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Air-Stable and Highly Active Dendritic Phosphine Oxide-Stabilized Palladium Nanoparticles: Preparation, Characterization and Applications in the Carbon-Carbon Bond Formation and Hydrogenation Reactions

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Abstract: Dendrimer-stabilized palladium nanoparticles were formed in the reduction of palldium bis(acetylacetonate) [Pd(acac)$_2$] in the presence of phosphine dendrimer ligands using hydrogen in tetrahydrofuran. The resulting Pd nanoparticles were characterized by TEM, ^{31}P NMR and ^{31}P MAS NMR. The results indicated that the dendritic phosphine ligands were oxidized to phosphine oxides. These dendrimer-stabilized Pd nanoparticles were demonstrated to be efficient catalysts for Suzuki and Stille coupling reactions and hydrogenations. The dendritic wedges served as a stabilizer for keeping the nanoparticles from aggregating, and as a vehicle for facilitating the separation and/or the recycling of the Pd catalyst. In the case of the Suzuki coupling reaction, these Pd nanoparticles exhibited high catalytic efficiency (TON up to 65,000) and air stability as compared with the commonly used homogeneous catalyst tetrakis(triphenylphosphine)palladium [Pd(PPh$_3$)$_4$]. In addition, the results obtained from the bulky dendritic substrate suggest that the Pd nanoparticles might act as reservoir of catalytically active species, and that the reaction is actually catalyzed by the soluble Pd(0) and/or Pd(II) species leached from the nanoparticle surface.

Keywords: hydrogenation; palladium nanoparticles; phosphine dendrimer; Stille coupling reaction; Suzuki coupling reaction

Introduction

Colloidal metal particles and metal clusters have attracted much interest because of their unique properties and potential applicability to microelectronics,[1] chemical sensing,[2] data storage,[3] and catalysts.[4] Due to their large surface-to-volume ratio and densely populated unsaturated surface coordination sites, nanosized transition metal particles have proven to exhibit much higher catalytic efficiency as compared with the corresponding bulk materials.[4] However, such metal nanoparticles are prone to formation of bulk materials of identical composition, and necessarily require stabilization to prevent aggregation and precipitation, which would sacrifice most of their desirable advantages. Recently, a number of methods has been developed to control the formation of metal nanoparticles by using surfactants,[5] organic ligands,[6,7] polymers[8] and dendrimers[4b] as stabilizers. It has been demonstrated that the size, shape, and surface properties of metal nanoparticles can be controlled by the nature of protective stabilizers.

Dendrimers are well-defined, highly branched, three-dimensional macromolecules, and behave as molecular boxes.[9] The formation of metal nanoparticles stabilized by dendrimers was originally demonstrated by the groups of Crooks, Tomalia and Esumi.[10] The nanoparticles could be encapsulated inside dendrimers, or located at the dendrimer periphery. Dendrimer-stabilized metal nanoparticles in catalysis are one of their main applications. For example, polyamidoamines (PAMAMs)-encapsulated metal particles have been demonstrated to be effective catalysts for olefin hydrogenations and C–C coupling reactions, and the dendrimers acted as both templates and porous nanoreactors.[11] In addition, different dendrimer terminal groups can be selected to provide desirable solubility in organic, aqueous, or fluorous medium, which enable us to facilitate easy separation and reuse of the nanoparticles.

Alternatively, dendrons with coordinating groups at the focal point can be used as capping ligands for the preparation and stabilization of metal nanoparticles. In contrast to the small molecule ligand-stabilized nanoparticles, limited dendritic ligands can be bound to metallic cores due to the sterically demanding dendritic structure. Therefore a substantial fraction of their surface is unpassivated and available to participate in catalytic reactions. These properties have the potential to promote the activity of the nanoparticle catalysts. However, successful examples of such metal nanoparticles reported in catalysis are rather limited.[12,13] Recently, Fox et al. reported the first example of thiol dendrimer-stabilized Pd nanoparticles using a third-generation Fréchet-type dendrimer with a disulfide group at the core.[12] These nanoparticles exhibited very high catalytic activities in Heck and Suzuki coupling reactions. However, no activity was observed for hydrogenation reactions due to the hydrogenolysis of the carbon-sulfur bonds.

More recently, in the hope of combining the desirable properties of both dendrimer[4b] and phosphine ligand[7,14] into palladium nanoparticles, we reported the synthesis and application of a new type of phosphine dendrimer-stabilized Pd nanoparticles.[13] We expected that the dendritic ligands could serve multiple functions, that is, as a stabilizer for keeping the nanoparticles from aggregating; as a ligand for adjusting the catalytic activity; and as a vehicle for facilitating the catalyst recycling. The preliminary results have demonstrated that these Pd catalysts were highly effective for Suzuki coupling reactions and hydrogenations. To our astonishment, our further study indicated that the dendritic phosphine ligands were oxidized during the formation of Pd nanoparticles, giving the dendritic phosphine oxide-stabilized metal nanoparticles.[15] These Pd nanoparticles were found to be air-stable and could be easily recycled *via* solvent precipitation. Herein, we describe the details of our research.

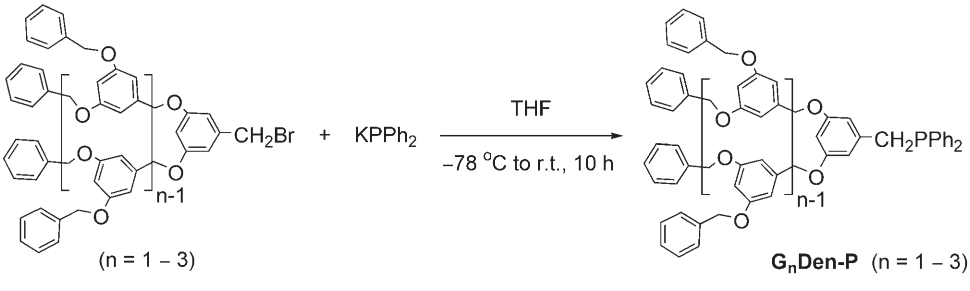
Results and Discussion

Synthesis of Dendritic Phosphine Ligands

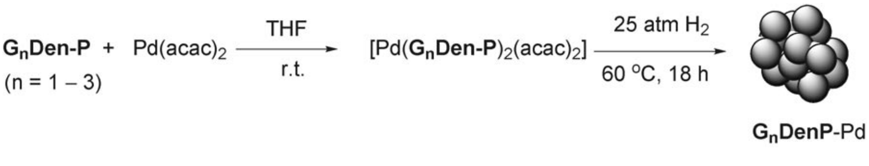
Fréchet-type polyaryl ether dendrons required for the synthesis of Pd nanoparticle-cored dendrimers were prepared by the reported convergent method.[16] Then, the three different generation phosphine ligands **G$_n$DenP** ($n=1$–3) were synthesized by reaction of the corresponding dendritic bromides with $KPPh_2$ according to the reported procedure with some modifications (Scheme 1).[17] Upon completion of the reaction, the dendritic phosphine ligands could be easily isolated *via* solvent precipitation, and further purified by flash column chromatography. Their molecular structures and purities were confirmed by ^1H and ^{31}P NMR as well as elemental analysis.

Preparation and Characterization of Dendrimer-Stabilized Palladium Nanoparticles

According to the published method,[18] palladium nanoparticles were prepared by the reduction of Pd(acac)$_2$ with hydrogen in THF in the presence of the dendritic phosphine ligand **G$_n$DenP** (Scheme 2). Different from the commonly used Brust's two-phase method, no phase-transfer agent was needed, which affirmatively contaminate the metal nanoparticles.[19] Firstly, the Pd(II) complex was formed *in situ* by reac-



Scheme 1. Synthesis of dendritic phosphine ligands.



Scheme 2. Preparation of dendritic phosphine ligand-stabilized Pd nanoparticles.

tion of Pd(acac)$_2$ with ligand **G$_n$DenP** ($n = 1$–3) in THF at room temperature under a nitrogen atmosphere. Then, the obtained complex was reduced by hydrogen (25 atm) at 60 °C in THF overnight, generating a black solution. Notably, the ligand/Pd mole ratio was found to influence the stability of the resulting nanoparticles in solution significantly. For example, in the case of a ligand/Pd ratio of 2, we did not observe any precipitation or formation of insoluble materials for several months in air. However, when the ligand/Pd ratio decreased to 1, Pd black was formed already after one week. Upon evaporation of the solvent, a black solid was isolated and could be redissolved in low polar organic solvents, such as THF, toluene, chloroform, and dichloromethane. On the other hand, all these Pd nanoparticles were insoluble in methanol, ethanol, and diethyl ether. This difference in solubility would provide a possibility for catalyst recycling by a solvent precipitation method. In addition, we attempted to purify these Pd nanoparticles by sonication in ethanol for several times. Unfortunately, some of the excess phosphine ligands could not be removed due to their very similar solubility with that of the nanoparticles. The Pd contents in the first- to the third-generation nanosized catalysts were determined by ICP-XRF as follows: **G$_1$DenP**-Pd, 6.46%; **G$_2$DenP**-Pd, 5.96%; and **G$_3$DenP**-Pd, 5.15%. We also estimated the Pd content in the catalyst **G$_3$DenP**-Pd by using an elemental analysis method. A very similar result was obtained as compared to that obtained from ICP-XRF (5.14% *vs.* 5.15% Pd).

The formation of Pd nanoparticles was confirmed by TEM (Figure 1). The diameter and size distribution of these nanosized catalysts **G$_1$DenP**-Pd, **G$_2$DenP**-Pd and **G$_3$DenP**-Pd were found to be 5.0 nm ± 0.4 nm, 4.6 nm ± 0.5 nm and 3.2 nm ± 0.5 nm, respectively. Thus, the mean diameter decreased with the increase of the generation of the dendritic ligands, and a similar trend was observed in other reported dendrimer-stabilized metal nanoparticles.[20]

We tried to further characterize these Pd nanoparticles by using ^{31}P NMR spectroscopy, and the data are summarized in Table 1. Based on the high stability of the nanoparticles solution as described above, it seems reasonable to assume that the dendritic phosphine ligands have coordinated to the surface of the Pd nanoparticles. Interestingly, the ^{31}P NMR spectra showed no signal at *ca.* −10 ppm for the excess non-coordinated ligands. Instead, a strong signal at *ca.* 28.7 ppm was observed for all the three Pd nanoparticles. For comparison, we also determined the ^{31}P NMR spectra of the **G$_3$DenP**-Pd(II) and **G$_3$DenP**-Pd(0) complexes. These data are also collected in Table 1. The comparison of the peak shifts for the Pd complexes [**G$_3$DenP**-Pd(II): 30.07 ppm; **G$_3$DenP**-Pd(0): 21.45, 22.54 ppm] and $\delta = 28.7$ ppm for the dendrimer-stabilized Pd nanoparticles suggested that there was no existence of any type of Pd complexes. Furthermore, we also characterized the Pd(0) complex and the Pd nanoparticles containing the third-generation dendrimer ligand in solid state by using ^{31}P MAS NMR. Although the NMR lines broadened obviously, the peak shifts were very close to those obtained in the solution state.

Table 1. ^{31}P NMR data of dendritic phosphine, Pd complexes, and Pd nanoparticles.

Ligand or complex	^{31}P NMR (ppm)	^{31}P MAS NMR (ppm)
G$_1$DenP	−10.30	
G$_2$DenP	−10.32	
G$_3$DenP	−10.32	−10.9
G$_1$DenP-Pd	28.64	
G$_2$DenP-Pd	28.64	
G$_3$DenP-Pd	28.70	28.1
G$_3$DenP-Pd(II)[a]	30.07	
G$_3$DenP-Pd(0)[b]	21.45, 22.54	20.4
G$_3$DenP oxide	29.00	

[a] Complex **G$_3$DenP**-Pd(II) was prepared *in situ* by mixing of Pd(acac)$_2$ with **G$_3$DenP** (2 equiv.) in THF.

[b] Complex **G$_3$DenP**-Pd(0) was prepared *in situ* by mixing of Pd(dba)$_2$ and **G$_3$DenP** (2 equiv.) in THF.

Considering the very similar chemical shifts for the Pd nanoparticles and the corresponding phosphine oxide (28.70 ppm *vs.* 29.00 ppm), we determined the ^{31}P NMR of the mixture of **G$_3$DenP**, **G$_3$DenP** oxide and **G$_3$DenP**-Pd. Surprisingly, only two peaks with shifts of $\delta = 28.36$ and −10.17 ppm were observed, indicating that the phosphine ligands might be oxidized upon nanoparticle formation. The reproducibility of this experiment, however, was ascertained even under strict exclusion of oxygen.[21] Although the oxidization mechanism is not clear at the present stage, the trace amount of water in the reaction system was considered as the source of oxygen in the phosphine oxidation reaction.[22] During our study, a similar oxidization of phosphine ligand in the preparation of Rh nanoparticles in the presence of hydrogen was reported by Kläui et al.[15b]

Suzuki Coupling Reaction

The catalytic activities of **G$_n$DenP**-Pd catalysts were first examined in the Suzuki coupling reactions. This choice was based on the fact that such a reaction provides a powerful tool for the synthesis of biaryls, which are found in many natural and synthetic products.[23,24] Furthermore, the coupling reactions are generally carried out at high temperature and in the presence of a base, which requires a catalyst with high stability.

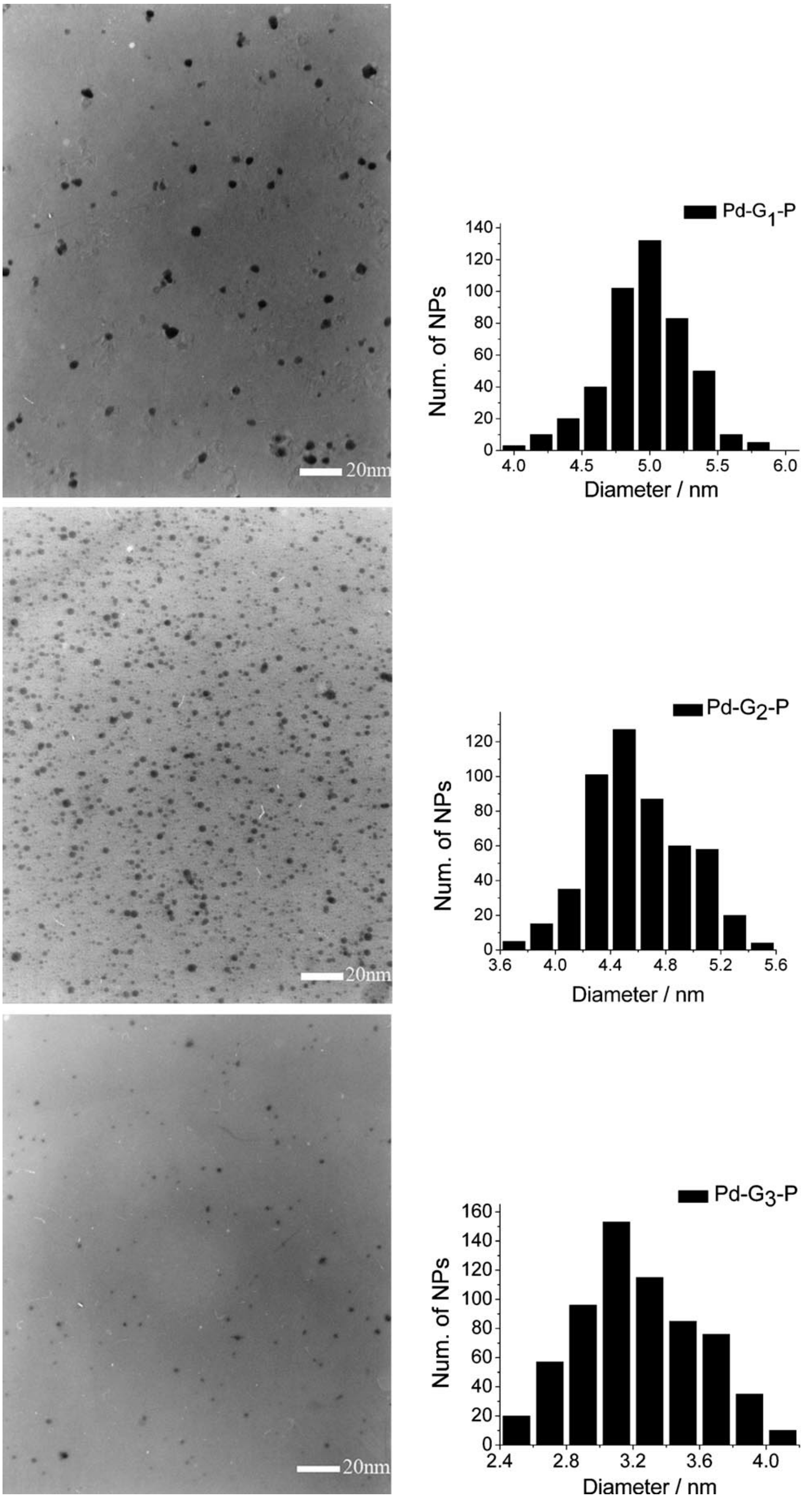
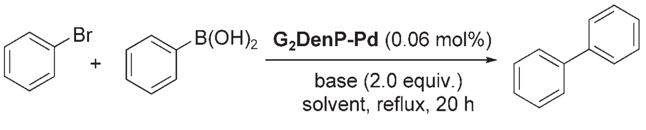


Figure 1. TEM images of **G$_n$DenP**-Pd nanoparticles.

Table 2. Effect of bases and solvents on the coupling reactions.[a]



Entry	Base	Solvent	Yield [%][b]
1	NaOAc	Toluene	<10
2	NaOAc	Toluene/H_2O (4:1, v/v)	45
3	$K_3PO_4 \cdot 7H_2O$	Toluene	94
4	Et_3N	Dioxane	<10
5	K_3PO_4 (anhydrous)	Dioxane	94
6	$K_3PO_4 \cdot 7H_2O$	Dioxane	97
7	K_2CO_3	Dioxane/H_2O (4:1, v/v)	52
8	$K_3PO_4 \cdot 7H_2O$	Dioxane/H_2O (4:1, v/v)	97
9	$K_3PO_4 \cdot 7H_2O$	THF	91
10	$K_3PO_4 \cdot 7H_2O$	DMF	92
11[c]	$K_3PO_4 \cdot 7H_2O$	Dioxane	98

[a] 1.25 mmol bromobenzene, 1.87 mmol benzylboronic acid, 2.50 mmol base, 0.06 mol% **G_2DenP**-Pd, 10 mL solvent, reflux, 20 h.

[b] Isolated yield based on bromobenzene.

[c] Under N_2 atmosphere.

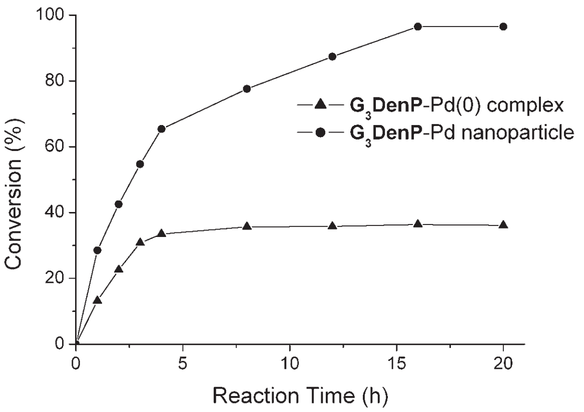


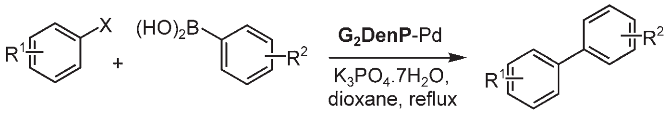
Figure 2. Plot of conversion versus reaction time for the coupling reaction of 5-bromo-1,2,3-trimethoxylbenzene with phenylboronic acid under air.

Firstly, the coupling reaction of bromobenzene with phenylboronic acid in the presence of **G_2DenP**-Pd was studied to optimize the reaction conditions. A variety of bases and solvents were screened and the experimental results are summarized in Table 2. It was found that the reaction yield was quite sensitive to the base used. When triethylamine, sodium acetate, potassium carbonate or potassium phosphate was used as the base, the reaction was carried out with low to high reaction yields (entries 1–8). Potassium phosphate was found to be the best base for this reaction. Furthermore, the reaction was also influenced by the solvent. Among the solvents investigated, dioxane was found to be the best choice of solvent for this reaction. We also noticed that a small amount of water could slightly improve the formation of the coupling products (entries 5, 6, 8 and 11). The catalytic reaction proceeded smoothly in the solvent mixture of dioxane/H_2O (4:1, v/v) in a homogeneous manner (entry 8). Notably, the reaction carried out in air also gave a comparable result to that in nitrogen under otherwise identical conditions (entries 6 and 11). This result indicated that the Pd nanoparticle catalyst was highly stable and insensitive to oxygen.

To gain more insight into the air stability of these dendrimer-stabilized nanoparticles, the time conversion courses of a representative coupling reaction catalyzed by **G_3DenP**-Pd nanoparticles and **G_3DenP**-Pd(0) complex were examined in dioxane/water (4:1, v/v) under identical reaction conditions in air (Figure 2). We chose the coupling of 5-bromo-1,2,3-trimethoxylbenzene with phenylboronic acid as model reaction, and used ^{1}H NMR to monitor the progress of the coupling reaction. At the beginning of the reaction, the **G_3DenP**-Pd(0) complex could catalyze the reaction efficiently although the rate was lower than that of the Pd nanoparticles. However, the reaction suddenly stopped at about 30% conversion after 4 h. Palladium black was observed in the reaction mixture, indicating decomposition of the Pd(0) complex. In contrast, almost quantitative conversion to coupling product was achieved for the Pd nanoparticle catalyst approximately after 15 h. It was noted that no Pd precipitate was observed under such rigorous conditions during the whole reaction. Therefore, these dendritic phosphine oxide-stabilized Pd nanoparticles have proven to be air stable, and their catalytic activity was virtually independent of the presence of air.

On the basis of the optimized reaction conditions, the coupling reactions between a range of aryl halides (I and Br) and different arylboronic acids were carried out under an air atmosphere. As shown in Table 3, no obvious difference in catalytic activity was observed when aryl iodides or aryl bromides were used in the reactions (entries 1–3). In contrast, when PAMAM-encapsulated Pd nanoparticles were used as catalyst, aryl bromides reacted only at elevated temperature (153 °C in DMF).[11g] Aryl bromides with electron-withdrawing substituents were found to give excellent to quantitative yields (entries 4–10). Reactions between phenylboronic acid and a variety of electron-rich substrates like 3-methoxy-, 4-methyl-, 2-methyl-, and 4-amino-substituted aryl bromides, also proceeded smoothly, giving the coupling products in good to excellent yields (entries 11–16). In addition, various arylboronic acids with electron-donating or

Table 3. The coupling reactions of aryl iodides and bromides with various arylboronic acids.[a]



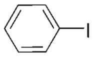
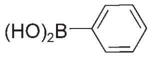
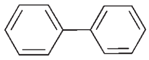
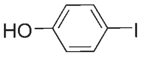
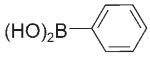
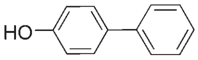
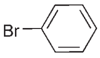
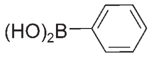
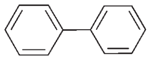
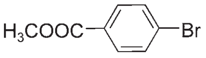
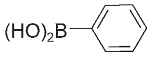
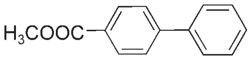
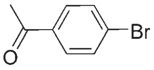
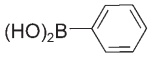
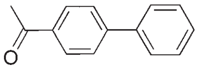
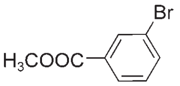
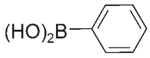
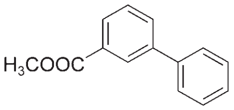
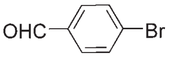
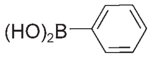
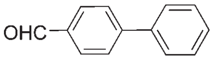
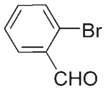
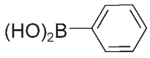
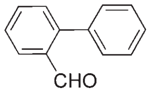
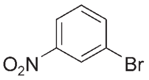
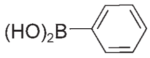
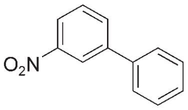
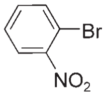
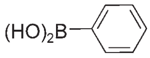
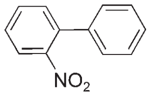
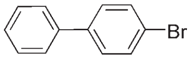
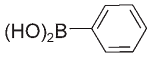
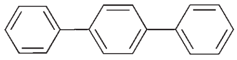
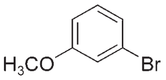
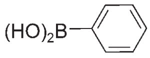
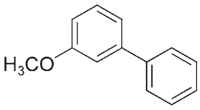
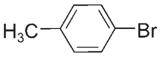
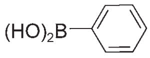
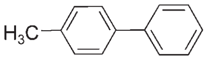
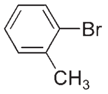
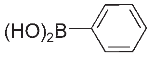
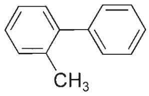
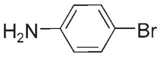
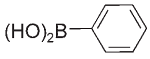
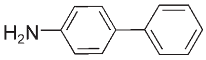
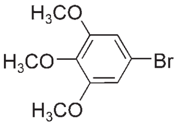
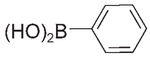
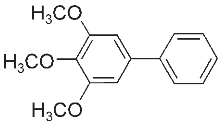
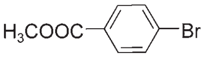
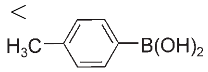
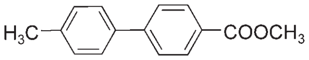
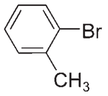
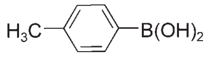
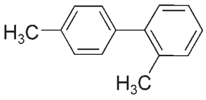
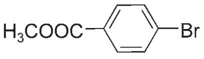
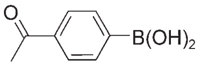
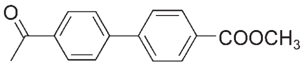
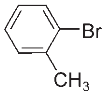
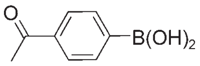
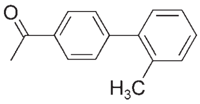
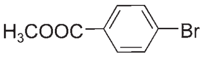
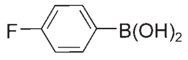
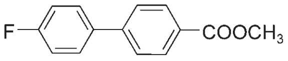
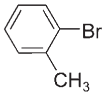
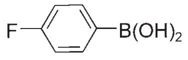
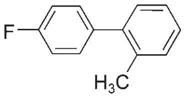
Entry	Aryl halide	Arylboronic acid	Coupling product	Yield [%][b]
1				99
2				98
3				97
4				quant.
5				99
6				99
7				99
8				97
9				99
10				99
11				98
12				95
13				98
14				96
15				94
16				96
17				quant.
18				98

Table 3. (Continued)

Entry	Aryl halide	Arylboronic acid	Coupling product	Yield [%][b]
19				92
20				90
21				88
22				86

[a] 1.25 mmol aryl halide, 1.87 mmol arylboronic acid, 2.50 mmol $K_3PO_4 \cdot 7H_2O$, 0.06 mol% **G_2DenP**-Pd, 10 mL dioxane, reflux, 20 h.

[b] Isolated yield based on aryl halide.

electron-withdrawing substituents were used in this reaction (entries 16–22). It was found that the yields decreased slightly for the electron-deficient arylboronic acids. Notably, the sterically hindered *ortho*-substituted aryl bromides also gave good to excellent yields (entries 8, 10, 14, 18, 20 and 22).

In order to further demonstrate the high efficacy of these Pd nanoparticles, the coupling reaction of bromobenzene with phenylboronic acid was used to assess the minimum amount of catalysts. When we decreased the catalyst (**G_2DenP**-Pd) loading from 0.06 mol% to 0.003 mol%, the reaction was found to proceed smoothly and gave 89% yield upon a prolonged reaction time. Notably, the third-generation catalyst **G_3DenP**-Pd was preserved under an air atmosphere for three months, and found to be very active under rather low catalyst loading (0.001 mol%, 65% yield in 96 h). Thus, the average TON reached 65,000, to our knowledge this is the highest TON obtained so far for the preformed Pd nanoparticles.[11g,24,25] In contrast, with the most commonly used catalyst $Pd(PPh_3)_4$, the reaction provided a much lower yield (15%) even under 0.5 mol% catalyst loading, and palladium black was observed from the beginning of the reaction.

To further demonstrate the general effectiveness of these nanoparticle catalysts, we extended the substrates to aryl or heteroaryl chlorides, which are considerably more challenging and readily accessible substrates.[26] As illustrated in Table 4, several deactivated or sterically hindered *ortho*-substituted aryl chlorides were employed in the **G_3DenP**-Pd catalyzed coupling reaction with boronic acids. Good yields were achieved with 2 mol% catalyst in all cases (Table 4). To our delight, the coupling reactions of pyridine-derived aryl bromides, even pyridine-derived aryl chlorides with phenylboronic acid or aryl chloride with 3-pyridineboronic acid, also proceeded smoothly with good yields (Table 5, entries 1–8). However, the rather difficult coupling reaction between 2-chloropyridine and 3-pyridineboronic acid failed (entry 9). To our knowledge, these were the best results so far obtained for the preformed polymer- and/or dendrimer-stabilized Pd nanoparticles.

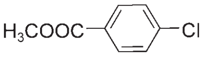
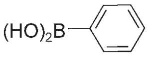
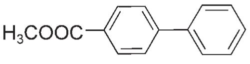
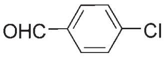
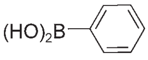
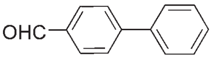
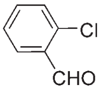
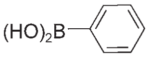
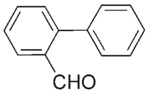
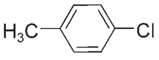
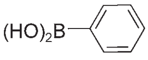
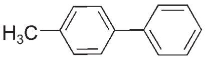
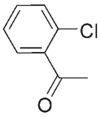
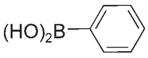
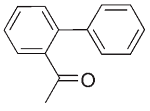
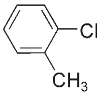
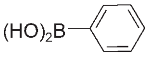
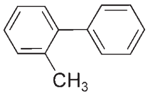
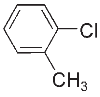
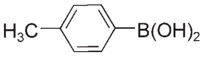
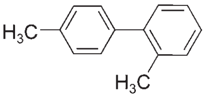
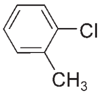
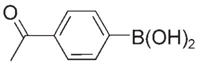
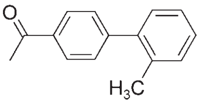
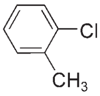
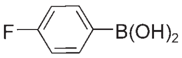
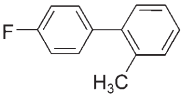
Catalyst Recycling in Suzuki Coupling Reactions

Having established the efficacy of the **G_nDenP**-Pd nanoparticles in the Suzuki coupling reactions, we then investigated their recyclability (Table 6). Although, as homogeneous catalysts, the soluble polymer- and dendrimer-stabilized noble metal nanoparticles showed unique catalytic characteristics, they still suffered from difficulties in separation and reuse. For the recycling experiment, the coupling reaction of 4-hydroxyphenyl iodide with phenylboronic acid in the presence of 0.2 mol% **G_3DenP**-Pd was chosen as standard reaction. Upon the completion of the reaction, the catalyst was quantitatively precipitated by adding a large amount of methanol, and reused for at least eight times without any loss in activity in the first four runs (>95% yield) and with reduced yields from the 5th run. High yields could be also achieved at prolonged reaction times. The leaching of palladium was measured by ICP-XRF at the 2nd and 3rd cycles, and found to be no more than 0.84% (8.1 ppm) and 0.37% (3.6 ppm), respectively.

The Role of Pd Nanoparticles in Suzuki Coupling Reaction

Although various metal nanoparticles have been applied in catalysis, the nature of the true metal species in catalytic cycles remained to be elucidated.[27] It is a rather difficult task to distinguish homogeneous,

Table 4. The coupling reactions of aryl chlorides with arylboronic acids.[a]

Entry	Aryl chloride	Arylboronic acid	Coupling product	Yield [%][b]
1				94
2				90
3				88
4				83
5				81
6				80
7				88
8				86
9				84

[a] 0.75 mmol aryl chlorides, 1.13 mmol arylboronic acid, 1.50 mmol $K_3PO_4{\cdot}7H_2O$, 2 mol% **G_3DenP**-Pd, 10 mL dioxane, reflux, 48 h.

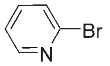
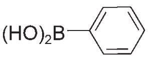
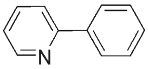
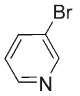
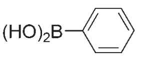
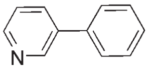
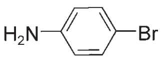
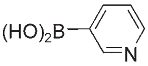
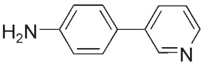
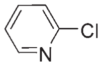
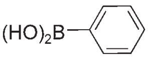
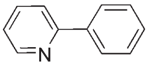
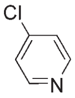
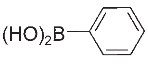
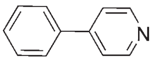
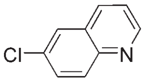
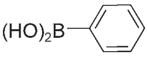
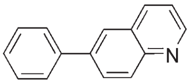
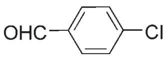
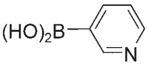
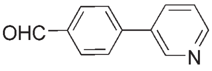
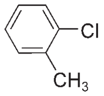
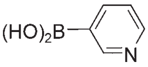
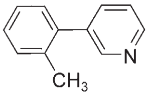
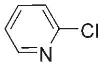
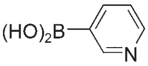
[b] Isolated yield based on aryl halide.

single metal-complex catalysts from soluble nanocluster or colloid catalysts in the study of nanocluster catalysis.[28] Recently, El-Sayed et al. systematically studied the effects of size and shape of PVP- and dendrimer-stabilized Pd nanoparticles on the catalytic Suzuki reaction.[29] The reaction was proposed to occur on the surface of the nanoparticles based on the fact that the phenylboronic acid bound to the surface before reacting with iodobenzene. On the other hand, there is increasing experimental evidence that demonstrated the soluble metal species to be the true catalyst.[30] For example, Rothenberg et al. reported a simple experiment based on exclusion of Pd nanoparticles to identify the true catalytic species in cluster-catalyzed Heck cross-couplings.[30e,f] They used a special reactor in which two compartments were separated by a nanoporous membrane that only allowed the passage of Pd atom and ions. It was found that Pd nanoparticles were not the true catalysts in C–C coupling reactions, and the catalysis was carried out by either Pd(0) atoms or Pd(II) ions that leached into the solution. Here, we attempt to elucidate the role of the Pd nanoparticles in the Suzuki reaction by performing two types of experiments as follows.

Firstly, we designed and synthesized a bulky AB_3-type dendritic aryl bromide substrate for the Suzuki coupling reaction. It seems reasonable to assume that if the catalytic reaction occurred on the surface of the Pd nanoparticles inside the 'dendritic box' formed by the dendritic ligands, the efficiency of the coupling reaction was greatly affected by the size of the dendritic substrate. The third-generation nanoparticle **G_3DenP**-Pd and the homogeneous complex $Pd(PPh_3)_4$ were used as the catalysts, respectively. Both reactions between dendritic bromobenzene and 4-acetylphenylboronic acid in the presence of 0.3 mol% catalyst proceeded smoothly under a nitrogen atmosphere (Scheme 3). Notably, the dendritic coupling product was obtained in 96% yield with **G_3DenP**-Pd, which was higher than that obtained with $Pd(PPh_3)_4$. This result indicated that the catalytic reaction should not happen inside the dendritic box completely at least.

In addition, we determined the average diameter of the third-generation Pd nanoparticles after the ninth catalytic cycle. As shown in Figure 3, the recycled pal-

Table 5. The coupling reactions of heteroaryl halides with arylboronic acids.[a]

Entry	Aryl halide	Arylboronic acid	Product	Yield [%][b]
1				89
2				92
3				85
4				82
5				84
6				90
7				90
8				86
9			-	-

[a] 0.75 mmol aryl chlorides (or heteroaryl halides), 1.13 mmol arylboronic acid, 1.50 mmol $K_3PO_4 \cdot 7H_2O$, 2 mol% **G$_3$DenP**-Pd, 10 mL dioxane, reflux, 48 h.

[b] Isolated yield based on aryl halide.

Table 6. Recovery and recycling of **G$_3$DenP**-Pd (0.2 mol%).[a]

Cycle	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
Yield [%][b]	98	95	96	97	79	94	95	94	75

[a] Reaction time: runs 1–5, 20 h; runs 6–9, 48 h.

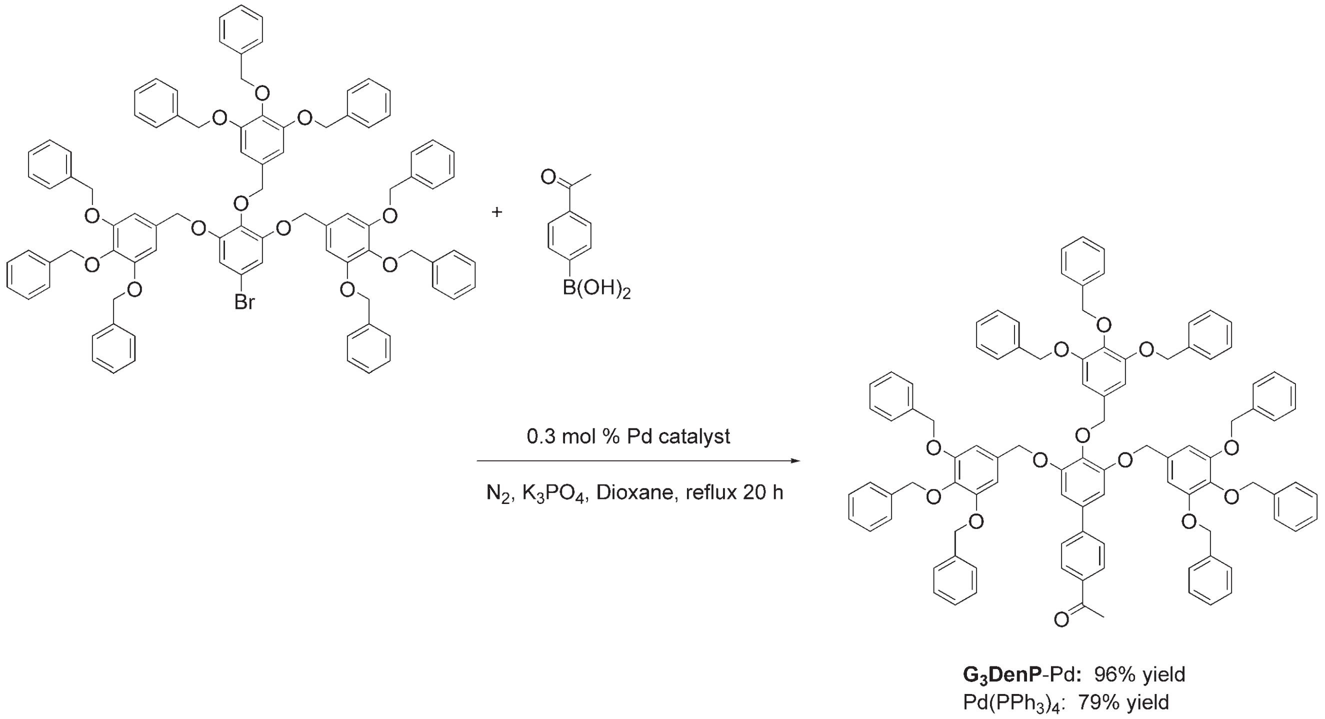
[b] Isolated yield. Purity was confirmed by ^{1}H NMR.

ladium nanoparticles displayed an irregular shape with a size distribution of 10 (±1) nm, indicating the occurrence of aggregation during the reactions. This result further indicated that the soluble Pd(0) and/or Pd(II) species leached from the nanoparticles catalyzed the coupling reaction, and fell back to the nanoparticle surface during and/or at the end of reaction.

Stille Coupling Reaction

The Stille reaction has established itself as one of the two most general selective palladium-catalyzed cross-coupling reactions along with the Suzuki cross-coupling described above. Its tolerance towards most functional groups makes the Stille coupling reaction particularly effective for transformations of highly functionalized molecules.[31] Recent developments in cross-coupling methodology allow the Stille reaction to be performed under very mild conditions,[32] and palladium complexes bearing bulky phosphane ligands, such as P(*t*-Bu)$_3$ or proazaphosphatranes, were found to be excellent catalysts for this reaction at room temperature.[33,34] However, these methods often involved the use of highly air-sensitive catalysts and/or Cu(I) salt as co-catalyst. Since our Pd nanoparticle catalysts exhibited high activity and air stability in the Suzuki coupling reactions, we thus further employed the most active **G$_3$DenP**-Pd catalyst in the Stille coupling reaction.

At the outset, the coupling of methyl 4-bromobenzoate with tributyl(phenyl)stannane in the presence of 1.5 mol% **G$_3$DenP**-Pd in air was chosen as model reaction. As fluoride additives have been reported as ef-



Scheme 3. Suzuki coupling of dendritic bromobenzene with 4-acetylphenylboronic acid.

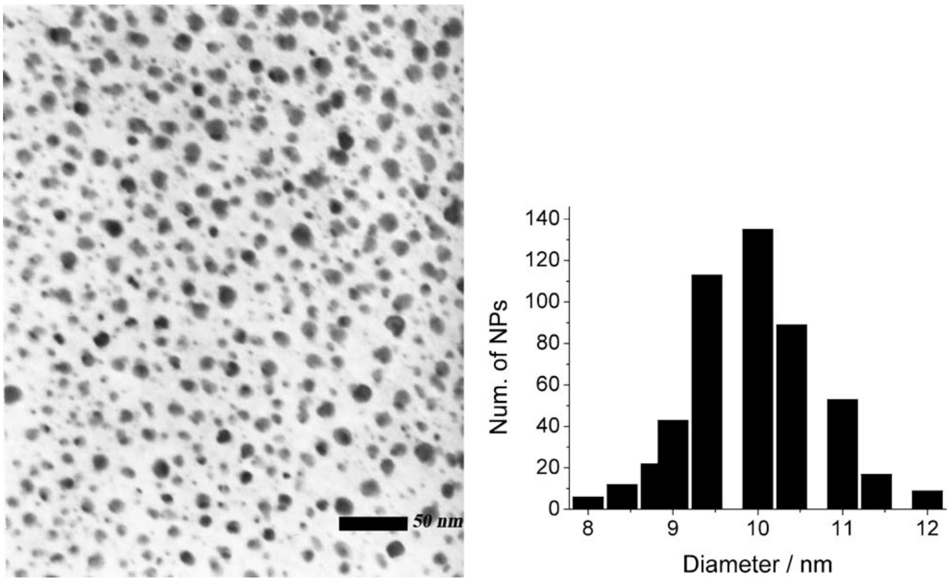
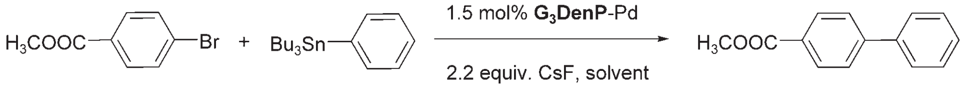


Figure 3. TEM image of **G$_3$DenP**-Pd nanoparticles after the ninth catalytic run.

fective activators for this coupling reaction,[35] CsF was selected as the base. To achieve the optimized reaction conditions, several types of organic solvents and different reaction temperature were tested. As shown in Table 7, the reactions were found to be rather sluggish at room temperature even upon the addition of CuI as cocatalyst (entries 1–3). When reaction temperature increased to 40 °C and a solvent mixture of DMF and water was used, the coupling reaction proceeded smoothly, providing excellent yield (entry 4). Notably, a small amount of water improved the formation of the coupling product greatly, and the mixture of DMF and water (10:1, v/v) was found to be the best choice of solvent for this reaction(entries 4–9).

Under the optimized reaction conditions, the Stille coupling reactions between a broad spectrum of aryl bromides and tributylphenyltin or 2-(tributylstannyl)-

Table 7. Optimization of catalytic system in the Stille coupling of methyl 4-bromobenzoate with tributyl(phenyl)stannane.[a]



Entry	Solvent	Additive	Temperature [°C]	Time [h]	Yield [%][b]
1	DMF	-	25	20	<20
2	DMF	CuI	25	20	<20
3	DMF-H_2O (10:1, v/v)	-	25	20	<20
4	DMF-H_2O (10:1, v/v)	-	40	5	98
5	DMF	-	40	5	20
6	THF	-	40	5	26
7	THF-H_2O (10:1, v/v)	-	40	5	65
8	Toluene	-	40	5	<5
9	Toluene-H_2O (10:1, v/v)	-	40	5	16

[a] 0.47 mmol 4-bromobenzoate, 0.52 mmol tributyl(phenyl)stannane, 1.5 mol% **G_3DenP**-Pd, 1.02 mmol CsF, 20 mL solvent.
[b] Isolated yield.

thiophene were carried out under an air atmosphere.[36] As shown in Table 8, all aryl bromides bearing electron-withdrawing or electron-donating substituents were found to furnish the biaryl products in good to excellent yields (entries 1–6). It was noted that the sterically hindered *ortho*-substituted aryl bromides, 2-bromo-*m*-xylene and 2-bromo-*p*-xylene, underwent the Stille reaction smoothly, giving high yields (entries 5 and 6). We also noticed that reactions with heteroatom-containing substrates proceeded smoothly, giving good to high yields (entries 7–10). Notably, under these mild reaction conditions, the cross-coupling of 4-bromophenyl 4′-chlorobenzoate with tributylphenyltin only afforded the corresponding biaryl compound without affecting the chloride group in 87% yield (entry 11).

To further extend this catalytic system to the most challenging yet readily accessible aryl chloride substrates, the high reaction temperature (110 °C) was tested. To our delight, the cross-coupling of both the activated and unactivated aryl chlorides with tributylphenyltin proceeded smoothly in the presence of 1.5 mol% **G_3DenP**-Pd under an air atmosphere (Table 9), furnishing the biaryl compounds in good to high yields. Importantly, the heteroatom-containing substrates, 2-chloropyridine and 4-chloropyridine, also gave good reaction yields (entries 5 and 6).

Hydrogenation

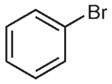
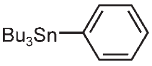
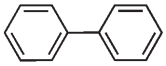
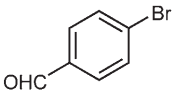
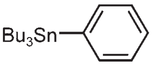
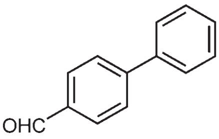
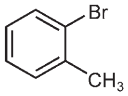
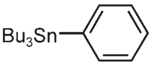
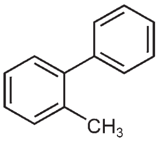
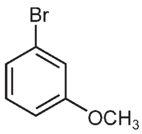
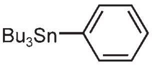
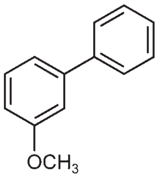
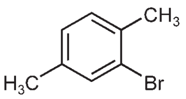
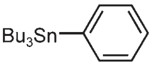
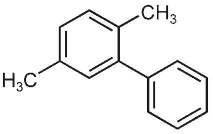
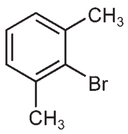
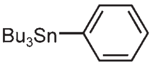
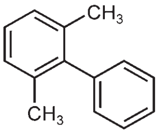
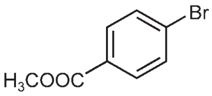
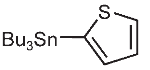
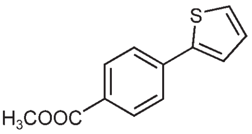
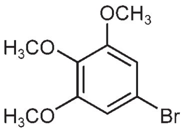
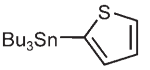
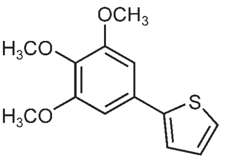
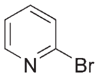
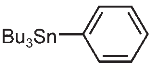
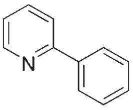
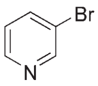
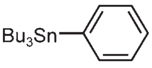
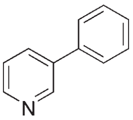
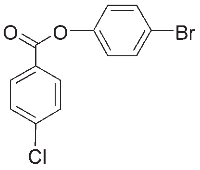
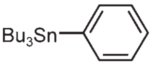
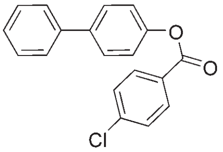
Palladium-catalyzed hydrogenation is frequently used not only in laboratories but also in industry. To further expand the catalytic scope of the dendrimer-stabilized Pd nanoparticles, we then investigated the catalytic hydrogenation of a range of unsaturated compounds. As shown in Table 10, quantitative conversions and high selectivities for all substrates studied were achieved. For example, the hydrogenation of α,β-unsaturated cyclohexanone using 0.5 mol% **G_2DenP**-Pd under 15 atm hydrogen at 60 °C for 8 h afforded cyclohexanone in excellent yield (entry 4). It was noted that the hydrogenation of imines under relatively low temperatures proceeded smoothly (entries 7 and 8). Most interestingly, unlike the commonly used heterogeneous catalyst Pd/C, the Pd nanoparticles could not cleave the benzyl substituent on the N atom. Quinoline and pyridine derivatives could also be hydrogenated to 1,2,3,4-tetrahydroquinoline and piperidine derivative quantitatively by using 2 mol% **G_3DenP**-Pd as catalyst and 25 mol% acetic acid as additive, respectively (entries 9 and 10). Notably, in all cases, hydrogenation reactions were carried out under homogeneous manner. Unlike the reported thiol dendrimer-stabilized Pd nanoparticles,[12] no palladium aggregation was observed. After the reaction was completed, the catalyst was quantitatively precipitated upon addition of a large amount of methanol. The recycled Pd catalyst, which could be redissolved in organic solvent, however, exhibited no catalytic activity.

Tandem Reaction

Finally, based on the successful applications in Suzuki coupling and hydrogenation reactions, we employed the **G_3DenP**-Pd catalyst to a tandem reaction (Scheme 4). Firstly, Suzuki coupling of 3-pyridinylboronic acid with *p*-bromodiphenyl was carried out by using 0.06 mol% catalyst in dioxane under refluxing temperature for 20 h. Upon the completion of the Suzuki coupling, the reaction mixture was then acidified with 2 equiv. acetic acid and pressurized with 40

Table 8. Stille cross coupling reaction of organotin reagents with various aryl bromides.[a]

$$\text{Ar-Br} + \text{Bu}_3\text{Sn-R} \xrightarrow[\text{2.2 equiv. CsF, DMF-H}_2\text{O (10:1), 40 °C}]{\text{1.5 mol\% } \mathbf{G_3DenP}\text{-Pd}} \text{Ar-R}$$

Entry	Aryl bromide	Organotin	Coupling product	Time [h]	Yield [%][b]
1				5	98
2				5	98
3				5	96
4				5	96
5				12	91
6				12	89
7				8	97
8				10	86
9				8	78
10				8	80
11				8	87

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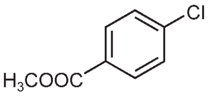
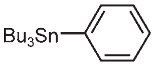
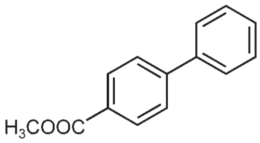
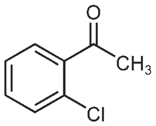
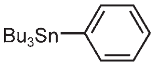
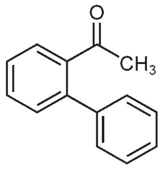
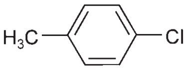
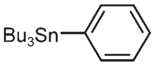
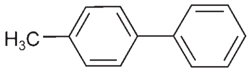
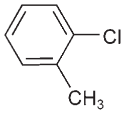
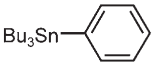
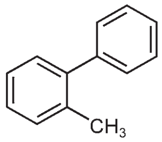
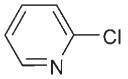
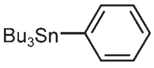
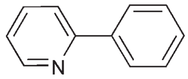
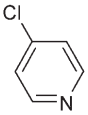
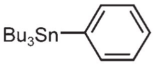
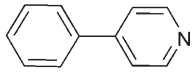
[a] 0.47 mmol aryl bromides, 0.52 mmol organotin, 1.5 mol% **G_3DenP**-Pd, 1.02 mmol CsF, 20 mL solvent, 40 °C.

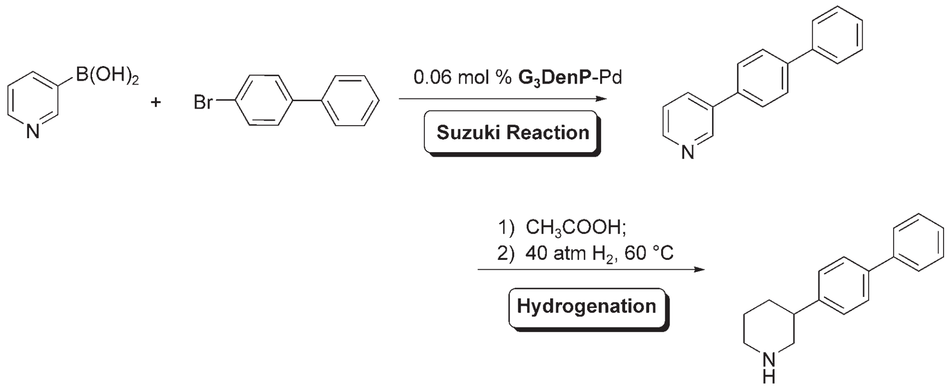
[b] Isolated yield.

Table 9. Stille cross-coupling reaction of tributylphenyltin with aryl chlorides.[a]

$$\text{Ar-Cl} + \text{Bu}_3\text{Sn-R} \xrightarrow[\text{2.2 equiv. CsF, DMF-H}_2\text{O (10:1), 110 °C}]{\text{1.5 mol\% }\mathbf{G_3DenP}\text{-Pd}} \text{Ar-R}$$

Entry	Aryl chloride	Organotin	Product	Time [h]	Yield [%][b]
1				20	95
2				20	93
3				20	91
4				20	88
5				20	75
6				20	78

[a] 0.47 mmol aryl chlorides, 0.52 mmol organotin, 1.5 mol% **G$_3$DenP**-Pd, 1.02 mmol CsF, 20 mL solvent, 110 °C.
[b] Isolated yield.



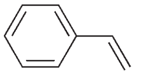
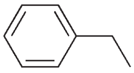
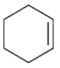
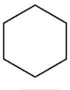
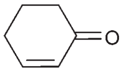
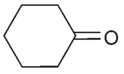
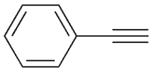
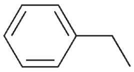
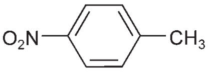
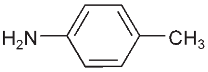
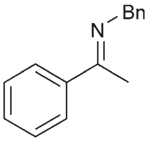
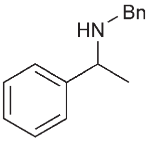
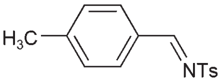
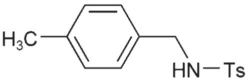
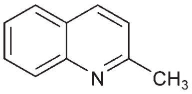
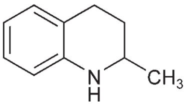
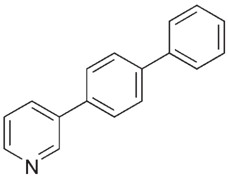
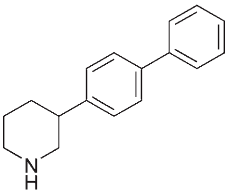
Scheme 4. Tandem reaction catalyzed by **G$_3$DenP**-Pd.

atm H_2 without addition of new Pd catalyst. The mixtures were stirred at 60 °C for further 20 h, furnishing 3-diphenylpiperidine in 96% total yield.

Conclusions

In conclusion, we have successfully prepared a new type of dendritic phosphine oxide-stabilized Pd nanoparticles as homogeneous catalysts for Suzuki and Stille coupling reactions and hydrogenations. It was

Table 10. Hydrogenation of various of unsaturated compounds.[a]

Entry	Substrate	Product	H_2 [atm]	Temperature [°C]	Time [h]	Yield [%]
1	$CH_3(CH_2)_8CH{=}CH_2$	$CH_3(CH_2)_9CH_3$	5	60	3	> 95
2			5	40	4	> 95
3			15	60	6	> 95
4			15	60	8	> 95
5			5	60	5	> 95
6			30	80	12	> 95
7			40	15	5	> 95
8			40	15	5	> 95
9[b]			40	15	5	> 95
10[b]			40	60	20	> 95

[a] 0.5 mol% **G_2DenP**-Pd was used as catalyst. Reaction yields were determined based on GC or ^{1}H NMR analysis.
[b] 2 mol% **G_3DenP**-Pd was used as catalyst, and 25 mol% acetic acid as additive.

demonstrated that the dendritic wedges served as a stabilizer for keeping the nanoparticles from aggregating, and as a vehicle for facilitating the separation and/or the recycling of the Pd catalyst. Unlike the commonly used homogeneous catalyst $Pd(PPh_3)_4$, these Pd nanoparticles exhibited very high catalytic efficiency and air stability in the Suzuki and Stille coupling reactions. We believe that this new type of robust Pd catalysts has the potential not only for laboratory scale research but also for industrial applications.

Experimental Section

General Information

Unless otherwise stated, all starting materials were obtained from commercial suppliers and used as received. Anhydrous solvents were obtained as follow: THF, dioxane and toluene were distilled from sodium and benzophenone (traces of thiophene in toluene was firstly removed by using concentrated H_2SO_4); dichloromethane was distilled from CaH_2. All moisture- and air-sensitive reactions were carried out in a flame-dried flask under a nitrogen atmosphere. Column chromatography was performed with silica gel 200–300 mesh. All ^{1}H NMR (300 MHz), ^{13}C NMR (75 MHz) spectra were recorded on a Bruker-DMX 300 as $CDCl_3$ solution in the presence of tetramethylsilane as an internal standard and are reported in ppm (δ). ^{31}P NMR (121 MHz) spectra were measured on a Bruker-DMX 400 and referenced to an external sample (85% H_3PO_4). ^{31}P MAS NMR spectra were measured on a Varian INOVA 400M NMR spectrometer. Mass spectra measurements were carried out with a Finnigan model Mat SSQ-710 instrument. MALDI-TOF mass spectra were recorded on a BIFLEX instrument with α-cyano-4-hydroxycinnamic acid (CCA) as the matrix. Elemental analysis was carried out on a Flash EA 112 instrument. Transmission electron microscopy (TEM): the chloroform dispersion of Pd catalyst was drop-cast onto a 300 mesh carbon coated copper grid, and TEM pictures were taken on a Hitachi H600 microscope at an accelerating voltage of 75 kV.

General Procedure for the Preparation of Dendritic Phosphine Ligands

A flame-dried, 25-mL, two-neck flask was charged with $KPPh_2$ (0.5 M in THF, 5 mL) and cooled to −78 °C. A solution of the corresponding dendritic bromide G_nCH_2Br ($n = 1\sim3$, 0.5 mmol) in dried and degassed THF was added dropwise with vigorous stirring. After 3 h, the mixture was allowed to stir at room temperature for 10 h. Most of the solvent was removed under reduced pressure. Then MeOH (30 mL) was added to precipitate the crude product, which was further purified by flash chromatograph on silica gel eluting with CH_2Cl_2/petroleum ether (2:1, v/v), affording the dendritic phosphine ligands in 80–90% yields.

G_1DenP: yield: 82%, white solid, mp 100–102 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 3.30$ (s, 2H), 4.80 (s, 4H), 6.25 (s, 2H), 6.35 (s, 1H), 7.27–7.38 (m, 20H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 36.31$, 69.94, 100.34, 108.40, 108.49, 127.55, 127.93, 128.38, 128.46, 128.56, 128.76, 132.89, 133.14, 137.03, 159.76; ^{31}P NMR (121 MHz, CH_2Cl_2): $\delta = -10.30$. MALDI-TOF MS: $m/z = 489.4$ ($[M+H]^+$).

G_2DenP: yield: 85%, white solid, mp 112–114 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 3.30$ (s, 2H), 4.74 (s, 4H), 4.97 (s, 8H), 6.23 (s, 2H), 6.38 (s, 1H), 6.51–6.58 (m, 6H), 7.3–7.44 (m, 30H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 36.48$, 68.01, 69.80, 70.13, 100.29, 101.55, 106.37, 108.39, 108.47, 127.59, 128.03, 128.25, 128.37, 128.46, 128.62, 128.79, 132.87, 133.11, 136.83, 139.44, 139.61,159.62, 160.15; ^{31}P NMR (121 MHz, CH_2Cl_2): $\delta = -10.32$. MALDI-TOF MS: $m/z = 913.4$ ($[M+H]^+$).

G_3DenP: yield: 90%, white solid, mp 124–126 C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 3.32$ (s, 2H), 4.77 (s, 2H), 4.93 (s, 8H), 4.99 (s, 16H), 6.27 (s, 2H), 6.39 (s, 1H), 6.51–6.67 (m, 18H), 7.28–7.39 (m, 50H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 36.39$, 69.77, 69.98, 70.08, 100.26, 101.53, 101.61, 106.38, 108.38, 108.47, 127.54, 127.97, 128.34, 128.43, 128.56, 128.76, 132.83, 133.07, 136.77, 137.92, 138.11, 139.24, 139.40, 139.59 159.63, 160.02, 160.16; ^{31}P NMR (121 MHz, CH_2Cl_2): $\delta = -10.32$; MS (APCI): $m/z = 1763.0$ ($[M+H]^+$); MALDI-TOF MS: $m/z = 1762.0$ ($[M+H]^+$); anal. calcd. for $C_{117}H_{101}O_{14}P$: C 79.75, H 5.78; found: C 79.52, H 5.86%.

General Procedure for the Preparation of Dendrimer-Stabilized Palladium Nanoparticles

A 25-mL, glass-lined stainless autoclave with a magnetic stirring bar was charged with 20 mg $Pd(acac)_2$ (0.066 mmol), **G_nDenP** (2 equiv.) and 10 mL dried, degassed THF. The mixture was stirred for 5 min at room temperature. Then the autoclave was pressurized with hydrogen to 25 atm, and stirred at 60 °C for 18 h. After the H_2 was carefully released, the solvent was removed under reduced pressure. The resulting black powders were further purified by sonication in ethanol several times.

Synthesis of AB_3-type Dendritic Bromobenzene

To a solution of the first-generation AB_3-type dendritic bromide G_1CH_2Br (1.96 g, 4 mmol)[35] and 5-bromobenzene-1,2,3-triol (205 mg, 1 mmol) in acetone was added K_2CO_3 (5 equiv.) and 18-crown-6 (50 mg). The mixture was stirred in a Schlenk flask under a nitrogen atmosphere and heated to reflux for 48 h. After the solvent was removed under reduced pressure, the residue was washed with water and extracted with CH_2Cl_2 (20 mL × 3). The AB_3-type dendritic bromobenzene was obtained as a white solid after purification by chromatography on a silica gel column with CH_2Cl_2 as eluent; yield: 80%; mp 135–136 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 4.84$ (s, 4H), 4.89–4.90 (m, 8H), 4.98–5.00 (m, 12H), 6.71–6.75 (m, 8H), 7.24–7.35 (m, 45H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 71.04$, 71.25, 71.66, 75.11, 75.19, 106.96, 107.76, 112.04, 116.08, 127.43, 127.48, 127.76, 127.88, 128.10, 128.15, 128.39, 128.43, 128.49, 132.11, 133.09, 136.96, 137.04, 137.70, 137.89, 138.33, 152.81, 153.11, 153.45; MS (ESI): $m/z = 1453.43$ ($[M+Na]^+$).

General Procedure for Suzuki Coupling Reaction of Aryl Halides with Arylboronic Acids

To a 25-mL flask was added aryl halide (1.25 mmol), arylboronic acid (1.87 mmol), 676 mg $K_3PO_4 \cdot 7H_2O$, 0.06 mol% **G_nDenP**-Pd (1.5 mg, $n = 2$) and 10 mL distilled 1,4-dioxane. The reaction mixture was heated to reflux and stirred for 20 h under air atmosphere. After most of the dioxane was removed under reduced pressure, CH_3OH (20 mL × 3) was added to the residue to extract the product and to precipitate the catalyst. The collected catalyst was washed with 5 mL distilled H_2O for three times, dried under reduced pressure, then reused directly in the next run. The coupling product in the combined MeOH solution was obtained after purification by chromatography on a silica gel column.

Suzuki Coupling of AB_3-Type Dendritic Bromobenzene with 4-Acetylphenylboronic Acid

To a 25-mL flask were added AB_3-type dendritic bromobenzene (715 mg, 0.50 mmol), 4-acetylphenylboronic acid (123 mg, 0.75 mmol), 338 mg $K_3PO_4 \cdot 7H_2O$, **G_3DenP**-Pd (3.1 mg, 0.3 mol%) or $Pd(PPh_3)_4$ (4.4 mg, 0.3 mol%) and 10 mL distilled 1,4-dioxane. The reaction mixture was heated to reflux and stirred for 20 h under N_2 atmosphere. After most of the dioxane was removed under reduced pressure, the residue was washed with water and extracted with CH_2Cl_2 (20 mL × 3). The coupling product was obtained after purification by chromatography on a silica gel column. Yield: **G_3DenP**-Pd as catalyst, 96%; $Pd(PPh_3)_4$ as catalyst, 79%. White solid, mp 139–140 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 2.62$ (s, 3H), 4.87 (s, 4H), 4.90 (s, 2H), 4.98–5.00 (m, 14H), 5.05 (s, 4H), 6.77 (s, 4H), 6.81 (s, 2H), 6.87 (s, 2H), 7.20–7.35 (m, 45H), 7.54 (d, $J = 8.37$ Hz, 2H), 7.99 (d, $J = 8.35$ Hz, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 26.68$, 71.07, 71.28, 71.82, 75.22, 75.33, 107.01, 107.72, 108.02, 127.07, 127.44, 127.51, 127.68, 127.78, 127.89, 128.12, 128.17, 128.41, 128.43, 128.50, 128.98, 132.62, 136.98, 137.07, 137.90, 138.30, 152.88, 153.14, 153.20, 197.56; MS (ESI): $m/z = 1491.71$ ($[M+Na]^+$).

General Procedure for Stille Coupling Reactions of Aryl Halides with Organotins

To a 25-mL flask were added aryl halide (0.465 mmol), organotin (1.1 equiv., 0.512 mmol), **G_3DenP**-Pd (1.5 mol%), CsF

(155.4 mg, 1.02 mmol), and DMF/H_2O (20 mL, 10:1, v/v). The mixture was stirred for the desired time and temperature until the complete consumption of the starting material as monitored by TLC. Then, the reaction mixture was extracted with diethyl ether two times. The combined organic solution was washed with water, and dried over anhydrous Na_2SO_4 and evaporated into dryness. The residue was purified by flash column chromatography to afford the desired coupling products.

General Procedure for Hydrogenation of Unsaturated Compounds

In a 50-mL, glass-lined, stainless steel reactor with a magnetic stirring bar was charged with substrates (1 mmol), **G$_2$DenP**-Pd or **G$_3$DenP**-Pd (0.5 mol%), and appropriate solvent (10 mL). The autoclave was closed and was pressurized with H_2 (5 to 40 atm). The mixture was stirred under the given pressure at 15–80 °C for several hours. After carefully venting of hydrogen, most of the reaction solvent was removed under reduced pressure. The reaction yield was determined by GC or ^1H NMR.

Tandem Reaction of Suzuki Coupling and Hydrogenation

To a 25-mL flask were added *p*-bromobiphenyl (583 mg, 2.50 mmol), 3-pyridinylboronic acid (461 mg, 3.75 mmol), $K_3PO_4 \cdot 7H_2O$ (1.69 g), **G$_3$DenP**-Pd (3.1 mg, 0.06 mol%) and newly distilled 1,4-dioxane (10 mL). The reaction mixture was heated to reflux and stirred for 20 h under an air atmosphere. After the reaction was completed, half of the mixture was removed for the determination of the coupling product (277 mg, 96% yield). The other half of the reaction mixture was acidified with CH_3COOH to pH 5, and pressurized with 40 atm H_2. The mixture was then stirred at 60 °C overnight. After carefully venting of hydrogen, most of the reaction solvent was removed under reduced pressure. The residue was washed with saturated $NaHCO_3$ aqueous solution, and extracted with diethyl ether. The organic solvent was removed under reduced pressure, giving the reduced product with almost quantitative yield.

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