



## Palladium-catalyzed dehydrogenation of benzylic alcohols in molten ammonium salts, a recyclable system<sup>†</sup>

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**Abstract**—Heating secondary benzylic alcohols in molten tetra-*n*-butyl ammonium bromide with catalytic amounts of palladium chloride under a gentle flow of argon produced corresponding ketones in good yields. Neither cooxidant nor additive were required, with the added advantage of catalyst and ammonium salt recycling. The dehydrogenation of primary benzylic alcohols was less selective. Such a reaction was ineffective from allylic and saturated alcohols. © 2002 Elsevier Science Ltd. All rights reserved.

Ionic liquids (**IL**) and molten salts (**MS**) are emerging as effective solvents for 'green' chemical reactions.<sup>1</sup> Having observed that anionic catalysts,  $[\text{PdX}_4][n\text{-Bu}_4\text{N}]_2$  and  $[\text{PdX}_6][n\text{-Bu}_4\text{N}]_2$  can be obtained from  $\text{PdCl}_2$  and  $n\text{-Bu}_4\text{NX}$  (X: Cl, Br),<sup>2</sup> we have carried out Heck reactions using molten  $n\text{-Bu}_4\text{NBr}$  as solvent and  $\text{PdCl}_2$  as catalyst; interestingly, no extra ligand was required and recycling of both catalyst and solvent was possible.<sup>3</sup>

For some years, we are interested in palladium(II)-catalyzed oxidations of alcohols.<sup>4</sup> Such reactions in organic solvents<sup>5,6</sup> and even water<sup>7</sup> have been reported using oxygen as single co-oxidant, the process often being carried out in the presence of a base. We envisaged performance of them in molten ammonium salts. Little attention was devoted to oxidations in **IL** or **MS** when we started our project;<sup>8</sup> no study mentioned their use as solvent in catalytic oxidation of alcohols.<sup>9</sup> Three recent reports on this subject,<sup>10</sup> in particular a Pd-catalyzed oxidation of benzyl alcohol in **IL**,<sup>10b,11</sup> prompted us to disclose our results.

Initial experimentation was undertaken in tetra-*n*-butyl ammonium bromide (1.5 g) using indan-1-ol (**1**) (1 mmol), sodium carbonate (1 mmol)<sup>12</sup> and catalytic amounts of palladium chloride (0.03 mmol) under an

oxygen atmosphere provided by a gas bag, the mixture being heated at 120°C for 21 h (Table 1, run 1). After extraction of organic compounds with diethyl ether, GC analysis of the solution indicated the formation of indan-1-one (**2**). Decreasing the amount of base to 0.06 equiv. increased both conversion and yield (run 2). Switching from  $\text{Na}_2\text{CO}_3$  to  $\text{NaHCO}_3$  or  $\text{Cs}_2\text{CO}_3$  (runs 3 and 4), and using  $(\text{bmim})(\text{PF}_6)^{13}$  instead of  $n\text{-Bu}_4\text{NBr}$  (run 5) led to lower yields. In fact, the presence of base was not necessary (run 6); this point is of interest if the ammonium salt is to be recycled. Surprisingly, a reaction carried out in the absence of oxygen in a closed vessel provided **2** also but with a lower selectivity (run 7). Under these latter conditions, we detected the formation of indane as by-product; this reductive cleavage of the C–OH bond of **1** indicated in situ formation of hydrogen<sup>14</sup> and/or  $[\text{Pd}]\text{H}_2$  species.<sup>15</sup> To avoid this hydrogenolysis, transfer dehydrogenation was attempted in adding indene and cyclohexene as hydrogen acceptors (runs 8–10): better selectivities were obtained with the latter. The reaction was then carried out under a gentle flow of argon in expecting the removal of hydrogen gas.<sup>16</sup> Fortunately, high conversion and yield were attained (run 11) and furthermore, the recycling of both catalyst and  $n\text{-Bu}_4\text{NBr}$  was efficient (runs 12–15). Under these conditions, the use of  $n\text{-Bu}_4\text{NCl}$  or  $n\text{-Bu}_4\text{NOAc}$  instead of  $n\text{-Bu}_4\text{NBr}$  led to troubles in the course of the work up and to low yields (runs 16 and 17).

The above observations—hydrogenolysis of the C–OH bond, no reoxidant of palladium required—led us to suspect a catalysis by  $\text{Pd}(0)$ .<sup>14,15,17</sup> Consequently, the reaction was attempted using Pd black<sup>15</sup> as catalyst; the

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**Table 1.** Influence of the experimental conditions on the oxidation of indan-1-ol<sup>a</sup>

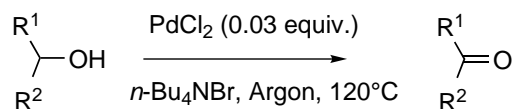
Run	Catalyst	Additive (equiv.)	Atmosphere	Time (h)	Conv. (%)	2 Yield (%) <sup>b</sup>
1	PdCl <sub>2</sub>	Na <sub>2</sub> CO <sub>3</sub> (1)	O <sub>2</sub>	21	51	41
2	PdCl <sub>2</sub>	Na <sub>2</sub> CO <sub>3</sub> (0.06)	O <sub>2</sub>	21	72	54
3	PdCl <sub>2</sub>	NaHCO <sub>3</sub> (0.06)	O <sub>2</sub>	22	62	45
4	PdCl <sub>2</sub>	Cs <sub>2</sub> CO <sub>3</sub> (0.06)	O <sub>2</sub>	22	62	41
5 <sup>c</sup>	PdCl <sub>2</sub>	Na <sub>2</sub> CO <sub>3</sub> (0.06)	O <sub>2</sub>	21	54	31
6	PdCl <sub>2</sub>	None	O <sub>2</sub>	21	64	50
7 <sup>d</sup>	PdCl <sub>2</sub>	None	Ar	21	94	50
8 <sup>d</sup>	PdCl <sub>2</sub>	Indene (1)	Ar	21	15	5
9 <sup>d</sup>	PdCl <sub>2</sub>	Cyclohexene (5)	Ar	21	52	42
10 <sup>d</sup>	PdCl <sub>2</sub>	Cyclohexene (5)	Ar	48	61	49
11	PdCl <sub>2</sub>	None	Ar <sup>e</sup>	22	100	95 (90)
12	1st reuse <sup>f</sup>	None	Ar <sup>e</sup>	22	96	94 (93)
13	2nd reuse <sup>f</sup>	None	Ar <sup>e</sup>	21	85	83
14	3rd reuse <sup>f</sup>	None	Ar <sup>e</sup>	22	79	77
15	4th reuse <sup>f</sup>	None	Ar <sup>e</sup>	22	67	64
16 <sup>g</sup>	PdCl <sub>2</sub>	None	Ar <sup>e</sup>	21	52	12
17 <sup>h</sup>	PdCl <sub>2</sub>	None	Ar <sup>e</sup>	22	76	44
18	Pd black	None	Ar <sup>e</sup>	21	71	61
19	0	None	Ar <sup>e</sup>	18	6	4

<sup>a</sup> See text and Ref. 16 for run 11.<sup>b</sup> GC yields, dec-9-en-1-ol as internal standard; isolated yields are in brackets.<sup>c</sup> Reaction carried out in (bmim)(PF<sub>6</sub>) instead of *n*-Bu<sub>4</sub>NBr.<sup>d</sup> Reaction carried out in a closed flask.<sup>e</sup> Reaction carried out under a gentle flow of argon.<sup>f</sup> Both catalyst and *n*-Bu<sub>4</sub>NBr recovered from the previous run were used.<sup>g</sup> Using *n*-Bu<sub>4</sub>NCl instead of *n*-Bu<sub>4</sub>NBr.<sup>h</sup> Using *n*-Bu<sub>4</sub>NOAc instead of *n*-Bu<sub>4</sub>NBr.

dehydrogenation took place but the efficiency and selectivity were lower than those attained with PdCl<sub>2</sub> (run 18 versus run 11). Control experiments have shown that conversion of the substrate decreased drastically in the absence of palladium (run 19).<sup>18</sup>

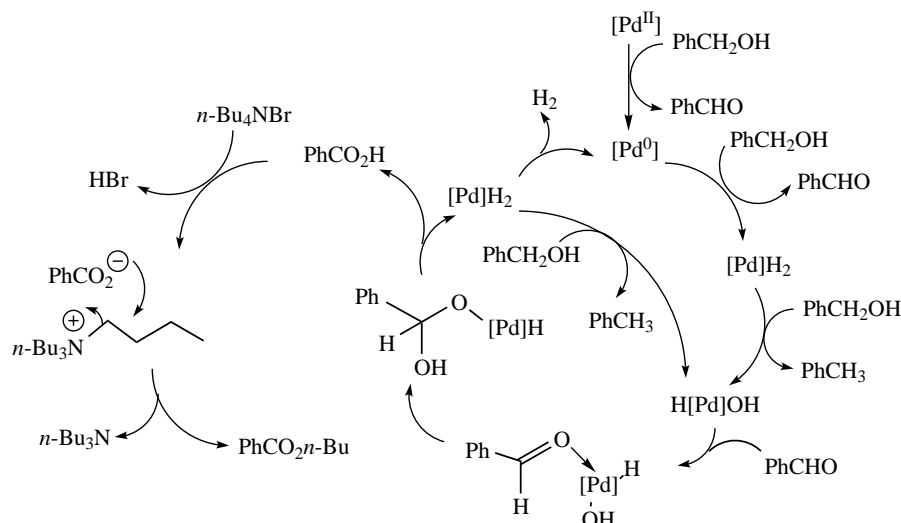
Having these results in hand, other alcohols have been subjected to conditions of run 11 (Table 2).

Various secondary benzylic alcohols afforded the corresponding ketones with good selectivities (runs 20–24)

**Table 2.** Palladium-catalyzed oxidation of various benzylic alcohols<sup>a</sup>

Run	Substrate	Time (h)	Conv. (%)	Product	Yield (%)
20	9-Hydroxyfluorene	48	81	Fluoren-9-one	73 <sup>b</sup>
21	Tetral-1-ol	24	89	Tetral-1-one	83 <sup>b</sup>
22	1-Phenylethan-1-ol	72	100	Acetophenone	81 <sup>b</sup>
23	1-Phenylpropan-1-ol	72	100	1-Phenylpropan-1-one	91 <sup>b</sup>
24	Benzhydrol	48	77	Benzophenone	67 <sup>b</sup>
25	Benzoin	48	70	Benzil	68 <sup>b</sup>
26	Benzyl alcohol	6	100	Benzaldehyde + <i>n</i> -butylbenzoate <sup>d</sup>	4 <sup>c</sup> 51 <sup>b</sup>
27	1-NaphthylCH <sub>2</sub> OH	72	76	1-NaphthylCHO <sup>e</sup>	39 <sup>b</sup>
28	2-NaphthylCH <sub>2</sub> OH	48	51	2-NaphthylCHO <sup>f</sup>	24 <sup>b</sup>

<sup>a</sup> Substrate (1 mmol), PdCl<sub>2</sub> (0.03 mmol), *n*-Bu<sub>4</sub>NBr (1.5 g), gentle flow of argon, 120°C.<sup>b</sup> Isolated yield calculated on the quantity of alcohol introduced.<sup>c</sup> GC yield, dec-9-en-1-ol as internal standard.<sup>d</sup> Also observed from GC–MS analysis: toluene.<sup>e</sup> Also observed from GC–MS analysis: 1-methylnaphthalene.<sup>f</sup> Also observed from GC–MS analysis: 2-methylnaphthalene.



Scheme 1.

and no cleavage reaction has been observed from an  $\alpha$ -ketol such as benzoin (run 25). Switching to benzyl alcohol as substrate provided low amounts of benzaldehyde, the main product being *n*-butylbenzoate (run 26). GC–MS analysis of the crude mixture showed the presence of *n*-butyl bromide and toluene. We firstly suspected the presence of some oxygen which would mediate the oxidation of benzaldehyde into benzoic acid, and subsequent esterification of this latter.<sup>19</sup> This seemed to agree with the formation of *n*-butylbenzoate using benzoic acid as substrate under similar experimental conditions and also in the absence of any Pd-catalyst. However, to repeat run 26 in thoroughly removing traces of oxygen and even in a closed flask also afforded the ester. This latter was not detected using benzaldehyde as substrate under such conditions and even in the presence of added water. Actually, we suggest the mechanism depicted in Scheme 1 to explain the formation of *n*-butylbenzoate: (i) the oxidation of PhCH<sub>2</sub>OH by [Pd<sup>II</sup>] leads to PhCHO and [Pd<sup>0</sup>], (ii) a second molecule of PhCH<sub>2</sub>OH reacts with [Pd<sup>0</sup>] giving PhCHO and [Pd]H<sub>2</sub>,<sup>14</sup> (iii) hydrogenolysis of a third molecule of PhCH<sub>2</sub>OH produces H[Pd]OH, (iv) insertion of CO double bond of PhCHO into [Pd]–OH followed by  $\beta$ -H elimination affords PhCO<sub>2</sub>H and [Pd]H<sub>2</sub>,<sup>20</sup> (v) the interaction of PhCO<sub>2</sub>H with *n*-Bu<sub>4</sub>NBr provides PhCO<sub>2</sub>N(*n*-Bu)<sub>4</sub> and (vi) this last intermediate evolves to PhCO<sub>2</sub>*n*-Bu and *n*-Bu<sub>3</sub>N. It is important to note that [Pd]H<sub>2</sub> produced from PhCH(OH)–O[Pd]H intermediate would have the possibility to evolve to the [Pd<sup>0</sup>] active dehydrogenation or to mediate the hydrogenolysis of the alcohol. This could explain, at least in part, the low selectivity of the process.

Compared to benzyl alcohol, 1- and 2-naphthylmethanol react much more slowly but they afford corresponding aldehydes without the production of any ester (runs 27, 28); some hydrogenolysis of the C–OH bond of these two substrates was detected from GC–MS analysis. No or solely traces of the expected car-

bonyl compounds were obtained from allylic and saturated alcohols.

In conclusion, molten tetra-*n*-butyl ammonium bromide is a good medium for the Pd-catalyzed dehydrogenation of secondary benzylic alcohols as substrates; palladium chloride is an effective catalyst and the reaction takes place without any oxygen donor or additive. The system—catalyst+ammonium salt—is recyclable but gradually loses its oxidative properties. As we previously suspected,<sup>3,4a</sup> the ammonium salt apparently stabilizes palladium species which are active for catalysis. These results extend the use of molten ammonium salts as solvents for Pd-catalyzed organic reactions.

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16. Typical experiment, run 11. A round-bottomed flask (10 ml) equipped with a magnetic stir bar and reflux condenser was charged with PdCl<sub>2</sub> (5 mg, 0.03 mmol) and *n*-Bu<sub>4</sub>NBr (1.5 g). The system was connected to a vacuum/argon line and the flask was heated under vacuum at 120°C (oil bath) for 2 h. After switching to the argon line, indan-1-ol (134 mg, 1 mmol) was introduced and the temperature of the oil bath was maintained at 120°C for 22 h. After removing the oil bath, diethyl ether (5 ml) was added by the top of the condenser. The mixture was stirred for a few minutes and then poured on a sintered-glass frit. The flask was washed with diethyl ether and the solid carefully triturated with the same solvent (2 ml×5). GC analysis (capillary column HP-Innowax, 170°C, dec-9-en-1-ol as internal standard) of the solution showed the complete conversion of the substrate and the formation of indan-1-one (95%).
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