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# Poly(amidoamine)-Dendrimer-Stabilized Pd(0) Nanoparticles as a Catalyst for the Suzuki Reaction

Michael Pittelkow,<sup>†</sup> Kasper Moth-Poulsen,<sup>†,‡</sup>  
Ulrik Boas,<sup>§</sup> and Jørn B. Christensen<sup>\*,†</sup>

Chemical Laboratory II, University of Copenhagen,  
Universitetsparken 5, DK-2100 Copenhagen, Denmark,  
The Nano-Science Center, University of Copenhagen,  
Universitetsparken 5, DK-2100 Copenhagen, Denmark, and  
The Danish Veterinary Institute,  
Bülowsvej 27, DK-1790 Copenhagen, Denmark

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## Introduction

Nanoparticles and polymer-stabilized nanoobjects are promising candidates for applications in catalysis and nanotechnology.<sup>1,2</sup> An important issue when dealing with nanoparticles is to achieve protection of the particles against aggregation without disturbing the desired properties. In traditional catalysis, this is done by immobilizing the particles on a suitable inert surface. In homogeneous catalysis, this can be achieved by stabilization with micelles or vesicles made of polymers or surfactants. Common for both types of stabilization is that the possibilities for controlling or designing the microenvironment surrounding the particles are limited. A simple way to get well-defined cavities for the protection of nanoparticles is to use a well-defined macromolecule as a host. This will also allow for the design of different types of nanoenvironments and open up for an investigation of the interplay between the properties of the nanoparticle and the surrounding microenvironment. We have chosen to study dendrimers as hosts for nanoparticles from a purely synthetic point of view.

Dendrimers are highly branched, well-defined, synthetic macromolecules available in nanometer dimensions. One of the properties of dendrimers is the presence of cavities inside the molecules. This was first demonstrated with the so-called "dendritic box"<sup>3</sup> and has since been a major topic in the field of dendrimer science.<sup>4</sup>

Encapsulation of metal nanoparticles inside dendrimers was originally shown by the groups of Tomalia<sup>5</sup> and

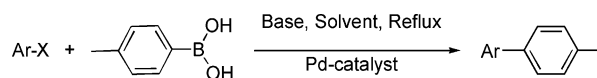


Figure 1. Suzuki cross-coupling reaction.

Crooks.<sup>6</sup> Cu(0) clusters were formed inside hydroxy-terminated poly(amidoamine) (PAMAM) dendrimers, and it was shown that the dendrimer host stabilizes the cluster against aggregation and prevents precipitation of the metal. More recently, the preparation of Pt(0) and Pd(0) dendrimer-stabilized metal clusters was reported.<sup>7</sup> These complexes have the interesting property that the metal clusters are formed inside the dendrimer as a result of the affinity of the metal to the amino groups inside the dendrimer, and the complexes are water soluble as a result of the hydroxy groups on the dendrimer surface.

The catalytic properties of dendrimer-encapsulated Pd(0) nanoparticles in homogeneous catalysis have only been subject to preliminary investigations. The reduction of olefins within the nanoparticles was demonstrated by Zhao and Crooks in aqueous solution<sup>7</sup> and by Kaneda et al. in organic solvents,<sup>8</sup> and size selectivity was observed. Previous work from our group has showed catalysis of the Heck reaction using PAMAM-dendrimer-encapsulated Pd(0) nanoparticles with a very low amount of catalyst.<sup>9</sup> The Crooks group showed fluorine-phase catalysis of the Heck reaction using a modified poly(propylene imine)-dendrimer-encapsulated Pd(0) nanoparticle.<sup>10</sup>

One of the most important palladium-catalyzed reactions is the Suzuki cross-coupling reaction between aryl halides (or triflates) and boronic acid derivatives<sup>11</sup> (Figure 1).

The classical conditions for performing the Suzuki reaction involve the use of a Pd(0) complex or a Pd(II) salt and a phosphine ligand, which stabilizes Pd(0) as PdL<sub>4</sub> or PdL<sub>3</sub> complexes.<sup>12</sup> Pd-catalyzed reactions under phosphine-free conditions is a topic of considerable interest because of both economic as well as environmental reasons. Suzuki cross-couplings with dendrimer-encapsulated Pd(0) nanoparticles have previously been reported by Li and El-Sayed.<sup>2e</sup> However, their findings on the preparation and use of small Pd(0) nanoparticles (Pd<sub>10</sub>) differ so much from our own findings on the preparation and use of Pd<sub>60</sub> nanoparticles that we report on our results.

## Experimental Section

**Measurements.** Transmission electron microscopy (TEM) pictures were obtained with a Philips CM20 at 200 kV and a magnification of 150 000×.

**Chemicals.** PAMAM G4-OH dendrimer was purchased from Aldrich Chemical Company. *p*-Tolylboronic acid was prepared

\* To whom correspondence should be addressed. E-mail: jbc@kiku.dk. Fax: +45 35320212.

<sup>†</sup> Chemical Laboratory II, University of Copenhagen.

<sup>‡</sup> The Nano-Science Center, University of Copenhagen.

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


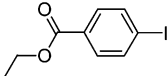
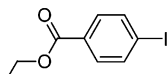
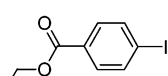

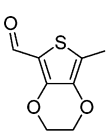
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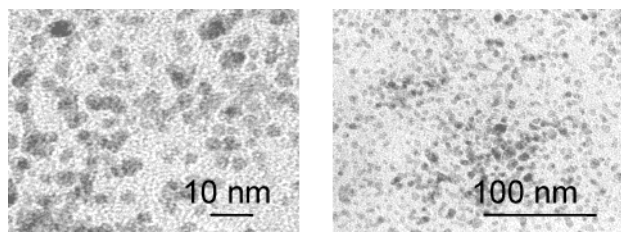
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Table 1

Entry	Ar-X	Temperature	Solvent	Time (hrs)	Yield (%) <sup>a,b</sup>	TON	TOF (hrs <sup>-1</sup> )
1		78°C	EtOH	48	≈ 0	≈ 0	≈ 0
2		78°C	EtOH	18	98	1771	98
3		153°C	DMF	48	70	1265	26
4 <sup>c</sup>		78°C	EtOH	2	99	1789	895
5 <sup>c</sup>		78°C	EtOH	2	91	1644	822
6 <sup>c</sup>		78°C	EtOH	2	80	1446	723
7		78°C	EtOH	2	92	1663	831
8		78°C	EtOH	2	90	1807	904

<sup>a</sup> Isolated yields. <sup>b</sup> The products were identified by GC-MS, <sup>1</sup>H NMR, and their melting points. <sup>c</sup> Recycling of catalyst in a bag of dialysis tubing: entry 5, first run; entry 6, second run; and entry 7, third run.



**Figure 2.** Typical TEM images of the G4-stabilized Pd nanoparticles.

from *p*-bromotoluene following a reported procedure.<sup>13</sup> 7-Iodo-2,3-dihydro-thieno[3,4-*b*][1,4]dioxine-5-carbaldehyde was prepared from the corresponding aldehyde with NIS in acidic acid following a general procedure described earlier.<sup>14</sup> All other chemicals were purchased from commercial sources.

**Preparation of Pd<sub>60</sub> [PAMAM G4-OH] Nanoparticles.** The maximal loading of a PAMAM G4-OH terminated dendrimer with respect to Pd<sup>2+</sup> ions had been established in connection with our earlier reported work<sup>9,15</sup> by titration of the dendrimer with an aqueous solution of PdCl<sub>4</sub><sup>2-</sup> monitored by UV–visible spectroscopy. In these experiments, however, we observed a time dependence on the observed spectra that we interpreted as due to a relatively slow ligand exchange on Pd<sup>2+</sup>. It is known that the rates of ligand exchange get lower in the series Ni<sup>2+</sup> < Pd<sup>2+</sup> < Pt<sup>2+</sup>, with Pt<sup>2+</sup> forming the most stable complexes.<sup>16</sup> Pd(0) nanoparticles were prepared according to the method reported

by Zhao and Crooks<sup>7</sup> with some modifications. A solution of PAMAM G4-OH dendrimer (1.0 g of a 10 wt % solution in methanol,  $7 \times 10^{-6}$  mol of dendrimer) was evaporated to dryness in vacuo. The resulting residue was redissolved in water (7 mL) and K<sub>2</sub>PdCl<sub>4</sub> (137 mg,  $4.2 \times 10^{-4}$  mol, 60 equiv) was added. The resulting brown solution was stirred for 30 min at room temperature. Then, a solution of NaBH<sub>4</sub> (79 mg,  $2.1 \times 10^{-3}$  mol, ~5 equiv as compared to Pd) in methanol (2 mL) was added over 10 min. This solution was stirred overnight at room temperature under a N<sub>2</sub> atmosphere. No precipitation of Pd-black was seen, however, in contrast to the report by Li and El-Sayed.<sup>2e</sup> The reaction mixture was evaporated in vacuo, dissolved in water (252 mL), and stored under a N<sub>2</sub> atmosphere in the dark. This gives a brown stock solution of 1.66 mM Pd<sub>60</sub> [PAMAM G4-OH] that was characterized by UV–visible spectroscopy and TEM (Figure 2) and was used in the Suzuki cross-coupling reactions.

**General Reaction Conditions for Suzuki Coupling Reactions.** To a 50-mL round-bottomed flask were added *p*-tolylboronic acid (3.3 mmol), aryl halide (3.0 mmol), K<sub>2</sub>CO<sub>3</sub> (9.0 mmol), and the solvent stated (20 mL). Then, an aqueous solution of Pd<sub>60</sub> [PAMAM G4-OH] (1.0 mL, 1.66 mM based on Pd) was added, and the reaction mixture was heated to reflux for the time stated. Water (50 mL) was added, and the mixture was extracted with CH<sub>2</sub>Cl<sub>2</sub>. The combined organic phases were evacuated in vacuo, and the product was purified (by column chromatography on silica using heptane/EtOAc mixtures) and characterized.

## Results and Discussion

The Pd(0) nanoparticles were examined by TEM, and two typical pictures are shown in Figure 2. The size of the particles was found to be  $3.2 \pm 1.0$  nm. Because the diameter of a G4 dendrimer is 4.5 nm, this points toward palladium nanoparticles stabilized by the dendrimer rather than particles encapsulated in the dendrimer. However, this does not seem to influence the stability because catalyst solutions are stable for long periods

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(>6 months). TEM pictures of an old solution (6 months) were similar to those shown in Figure 2.

The results of some of the coupling reactions between a selection of aromatic halides and *p*-tolylboronic acid in ethanol or in dimethylformamide are shown in Table 1. Aryl bromides react, but only at an elevated temperature. Aryl chlorides were found to be completely unreactive.

The turnover numbers (TONs) and the turnover frequencies (TOFs), which are defined as mol product/mol catalyst and mol product/(mol catalyst·hr), were calculated from the isolated yields, the amount of Pd used, and the reaction times.

The results shown in Table 1 are similar to the traditional catalysts with respect to substrate reactivity and yields, but the amount of Pd used is significantly smaller (0.055 mol % compared to 5–10 mol %). The catalyst can be recycled but gradually loses reactivity due to formation of Pd-black.

Our findings with respect to the preparation of the dendrimer-stabilized Pd nanoparticles differs significantly

from the report by Li and El-Sayed.<sup>2e</sup> We do not see any formation of Pd-black despite the fact that we use a larger loading of Pd in the dendrimer and we do not adjust the pH of the solution prior to reduction. The reason for this behavior is not clear for the moment and must await further investigations.

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**Supporting Information Available:** Characterization of thiophene **14**. Additional examples of Suzuki cross-couplings and references for known compounds. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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