catalysts

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Abstract

Pd nanoparticles of homogeneous size were prepared by $PdCl_2$ reduction with hydrazine in an inverse micelle microemulsion. These Pd nanoparticles were stabilized with dodecanethiol and 3-mercaptopropyltrimethoxysilane. The latter ligands were co-condensed with tetraethylorthosilicate, yielding an amorphous, sponge-like silica framework embedding the Pd nanoparticles. The resulting npPd@SiO_2 exhibits significant catalytic activity for the demanding Suzuki coupling of electron-rich 4-bromoanisole and phenylboronic acid. The solid can be recovered and reused with only a gradual decrease in catalytic activity. Using the cross-coupling of 4-bromoacetophenone and phenylboronic acid, a total turnover number of 63,000 was obtained. npPd@SiO_2 can considered one of the most active phosphine-free Pd solid catalysts reported to date.

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1. Introduction

Catalysis by palladium and gold has become an important topic in chemistry [1,2]. Although the development of extremely active soluble palladium complexes over the last few years has been impressive [3], further work on developing specific ligands and increasing the stability of the palladium complexes is needed. In almost all cases reported to date, the Pd complexes end up forming palladium particles during the reaction, and the activity of the initial catalyst decreases as the particle size grows beyond a few tens of nanometers. Thus, whereas some phosphine ligands, such as derivatives of biphenyl [4–7] or xanthyl [8–10], form palladium complexes and exhibit very high catalytic activity for cross-coupling carbon–carbon bond-forming reactions, they present intrinsic problems derived from the availability of these ligands and the tendency of the complexes to decompose under reaction conditions, leading eventually to deactivation of the catalytic system [11–15]. On the other hand, gold complexes are more stable under reaction conditions but generally give lower reactivity then Pd for more demanding carbon–carbon forming reactions [16–18].

The heterogeneous Pd catalysts could be a solution to avoid metal agglomeration. However, it has been shown that the catalytic activity of supported palladium catalysts is significantly lower than that achieved with palladium phosphine ligands [19,20]. For instance, palladium-exchanged zeolites and Pd/Cu hydrotalcites are active catalysts for the Suzuki, Heck, Sonogashira, and cycloisomerization reactions [21–25].

Attempts to combine the advantages of palladium complexes with those derived from using insoluble supports have been made by synthesizing periodic mesoporous organosilicas containing carbapalladacycle subunits in their structure. This hybrid organic–inorganic solid is active for Suzuki coupling but rapidly deactivates on reuse [26,27]. It appears, then, that in all reported cases there is much room for improvement, and a relevant task could be to develop palladium-containing solids with catalytic activity for the most challenging substrates, at least comparable with those of the current state-of-the-art homogeneous phosphine palladium complexes.

With this goal in mind, here we report on the synthesis and the catalytic activity of palladium nanoparticles embedded in an

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amorphous silica matrix (npPd@SiO_2). The catalysts present a homogeneous distribution of palladium nanoparticles (average particle size 4 or 7 nm) included in an "open", highly porous, amorphous silica matrix surrounding the palladium nanoparticles and thwarting their agglomeration, stabilizing their size, and allowing easy mass transfer through the pores. The catalytic activity of the material derives from the small size of the palladium nanoparticles and its stability within the embedding silica matrix. In this regard, it has been reported that small palladium nanoparticles can exhibit catalytic activity comparable to that exhibited by some palladium complexes [28–30]. It also has been proposed that these palladium nanoparticles can act as reservoirs for small atomic palladium clusters that go into the solution, promoting carbon–carbon coupling reactions in the homogeneous phase [19,29,31–37]. Then, even if the activity of Pd-supported solid catalyst were due mainly to the leached Pd, the results could be of general interest provided that the total TON was as high as it was with the homogeneous catalysts but without requiring the sometimes costly and time-consuming synthesis of ligands.

2. Experimental

2.1. Catalyst preparation

Palladium nanoparticles (npPd) were prepared in a water-in-oil microemulsion [38]. The three-phase system comprised water, isooctane, and AOT [sodium bis(2-ethylhexyl)sulfosuccinate], with a molar ratio of 4.5:60:1 [39]. Two milliliters of 0.1 M $PdCl_2$ in 0.2 M HCl was added to the previously formed AOT-isooctane emulsion stirred for 20 min. After another 15 min of stirring in N_2 atmosphere, the ionic Pd was reduced with an excess of hydrazine (100 µL), forming metallic Pd nanoparticles in the aqueous phase.

The npPd was stabilized with a mixture of thiols (60 µL) composed of 1-dodecanethiol (DT) and a small amount of 3-mercaptopropyltrimethoxysilane (MPMS) (molar ratio 18:1). npPd values of 2.9 and 1.5 nm were obtained by adding the thiol mix 5 min after or 2 min before the hydrazine, respectively. To destabilize the microemulsion and promote precipitation of the Pd particles, 40 mL of water and about 0.8 L of ethanol were added to the microemulsion. Under these conditions, a single liquid phase was observed and a suspension was formed. After 12 h, the solid was filtered using a 0.45-µm Whatman nylon membrane and washed with H_2O and ethanol. The precipitate was finally redispersed in 12 mL of ethanol.

The supported Pd catalysts were prepared following a sol–gel process [40] in the presence of thiol-capped npPd. Then 5.2 mL of tetraethyl orthosilicate (TEOS) and 0.1 mL of H_2O were added to 12 mL of the ethanol solution containing the capped npPd. The hydrolysis was catalyzed by 1.8 mL of a 0.0434 M aqueous solution of NH_4F. After 40 min under continuous stirring, the sol became a gel that slowly converted to a light-brown powder. The final npPd@SiO_2 catalyst was prepared treating the dried powder at 450 °C for 4 h in 100 $mL\,min^{-1}$ of air and subsequently at 450 °C for 3 h in 100 $mL\,min^{-1}$ of 20% H_2 80% N_2. The materials were characterized by transmission electron microscopy (Philips CM300 FEG system with an operating voltage of 100 kV), quantitative atomic absorption spectroscopy (Varian-Spectra A-10 Plus), N_2 absorption (Micrometrics ASAP 2000), and thermogravimetric analysis (Mettler TGA/SDTA 851e).

2.2. General procedure for the Suzuki coupling of 4-bromoanisole and phenylboronic acid [4]

4-Bromoanisole (3.6 mmol), phenylboronic acid (5.4 mmol) and K_2CO_3 (10.8 mmol) in 4 mL of DMF were added at the open air to a 10 mL round bottom flask equipped with a stirring bar. Then, the mixture was heated in an oil bath to 135 °C. When this temperature was reached, the catalyst was added. After 24 h of reaction under vigorous stirring, the mixture was filtered under vacuum and the catalyst washed with CH_2Cl_2. The combined extracts were analyzed by CG using nitrobenzene as the external standard.

2.3. General procedure for the Suzuki coupling of 4-bromoacetophenone and phenylboronic acid

A 25-mL round-bottomed flask was charged with 4-bromoacetophenone (3.5 mmol), phenylboronic acid (5.25 mmol), and K_3PO_4 (7 mmol) using toluene (10.7 mL) as a solvent. Then the mixture was heated in an oil bath at 100 °C under vigorous stirring, and the catalyst, npPd@SiO_2 (0.001 mol% Pd), was added. After 19 h of reaction, the mixture was filtered under vacuum, and the catalyst was washed with CH_2Cl_2. The combined organic extracts were analyzed by CG using nitrobenzene as an external standard.

2.4. Three-phase test

A sample of 4-bromobenzamide covalently bound to silica was obtained by reacting in toluene at reflux temperature a suspension of commercial 3-aminopropyl-functionalized silica (Aldrich) and 4-bromobenzoyl chloride in the presence of a few drops of pyridine. The functionalized silica solid was found to be stable under the Suzuki reaction conditions in the absence of palladium catalyst. Blank controls established that 4-bromobenzoic acid can be recovered from the solid in 60% efficiency by refluxing a suspension of the 4-bromobenzamide containing silica in 0.5 M aqueous solution of NaOH for 3 days. The corresponding 4-bromobenzamide or its derivative could be isolated after blank controls. The resulting silica-bound 4-bromobenzamide was added to a mixture of phenylboronic acid and 4-bromoanisole in DMF under analogous conditions to those specified previously. At the end of the reaction, the solids (catalyst, inorganic salts, and functionalized silica) were collected, washed with CH_2Cl_2, and submitted to digestion at the reflux temperature with an aqueous 0.5 M solution of NaOH for 3 days. After this period, the solution was acidified and the products were extracted with CH_2Cl_2. The combined liquid solutions were concentrated under reduced pressure and analyzed by GC. The formation of benzoic acid and 4-carboxybiphenyl was determined by GC–MS.

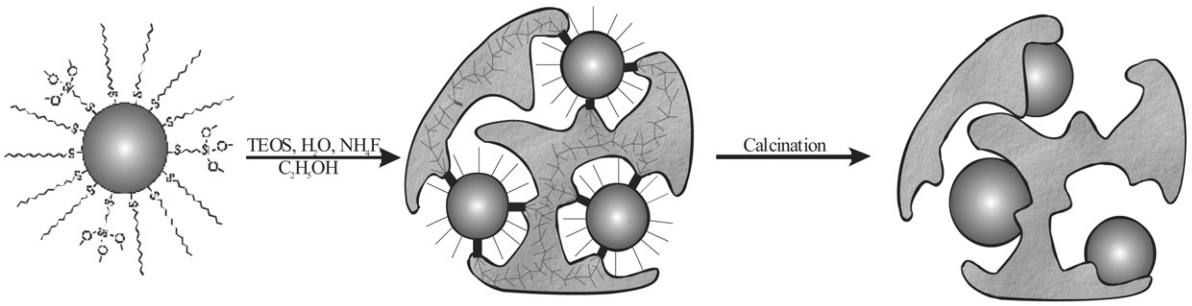


Fig. 1. Schematic representation of npPd capped with DT and MPMS and the npPd@SiO_2 structure. The MPMS (thick lines) provides the organic links between the metal particles and the inorganic sponge-like silica.

3. Results and discussion

3.1. Catalyst preparation

The npPd@SiO_2 catalyst was prepared from a metal–organic–inorganic material [41] formed by palladium nanoparticles (npPd) linked to the inorganic silica through organic bridges of 3-mercaptopropylsilyl. The synthesis involved a sol–gel process performed in presence of npPd coordinated to MPMS as ligand and using TEOS as an additional source of silica. The npPd were prepared in an inverse microemulsion system, reducing $PdCl_2$ with hydrazine and stabilizing the metal particles with a convenient mixture of two thiols, DT and MPMS, at a ratio of 18:1. Thus, these particles will be covered with an excess of DT and a smaller amount of MPMS (Fig. 1).

This method, based on the use of microdroplets in a confined reactor to form metal nanoparticles, was recently used to prepare Au-SiO_2 catalyst [41]. It allows us to obtain small nanoparticles with a diameter of few nm and a narrow particle size distribution. In this work, we prepared npPd with average diameters of 2.9 and 1.5 nm (Figs. 2a and 2c) by adding the stabilizing agents after and before the hydrazine, respectively. In the former case, the npPd were first formed in the water droplets and then stabilized to prevent agglomeration. In the latter case, smaller particles were obtained because the thiols interacted with the Pd before the reduction, providing a driving force against particle growth. It has been reported that, different from Au, in Pd, the addition of thiols before the reducing agent may promote the formation of polymeric complexes with a $[Pd(SR)_2]_n$ structure [42] in which the Pd is in the reduced form but not aggregated in particles. In our study, nanoparticles were observed in the TEM images of the unsupported Pd samples (Fig. 2c). Some formation of $[Pd(SR)_2]_n$ complex cannot be completely ruled out. However, we note that the final thermal treatment would eliminate the organic component, leading in all cases to organic-free Pd metal particles.

The two molecules, DT and MPMS, selected as ligands to stabilize the nanoparticles, play specific roles in the hydrolysis of TEOS and formation of the supported catalyst. The siloxane groups of MPMS form a link between npPd and silica, whereas DT acts as a spacer between npPd and silica, preventing complete occlusion of the particle. The final material can be viewed as an "open" silica that will limit the sintering of the particles at high temperature while preventing total occlusion of the particles and consequently favoring accessibility of the reactants to the catalytic sites (Fig. 1).

The final npPd@SiO_2 catalysts were prepared from this metal–organic–inorganic material, eliminating the organic material by calcination at 450 °C and then reducing the metal at 450 °C. In particular, two catalysts were prepared starting from the 2.9- and 1.5-nm npPd. The TEM images of these supported catalysts show that after thermal treatment, Pd sintering occurred, and the average particle size grew to 6.8 nm (Fig. 2e) and 3.9 nm (Fig. 2g). These two catalysts are designated npPd@SiO_2 (7 nm) and npPd@SiO_2 (4 nm). The thermal decomposition of the organic DT and MPMS can be observed in the thermogravimetric profile between 250 and 350 °C (Fig. 3).

The npPd@SiO_2 catalysts showed BET surface areas of $\approx$320 $m^2\,g^{-1}$, with the shape of the N_2 isotherms corresponding to a no-ordered mesoporous material with pore size distribution centered at 7 to 8 nm (Fig. 4). The metal loading, as measured by atomic absorption spectroscopy, was 1.4% for npPd@SiO_2 and 0.7% for npPd@SiO_2. These different loadings reflect the effect of the preparation procedure on the formation and stabilization of the palladium nanoparticles.

3.2. Catalytic tests

Suzuki coupling between 4-bromoanisole with phenylboronic acid was chosen to test the catalytic activity of npPd@SiO_2. This reaction has been proposed as a benchmark for comparing the efficiency of various palladium catalysts [43,44]. The presence of a methoxy substituent in the 4-position makes the aryl bromide more reluctant to undergo carbon–carbon coupling, thus providing an opportunity to rank the palladium catalysts according to activity. The reaction was carried out in DMF using K_2CO_3 as a base and a substrate/Pd molar ratio of 0.4% at two different temperatures. The results are indicated in Scheme 1.

As can be seen, working at moderate temperatures, the cross-coupling product was formed with a high selectivity and a turnover frequency (TOF), calculated from the time conversion plot at low conversions, of 1521 $\mathrm{mol_{4\text{-}bromobiphenyl}\,mol_{Pd}^{-1}\,h^{-1}}$. To determine the maximum TOF, the reaction was performed under the conditions listed in Table 1, but using a substrate/Pd molar ratio of 0.2%.

It is noteworthy that high temperatures led to considerably lower selectivity, due mainly to formation of the debromination

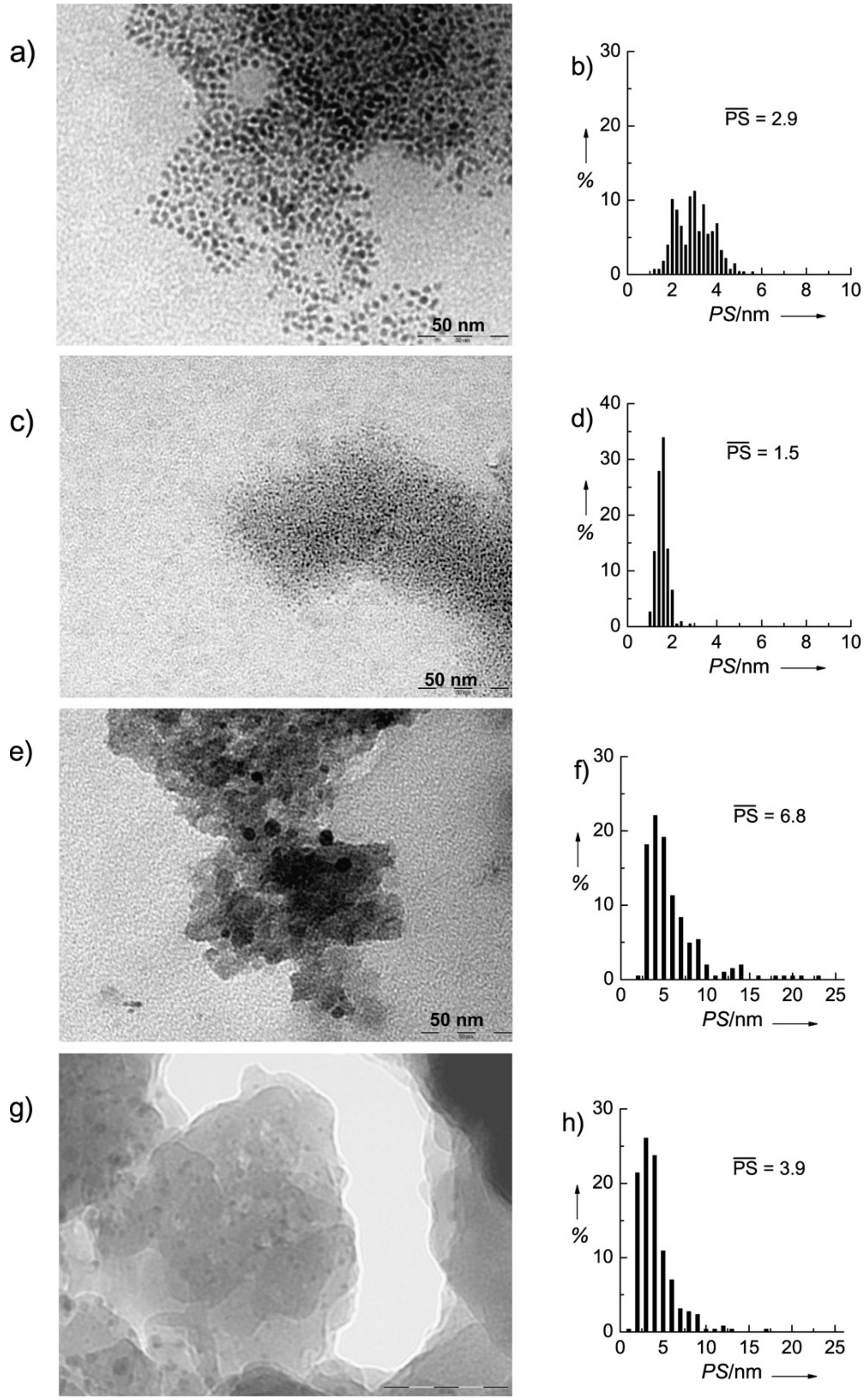


Fig. 2. (a and c) TEM micrographs of the stabilized npPd of 2.9 nm and 1.5 nm average size, respectively. (e and g) TEM micrographs of the catalysts npPd@SiO_2 (7 nm) and npPd@SiO_2 (4 nm). Bars = 50 nm. Plots (b), (d), (f) and (h) show the corresponding particle size distribution calculated over 200–400 particles. The average Pd particles size (PS) for each sample is also indicated.

product. A likely explanation for this negative influence of temperature on selectivity is related to the occurrence of leaching from the solid catalyst to the solution, because higher temperatures favor the presence in the liquid phase of palladium species that can effect debromination without promoting C–C cross-coupling. Indeed, the literature includes reports of studies using the three-phase test that have established that leached palladium species can produce dehalogenation but are inefficient in

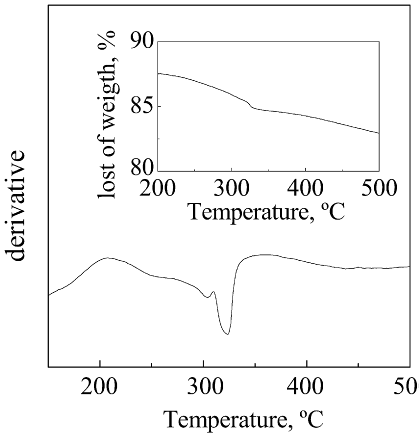
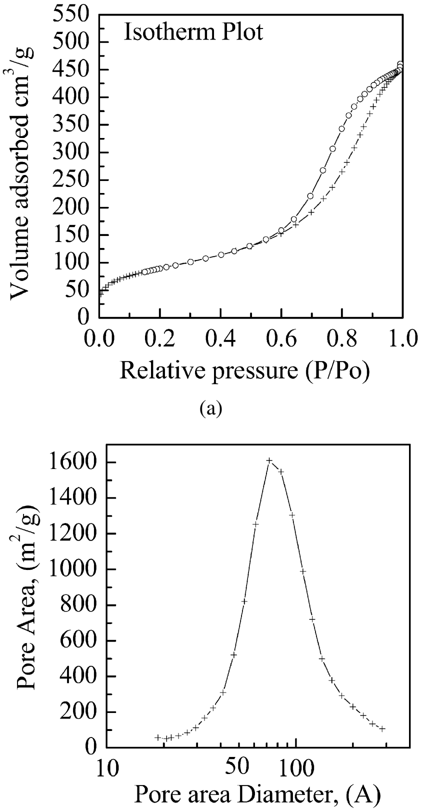


Fig. 3. Thermogravimetric profile of the metal–organic–inorganic precursor of npPd@SiO_2 (4 nm).



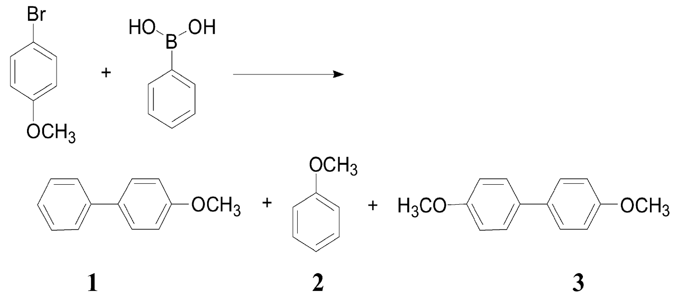
(a)

(b)

Fig. 4. Absorption/desorption isotherm cycle and pore size distribution of npPd@SiO_2 (4 nm).

promoting the Suzuki reaction [25]. We suggest here that the size of the palladium species migrating to the solution increases with increasing temperature, whereas the catalytic activity for the coupling reaction decreases with increasing particle size. We will discuss this later on the basis of further experimental results.

Most previous reports on heterogeneous solid palladium catalysts have noted lower activity and TOF [45–55] than the values we report here. In other cases in which the solid catalyst exhibits high activity, the solid contains an atomic palladium



Temperature (°C)	Conversion[a] (%)	Selectivity (%)		
		1	2	3
165	61	51	43	6
135	62	>95	–	–

[a] Reaction conditions: 4-bromoanisole (682 mg), phenylboronic acid (1.5 eq.), K_2CO_3 (3 eq.), DMF (4 mL). Catalytic data measured at 24 h.

Scheme 1.

Table 1
Results of the Suzuki cross-coupling between 4-bromoanisole and phenylboronic acid catalyzed by npPd@SiO_2. Reaction conditions: 4-bromoanisole (682 mg using fresh catalyst and same substrate to Pd ratio for consecutive reuses), phenylboronic acid (1.5 eq.), DMF (4 mL using fresh catalyst, same substrate to solvent ratio for consecutive reuses), reaction temperature 135 °C, reaction time 24 h

Run	Catalyst	Catalyst treatment	Yield (%)
1	npPd@SiO_2 (7 nm)	Fresh catalyst activated under H_2 at 450 °C	62
2	npPd@SiO_2 (7 nm)	Catalyst from run 1 without reactivation	22
3	npPd@SiO_2 (7 nm)	Catalyst from run 2 reactivated with water (pH 5) followed by calcination under H_2 at 450 °C	42
4	npPd@SiO_2 (7 nm)	Catalyst from run 3 reactivated with water washings (1 L at pH 1), followed by calcination under O_2 at 200 °C and subsequently under H_2 at 200 °C	76
5	npPd@SiO_2 (7 nm)	Catalyst from run 4 using the same reactivation procedure as run 4	33
6	npPd@SiO_2 (4 nm)	Fresh catalyst activated under H_2 at 200 °C[a]	96
7	npPd@SiO_2 (4 nm)	Catalyst from run 6 using the same reactivation procedure as run 4	70
8	npPd@SiO_2 (4 nm)	Catalyst from run 7 using the same reactivation procedure as run 4	52
9	npPd@SiO_2 (4 nm)	Catalyst from run 6 using analogous reactivation as run 4 but water washings (1 L) at pH 5	63
10	npPd@SiO_2 (4 nm)	Catalyst from run 9 using the same reactivation procedure as run 9	50
11	npPd@SiO_2 (4 nm)	Catalyst from run 10 using analogous reactivation as run 9 but water washings (300 mL) at pH 11	60
12	npPd@SiO_2 (4 nm)	Not calcined catalyst	51
13	npPd@SiO_2 (4 nm)	Catalyst from run 11 reactivated with washings with distilled water (250 mL)	31

[a] The reduction temperature was reduced to 200 °C because no differences in activity were observed activating at higher temperature.

complex [56–58] rather than palladium nanoparticles as in the present case. Considering that the stability of palladium complexes is generally lower than desired and that they are generally considered to act as precatalysts [59], the use of supported palladium nanoparticles has the conceptual advantage of avoiding complex and ligands. As mentioned previously, ligands are sometimes not easily available and their preparation requires dedicated, time-consuming synthesis, and, moreover, their use in the preparation of pharmaceuticals and food additives may introduce additional problems.

It has been reported that palladium nanoparticles supported on clays exhibited extremely high activity for the cross-coupling of 4-bromoanisole (TON = 56,000) combined with some reusability (two uses reported), but, disappointingly, also exhibited an unexpected "reverse" catalytic behavior and lower activity than expected for supposedly more reactive aryl halides, including iodobenzene [60]. In our case, we observed normal catalytic behavior for npPd@SiO_2, with reactivity following the expected chemical behavior of the reactants.

In any case, the results of Table 1, particularly the TOF values obtained using the minimum palladium amount, rank npPd@SiO_2 (7 nm) at the top of the list of solid catalysts exhibiting high activity for C–C cross-coupling reactions.

3.3. Catalyst recovery and regeneration

As noted in Section 1, an advantage of using solid catalysts is the possibility of their recovery and reuse. In particular, it must be demonstrated that the final productivity (i.e., kg of product per g of palladium atom of the solid catalyst) on reuse is higher than the productivity of homogeneous catalysts. In other words, the mere fact that the solid catalyst can be recovered does not represent any advantage versus an extremely active homogeneous catalyst that can act at a much higher substrate-to-palladium ratio, making its recovery for the reaction unnecessary. We note, however, that the substrate-to-palladium molar ratio used in this work is generally 0.4%, a value not uncommon for many homogeneous catalysts [5,61,62].

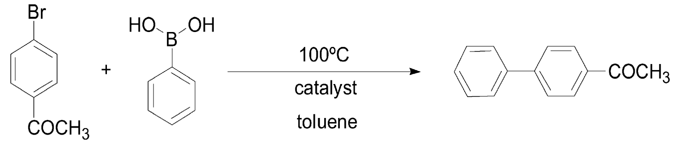
To evaluate the reusability of npPd@SiO_2 (7 nm), we performed a series of consecutive runs after reaction by simple filtration of the catalyst. Working under these conditions (run 2 in Table 1), the solid catalyst became considerably deactivated. However, we believe that this deactivation is due mainly to the presence on the solid catalyst of inorganic and organic reagents and products acting as poisons. To test this possibility, we carried out a reactivation procedure involving water washings to remove inorganic poisons (excess of K_2CO_3, as well as KBr and K_3BO_3 formed as reaction byproducts) followed by calcinations to degrade/oxidize the adsorbed organic material and a thermal reduction to reform palladium metal. According to this regeneration scheme, water washings at pH 5 and calcination under hydrogen at 450 °C were performed. As shown in Table 1 (run 3), this reactivation conditions were unsatisfactory, leading to only partial recovery of the activity. To increase the activity of used npPd@SiO_2 to the level of that of fresh catalyst, the pH of the washing water was decreased to ensure the removal of any base, followed by the calcination under oxygen to burn off any organic material before the final reduction of palladium. This regeneration protocol led to optimal recovery of the fresh catalyst activity (Table 1, runs 4, 7, and 8). We note, however, that extensive acid washings can lead to palladium depletion; for this reason, the pH of the washing water was maintained at 5 (Table 1, runs 9 and 10).

3.4. Influence of the size of Pd nanoparticles

Le Bars et al. [63] reported that Heck cross-coupling catalyzed by PVP-stabilized Pd nanoparticles is structure-sensitive. In particular, higher reaction rates were observed with smaller nanoparticles. The authors related the higher activity to the low-coordination surface Pd. To determine whether there is any benefit to decreasing the particle size in Suzuki cross-coupling, we prepared the npPd@SiO_2 (4 nm) catalyst. TEM analysis of npPd@SiO_2 (4 nm) after calcination demonstrated a particle size of around 4 nm, significantly smaller than that of npPd@SiO_2 (7 nm).

We evaluated the catalytic activity of this new npPd@SiO_2 (4 nm) sample for the cross-coupling of 4-bromoanisole and phenylboronic acid under the same conditions used in the previous study. The results, also given in Table 1 (runs 6–11), show that npPd@SiO_2 (4 nm) has considerably higher catalytic activity compared with npPd@SiO_2 (7 nm). The solid could be reused in the previously described reactivation procedure, with a gradual decrease in catalytic activity on reuse. This decreased catalytic activity of npPd@SiO_2 (4 nm) is due mainly to the depletion of palladium during water washings. To determine the TON, a specific run was performed with a substrate-to-Pd molar ratio of 7000. Working under these conditions, the TON was 1632, which falls in the range of the most active homogeneous Pd catalyst [5]. This TON value was calculated considering that all Pd atoms act as active catalytic sites. If only the fraction of Pd located at the surface of the 4-nm particles are considered (∼25% of the total Pd atoms), then the TON for the accessible Pd atoms should be 6448. We note that homogeneous catalysts are normally tested at temperatures below 100 °C, because high temperatures are avoided to prevent rapid decomposition. However, TONs can be fairly compared also when obtained at different temperatures.

In addition to 4-bromoanisole, we also performed the Suzuki coupling using 4-bromoacetophenone and phenylboronic acid as reagents. Taking into account that a considerable amount of information is available about the reactivity of 4-bromoacetophenone, the use of npPd@SiO_2 (4 nm) as a catalyst for the coupling of 4-bromoacetophenone provides another opportunity to compare the catalytic activity of npPd@SiO_2 with that of other systems reported in the literature [4]. In particular, performing the reaction under very low substrate-to-catalyst molar ratios and using biphenyl phosphane ligands, Buchwald et al. reported a TON as high as 100,000 for this reaction (Scheme 2) [4]. Working under the same experimental conditions as reported for homogeneous catalysis with biphenylphosphine but using the npPd@SiO_2 (4 nm) catalyst, we obtained a TON of 37,249 at 19 h in a single run. After one reuse, the total TON was 62,980. This TON was calculated on the basis of all Pd atoms present in the material. However, if, as mentioned before, this number is corrected to account exclusively for the activity of the external Pd atoms of the particles, then the resulting value (TON 251,920) compares very favorably even to those reported for the most active homogeneous phosphine Pd complex, but without the need for any phosphane ligand.



Conditions: 4-bromoacetophenone (1 eq.), phenylboric acid (1.5 eq.), K_3PO_4 (2 eq.), 0.001% molar of Pd, toluene (3 $mL/mmol_{halide}$), 100 °C, 19 h of reaction

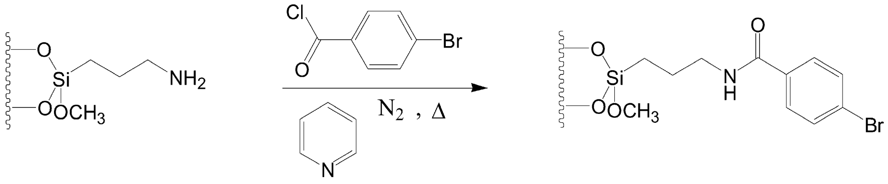
Catalyst	TON[a] ($mol_{product}/at\ g_{Pd}$)	
	100,000	
npPd@SiO_2 (4 nm)	First use	37,249
	Second use	62,980

[a] Data of catalytic activity for the biphenylphosphine ligand taken from Ref. [4].

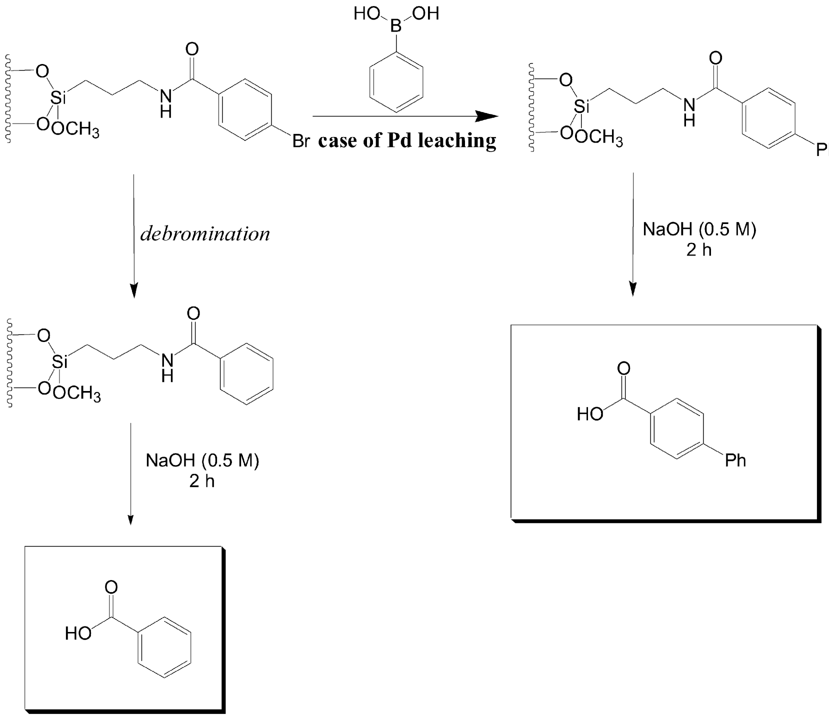
Scheme 2.

3.5. *Pd leaching tests*

Although, as described previously, it was possible to recover the npPd@SiO_2 catalyst and reuse it in consecutive runs with a significant residual activity, it is very likely that during the course of the reaction, some Pd species migrate from the solid to the solution, and catalysis also may occur in the liquid phase. In fact, most of the heterogeneous Pd catalysts are suspected to act as reservoirs of leachable Pd species that would migrate to the solution. Several tests are available to specifically address the occurrence and extent of leaching in the npPd@SiO_2 (7 nm) solids; one of the most commonly used involves filtration of the solid catalyst while the reaction mixture is hot and using the liquid filtrate for further reaction in the absence of solid. We performed this "filtration while hot" test and observed that the conversion of 4-bromoanisole stopped completely after filtration of the solid catalyst. But Davies et al. [64] have challenged the validity of these types of leaching test, arguing that the unavoidable temperature decrease during filtration of the solid is sufficient to effect a complete redeposition of Pd species on the surface of the solid, thus disguising the leaching test. These authors proposed a more elaborate alternative test to safely determine the occurrence of leaching when using Pd-supported catalysts. In their three-phase test, a compound analogous to



Scheme 3. Preparation of 4-bromobenzoyl-bonded silica.



Scheme 4. Three-phase test.

one of the substrates is covalently anchored to an insoluble support and, after reaction under the usual conditions, the solid is analyzed to determine whether or not the anchored compound has reacted. For truly heterogeneous catalysis, no reaction of the covalently anchored compound should be observed.

To perform the three-phase test, we proceeded to form a peptidic bond between aminopropyl-functionalized silica and 4-bromobenzoic acid (Scheme 3) to obtain BrPhCO@SiO_2. A preliminary control was performed, optimizing the basic conditions that allow hydrolyzation of the peptidic bond and recovery of the largest possible part (60% recovery) of the anchored benzoic acid.

When performing the reaction of 4-bromoanisole and phenylboronic acid using npPd@SiO_2 (7 nm) as a catalyst, we added BrPhCO@SiO_2 solid as a third phase. At the end of the reaction, we collected the solids, washed them with ethanol, and submitted them to hydrolysis with NaOH. This treatment allowed us to detect 4-carboxybiphenyl and benzoic acid in the organic extracts, thereby demonstrating the presence of leached Pd in the solution during Suzuki coupling (Scheme 4) and/or the fact that some coupling occurred under the basic aqueous conditions of the dissolution. In any case, we note that leached Pd species was more selective for dehalogenation than for cross-coupling, as demonstrated by the greater amount of benzoic acid formation compared with 4-carboxybiphenyl.

Recently, Vries [65,66] proposed ligand-free Pd catalysts, such as simple $Pd(AcO)_2$, as another useful and economical alternative to the homogeneous complexes. Vries showed that high activity can be obtained as long as a precise reactant/catalyst ratio is used and proposed that the ligand-free Pd^0 species are the real active catalysts. Pd salt catalysts also have been reported for use in Suzuki cross-coupling; in particular, $PdCl_2$ in a ionic liquid [67] and $Pd(OAc)_2$ stabilized by DABCO [68] have been tested for phenyl-bromide substrate. The latter work found remarkable performance similar to that obtained in the present work; however, it must be noted that no stabilizing agent is required when using supported Pd catalyst. Thus, the results for npPd@SiO_2 confirms that ligand-free Pd can provide a convenient alternative to the elaborate homogeneous complexes and that the active species can be efficiently generated from a solid precatalyst as well.

4. Conclusion

In the present work, we have shown that Pd nanoparticles embedded in a porous sponge-like silica is a suitable catalyst for the Suzuki–Miyaura coupling of electron-rich aryl bromides. The TON measured after reuse compares well with the values reported in the literature for the most active phosphine Pd complexes. The three-phase test experiments have revealed that the catalytic activity is due, at least in part, to the leaching of Pd species from the solid to the solution. Taking into account what is claimed when using homogeneous catalysts based on noble metals (i.e., the decisive factor is not catalyst recovery, but rather catalyst TON), the TON obtained with the catalyst presented here (considering the Pd remaining) is higher than that of any of the homogeneous catalysts reported to date for highly demanding reactions. Moreover, we note that in some cases, preparation of the ligands for the most active catalysts requires at least three synthesis steps, and the presence of oxygen and moisture should be carefully excluded during synthesis and handling of the phosphanes to avoid oxidation to phosphine oxide. These requirements do not apply to our case, because when using the silica-embedded Pd catalyst, the reactions can be carried out under ambient atmosphere.

Overall, our findings demonstrate that materials containing stabilized nanoparticles of sufficiently small size can be highly active for palladium-catalyzed reactions and can provide an complementary alternative to the use of specially designed ligands under homogeneous conditions.

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