

Development of an amphiphilic resin-dispersion of nanopalladium catalyst: Design, preparation, and its use in aquacatalytic hydrodechlorination and aerobic oxidation

Yasuhiro Uozumi *, Ryu Nakao, Hakjune Rhee

Institute for Molecular Science and CREST, Higashiyama 5-1, Myodaiji, Okazaki 444-8787, Japan

Received 27 January 2006; accepted 21 February 2006

Available online 1 September 2006

Abstract

An amphiphilic polystyrene-poly(ethylene glycol) (PS-PEG) resin-dispersion of nanoparticles of palladium was designed and prepared with a view toward use for catalysis in water. The amphiphilic PSPEG resin-dispersion of nanoparticles of palladium exhibited high catalytic performance in the hydrodechlorination of chloroarenes under aqueous conditions. The amphiphilic resin-supported nanopalladium particle also catalyzed alcohol oxidation, which is one of the most fundamental and important yet immature processes in organic chemistry, in water under an atmospheric pressure of oxygen gas to form aldehydes, ketones, and carboxylic acids.

© 2006 Elsevier B.V. All rights reserved.

Keyword: Aerobic oxidation

1. Introduction

In recent years, much attention has been focused on aqueous- [1] and heterogeneous-switching [2,3] of organic transformations. We have developed amphiphilic polystyrene-poly(ethylene glycol) (PS-PEG) resin-supported palladium complexes, which catalyze various synthetic organic reactions in water under heterogeneous conditions [4]. Thus, for examples, aquacatalytic π -allylic substitution, Heck reaction, carbonylation, cross-coupling, and cycloisomerization etc. were found to proceed smoothly in water with the PS-PEG supported palladium-phosphine complexes where organic substrates must diffuse into the hydrophobic PS matrix to form the highly concentrated reaction sphere with an anchored catalyst performing efficient organic transformations in water.

On the other hand, with the advent of accessible methods for the preparation and/or handling of nanometal particles, catalytic organic transformations with nanometal particles have been gaining popularity [5,6]. One approach employs functional polymer-supported nanoparticles that can be used in an appropriate reaction medium and readily removed by filtration. Providing that an amphiphilic resin-dispersion of palladium nanoparticle catalyst is developed, the catalyst should exhibit following features combined in one system; e.g. (1) high catalytic activity owing to the large surface area of the nanoparticles, (2) water-based reactivity provided by the amphiphilicity of the PS-PEG matrix, and (3) good recyclability of heterogeneous catalysts. We wish to report herein design and preparation of an amphiphilic PS-PEG resin-dispersion of nanosized particles of palladium, and catalytic hydrodechlorination of aryl chlorides [7] and aerobic oxidation of alcohols [8] with the PS-PEG supported palladium nanoparticles under mild, aqueous conditions.

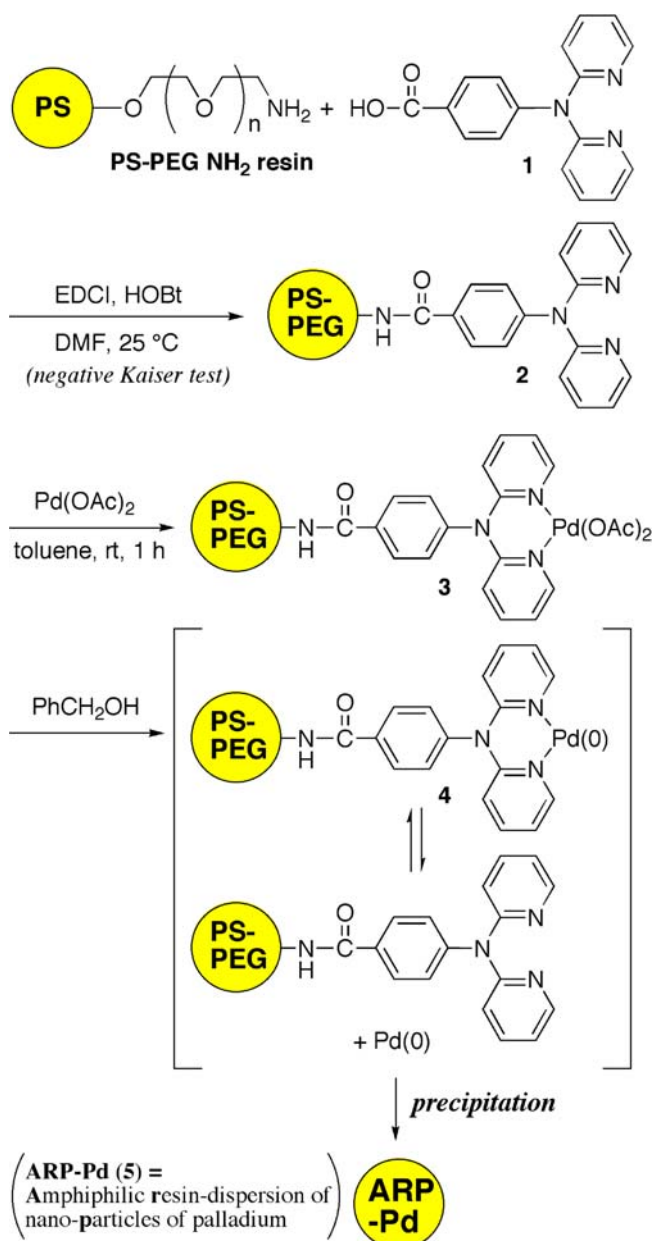
* Corresponding author.

E-mail address: uo@ims.ac.jp (Y. Uozumi).

2. Results and discussion

2.1. Preparation of an amphiphilic resin-dispersion of palladium nanoparticles

An amphiphilic resin-dispersion of palladium nanoparticles was readily prepared by reduction of a PS-PEG resin-supported bispyridine chelating palladium(II) complex (Scheme 1). Thus, a bispyridine chelating ligand anchored on PS-PEG amino-resin was obtained via dehydrative condensation of *N,N*-bis(pyrid-2-yl)-4-aminobenzoic acid (**1**) and PS-PEG resin bearing primary amino residue at the terminal of the PEG chain (1% DVB cross-linked, average diameter of polymer beads = 170 μm)[9] with 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (EDCI; 3 equiv.) and 1-hydroxybenzotriazole hydrate (HOBt; 4 equiv.) in DMF. A negative Kaiser test [10] indicated that the condensation was completed to form polymer-supported bis(pyridyl) ligand **2** quantitatively. The polymeric ligand **2** was complexed to palladium by treatment with an equimolar amount of $\text{Pd}(\text{OAc})_2$ in toluene at 25 °C to give the stable 16-electron divalent palladium complex **3**. The complex **3** was treated with benzyl alcohol in refluxing water for 12 h to generate palladium(0) complex **4** in situ, which should readily release the neutral palladium species. The nanopalladium particles were precipitated out in PS-PEG matrix to give the desired amphiphilic PS-PEG resin-dispersion of palladium nanoparticles (**5**, ARP-Pd) (loading value: 0.37 mmol Pd/g). Transmission electron microscopy (TEM) of the resulting palladium-resin shows that the palladium particles have a mean diameter of 9.1 nm with a narrow size distribution (Fig. 1).



Scheme 1.

ride (EDCI; 3 equiv.) and 1-hydroxybenzotriazole hydrate (HOBt; 4 equiv.) in DMF. A negative Kaiser test [10] indicated that the condensation was completed to form polymer-supported bis(pyridyl) ligand **2** quantitatively. The polymeric ligand **2** was complexed to palladium by treatment with an equimolar amount of $\text{Pd}(\text{OAc})_2$ in toluene at 25 °C to give the stable 16-electron divalent palladium complex **3**. The complex **3** was treated with benzyl alcohol in refluxing water for 12 h to generate palladium(0) complex **4** in situ, which should readily release the neutral palladium species. The nanopalladium particles were precipitated out in PS-PEG matrix to give the desired amphiphilic PS-PEG resin-dispersion of palladium nanoparticles (**5**, ARP-Pd) (loading value: 0.37 mmol Pd/g). Transmission electron microscopy (TEM) of the resulting palladium-resin shows that the palladium particles have a mean diameter of 9.1 nm with a narrow size distribution (Fig. 1).

2.2. Catalytic properties of ARP-Pd

The catalytic properties of an amphiphilic resin-dispersion of palladium nanoparticles (ARP-Pd) were examined for hydrodechlorination of aryl chlorides and aerobic oxidation of alcohols in water.

2.2.1. Hydrodechlorination

Hydrodehalogenation of aryl halides, especially of chloroarenes, has been recognized as an important chemical transformation in organic synthesis as well as in industrial applications [11]. Furthermore, because of the harmful nature of aryl chlorides, dechlorination has attracted increasing attention. Consequently, a wide variety of hydrodehalogenation reaction systems have appeared in the literature, among them, catalytic systems, which are usually performed with transition metal catalysts (e.g., Ni, Rh, Pd) and hydrogen sources (e.g., H_2 , metal hydrides, formic acid, hydrazine) [12]. If the hydrodechlorination of aryl chlorides proceeded in aqueous media with a recyclable catalyst and a mild hydrogen source, the reaction system would be an enormous plus since it would meet most environmental requirements. It was found that hydrodechlorination of aryl chlorides took place smoothly in aqueous reaction media with ammonium formate in the presence of the amphiphilic resin-dispersion of palladium nanoparticles, ARP-Pd. Representative results are shown in Table 1. When chlorobenzene was treated with ammonium formate in 10% aqueous isopropanol in the presence of 5 mol% palladium of the ARP-Pd catalyst at 25 °C for 120 min, hydrodechlorination proceeded smoothly to give benzene in quantitative yield (>99% GC yield) (Table 1, entry 1). Electron-rich (entries 2–6) as well as electron-deficient (entries 7–10) aromatics were readily dechlorinated under similar conditions to give the corresponding reduced products in high yields ranging from 89% to >99%, where wide functional group tolerance for benzylic hydroxyl, phenolic hydroxyl, amine, ketone, amide, carboxylic acid, and

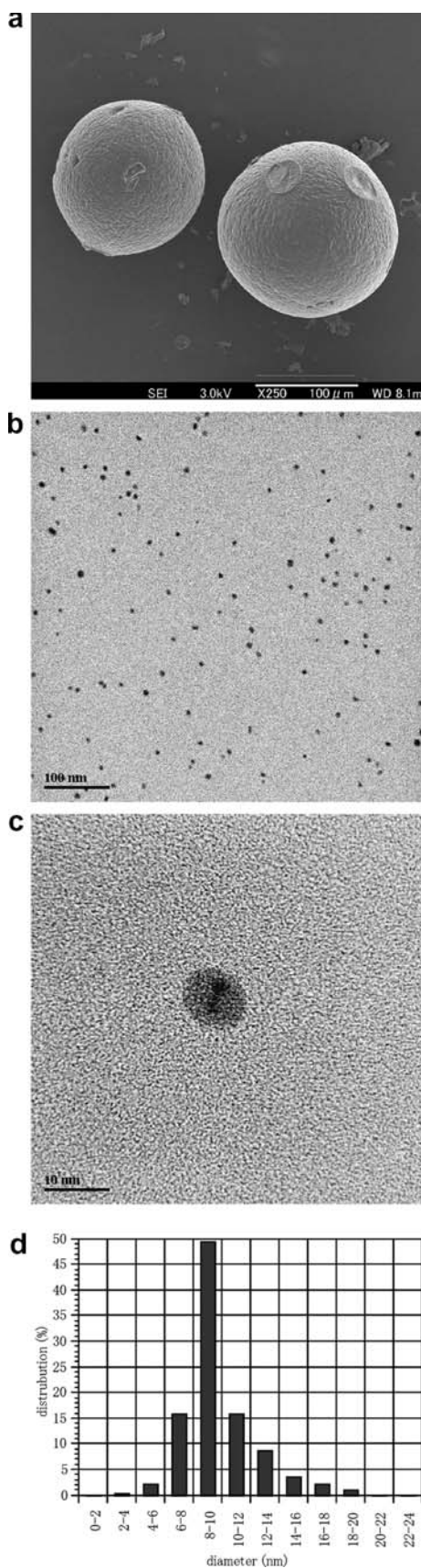
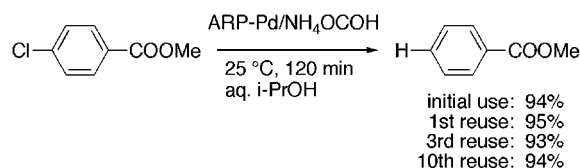


Fig. 1. A scanning electron microscopy (SEM) image (a), transmission electron microscopy (TEM) images (b and c), and the respective histogram of particle size distribution (d).

carboxylic ester was noted. Naphthyl chloride and pyridyl chloride underwent hydrodechlorination to afford naphthalene and pyridine in 95% and 99% yield, respectively (entries 11 and 12). Complete dechlorination of perchlorinated aromatics to non-chlorinated aromatics is of great value due to the high toxicity of the perchloroarenes. Hydrodechlorination of dichloroarenes (entries 13–16) and trichloroarenes (entries 17–20) took place smoothly with the ARP-Pd catalyst and ammonium formate to give benzene, phenol, aniline, and benzoic acid in excellent yields. Neither partially dechlorinated monochloroarenes or dichloroarenes were detected by GC–MS analysis. Dechlorination of pentachloroaniline was carried out using 3 equiv. of ammonium formate with respect to the chloroarene under otherwise similar conditions to give aniline in 85% isolated yield, using 1 mol% of palladium to the chloroarene (entry 21). Recycling experiments were examined for dechlorination of methyl 4-chlorobenzoate (Scheme 2). After the first use of the polymeric nanopalladium catalyst (Table 1, entry 10) to give 94% of methyl benzoate, the recovered catalyst ARP-Pd was taken on to ten subsequent reuses and exhibited stable catalytic activity. Thus, all ten recycling runs gave >99% GC yields of methyl benzoate, the first, third and tenth runs of which were chosen to confirm the isolated chemical yields of the dechlorinated product to give 95%, 93% and 94% yield of methyl benzoate, respectively.

2.2.2. Aerobic oxidation

Oxidation of alcohols forming carbonyl compounds is one of the most fundamental and important yet immature processes in organic chemistry [13]. Thus, although a variety of methods and reagents for the oxidation have been developed, until recently the traditional oxidation reactions have been performed with stoichiometric amounts of heavy metal reagents (e.g., Cr, Mn, etc.) or moisture sensitive expensive oxidants (e.g., DCC, oxalyl chloride, etc.) and often in environmentally undesirable media like chlorinated solvents which render them impractical [14]. There is good reason to believe that the ideal goal of alcohol oxidation would be the aerobic oxidation in water promoted by a heterogeneous catalyst under atmospheric pressure conditions resulting in a much cheaper, safer, and more environmentally benign oxidation protocol [15]. Recently, much work has appeared on catalytic oxidation of allylic or benzylic alcohols with molecular oxygen and several palladium catalyst systems have been developed for the oxidation. To explore the aquacatalytic potential of the ARP-Pd, we elected to study catalytic aerobic oxidation of alcohols



Scheme 2.

in water. Representative results are shown in Table 2. Thus, a mixture of 1 mol% palladium of ARP-Pd and benzyl alcohol was refluxed in water under atmospheric pres-

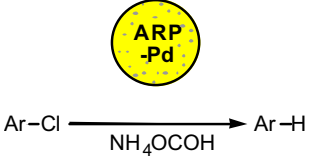
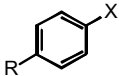
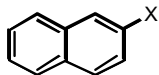
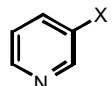
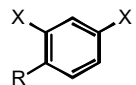
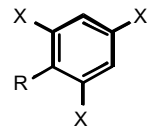
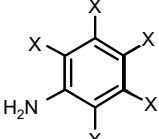
sure of oxygen gas for 90 min. After being cooled, the mixture was filtered and the catalyst resin was rinsed twice with a small portion of diethyl ether. The washings were concentrated in vacuo to give benzaldehyde quantitatively, the purity of which was analyzed by proton nuclear magnetic resonance (^1H NMR) and gas chromatography (GC) to be 97% without any chromatographic purification (Table 2, entry 1). During the reaction, no deposit of palladium black on the glass wall (the so-called palladium mirror) was observed. The recovered ARP-Pd showed essentially the same TEM image and was reused with negligible loss of catalytic activity. After the workup, the aqueous filtrate exhibited no catalytic activity for the oxidation. These observations would indicate that the palladium species does not leach into the aqueous phase under the reaction conditions.

Secondary alcohols gave the corresponding ketones under essentially the same conditions. Thus, phenethyl alcohol, benzhydrol, and 1-hydroxyindane underwent catalytic oxidation in water to give acetophenone, benzophenone, and indanone in >99%, 85%, and 95% yield, respectively (entries 2, 3 and 4). The catalytic oxidation of benzoin bearing an α -keto hydroxy group and isophorol bearing an allylic hydroxy group also proceeded smoothly to give benzyl and isophorone in 98% and 78% yields (entries 5 and 6). It is noteworthy that this catalyst system was also effective on the oxidation of non-activated alkanols. Thus, the oxidation of cyclooctanol took place in water under atmospheric pressure of oxygen gas to give 88% yield of cyclooctanone (entry 7). Catalytic aerobic oxidation of primary alcohols was carried out in 0.2 M aqueous solution of potassium carbonate under otherwise similar conditions. Thus, 1-octanol, 1-hexanol, and 1-butanol were oxidized by 20 mol% palladium of the ARP-Pd catalyst under oxygen gas (1 atm) in refluxing water in the presence of potassium carbonate. The mixture was filtered and the filtrate was acidified with hydrochloric acid, and extracted with diethyl ether to give excellent yields of the corresponding carboxylic acids (entries 11, 12, and 13). Recycle experiments were examined for the oxidation of cyclooctanol. Thus, after the first run giving 88% yield of cyclooctanone (entry 7), the ARP-Pd catalyst was successively subjected to a second oxidation to give 86% yield of cyclooctanone (entry 8), the average of the chemical yields for 4 continuous runs being 86%, demonstrating the practical recyclability of this catalyst (entries 7–10).

3. Conclusion

In summary, a novel amphiphilic PS-PEG resin-dispersion of nanoparticles of palladium, ARP-Pd, was designed and prepared with a view toward using it for palladium catalysis in water. ARP-Pd exhibited high catalytic performance in the hydrodechlorination of chloroarenes and the aerobic oxidation of alcohols under aqueous conditions. Dechlorination was found to take place smoothly using

Table 1
Hydrodechlorination of ArCl using ARP-Pd and Ammonium Formate^a


Entry	Ar-Cl/Ar-H (X = Cl/H)	Yield (%) ^b
		
		
1	R = H	> 99 ^c
2	R = CH ₃	> 99 ^c
3	R = CH ₂ OH	99
4	R = OCH ₃	89
5	R = OH	93
6	R = NH ₂	91
7	R = COCH ₃	97
8	R = CONH ₂	99
9	R = COOH	> 99
10	R = COOCH ₃	94
11		95 ^c
12		> 99 ^c
		
13	R = H	99 ^c
14	R = OH	97
15	R = NH ₂	92
16	R = COOH	99
		
17	R = H	> 99 ^c
18	R = OH	96
19	R = NH ₂	92
20	R = COOH	99
21		85
		

^a All reactions were carried out in 10% aqueous 2-propanol in the presence of 5 mol % palladium (with respect to substrate) of ARP-Pd and 3 equiv. of ammonium formate with respect to the chloroarene at 25 °C for 120 min.

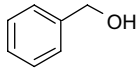
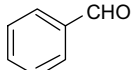
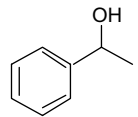
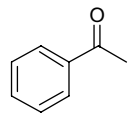
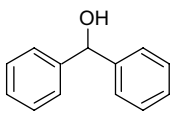
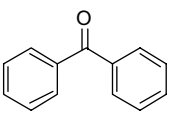
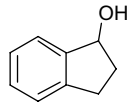
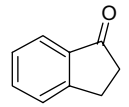
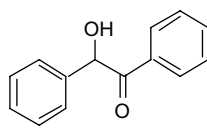
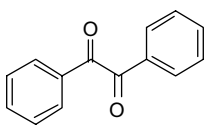
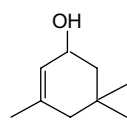
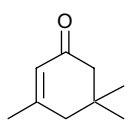
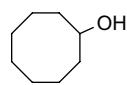
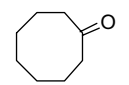
^b Isolated yield unless otherwise noted.

^c GC yield.

Table 2
ARP-Pd Catalyzed Oxidation of Alcohols in Water^a



$$\text{R}^1\text{CH(OH)R}^2 \xrightarrow[\text{H}_2\text{O, reflux}]{\text{O}_2 (1 \text{ atm})} \text{R}^1\text{C(=O)R}^2$$

Entry	Substrate	Product	Pd (mol%)	Time (h)	Yield (%)
1			1	1.5	97
2			5	20	> 99
3			5	20	85
4			5	20	95
5			1	2.5	98
6			5	20	78
7			20	20	88
8			(second run)	20	86
9			(third run)	20	83
10			(forth run)	20	87
11	<i>n</i> -C ₈ H ₁₇ OH	<i>n</i> -C ₇ H ₁₅ COOH	20	40	90
12	<i>n</i> -C ₆ H ₁₃ OH	<i>n</i> -C ₅ H ₁₁ COOH	20	40	98
13	<i>n</i> -C ₄ H ₉ OH	<i>n</i> -C ₃ H ₇ COOH	20	40	93

^a All reactions were carried out in refluxing water under 1 atm of oxygen gas. Pd mol%/reaction time (h): entries 1 and 5 = 1/2, entries 2–5 = 5/20, entry 7 = 20/20, entries 11–13 = 20/40. A ratio of alcohol (mmol)/water (mL) = 1/1.3. All yields are for the pure products. Oxidation of 1-alkanols were performed in 0.2 M aqueous solution of potassium carbonate.

aqueous ammonium formate with high recyclability, which would provide a safe and clean detoxification protocol for aqueous chloroarene pollutants. The catalytic alcohol oxi-

dation was achieved in water under atmospheric pressure of molecular oxygen with high recyclability to achieve high level of chemical greenness.

4. Experimental

4.1. General

All starting materials and the authentic samples of the products (dechlorination and oxidation) were purchased from Aldrich Chemical Co. Inc. and Tokyo Kasei Co. Ltd., and used without further purification. All catalytic reactions were carried out with shaking on a wrist-action shaker (Burrel Scientific Inc.) or a Petri-Syzer (Hi-Pep Co. Ltd.). All reaction products were identified by comparison of their GC-MS spectra (performed on Hewlett Packard HP 6890 with 5973 Network Mass Detector) and ^1H NMR spectra (JEOL JNM-AL400 spectrometer (400 MHz) or JEOL JNM-AL500 spectrometer (500 MHz)) with the authentic data. Swollen gel-phase magic angle spinning carbon 13 NMR were recorded on JEOL JNM-AL400 spectrometer (100 MHz for ^{13}C). Chemical shifts of ^{13}C NMR are given relative to CDCl_3 as an internal standard (δ 77.0).

4.2. PS-PEG resin-supported bispyridine ligand **2**

A mixture of 5.0 g of PS-PEG amino resin (average diameter = 170 μm , 1% divinylbenzene cross-linked, loading value of amino residue = 0.4 mmol/g), EDCI (709 mg, 3.70 mmol), HOBt (625 g, 4.63 mmol), and 4-(bis(pyrid-2-yl)amino)benzoic acid (808 mg, 2.78 mmol) in 60 mL of DMF was shaken at room temperature for 10 h. The mixture was filtered and the resulting resin beads were rinsed three times with DMF and three times with dichloromethane, then dried in vacuo to give **2**. Swollen gel-phase magic angle spinning carbon 13 NMR (characteristic signals are given below. Signals of PS and PEG moieties are omitted for simplicity): δ 117.2, 118.5, 125.4, 128.2, 130.5, 137.4, 147.4, 148.3, 157.6, 166.4.

4.3. PS-PEG resin-supported palladium acetate-bispyridine complex **3**

A mixture of 5.5 g of **2** (loading value of ligand residue = 0.37 mmol/g), palladium diacetate (457 mg, 2.04 mmol) in 60 mL of toluene was shaken at room temperature for 1 h. The mixture was filtered and the resulting resin beads were rinsed three times with dichloromethane and then dried in vacuo to give **3**. Swollen gel-phase magic angle spinning carbon 13 NMR (Characteristic signals are given below. Signals of PS and PEG moieties are omitted for simplicity): δ 23.0, 116.4, 117.2, 120.1, 129.7, 135.7, 140.0, 142.1, 150.3, 150.7, 165.5, 177.5.

4.4. PS-PEG resin-dispersion of palladium nanoparticles **5** (ARP-Pd)

A mixture of 5.6 g of **3** (loading value of palladium residue = 0.37 mmol/g) and 18 mL of benzyl alcohol in 56 mL of water was refluxed for 12 h (no leaching of palladium to

the water phase was observed, which would have resulted in the formation of palladium black). The mixture was filtered and the resulting resin beads were rinsed three times with water and three times with acetone, then dried in vacuo to give ARP-Pd.

4.5. General procedure for the hydrodechlorination

A typical procedure for the reaction of methyl 4-chlorobenzoate in the presence of ARP-Pd to give benzoic acid is as follows: To a mixture of ARP-Pd (60 mg, 24 μmol Pd) and methyl 4-chlorobenzoate (85 mg, 0.5 mmol) in 10% aqueous isopropanol (1.0 mL) was added an aqueous solution of ammonium formate (63 mg, 1.0 mmol in 0.2 mL of H_2O) at 25 $^\circ\text{C}$. The mixture was stirred at 25 $^\circ\text{C}$ for 120 min. The reaction mixture was filtered and the catalyst beads were extracted with ethyl acetate (5 mL, 3 times). The combined extract was washed with brine and dried over Na_2SO_4 (100% conversion; >99% GC yield). The crude product was chromatographed on silica gel to give 94% isolated yield of methyl benzoate. GC-MS spectrum of the product showed good similarity (>95%) with the authentic data.

4.6. Catalytic oxidation of alcohols in water

A typical procedure is given for the oxidation of 1-hexanol. A mixture of 106 mg of ARP-Pd (39 μmol of palladium), 1-hexanol (22 μL , 0.17 mmol), and potassium carbonate (24 mg, 0.17 mmol) in 0.9 mL of water was refluxed for 40 h under an atmospheric pressure of oxygen gas. After being cooled, the mixture was filtered and the resin beads were rinsed three times with saturated aqueous sodium bicarbonate solution. The combined filtrate was acidified with 5% hydrochloric acid and extracted with diethyl ether. The extract was dried over magnesium sulfate and concentrated in vacuo to give 20 mg of hexanoic acid (98%) as a pure compound (>99% purity on GC and proton NMR analysis).

References

- [1] For reviews on aqueous-switching, see (a) C.-J. Li, T.-H. Chan, *Organic Reactions in Aqueous Media*, Wiley-VCH, New York, 1997; (b) P.A. Grieco, *Organic Synthesis in Water*, Kluwer Academic Publishers, Dordrecht, 1997; (c) W.A. Herrmann, C.W. Kohlpaintner, *Angew. Chem., Int. Ed. Engl.* 32 (1993) 1524; (d) U.M. Lindström, *Chem. Rev.* 102 (2002) 2751.
- [2] For reviews on heterogeneous-switching, see (a) D.C. Bailey, S.H. Langer, *Chem. Rev.* 81 (1981) 109; (b) S.J. Shuttleworth, S.M. Allin, P.K. Sharma, *Synthesis* (1997) 1217; (c) S.J. Shuttleworth, S.M. Allin, R.D. Wilson, D. Nasturica, *Synthesis* (2000) 1035; (d) F.Z. Dörwald, *Organic Synthesis on Solid Phase*, Wiley-VCH, Weinheim, 2000; (e) N.E. Leadbeater, M. Marco, *Chem. Rev.* 102 (2002) 3217;

- (f) C.A. McNamara, M.J. Dixon, M. Bradley, *Chem. Rev.* 102 (2002) 3275;
- (g) D.E. De Vos, I.F.J. Vankelecom, P.A. Jacobs (Eds.), *Chiral Catalyst Immobilization and Recycling*, WILEY-VCH, Weinheim, 2000;
- (h) S.V. Ley, I.R. Baxendale, R.N. Bream, P.S. Jackson, A.G. Leach, D.A. Longbottom, M. Nesi, J.S. Scott, R.I. Storer, S.J. Taylor, *J. Chem. Soc., Perkin Trans. 1* (2000) 3815;
- (i) Q.-H. Fan, Y.-M. Li, A.S.C. Chan, *Chem. Rev.* 102 (2002) 3385.
- [3] For a recent review on polymer-supported palladium catalysts, see Y. Uozumi, *Top. Curr. Chem.* 242 (2004) 77.
- [4] For studies on polymer-supported palladium catalysts from the author's group, see (a) Y. Uozumi, H. Danjo, T. Hayashi, *Tetrahedron Lett.* 38 (1997) 3557, π -allylic substitution;
- (b) H. Danjo, D. Tanaka, T. Hayashi, Y. Uozumi, *Tetrahedron* 55 (1999) 14341, π -allylic substitution;
- (c) Y. Uozumi, H. Danjo, T. Hayashi, *J. Org. Chem.* 64 (1999) 3384, cross-coupling;
- (d) Y. Uozumi, T. Watanabe, *J. Org. Chem.* 64 (1999) 6921, carbonylation reaction;
- (e) Y. Uozumi, Y. Nakai, *Org. Lett.* 4 (2002) 2997, Suzuki-Miyaura coupling;
- (f) Y. Uozumi, T. Kimura, *Synlett* (2002) 2045, Heck reaction;
- (g) Y. Uozumi, Y. Kobayashi, *Heterocycles* 59 (2003) 71, Sonogashira reaction;
- (h) Y. Uozumi, K. Shibatomi, *J. Am. Chem. Soc.* 123 (2001) 2919, asymmetric alkylation;
- (i) Y. Uozumi, H. Tanaka, K. Shibatomi, *Org. Lett.* 6 (2004) 281, asymmetric amination;
- (j) H. Hocke, Y. Uozumi, *Synlett* 12 (2002) 2049, asymmetric catalysis;
- (k) H. Hocke, Y. Uozumi, *Tetrahedron* 59 (2003) 619, asymmetric catalysis;
- (l) H. Hocke, Y. Uozumi, *Tetrahedron* 60 (2004) 9297, asymmetric catalysis;
- (m) Y. Nakai, Y. Uozumi, *Org. Lett.* 7 (2005) 291, asymmetric cycloisomerization;
- (n) Y. Uozumi, M. Kikuchi, *Synlett* (2005) 1775, cross-coupling;
- (o) Y. Uozumi, M. Kimura, *Tetrahedron Asymmetry* 17 (2006) 161, asymmetric etherification.
- [5] For reviews, see (a) M. Králík, A. Biffis, *J. Mol. Cat. A* 177 (2001) 113;
- (b) B. Corain, M. Králík, *J. Mol. Cat. A* 173 (2001) 99.
- [6] (a) For several examples of polymer-stabilized palladium nanoparticles, see K. Okamoto, R. Akiyama, H. Yoshida, T. Yoshida, S. Kobayashi, *J. Am. Chem. Soc.* 127 (2005) 2125;
- (b) F. Artuso, A.A. D'Archivio, S. Lora, K. Jerabek, M. Kralik, B. Corain, *Chemistry – A European Journal* 9 (2003) 5292;
- (c) M.M. Demir, M.A. Gulgun, Y.Z. Menciloglu, B. Erman, S.S. Abramchuk, E.E. Makhaeva, A.R. Khokhlov, V.G. Matveeva, M.G. Sulman, *Macromolecules* 37 (2004) 1787;
- (d) K. Esumi, R. Isono, T. Yoshimura, *Langmuir* 20 (2004) 237;
- (e) T. Hashimoto, A. Okumura, D. Tanabe, *Macromolecules* 36 (2003) 7324;
- (f) S. Horiuchi, T. Fujita, T. Hayakawa, Y. Nakao, *Langmuir* 19 (2003) 2963;
- (g) S.V. Ley, C. Mitchell, D. Pears, C. Ramarao, J.-Q. Yu, W. Zhou, *Org. Lett.* 5 (2003) 4665;
- (h) N. Bremeyer, S.V. Ley, C. Ramarao, I.M. Shirley, S.C. Smith, *Synlett* (2002) 1843;
- (i) S.V. Ley, C. Ramarao, R.S. Gordon, A.B. Holmes, A.J. Morrison, I.F. McConvey, I.M. Shirley, S.C. Smith, M.D. Smith, *Chem. Commun.* (2002) 1134;
- (j) J.-Q. Yu, H.-C. Wu, C. Ramarao, J.B. Spenver, S.V. Ley, *Chem. Commun.* (2002) 678;
- (k) N. Toshima, Y. Shiraishi, T. Teranishi, M. Miyake, T. Tominaga, H. Watanabe, W. Brijoux, H. Bönemann, G. Schmid, *Appl. Organometal. Chem.* 15 (2001) 178;
- (l) T. Teranishi, M. Miyake, *Chem. Mater.* 10 (1998) 594;
- (m) D.E. Bergbreiter, B. Chen, T.J. Lynch, *J. Org. Chem.* 48 (1983) 4179.
- [7] A preliminary communication has been reported, see R. Nakao, H. Rhee, Y. Uozumi, *Org. Lett.* 7 (2005) 163.
- [8] (a) A preliminary communication has been reported, see Y. Uozumi, R. Nakao, *Angew. Chem., Int. Ed. Engl.* 42 (2003) 194;
- (b) Y. Uozumi, R. Nakao, *Angew. Chem.* 115 (2003) 204.
- [9] (a) E. Bayer, W. Rapp, in: W. Voelter, E. Bayer, Y.A. Ovchinnikov, V.T. Iwanov (Eds.), *Chemistry of Peptides and Proteins*, vol. 3, Walter de Gruyter, Berlin, 1986, p. 3;
- (b) W. Rapp, in: G. Jung (Ed.), *Combinatorial Peptide and Nonpeptide Libraries*, VCH, Weinheim, 1996, p. 425;
- (c) X. Du, R.W. Armstrong, *J. Org. Chem.* 62 (1997) 5678;
- (d) O.W. Gooding, S. Baudert, T.L. Deegan, K. Heisler, J.W. Labadie, W.S. Newcomb, J.A. Porco Jr., P. Eikeren, *J. Comb. Chem.* 1 (1999) 113.
- [10] E. Kaiser, R.L. Colescott, C.D. Bossinger, P.I. Cook, *Anal. Biochem.* 34 (1970) 595.
- [11] For a review, see F. Alonso, I.P. Beletskaya, M. Yus, *Chem. Rev.* 102 (2002) 4009.
- [12] For recent examples of palladium-mediated hydrodechlorination of chloroarenes, see (a) R. Kang, X. Ouyang, J. Han, X. Zhen, *J. Mol. Cat. A* 175 (2001) 153;
- (b) C. Desmarets, S. Kuhl, R. Schneider, Y. Fort, *Organometallics* 21 (2002) 1554;
- (c) R.E. Maleczka Jr., R.J. Rahaim Jr., R.R. Teixeira, *Tetrahedron Lett.* 43 (2002) 7087;
- (d) H. Sajiki, A. Kume, K. Hattori, K. Hirota, *Tetrahedron Lett.* 43 (2002) 7247;
- (e) H. Sajiki, A. Kume, K. Hattori, H. Nagase, K. Hirota, *Tetrahedron Lett.* 43 (2002) 7251;
- (f) P.P. Cellier, J.-F. Spindler, M. Taillefer, H.-J. Cristau, *Tetrahedron Lett.* 44 (2003) 7191;
- (g) O. Navarro, H. Kaur, P. Mahjoor, S.P. Nolan, *J. Org. Chem.* 69 (2004) 3173;
- (h) P. Selvam, S.U. Sonavane, S.K. Mohapatra, R.V. Jayaram, *Tetrahedron Lett.* 45 (2004) 3071.
- [13] For reviews on metal-mediated oxidations, see (a) W.J. Mijs, C.R.H.I. De Jonge (Eds.), *Organic Syntheses by Oxidation with Metal Compounds*, Plenum Press, New York, 1986;
- (b) R.A. Sheldon, I.W.C.E. Arends, A. Dijkstra, *Catal. Today* 57 (2000) 157;
- (c) J. Muzart, *Tetrahedron* 59 (2003) 5789;
- (d) S.S. Stahl, *Angew. Chem., Int. Ed.* 43 (2004) 3400.
- [14] For a general review, see M. Hudlicky, *Oxidations in Organic Chemistry* ACS monograph, vol. 186, ACS, Washington, DC, 1990.
- [15] (a) For recent examples of aerobic oxidations with palladium compounds, see K.P. Peterson, R.C. Larock, *J. Org. Chem.* 63 (1998) 3185;
- (b) T. Nishimura, T. Onoue, K. Ohe, S. Uemura, *Tetrahedron Lett.* 39 (1998) 6011;
- (c) T. Nishimura, T. Onoue, K. Ohe, S. Uemura, *J. Org. Chem.* 64 (1998) 6750;
- (d) N. Kakiuchi, Y. Maeda, T. Nishimura, S. Uemura, *J. Org. Chem.* 66 (2001) 6620;
- (e) G.-J. ten Brink, I.W.C. Arends, R.A. Sheldon, *Science* 287 (2000) 1636;
- (f) M.J. Schultz, C.C. Park, M.S. Sigman, *Chem. Commun.* (2002) 3034;
- (g) D.R. Jensen, M.J. Schultz, J.A. Mueller, M.S. Sigman, *Angew. Chem., Int. Ed.* 42 (2003) 3810;
- (h) G.-J. ten Brink, I.W.C.E. Arends, R.A. Sheldon, *Adv. Synth. Catal.* 344 (2002) 355;
- (i) T. Nishimura, S. Uemura, *Synlett* (2004) 201;
- (j) S. Paaavola, K. Zetterberg, T. Privalov, I. Csoregh, C. Moberg, *Adv. Synth. Catal.* 346 (2004) 237;

- (k) T. Iwasawa, M. Tokunaga, T. Obora, Y. Tsuji, *J. Am. Chem. Soc.* 126 (2004) 6554;
- (l) M.J. Schultz, S.S. Hamilton, D.R. Jensen, M.S. Sigman, *J. Org. Chem.* 70 (2005) 3343;
- (m) For recent leading references on heterogeneous palladium catalysts for aerobic oxidation of alcohols see T. Nishimura, N. Kakiuchi, M. Inoue, S. Uemura, *Chem. Commun.* (2000) 1245;
- (n) N. Kakiuchi, Y. Maeda, T. Nishimura, S. Uemura, *J. Org. Chem.* 66 (2001) 6620;
- (o) K. Moroi, K. Yamaguchi, T. Hara, T. Mizugaki, K. Ebitani, K. Kaneda, *J. Am. Chem. Soc.* 124 (2002) 11572;
- (p) N. Kakiuchi, M. Nishimura, M. Inoue, S. Uemura, *Bull. Chem. Soc. Jpn.* 74 (2001) 165;
- (q) K. Mori, T. Hara, T. Mizugaki, K. Ebitani, K. Kaneda, *J. Am. Chem. Soc.* 126 (2004) 10657;
- (r) M.S. Kwon, N. Kim, C.M. Park, J.S. Lee, K.Y. Kang, J. Park, *Org. Lett.* 7 (2005) 1077;
- (s) U.R. Pillai, E. Sahle-Demessie, *Green Chem.* 6 (2004) 161.