



A single-step procedure for the preparation of palladium nanoparticles and a phosphine-functionalized support as catalyst for Suzuki cross-coupling reactions

Natália J.S. Costa^a, Pedro K. Kiyohara^b, Adriano L. Monteiro^c, Yannick Coppel^{d,e}, Karine Philippot^{d,e}, Liane M. Rossi^{a,*}

^a Instituto de Química, Universidade de São Paulo, Av. Prof. Lineu Prestes 748, São Paulo 05508-000, SP, Brazil

^b Instituto de Física, Universidade de São Paulo, 05315-970 São Paulo, SP, Brazil

^c Laboratory of Molecular Catalysis, Instituto de Química, UFRGS, Av. Bento Gonçalves 9500, Porto Alegre 91501-970, CP 15003, RS, Brazil

^d CNRS, LCC (Laboratoire de Chimie de Coordination du CNRS), 205, route de Narbonne, F-31077 Toulouse, France

^e Université de Toulouse, UPS, INPT, LCC, F-31077 Toulouse, France

ARTICLE INFO

Article history:

Received 21 July 2010

Revised 29 September 2010

Accepted 29 September 2010

Available online 30 October 2010

Keywords:

Palladium

Iminophosphine

Suzuki reaction

Nanoparticle

Magnetic separation

ABSTRACT

We here report the preparation of supported palladium nanoparticles (NPs) stabilized by pendant phosphine groups by reacting a palladium complex containing the ligand 2-(diphenylphosphino)benzaldehyde with an amino-functionalized silica surface. The Pd nanocatalyst is active for Suzuki cross-coupling reaction avoiding any addition of other sources of phosphine ligands. The Pd intermediates and Pd NPs were characterized by solid-state nuclear magnetic resonance and transmission electron microscopy techniques. The synthetic method was also applied to prepare magnetically recoverable Pd NPs leading to a catalyst that could be reused for up to 10 recycles. In summary, we gathered the advantages of heterogeneous catalysis, magnetic separation and enhanced catalytic activity of palladium promoted by phosphine ligands to synthesize a new catalyst for Suzuki cross-coupling reactions. The Pd NP catalyst prepared on the phosphine-functionalized support was more active and selective than a similar Pd NP catalyst prepared on an amino-functionalized support.

© 2010 Elsevier Inc. All rights reserved.

1. Introduction

The Pd-catalyzed Suzuki cross-coupling reaction has been shown as an efficient method for the construction of C–C bonds and plays an important role in pharmaceutical industry and organic synthesis [1–3]. Various efficient Pd catalyst precursors have been developed in recent years that allow aryl halides to be effectively coupled with aryl boronic acids under mild reaction conditions [4,5]. Most catalysts for the Suzuki cross-coupling reaction make use of phosphines. Triarylphosphine was the first class of phosphine ligands used, and bulky and electron-rich phosphine ligands that can highly improve the efficiency and selectivity of such cross-coupling reactions were introduced later [1]. Iminophosphines are bidentate ligands with both hard and soft donor atoms and are expected to exhibit hemi-labile behavior when coordinated to palladium [6,7]. These ligands can be easily obtained by the reaction of *o*-(diphenylphosphino)benzaldehyde with an amine, while the steric and electronic properties of the N atom can be modulate by the amine used. The catalytic activity of amin-

ophosphino-palladium complexes in Suzuki reactions has been investigated [8–11]. As the reactions are typically catalyzed by homogeneous palladium complexes, the possibility of reuse in successive reactions is limited. Alternatively, heterogenized palladium catalysts have been developed in order to improve catalyst stability and handling during workup procedures and recycling [12]. Recycle and reuse of the catalyst were improved by using palladium catalyst based on polymer-supported dialkylphosphinobiphenyl ligands [13]. In this example, the presence of phosphine ligands on the support is the key factor for the catalytic activity achieved, since the polymer containing only palladium acetate led to only traces of products in the Suzuki reaction [13]. However, another example shows that palladium acetate impregnated in PEG 200 in the absence of any ligand is an active catalyst for Suzuki reaction [14]. Recent examples show that palladium nanoparticles (NPs) are active catalysts for cross-coupling reactions in the presence [15] or absence [16–18] of phosphine ligands.

Magnetic separation has emerged as a robust, highly efficient and fast separation tool with many advantages compared with product/catalyst isolation by means of other chemical or physical procedures, such as liquid–liquid extraction, chromatography, distillation, filtration or centrifugation. The catalyst immobilized on

* Corresponding author. Fax: +55 11 38155579.

E-mail address: lrossi@iq.usp.br (L.M. Rossi).

superparamagnetic nanomaterials can be easily separated from the products due to a strong interaction between the magnetic NPs and an external applied magnetic field, and it can be easily redispersed in the absence of the magnetic field due to the absence of “magnetic memory”. This is of special importance for washing steps (with the catalysts inside the reactor) and for redispersion of the catalyst for successive reactions. Many authors described palladium complexes and palladium NPs supported on magnetic NPs as catalysts for Suzuki reactions showing excellent catalytic activity [19–25]. As for example, a palladium(II)–phosphine complex supported on silica-coated magnetic nanoparticles [25] was reported as a highly active and recyclable catalyst for the Suzuki–Miyaura cross-coupling reaction.

In this work, we gathered the advantages of heterogeneous catalysis, magnetic separation and enhanced catalytic activity of palladium in the presence of phosphine ligands to synthesize a new catalyst for Suzuki cross-coupling reaction. In a single-step procedure, Pd NPs are formed and phosphine ligands were covalently attached to conventional and magnetic support surfaces. As a result, the Pd NPs stabilized by the phosphine pendant groups lead to an active heterogeneous catalyst system to coupling reactions.

2. Materials and methods

2.1. Methods

The transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDS) analysis were accomplished using a Philips CM 200 Microscope operating at a 200 kV. Mass spectra were obtained on a GC-MS Shimadzu 14B/QP5050A with a 30-m column DB5. Gas chromatography analyses were performed on a Shimadzu GC-2010 with a 30-m column Rtx-5. The metal was quantified by inductively coupled plasma atomic emission spectroscopy (ICP-AES) with the Spectro Ciros CCD. Nuclear magnetic resonance (NMR) experiments in solution were recorded on a Bruker DPX300 spectrometer. Solid-state NMR experiments were recorded on a Bruker Avance 400 spectrometer equipped with a 4-mm probe. Samples were spun between 8 and 12 kHz at the magic angle using ZrO₂ rotors. ¹³C{¹H} and ³¹P{¹H}-CPMAS spectra were recorded with a recycle delay of 5 s and contact times of 2 and 3 ms, respectively. All chemical shifts for ¹H and ¹³C are relative to tetramethylsilane (TMS) and ³¹P chemical shifts were referenced to an external 85% H₃PO₄ sample.

2.2. Synthesis of the catalyst support

The catalyst support comprised of silica-coated magnetic NPs was synthesized by a reverse microemulsion method, and the silica surfaces were modified with 3-(aminopropyl)-triethoxysilane (APTES) to give the amino-functionalized solid (Fe₃O₄@SiO₂-NH₂) as previously reported by us [26–30].

2.3. Synthesis of the supported catalyst

Palladium acetate (12.6 mg, 0.056 mmol) and 2-(diphenylphosphino)benzaldehyde (*o*PCHO) (32.6 mg, 0.112 mmol) were reacted in 40 mL of dry toluene under N₂ in a Schlenk flask. The solution was stirred for 30 min at room temperature and immediately used for the next step of the preparation of the supported catalyst. *o*-PCHO – ³¹P NMR (121 MHz, H₃PO₄): δ (ppm) –10.80 (s). ¹³C NMR (300 MHz, CDCl₃): δ (ppm) 191.7, 141.4, 136.2, 133.9, 132.6, 132.3, 132.1, 130.9, 129.4, 129.1, 128.9. [Pd(OAc)₂(*o*PCHO)₂]: ³¹P NMR (121 MHz, H₃PO₄): δ (ppm) 24.2 (s), 17.5 (s).

The amino-modified catalyst support Fe₃O₄@SiO₂-NH₂ (300 mg) was added to the Pd(II) complex stock solution, and the suspension was refluxed for 24 h. The resulting solid (Fe₃O₄@SiO₂-iminophosphine-Pd) was recovered magnetically, washed three times with toluene and dried at room temperature.

As a reference, another catalyst was prepared in similar conditions by reacting the amino-functionalized support (Fe₃O₄@SiO₂-NH₂) with Pd(OAc)₂ giving rise to a catalyst system without phosphine ligands.

2.4. General conditions for Suzuki–Miyaura reactions

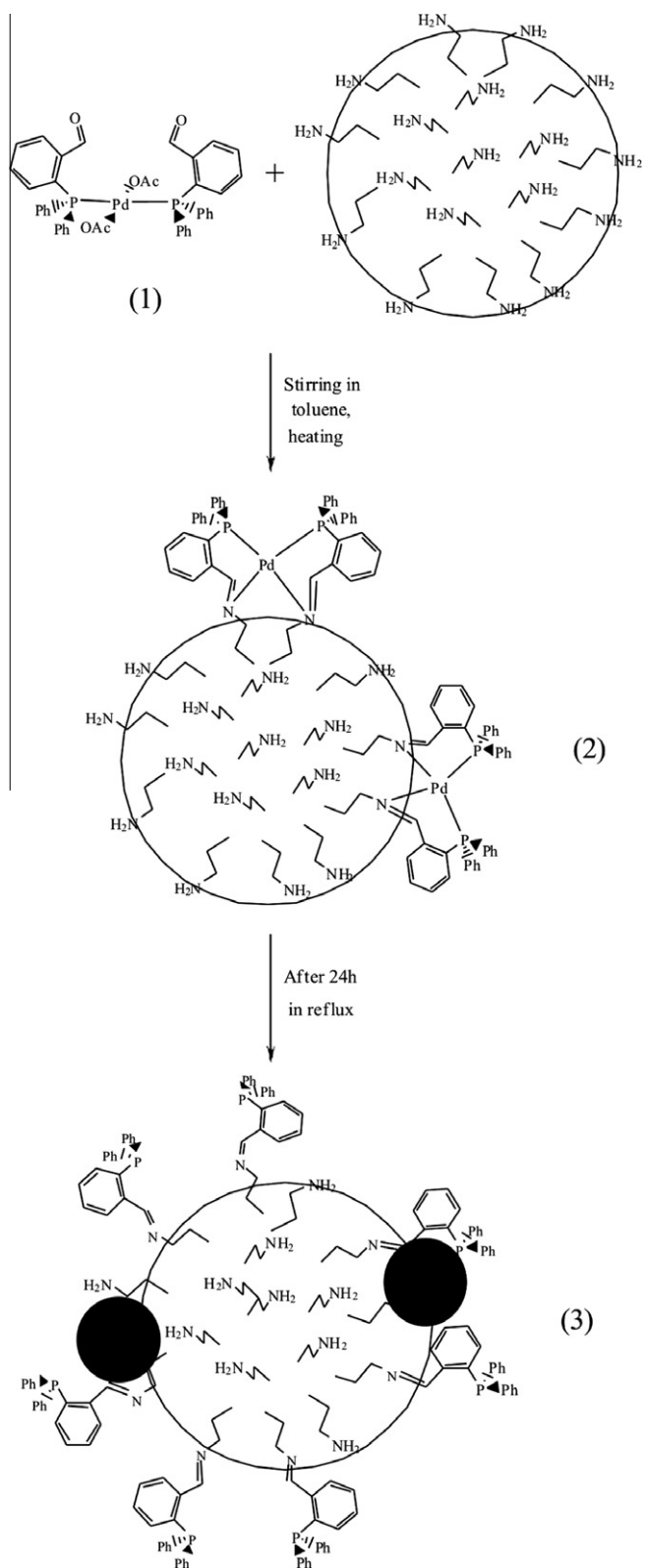
The cross-coupling reactions were carried out in a sealed Schlenk flask containing 0.2 mmol of aryl halide, 0.24 mmol of phenylboronic acid, 0.4 mmol of base, 0.001 mmol of palladium (0.5 mol%) and 3 mL of solvent. The reactions were conducted under magnetic stirring (700 rpm) for 2 h at 100 °C. The temperature was maintained using an oil bath and a hot-stirring plate connected to a digital controller (ETS-D4 IKA). The catalyst was separated with a permanent magnet, and the products were characterized by GC-MS and quantified by GC – FID.

The magnetically recovered catalyst was washed three times with ethanol and dried in vacuum. For recycling experiments, new portions of substrates and base were added. The leaching of palladium in hot solutions after removing the catalyst magnetically was measured by ICP-AES.

3. Results and discussion

3.1. Catalyst characterization

Palladium acetate was reacted with 2-(diphenylphosphino)benzaldehyde (*o*PCHO) in order to prepare the catalyst precursor [Pd(OAc)₂(*o*PCHO)₂] **1**. Palladium is known to form a square-planar complex with *o*PCHO [31], which can be characterized by the disappearance of the free ligand chemical shift at –10.8 ppm and the appearance of new positive peaks in the ³¹P NMR. The appearance of ³¹P NMR peaks at 17.5 and 24.2 ppm, which were attributed to the *trans* and *cis* complex [Pd(OAc)₂(*o*PCHO)₂], respectively [32], attested to the formation of the palladium precursor **1**. This palladium complex **1** was further used for the immobilization of a palladium–iminophosphine complex taking profit of the presence of free aldehyde groups in the coordinated ligands that can react with amino groups grafted on a silica surface through the formation of Schiff bases [33,34]. Therefore, we expect the complex [Pd(OAc)₂(*o*PCHO)₂] **1** to react with amino groups grafted on the surface of the silica support forming an iminophosphino–palladium complex **2**. However, under reflux conditions, this complex decomposes into supported Pd NPs and thus leaving the support surface functionalized with pendant phosphine groups, as shown in Scheme 1. The proposed intermediates on Scheme 1, the phosphine-functionalized support and supported Pd NPs, were studied by solid-state NMR techniques using non-magnetic silica spheres (SiO₂) synthesized by the same microemulsion methodology used for the preparation of the magnetic support. The same steps were followed to prepare the palladium catalyst **1** and intermediates **2** and **3** using this non-magnetic silica support functionalized with APTES. The amino-functionalized support (SiO₂-NH₂) and the solids containing palladium obtained before and after reflux were analyzed by ¹³C and ³¹P cross-polarization technique combined with magic angle spinning (CPMAS) solid-state NMR experiments, as shown in Figs. 1 and 2. The ¹³C{¹H} CPMAS NMR spectrum of the amino-functionalized support SiO₂-NH₂ (Fig. 1a) exhibits peaks at 10.2 (CH₂Si groups), around 23.0 ppm (CH₂ groups) and at 42.7 ppm (CH₂ group in α-position



Scheme 1. Step-by-step synthesis of the $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd catalyst.

of the NH_2 function), corresponding to the propylamine chain [35]. The weak peaks at 17.3 and 60.7 ppm may correspond to CH_3 and CH_2O groups of remaining ethoxysilane. The $^{13}\text{C}\{^1\text{H}\}$ CPMAS NMR spectrum of the solid **2** obtained after reaction with the complex $[\text{Pd}(\text{OAc})_2(\text{oPCHO})_2]$ **1** (Fig. 1b) shows an additional signal at 129.3 ppm corresponding to the presence of phenyl groups and

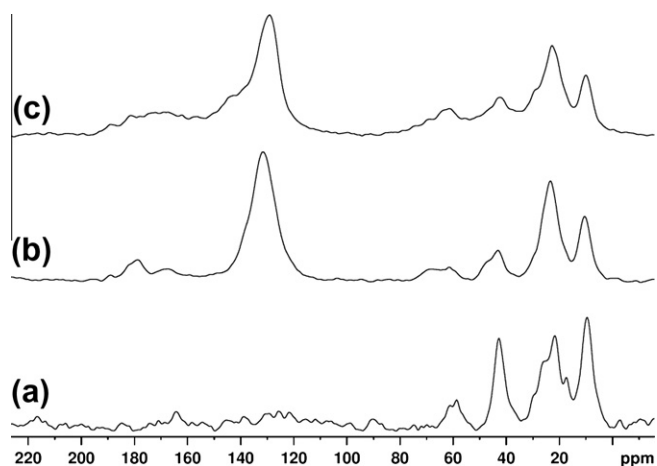


Fig. 1. ^{13}C MAS NMR spectra of (a) silica amino-functionalized ($\text{SiO}_2\text{-NH}_2$), (b) SiO_2 -iminophosphine-Pd(II) and (c) SiO_2 -iminophosphine-Pd(0).

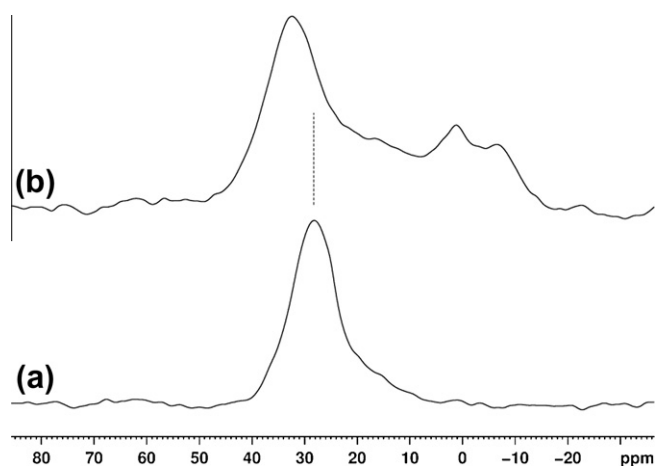


Fig. 2. ^{31}P MAS NMR spectra of (a) SiO_2 -iminophosphine-Pd(II) and (b) SiO_2 -iminophosphine-Pd(0).

two other new broad peaks at 168.3 and 178.6 ppm that could be attributed to $\text{C}=\text{N}$ bond formation with at least two different geometries or environments. Another new peak at 47.3 ppm agrees with CH_2 in α -position of the imine function. The signal corresponding to the carbonyl group of the ligand *o*-PCHO at 191.7 ppm is not present in $^{13}\text{C}\{^1\text{H}\}$ CPMAS NMR spectrum of the solid **2**, which is another strong evidence of the formation of $\text{C}=\text{N}$ bond. The $^{31}\text{P}\{^1\text{H}\}$ CPMAS NMR spectrum shown in Fig. 2a exhibits a peak at 28.8 ppm, which characterize the palladium complex **1**, since the free phosphine ligand peak appears at -10 ppm in solution ^{31}P NMR. The chemical shift at 28.8 ppm is close to the one found for related tertiary phosphine palladium complexes [35]. The $^{13}\text{C}\{^1\text{H}\}$ CPMAS NMR spectrum of the solid isolated after 24 h of reflux (Fig. 1c) exhibits the same signals than before the reflux step. However, the peaks of the iminophosphine are now significantly broader than before. This broadening could result from an increase of the structure, geometry or environment heterogeneity of the iminophosphine at the surface of the NPs in **3**. Possibly also, bulk magnetic susceptibility (BMS) effects and metal-ligand electron nuclear interactions, due to the presence of Pd NPs, could contribute to the broadening, as previously observed [36–41]. The $^{31}\text{P}\{^1\text{H}\}$ CPMAS NMR spectrum (Fig. 2b) exhibits a predominant peak at 32.6 ppm showing that the palladium complex was not totally dissociated or most probably that there is an

interaction of the phosphine ligand with the Pd NPs surface (shift of 3.8 ppm). The signals at -7.0 and 1.5 ppm could be attributed to phosphine ligands bound directly to the silica NPs with different geometries or environments. There are also minor peaks between 5 and 25 ppm that have not been identified at this time.

The preparation of the palladium catalyst supported on the magnetic support was performed following the same steps of Scheme 1. The solid support $\text{Fe}_3\text{O}_4@SiO_2-NH_2$ was reacted with complex **1** followed by reflux to give $\text{Fe}_3\text{O}_4@SiO_2$ -iminophosphine-Pd **3**. The content of Pd in the catalyst **3** was found to be 1.3 wt.% (determined by ICP-AES analysis). Similarly, a palladium catalyst was prepared without phosphine ligands using the same support and $\text{Pd}(\text{OAc})_2$ and named $\text{Fe}_3\text{O}_4@SiO_2-NH_2$ -Pd **4**. The catalyst **4** contains 0.95 wt.% of Pd (determined by ICP-AES analysis),

and it was used for comparative studies in Suzuki cross-coupling reactions.

The TEM images of $\text{Fe}_3\text{O}_4@SiO_2$ -iminophosphine-Pd **3** and $\text{Fe}_3\text{O}_4@SiO_2-NH_2$ -Pd **4** (Fig. 3) show the morphological features of the support, which is comprised of silica spheres of about 40 nm containing one or more magnetic NPs of about 10 nm inside each particle, and the formation of palladium NPs of about 3 nm on the support surface. The Pd nanoparticles mean diameters determined by size distribution histograms fitted to Gaussian function were 2.9 ± 0.6 and 3.8 ± 1.2 nm for iminophosphine and amino-functionalized supports, respectively. The smaller size of the nanoparticles formed in the presence of phosphine groups indicates an influence of the ligands on the nucleation and growth process of the palladium nanoparticles, as reported elsewhere for different amines [30].

3.2. Catalytic activity

The catalytic activity of the so-prepared catalysts was tested in Suzuki reactions of aryl halides with phenyl boronic acid. The C–C coupling reaction is more difficult when there is an electron donor group as substituent for the aryl halide. The conditions for the reaction were thus determined using the coupling of the deactivated aryl bromide 4-bromoanisole and phenylboronic acid as a model reaction. The Suzuki coupling reactions product and by-products were depicted in Table 1. In a typical Suzuki experiment, 0.2 mmol of the aryl bromide was taken in 3 mL of solvent. To this were added 1.2 equiv. of phenyl boronic acid and 3 equiv. of base. The amount of catalyst used in each reaction was 8 mg, corresponding to 0.5 mol%. After 2 h of heating, the reaction mixture was cooled down to room temperature and then a magnet was used to separate the catalyst from the reaction mixture. The products were analyzed by GC-MS. Table 1 summarizes the Suzuki coupling reaction results with 4-bromoanisole using different bases and solvents. All reactions give 100% selectivity to the biaryl coupling product, and the best catalytic conditions for the reaction were obtained at 100°C with KOH as base and toluene as solvent (Table 1, entry 3). An important feature of our catalytic system is that it does not need any additional phosphine ligand to carry out the reactions, because the pendant phosphine ligands present on the support are probably sufficient for the stability of the catalytic sites. The formation of biphenyl, a product of homocoupling of phenylboronic acid, is less than 3% of the final product.

In order to exclude any activity related to the catalyst support, the reaction of phenylboronic acid and 4-bromobenzaldehyde, a much more activated aryl halide, was carried out in the same condition of the model reaction (Table 1, entry 3), without metal catalyst, in the presence and absence of the support ($\text{Fe}_3\text{O}_4@SiO_2-NH_2$). It is worth to mention that the biaryl coupling product was not formed, but a small amount of the biphenyl product was observed in both reactions.

The catalyst separation at the end of the reaction was performed exclusively by using a permanent magnet to recover the catalyst in the reactor wall, taking profit of the composition of the catalyst support that consists of silica-coated magnetite NPs. Such a catalytic support shows excellent magnetic properties to render magnetic separation, as previously reported [28]. The material responds to an external magnetic field due to the high saturation magnetization at room temperature ($M_S = 69 \text{ emu g}^{-1}$ of Fe_3O_4 at 70 kOe) and it does not remain magnetized when the magnetic field is removed (negligible coercivity field at room temperature) [28]. These magnetic properties allow a fast separation of the catalyst from the multi-component reaction media and the easy redispersion for washing steps or reuse in successive reactions. All this procedures can be done with the great advantage of having the catalyst inside the reactor, which minimizes the

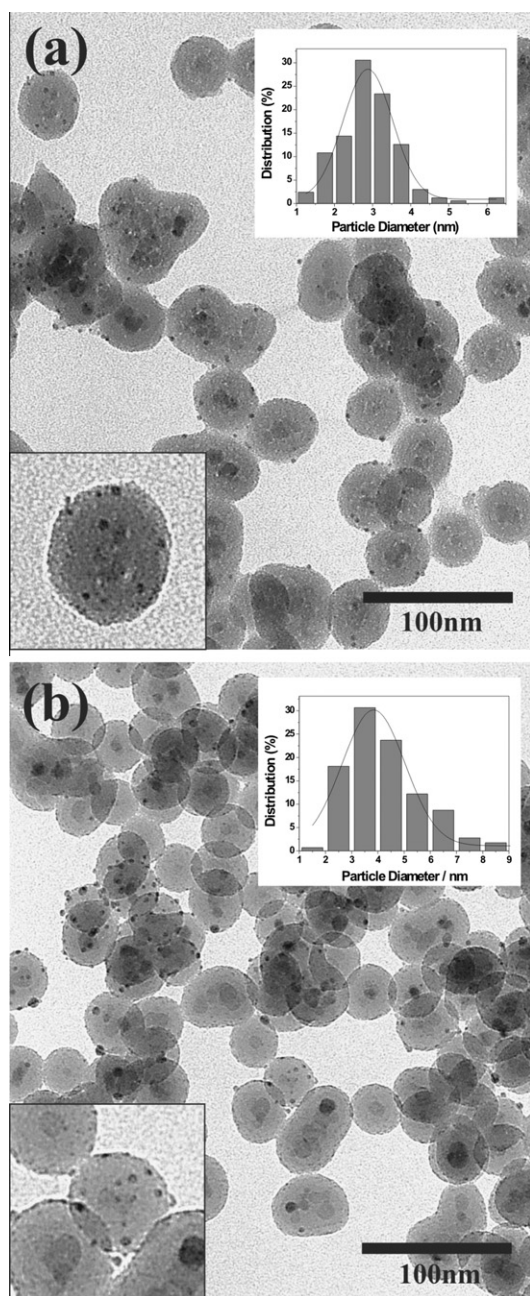
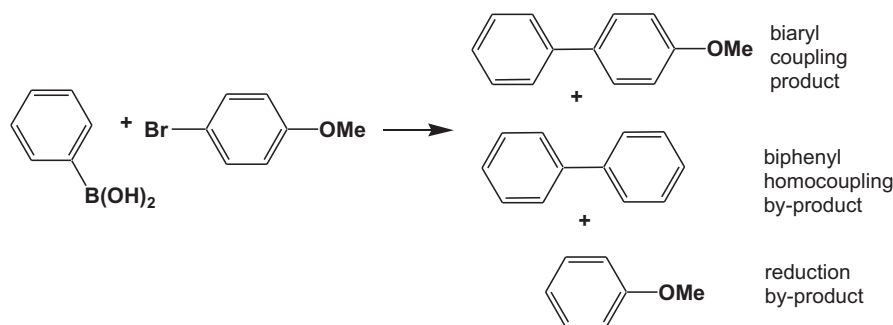


Fig. 3. TEM images of fresh Pd NP-catalysts: (a) with phosphine, $\text{Fe}_3\text{O}_4@SiO_2$ -iminophosphine-Pd, and (b) without phosphine, $\text{Fe}_3\text{O}_4@SiO_2-NH_2$ -Pd. Inset: histograms illustrating the Pd nanoparticle size distribution.

Table 1
Suzuki cross-coupling reactions catalyzed by $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd **3**.



Entry	Temp. (°C)	Base	Solvent	Biaryl coupling product ^b (%)	Biphenyl homocoupling product ^c (%)
1	100	KOH	DMF	5	1
2	100	KOH	Dioxane	97	2
3	100	KOH	Toluene	>99	0
4	100	Et_3N	Toluene	0	0
5	100	Na_2CO_3	Toluene	3	0
6	100	K_2CO_3	Toluene	39	0
7	80	KOH	Toluene	48	3
8	60	KOH	Toluene	13	1

^a Reaction conditions: 0.2 mmol of 4-bromoanisole, 0.24 mmol of phenylboronic acid, 0.5 mol% of $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd catalyst (8 mg, 1 μmol of Pd), 0.4 mmol of base and 3 mL of solvent in inert atmosphere, 2 h. No reduction by-products were observed.

^b 100% selectivity with respect to 4-bromoanisole.

^c Based on the initial amount of phenylboronic acid.

Table 2
Recyclability of the Pd catalysts in Suzuki reaction^a.

Catalyst (0.5 mol%)	Conv. (%)	Biphenyl ^b (%)	Selectivity to anisole ^c (%)	Selectivity to biaryl ^c (%)
<i>Fe₃O₄@SiO₂-iminophosphine-Pd</i>				
1	>99	0	0	100
2	>99	0	0	100
3	69	1	0	100
4	60	3	0	100
5	32	2	0	100
<i>Fe₃O₄@SiO₂-NH₂-Pd</i>				
1	88	3	4	96
2	96	8	5	95
3	44	3	0	100

^a Reaction conditions: 0.2 mmol of 4-bromoanisole, 0.24 mmol of phenylboronic acid, 0.5 mol% of catalyst (1 μmol of Pd), 0.4 mmol of KOH and 3 mL of toluene. The reaction was carried out at 100 °C for 2 h in air atmosphere.

^b Based on the initial amount of phenylboronic acid.

^c Based on the 4-bromoanisole conversion.

use of auxiliary substances, the use of solvents, catalyst losses, catalyst oxidation and the time consumption in laborious filtration procedures.

The performance of the Pd catalyst supported on phosphine-functionalized solid ($\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd **3**) was compared with another Pd catalyst supported on amino-functionalized solid ($\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -NH₂-Pd **4**) in the coupling reaction of phenylboronic acid with 4-bromoanisole. The results are summarized in Table 2. The catalyst **3** was more active and selective and could be reused five times, with >99% conversion and selectivity in the two first reactions. After the third reuse, the catalyst lost activity gradually. The catalyst **4** is less selective (the reduction product anisole was observed) and less active when compared with cata-

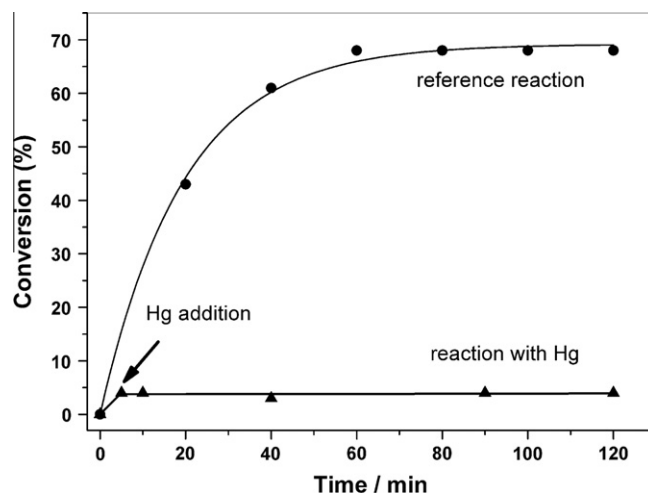


Fig. 4. Kinetic profiles for Suzuki cross-coupling reactions catalyzed by $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd **3**: (●) reference reaction and (▲) reaction with Hg (300 equiv) added after 5 min. Reaction conditions: 1 mmol of 4-bromoanisole, 1.2 mmol of phenylboronic acid, 0.5 mol% of $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd catalyst (40 mg, 5 μmol of Pd), 2.0 mmol of KOH and 15 mL of toluene. The reaction was carried out at 100 °C for 2 h in air atmosphere. No reduction product was observed.

lyst **3**. The presence of pendant phosphine groups on the catalyst support seems to play a special role in the catalytic activity of the Pd NPs, resulting in higher selectivity, conversion and reusability. Phosphine groups are softer donors and would be better stabilizers for the catalytic active palladium species than amine groups, and thus might explain why phosphine-containing catalysts outperform those without phosphine.

In palladium-catalyzed coupling reactions, it is increasingly found that leached soluble species are the true catalytic entities

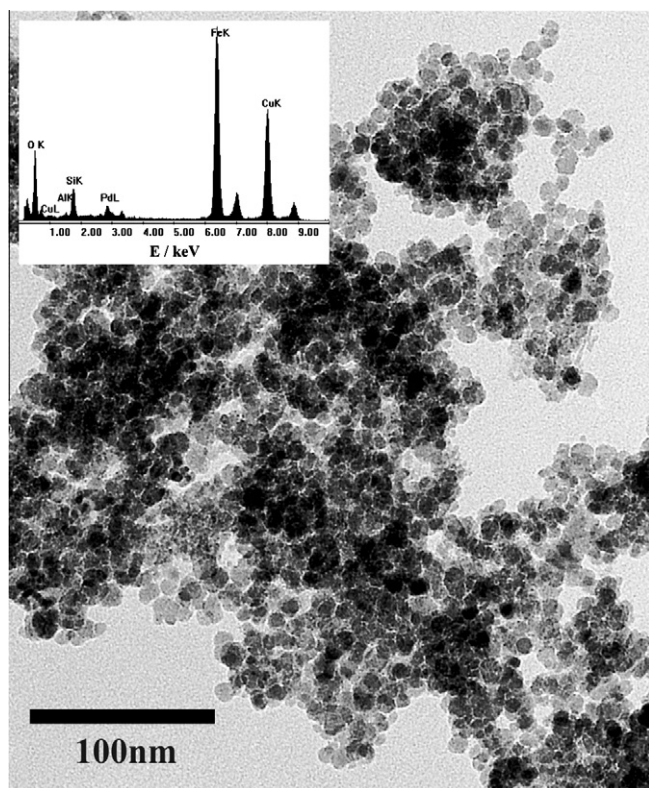


Fig. 5. TEM image of the $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd catalyst isolated after five successive Suzuki reactions. Inset: EDS analysis.

of heterogeneous catalyst [12]. Therefore, poisoning experiments with $\text{Hg}(0)$ were performed by adding 300 equiv. of mercury to a typical Suzuki reaction catalyzed by the $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd **3**. The addition of $\text{Hg}(0)$ at 5 min of reaction (4% conversion) immediately quenches the activity of catalyst **3** as shown in Fig. 4. This result is consistent with the presence of Pd(0) active species; however, the $\text{Hg}(0)$ test does not distinguish catalyses by the supported Pd NPs or leached Pd(0) species.

One of the key factors to be investigated is the possible leaching of active metal into the reaction mixture, thereby leading to catalytic activity decrease under recycling. To address this possibility, the leaching of palladium to still hot solutions of the first reaction of both catalysts isolated after magnetic separation was analyzed by ICP-AES. The results have shown that only 0.2 ppm (0.56 wt.% of the initial metal present in the support) of palladium leached from $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd **3** and undetectable amount (<0.01 ppm) of palladium leached from $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ - NH_2 Pd **4**. This result demonstrates the high affinity palladium-support, the good performance of the magnetic separation in the present catalytic system and, as a first conclusion, indicates that the catalyst deactivation under reuse should not be directly related to metal losses. Another key factor to be considered is the stability of the catalyst support when submitted to the reaction conditions, especially with the use of strong base in the Suzuki reaction. The TEM image and the corresponding EDS analysis of the catalyst **3** after five recycles, shown in Fig. 5, provided evidences of changes in the catalyst structure under recycling. The core-shell morphology of the $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ catalyst support is no longer observed in the spent catalyst. The EDS analysis confirmed that palladium is still present. Therefore, it is reasonable to conclude that excess of base etched the silica layer and, consequently, caused leaching and aggregation of the Pd NPs.

In order to avoid the silica shell etching, an alternative experimental condition was considered to minimize the contact of the

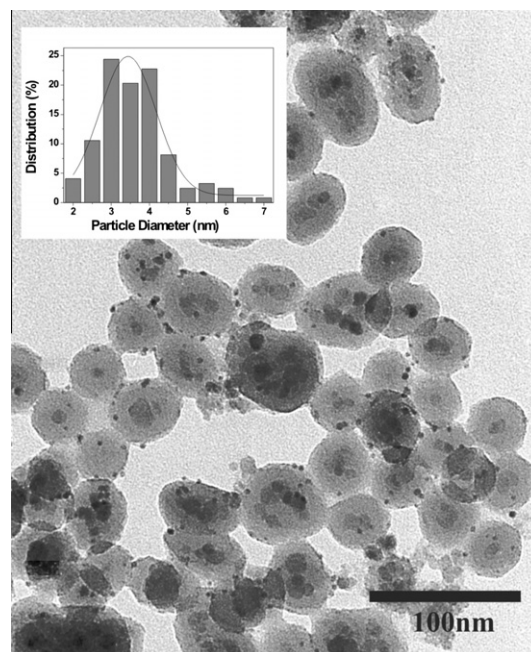


Fig. 6. TEM image of $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd catalyst isolated after ten successive Suzuki reactions using an alternative procedure (the phenylboronic acid was previously reacted with KOH and then the catalyst was added). Inset: histogram illustrating the Pd nanoparticle size distribution.

Table 3

Recyclability of the $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd **3** catalyst in Suzuki reaction using as strategy the reaction of phenylboronic acid and base before the catalyst addition to the reaction medium.^a

Cycle	Conv. (%)	Biphenyl ^b (%)	Selectivity to biaryl ^c (%)
1	56	4	100
2	63	2	100
3	49	1	100
4	52	2	100
5	55	2	100
6	57	1	100
7	47	1	100
8	34	1	100
9	42	1	100
10	25	1	100

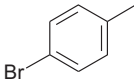
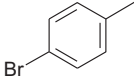
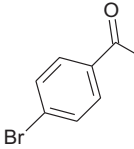
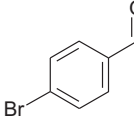
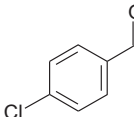
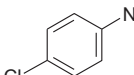
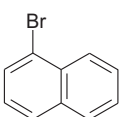
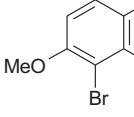
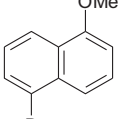
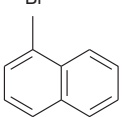
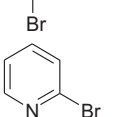
^a Reaction conditions: 0.24 mmol of phenylboronic acid, 0.24 mmol of KOH, 0.2 mmol of 4-bromoanisole, 0.5 mol% of $\text{Fe}_3\text{O}_4@/\text{SiO}_2$ -iminophosphine-Pd catalyst (8 mg, 1 μmol of Pd) and 3 mL of toluene. The reaction was carried out at 100 °C for 2 h in air atmosphere. No reduction product was observed.

^b Based on the initial amount of phenylboronic acid.

^c Based on the 4-bromoanisole conversion.

free base with the catalyst. Solutions of phenylboronic acid and KOH (1:1 M ratio) in toluene were mixed under magnetic stirring for 1 h, and then added to the reaction medium containing 4-bromoanisole and catalyst **3**. The TEM image shown in Fig. 6 confirms the preservation of the support core-shell morphology and a slightly increase in the Pd nanoparticles size to 3.4 ± 0.7 nm in the spent catalyst. The catalytic performance of catalyst **3** using this alternative method in successive Suzuki reactions is reported in Table 3. The improved stability of the catalyst **3** allowed ten successive recycles, while keeping similar conversion and selectivity for seven successive runs. The Pd leaching in the recycling process is negligible (0.04 ppm, which corresponds to only 0.1 wt.% of the initial metal present in the support). The small amount of biphenyl observed in the product distribution in Table 3 is related to the reaction temperature and the presence of the Pd catalyst, since

Table 4
Selected examples for the Suzuki cross-coupling reaction with phenylboronic acid catalyzed by $\text{Fe}_3\text{O}_4@\text{SiO}_2$ -iminophosphine-Pd **3**^a.

Entry	Substrate	Conv. (%)	Biphenyl ^c (%)	Selectivity to biaryl ^d (%)
1		70	1	100
2 ^b		54	3	100
3 ^b		93	3	100
4 ^b		>99	–	100
5		0	–	–
6		0	–	–
7		>99	0.5	100
8		53	1	100
9		92	1	100
10		>99	1	100
11		22	1	100

^a Reaction conditions: 0.2 mmol of substrate, 0.24 mmol of phenylboronic acid, 0.5 mol% of $\text{Fe}_3\text{O}_4@\text{SiO}_2$ -iminophosphine-Pd catalyst (8 mg, 1 μmol of Pd), 0.4 mmol of KOH and 3 mL of toluene. The reaction was carried out at 100 °C for 2 h in inert atmosphere. No reduction product was observed.

^b Reaction carried out in air atmosphere.

^c Based on the initial amount of phenylboronic acid.

^d Based on the aryl halide conversion.

no biphenyl product was observed in the neutralization step when KOH and phenylboronic acid are reacted before addition of 4-bromoanisole.

The catalytic activity of $\text{Fe}_3\text{O}_4@\text{SiO}_2$ -iminophosphine-Pd **3** in the presence of a series of different substrates was studied (Table 4). As expected for iminophosphine ligands, good conversion and selectivity were obtained, except for aryl chlorides. The lack of reduction by-products in the reactions makes more attractive the catalyst proposed. It is important to notice that although the reac-

tion using 4-bromoanisole displays good performance in air atmosphere, for others substrates the presence of oxygen decreased the conversion rate (entry 1 and 2 of Table 4).

4. Conclusion

The complex $[\text{Pd}(\text{OAc})_2(\text{oPCHO})_2]$ reacts with amino groups grafted on a silica support to form an anchored iminophosphine-

palladium complex. Under reflux, this iminophosphine–palladium complex decomposes into supported Pd NPs leaving the support surface functionalized with pendant phosphine groups. This new heterogeneous palladium catalyst presented good activity and high selectivity in Suzuki cross-coupling reaction without the need of addition of other sources of phosphine ligands. The supported catalyst developed in this study also has the advantage to be completely recoverable with the simple application of an external magnetic field, while keeping unaltered its efficiency for a second run. Catalyst deactivation caused by silica etching and Pd NPs aggregation was observed in the successive runs. However, following an alternative method consisting in adding the base to the arylboronic acid solution before the contact with the catalyst minimizes such problems and the catalyst could be reused for up to 10 recycles, while keeping similar catalytic activity for seven successive reactions. Poisoning experiments with Hg(0) immediately quenches the activity of the PdNPs catalyst, which is consistent with the presence of Pd(0) active species.

Acknowledgments

The authors are grateful to the Brazilian agencies FAPESP, CAPES, CNPq and CNPq/INCT-Catálise for financial support and fellowships. We also thank the support from the International Cooperation Programs PICS-CNPq Brazil–France (Grant 490678/2008–4) and CAPES-COFEUCUB (Grant 695/10).

References

- [1] R. Martin, S.L. Buchwald, *Acc. Chem. Res.* 41 (2008) 1461.
- [2] A. Suzuki, *J. Organomet. Chem.* 576 (1999) 147.
- [3] N. Miyaura, *Top. Curr. Chem.* 219 (2002) 11.
- [4] S. Kotha, K. Lahiri, D. Kashinath, *Tetrahedron* 58 (2002) 9633.
- [5] F. Bellina, A. Carpita, R. Rossi, *Synthesis-Stuttgart* (2004) 2419.
- [6] Z.Q. Weng, S.H. Teo, T.S.A. Hor, *Acc. Chem. Res.* 40 (2007) 676.
- [7] M.A. Garralda, *CR Chim.* 8 (2005) 1413.
- [8] B. Crociani, S. Antonaroli, A. Marini, U. Matteoli, A. Scrivanti, *Dalton Trans.* (2006) 2698.
- [9] A. Scrivanti, M. Bertoldini, U. Matteoli, V. Beghetto, S. Antonaroli, A. Marini, B. Crociani, *J. Mol. Catal. A: Chem.* 235 (2005) 12.
- [10] A. Scrivanti, U. Matteoli, V. Beghetto, S. Antonaroli, R. Scarpelli, B. Crociani, *J. Mol. Catal. A: Chem.* 170 (2001) 51.
- [11] S.M. Nobre, A.L. Monteiro, *J. Mol. Catal. A: Chem.* 313 (2009) 65.
- [12] N.T.S. Phan, M. Van Der Sluys, C.W. Jones, *Adv. Synth. Catal.* 348 (2006) 609.
- [13] C.A. Parrish, S.L. Buchwald, *J. Org. Chem.* 66 (2001) 3820.
- [14] T.M. Razler, Y. Hsiao, F. Qian, R. Fu, R.K. Khan, W. Doubleday, *J. Org. Chem.* 74 (2009) 1381.
- [15] B. Tamami, S. Ghasemi, *J. Mol. Catal. A: Chem.* 322 (2010) 98.
- [16] T. Borkowski, A.M. Trzeciak, W. Bukowski, A. Bukowska, W. Tylus, L. Kepinski, *App. Catal. A: Gen.* 378 (2010).
- [17] S. Ogaasawara, S. Kato, *J. Am. Chem. Soc.* 132 (2010) 4608.
- [18] S. Fujii, S. Matsuzawa, Y. Nakamura, A. Ohtaka, T. Teratani, K. Akamatsu, T. Tsuruoka, H. Nawafune, *Langmuir* 26 (9) (2010) 6230.
- [19] A. Taber, J.B. Kirn, J.Y. Jung, W.S. Ahn, M.J. Jin, *Synlett* (2009) 2477.
- [20] G.H. Lv, W.P. Mai, R. Jin, L.X. Gao, *Synlett* (2008) 1418.
- [21] A.J. Amali, R.K. Rana, *Green Chem.* 11 (2009) 1781.
- [22] U. Laska, C.G. Frost, G.J. Price, P.K. Plucinski, *J. Catal.* 268 (2009) 318.
- [23] D. Rosario-Amorin, X. Wang, M. Gaboyard, R. Clérac, S. Nlate, K. Heuzé, *Chem. – Eur. J.* 15 (2009) 12636.
- [24] D. Yuan, Q. Zhang, J. Dou, *Catal. Commun.* 11 (2010) 606.
- [25] S. Shylesh, L. Wang, W.R. Thiel, *Adv. Synth. Catal.* 352 (2010) 425.
- [26] M.J. Jacinto, P.K. Kiyohara, S.H. Masunaga, R.F. Jardim, L.M. Rossi, *Appl. Catal. A: Gen.* 338 (2008).
- [27] M.J. Jacinto, R. Landers, L.M. Rossi, *Catal. Commun.* 10 (2009) 1971.
- [28] M.J. Jacinto, O. Santos, R.F. Jardim, R. Landers, L.M. Rossi, *Appl. Catal. A: Gen.* 360 (2009).
- [29] M.J. Jacinto, O. Santos, R. Landers, P.K. Kiyohara, L.M. Rossi, *Appl. Catal. B: Environ.* 90 (2009).
- [30] L.M. Rossi, I.M. Nangoi, N.J.S. Costa, *Inorg. Chem.* 48 (2009) 4640.
- [31] H. Mahalakshmi, P.P. Phadnis, V.K. Jain, E.R.T. Tiekink, *Indian J. Chem. Sect. A: Inorg., Bio-inorg., Phys., Theor., Anal. Chem.* 43 (2004) 2287.
- [32] J.J.M. de Pater, B.J. Deelman, C.J. Elsevier, G. van Koten, *J. Mol. Catal. A: Chem.* 258 (2006) 334.
- [33] A. Scrivanti, U. Matteoli, V. Beghetto, S. Antonaroli, B. Crociani, *Tetrahedron* 58 (2002) 6881.
- [34] S. Antonaroli, B. Crociani, *J. Organomet. Chem.* 560 (1998) 137.
- [35] R.A. Komoroski, A.J. Magistro, P.P. Nicholas, *Inorg. Chem.* 25 (1986) 3917.
- [36] R.H. Terrill, T.A. Postlethwaite, C.H. Chen, C.D. Poon, A. Terzis, A. Chen, J.E. Hutchison, M.R. Clark, G. Wignall, J.D. Londono, R. Superfine, M. Falvo, C.S. Johnson Jr., E.T. Samulski, R.W. Murray, *J. Am. Chem. Soc.* 117 (1995) 12537.
- [37] A. Badia, W. Gao, S. Singh, L. Demers, L. Cuccia, L. Reven, *Langmuir* 12 (1996) 1262.
- [38] A. Badia, L. Cuccia, L. Demers, F. Morin, R.B. Lennox, *J. Am. Chem. Soc.* 119 (1997) 2682.
- [39] M.J. Hostetler, J.E. Wingate, C.J. Zhong, J.E. Harris, R.W. Vachet, M.R. Clark, J.D. Londono, S.J. Green, J.J. Stokes, G.D. Wignall, G.L. Glish, M.D. Porter, N.D. Evans, R.W. Murray, *Langmuir* 14 (1998) 17.
- [40] C. Pan, K. Pelzer, K. Philippot, B. Chaudret, F. Dassenoy, P. Lecante, M.J. Casanove, *J. Am. Chem. Soc.* 123 (2001) 7584.
- [41] E. Ramirez, S. Jansat, K. Philippot, P. Lecante, M. Gomez, A.M. Masdeu-Bulto, B. Chaudret, *J. Organomet. Chem.* 689 (2004) 4601.