Catalytic conversions in water. Part 4 [1]: Carbonylation of 5-hydroxymethylfurfural (HMF) and benzyl alcohol catalysed by palladium trisulfonated triphenylphosphine complexes

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Abstract

Carbonylation of renewable 5-hydroxymethylfurfural (HMF) under aqueous phase catalytic conditions using the water soluble catalyst $Pd(TPPTS)_3$ (TPPTS = sodium salt of trisulfonated triphenylphosphine, $P(C_6H_4\text{-}m\text{-}SO_3Na)_3$) was investigated. $Pd(TPPTS)_3$ was easily prepared in situ via complexation of $PdCl_2$ in an aqueous TPPTS solution and reduction with carbon monoxide. Using the $Pd(TPPTS)_3$ catalyst at 70°C, 5 bar CO pressure and [Pd] = 150 ppm chemoselective carbonylation of HMF was observed to yield 5-formylfuran-2-acetic acid (FFA) as the sole carbonylation product; the only by-product was 5-methylfurfural (MF). The formation of MF under these conditions amounts to a new type of catalytic and very selective reduction with CO, formally equivalent to hydrogenolysis of an alcohol group without using H_2. This is surprising since one would expect the water gas shift reaction. Both the activity and selectivity of HMF carbonylation were strongly influenced by the TPPTS/Pd molar ratio; maximum efficiency being observed for TPPTS/Pd = 6. The nature of the anion of the added acid markedly influenced the selectivity. Acids of weakly or non-coordinating anions, such as H_3PO_4, CF_3COOH, $p\text{-}CH_3C_6H_4SO_3H$, H_2SO_4, and HPF_6 afforded mainly carbonylation. The selectivity decreased dramatically with acids of strongly coordinating anions such as HBr and HI. With the latter the only product observed was MF. Replacement of TPPTS by ligands containing less $-SO_3Na$ groups such as disulfonated triphenylphosphine (TPPDS) or disulfonated tris(p-fluorophenyl)phosphine (TFPPDS) gives rise to a dramatic drop in the catalytic activity. Using palladium catalysts modified with monosulfonated triphenylphosphine (TPPMS) only traces of FFA and MF were obtained. $Pd(TPPTS)_3$ in aqueous media similarly catalyses the selective carbonylation of benzyl alcohol to phenylacetic acid. In sharp contrast, classical hydrophobic Pd/PPh_3 catalysts are inactive in this carbonylation reaction in organic solvents. A catalytic cycle is proposed to explain the observed results.

Keywords: Carbonylation; Aqueous phase catalysis; 5-hydroxymethylfurfural; Renewable resources; Palladium; TPPTS; TPPDS; TPPMS; TFPPDS; Benzyl alcohol

1. Introduction

Increasing interest in the use of carbohydrates as renewable raw materials is being stimulated both by the projected long-term limitations of fossil feedstocks and by environmental restrictions regarding the biodegradability and biocompatibility of many petrochemical-based products [1–5]. In general, oxidation with e.g. hypochlorite has been used to convert carbohydrates into commercially interesting

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[1] For part 3 of this series see Ref. [18].

products such as polycarboxylates [4,5]. A potentially interesting alternative to oxidation is catalytic carbonylation of reactive –OH groups in carbohydrates.

The metal-catalysed carbonylation of alcohols is well-known and forms the basis of the Monsanto process for the commercial manufacture of acetic acid by rhodium-catalysed carbonylation of methanol [6,7]. The only reported carbonylation of a carbohydrate is the carbonylation of sorbitol, to a mixture of heptanoic acid and 2-methylhexanoic acid in 3.5% and 20% yield, respectively, using the Monsanto catalyst system (rhodium with an iodide promotor) at 180°C and 37.5 bar CO pressure [8].

Palladium catalysts modified with triphenylphosphine ligands are known to catalyse the carbonylation of certain benzylic alcohols in organic solvents [9,10]. In contrast, very low activities were observed with aliphatic alcohols such as methanol which gave acetic acid in only 2% yield at 120°C and 250 bar [11].

Due to the hydrophilicity of carbohydrates carbonylations should preferably be performed in aqueous media which necessitates the use of water-soluble transition metal complexes. Trisulfonated triphenylphosphine (TPPTS) complexes of transition metals are highly soluble in water and Rh/TPPTS catalysts have found important industrial applications in, for example, the Ruhrchemie/Rhône–Poulenc process for the hydroformylation of propene [12–14] in an aqueous/organic biphasic system.

5-hydroxymethylfurfural (HMF) is readily obtained from acid-catalysed dehydration of various carbohydrates, especially fructose [1,15]. Because it contains both an aldehyde and a primary alcohol functionality it constitutes a relatively simple model compound for carbohydrates. Recently, we reported the selective carbonylation of HMF in the presence of the Pd(TPPTS)$_3$ catalyst [16–18]. We now report a detailed study of the influence of various reaction parameters on the carbonylation and on the extension of this technique to the carbonylation

of benzyl alcohol to phenylacetic acid in an aqueous medium.
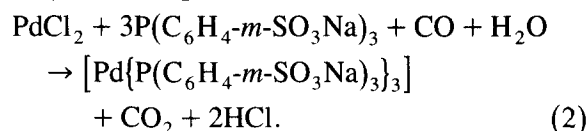
2. Results and discussion

2.1. Synthesis of the Pd(TPPTS)$_3$ catalyst

For the synthesis of the homoleptic Pd(TPPTS)$_3$ complex (Fig. 1) we first used the method of Kuntz [12] and subsequent modification thereof of Herrmann et al. [19] which is a ligand exchange by extraction of Pd(PPh$_3$)$_4$ in toluene with a solution of TPPTS in water. Using a TPPTS/Pd molar ratio of 6, the Pd(TPPTS)$_3$ complex was obtained with a yield of 68% at $\delta = +22.97$ ppm (s) in the ^{31}P{^{1}H} NMR spectrum (80.98 MHz, 25°C, D$_2$O). This synthesis as well as other known routes to the Pd(TPPTS)$_3$ complex, by reduction of K$_2$PdCl$_4$ by NaBH$_4$ in the presence of TPPTS [19] or reduction of Pd(OAc)$_2$ by TPPTS itself [20] lead to moderate yields, require either expensive reducing agents such as sodium borohydride and palladium starting materials or high excess of TPPTS to palladium precursor (P/Pd molar ratio of 12.5) in addition to prolonged reaction times (2 h) and the use of organic solvents. Furthermore, all these procedures tend to yield products contaminated either with potassium chloride, sodium hydroxide, boric acid and unreacted potassium tetrachloropalladate(II), or with the low-ligated zerovalent Pd(TPPTS)$_2$ complex. Moreover, the separation of potassium chloride from transition metal TPPTS complexes by gelpermeation chromatography [21] is cumbersome [19]. The facile reduction of PdCl$_2$ with carbon monoxide in water to afford palladium(0), CO$_2$, and HCl (Eq. (1)) is known since 1894 [22].

$$PdCl_2 + CO + H_2O \rightarrow Pd^0 + CO_2 + 2HCl.$$
$$(1)$$
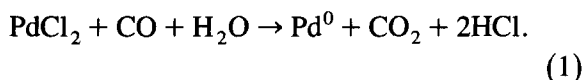
We have similarly developed a simpler, more convenient route, which utilizes carbon monoxide to reduce the [PdCl(TPPTS)$_3$]$^+$ intermediate

[17] formed quantitatively from $PdCl_2$ and TPPTS in water within 25 min at 25°C. Pd(TP-PTS)$_3$ is obtained in quantitative yield (based on $PdCl_2$; $^{31}P\{^1H\}$ NMR of the solution) in 5 min at 25°C and a carbon monoxide pressure of only 2 bar (Eq. (2)).

$$PdCl_2 + 3P(C_6H_4\text{-}m\text{-}SO_3Na)_3 + CO + H_2O$$
$$\rightarrow \left[Pd\{P(C_6H_4\text{-}m\text{-}SO_3Na)_3\}_3\right]$$
$$+ CO_2 + 2HCl. \qquad (2)$$

Using a TPPTS/Pd molar ratio of 6 and CO as reducing agent, according to Eq. (2), we separated Pd(TPPTS)$_3 \cdot 9H_2O$ as a brownish yellow powder from TPPTS by gelpermeation chromatography on Sephadex G-25 and eluting with deoxygenated distilled demineralized water (100%). $^{31}P\{^1H\}$ NMR spectrum (80.98 MHz, 25°C, D_2O): $\delta = +22.95$ ppm, sharp singlet

($\Delta\nu_{1/2} = 5.5$ Hz) with further characterization by IR and elemental analysis.

If oxygen is present in the reaction mixture during the formation of the $[PdCl(TPPTS)_3]^+$ intermediate from $PdCl_2$, TPPTS, and H_2O, uncomplexed $PdCl_2$ acts as catalyst for the oxidation of TPPTS to TPPTS oxide. The complexation of $PdCl_2$ with TPPTS in water to $[PdCl(TPPTS)_3]^+$ was also monitored by ^{17}O NMR spectroscopy, using as solvent water H_2O/D_2O (25/75) with 5 at% ^{17}O enrichment. No signals in high field were observed, which excludes the formation of hydroxo palladium TPPTS complexes. Palladium species with hydroxo or aqua ligands such as $[Pd(OH)_4]^{2-}$ or $[Pd(H_2O)_4]^{2+}$ can be identified in aqueous solution by ^{17}O NMR spectroscopy [23]. It is relevant to point out that $^{31}P\{^1H\}$ NMR spectra
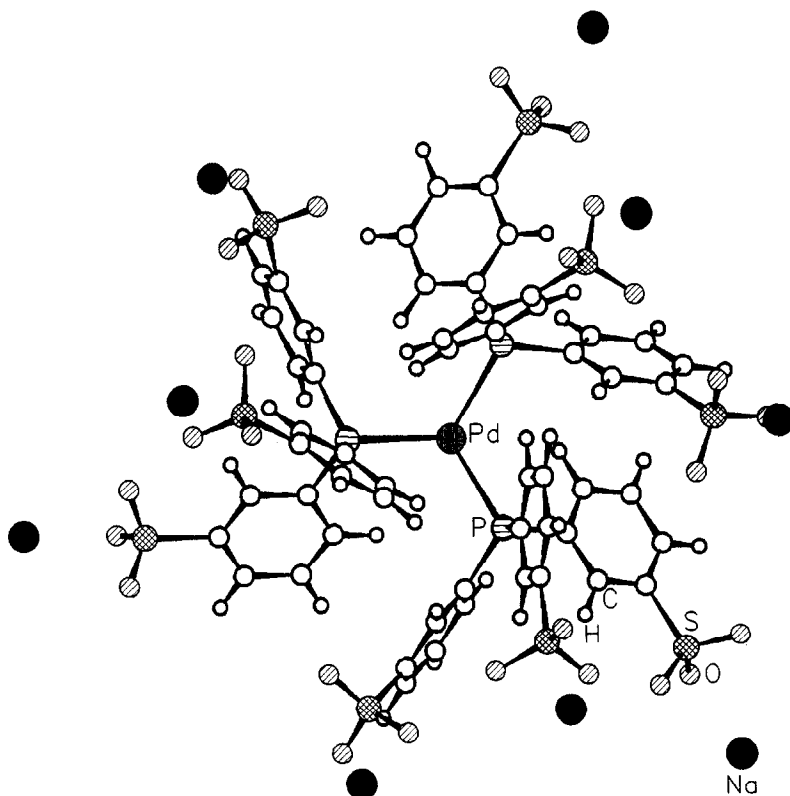

Fig. 1. The water-soluble catalyst, tris[tris(sodium *m*-sulfonatophenyl)phosphino]palladium(0), Pd(TPPTS)$_3$. Drawing is generated with Biosym, Insight II.
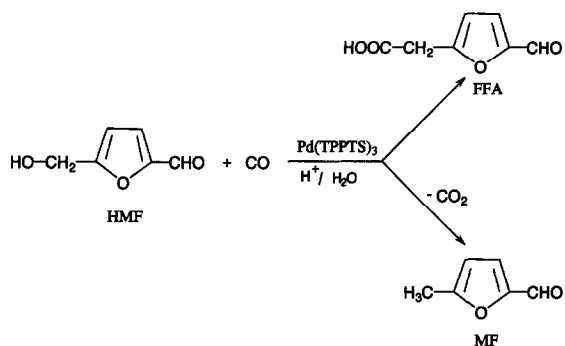
Fig. 2. Pd(TPPTS)$_3$-catalysed carbonylation and reduction of HMF.

recorded from chloro or hydroxo TPPTS complexes of rhodium such as RhCl(TPPTS)$_3$ or Rh(OH)(TPPTS)$_3$ are identical, which makes their direct identification in aqueous solution difficult [21].

The Pd(TPPTS)$_3$ catalyst used in all of the following carbonylation reactions was synthesized in situ after complexation of PdCl$_2$ with TPPTS in H$_2$O and subjection of formed [PdCl(TPPTS)$_3$]$^+$ to a carbon monoxide atmosphere under the chosen carbonylation reaction conditions.

2.2. Pd(TPPTS)$_3$-catalysed carbonylation of HMF in aqueous media

HMF was selectively carbonylated on the alcohol function to 5-formylfuran-2-acetic acid (FFA) (Fig. 2) under mild reaction conditions (70°C, 5 bar carbon monoxide pressure, 150 ppm Pd in the solution) in the presence of Pd(TPPTS)$_3$. The only by-product observed in this reaction was 5-methylfurfural (MF); no carbonylation of the aldehyde or cis-diene group of HMF was observed. This is the first example of a catalytic carbonylation using transition metal TPPTS catalysts in a completely aqueous medium. Levulinic acid (4-oxopentanoic acid) and formic acid, the hydrolysis products of HMF, were observed only in strongly acidic media (pH: −0.18) at higher temperatures (100°C).

Blank runs demonstrated that MF was not formed by reaction of HMF with acids, e.g., HI in the absence of the Pd(TPPTS)$_3$ catalyst. The formation of MF under the carbonylation conditions amounts to a new type of catalytic reaction: the reduction of an alcohol to the corresponding hydrocarbon (Eq. (3)).

$$ROH + CO \rightarrow RH + CO_2. \tag{3}$$
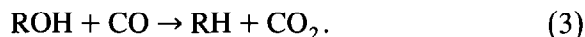
This reduction is equivalent to hydrogenolysis of an alcohol group to a hydrocarbon without using hydrogen. The concomitant formation of a molecule of carbon dioxide was proved by gas chromatographic analysis. A possible alternative explanation — the water gas shift reaction (Eq. (4)) followed by catalytic hydrogenation — can be excluded since no hydrogenation products of other functionalities of HMF were observed and no H$_2$ was detected in the gas phase.

$$CO + H_2O \rightleftharpoons CO_2 + H_2. \tag{4}$$
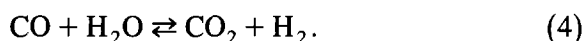
Quantitative reduction of HMF to MF was observed using protonic acids with strongly coordinating anions, e.g., HI (Table 2, run 2/14). Indeed, the quantitative reduction of HMF to MF is even more remarkable when one considers that HMF contains a reactive aldehyde group. In contrast, catalytic hydrogenation of HMF in aqueous media affords 2,5-bis(hydroxymethyl)furan; cis-2,5-bis(hydroxymethyl)tetrahydrofuran; hexane-1,2,5-triol or 1-hydroxyhexane-2,5-dione which are products of hydrogenation of the aldehyde moiety or the cis-diene system as well as hydrogenolysis of the furan ring [24].

2.2.1. Effect of TPPTS addition to palladium precursor (P / Pd molar ratio)

The palladium-catalysed carbonylation of HMF is strongly influenced by the amount of TPPTS added to the palladium precursor. The effect of the P/Pd molar ratio is shown in Table 1. No catalytic activity was observed with PdCl$_2$ in the absence of TPPTS and low catalytic activity resulted when the TPPTS ligand was

Table 1
Carbonylation and reduction of HMF using Pd/TPPTS catalysts at different P/Pd molar ratios [a]

Run	P/Pd molar ratio	Conversion [b] (mol%)	Selectivity [b] (%)	
			FFA	MF
1/1	0	0	0	0
1/2	2	1	22.4	77.3
1/3	4	53	64.9	34.4
1/4	5	74	67.7	31.9
1/5	6	90	71.6	27.9
1/6	7	87	71.8	27.6
1/7	8	71	72.2	27.2
1/8	12	40	72.9	26.3

[a] Reaction conditions: T: 70°C, P_{co}: 5 bar, t: 20 h, 35.5 mg (0.2 mmol) $PdCl_2$, 0.63 g (5 mmol) HMF (HMF/Pd = 25), 704.6 mg of 17.4 wt% H_2SO_4 solution in $H_2O \equiv 122.6$ mg (1.25 mmol) H_2SO_4, addition of deaerated H_2O for 141.9 g of reaction mixture, [Pd] = 150 ppm, pH of the catalyst solution: 2.1–2.9; after the reaction: pH = 1.5–1.9; Runs 1/1–1/5: black precipitate and black autoclave wall presumed to be metallic palladium; Runs 1/6–1/8: No metallic palladium formation;
[b] Determined by HPLC on the basis of HMF.

added either in relatively small amounts or in large excess. The highest yield of FFA was obtained when P/Pd = 6 (run 1/5). According to the literature [9] the carbonylation of substituted benzyl alcohols in organic solvents under acidic conditions using the hydrophobic catalyst Pd/PPh_3 leads to the formation of metallic palladium. In contrast, we observed no metallic palladium formation in the carbonylation of HMF at P/Pd > 6 which indicates no catalyst degradation occurs under these conditions. The stability of the Pd/TPPTS catalyst at P/Pd ≥ 6, low H^+ concentrations (H^+/Pd ≤ 12.5) and [Pd] = 150 ppm suggests that the Pd–P bond in the Pd/TPPTS catalyst in aqueous medium is more stable than in the Pd/PPh_3 systems in organic solvents, which may result from intramolecular association of sulfonate substituents of neighbouring TPPTS ligands via hydrogen bonding in aqueous medium [25].

2.2.2. Effect of acid or base addition

Carbonylation reactions of HMF were carried out with the $Pd(TPPTS)_3$ catalyst using different acids and bases as well as different amounts of added acid in aqueous media. The results are summarized in Table 2. When the catalyst precursor was employed in combination with a base, such as $CH_3CH_2NH_2$ or CH_3COONa no reaction was observed (runs 2/1, 2/2). In contrast, when protonic acids were added high conversions of HMF to FFA and MF were obtained (runs 2/3–2/14). The nature of the anion of the acid component markedly influenced the selectivity. Acids of weakly or non-coordinating anions, such as trifluoroacetic, p-toluenesulfonic, and hexafluorophosphoric acid, afforded mainly carbonylation. A slightly lower selectivity was observed with hydrogen chloride but the selectivity decreased dramatically with acids of strongly coordinating anions such as hydrogen bromide and hydrogen iodide. With the latter the only product observed was the reduction product (MF) in essentially quantitative selectivity (run 2/14).

Table 2
Carbonylation and reduction of HMF using $Pd(TPPTS)_3$ catalysts and addition of different bases and protonic acids [a]

Run	Base or acid added	Conversion (mol%)	Selectivity (mol%)	
			FFA	MF
2/1	$CH_3CH_2NH_2$	0	0	0
2/2	CH_3COONa	0	0	0
2/3	H_3PO_4	24	83.2	16.2
2/4	H_3PO_4	70	77.3	22.2
2/5	CF_3COOH	75	76.0	23.4
2/6	p-$CH_3C_6H_4SO_3H$	78	75.0	24.3
2/7	$HClO_4$	69	74.9	24.6
2/8	CF_3SO_3H	55	74.8	24.7
2/9	H_2SO_4	80	74.3	25.1
2/10	HPF_6	77	74.1	25.3
2/11	HCl	76	70.8	28.6
2/12	HNO_3	21	58.8	38.4
2/13	HBr	77	47.8	51.5
2/14	HI	54	0	99.8

[a] Reaction conditions: T: 70°C, P_{co}: 5 bar, t: 20 h, 35.5 mg (0.2 mmol) $PdCl_2$, 681.8 mg (1.2 mmol) TPPTS (P/Pd = 6), 0.75 mmol base or acid; 0.63 g (5 mmol) HMF (HMF/Pd = 25); except run 2/3: P_{co}: 10 bar, P/Pd = 8, HMF/Pd = 50, addition of 0.4 mmol H_3PO_4; addition of deaerated H_2O for 141.9 g of reaction mixture, [Pd] = 150 ppm; run 2/13: conversion (based on CO): 79%; pH of the catalyst solution: 2.1–2.9; pH of the mixture after the reaction: run 2/1: 8.12; 2/2: 4.12; 2/3–2/14: 1.6–1.8; run 2/3: No metallic Pd formation.

Table 3
Carbonylation and reduction of HMF using Pd(TPPTS)$_3$ catalysts with an addition of different amounts of H$_2$SO$_4$ and a palladium concentration of 150 ppm in the aqueous solution [a]

Run	H$_2$SO$_4$ addition (mol%)	Conversion (mol%)	Selectivity (mmol)	
			FFA	MF
3/1	0	37	73.7	25.5
3/2	0.75	80	74.3	25.1
3/3	1.0	85	72.8	26.5
3/4	1.25	90	71.6	27.9
3/5	1.50	79	70.1	29.4
3/6	2.0	78	66.7	33.2

[a] Reaction conditions: T: 70°C, P_{co}: 5 bar, t: 20 h, 35.5 mg (0.2 mmol) PdCl$_2$, 681.8 mg (1.2 mmol) TPPTS (P/Pd = 6), amount of H$_2$SO$_4$, 0.63g (5 mmol) HMF (HMF/Pd = 25), addition of deaerated H$_2$O for 141.9 g of reaction mixture, [Pd] = 150 ppm, pH of the catalyst solution: 2.1–2.9; after the reaction pH: 1.5–2.0.

Monflier et al. [26] similarly observed that telomerization reactions of 1,3-butadiene, catalysed by Pd/TPPTS and Pd/TPPMS complexes in water, were inhibited by bromide and chloride ions and they ascribed this to the blocking of free coordination sites on palladium.

In order to check the effect of the H$^+$ concentration, reactions were carried out without addition of acid (only the HCl formed during the complexation of PdCl$_2$ with TPPTS in the aqueous catalyst solution) and with addition of protonic acids (Table 3). Higher H$^+$ concentrations in the reaction mixture favour the formation of MF and also favour the degradation of the catalyst to metallic palladium. The fact that when the concentration of acid is increased, Pd/PPh$_3$ catalysts in organic solvents decompose more easily to metallic palladium has been reported [9,27,28].

At higher acid concentrations (H$^+$/Pd = 50) under more forcing conditions (T: 100°C) acid-catalysed hydrolysis of HMF to levulinic acid and formic acid together predominates.

2.2.3. Effect of temperature and carbon monoxide pressure

The best yields of FFA were obtained under relatively mild conditions of temperature and carbon monoxide pressure, i.e. 70°C and 5 bar CO, respectively. By comparison, carbonyla-

tions with Pd/PPh$_3$ catalysts in organic solvents are generally carried out at 110–130°C and > 130 bar CO pressure [9,10]. Similarly, carbonylation of bromobenzene with Pd(TPPTS)$_3$ [20] and benzyl chloride [29] using water-soluble Pd/TPPMS catalysts in a biphasic system proceeded at low CO pressure (15 and 1 bar, respectively).

2.2.4. Effect of palladium precursors and palladium concentration

The Pd/TPPTS-catalysed carbonylation of HMF was carried out using various palladium precursors (Table 4). The best results were obtained using PdCl$_2$. With PdBr$_2$ higher amounts of MF were formed consistent with the results observed with HBr as the added acid (vide supra). The palladium concentration strongly influences the conversion of HMF as well as the selectivities of FFA and MF (Table 5). At higher Pd concentrations the conversion of HMF and the selectivity to FFA drop dramatically with increasing selectivity of MF and with formation of palladium black.

2.2.5. Effect of ligands

The carbonylation of HMF was performed using palladium compounds modified with the sodium salt of the disulfonated triphenylphosphine (TPPDS) as a more basic ligand and

Table 4
Carbonylation and reduction of HMF using Pd/TPPTS catalyst prepared from different palladium compounds [a]

Run	Palladium compound	Conversion (mol%)	Selectivity (mol%)	
			FFA	MF
4/1	PdCl$_2$	23	71.0	25.3
4/2	PdBr$_2$	24	50.2	48.5
4/3	Pd(OAc)$_2$	13	67.5	23.0
4/4 [b]	Pd(acac)$_2$	13	43.9	5.4
4/5 [c]	Pd(PPh$_3$)$_4$	14	33.2	16.8

[a] Reaction conditions: T:70°C, P_{co}: 5 bar, t: 14 h, 0.2 mmol palladium compound, 681.8 mg (1.2 mmol) TPPTS (P/Pd = 6), 2.52 g (20 mmol) HMF (HMF/Pd = 100), 68.4 mg (0.36 mmol) p-CH$_3$C$_6$H$_4$SO$_3$H (H$^+$/Pd = 1.8), 49.9 g H$_2$O. [Pd] = 400 ppm.
[b] 106.5 mg (0.56 mmol) p-CH$_3$C$_6$H$_4$SO$_3$H.
[c] 0.2 mmol of Pd(PPh$_3$)$_4$ in toluene was extracted partly by an aqueous solution containing 1.2 mmol of TPPTS.

Table 5

Carbonylation of HMF using Pd(TPPTS)$_3$ catalysts at different palladium concentrations in the aqueous solution [a]

Run	Palladium concentration (ppm)	Conversion (mol%)	Selectivity (mol%)	
			FFA	MF
5/1	100	38	66.4	32.2
5/2	200	38	57.9	41.2
5/3	400	28	29.7	68.9
5/4	600	14	13.0	85.8
5/5	800	13	6.3	92.4

[a] Reaction conditions: T: 70°C, P_{co}: 5 bar, t: 20 h, 35.5 mg (0.2 mmol) PdCl$_2$, 681.8 mg (1.2 mmol) TPPTS (P/Pd = 6), 2.52 g (20 mmol) HMF (HMF/Pd = 100), 760.9 mg (4 mmol) p-CH$_3$C$_6$H$_4$SO$_3$H; addition of deaerated H$_2$O: Runs 5/1: 208.7 g; 5/2: 102.3 g; 5/3: 49.1 g; 5/4: 31.4 g; 5/5:22.5 g.

monosulfonated triphenylphosphine (TPPMS) as a much more basic ligand than TPPTS as well as with the sodium salt of a mixture containing 93.7% disulfonated and 6.3% trisulfonated tris(p-fluorophenyl)phosphine (TFPPDS and TFPPTS) [30–32]. The results are summarized in Table 6. Lower conversions and selectivities to FFA were obtained in the carbonylation of HMF using Pd/TPPDS compared to Pd/TP-PTS and only traces of FFA and MF were observed with Pd/TPPMS. Very low conversions of HMF and selectivities of FFA were also obtained with Pd/TFPPDS.

Table 6

Carbonylation of HMF using PdCl$_2$ as catalyst precursor modified with TPPTS, TPPDS, TPPMS, and TFPPDS (with TFPPTS) ligands [a]

Run	Ligand	Conversion (%)	Selectivity (%)	
			FFA	MF
6/1	TPPTS	35	78.8	17.9
6/2 [b]	TPPDS	4	39.0	59.3
6/3 [b]	TPPMS	trace	trace	trace
6/4 [b]	TFPPDS [c]	3	57.6	41.3

Reaction conditions: T:70°C, P_{co}: 5 bar, t:20 h, 35.5 mg (0.2 mmol) PdCl$_2$, 1.2 mmol ligand (P/Pd = 6), 2.52g (20 mmol) HMF (HMF/Pd = 100), 68.4 mg (0.36 mmol) p-CH$_3$C$_6$H$_4$SO$_3$H (H$^+$/Pd = 1.8), addition H$_2$O for 141.9 g of reaction mixture: 150 ppm Pd in the solution; pH of the catalyst solution: 2.8–3.9; pH after the reaction: 2.1–3.4; run 6/3: No metallic palladium formation.
[b] The complexation of PdCl$_2$ with these ligands is longer than 50 min.
[c] TFPPDS contains 6.3% TFPPTS.

2.3. Pd(TPPTS)$_3$-catalysed carbonylation of benzyl alcohol in a two phase system

Activated benzyl alcohols such as 4-hydroxy-benzyl alcohol can be carbonylated to 4-hydroxyphenylacetic acid ethyl ester in the presence of classical hydrophobic Pd/PPh$_3$ catalysts in organic solvents [9]. However, the Pd/PPh$_3$ catalytic system is inactive in the carbonylation of benzyl alcohol [9]. Carbonylation reactions of benzyl chloride catalysed by water-soluble Pd/TPPMS or Pd/TPPTS complexes to afford phenylacetic acid in an aqueous/organic two phase system are known [29,33,34].

We have carbonylated benzyl alcohol to phenylacetic acid (Eq. (5)) using Pd(TPPTS)$_3$ catalysts under mild reaction conditions in an acidic aqueous medium.

$$C_6H_5CH_2OH + CO \rightarrow C_6H_5CH_2COOH. \quad (5)$$
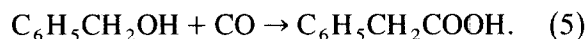
The only product obtained in the biphasic Pd(TPPTS)$_3$-catalysed carbonylation of benzyl alcohol was phenylacetic acid (Table 7) without any formation of toluene, the reduction product of benzyl alcohol or the dibenzyl ether. The best result (77% yield of phenylacetic acid) was obtained at 100°C and a TPPTS/Pd molar ratio of 12 (run 7/8).

Table 7

Carbonylation of benzyl alcohol to phenylacetic acid using Pd(TP-PTS)$_3$ catalysts [a]

Run	Temperature (°C)	P/Pd molar ratio	Yield phenylacetic acid (%)
7/1	70	10	7
7/2	80	10	18
7/3	90	10	29
7/4	100	10	49
7/5	110	10	36
7/6	100	6	42
7/7	100	8	45
7/8	100	12	77

[a] Reaction conditions: P_{co}: 60 bar, t: 10 h, 35.5 mg (0.2 mmol) PdCl$_2$, 540.7 mg (5 mmol) benzyl alcohol (benzyl alcohol/Pd = 25), 1.902 g (10 mmol) p-CH$_3$C$_6$H$_4$SO$_3$H (H$^+$/benzyl alcohol = 2), addition of deaerated H$_2$O for 141.9 g of reaction mixture, [Pd] = 150 ppm; No addition of organic solvents.

2.4. The catalytic cycle

In order to explain the results obtained in the Pd(TPPTS)$_3$ catalysed carbonylation and reduction of HMF we propose the mechanism depicted in Fig. 3, for the catalytic cycle [9,35–43] which involves the following steps:

(A) Oxidative addition of RX to the Pd(TPPTS)$_3$ complex, after dissociation of a TPPTS ligand, with formation of the cationic alkyl–palladium intermediate I. We propose that oxidative addition involves an SN1 mechanism (see later). The preference for *cis*-coordination of the TPPTS ligands in I could be explained in terms of intramolecular association of sulfonated substituents of the neighbouring TPPTS ligands via hydrogen bonding in aqueous medium [25]

(B) When X$^-$ is a weakly or non-coordinating anion, such as p-CH$_3$C$_6$H$_4$SO$_3^-$ or PF$_6^-$, CO coordinates at the free site of the species I with formation of the cationic intermediate II. The free coordination site could be occupied by a molecule of the solvent H$_2$O which is replaced by CO
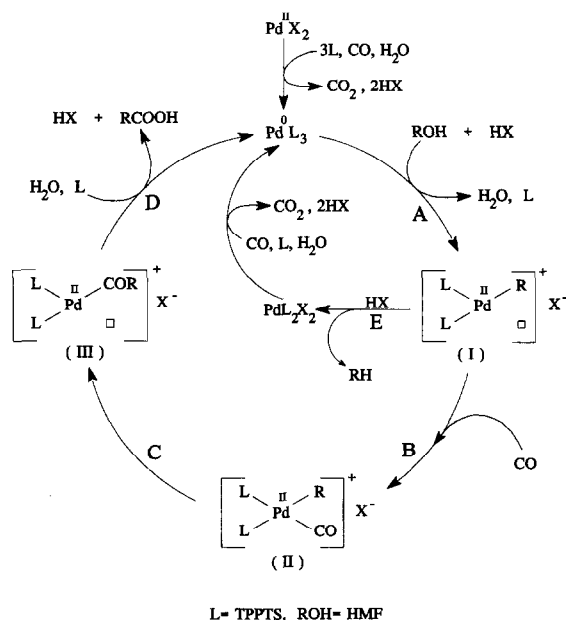
(C) CO Insertion into the Pd–C σ bond of intermediate II with formation of the cationic acyl palladium species III
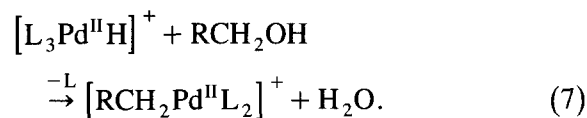
(D) Nucleophilic attack of H$_2$O on the carbon atom of the acyl intermediate III to give FFA and after coordination of TPPTS return the catalyst to the catalytic cycle

(E) When X$^-$ is a strongly coordinating anion, such as I$^-$, the free coordination site on the intermediate I is occupied and coordination of CO (step (B)) is inhibited. The X$^-$ ligand increases the electron density on the alkyl group of the formed RPdXL$_2$ complex and facilitates its protonolysis to give MF and PdX$_2$L$_2$. The latter undergoes subsequent reduction by CO and addition of a TPPTS ligand to regenerate the Pd(TPPTS)$_3$ catalyst. In contrast, protonolysis of a cationic complex with a non-coordinating anion is expected to be unfavourable.

We assume that step (A) involves an SN1 type mechanism [44], i.e. in the presence of strong acid the protonated alcohol undergoes dissociation to a carbenium ion (RCH$_2^+$) which subsequently undergoes oxidative addition to the palladium(0) complex (reaction (6)).

$$RCH_2^+ + L_3Pd^0 \xrightarrow{-L} \left[RCH_2Pd^{II}L_2\right]^+. \qquad (6)$$

We cannot exclude, however, an alternative mechanism involving initial protonation of Pd(TPPTS)$_3$ followed by its reaction with the alcohol (reaction (7)).

$$\left[L_3Pd^{II}H\right]^+ + RCH_2OH$$
$$\xrightarrow{-L} \left[RCH_2Pd^{II}L_2\right]^+ + H_2O. \qquad (7)$$

The influence of the TPPTS/Pd molar ratio (vide supra) suggests that the σ-donor properties of the TPPTS ligand also facilitate the oxidative addition (step (A)) to form the putative alkyl–palladium intermediate I by enhancing the electron density on the metal. In addition, the π-acceptor properties of TPPTS facilitate the coordination of carbon monoxide (step (B)) with formation of the species II and the subsequent nucleophilic attack of H$_2$O at the carbon atom of the acyl intermediate III to give

Fig. 3. Proposed catalytic cycle in the Pd(TPPTS)$_3$-catalysed carbonylation and reduction of HMF.
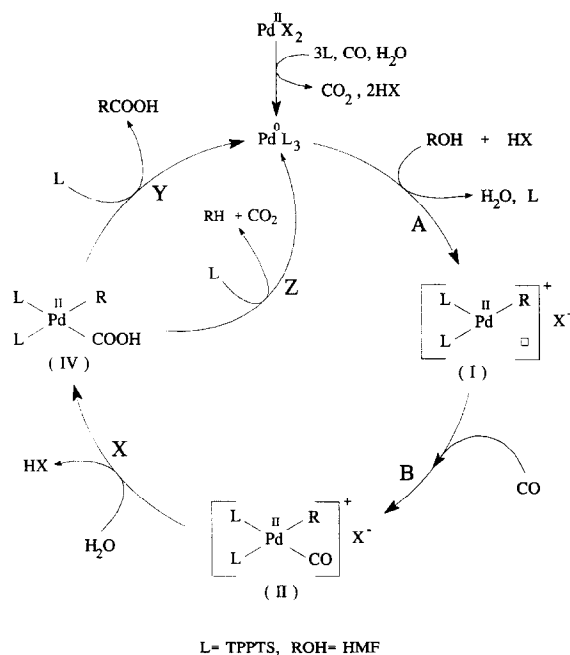
L= TPPTS, ROH= HMF

Fig. 4. The 'palladium–hydroxocarbonyl' catalytic cycle.

FFA. When the ligand is present in relatively large excess the catalytic activity drops dramatically, probably because TPPTS competes with carbon monoxide for the coordination to the metal.

A possible explanation for the higher activity of Pd/TPPTS in comparison to Pd/TPPDS, Pd/TFPPDS or Pd/TPPMS (vide supra) is that stabilization of the cis-form of the TPPTS cationic palladium intermediate I via intramolecular association of sulfonate groups of neighbouring TPPTS ligands via hydrogen bonding in water [25] is more effective in this case. In contrast, TPPDS, TFPPDS, and TPPMS contain less $-SO_3^-$ groups in comparison to TPPTS and may not stabilize the cis-$[RPdL_2]^+$ species.

The carbonylation and reduction of HMF may proceed by a second mechanism, depicted in Fig. 4, involving formation of the hydroxocarbonyl–alkyl–palladium intermediate IV by nucleophilic attack of H_2O at the carbon atom of the carbonyl group of the species II (step (X)). The hydroxocarbonyl adduct IV, after addition of a TPPTS ligand, yields FFA via reductive

elimination (step (Y)) or gives MF via the covalent hydride, $HPdR(TPPTS)_2$ after expulsion of CO_2 (step (Z)). Although we cannot rule out this mechanism we consider it to be less likely because hydroxocarbonyl adducts [45] are in general readily decomposed by acids [46] to regenerate the carbonyl moiety. Similarly, covalent palladium hydrides are easily attacked by protonic acids with formation of H_2 [47].

3. Concluding remarks

For the first time an efficient and selective carbonylation of benzylic type alcohols to the corresponding carboxylic acids has been achieved in aqueous medium. The procedure developed makes use of the water soluble $Pd(TPPTS)_3$ catalyst and performs under very mild conditions. The highest activity is observed with $PdCl_2$ as precursor and at a TPPTS/Pd molar ratio of 6. At this or higher ratios, with low H^+ concentrations, and a palladium concentration of 150 ppm, the catalyst remains intact without any degradation to metallic palladium. Using ligands containing less $-SO_3Na$ groups than in TPPTS the catalytic activity drops; with TPPMS only traces of the carbonylation are observed. This work also shows that the type of protonic acids changes the selectivity dramatically. When acids with strongly coordinating anions are used, a side-reaction, namely the reduction of HMF to MF, becomes the main reaction. This is a novel type of a catalytic and very selective reduction with CO, equivalent to hydrogenolysis of an alcohol group without using hydrogen.

4. Experimental

4.1. Materials

Carbon monoxide (quality 4.7) was purchased from Hoek Loos (Dieren) and was used without further purification. Distilled demineral-

ized water was deoxygenated in an ultrasound bath under high vacuum for 1 h. During the deoxygenation the flask was disconnected from vacuum and the aqueous solvent was saturated with argon; this procedure was repeated several times. The time for deoxygenation of water using vacuum obtained by a water aspirator is more than 2 h. $PdCl_2$ was purchased from Alfa (Johnson Matthey) and Sephadex G-25 (medium) from Pharmacia Fine Chemicals AB. Sephadex G-25 was degassed for 3 h in high vacuum and after addition of deoxygenated distilled demineralized water left to swell up under argon for 18 h (the flask was shaken several times, no magnetic stirrer was used). Pure $Pd(TPPTS)_3 \cdot 9H_2O$ as a brownish yellow powder was obtained after chromatographic purification on Sephadex G-25 and drying in high vacuum for 10 h with a yield of 94%. IR (KBr pellet) ν_{max}/cm^{-1} 3452 (br, vs, νO–H), 3068 (w, νC–H), 1632 (m, δO–H), 1463 (m, νC=C), 1401 (m, νP–C), 1205 (br, vs, νS–O), 1039 (vs, νS–O); elemental analysis. Found: C, 32.30; H, 2.93; P, 4.46. Calculated for $C_{54}H_{54}Na_9O_{36}P_3PdS_9$ (1973.81): C, 32.86; H, 2.76; P, 4.71%. TPPTS, TPPDS and TPPMS were prepared according to the procedure of Hoechst AG Werk Ruhrchemie [48]. $^{31}P\{^1H\}$ NMR (80.98 MHz, 25°C, D_2O): δ TPPTS: -5.56 ppm; δ TPPDS: -5.96 ppm; δ TPPMS: -6.28 ppm. All three ligands were isolated with purity higher than 99.3%. TFPPDS containing 6.3% TFPPTS was prepared according to a previously described procedure [30–32]. $^{31}P\{^1H\}$ NMR (161.89 MHz, 25°C, D_2O): δ TFPPDS: -9.22 ppm; $^5J_{P,F} = 4.0$ Hz; δ TF-PPTS: -8.74 ppm; $^5J_{P,F} = 3.8$ Hz.

4.2. Isolation, identification and analysis of the products

The aqueous HMF carbonylation mixture was extracted with methyl acetate in order to separate the substrate and products from the highly hydrosoluble ligand TPPTS. The methyl acetate layer was evaporated and during the evaporation

two phases were obtained. The lower layer, H_2O and TPPTS, was separated off. The upper methyl acetate layer was evaporated further and two layers were obtained once again. After separation the methyl acetate layer was cooled with an ice–salt mixture. Two layers were formed once again. The upper methyl acetate layer was separated off and dried over $MgSO_4$. After filtration the solution was concentrated under vacuum to a thick oil. Separation and isolation of FFA from MF and HMF as well as their characterization is described in Ref. [17]. NMR spectra were recorded on a Varian VXR-400 S spectrometer ($^{31}P\{^1H\}$ NMR (161.89 MHz) external reference, H_3PO_4: 1%) and Nicolet NT-200 WB spectrometer ($^{31}P\{^1H\}$ NMR (80.98MHz), external reference, H_3PO_4: 1%). The HMF carbonylation products in the aqueous solution were quantitatively and qualitatively analyzed with the aid of HPLC. The reaction mixtures, after filtration, were analyzed by HPLC using a 7.8 × 300 mm Rezex ROA Organic Acids Column (Phenomenex) at a temperature of 60 ± 1°C. The mobile phase was 0.01 M trifluoroacetic acid in water (0.6 ml/min). A refractive index detector (Shodex RI SE-51) and a UV spectrophotometric detector (Shimadzu SPD-6A, wavelength: 250 nm) were used. Glycolic acids as internal standard was added to the samples after the reaction. Retention times (min): TPPTS–Na (7.27); FFA (26.90); HMF (31.04); MF (65.62).

The gas phase of the carbonylation reaction was analysed by GC (Column: Carboplot 007 12.5 m × 0.53 mm; T_{init}: 30°C, t_{init}: 1 min, T_{final}: 50°C, rate: 10°C/min, t_{final}: 2 min; T_{inj}: 150°C; Carrier: He 6 ml/min, make up: 2 ml/min; reference: 20 ml/min).

The benzyl alcohol carbonylation mixture was extracted with ethyl acetate. The solvent was evaporated and after addition of methanol analyzed by HPLC using a Novapak C_{18} column at 25°C. The mobile phase was a mixture of CH_3OH/H_2O:50/50 containing 0.1 M buffer of CH_3COOH/CH_3COONa (pH:4.7). The flow was 1.0 ml/min. Retention times (min): Pheny-

lacetic acid (4.23) and benzyl alcohol (6.74). Phenylacetic acid was identified by comparison of spectral data with data of the authentic sample.

4.3. Preparation of the catalyst solution and typical carbonylation procedure

$PdCl_2$ and TPPTS were charged into a Schlenk-tube which was evacuated, heated with a heat gun and filled at room temperature with argon. The procedure to remove air oxygen was repeated. 50 g of deoxygenated distilled demineralized H_2O was added to the $PdCl_2$/TPPTS mixture. After 25–30 min of stirring at room temperature the $PdCl_2$ was completely dissolved and the mixture became bright yellow indicating complexation of $PdCl_2$ with TPPTS to give the $[PdCl(TPPTS)_3]^+$ catalyst precursor.

The $[PdCl(TPPTS)_3]^+$ catalyst solution, HMF, protonic acid and the rest amount of deoxygenated water (see Tables) were charged into a Hastelloy C autoclave (300 ml) which was previously evacuated and filled with argon. After a number of pressurising–depressurising cycles with carbon monoxide to remove the last traces of argon, the autoclave was pressured and the contents were heated with stirring. After the reaction the autoclave was cooled to room temperature, vented of CO and the reaction mixture removed. After filtration the aqueous HMF carbonylation solution was direct analyzed by HPLC. The benzyl alcohol carbonylation mixture was extracted with ethyl acetate and after evaporation of the solvent analyzed by HPLC.

Acknowledgements

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