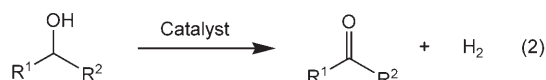
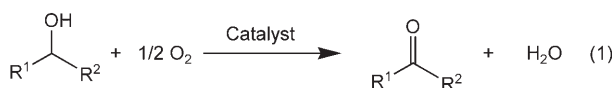


Oxidant-Free Alcohol Dehydrogenation Using a Reusable Hydrotalcite-Supported Silver Nanoparticle Catalyst**

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The dehydrogenation of alcohols to carbonyl compounds is one of the most important transformations in synthetic chemistry.^[1] Recently, much attention has been paid to the development of homogeneous^[2] and heterogeneous^[3] catalysts for the highly efficient oxidation of alcohols using molecular oxygen (O₂) as the oxidant because of the necessity of replacing stoichiometric reactions involving toxic oxidants such as chromium and manganese salts with environmentally benign catalytic oxidation systems [Eq. (1)].^[4] Alternative



designs can be conceived for advanced, more atom-efficient catalyst systems, which do not use molecular oxygen or air as the oxidant for the above oxidation [Eq. (2)]. Our development of such a promising O₂-free methodology is particularly interesting both from a practical and an environmental point of view because 1) it eliminates the formation of H₂O, a by-product which often deactivates catalysts and necessitates

tedious purification of products from the aqueous reaction mixture; 2) it is tolerant toward alcohols having O₂-sensitive functional groups; 3) it produces H₂, which is an attractive feedstock for energy generation; and 4) it suppresses over-oxidation of the substrate to carboxylic acids. Despite industrial success in the gas-phase dehydrogenation of alcohols,^[5] few examples of milder liquid-phase catalyst systems for the acceptor-free dehydrogenation of alcohols have appeared to date, and these systems have often suffered from low activity, limited substrate scope, and reusability.^[6]

Hydrotalcites (HTs) are inorganic, layered materials that have attracted attention because of their potential not only for adsorption^[7] and drug delivery^[8] but also as catalysts.^[9] Recently, we reported new strategies for the design of solid catalysts by utilizing modified HTs for various organic reactions such as the epoxidation of olefins using hydrogen peroxide,^[9c] the oxidation of alcohols,^[9a] and carbon–carbon bond formation.^[9c] We now describe the highly effective acceptor-free dehydrogenation of alcohols using heterogeneous hydrotalcite-supported silver nanoparticles^[10] (Ag/HT). This Ag/HT catalyst system showed remarkably high catalytic activity for a wide range of alcohols. Moreover, the catalyst could be readily reused without any loss of activity and selectivity.

Hydrotalcite (HT, Mg₆Al₂(OH)₁₆CO₃) was synthesized according to literature procedures.^[11] To prepare the catalyst 1.0 g of the HT was added to 10 mL of a 5.0 mM aqueous solution of AgNO₃, after which the heterogeneous mixture was stirred for 1 h in air at 3 °C. The resulting slurry was filtered, washed thoroughly with deionized water, and dried in vacuo at room temperature to yield a white powder. The HT-supported Ag^I ions were reduced with H₂ at 110 °C for 30 minutes to give Ag/HT before it was used in the dehydrogenation. The positions of the peaks in the X-ray diffraction (XRD) spectrum of Ag/HT after the above pretreatment were similar to those of the parent HT. The fraction of Ag atoms in the Ag/HT composite was determined by elemental analysis to be 0.005 wt %. The transmission electron microscopy image of the Ag/HT showed Ag nanoparticles with a mean diameter of 3.3 nm.^[12]

When a mixture of 1-phenylethanol and Ag/HT in *p*-xylene was heated at 130 °C in an Ar atmosphere, quantitative dehydrogenation of 1-phenylethanol occurred within 16 h to afford acetophenone. The turnover frequency (TOF) and turnover number (TON) reached up to 1375 h⁻¹ and 22 000, respectively (Table 1, entry 1). The reaction rate could be accelerated under a stream of Ar, and the TOF significantly increased to 2000 h⁻¹ (entry 2).^[13] The mole ratio of H₂ to acetophenone generated in the dehydrogenation of 1-phenyl-

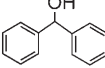
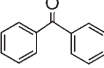
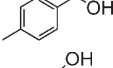
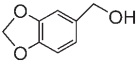
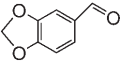
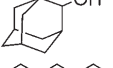
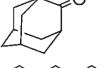
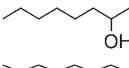
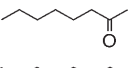
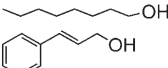
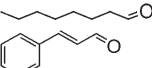
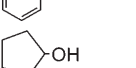
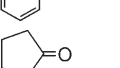
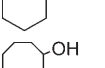
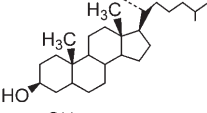
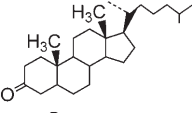
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[**] This study was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science, and Technology of Japan (18360389). This work was also supported by a Grant-in-Aid for Scientific Research on Priority Areas (no. 18065016, "Chemistry of Concerto Catalysis") from the Ministry of Education, Culture, Sports, Science, and Technology (Japan). Some of the experiments were carried out at a facility in the Research Center for Ultrahigh Voltage Electron Microscopy, Osaka University.

Supporting information for this article is available on the WWW under <http://www.angewandte.org> or from the author.

Table 1: Dehydrogenation of various alcohols catalyzed by Ag/HT.^[a]

Entry	Substrate	Product	t [h]	Conv. [%]	Sel. [%]	TON
1			16	> 99	> 99	22000
2 ^[b]			11	> 99	> 99	22000
3	reuse 1		16	99	> 99	21800
4	reuse 2		16	96	> 99	21200
5	reuse 3		16	99	> 99	21800
6	reuse 4		16	99	> 99	21800
7			12	> 99	99	22000
8			15	> 99	98	21800
9 ^[c]			10	> 99	90	5900
10			14	98	99	21600
11 ^[d]			40	> 99	98	11000
12 ^[d]			31	84	99	9200
13			18	97	97	21300
14			24	59	99	13000
15 ^[c,d]			72	17	99	600
16			18	> 99	> 99	22000
17 ^[d,e]			22	> 99	99	1100
18 ^[d,e]			21	> 99	99	1100
19			15	> 99	> 99	22000
20			24	93	> 99	20500
21 ^[d,e]			96	83	> 99	900
22 ^[c,d]			24	99	98	3300
23 ^[c,d]			30	> 99	99	3300

[a] Reaction conditions: Ag/HT 0.10 g (Ag: 45 nmol), substrate (1 mmol), *p*-xylene (5 mL), 130 °C, Ar atmosphere. [b] Under a flow of Ar. [c] Substrate (0.3 mmol). [d] Ag/HT (0.20 g). [e] Substrate (0.1 mmol).

ethanol was about 1:1, thus showing that H₂ was generated quantitatively during the dehydrogenation. The use of other heterogeneous catalysts such as Ag/SiO₂ or Ag/TiO₂ instead of Ag/HT yielded only trace amounts of acetophenone. The AgNO₃ precursor and the parent HT displayed almost no catalytic activity under similar reaction conditions.^[14]

To confirm whether the dehydrogenation of 1-phenylethanol proceeded on the solid catalyst surface, the reaction

mixture was hot-filtered at 50% conversion of the alcohol. Further treatment of the solid-free solution did not give any products. Moreover, no silver leached into the filtrate, as confirmed by an inductively coupled plasma analysis (detection limit: 0.007 ppm). It thus became clear that dehydrogenation took place only on the surface of the Ag/HT catalyst.

The scope of the dehydrogenation reaction using the Ag/HT catalyst was explored next. The results shown in Table 1 demonstrate that this methodology can be employed for the synthesis of various carbonyl compounds, including benzylic and secondary aliphatic alcohols (entries 1–14). In the case of α -cyclopropylbenzyl alcohol, the dehydrogenation of the alcohol moiety occurred without cleavage of the cyclopropyl ring (entry 7). The oxidation of benzyl alcohol by the use of Ag/HT showed moderate selectivity, and benzyl benzoate was obtained as a side product (entry 9).^[13] Allylic alcohol was also tolerated, thereby affording the corresponding α,β -unsaturated carbonyl compound (entry 16). Notably, this dehydrogenation could also be carried out using less reactive alicyclic alcohols, such as cyclopentanol and cyclohexanol (entries 17–20), as well as bulky alcohols, despite their steric hindrance (entry 21). Moreover, this oxygen-free dehydrogenation system was applicable to heterocyclic alcohols containing nitrogen atoms, and gave high yields of the products (entries 22 and 23). Unfortunately, primary aliphatic alcohols such as 1-octanol were not dehydrogenated efficiently under the present conditions (entry 15).

Furthermore, although various catalyst systems have often been reported to suffer from the problem of decreasing reusability, the Ag/HT recovered after its first use in the dehydrogenation of 1-phenylethanol was successfully used in four subsequent reactions with no reduction in the reaction rate: the total TON based on Ag was greater than 100000 (entries 3–6). This value is significantly higher than the reported TONs at high conversion for other oxidant-free catalyst systems, for example, Ru/Al₂O₃ (TON = 20),^[6a] Ru/AlO(OH) (333),^[6b] [Cp*Ir-

(PyOH)] (Cp* = C₅Me₅; 700),^[6c] [Ru(μ-OCOC₂F₄OCO)-(CO)(H₂O)(binap)]₂ (binap = 2,2'-bis(diphenylphosphanyl)-1,1'-binaphthyl; 186),^[6d] and [(PNP)Ru(H)Cl(N₂)] (PNP = 2,6-bis-(di-*tert*-butylphosphinomethyl)pyridine; 160).^[6e]

We compared Ag/HT, Ru/HT, and Pd/HT for the oxidation of cinnamyl alcohol in an Ar atmosphere. Of these, Ag/HT showed the highest chemoselectivity for the dehydrogenation of cinnamyl alcohol to cinnamaldehyde without hydrogen transfer or isomerization (Figure 1). Moreover, when 1-phenylethanol was oxidized by the Ag/HT

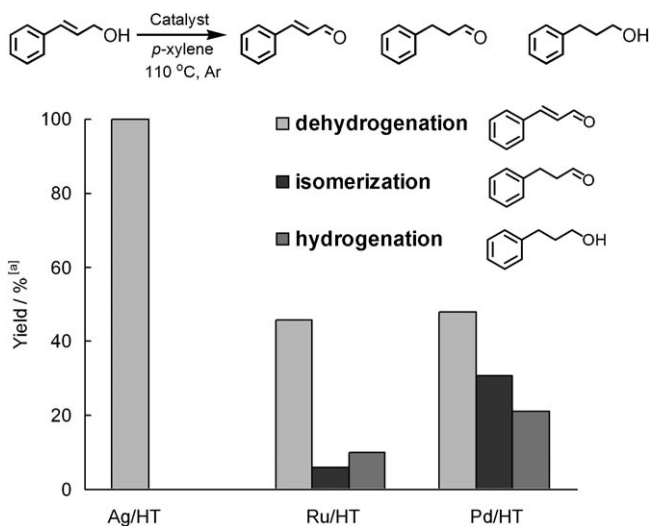
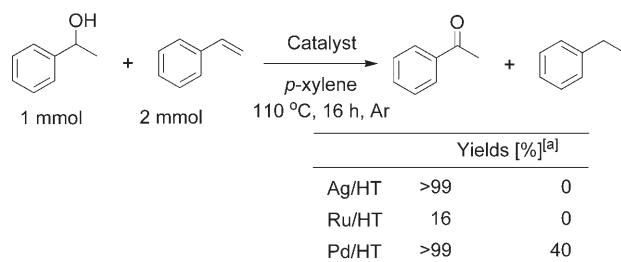


Figure 1. Oxidation of cinnamyl alcohol using Ag/HT, Ru/HT, and Pd/HT. Reaction conditions: catalyst [Ag/HT (Ag: 45 nmol), Ru/HT (Ru: 5 μmol), Pd/HT (Pd: 5 μmol)], *p*-xylene (5 mL), cinnamyl alcohol (1 mmol), 110 °C, 18 h, Ar atmosphere. The conversions were > 99% (Ag/HT), 72% (Ru/HT), and > 99% (Pd/HT), respectively. [a] Determined by GC and GC-MS.

catalyst in the presence of styrene in an argon atmosphere, acetophenone was obtained in 99% yield and no hydrogen-transfer product derived from styrene was formed (Scheme 1). The above results are in sharp contrast to those obtained using Ru/HT or Pd/HT, where intra- and intermolecular hydrogen transfer was induced by metal hydride species. These results constituted clear evidence of the facile release of molecular hydrogen from the Ag particle surface, which is in agreement with a previous report that Ag nanoparticles only weakly absorb hydrogen.^[15]



Scheme 1. Oxidation of 1-phenylethanol in the presence of styrene as a hydrogen acceptor. [a] Yields based on 1-phenylethanol.

In conclusion, we have created a highly atom-efficient and reusable Ag/HT catalyst system for the heterogeneous dehydrogenation of alcohols under oxidant- and additive-free conditions. The Ag/HT afforded high yields of the corresponding carbonyl compounds with coproduction of equivalent molar amounts of H₂.

Received: July 6, 2007

Revised: September 26, 2007

Published online: November 23, 2007

Keywords: alcohols · dehydrogenation · heterogeneous catalysis · nanoparticles · silver

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