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Controlled Synthesis of Hydroxyapatite-Supported Palladium Complexes as Highly Efficient Heterogeneous Catalysts

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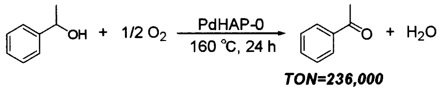
Precise architectures of steric and electronic properties of palladium species play a crucial role in designing highly functionalized catalyst systems responsible for the target of organic transformations.[1] Organic ligands can tune-up the properties of metal complex catalysts; however, they are faced with a number of disadvantages such as thermal instability and difficulties associated with corrosions. The use of solid surface as a macroligand is a powerful protocol to create stable active sites, which also provides unique catalytic functions including site isolation of well-defined active species, cooperative action by several sites, and steric control of a reaction intermediate.[2]

Hydroxyapatites, the main component of bones and teeth, are of considerable interest in many areas because of ion-exchange ability, adsorption capacity, and acid−base properties. The chemical composition of hydroxyapatites can be modified from the stoichiometric form to the nonstoichiometric Ca-deficient form. Recently, we created a monomeric Ru phosphate complex on the hydroxyapatite surface using cation-exchange ability as an excellent catalyst for aerobic oxidations of alcohols and amines.[3] These successes have provided us with a new strategy for the design of high-performance heterogeneous catalysts based on hydroxyapatites, having potential application as a macroligand for catalytic active centers. In this paper, we present two new classes of hydroxyapatite-bound Pd complexes designed with strict compositional and structural control. Both stoichiometric and Ca-deficient hydroxyapatites are employed, and the catalysts exhibit specific novel functions as heterogeneous catalysts.

Hydroxyapatites were synthesized from $Ca(NO_3)_2{\cdot}4H_2O$ and $(NH_4)_2HPO_4$ by the precipitation method.[4] Selecting appropriate Ca/P molar ratios gave the stoichiometric hydroxyapatite $Ca_{10}(PO_4)_6(OH)_2$ (Ca/P = 1.67, HAP-0) and the nonstoichiometric Ca-deficient hydroxyapatite $Ca_9(HPO_4)(PO_4)_5(OH)$ (Ca/P = 1.50, HAP-1), respectively. The treatment of the HAP-0 with an acetone solution of $PdCl_2(PhCN)_2$ yielded the hydroxyapatite-bound Pd complex, PdHAP-0 (Pd content: 0.02 mmol g^{-1}), while the PdHAP-1 (Pd content: 0.015 mmol g^{-1}) was obtained using the HAP-1 by the same method.

XPS and EDX showed that the atomic ratio of Pd to Cl was 1:2 for the PdHAP-0 and chlorine was not detected in the PdHAP-1. ICP analysis revealed that no Ca^{2+} was present in the filtrate after palladium loading. Therefore, isomorphic substitution of Ca for Pd did not occur in organic media, which is in sharp contrast to the Ru-exchanged hydroxyapatite prepared previously by the cation-exchange method in water.[3] The Pd K-edge XANES spectra of both PdHAPs reveal that all Pd species are in the 2+ oxidation state. In the Fourier transform (FT) of k^3-weighted EXAFS for the PdHAPs, the absence of peaks around 2.5 Å shows that there are no Pd−Pd bonds in the PdHAPs (Figure 1aA and B). The inverse FT of the peaks around 1−2 Å for the PdHAP-0 was well fitted using Pd−Cl and Pd−O shells, whereas the best fit for the PdHAP-1 was achieved using only a Pd−O shell. Conclusively, a monomeric $PdCl_2$ species is grafted by chemisorption on the HAP-0 surface (Figure 1bE), and a monomeric Pd^{II} phosphate complex surrounded by four oxygens is formed in a Ca-deficient site of the HAP-1 (Figure 1bF). *Two unique monomeric Pd species with intrinsically different surroundings can be created on the solid surfaces through precise control of the Ca/P ratios of the parent hydroxyapatites.*

As summarized in Table 1, the PdHAP-0 is an effective heterogeneous catalyst for the aerobic oxidation of a wide variety of alcohols. Especially, it exhibited high catalytic activity for benzylic and allylic alcohols, giving the corresponding carbonyl compounds in excellent yields. In the case of cyclopropylphenylmethanol, the oxidation of a hydroxyl function occurred without cleavage of a cyclopropyl ring (entry 5). Aliphatic and heterocyclic alcohols were also smoothly oxidized into the corresponding ketones and aldehyde (entries 9−12). A 250 mmol scale oxidation of 1-phenylethanol efficiently proceeded without organic solvents, and the TON of acetophenone based on Pd approached 236 000 (eq 1).



(1)

This TON value is 3 orders of magnitude larger than those previously reported for any catalyst systems under an atmospheric O_2 pressure.[5] The FT of k^3-weighted EXAFS for the recovered PdHAP-0 exhibited a single peak at approximately 2.5 Å due to the formation of Pd metal as shown in Figure 1aC. TEM also revealed the presence of Pd particles with a diameter of ca. 40 Å. ICP analysis of the filtrate confirmed that no leaching of Pd species occurred during the above oxidations, and then the PdHAP-0 could be reused without loss of the catalytic activity and selectivity.[6] It is notable that the above oxidations hardly occurred in the presence of the PdHAP-1, accompanied with none of the structural change around the Pd^{II} center as confirmed by EXAFS (Figure 1aD).

Furthermore, we found that the PdHAP-1 was an outstanding catalyst for the Heck and Suzuki reactions as shown in Table 2. For example, the TON based on Pd reached 47 000 for 24 h in the case of bromobenzene (**1a**) with styrene (**2a**) (entry 1). To the best of our knowledge, *the PdHAP-1 is the most active heterogeneous catalyst among those reported so far*.[7] The recovered PdHAP-1 had an original monomeric Pd^{II} structure and was recyclable with retention of its high catalytic activity. In the Heck reaction of **1a** with **2a**, the catalyst was removed at 50% conversion under Ar atmosphere, and the filtrate was further reacted with fresh K_2CO_3 at 130 °C for 6 h. The above treatment of the filtrate gave no yield

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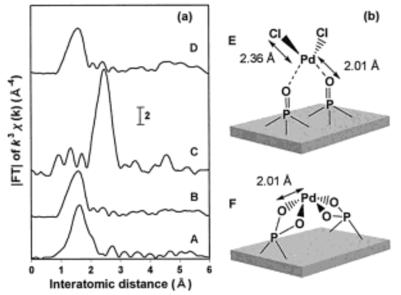


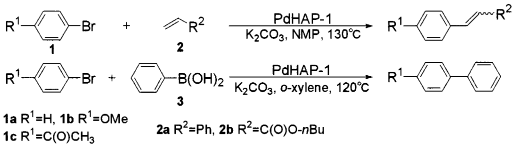
Figure 1. (a) Fourier transforms of k^3-weighted Pd K-edge EXAFS experimental data for (A) PdHAP-0, (B) PdHAP-1, (C) recovered PdHAP-0, and (D) recovered PdHAP-1 for the oxidation of 1-phenylethanol. Phase shift was not corrected. Reactions were conducted with 1-phenylethanol (1 mmol), PdHAP (0.1 g, Pd: 2 μmol), and trifluorotoluene (5 mL) at 90 °C for 1 h under O_2 atmosphere. (b) Proposed surface structures around Pd^{II} of PdHAP-0 (E) and PdHAP-1 (F).

Table 1. Aerobic Oxidation of Alcohols Catalyzed by PdHAP-0[a]

entry	alcohol	Pd (mol %)	*t*/h	yield (%)[b]
1	benzyl alcohol	0.2	1	99
2	4-methylbenzyl alcohol	0.2	3	99
3	4-isopropylbenzyl alcohol	0.2	3	99
4	1-phenylethanol	0.2	1	98
5	cyclopropylphenylmethanol	0.6	24	94
6[c]	cinnamyl alcohol	0.2	6	87
7[c]	3-octen-2-ol	0.2	24	80
8[c]	carveol	0.2	24	80
9	2-octanol	0.6	24	91
10	cyclobutanol	0.6	24	84
11	cyclopentanol	0.6	24	84
12	2-thiophenemethanol	0.6	24	99

[a] Reaction conditions: alcohol (1 mmol), trifluorotoluene (5 mL), PdHAP-0 (0.1−0.3 g, Pd: 2−6 μmol), 90 °C, O_2 atmosphere. [b] Yields were determined by GC analysis based on alcohol using an internal standard technique. [c] Toluene (5 mL) was used as the solvent.

Table 2. Heck and Suzuki Reactions Catalyzed by PdHAP-1[a]



entry	aryl bromide	acceptor	*t*/h	yield (%)[b]	TON (–)
1	**1a**	**2a**	24	94	47 000
2	**1b**	**2a**	24	90	45 000
3	**1c**	**2a**	20	96	48 000
4	**1a**	**2b**	20	91	45 500
5	**1b**	**2b**	24	94	47 000
6	**1c**	**2b**	20	98	49 000
7[c]	**1a**	**3**	4	80	40 000
8[c]	**1b**	**3**	6	91	45 500
9[c]	**1c**	**3**	4	94	47 000

[a] Reaction conditions: aryl halide (37.5 mmol), acceptor (45 mmol), PdHAP-1 (0.05 g, $2-10^{-3}$ mol % of Pd based on aryl bromide), K_2CO_3 (45 mmol), NMP (50 mL), 130 °C, Ar atmosphere. [b] Yields were determined by GC analysis based on aryl halid using an internal standard technique. [c] *o*-Xylene (50 mL) was used as solvent; 120 °C.

of coupling products. Pd leaching in the filtrate was not detected by ICP. Therefore, it can be said that this Heck reaction proceeds on the PdHAP-1 surface, but not with dissolved palladium species.[8] In contrast, the PdHAP-0 catalyst was less effective in the Heck reaction of **1a** with **2a** (TON = 1060 for 24 h), where the formation of Pd^0 particles with a diameter of ca. 50 Å was observed by TEM.

In the present PdHAP-1 catalyst system, the competitive Heck reactions in an equimolar mixture of *p*-substituted iodobenzenes using **2a** gave a Hammett ρ value of 1.09, which differs from 2.00 with $Pd(PPh_3)_4$,[9] but is similar to 1.39 with the Pd^{II} PCP-type complex.[10] In a competitive reaction of olefins between **2a** and *n*-butylacrylate (**2b**) with iodobenzene, the PdHAP-1 gave a high product ratio of 9.6 for *n*-butylcinnamate to stilbene, which significantly exceeded 4.1 observed with $Pd(PPh_3)_4$. The above phenomena support that this Heck reaction does not proceed via the traditional Pd^0/Pd^{II} cycle but via the Pd^{II}/Pd^{IV} mechanism.[10,11] These unusual performances of Pd are attributed to the extremely robust monomeric Pd^{II} structure surrounded by phosphate ligands on the hydroxyapatite surface, which effectively serves as a powerful alternative to organic ligands.

We have demonstrated a novel approach to catalyst design using hydroxyapatites and realized excellent catalytic performances. No Pd leaching was observed, and then the catalysts were recyclable. The PdHAP catalytic systems are therefore suitable for large-scale operations, meeting the increasing demands for environmentally friendly chemical processes. We expect that our immobilizing protocol based on hydroxyapatites as a macroligand will offer an attractive route for the design of functional catalysts at the atomic and molecular level.

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Supporting Information Available: Experimental procedure, curve fitting analysis, and TEM images (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

References

(1) (a) Heck, R. F. *Palladium Reagents in Organic Syntheses*; Academic Press: London, 1985. (b) Tsuji, J. *Palladium Reagents and Catalysts*; Wiley: Chichester, 1995. (c) Trost, B. M. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 259. (d) *Applied Homogeneous Catalysis with Organometallic Compounds*; Cornils, B., Herrmann, W. A., Eds.; VCH: Weinheim, 1996. (e) Jia, C.; Kitamura, T.; Fujiwara, Y. *Acc. Chem. Res.* **2001**, *34*, 633.

(2) (a) Gates, B. C. *Chem. Rev.* **1995**, *95*, 511. (b) Basset, J.-M.; Lefebre, F.; Santini, C. *Coord. Chem. Rev.* **1998**, *178−180*, 1703. (c) Iwasawa, Y. *Prepr. Solid Catal.* **1999**, 427. (d) Bergbreiter, D. E. *Med. Res. Rev.* **1999**, *19*, 439.

(3) (a) Yamaguchi, K.; Mori, K.; Mizugaki, T.; Ebitani, K.; Kaneda, K. *J. Am. Chem. Soc.* **2000**, *122*, 7144. (b) Mori, K.; Yamaguchi, K.; Mizugaki, T.; Ebitani, K.; Kaneda, K. *Chem. Commun.* **2001**, 461.

(4) Sugiyama, S.; Minami, T.; Hayashi, H.; Tanaka, M.; Shigemoto, N.; Moffat, J. B. *J. Chem Soc., Faraday Trans.* **1996**, *92*, 293.

(5) For recent reports of aerobic alcohol oxidation, see: (a) Markó, I. E.; Giles, P. R.; Tsukazaki, M.; Chellé-Regnaut, I.; Urch, C. J.; Brown, S. M. *J. Am. Chem. Soc.* **1997**, *119*, 12661. (b) Peterson, K. P.; Larock, R. C. *J. Org. Chem.* **1998**, *63*, 3185. (c) Hanyu, A.; Takezawa, E.; Sakaguchi, S.; Ishii, Y. *Tetrahedron Lett.* **1998**, *39*, 5557. (d) Nishimura, T.; Onoue, T.; Ohe, K.; Uemura, S. *J. Org. Chem.* **1999**, *64*, 6750. (e) ten Brink, G.-J.; Arends, I. W. C. E.; Sheldon, R. A. *Science* **2000**, *287*, 1636. (f) Dijksman, A.; Marino-Gonzalez, A.; Payeras, A. M. I.; Arends, I. W. C. E.; Sheldon, R. A. *J. Am. Chem. Soc.* **2001**, *123*, 6826. (g) Son, Y.-C.; Makwana, V. D.; Howell, A. R.; Suib, S. L. *Angew. Chem., Int. Ed.* **2001**, *40*, 4280. (h) Liotta, L. F.; Venezia, A. M.; Deganello, G.; Longo, A.; Martorana, A.; Schay, Z.; Guczi, L. *Catal. Today* **2001**, *66*, 271. (i) Döbler, C.; Mehtretter, G. M.; Sundermeier, U.; Eckert, M.; Militzer, H.-C.; Beller, M. *Tetrahedron Lett.* **2001**, *42*, 8447. (j) Steinhoff, B. A.; Fix, S. R.; Stahl, S. S. *J. Am. Chem. Soc.* **2002**, *124*, 766.

(6) See Supporting Information for experimental details.

(7) For recent reports of heterogeneous Pd-catalyzed Heck and Suzuki reactions, see: (a) Christian, P. M.; David, W. W.; Jackie, Y. Y. *J. Am. Chem. Soc.* **1998**, *120*, 12289. (b) Jayasree, S.; Seayad, A.; Laurent, R. D.; Henrike, H.; Klaus, K. *J. Am. Chem. Soc.* **2001**, *123*, 5990. (c) Mubofu, E. B.; Clark, J. H.; Macquarrie, D. J. *Green Chem.* **2001**, *3*, 23. (d) Köhler, K.; Heidenreich, R. G.; Krauter, J.-G. E.; Pietsch, J. *Chem.-Eur. J.* **2002**, *8*, 622.

(8) There is controversy whether the Heck reaction using solid Pd catalysts occurred on their surface or not, see: (a) Zhao, F.; Murakami, K.; Shirai, M.; Arai, M. *J. Catal.* **2000**, *194*, 479. (b) Davies, I. W.; Matty, L.; Hughes, D. L.; Reider, P. J. *J. Am. Chem. Soc.* **2001**, *123*, 10139.

(9) Fauvarque, J.-F.; Pflüger, F. *J. Organomet. Chem.* **1981**, *208*, 419.

(10) Ohff, M.; Ohff, A.; van der Boom, M. E.; Milstein, D. *J. Am. Chem. Soc.* **1997**, *119*, 11687.

(11) (a) Herrmann, W. A.; Brossmer, C.; Öfele, K.; Reisinger, C.-P.; Priermeier, T.; Beller, M.; Fischer, H. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1844. (b) Shaw, B. L.; Perera, S. D.; Staley, E. A. *Chem. Commun.* **1998**, 1361.

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