

# Polymer-Incarcerated Chiral Rh/Ag Nanoparticles for Asymmetric 1,4-Addition Reactions of Arylboronic Acids to Enones: Remarkable Effects of Bimetallic Structure on Activity and Metal Leaching

Tomohiro Yasukawa, Hiroyuki Miyamura, and Shū Kobayashi\*

Department of Chemistry, School of Science, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan

**S** Supporting Information

**ABSTRACT:** Robust and highly active bimetallic Rh nanoparticle (NP) catalysts, PI/CB Rh/Ag, have been developed and applied to the asymmetric 1,4-addition of arylboronic acids to enones without leaching of the metals. We found that the structures of the bimetallic Rh/Ag catalysts and chiral ligands strongly affect their catalytic activity and the amount of metal leaching. PI/CB Rh/Ag could be recycled several times by simple operations while keeping high yields and excellent enantioselectivities. To show the versatility of the PI/CB Rh/Ag catalyst, a one-pot, oxidation-asymmetric 1,4-addition reaction of an allyl alcohol and an arylboronic acid was demonstrated by combining the PI/CB Rh/Ag catalyst with PI/CB Au as an aerobic oxidation catalyst.

Heterogeneous metal nanoparticle (NP) catalysis has been of great interest in both academia and industry and has expanded rapidly because of these catalysts' unique reactivity and selectivity, stability, recyclability, avoidance of metal contamination of products, and availability for reaction integration such as in continuous flow systems and tandem reactions.<sup>1</sup> Also, their activities and selectivities can be controlled by the formation of multimetallic NPs.<sup>2</sup> Several recent reports have shown that homogeneous transition-metal-catalyzed reactions affording complex organic molecules can be conducted by using metal NP catalytic systems, with the advantages mentioned above.<sup>3</sup> However, there have been few reports of metal NP catalysts that can provide excellent enantioselectivity in asymmetric C–C bond-forming reactions.<sup>3c,e,f,h,i</sup> Moreover, only single-metal NPs are generally used in those reactions, and the effects of a second dopant metal to form bimetallic NPs have scarcely been discussed.

The Rh-catalyzed asymmetric 1,4-addition of boron compounds to  $\alpha,\beta$ -unsaturated carbonyl compounds was developed by Hayashi and Miyaura and is one of the most useful tools for constructing asymmetric C–C bonds.<sup>4</sup> Although both academic research and large-scale (up to 20 kg) processes involving this reaction have been widely reported,<sup>5</sup> recyclable and robust chiral heterogeneous Rh catalysts that can work with high catalytic turnover and long lifetimes without metal leaching are required because Rh is one of the most expensive precious metals and Rh contamination in products is problematic.<sup>5c</sup> Reported strategies for immobilization of Rh catalysts have used two approaches: immobilization of ligands on supports<sup>6</sup> or immobilization of cationic Rh on supports.<sup>7</sup> The former strategy has already been

investigated for several C–C bond-forming reactions by using immobilized phosphine ligands; however, these systems require complicated preparation of monomeric ligands and individual fabrication of heterogeneous polymers. In addition, these catalysts themselves are not robust because of the instability of the immobilized ligands, such as intolerance to oxidative conditions. In contrast, the latter strategy easily allows the optimization of ligand structures by external addition of ligands to immobilized metal catalysts. However, control of metal leaching is more difficult with this strategy because strong coordination of the ligands to cationic Rh may allow the metal to leach out from the support.<sup>7a,g</sup> To the best of our knowledge, there has been no report of an asymmetric version of the 1,4-addition reaction of boron compounds with  $\alpha,\beta$ -unsaturated carbonyl compounds in heterogeneous systems using the latter strategy. Therefore, to develop immobilized chiral Rh catalysts for asymmetric C–C bond-forming reactions with both high efficiency and robustness, a new strategy is required.

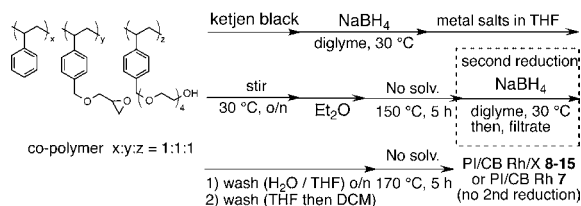
Our group has already developed polystyrene (PS)-based polymer-incarcerated metal (PI-M) NP catalysts and reported that they show high catalytic activity and robustness, such as recyclability and restoration of the activity of deactivated catalysts that had been used repetitively for many kinds of reactions without metal leaching.<sup>1c,8</sup> With this PI method, multimetallic NP catalysts were readily prepared, and some bimetallic catalysts showed higher catalytic activities and unique selectivities compared with the monometallic NP catalysts.<sup>1e,9</sup> This work led us to hypothesize that the development of truly robust, chiral Rh NP catalysts<sup>10</sup> could be achieved using the PI method.<sup>11</sup> Herein we report the development of novel, robust, chiral Rh and bimetallic NP catalysts by the PI method and their use in asymmetric 1,4-additions of boronic acids to enones.

We first chose Rh(PPh<sub>3</sub>)<sub>3</sub>Cl as the Rh precursor for the preparation of PI/CB Rh catalyst **7** containing Rh NPs through in situ reduction of cationic Rh by NaBH<sub>4</sub> in the presence of a PS-based copolymer, followed by thermal cross-linking (Scheme 1). With the copolymer and carbon black (CB) as a second support to expand the surface area, PI/CB catalysts were prepared using a reported method.<sup>12</sup> 2-Cyclohexenone **1a** and phenylboronic acid **2a** were chosen as model substrates, and the reaction was conducted with the external addition of BINAP **4** as a chiral ligand (substrates and ligands are shown in Chart 1). In a 1:2 toluene/water cosolvent system, the desired product **3aa** was

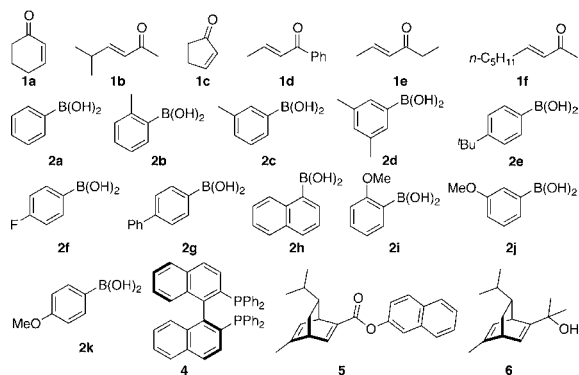
Received: August 8, 2012

Published: September 24, 2012

## Scheme 1. Preparation of Rh NP catalysts



## Chart 1. Substrates and Ligands



obtained in high yield with high enantiomeric excess (ee) at 100 °C, but >10% leaching of Rh was observed by inductively coupled plasma (ICP) analysis (Table 1, entry 1). As our control experiments showed that no leaching of Rh occurred in the presence of only **4** or only the substrates under the same conditions,<sup>13</sup> we hypothesized that the leaching might result from the formation of an intermediate involving interactions with both the ligand and the substrates.

To prevent the leaching, chiral ligands with various structures were examined to see whether the size or strength of the interaction affected the degree of leaching. Interestingly, we chose chiral dienes as ligands<sup>4b,g,14</sup> and found that the leaching was dramatically decreased when chiral diene **5** was used, in spite of the lower yield and ee (Table 1, entry 2). On the other hand, when chiral diene **6** was used, excellent ee was obtained and ~5% Rh leaching was observed (entry 3). Preheating the solvents to 100 °C improved the yield (entry 4), probably because side reactions occurring at  $T < 100$  °C were suppressed. Finally, the use of PI/CB Rh catalyst **8** prepared from [Rh(OAc)<sub>2</sub>]<sub>2</sub> completely suppressed the leaching (entry 5), while the combination of **8** and **4** could not suppress the leaching (entry 6). The second reduction in the catalyst preparation (Scheme 1)<sup>13</sup> provided better reproducibility of the catalytic activity and metal leaching. We also applied this system to the acyclic substrate **1b**. Disappointingly, the product **3ba** was obtained in poor yield in the presence of **8** (entry 8). Because our previous work showed that the use of bimetallic NP catalysts enhanced the catalytic activity,<sup>9</sup> we then screened bimetallic NP catalysts prepared by the same procedure as for **8** with simultaneous reduction of the Rh salt and another metal salt. Initially, catalysts prepared with a 1:1 Rh/M ratio (M = Ag, Co, Pd, Ru, Au) and a commercially available 5% Rh on carbon (Rh/C) catalyst were examined (entries 9–14), and PI/CB Rh/Ag catalyst **9** showed the highest catalytic activity with 2.3% Rh leaching (entry 9). The high catalytic activity of **9** for cyclic substrate **1a** was also confirmed, and no leaching of either Rh or Ag was observed (entry 7) and the loading of ligand **6** was successfully reduced to 0.0375 mol % without loss of catalytic activity and ee.<sup>13</sup> The yield

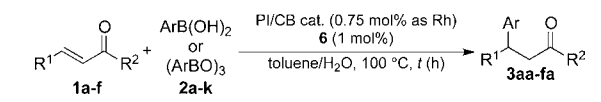
Table 1. Optimization of the Reaction Conditions<sup>a</sup>

entry	1	L	cat.	t	yield (%) <sup>b</sup>	ee (%) <sup>c</sup>	Rh leaching <sup>d</sup>
1	<b>1a</b>	<b>4</b>	Rh <b>7</b>	16	93	97	>10%
2	<b>1a</b>	<b>5</b>	Rh <b>7</b>	16	72	80	1.4%
3	<b>1a</b>	<b>6</b>	Rh <b>7</b>	16	79	98	5.7%
4 <sup>e</sup>	<b>1a</b>	<b>6</b>	Rh <b>7</b>	2	94	98	7.4%
5 <sup>e</sup>	<b>1a</b>	<b>6</b>	Rh <b>8</b>	6	>99	98	ND
6 <sup>e</sup>	<b>1a</b>	<b>4</b>	Rh <b>8</b>	6	16	–	7.2%
7 <sup>e</sup>	<b>1a</b>	<b>6</b>	Rh/Ag <b>9</b> <sup>f</sup>	6	>99	98	ND (ND) <sup>g</sup>
8 <sup>e</sup>	<b>1b</b>	<b>6</b>	Rh <b>8</b>	6	18	–	ND
9 <sup>e</sup>	<b>1b</b>	<b>6</b>	Rh/Ag <b>9</b> <sup>f</sup>	6	60	92	2.3%
10 <sup>e</sup>	<b>1b</b>	<b>6</b>	Rh/Co <b>10</b> <sup>f</sup>	6	42	–	ND
11 <sup>e</sup>	<b>1b</b>	<b>6</b>	Rh/Pd <b>11</b> <sup>f</sup>	12	<1	–	ND
12 <sup>e</sup>	<b>1b</b>	<b>6</b>	Rh/Ru <b>12</b> <sup>f</sup>	12	2	–	ND
13 <sup>e</sup>	<b>1b</b>	<b>6</b>	Rh/Au <b>13</b> <sup>f</sup>	12	3	–	ND
14 <sup>e</sup>	<b>1b</b>	<b>6</b>	Rh/C	12	11	–	ND
15 <sup>e</sup>	<b>1b</b>	<b>6</b>	Rh/Ag <b>14</b> <sup>h</sup>	6	60	92	0.6%
16 <sup>e</sup>	<b>1b</b>	<b>6</b>	Rh/Ag <b>15</b> <sup>i</sup>	6	77	92	ND
17 <sup>e,j</sup>	<b>1b</b>	<b>6</b>	Rh/Ag <b>15</b> <sup>i</sup>	12	91	92	ND

<sup>a</sup>Reaction conditions: either **1a** (0.2 mmol), **2a** (0.3 mmol), toluene (0.25 mL), and water (0.5 mL) or **1b** (0.3 mmol), **2a** (0.45 mmol), toluene (0.375 mL), and water (0.75 mL), and water (0.75 mL) at 100 °C for *t* h. <sup>b</sup>Determined by GC analysis. <sup>c</sup>Determined by HPLC analysis. “–” = not determined. <sup>d</sup>ND = below the detection limit of the ICP equipment (<0.003–0.005 ppm).<sup>13</sup> <sup>e</sup>The solvent was heated to 100 °C before use. <sup>f</sup>Rh/M = 1:1. <sup>g</sup>ICP analysis confirmed that there was no leaching of Ag. <sup>h</sup>Rh/Ag = 1:2. <sup>i</sup>Rh/Ag = 1:3. <sup>j</sup>**2a** (0.6 mmol), **15** (1.5 mol % as Rh), and **6** (2 mol %) were used.

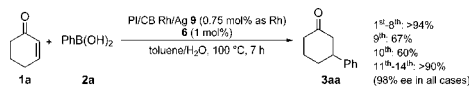
and amount of Rh leaching were improved by increasing the proportion of Ag (entries 15 and 16), and further optimization gave **3ba** in 91% yield and 92% ee with no leaching of the metals (entry 17). Furthermore, a filtrate transfer experiment<sup>3b,13</sup> confirmed that the filtrate after the reaction did not catalyze the 1,4-addition, indicating that the reaction is not catalyzed by homogeneous leached species. It is noteworthy that the notorious metal leaching was suppressed by the use of bimetallic NP catalysts.

With the optimized bimetallic catalysts **9** and **15**, the substrate scope of the asymmetric 1,4-addition was surveyed (Table 2). Arylboronic acids with either electron-donating or electron-withdrawing groups were employed for the reaction with **1a** under the optimized conditions, and in all cases the desired 1,4-addition products were obtained in high yields with excellent ee (entries 2–4, 7, 8, and 10–12). No leaching of Rh occurred in any cases. Arylboronic acids with substituent groups at the ortho, meta, and para positions also provided the desired products in high yields with excellent ee without leaching of Rh (entries 3, 4, and 10–12). *o*-Methyl-substituted phenylboronic acid **2b** and 1-naphthylboronic acid **2h** were found to be less reactive, but slight increases in the amounts of arylboronic acid, catalyst, and ligand led to high yields of the desired products with excellent ee (entries 2 and 9). In the reaction of **2e**, Rh/Ag catalyst **15** gave a high yield with excellent ee and no leaching of Rh (entry 6), while **9** showed a small amount of metal leaching (entry 5). The five-membered-ring enone **1c** also afforded the 1,4-addition product in high yield with good ee under the same conditions (entry 14). For acyclic enones **1d–f**, the optimized conditions for **1b** (entry 13) were used, and in all cases the desired products were obtained in good to high yields with excellent ee and no leaching of Rh (entries 15–17). In the reaction of **1f**, the yield was improved by using Rh catalyst **8** (entry 18). Overall, a wide

Table 2. Scope of the Asymmetric 1,4-Addition<sup>a</sup>


entry	1	2 (eq.)	cat.	t	yield (%) <sup>b</sup>	ee (%) <sup>c</sup>	Rh leaching <sup>d</sup>
1	1a	2a (1.5)	Rh/Ag 9	7	quant. <sup>e</sup>	98	ND
2 <sup>f</sup>	1a	2b (2.0)	Rh/Ag 9	24	81	96	ND
3	1a	2c (1.5)	Rh/Ag 9	9	99	96	ND
4	1a	2d (1.5)	Rh/Ag 9	11	96	97	ND
5	1a	2e (1.5)	Rh/Ag 9	6	40	–	1.4%
6	1a	2e (1.5)	Rh/Ag 15	24	89	97	ND
7	1a	2f (1.5)	Rh/Ag 9	24	87	98	ND
8	1a	2g (1.5)	Rh/Ag 9	10	quant.	98	ND
9 <sup>g</sup>	1a	2h (2.0)	Rh/Ag 9	12	90	95	ND
10	1a	2i (1.5)	Rh/Ag 9	7	95	93	ND
11	1a	2j (1.5)	Rh/Ag 9	10	93	98	ND
12	1a	2k (1.5)	Rh/Ag 9	7	82	97	ND
13 <sup>h</sup>	1b	2a (2.0)	Rh/Ag 15	12	91 <sup>e</sup>	92	ND
14	1c	2a (1.5)	Rh/Ag 9	7	86	74	ND
15 <sup>ih</sup>	1d	2a (2.0)	Rh/Ag 15	12	72	92	ND
16 <sup>g</sup>	1e	2a (2.0)	Rh/Ag 15	12	82	96	ND
17 <sup>ih</sup>	1f	2a (2.0)	Rh/Ag 15	12	70	95	ND
18 <sup>f</sup>	1f	2a (2.0)	Rh 8	12	83	95	ND

<sup>a</sup>Reaction conditions: 100 °C, enone (0.3 mmol), toluene (0.375 mL), water (0.75 mL); all solvents were heated to 100 °C before use. <sup>b</sup>Calculated from product isolated from 70% of the reaction mixture. <sup>c</sup>Determined by HPLC analysis. “–” = not determined. <sup>d</sup>ND = below the detection limit of the ICP equipment (<0.003–0.005 ppm).<sup>13</sup> <sup>e</sup>Determined by GC analysis. <sup>f</sup>The catalyst (1.5 mol % as Rh) and **6** (2 mol %) were used. <sup>g</sup>The catalyst (1.5 mol % as Rh) and **5** (2 mol %) were used. <sup>h</sup>The catalyst was further treated in mesitylene at 150 °C for 5 h before use.

Scheme 2. Reuse of the Catalyst<sup>a</sup>

<sup>a</sup>The recovered catalyst was heated at 170 °C for 4 h between the 10th and 11th uses. In all cases, **3aa** was obtained with 98% ee and no metal leaching.

substrate scope with high yields and excellent ee was found, and in all cases, no metal leaching occurred.

The viability of recycling **9** was examined in the asymmetric 1,4-addition reaction of **1a** with **2a** (Scheme 2). The catalysts were easily recovered by simple filtration and reused for the next cycle with additional **6** after washing with tetrahydrofuran and drying. For eight cycles, no significant loss of activity was observed; however, the yield suddenly dropped to 67% for the ninth use. Similar low activity was observed for the 10th use when no special treatment was performed before use. Interestingly, when the catalyst collected after the 10th use was heated at 170 °C for 4 h, the high activity was successfully restored and maintained for a further four uses, probably because the heating eliminated impurities such as small amounts of solvents, products, or side products that were adsorbed on the surface of the NPs. No significant structural changes before use, after the 10th use, or after heating were observed using scanning transmission electron microscopy (STEM).<sup>13</sup> In all cycles, the product was obtained in excellent yield and ee with no leaching of Rh. This demonstrates the robustness of the PI/CB Rh/Ag catalyst in asymmetric catalysis.

To understand why Ag affects both the catalytic activity and the Rh leaching, STEM and energy-dispersive X-ray spectrometry (EDS) analyses were performed. In Rh catalyst **8**, although

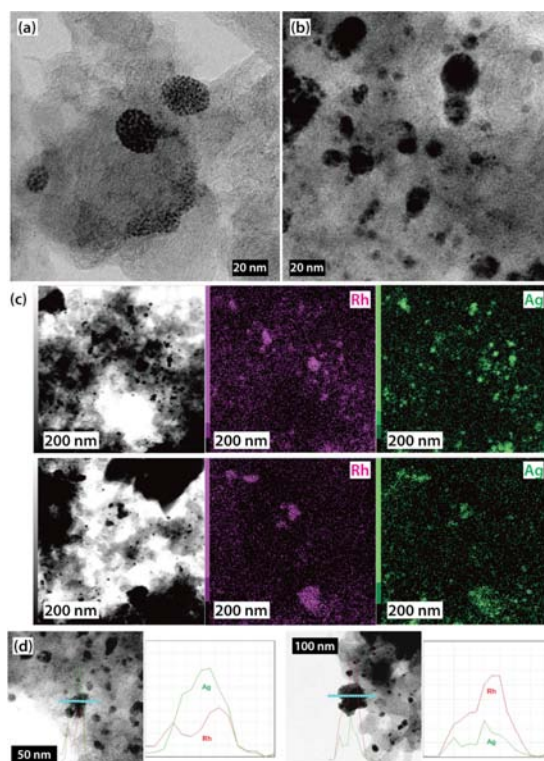
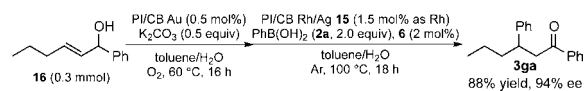


Figure 1. (a, b) STEM images of (a) **8** and (b) **9**. (c) EDS mappings of **9**. (d) EDS line analyses of **9**.

small NPs (~3 nm) were formed, they were assembled on one area and not dispersed widely over the support (Figure 1a). In contrast, the NPs in Rh/Ag catalyst **9** were dispersed over the support (Figure 1b), and EDS mapping showed that bimetallic alloy NPs were formed (Figure 1c). EDS line analyses of those alloy NPs (Figure 1d) showed that the Rh/Ag ratio in the NPs was random (1:2–2:1). Thus, the effects of the bimetallic structure might be explained by the size effect<sup>10a</sup> and the existence of metal–metal interactions. At this stage, we believe that the reaction proceeds on the surface of the bimetallic NPs, as there were no significant morphological changes in the catalyst after use and after heating. We did not determine the oxidation states of the metals on the surface of the NPs at this stage.

To show the general versatility and applicability of the PI/CB Rh/Ag catalyst, a one-pot, oxidation-asymmetric 1,4-addition reaction of an allylic alcohol and an arylboronic acid was performed (Scheme 3). The reaction was started from allylic

Scheme 3. One-Pot Reaction Using Allylic Alcohol **16**

alcohol **16** at 60 °C under an O<sub>2</sub> atmosphere in the presence of K<sub>2</sub>CO<sub>3</sub> and a PI/CB Au catalyst that was shown to be an excellent catalyst for aerobic oxidation of alcohols.<sup>12,15</sup> After the oxidation step was complete, **2a**, **15**, and **6** were added to the same pot, and the reaction mixture was stirred at 100 °C; this gave the desired product **3ga** in high yield with excellent ee. Such one-pot processes are very useful because workup/purification steps are reduced and a relatively unstable intermediate can be generated in situ. Moreover, this one-pot reaction shows the



robustness of **15**, as its catalytic activity was maintained in the presence of the Au catalyst and  $K_2CO_3$ .

In summary, we have developed robust and active bimetallic NP catalysts, PI/CB Rh/Ag, and used them in chiral metal-NP-catalyzed asymmetric 1,4-additions of arylboronic acids to enones without leaching of the metals. Wide substrate scope, high yields, high ee, and no metal leaching were attained in the chiral metal-NP-catalyzed asymmetric C–C bond-forming reactions. We also found that the structures of the bimetallic Rh/Ag NPs and chiral ligands strongly affected the catalytic activity and the amount of metal leaching. STEM analysis and EDS mapping showed that Ag formed alloy NPs with Rh, preventing aggregation of the Rh NPs to enhance the catalytic activity and control the metal leaching. This is a remarkable example of the positive effects of a second dopant metal in metal-NP-catalyzed systems. In addition, the PI/CB Rh/Ag catalyst could be recycled using simple operations while keeping high yields and high ee for several cycles, and the deactivated catalyst after repetitive use could be restored simply by heating. Finally, to show the versatility of the PI/CB Rh/Ag catalysts, we developed a one-pot, oxidation-asymmetric 1,4-addition reaction of an allyl alcohol and an arylboronic acid by combining the PI/CB Rh/Ag catalyst with a PI/CB Au catalyst as an aerobic oxidation catalyst. Thus, the developed catalytic system is not only useful as a synthetic methodology but also should provide precious scientific knowledge and new avenues for heterogeneous, homogeneous, and metal-NP catalysis.

## ■ ASSOCIATED CONTENT

### Supporting Information

Reaction procedures, STEM images, and spectra. This material is available free of charge via the Internet at <http://pubs.acs.org>.

## ■ AUTHOR INFORMATION

### Corresponding Author

shu\_kobayashi@chem.s.u-tokyo.ac.jp

### Notes

The authors declare no competing financial interest.

## ■ ACKNOWLEDGMENTS

This work was partially supported by a Grant-in-Aid for Scientific Research from the Global COE Program of JSPS, the University of Tokyo, MEXT, and NEDO. We thank Mr. Noriaki Kuramitsu (The University of Tokyo) for STEM and EDS analyses.

## ■ REFERENCES

- (1) (a) *Metal Nanoclusters in Catalysis and Materials Science: The Issue of Size Control*; Corain, B., Schmid, G., Toshima, N., Eds.; Elsevier: Amsterdam, 2007. (b) Feldheim, D. L.; Foss, C. A. *Metal Nanoparticles: Synthesis, Characterization, and Applications*; CRC Press: Boca Raton, FL, 2001. (c) Kobayashi, S.; Miyamura, H. *Chem. Rec.* **2010**, *10*, 271. (d) Yan, N.; Xiao, C.; Kou, Y. *Coord. Chem. Rev.* **2010**, *254*, 1179. (e) Yoo, W.-J.; Miyamura, H.; Kobayashi, S. *J. Am. Chem. Soc.* **2011**, *133*, 3095. (f) Wang, N.; Matsumoto, T.; Ueno, M.; Miyamura, H.; Kobayashi, S. *Angew. Chem., Int. Ed.* **2009**, *48*, 4744.
- (2) (a) Munoz-Flores, B. M.; Kharisov, B. I.; Jimenez-Perez, V. M.; Martinez, P. E.; Lopez, S. T. *Ind. Eng. Chem. Res.* **2011**, *50*, 7705. (b) Ferrando, R.; Jellinek, J.; Johnston, R. L. *Chem. Rev.* **2008**, *108*, 845. (c) Liu, P.; Nørskov, J. K. *Phys. Chem. Chem. Phys.* **2001**, *3*, 3814. (d) Toshima, N.; Yonezawa, T. *New J. Chem.* **1998**, *22*, 1179.
- (3) (a) Cong, H.; Porco, J. A. *ACS Catal.* **2012**, *2*, 65. (b) Witham, C. A.; Huang, W.; Tsung, C.-K.; Kuhn, J. N.; Somorjai, G. A.; Toste, F. D. *Nat. Chem.* **2010**, *2*, 36. (c) Ranganath, K. V. S.; Kloesges, J.; Schäfer, A. H.; Glorius, F. *Angew. Chem., Int. Ed.* **2010**, *49*, 7786. (d) Cong, H.;

Becker, C. F.; Elliott, S. J.; Grinstaff, M. W.; Porco, J. A. *J. Am. Chem. Soc.* **2010**, *132*, 7514. (e) Mori, K.; Kondo, Y.; Yamashita, H. *Phys. Chem. Chem. Phys.* **2009**, *11*, 8949. (f) Sawai, K.; Tatum, R.; Nakahodo, T.; Fujihara, H. *Angew. Chem., Int. Ed.* **2008**, *47*, 6917. (g) Abad, A.; Corma, A.; Garcia, H. *Top. Catal.* **2007**, *44*, 237. (h) Park, K. H.; Chung, Y. K. *Adv. Synth. Catal.* **2005**, *347*, 854. (i) Akiyama, R.; Kobayashi, S. *Angew. Chem., Int. Ed.* **2001**, *40*, 3469.

(4) (a) Tian, P.; Dong, H.-Q.; Lin, G.-Q. *ACS Catal.* **2012**, *2*, 95. (b) Feng, C.-G.; Xu, M.-H.; Lin, G.-Q. *Synlett* **2011**, 1345. (c) Hargrave, J. D.; Allen, J. C.; Frost, C. G. *Chem.—Asian J.* **2010**, *5*, 386. (d) Edwards, H. J.; Hargrave, J. D.; Penrose, S. D.; Frost, C. G. *Chem. Soc. Rev.* **2010**, *39*, 2093. (e) Youn, S. W. *Eur. J. Org. Chem.* **2009**, 2597. (f) Miyaura, N. *Bull. Chem. Soc. Jpn.* **2008**, *81*, 1535. (g) Defieber, C.; Grützmaier, H.; Carreira, E. M. *Angew. Chem., Int. Ed.* **2008**, *47*, 4482. (h) Paquin, J.-F.; Defieber, C.; Stephenson, C. R. J.; Carreira, E. M. *J. Am. Chem. Soc.* **2005**, *127*, 10850. (i) Guo, H. C.; Ma, J. A. *Angew. Chem., Int. Ed.* **2006**, *45*, 354. (j) Hayashi, T.; Yamasaki, K. *Chem. Rev.* **2003**, *103*, 2829. (k) Takaya, Y.; Ogasawara, M.; Hayashi, T.; Sakai, M.; Miyaura, N. *J. Am. Chem. Soc.* **1998**, *120*, 5579.

(5) (a) Howell, G. P. *Org. Process Res. Dev.* **2012**, *16*, 1258. (b) Magano, J.; Dunetz, J. R. *Chem. Rev.* **2011**, *111*, 2177. (c) Brock, S.; Hose, D.; Moseley, J.; Parker, A.; Patel, I.; Williams, A. *Org. Process Res. Dev.* **2008**, *12*, 496.

(6) (a) Makhubela, B. C. E.; Jardine, A.; Smith, G. S. *Green Chem.* **2012**, *14*, 338. (b) Jana, R.; Tunge, J. A. *J. Org. Chem.* **2011**, *76*, 8376. (c) Jana, R.; Tunge, J. A. *Org. Lett.* **2009**, *11*, 971. (d) Laska, U.; Frost, C. G.; Plucinski, P. K.; Price, G. J. *Catal. Lett.* **2007**, *122*, 68. (e) Otomaru, Y.; Senda, T.; Hayashi, T. *Org. Lett.* **2004**, *6*, 3357. (f) Uozumi, Y.; Nakazono, M. *Adv. Synth. Catal.* **2002**, *344*, 274. (g) Guerreiro, P.; Ratovelomanana-Vidal, V.; Genêt, J.-P.; Dellis, P. *Tetrahedron Lett.* **2001**, *42*, 3423.

(7) (a) Motokura, K.; Hashimoto, N.; Hara, T.; Mitsudome, T.; Mizugaki, T.; Jitsukawa, K.; Kaneda, K. *Green Chem.* **2011**, *13*, 2416. (b) Neatu, F.; Besnea, M.; Komvokis, V. G.; Genêt, J. P.; Michelet, V.; Triantafyllidis, K. S.; Parvulescu, V. I. *Catal. Today* **2008**, *139*, 161. (c) Laska, U.; Frost, C. G.; Plucinski, P. K.; Price, G. J. *Catal. Lett.* **2008**, *122*, 68. (d) Kantam, M. L.; Subrahmanyam, V. B.; Kumar, K. B. S.; Venkanna, G. T.; Sreedhar, B. *Helv. Chim. Acta* **2008**, *91*, 1947. (e) Handa, P.; Witula, T.; Reis, P.; Holmberg, K. *ARKIVOC* **2008**, No. vi, 107. (f) Handa, P.; Holmberg, K.; Sauthier, M.; Castanet, Y.; Mortreux, A. *Microporous Mesoporous Mater.* **2008**, *116*, 424. (g) Fujita, N.; Motokura, K.; Mori, K.; Mizugaki, T.; Ebitani, K.; Jitsukawa, K.; Kaneda, K. *Tetrahedron Lett.* **2006**, *47*, 5083.

(8) Akiyama, R.; Kobayashi, S. *Chem. Rev.* **2009**, *109*, 594.

(9) (a) Kaizuka, K.; Miyamura, H.; Kobayashi, S. *J. Am. Chem. Soc.* **2010**, *132*, 15096. (b) Miyamura, H.; Matsubara, R.; Kobayashi, S. *Chem. Commun.* **2008**, 2031.

(10) (a) Yuan, Y.; Yan, N.; Dyson, P. J. *ACS Catal.* **2012**, *2*, 1057. (b) Guyonnet-Bilé, E.; Denicourt-Nowicki, A.; Sassine, R.; Beaunier, P.; Launay, F.; Roucoux, A. *ChemSusChem* **2010**, *3*, 1276. (c) Han, D.; Li, X.; Zhang, H.; Liu, Z.; Li, J.; Li, C. J. *Catal.* **2006**, *243*, 318. (d) Bile, E. G.; Cortelazzo-Polisini, E.; Denicourt-Nowicki, A.; Sassine, R.; Launay, F.; Roucoux, A. *ChemSusChem* **2012**, *5*, 91. (e) Crabtree, R. H. *Chem. Rev.* **2012**, *112*, 1536. (f) Heitbaum, M.; Glorius, F.; Escher, I. *Angew. Chem., Int. Ed.* **2006**, *45*, 4732.

(11) Before developing the PI method, we exploited micro-encapsulated (MC) catalysts. MC Pd with an NP structure was successfully used in asymmetric allylic substitution.<sup>3i,8</sup>

(12) Lucchesi, C.; Inasaki, T.; Miyamura, H.; Matsubara, R.; Kobayashi, S. *Adv. Synth. Catal.* **2008**, *350*, 1996.

(13) See the Supporting Information for details.

(14) (a) Okamoto, K.; Hayashi, T.; Rawal, V. H. *Chem. Commun.* **2009**, 4815. (b) Okamoto, K.; Hayashi, T.; Rawal, V. H. *Org. Lett.* **2008**, *10*, 4387.

(15) Miyamura, H.; Matsubara, R.; Miyazaki, Y.; Kobayashi, S. *Angew. Chem., Int. Ed.* **2007**, *46*, 4151.