

Palladium-catalyzed carbonylation of *tert*-butyl alcohol to esters of *iso*-valeric acid

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Abstract

Tert-butyl alcohol was carbonylated to esters of *iso*-valeric acid in the presence of a tris(dibenzylideneacetone)dipalladium(0)–triphenylphosphine–*p*-Ts catalytic system without any halogen promoter or other extreme conditions. Typical reaction conditions are: temperature 120–160°C; $p(\text{CO}) = 4.0\text{--}7.0$ MPa; *tert*-butyl alcohol/ROH/Pd = 400/3280/1; $[\text{Pd}] = 4.3 \times 10^{-3}$ mol/l; Pd/PPh₃/*p*-Ts = 1/24/65; reaction time 6–24 h. Under these experimental conditions a high yield (98.9%) and selectivity (99.2%) for esters are obtained. The carbonylation of other similar alcohols were studied using this catalyst system. The mechanism of this reaction has also been discussed.

Keywords: Palladium; Carbonylation; *tert*-Butyl alcohol; Valeric acid

1. Introduction

Catalytic systems of palladium modified by phosphorus ligands have attracted a great deal of interest due to the high activity that they exhibit for many reactions [1–12]. Especially, catalytic carbonylation of olefins [7] is the basis of useful methods for the synthesis of organic acid derivatives. Eventually, in place of the olefin, the corresponding hydroxylic compounds may be employed. The study of carbonylation of alcohols to esters using palladium compounds has received much less attention in spite of the possibility that it could provide an interesting route to fine chemicals. Recently, Cavinato and Toniolo reported that benzyl alcohols

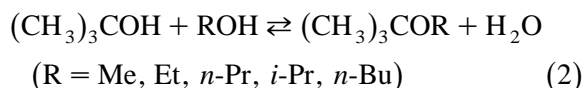
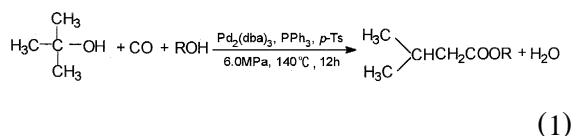
were carbonylated to phenylacetic acid derivatives in the presence of PdCl₂(PPh₃)₂–PPh₃ catalyst [12]. Such catalytic reactions were also reported in a European Patent [13], but all those carbonylation reactions of alcohols need the promotion of a halogen or other extreme conditions.

We have found that the catalytic system obtained in situ from tris(dibenzylideneacetone)dipalladium(0) (Pd₂(dba)₃), PPh₃ and *p*-toluenesulfonic acid (*p*-Ts) promotes a highly selective formation of ethyl valerate from *tert*-butyl alcohol and carbon monoxide in ethanol without any halogen. Here we present the results of a full investigation of the carbonylation of *tert*-butyl alcohol and other similar alcohols to various esters catalyzed by the tris(dibenzylideneacetone)dipalladium(0)–PPh₃–*p*-Ts catalyst system.

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2. Results and discussion

The reaction of carbonylation of *tert*-butyl alcohols to iso-valeric acid derivatives is shown in Eq. (1), and the side reaction in Eq. (2),



Typical reaction conditions are: temperature 120–160°C; $p(\text{CO}) = 3.0\text{--}7.0$ MPa; *tert*-butyl alcohol/ROH/Pd = 400/3280/1; [Pd] = 4.3×10^{-3} mol/l; Pd/PPh₃/*p*-Ts = 1/24/65; reaction time = 6–24 h.

This reaction was strongly influenced by the amount of *p*-Ts; the results are listed in Table 1. Under the reported experimental conditions high yields are obtained when *p*-Ts/Pd(mol/mol) = 65 and reaction time is 12 h. These results suggest that the starting *tert*-butyl alcohol may undergo equilibrium (3). The *tert*-butyl alcohol is dehydrated to 2-methylpro-

Table 1
The effect of the amount of *p*-Ts on carbonylation of *tert*-butyl alcohol

Run No.	<i>p</i> -Ts/Pd (mol/mol)	Conversion of <i>tert</i> -butyl alcohol (mol%)	Yield (mol%) ^a		Selectivity to ester (%)
			ester	ether	
1	33	90.2	70.2	20.0	77.8
2	49	89.0	79.6	9.4	89.4
3	57	88.1	81.7	6.4	92.7
4	65	91.1	82.3	8.89	0.3
5 ^b		79.7	0	79.7	0
6 ^c	65	91.1	63.0	28.1	69.2
7	82	86.4	80.4	6.0	93.3

Reaction conditions: [Pd] = 4.3×10^{-3} mol/l; PPh₃, 0.63 mmol; *tert*-butyl alcohol, 10.4 mmol; ethanol, 5.0 ml; $p(\text{CO}) = 6.0$ MPa; temperature, 140°C; reaction time, 12 h.

^a Yield based on the starting alcohol.

^b In absence of [Pd]-PPh₃.

^c Added [Pd]-PPh₃ to the mixture of ether and alcohol of run 5.

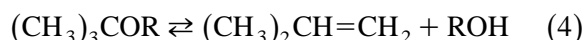
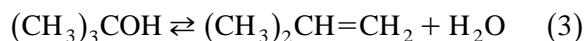
Table 2

Catalytic hydroesterification of *tert*-butyl alcohol in different solvents

Run No.	Solvent (5 ml)	Conversion of <i>tert</i> -butyl alcohol (mol%)	Yield (mol%)		Selectivity to ester (%)
			ester	ether	
1	methanol	94.0	31.2	62.8	33.2
2	ethanol	91.1	82.3	8.8	90.3
3	<i>n</i> -propanol	95.5	78.5	17.0	82.5
4	<i>iso</i> -propanol	78.0	70.3	7.7	90.1
5	<i>n</i> -butanol	89.5	84.4	5.1	94.3

Reaction conditions: same as in Table 1, except that *p*-Ts/Pd = 65 (mol/mol) and the solvent varied.

pane in the presence of certain amounts of *p*-Ts. Run 5 showed that the sole product is ethyl *tert*-butyl ether in the absence of Pd₂(dba)₃ and PPh₃, and the yield of ether is 79.7% (based on the *tert*-butyl alcohol); no 2-methylpropene can be detected. When we add Pd₂(dba)₃ and PPh₃ to the mixture of ethyl *tert*-butyl ether and *tert*-butyl alcohol, the yield of ester is 63.0% (based on the *tert*-butyl alcohol). This result (run 6) showed that ethyl *tert*-butyl ether can also be converted to 2-methylpropene in the presence of certain amounts of *p*-Ts (equilibrium (4)). From the above we concluded that 2-methylpropene may be an unstable intermediate. As soon as the alkene is produced, it is carbonylated to the ester of valeric acid by Pd-PPh₃-*p*-Ts. The *p*-Ts serves a dual purpose in this reaction.



Reaction (1) is strongly influenced by the nature of the solvents and the results are listed in Table 2. It can be seen from Table 2 that the yields of various esters decrease in the order: *n*-butanol > ethanol > propanol > *iso*-propanol > methanol. According to palladium-catalyzed carbonylation of olefins [14], higher yields of esters are obtained when methanol is used as solvent. But in this reaction, a poor yield is obtained when methanol is used as solvent. A

Table 3

The effect of pressure on the catalytic carbonylation of *tert*-butyl alcohol in ethanol

Run No.	Pressure (MPa)	Conversion of <i>tert</i> -butyl alcohol (mol%)	Yield (mol%)		Selectivity to ester (%)
			ester	ether	
1	3.0	86.3	61.4	24.9	71.1
2	4.0	86.7	65.8	20.9	75.9
3	5.0	91.4	79.4	12.0	86.9
4	6.0	91.1	82.3	8.8	90.3
5	7.0	87.5	72.4	15.1	82.7

Reaction conditions: same as in Table 1, except that *p*-Ts/Pd = 65 (mol/mol) and the pressure varied.

possible explanation is that reaction (2) takes place easily to produce the methyl *tert*-butyl ether, which is too stable to undergo equilibrium (4). Because *iso*-propanol is sterically crowded, it is unfavorable to both reaction (1) and (2).

The effect of carbon monoxide pressure on the yield is shown in Table 3. As expected, the yield increases with increasing gas pressure (3.0–6.0 MPa). However, the yield decreases when the gas pressure is above 6.0 MPa. In fact, this is usually found in palladium-catalyzed carbonylation of olefins [13].

Table 4 shows that the highest yields are obtained when operating at 140–150°C, similar to what has been observed for related hydroesterification of olefins catalyzed by the Pd–PPh₃–*p*-Ts system [14].

Table 4

The effect of temperature on the catalytic carbonylation of *tert*-butyl alcohol in ethanol

Run No.	Temperature (°C)	Conversion of <i>tert</i> -butyl alcohol (mol%)	Yield (mol%)		Selectivity to ester (%)
			ester	ether	
1	120	86.2	35.9	50.3	41.6
2	130	87.5	53.8	33.7	61.5
3	140	91.1	82.3	8.8	90.3
4	150	89.5	85.7	3.8	95.8
5	160	83.5	72.4	11.1	86.7

Reaction conditions: same as in Table 1, except that *p*-Ts/Pd = 65 (mol/mol) and the temperature varied.

Table 5

The effect of reaction time on the catalytic carbonylation of *tert*-butyl alcohol in ethanol

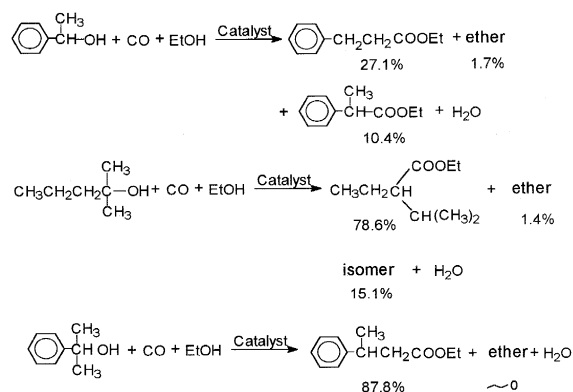
Run No.	Time (h)	Conversion of <i>tert</i> -butyl alcohol (mol%)	Yield (mol%)		Selectivity to ester (%)
			ester	ether	
1	6.0	87.8	65.0	22.8	74.0
2	12.0	91.1	82.3	8.8	90.3
3	18.0	87.8	85.0	2.8	96.8
4	24.0	99.7	98.9	0.8	99.2

Reaction conditions: same as in Table 1, except that *p*-Ts/Pd = 65 (mol/mol) and the temperature varied.

The effect of the reaction time on the catalytic carbonylation of *tert*-butyl alcohol can be found in Table 5. The yields of ester increase and the yields of ether decrease when the reaction time is prolonged. The highest yield and selectivity for ester are obtained when the reaction time was 24 h.

2.1. The carbonylation of other similar alcohols

Other tertiary and special secondary alcohols were also carbonylated by the Pd–PPh₃–*p*-Ts catalytic system. We have investigated the carbonylation of three kinds of alcohols in ethanol: α -phenyl ethanol, 2-methyl-2-pentanol and 2-phenyl-2-propanol. The results are listed in Scheme 1 (reaction conditions were the same as in Table 1, yields based on the starting alcohols).



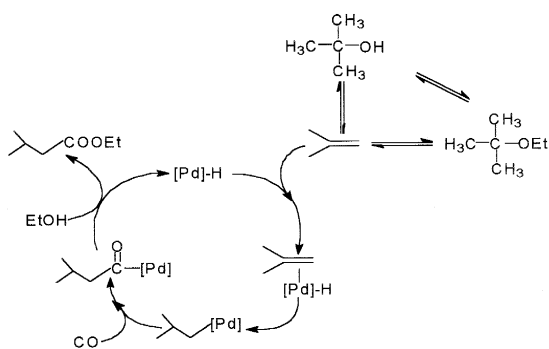
Scheme 1.

2.2. Proposed catalytic cycle

According to the above experimental results, we suggest the following catalytic cycle for the carbonylation of *tert*-butyl alcohol. As pointed out previously, it is likely that the starting *tert*-butyl alcohol is in equilibrium with 2-methylpropene, and the byproduct ethyl *tert*-butyl ether is also in equilibrium with 2-methylpropene (Scheme 2). As soon as 2-methylpropene is produced, it follows the catalytic cycle shown in Scheme 2. After the formation of alkyl species, followed by CO insertion, attack of the OEt group of ethanol forms the ester and regenerates the active hydride species. This mechanism is proposed for hydroesterification of olefins in general [15–17].

It is believed that this mechanism is also reasonable for the carbonylation of other similar alcohols (Scheme 1). For example, 2-methyl-2-pentanol is first dehydrated to form 2-methyl-2-pentene in the presence of *p*-Ts, then it follows the catalytic cycle shown in Scheme 2. The distinction from *tert*-butyl alcohol is that there exist two kinds of alkyl species owing to migration of the double bond in the presence of palladium catalyst. So two kinds of isomeric products are obtained under these reaction conditions. This is the same as in the carbonylation of α -phenyl ethanol.

In conclusion, esters of *iso*-valeric acid can



Scheme 2.

be obtained in good yields with excellent regio-chemical control by the hydroesterification of *tert*-butyl alcohol with tris(dibenzylideneacetone)dipalladium and *p*-toluenesulfonic acid in the presence of phosphine ligands. Other similar alcohols can also be carbonylated by the same catalytic system.

3. Experimental

3.1. General considerations

Carbon monoxide was the product of our institute. Solvents and reagents were of commercial grade. $\text{Pd}_2(\text{dba})_3$ was prepared as described in the literature [18]. Products were identified by GC-MS, and analyzed by GC (SP-1102 chromatograph on a 22.5 m SE-54 column using helium as carrier gas). A 25 ml stainless steel autoclave was used for catalytic reactions.

3.2. Representative procedure for hydroesterification reaction

In a 25 ml autoclave *tert*-butyl alcohol 1.0 ml (10.4 mmol), *p*-Ts 325.6 mg (1.71 mmol), $\text{Pd}_2(\text{dba})_3$ 12.3 mg (0.013 mmol), PPh_3 167.7 mg (0.64 mmol) and 5.0 ml of ethanol were placed. The autoclave was purged 3 times with CO and then charged with 6.0 MPa of CO (at room temperature) and the mixture was stirred at 140°C for 12 h. At the end of experiment the autoclave was cooled in an ice bath and slowly depressurized. After the usual workup the reaction mixture was analyzed by GC.

Acknowledgements

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