Palladium Clusters Stabilized by Cyclodextrins Catalyze Suzuki-Miyaura Coupling Reactions in Water

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Palladium clusters were prepared by reduction of Pd (II) in the presence of α, β, or γ–cyclodextrin (CDs). TEM observations of the Pd/CD clusters have revealed that they are not spherical in shape and their sizes are distributed in the range of 2–6 nm. Any noticeable difference was not observed in the morphologies of the Pd/CD clusters regardless of the CD used. The Pd/CD clusters were found to exhibit an excellent catalytic activity toward the Suzuki-Miyaura cross–coupling reactions in water: reactions between iodophenols and phenylboronic acid in the presence of the Pd/CD clusters yielded the coupling products, hydroxybiphenyls, in good to excellent yields. It was shown that the yields depend on the CD used to stabilize the clusters, suggesting the CD molecules on the cluster surface play a significant role in the reaction. A reaction scheme is proposed on the basis of that for Pd (0)/ligand systems.
Key words: Suzuki-Miyaura reaction, palladium clusters, cyclodextrins, catalytic activity

1. INTRODUCTION

Recently, metal clusters of nanometer scale protected by a shell of ligands, polymers, or surfactants have gained much attention as a new class of catalysts [1–4]. These types of nanoclusters exhibit superior and unique catalytic properties because of their structural peculiarities of the metallic cores: most of the constituent atoms locate at the cluster surface and the coordination numbers of the surface atoms are lower than those of the bulk. Moreover, the electrons in the nanocluster behave differently from those of the bulk due to quantum size effects. Another important factor which will determine the catalytic properties is the capping of the cluster surface by ligand molecules so that the cluster is kinetically stabilized from further agglomeration. Intuitively, it is anticipated that the cluster becomes less reactive when it is strongly stabilized by ligand molecules. Thus, one can tune the catalytic activity of the nanoclusters through the control of the sizes and structures of metallic cores and their ligands.

Zerovalent metallic species have played an important role in chemical transformations in organic synthesis. Especially, palladium (0) complexes, such as $Pd(PPh_3)_4$, have been known as active catalysts for the formation of carbon–carbon bonds via coupling reactions: they can catalyze the cross–coupling reactions of aryl/alkenyl halides with boronic acids (Suzuki–Miyaura reaction [5]) or with alkenes (Heck reactions [6]). Recently, it has been reported that Pd nanoclusters also act as active catalysts for the Heck [7–12] and Suzuki reactions [8, 12–14]. Bars *et al.* showed that Pd atoms at defect sites having low coordination numbers are responsible for high catalytic activity against Heck reactions [11]. Li *et al.* found anticorrelation between the stabilities and catalytic activities of the clusters in Suzuki-Miyaura reactions [14].

In this paper, we report on the preparation of Pd clusters stabilized by a series of cyclodextrins (CDs) and their catalytic activities toward Suzuki–Miyaura reactions. Cyclodextrins are host compounds that can accommodate various guest molecules and clusters [15, 16] into their truncated cone–shaped hydrophobic cavity of a sub–nanometer. The main purpose of the present study is to investigate the effect of the CD structures on the morphologies, stabilities, and catalytic activities of the Pd clusters.

n=6, α–CD
n=7, β–CD
n=8, γ–CD

2. EXPERIMENTAL

2.1 Typical synthetic procedures of Pd/CD clusters

Colloidal dispersions of palladium clusters were synthesized by the alcohol reduction method developed by Toshima and coworkers [17] as briefly described below. Ethanol solution of $PdCl_2$ was prepared by stirring overnight a mixture of $PdCl_2$ (11.7 mg; 0.066 mmol) and ethanol (50 mL). Into 50 mL of water was dissolved 0.165 mmol of CD (α-CD, 160.5 mg; β-CD, 187.3 mg; γ-CD, 214.0 mg). Then 10 mL of both solutions were mixed and refluxed at ~95 ℃ for 1 hour under ambient atmosphere. Black suspension was finally obtained. After all the

solvent was evaporated in vacuo, 200 mL of water was added. The suspension thus obtained was stored in a refrigerator (~5 ℃) for a day, resulting in the formation of black precipitate. After the top layer of the liquid containing excess amount of CD was removed carefully, the black precipitate was again dispersed into ~5 mL of water. All the chemicals were commercially available and used without further purification. The water used in the preparation was of Milli–Q grade with specific resistance above 18 MΩ·cm.

2.2 Characterization of Pd/CD clusters

The specimens for TEM examination were prepared by dropping 20 μL of the hydrosol onto carbon-coated collodion films supported on copper grids. TEM images of the Pd clusters were observed by using a JEM4000FX apparatus operated at an acceleration voltage of 300 or 400 kV.

2.3 Catalytic properties of Pd/CD clusters

The coupling reactions between iodophenols and phenylboronic acid were performed in the presence of the Pd/CD clusters. 0.66 mol% of the Pd/CD clusters were dispersed in aqueous solution (50 mL) of K_2CO_3 (3 mmol) followed by addition of iodophenol (1 mmol) and phenylboronic acid (1 mmol). After stirring for 48 h at room temperature [18], the reaction was quenched by 2 M HCl to precipitate white solids. The solids were collected by filtration and identified by chromatographically.

3. RESULTS AND DISCUSSION

3.1 Structures of Pd /CD clusters

Figure 1 shows a typical high-resolution TEM photograph of the Pd clusters prepared by using γ-CD. The image shows that most of the Pd clusters are non-spherical in shape. The sizes of the clusters are distributed in the range of 2–6 nm, although a quantitative estimation is difficult to be made because

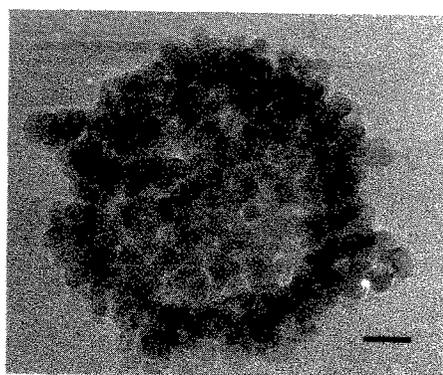of their non–spherical shapes and overlapping of their images. A closer examination of the HRTEM picture revealed that some of the clusters had the [111] lattice fringes showing their crystallinity. The stabilization by α- or β-CD did not lead to any noticeable difference in the morphologies of the Pd clusters as far as TEM measurements were concerned. Also the relative concentration of CD and Pd ions did not affect the size distributions of the resulting clusters. As in the case of Rh/CD clusters [16], the CD molecules are presumably adsorbed onto the Pd cluster surface due to hydrophobic interaction between the internal cavities of CD and the cluster surface. Since the clusters of our present concern are too large (2–6 nm) to be accommodated into an internal cavity of a single CD molecule, a number of CD molecules are involved in the stabilization of a single cluster. Namely, the Pd cluster is encapsulated as a guest into the hydrophobic space made by several CDs.

Another noticeable feature derived from the TEM images is that the individual clusters aggregate into circular shape (Fig. 2). The average diameter of the aggregates of Pd/γ-CD was determined to be 55 nm with a standard deviation of 20 nm (see inset of Fig. 2). The contrast of the aggregate was higher at the rim than the center, suggesting that the aggregate has a hollow structure. The spherical hollow structure of the aggregate was further confirmed by the following
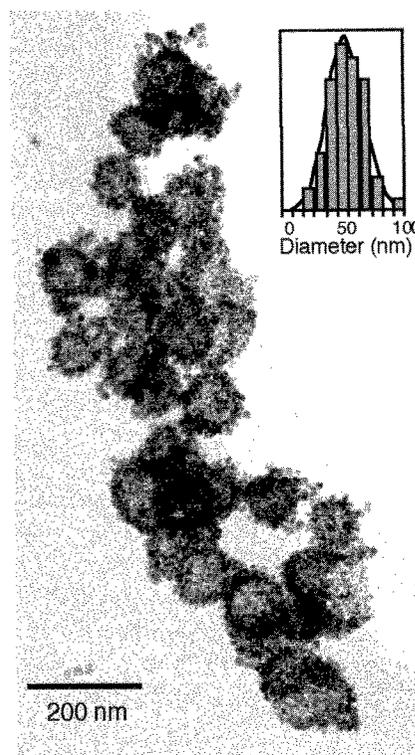

Fig. 1. HRTEM image of Pd/γ–CD clusters. The bar in the figure represents 10 nm.

Fig. 2. TEM image of Pd/γ–CD clusters. Histogram shows the size distribution of the cluster aggregates.

observations: 1) TEM images of the individual aggregates were observed while changing the tilt angle of the sample with respect to the electron beam.   When the angle was in the range of $\pm 30°$, the central parts of the aggregates were always less clear than their edges. 2) SEM images showed that the aggregates scattered electrons more from their edges than their centers. 3) AFM measurements showed that the height distribution of each aggregate exhibited maximum at the central part of the sphere.   The spherical hollow structure of the cluster assemblies described above is in sharp contrast with that of thiol–passivated Pd clusters: spherical (cuboctahedral) clusters, of which average diameter is 3.1 ± 0.6 nm, self-assemble into two-dimensional cross-linked structures [19].   We believe from the low dipersibility of the Pd/CD clusters into solvents that these aggregates are present in the liquid phase rather than formed on the TEM grids during the dry up process of the solvent: the Pd/CD clusters can be dispersed as fine suspensions in polar solvents, such as water, methanol, and DMSO, but precipitate in a day.   However, the detailed mechanism of the coagulation of the Pd/CD clusters into spherical hollow structures is unclear at present.

3.2 Catalytic activities of Pd/CD clusters for Suzuki–Miyaura reactions

We have conducted the Suzuki–Miyaura coupling reactions of o-, m-, or p–iodophenol with phenylboronic acid in the presence of the Pd/CD clusters.   Table 1 shows the isolated yields of hydroxybiphenyls.   The yields are moderate to excellent in all the cases although the reactions are carried out at room temperature.   By considering the fact that $Pd(PPh_3)_4$ requires a reaction temperature around 80 ℃ [5, 20], the present results imply that the Pd/CD clusters are more active catalysts for the Suzuki–Miyaura reaction than the conventional palladium/phosphine complexes.   Note that the palladium black is obtained after the reactions are finished.

Table 1 Cross-coupling reactions of iodophenols and $PhB(OH)_2$ in H_2O catalyzed by Pd/CD clusters

	ortho	meta	para
α-CD	83	87	85
β-CD	75	90	77
γ-CD	64	89	84

It is well established that the catalytic cycle involving the conventional Pd (0) complexes proceeds via the following steps: oxidative addition, transmetalation and reductive elimination [5].   In the framework of this model [5], we propose a reaction scheme for Suzuki–Miyaura coupling reaction catalyzed by the Pd/CD clusters as shown in Fig. 3. Firstly palladium atom is removed from the cluster surface in the oxidative addition process to form phenylpalladium species **1**.   Then intermediate **2** is formed in the reactions of species **1** with phenylboronic, followed by elimination of palladium in the zerovalent state.   Palladium (0) species reproduced in the reductive elimination may be again attached to the surface of the Pd/CD clusters and/or aggregate to form precipitation (Pd black).
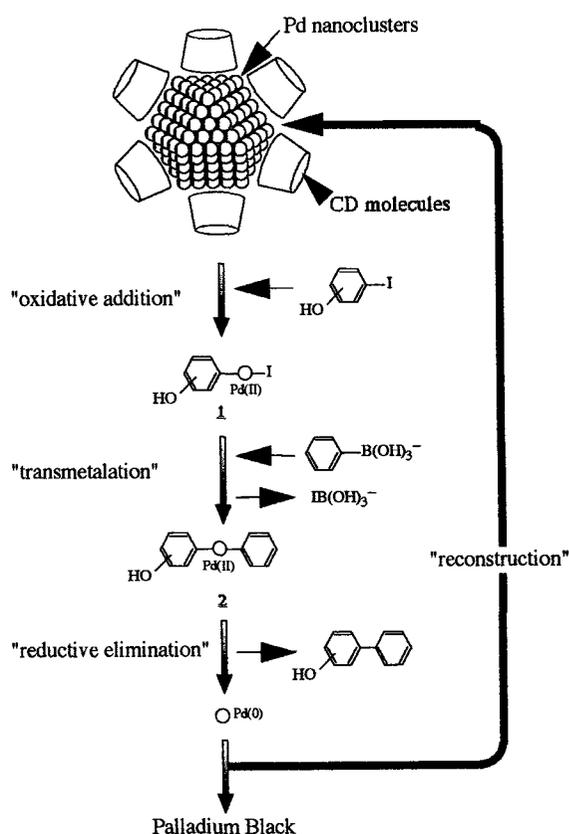

Fig. 3. Schematic representation of Suzuki–Miyaura reactions catalyzed by Pd/CD clusters.   The Pd clusters are represented as cubooctahedral structure for simplicity.

The higher catalytic activity of the Pd/CD clusters than the conventional $Pd(PPh_3)_4$ is explained in such a manner that oxidative addition of Pd proceeds more easily at the surfaces of the Pd/CD clusters.   The Pd atom can be easily removed from the cluster surface by the action of iodophenols because of the following

reason(s): 1) poor capping ability of the CDs against the cluster surface, 2) low coordination numbers of the Pd atoms on the cluster surface, 3) efficient dissociative electron transfer from the cluster surface to iodophenols,. It is also important to note that *the yields depend on the CDs used to stabilize the Pd clusters* (Table 1). This observation indicates that the CD molecules on the cluster surface participate in the reaction [16]. Studies concerning the detailed mechanisms of the reactions are now underway.

Finally, it should be noted that the Pd/CD clusters will give us many practical benefits. Namely, the Pd/CD clusters can catalyze the reaction in the absence of "toxic" phosphine ligands [12, 20, 21], in aqueous media [22], and under relatively mild conditions. Because of these factors the Pd/CD clusters are promising candidates for active and environmentally friendly catalysis.

4. SUMMARY

To summarize, we have reported the preparation of CD-stabilized Pd clusters. An analysis of the sample by TEM and SEM revealed that the Pd/CD clusters in the size range of 2–6 nm aggregate into hollow spheres with an average diameter of ~55 nm. We have demonstrated that the Pd/CD catalysts are quite active for Suzuki–Miyaura reactions in water and the catalytic activities depend on the CD molecules present at the cluster surface.

ACKNOWLEDGMENTS

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