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Room-Temperature Suzuki–Miyaura Reaction Catalyzed by Pd Supported on Rare Earth Oxides: Influence of the Point of Zero Charge on the Catalytic Activity

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Abstract Five Pd/REO (rare earth oxide) compounds (Pd/La_2O_3, Pd/CeO_2, Pd/Pr_6O_{11}, Pd/Sm_2O_3, and Pd/Gd_2O_3) have been successfully used as precatalysts in the Suzuki–Miyaura C–C cross-coupling reaction of aryl bromides with arylboronic acids in ethanol/water at r.t. All Pd/REO showed high activity and selectivity. The effective catalyst arises from palladium leaching from the REO support. We have demonstrated that the activity of each Pd/REO (the decreasing order is $Pd/La_2O_3 > Pd/Pr_6O_{11} > Pd/Gd_2O_3 > Pd/Sm_2O_3 \gg Pd/CeO_2$) is strictly related to the corresponding PZC (point of zero charge) value. Accordingly, it can be reasonably argued that the metal is released in solution in the form of Pd^{2+}, and higher is the amount of positive charge on the surface in catalytic conditions, higher is the concentration of Pd^{2+} ions in solution and faster is the formation of the coupling product. Also the recycling of each Pd/REO is strictly connected with the PZC value of the REO support. As a matter of fact, Pd/CeO_2, which has the lowest PZC value (6.7), shows the best reusability, according to its lower tendency to release Pd^{2+} ions in solution.

Keywords Palladium · Suzuki–Miyaura reaction · Metal leaching · C–C bond formation · Rare earth oxides · Point of zero charge

1 Introduction

The metal catalyzed cross-coupling process has been proven to be amongst the most useful and widely applied methods for $C(sp^2)$–$C(sp^2)$ and $C(sp^2)$-heteroatom bonds formation [1–4]. The exponential growth of studies in this field is mainly due to the exceptional relevance of the Ar–Ar moiety present in several fine chemicals, drugs and natural products. Even more than others, the Suzuki–Miyaura (SM) cross-coupling method has found increasing application for the production of asymmetric biphenyls [3, 5–8]. The development of new palladium-containing heterogeneous catalysts is one of the main goals in this area in view of the recovery and reuse goal [2, 9]. However, it is now well recognized that Pd-containing heterogeneous systems employed as catalysts in the cross-coupling reaction generally act as precursors of active forms of palladium through a leaching process [10–17], even if there are a few studies suggesting that the catalytic process takes place (or may also occur) on the surface of the solid [18–23]. Emblematic is the case of Pd/C where conflicting interpretations have been put forward concerning the role of Pd leaching on the catalytic activity [13, 23]. Starting from precatalysts based on palladium supported on metal oxides, it is generally accepted that the released, catalytically active, metal particles originate from amorphous PdO [24–27]. The same is true also starting from various forms of (PdO contaminated) metallic palladium [28]. As a matter of fact, in the case of Pd/Al_2O_3 catalyst, a reductive pretreatment using hydrogen that partially converts Pd^{2+} into Pd(0) afforded a much less catalytically active species [25]. In addition, a neat decrease of catalytic efficiency has been also observed when a high crystalline form of PdO was provided by prolonged thermal treatment in air [28]. Such a finding is supported by the fact that thermally

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treated Pd/Al_2O_3 precatalyst showed reduced catalytic activity in the Suzuki coupling [25].

Efficiency and reusability of different Pd/supported catalyst have been correlated to the occurrence of a leaching/re-deposition mechanism [25, 27]. Accordingly, at the end of the catalytic organic transformation, Pd(0) is supposed to deposit back on the surface of the support. In a recent paper, we have described the SM reaction catalyzed by Pd/CeO_2 [14]. Clear evidences for re-adsorption of palladium onto the surface at the end of the catalytic process were not achieved. The HRTEM analysis of fresh and used (four times) precatalyst as well as particle size distribution did not show any remarkable modification. Despite this, Pd/CeO_2 showed to be reusable at least ten times without evident loss of catalytic activity. In principle, these results can be roughly interpreted in terms of heterogeneous coupling, but experimental results provided clear and unambiguous evidence for the occurrence of a homogeneous catalytic process [14]. Literature data strongly support this conclusion [10, 24, 25].

Another intriguing issue is the paramount importance of the nature of the base, absolutely necessary for the reaction to occur. For example, catalytic systems that showed high efficiency in the presence of NaOH, gave poor results using Na_2CO_3 [28]. Analogously, K_2CO_3 was a better choice with respect to KF or KO^tBu [14]. Notably, not only the nature of the anion is important for obtaining high yields of the coupling product, but also that of the cation. In a preliminary base screening of the present work, K_2CO_3 showed to be much more helpful than Na_2CO_3. By contrast, using palladium wire as the catalyst, the activity in the presence of NaOH or KOH was about the same [28]. Finally, very recently, the dramatic effect of the (polar or non polar) nature of the solvent on the formation of a well-defined species catalytically active in the SM reaction has been clearly evidenced [29].

In this contradictory context, the recent finding that palladium particles released by Au@Pd nanoparticles (NPs) are more active for a second catalytic run than the residual palladium present in the recovered NP is very interesting [30]. The authors also found that there is not a close relation between the amount of noble metal present in solution and the catalytic activity. Thus, most probably, only a part of the total palladium released by the NP is present in a catalytically active soluble form. But the most striking feature of the study is the demonstration of the exclusive and cooperative role played by the base and the arylboronic acid on the formation of catalytically active soluble Pd(0). A previous study based on Pd/C catalyst showed, on the contrary, that both the aryl halide and the arylboronic acid, but not the base, promote palladium leaching [13].

Stimulated by the need for new investigations that could give light into this scientific fix, we have extended the catalytic studies on the Pd/CeO_2 system to other Pd/REOs (rare earth oxide), namely, Pd/La_2O_3, Pd/Pr_6O_{11}, Pd/Sm_2O_3, and Pd/Gd_2O_3. On the bases of previous results obtained using Pd/CeO_2 [14], our first goal was to gain insights about the possibility that Pd^{2+} ions are leached from Pd/REO and then reduced to Pd(0). According to such a scenario, all features that favour a weaker palladium-surface interaction with consequent dissolution of Pd^{2+} ions should result eventually in an increase of the reaction rate. In particular, we focused our study on the degree of surface charging as indirectly estimated by measuring the point of zero charge (PZC) [30–32] of each REO, thus correlating the tendency of Pd^{2+} to enter into solution to the degree of positively/negatively charged surface. Then, Pd^{2+} ions in solution should be easily and rapidly reduced to Pd(0), the effective catalyst that undergoes oxidative addition by the aryl halide substrate, as the first step of the catalytic cycle. If this mechanism is true, then it is reasonable that the higher the amount of leached Pd^{2+} ions, the higher is the rate of formation of the coupling product, unless aggregation into catalytically inactive form causes a decrease of the amount of active metal centres.

2 Experimental Section

2.1 Materials

The salts $La(NO_3)_3{\cdot}6H_2O$, $Ce(NO_3)_3{\cdot}6H_2O$, $Pr(NO_3)_3{\cdot}6H_2O$, $Sm(NO_3)_3{\cdot}6H_2O$, and $Ga(NO_3)_3{\cdot}6H_2O$ were purchased from Aldrich. The Pd precursor was a $Pd(NO_3)_2$ solution (10 wt% in 10 wt% nitric acid, Pd 99.999 %) purchased from Aldrich. All solvents were reagent grade and used without further purification.

2.2 Synthesis of Pd/REO **1–5**

The Pd/REO catalysts Pd/La_2O_3 **1**, Pd/CeO_2 **2** Pd/Pr_6O_{11} **3**, Pd/Sm_2O_3 **4**, and Pd/Gd_2O_3 **5** were synthesized by a two-steps procedure as follows.

> *First step*: the rare earth oxides were prepared starting from the corresponding nitrate precursor. The lanthanide nitrate (3 g) was dissolved in water (100 mL) and the mixture was heated at 333 K under stirring to facilitate dissolution. Addition of a concentrated solution of NH_3 (5 mL) to the cooled solution resulted in the precipitation of the rare earth hydroxide. The stirring was stopped and the precipitate was allowed to stand for 1 h, then the suspension was filtered off and the solid was washed with water to remove traces of NH_3. The product was dried at 393 K for 15 h and then calcined at 873 K for

4 h with a temperature ramp of 10 K/min to afford the rare earth oxide.

Second step: the Pd/REO catalysts were prepared according to the incipient wetness technique. The Pd solution was added drop by drop to the REO support to obtain a Pd/REO catalyst with a nominal 2 wt% palladium loading. The solid was dried at 393 K for 1 h and impregnated again. Once all the precursor had been absorbed on REO, the solid was dried at 393 K for 15 h and then calcined at 873 K for 4 h with a temperature ramp of 10 K/min.

In the case of Pd/La_2O_3, a sample with a nominal 0.5 wt% palladium has been prepared following the same procedure.

A sample of Pd/La_2O_3 **1** has been reduced by treatment for 3 h at 573 K with H_2 (4 % in Ar) in a Carbolite oven. Cooling of the sample was performed at 10 °C/min cooling rate in He atmosphere.

2.3 PZC Determinations

The PZC value of each REO was measured according to a published procedure [31]. Water (100 mL) was thermostated under stirring at 298 K and a 0.12 M solution (0.8 mL) of $NaNO_3$ was added. The pH of the solution was measured and a solution of NaOH 1 M was added drop by drop until the pH reached a basic value. At this point, a crop of REO (about 15–20 mg) was added and the mixture was left under stirring for 2 min. After this time, the pH of suspension was measured and another crop of REO was added. After 2 min of stirring, the pH was measured again. This procedure was repeated until the pH of the solution remained unchanged.

The whole procedure was repeated starting from a different initial basic pH. Analogously, the method was applied to two starting solutions whose pH was adjusted to an acidic value by adding, drop by drop, a solution of 1 M HCl. The PZC value was obtained graphically from the four curves pH versus REO total mass.

2.4 Catalytic Runs

The following general procedure was adopted for all reactions catalyzed by **1**–**5**. In a thermostated bath at 298 K, a 10 mL Schlenk flask was charged in air with a magnetic stir bar, catalyst (1 mol% Pd), arylboronic acid (0.6 mmol), diethylene glycol di^{n}butyl ether (GC internal standard, 0.5 mmol), K_2CO_3 (0.6 mmol), ethanol (1.5 mL) and H_2O (0.5 mL). Then the reaction was started by the addition of aryl bromide (0.5 mmol). For the GC analysis, about 0.1 mL of mixture was extracted from the flask by means of a syringe and to the sample was added 0.5 mL of water, followed by extraction with dichloromethane (2 × 1 mL). The solution was dried over Na_2SO_4 and analysed by GC after purification on a microcolumn filled with silica gel. Analogous procedure was adopted when the Pd loading was 0.1 or 0.05 mol%.

2.5 Determination of the Palladium Amount in Solution

Four independent experiments were run with both Pd/La_2O_3 **1** and Pd/CeO_2 **2**.

(a) In a thermostated bath at 25 °C, a 10 mL Schlenk was charged in air with a magnetic stir bar, Pd/La_2O_3 **1** (1.5 mg, 0.05 mol%), 1-naphthylboronic acid (0.6 mmol), K_2CO_3 (0.6 mmol), ethanol (1.5 mL) and H_2O (0.5 mL), and the reaction was started upon addition of 1-bromo-4-nitrobenzene (0.5 mmol). After 2 min, the suspension was poured into a 100 mL round bottom vessel containing ethanol (30 mL) and H_2O (10 mL) to quench the reaction and then filtered immediately to eliminate the solid material. The palladium content of the solution was analyzed by ICP. Pd amount was 13.2 μg.

(b) The reaction was started as in point a) and was allowed to reach completion (20 min). The solution was then filtered in order to eliminate the solid and the palladium content of the solution was analyzed by ICP. Pd amount was found to be 9.5 μg.

(c) As in b). The organic product [1-(4-nitrophenyl)naphthalene] was extracted with dichloromethane (2 × 10 mL). After elimination of the solvent, the palladium content of the recovered crude solid (117 mg, yield 94 %) was analyzed by ICP. Pd amount was 8.7 μg.

(d) As in b) but Pd/CeO_2 **2** (1.4 mg, 0.05 mol%) was used instead of Pd/La_2O_3 **1**. Pd amount detected by ICP was 1.2 μg.

2.6 Catalyst Recycling

In a thermostatted bath at 25 °C, a 8 mL conical centrifuge test tube was charged in air with a magnetic stir bar, Pd/La_2O_3 **1** (30.2 mg), 4-methylphenylboronic acid (0.6 mmol), diethylene glycol di^{n}butyl ether (GC internal standard, 0.5 mmol), K_2CO_3 (0.6 mmol), ethanol (1.5 mL) and H_2O (0.5 mL), and the reaction was started upon addition of 1-bromo-4-nitrobenzene (0.5 mmol). After 1 h, the suspension was centrifuged for 3 min at 3,500 rpm and the supernatant was removed and analyzed by GC. The solid was washed with water and ethanol, dried on air and reused for the second test, which was performed upon addition in sequence of solvents, 4-methylphenylboronic acid, GC internal standard, base and 1-bromo-4-nitrobenzene, as indicated above. Again, the reaction was stopped after 1 h by centrifugation and the successive workup was analogous to that previously described. Iteration of this procedure was continued for four consecutive reuses of the catalyst. Yields of 4-methyl-4′-nitro-1,1′-biphenyl from the GC measurements were the following: 99.9 (first use), 99.7, 84.5, 20.8, 5.4.

The same procedure was adopted when Pd/CeO_2 **2** (27.5 mg) was used as the catalyst. In this case the reaction time was prolonged to 6 h. Yields of 4-methyl-4′-nitro-1,1′-biphenyl from the GC measurements were the following: 99.8 (first use), 99.3, 99.1, 98.6, 97.3.

After the fourth reuse, the residual palladium loading of Pd/La_2O_3 **1** was 0.04 %, while that of Pd/CeO_2 **2** was 0.58 % (measurements by ICP).

2.7 Instruments

The GC–MS analyses, run to control the identity of the compounds obtained in the catalytic trials, were carried out with a Fisons TRIO 2000 gaschromatograph-mass spectrometer working in the positive ion 70 eV electron impact mode. Injector temperature was kept at 250 °C and the column (Supelco® SE-54, 30 m long, 0.25 mm i.d., coated with a 0.5 μm phenyl methyl silicone film) temperature was programmed from 60 to 280 °C with a gradient of 10 °C/min. The GC analyses were run on a Fisons GC 8000 Series gaschromatograph equipped with a Supelco® PTA-5 column (30 m long, 0.53 mm i.d., coated with a 3.0 μm poly(5 % diphenyl-95 % dimethylsiloxane) film). Injector and column temperatures were as indicated above. The X-ray spectra were recorded on a Philips X'Pert diffractometer equipped with Cu K-alpha radiation source. Step size was 0.01° with a time-per-step of 80 s. SEM (Scanning Electron Microscopy) measurements were run on a ZEISS EVO scanning electron microscope. X-ray Photoelectron Spectroscopy was carried out with a SPECS system equipped with an Mg anode XR50 source operating at 200 W and a Phoibos MCD-9 detector. XP spectra were recorded with pass energy of 25 eV at 0.1 eV steps at a pressure below 10^{-9} mbar.

3 Results and Discussion

3.1 Synthesis and Characterization of **1–5**

Pd/REO **1–5** used in this work were easily prepared by a two-step synthesis, starting from nitrate salts of the rare earths and $Pd(NO_3)_2$. The detailed procedure is described in Sect. 2.2. Characterization of **1–5** was done by means of BET and XRD measurements and Pd elemental analysis. The data are shown in Table 1. Furthermore, compounds Pd/La_2O_3 **1** and Pd/CeO_2 **2** were subjected to X-ray Photoelectron Spectroscopy analysis. The XPS data have been collected in Table 2. The co-presence of both Pd^0 and Pd^{2+} was clearly evidenced in the two samples, with a neat prevalence of the latter.

Table 1 Physical and PZC data for compounds **1–5**

Compound	% Pd[a]	SA[b] (m^2/g)	PV[c] (cm^3/g)	PZC[d] (pH)
Pd/La_2O_3 **1**	1.76	16.6	0.24	8.8
Pd/CeO_2 **2**	1.93	31.5	0.18	6.7
Pd/Pr_6O_{11} **3**	1.93	22.4	0.36	7.8
Pd/Sm_2O_3 **4**	1.85	11.9	0.21	7.4
Pd/Gd_2O_3 **5**	1.99	10.2	0.09	7.5

[a] Determined by ICP

[b] Surface area

[c] Pore volume

[d] Point of zero charge measured by a procedure described in the literature [31]. The reported value is the mean of three independent determinations

Table 2 XPS data for compounds **1** and **2**

Compound	Binding Energy (eV)				%	
	$3d_{5/2}$ Pd^0	$3d_{5/2}$ Pd^{2+}	$3d_{3/2}$ Pd^0	$3d_{3/2}$ Pd^{2+}	Pd^0	Pd^{2+}
1[a]	335.5	336.9	340.7	342.5	36.2	63.8
1[b]	335.3	337.0	340.3	342.8	74.6	25.4
2[a]	335.7	336.6	341.1	342.6	21.8	78.2
2[b]	335.3	336.8	340.4	342.9	61.4	38.6

[a] Fresh sample

[b] Sample used 4 times

3.2 Catalytic Investigation

Preliminary catalytic tests were carried out according to Scheme 1. The coupling reaction was between 1-bromo-4-nitrobenzene and 4-methylphenylboronic acid in the presence of K_2CO_3, in a 3:1 ethanol/H_2O mixture, at 298 K in air, according to a well-established protocol [14, 15]. Initially, the reaction was performed using 1 mol% catalyst (with respect to the aryl bromide), then the catalyst amount was decreased to 0.1 mol%, and finally to 0.05 mol%. The results of the last series of catalytic tests are collected in Table 3. Among all precatalysts, Pd/La_2O_3 **1** gave the best catalytic performances. A slightly slower reaction was observed in the case of Pd/Pr_6O_{11} **3**, Pd/Sm_2O_3 **4**, and Pd/Gd_2O_3 **5**. Noticeably, Pd/CeO_2 **2** showed to be one order of magnitude less effective. Analogous trend was observed by reacting other substrates.

Scheme 1 The Suzuki–Miyaura model reaction

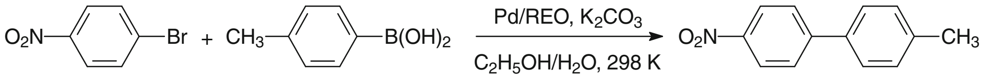


Table 3 Comparison of the catalytic activity of **1–5**

Entry	Catalyst (0.05 mol%)	Time[a] (min)	Yield[b] (%)	TON[c]	TOF[d] (h^{-1})
1	Pd/La_2O_3 **1**	13	68	1980	9,130
2	$Pd/La_2O_3^e$	420	0	1980	280
3	$Pd/La_2O_3^f$	360	0	1980	330
4	Pd/CeO_2 **2**	260	2	1980	450
5	Pd/Pr_6O_{11} **3**	17	60	1980	6,980
6	Pd/Sm_2O_3 **4**	21	52	1980	5,650
7	Pd/Gd_2O_3 **5**	20	56	1980	5,940

Reagents and conditions: 1-bromo-4-nitrobenzene (0.5 mmol), 4-methylphenylboronic acid (0.6 mmol), K_2CO_3 (0.6 mmol), catalyst, 1.5 mL ethanol, 0.5 mL water, T = 298 K

[a] Time necessary to achieve >99 % yield of 4-methyl-4′-nitro-1,1′-biphenyl, determined by GC using diethylene glycol di^{n}butyl ether as internal standard

[b] Product yield after 2 min of reaction

[c] Turnover number calculated for 99 % GC yield

[d] Turnover frequency (mol of product per mol of catalyst per hour)

[e] 0.025 mol% using nominal 0.5 wt% Pd (0.47 wt% Pd from ICP analysis)

[f] Catalyst **1** left for 3 h at 573 K under a stream of H_2 (4 % in Ar)

The scope of the catalyzed reaction has been explored. In particular, in the presence of Pd/La_2O_3 **1**, about twenty different combinations of aryl bromides and arylboronic acids always resulted in the quantitative formation of the cross-coupling product (isolated yields were in the range 89–97 %). Selected demonstrative results are presented in Table 4. The whole data will be reported in a forthcoming paper. Poor yields of the coupling product were observed starting from aryl chlorides. For example, the reaction between 1-chloro-4-nitrobenzene and 4-methylphenylboronic acid gave only 38 % (GC yield) of 4-methyl-4′-nitro-1,1′-biphenyl at 80 °C (Table 4, entry 8). On the other hand, only 3-chloro-3′-methoxy-1,1′-biphenyl has been detected in solution by GC–MS when 1-chloro-3-bromobenzene reacted with 3-methoxyphenylboronic acid at 25 °C (Table 4, entry 4). This clearly indicates that, in the given experimental conditions, the C–C coupling selectively occurs at the C–Br bond.

3.3 Insights into the Formation of the True Catalyst

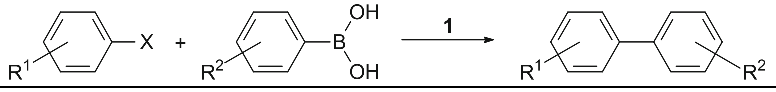
It is reasonable to expect that that the sequence of activity observed over the REO support (Pd/La_2O_3 **1** > Pd/Pr_6O_{11} **3** > Pd/Gd_2O_3 **5** > Pd/Sm_2O_3 **4** ≫ Pd/CeO_2 **2**) have to be related to the tendency of each Pd-REO combination to deliver different amounts of palladium in solution. In a previous investigation based on the application of both Pd/CeO_2 [14] and PdO hydrate [15] to the SM cross-coupling, we have found that the catalytic activity is completely suppressed in the presence of a diamine arm grafted on silica ("heterogeneous chelation test"). It is likely that the–$NHCH_2CH_2NH_2$ functionality is able to capture by chelation the Pd^{2+} ions present in solution. However, in principle, the much less probable co-ordination of Pd(0) atoms cannot be excluded [33, 34].

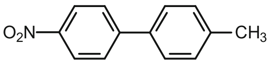
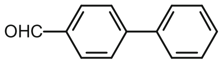
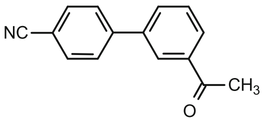
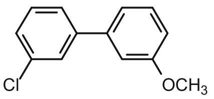
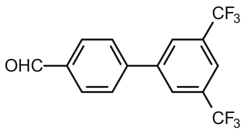
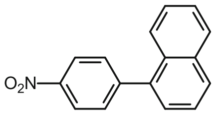
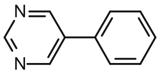
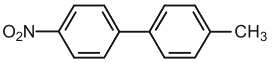
In literature it is reported that the properties of the support, in particular the surface charging that depends on its PZC, play a major role in the adhesion of metal nanoparticles onto the surface [35, 36]. For this reason we decided to measure the PZC of each REO under conditions close to that used in the catalytic runs. A reliable determination of PZC, according to the method of Kallay and coworkers [31, 32], was done in pure water (an example of PZC determination is shown in Fig. 1). The PZC values of **1**–**5** are collected in the last column of Table 1. The values obtained for CeO_2 and La_2O_3, 6.7 and 8.8, respectively, are very close to those previously reported [37], while no data have been found in the literature for the other REOs here investigated. It should be noted that the PZC value measured for a given REO is the same obtained for the corresponding Pd/REO, that is, the presence of ca. 2 wt% of palladium on the surface does not affect appreciably PZC, as expected.

The effective relation between the catalytic activity shown by **1**–**5** and their PZC values is clearly evidenced in Fig. 2, that shows a surprisingly good linear correlation between the yield of the coupling product in the early stages of the reaction (after 2 min) and the proton molar concentration corresponding to the related PZC ($[H_3O^+] = 10^{-PZC}$). Similar good linear correlation between product yield and $[H_3O^+]$ was also obtained at longer reaction times (5 and 10 min). The higher reactivity of Pd/La_2O_3 is therefore correlated to a marked degree of Pd^{2+} leaching from the surface of La_2O_3, favoured by its less negatively charged surface. According to the observations of Feltes et al. [38] in fact, at basic pH such as that of the catalytic reaction (~10.5), high PZC oxides are less negatively charged than low PZC ones. Within the systems under investigation, La_2O_3 shows the higher PZC and thus the lower density of negatively charged sites onto the surface. On the contrary, the lowest activity observed with Pd/CeO_2 is correlated to the higher degree of negatively charged surface which help keeping Pd^{2+} ions anchored to the support, as schematically represented in Fig. 3.

To confirm our hypothesis, two sets of measurements on the model reaction were carried out using modified

Table 4 Scope of the catalyzed reaction



Entry	X	R^1	R^2	Product	Yield[a]
1	Br	4-NO_2	4-CH_3		96
2	Br	4-CHO	–		91
3	Br	4-CN	3-$COCH_3$		89
4	Br	3-Cl	3-OCH_3		91
5	Br	4-CHO	3,5-CF_3		93
6	Br	4-NO_2	[b]		96
7	Br	[c]	–		97[d]
8	Cl	4-NO_2	4-CH_3		38[e]

Reagents and conditions: arylbromide (0.5 mmol), arylboronic acid (0.6 mmol), K_2CO_3 (0.6 mmol), Pd/La_2O_3 **1** (26.6 mg, 1 mol%), 1.5 mL ethanol, 0.5 mL water, 25 °C (unless otherwise stated)

[a] Isolated yield

[b] 1-Naphthylboronic acid

[c] 5-Bromopyrimidine

[d] Reaction run at 60 °C

[e] GC yield

Pd/La_2O_3 samples. The first one was prepared with a much lower metal loading (nominal 0.5 wt% Pd), the second one was obtained by reducing catalyst **1** at 573 K for 3 h under a stream of H_2. A very slow reaction rate was observed using nominal 0.5 wt% Pd (0.025 mol% Pd with respect to 1-bromo-4-nitrobenzene), see entry 2 in Table 3. In fact, the reaction was completed (yield >99 %) only after 7 h. Thus, the lower the noble metal loading on the REO surface, the lower the release of Pd^{2+} ions in solution. Consistently, the H_2-reduced Pd/La_2O_3 sample also showed a very low catalytic activity due to the prevailing presence of Pd(0) on the surface of the support [25], see entry 3 in Table 3.

The higher tendency of Pd^{2+} to enter in solution in the case of Pd/La_2O_3 **1** is also confirmed by the rapid deactivation of this precatalyst following recycling. Thus, only 5.4 % yield of the coupling product was obtained upon the fourth reuse of **1.** Not surprisingly, the recovered catalyst showed only 0.04 % residual palladium, as checked by ICP elemental analysis. Conversely, catalyst Pd/CeO_2 **2** showed better reusability, as almost quantitative formation of the coupling product (GC yield 97.3 %) was detected upon the fourth reuse. In this case, the ICP analysis of the recovered catalyst showed that the Pd content was still high (0.58 %).

Suitably designed experiments have been carried out in order to assess the Pd content in solution during catalysis, at the end of the reaction, and in the isolated organic product. In the coupling reaction between 1-bromo-4-

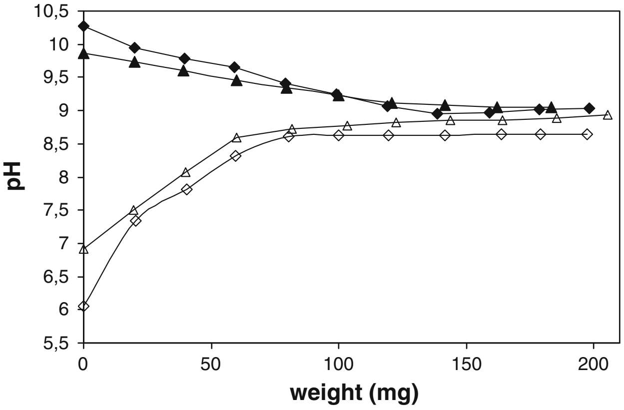


Fig. 1 PZC determination of La_2O_3 by adopting the mass titration method [26]. Experimental conditions: water (100 mL) was thermostated at 298 K and a 0.12 M solution (0.8 mL) of $NaNO_3$ was added under stirring. The pH of the solution was adjusted to a desired starting acidic or basic value by adding drop by drop 1 M solutions of HNO_3 or NaOH. Then, a crop of REO (about 15–20 mg) was added and the mixture was left under stirring for 2 min. After this time, the pH of the suspension was measured. This procedure was repeated until the pH values reached a plateau

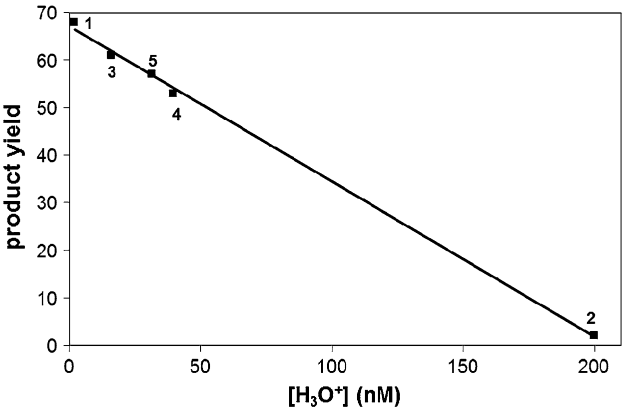


Fig. 2 Yield of 4-methyl-4′-nitro-1,1′-biphenyl (after 2 min of reaction) versus $[H_3O^+]$ concentration (10^{-PZC}) for Pd/REOs **1**–**5**. Reagents and conditions: 1-bromo-4-nitrobenzene (0.5 mmol), 4-methylphenylboronic acid (0.6 mmol), K_2CO_3 (0.6 mmol), catalyst, 1.5 mL ethanol, 0.5 mL water, T = 298 K

nitrobenzene and 1-napthylboronic acid catalyzed by Pd/La_2O_3 **1** (0.05 mol%, 26.4 µg Pd), the amount of Pd in solution was 9.5 µg (36 %) at the end of the reaction (20 min) and 13.2 µg (50 %) after 2 min, when about 65 % of the total coupling product was already formed. This findings are in line with those previously reported by Köhler and coworkers [25] using Pd/Al_2O_3 precatalyst at 60 °C, though they found a higher ratio between the two values (ca. 5 vs. 1.5). Their conclusion was that at the end of the reaction palladium was almost completely re-deposited onto the support. Reasonably, if it is assumed that 13.2 µg may be about the maximum amount of leached palladium in the first use of **1**, then it can be concluded that re-deposition onto the REO support involves less than 30 % of dissolved palladium. Interestingly, when Pd/CeO_2 **2** was used as the precatalyst, the amount of Pd in solution at the end of the reaction (ca. 4 h) was only 1.2 µg, in accordance with its much lower catalytic activity due to a reduced palladium leaching. In the case of **1**, we have also measured the amount of Pd on the isolated organic product. It was found that 1-(4-nitrophenyl)naphthalene was contaminated by 8.7 µg of Pd (of the residual 9.5 µg). Thus, more than 90 % of the noble metal detected in solution at the end of the reaction is present in the isolated crude coupling product.

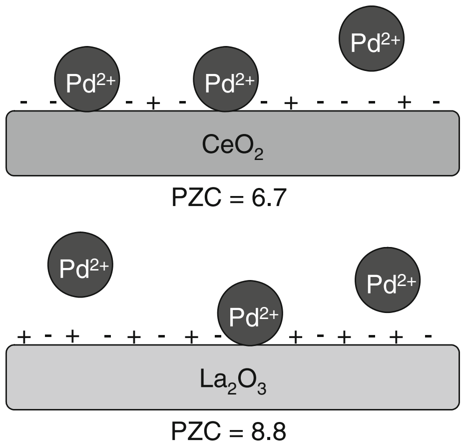


Fig. 3 Representation of adhesion and release of Pd^{2+} from the REO surface under catalytic conditions (pH ~ 10.5)

The XPS analysis of samples of **1** and **2** recovered after the fourth reuse showed a neat increase of the Pd(0)/Pd^{2+} ratio in the residual noble metal present on the surface of the REO support (Table 2). This may be seen as a further proof that the release of Pd^{2+} ions from Pd/REO is the crucial step for the formation of the actual catalyst. On the other hand, it may be due also to partial re-deposition of palladium on the surface of REO in the form of Pd(0). Furthermore, from the XPS analysis of both fresh and used precatalysts **1** and **2**, Pd/La and Pd/Ce ratios have been obtained. Very interestingly, while in the case of **2**, the Pd/Ce value remained unchanged (fresh: 0.066, used 4 times: 0.064), in the case of **1** the Pd/La ratio notably increased (fresh: 0.050, used 4 times: 0.073). Thus, albeit the amount of palladium on the La_2O_3 surface strongly decreases during repeated uses of **1**, the residual noble metal on the surface shows higher dispersion. At low temperature this may be ascribed mainly to a re-deposition process.

In a previous work from our group, it was demonstrated that a sample of Pd/CeO_2 calcinated at higher temperature (1027 instead of 827 K) gave still good performances upon the tenth reuse [14]. Thus, the higher the temperature of calcination of Pd/REO, the higher the reusability, but conversely the lower the reaction rate. Reasonably, a thermal treatment of the precatalyst at 1,027 K results in an increase of the grade of crystallinity of PdO, thus making more difficult the displacement of Pd^{2+} ions from the surface of the support.

Finally, a comparative SEM/EDXS analysis of freshly prepared and used (four times) Pd/La_2O_3 **1** did not show appreciable differences in the morphology of the two samples. However, it should be noted that this result may be due to limitation of the resolution. On the contrary, the elemental analysis confirmed the extremely low amount of palladium on the exhaust catalyst and revealed the presence of potassium (~ 10 %) on the La_2O_3 surface. This finding can be of importance regarding the potential role, if any, played by the cation of the base (K_2CO_3) on the abstraction of Pd^{2+} ions from the REO support. Studies are in due course to explore such intriguing issue.

4 Conclusions

In summary, different Pd/REO compounds have been prepared and tested for the first time as catalysts in the SM cross-coupling reaction. All of them have shown to effectively promote the coupling of aryl bromides with arylboronic acids at room temperature. Leaching of Pd^{2+} ions from the surface of Pd/REO seems to be the first step for achieving the true soluble catalyst. We have shown that a close relation does exist between the charge of the surface (measured trough the PZC value) and the extent of palladium leaching at the pH of catalysis. Thus, more positively charged is the surface (this is the case of Pd/La_2O_3), more consistent is the leaching process, and therefore higher is the reaction rate. Consistently, a much slower reaction is observed when Pd/CeO_2 is used as the catalyst, which shows the lowest PZC value within the series of Pd/REO **1**–**5**. This is confirmed by the much higher amount of palladium measured in solution for Pd/La_2O_3 with respect to Pd/CeO_2. As a consequence, prolonged recycling is possible in the case of Pd/CeO_2. On the contrary, after four reuses, almost all palladium is disappeared from the surface of more active Pd/La_2O_3. Thus, the use of Pd/CeO_2 as the precatalyst should be preferred for two reasons: (i) it can be recycled several times without decrease of activity, and (ii) the organic product is poorly contaminated by the noble metal. Such considerations are important in view of potential utilization of these systems in the production of drugs.

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