

# Methoxycarbonylation of olefins catalyzed by palladium(II) complexes containing naphthyl(diphenyl)phosphine ligands

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Palladium(II) complexes containing phosphine donor ligands derived from naphthyl(diphenyl)phosphine were synthesized and characterized by NMR and elemental analysis. The complexes were studied as catalyst precursors in the methoxycarbonylation reaction of several aromatic and aliphatic olefins under mild conditions. The catalysts reported high chemoselectivities (over 96%) and regioselectivities between 44% and 93% for different olefins. The best results were obtained over a styrene substrate with 97% of conversion after 6 h of reaction, with high regioselectivity (93%). Kinetic studies permitted the determination of the rate law ( $v = k [\text{substrate}]^{1.21 \pm 0.02} [\text{catalyst}]^{0.94 \pm 0.11} [\text{acid}]^{0.52 \pm 0.03} [\text{MeOH}]^{0.53 \pm 0.05} [\text{CO}]^{0.65 \pm 0.03}$ ) for methoxycarbonylation of styrene. Copyright © 2014 John Wiley & Sons, Ltd.

**Keywords:** methoxycarbonylation; olefin carbonylation; palladium catalysts; homogeneous catalysis

## Introduction

It has been widely reported that palladium complexes catalyze the reactions of aromatic or aliphatic olefins with CO to produce esters or acids in the presence of alcohol or water, respectively.<sup>[1]</sup> These products are important chemicals used in the manufacture of several industrial products such as solvents, perfumes, drugs and flavorings. The branched esters are of interest in the pharmaceutical industry because they are precursors for an important class of non-steroidal anti-inflammatory drugs like naproxen<sup>[2]</sup> and ibuprofen.<sup>[3,4]</sup> The most active catalysts for this reaction are Pd(II) complexes containing phosphine ligands, and the important issue is the selectivity towards either linear or branched products. Methoxycarbonylation of styrene produces compounds such as 2-phenylpropionic (methyl-2-phenylpropanoate) and 3-phenylpropionic esters. Regioselectivity is strongly dependent on the catalytic system employed and the reaction conditions used. In general, monocoordinated phosphorus ligands were mainly employed to produce branched esters.<sup>[5]</sup> When palladium(II) complexes with bidentate phosphorus ligands were used, predominantly linear esters were produced.<sup>[6,7]</sup> Some years ago, Kiss<sup>[8]</sup> reported on the Reppe carbonylation of several substrates by palladium–phosphine complexes. It is widely accepted that in this type of reaction the catalytic cycle starts from the insertion of olefin into the Pd-hydride complex or into a Pd-carboalkoxy species.<sup>[8,9]</sup> The Pd(II)-hydride species is formed from the precursor and a hydrogen source such as acid, water or hydrogen,<sup>[10,11]</sup> while the Pd-carboalkoxy species is formed by the action of an alcohol on the Pd-carbonyl species.<sup>[3,10,12,13]</sup> Recently, Fuente *et al.*<sup>[14]</sup> reported on the methoxycarbonylation of ethene in an interesting study of the mechanism of the catalytic reaction using palladium–phosphine complexes. This mechanism suggests that Pd-hydride and Pd-OME are the active species in the catalytic reaction. On the other hand the Claver group<sup>[15–17]</sup> proposed a mechanism for

hydroxycarbonylation of styrene using palladium complexes. They found that palladium hydride and palladium acyl species were present, which suggests a catalytic cycle involving palladium hydride, palladium alkyl and palladium acyl intermediates.<sup>[18]</sup> In our case, we have been studying the methoxycarbonylation of styrene using palladium complexes which contain phosphorus–nitrogen ligands.<sup>[19]</sup> We found that Pd-hydride formation was promoted by *p*-toluenesulfonic acid concentration, and deuterium labeling experiments confirmed that the branch and linear esters are products of the catalytic reaction.

Consistently high selectivities in the hydroesterification reaction towards branched isomers have been obtained using complexes of Pd(II) with PPh<sub>3</sub> and *p*-toluenesulfonic acid as a promoter.<sup>[8,10–12,20,21]</sup> The absence of both compounds generates traces of esters and Pd metal and an inactive complex of Pd(0). It has been proposed that the role of *p*-toluenesulfonic acid (*p*-TsOH) is to facilitate the formation of a Pd-hydride intermediate and to reactivate the Pd(0) species by the addition of PPh<sub>3</sub> via an oxidative addition of the acid.

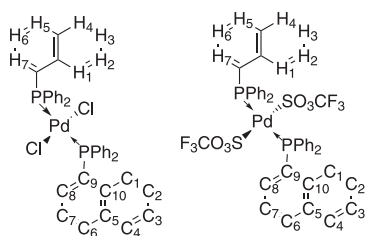
In this work we report on the synthesis and characterization of the palladium(II) complexes containing naphthyl(diphenyl)phosphine ligands (Scheme 1).

The complex dichloro-bis(1-naphthyl(diphenyl)phosphine)Pd(II) (**1**) was used as a catalyst precursor in the methoxycarbonylation

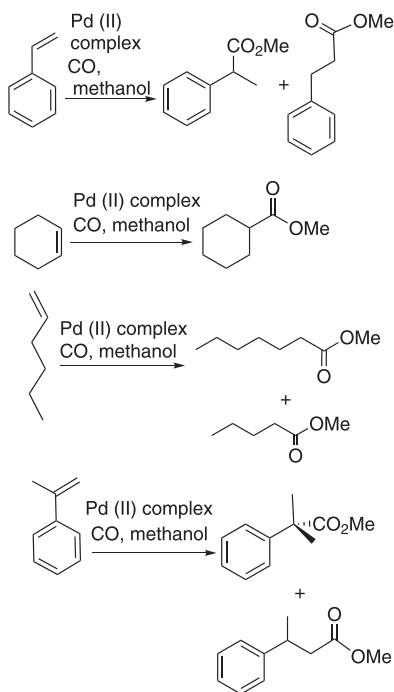
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**Scheme 1.** Palladium(II) complexes containing naphthyl(diphenyl)phosphine ligands.



**Scheme 2.** Products of methoxycarbonylation reactions.

reaction of various olefins under mild conditions of pressure and temperature (see Scheme 2). This precursor showed high activity in the methoxycarbonylation of styrene and moderate conversion for cyclohexene,  $\alpha$ -methylstyrene, or *n*-hexene. The complex (1) showed an activity of 93% for styrene methoxycarbonylation, with high selectivity toward the branched products. In contrast, cyclohexene,  $\alpha$ -methylstyrene and *n*-hexene showed conversion levels between 40% and 61% under the conditions of this catalytic reaction.

A similar result has been found with the complex trifluoromethanesulfonate [bis(1-naphthyl)diphenylphosphine]palladium(II) (2). This precursor shows high conversion and selectivity for the styrene methoxycarbonylation.

The catalytic behavior on styrene was studied in further detail. Modifications of several experimental conditions were performed in order to improve the results. To study the kinetics of the reactions we used the initial rates method. Moreover, the effect of several variables – such as CO, *p*-TsOH, MeOH, catalyst and substrate on turnover frequency (TOF), conversion, regioselectivities and initial rates – has also been studied.

On the other hand, when trying to determine the kinetic law for other olefins such as cyclohexene,  $\alpha$ -methylstyrene and *n*-hexene, it was not possible to obtain reliable values for the rate law, because the reactions with these olefins are slower and the

catalyst has an induction period, which makes it very difficult to determine the initial rate of reaction because it is not clear when the reaction was initiated.

## Material and Methods

### Method of Initial Rates

One of the first steps in studying the kinetics of a chemical reaction is to determine the rate law for the reaction. One method for making this determination is to measure experimentally how the concentration of a reactant or product varies with time, which makes it possible to build a typical plot of the kinetics. Another strategy for determining the rate law is to use the method of initial rates. This method involves measuring the rate of reaction at very short times before any significant changes occur in concentration. The rate law for the methoxycarbonylation of olefin reaction was determined using the method of initial rates.

Equation (1) shows the factors that influence the methoxycarbonylation of olefins.

$$v = k[\text{styrene}]^a[\text{CO}]^b[p\text{-toluenesulfonic acid}]^c[\text{catalyst}]^d[\text{MeOH}]^e \quad (1)$$

To determine the initial rate for each variable, the parameters are varied one at a time while the rest remain constant. For example, if only styrene concentration varies while all other parameters are kept constant, equation (1) takes the following form:

$$v = k'[\text{styrene}]^a \quad (2)$$

The natural logarithmic expression is

$$\ln v = \ln k' + a \ln[\text{styrene}]^a \quad (3)$$

The value of  $\ln v_{\text{initial}}$  obtained at different concentrations of styrene allows us to obtain the parameter *a* from a plot  $\ln v_{\text{initial}}$  versus  $\ln[\text{styrene}]$ . The same procedure was used to obtain *b*, *c*, *d* and *e*. The initial law was determined using the experimental conversion in short reaction times obtained from GC analyses.

The experimental data in all cases were determined with three replicates (*n* = 3) to ensure accuracy. Results are presented as the mean  $\pm$  SD (standard deviation) of three determinations.

## Experimental

### Materials

Diphenylphosphine chloride (PPh<sub>2</sub>Cl), 1-bromonaphthalene and *p*-toluenesulfonic acid monohydrate (*p*-TsOH) were obtained from Aldrich and used without previous treatment. All the substrates (styrene, cyclohexene, *n*-hexene and  $\alpha$ -methylstyrene) were purified using a short neutral alumina column (Merck) immediately prior to use. The analytical-grade solvents used (provided by Merck) were distilled by conventional methods and dried before use.

### Physical Measurements

Micro-elemental analysis was performed in a Fison-Carlo Erba EA 1108. NMR spectra were recorded on a Bruker 350 (MHz) instrument. GC analysis was carried out with a PerkinElmer 8500P instrument equipped with flame ionization detector, using a Carbowax 20M column and nitrogen as carrier gas. GC-MS was

performed in order to confirm the identities of the products in a Thermo Electron Corporation Trace GC Ultra double-focusing magnetic sector instrument (MAT 95XP).

### Synthesis of 1-Naphthyl(diphenyl)phosphine

The syntheses of 1-naphthyl(diphenyl)phosphine and Pd(II) complexes were carried out in Schlenk tubes under an inert atmosphere (N<sub>2</sub>) using procedures similar to those previously described for phosphorus–nitrogen complexes.<sup>[19]</sup>

### Synthesis of the Ligand

1-Bromonaphthalene (1g, 2.5 mmol) was dissolved in THF (10 mL). This solution was cooled to –78°C and butyllithium 1.6 M (in hexane, 1.9 mL, 3 mmol) was slowly added; the mixture was stirred for 1 h and diphenylphosphine chloride (PPh<sub>2</sub>Cl) (0.45 mL, 2.5 mmol) was added, allowing the temperature to increase slowly to 25°C. After 2 h the solvent was evaporated under vacuum and the oil obtained was dissolved in CHCl<sub>3</sub> and precipitated with diethyl ether. The solid powder obtained was dried under vacuum and recrystallized in chloroform–diethyl ether. White microcrystals were obtained with 75% yield. Analysis calcd (%) for C<sub>22</sub>H<sub>17</sub>P: C, 84.80; H, 5.49; found (%): C, 84.70; H, 5.35. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>): 8.40 (H<sub>1</sub>, dd, 7.8 Hz, 4.2 Hz, 1H); 7.89–7.84 (H<sub>4</sub>, H<sub>5</sub>, m, 2H); 7.52–7.30 (PPh<sub>2</sub>, m, 10H); 7.03–6.99 (H<sub>2</sub>, H<sub>3</sub>, H<sub>6</sub>, H<sub>7</sub>, m, 4H). <sup>13</sup>C NMR (CDCl<sub>3</sub>): 136.6 (C9, C—P); 136.4 (C11, C—P); 134.5 (*o*-Ph, C—H); 134.2 (*m*-Ph, C—H); 132.2 (C5); 129.6 (C10); 129.0 (C8, C—H); 128.8 (*p*-Ph, C—H); 128.7 (C6, C—H); 126.5 (C1, C—H); 126.2 (C3, C—H); 126.1 (C7, C—H); 125.8 (C2, C—H). <sup>31</sup>P-[<sup>1</sup>H] NMR (300 MHz, CDCl<sub>3</sub>): –21 (S). IR (KBr, cm<sup>–1</sup>): 3056 (C—H); 1504 (C—H); 1479, 1433 (C—H); 776 (P—C). UV–visible (λ nm; CHCl<sub>3</sub>): 270, 303.

### Synthesis of Dichloro[bis(1-naphthyl)diphenylphosphine]palladium(II) Complex (1)

Precursor PdCl<sub>2</sub> (200 mg, 1.13 mmol) was dissolved in CH<sub>3</sub>CN (20 mL) and (1-naphthyl)diphenylphosphine (705 mg, 2.26 mmol) was added. The mixture was stirred for about 6 h under nitrogen. A yellow solid was obtained with 80% yield. The product was washed with diethyl ether (2 × 5 mL) and dried under vacuum. The complex obtained showed low solubility in organic solvent. To obtain the <sup>13</sup>C NMR characterization, the chloro ligands of the complex were replaced by trifluoromethanesulfonate ligands. Analysis calcd (%) for C<sub>44</sub>H<sub>34</sub>Cl<sub>2</sub>P<sub>2</sub>Pd: C, 65.89; H, 4.27; found (%): C, 66.01; H, 4.21. <sup>1</sup>H NMR(CD<sub>2</sub>Cl<sub>2</sub>): 8.50 (H<sub>1</sub>, dd, 5.0 Hz, 8.5 Hz, 1H); 8.2 (H<sub>7</sub>, d, 9 Hz, 1H); 7.9–7.8 (H<sub>4</sub>, H<sub>5</sub>, m, 2H); 7.45–7.55 (H<sub>2</sub>, H<sub>3</sub>, m, 2H); 7.38–7.45 (PPh<sub>2</sub>, H<sub>6</sub>, m, 11H). <sup>13</sup>C NMR (CDCl<sub>3</sub>): 135.2 (C9, C—P); 135.3 (C11, C—P); 135 (o-Ph, C—H); 134.9 (*m*-Ph, C—H); 134 (C5); 133.6 (C10); 132.9 (C8, C—H); 131 (*p*-Ph, C—H); 130.5 (C6, C—H); 129.8 (C1, C—H); 128.9 (C3, C—H); 127.1 (C7, C—H); 126.5 (C2, C—H). <sup>31</sup>P NMR (CDCl<sub>3</sub>) 22 ppm (P<sub>1,S</sub>). IR (KBr, cm<sup>–1</sup>): 3052 (C—H); 1505 (C—H); 1480, 1434 (C—H); 775 (P—C). UV–visible (λ nm; CHCl<sub>3</sub>): 268, 300, 572.

### Synthesis of Trifluoromethanesulfonate[bis(1-naphthyl)diphenylphosphine]palladium(II) Complex (2)

The dichloro[bis(1-naphthyl)diphenylphosphine]palladium(II) complex (300 mg, 3.74 mmol) was suspended in CH<sub>2</sub>Cl<sub>2</sub> (10 mL) and silver trifluoromethanesulfonate (192 mg, 7.48 mmol) in CH<sub>2</sub>Cl<sub>2</sub> (5 mL) was added. The mixture was refluxed for 2 h and an orange solution

was obtained. The AgCl was removed by filtration under nitrogen and the solution evaporated under vacuum. The solid obtained was recrystallized in CH<sub>2</sub>Cl<sub>2</sub>–diethyl ether at 0°C, and was recovered by filtration and dried under vacuum. Yield 95%. Analysis: calcd (%) for C<sub>46</sub>H<sub>34</sub>F<sub>6</sub>O<sub>6</sub>P<sub>2</sub>PdS<sub>2</sub>: C, 53.68; H, 3.33; found (%): C, 53.55; H, 3.20. <sup>1</sup>H NMR (CDCl<sub>3</sub>): 8.14 (H<sub>1</sub>, d, 8.1 Hz, 1H); 8.01 (H<sub>7</sub>, d, 8.0 Hz, 1H); 7.86–7.76 (H<sub>5</sub>, H<sub>4</sub>, m, 2H); 7.63–7.52 (H<sub>2</sub>, H<sub>3</sub>, H<sub>6</sub>, m, 3H); 7.45–7.17 (PPh<sub>2</sub>, m, 10H). <sup>13</sup>C NMR (CDCl<sub>3</sub>): 135.7 (C9, C—P); 135.1 (C11, C—P); 135.0 (*o*-Ph, C—H); 134.2 (*m*-Ph, C—H); 133.5 (C5); 132.9 (C10), 132.1 (C8, C—H); 130.8 (*p*-Ph, C—H); 130.3 (C6, C—H); 130.1 (C1, C—H); 129.6 (C3, C—H); 128.4 (C7, C—H); 127.6 (C2, C—H); 122.7 (CF<sub>3</sub>SO<sub>3</sub>). <sup>31</sup>P NMR (CDCl<sub>3</sub>) 19 ppm (P<sub>1,S</sub>). IR (KBr, cm<sup>–1</sup>): 3055 (C—H); 1502 (C—H); 1482, 1437 (C—H); 693 (P—C); 1027 (–CF<sub>3</sub>); 1233 (–CF<sub>3</sub>); 1220 (S—O). UV–visible (λ nm; CHCl<sub>3</sub>): 269, 303, 577.

### Methoxycarbonylation Reaction

All experiments were carried out in a stainless steel reactor equipped with magnetic stirring, temperature control, pressure gauge and a Pyrex glass beaker in order to prevent contamination. In a typical experiment, the complex (32 mg, 0.04 mmol) was placed in a pre-vacuum sealed atmosphere (N<sub>2</sub>) glass reactor together with the substrate considered (16 mmol), *p*-TsOH (72 mg, 0.38 mmol) and methanol (5 mL, 123 mmol) in 1,2-dichloroethane (DCE) (15 mL) as solvent. The solution was introduced into the high-pressure reactor (110 mL), which was purged three times with CO, and then charged at the required pressure and heated at the desired temperature. Samples of the reaction mixture were periodically extracted for analysis by GC and the pressure was adjusted if necessary. The kinetic parameters were determined using 0.02 mmol palladium complex to obtain a low conversion in the first hour of reaction.

## Results and Discussion

PdCl<sub>2</sub> reacted with two equivalents of 1-naphthyl)diphenylphosphine, generating the Pd(II) complex with high yield. The paternal signal in <sup>1</sup>H NMR and <sup>31</sup>P NMR agreed well with the formula proposed for the complexes.

Complexes **1** and **2** are stable in air. When they are dissolved in CDCl<sub>3</sub> or CD<sub>2</sub>Cl<sub>2</sub>, yellow solutions are obtained. <sup>1</sup>H NMR and <sup>31</sup>P NMR spectra recorded at 5 m and after 24 h were similar, suggesting that the complexes are stable in solution. Solutions of the complexes prepared in solvent mixtures (methanol–toluene, 1:3 ratio) using concentrations in the range of those used in catalysis experiments showed complete solubility, and they were very stable.

The <sup>31</sup>P NMR spectra of the complexes showed a paternal signal for phosphine ligands in *trans* or *cis* configuration. The complexes were not crystallized with appropriate quality to obtain X ray diffraction; however, similar compounds synthesized in the literature suggest a *trans* phosphine configuration.<sup>[22,23]</sup> On the other hand, Guang-Cun *et al.*<sup>[24]</sup> recently reported the synthesis of polysubstituted furans using palladacycle catalysts containing naphthyl(diphenyl)phosphine as ligands. This type of compound was obtained when 1 equiv. palladium precursor reacts with 1 equiv. ligand after 24 h.<sup>[22–24]</sup> When the reaction was carried out using 2 equiv. of the phosphine ligand, it was possible to obtain only the complex of type PdL<sub>2</sub>Cl<sub>2</sub> (L = naphthyl(diphenyl)phosphine derivative ligand) and not the palladacycle complex.

Tables 1 and 2 show the catalytic activity of complexes **1** and **2** in the reaction of methoxycarbonylation of different olefins under mild conditions of reaction. The complexes show similar activities in all studied olefins. Both complexes show high conversion in the styrene methoxycarbonylation of 93% and 97% for complex **1** and **2** respectively in only 6 h of reaction. The other studied olefins showed conversion between 40% and 67% with similar behavior for both complexes.

The results indicate a high chemoselectivity towards the ester product for all olefins considered in the study. On the other hand, the regioselectivity (branched ester) for styrene and  $\alpha$ -methylstyrene was over 90%, except with hexene (>52% linear isomers).

Average values of several determinations are indicated in Fig. 1. The graph shows the substantial difference in the catalytic behavior observed with styrene with respect to the other alkenes. The activity of styrene increases and a maximum conversion is observed after around 6 h of reaction. The reaction of methoxycarbonylation with other olefins shows a slow conversion with a maximum after around 24 h of reaction.

### Kinetic Styrene Study

Experiments were carried out to study the effects of modifications of several reaction parameters on the activity and selectivity of both isomers formed during the methoxycarbonylation of styrene using the trifluoromethanesulfonate[bis(1-naphthyl)diphenylphosphine]palladium(II) (complex **2**).

Table 1. Methoxycarbonylation of olefins catalyzed by dichloro[bis(1-naphthyl)diphenylphosphine]palladium(II)				
Substrate	Selectivity		Conversion (%)	TOF
	Chemo- (%)	Regio- (%)		
Styrene	99	92 <sup>a</sup>	93	62
$\alpha$ -Methylstyrene	96	88 <sup>a</sup>	40	7
<i>n</i> -Hexene	98	44 <sup>a</sup>	61	10
Cyclohexene	99	100	47	8

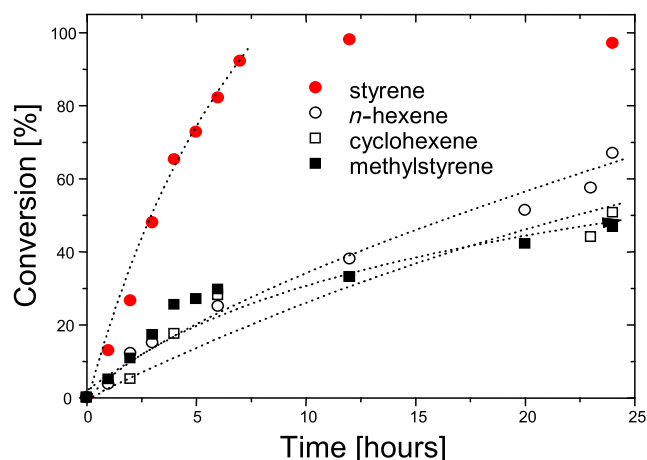
Reaction conditions: Pd complex 0.04 mmol; substrate:catalyst ratio = 400:1; dichloroethane 15 mL; methanol 5 mL; temperature = 75°C; styrene reaction time 6 h; reaction time of other olefins 24 h.

<sup>a</sup>Branched product.

Table 2. Methoxycarbonylation of olefins catalyzed by trifluoromethanesulfonate[bis(1-naphthyl)diphenylphosphine]palladium(II)				
Substrate	Selectivity		Conversion (%)	TOF
	Chemo- (%)	Regio- (%)		
Styrene	100	93 <sup>a</sup>	97	65
$\alpha$ -Methylstyrene	99	90 <sup>a</sup>	47	8
<i>n</i> -Hexene	100	48 <sup>a</sup>	67	11
Cyclohexene	97	100	51	9

Reaction conditions: Pd complex 0.04 mmol; substrate:catalyst ratio = 400:1; dichloroethane 15 mL; methanol 5 mL; temperature = 75°C; styrene reaction time 6 h; reaction time of other olefins 24 h.

<sup>a</sup>Branched product.



**Figure 1.** Methoxycarbonylation reaction of olefins catalyzed by trifluoromethanesulfonate [bis(1-naphthyl)diphenylphosphine]palladium(II) complex. Conditions of the reaction: Pd complex 0.04 mmol; substrate/catalyst = 400; dichloroethane 15 mL; methanol 5 mL; temperature = 75°C.

The order of reaction was obtained using the initial rate method. For example, in order to obtain the dependence on styrene, its concentration was varied between 0.4 M and 1.7 M, keeping constant all other parameters (concentration of *p*-toluenesulfonic acid, carbon monoxide concentration, catalyst concentration and methanol concentration). In this experiment the initial rate is a function only of the concentration of styrene (see Table 3). The slope of the graph,  $\ln v_{\text{initial}}$  vs.  $\ln [\text{styrene}]$ , allows one to obtain the order  $a$  for the reaction in which  $v = k[\text{styrene}]^a$ . Similar experiments were performed in order to determine  $b$ ,  $c$ ,  $d$  and  $e$  of [CO], [*p*-toluenesulfonic acid], [catalyst] and [MeOH] respectively.

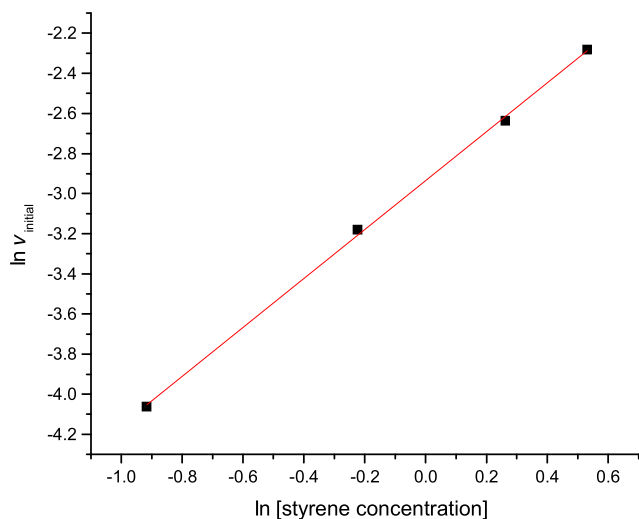
The  $k$  of the rate law can be obtained from the point of interception in a graph of  $\ln v_{\text{initial}}$  vs.  $\ln [\text{substrate}]$  (see Fig. 2). Where  $\ln k' = -2.93$ ,  $k' = 5.34 \times 10^{-2}$ . Thus, if the conditions are  $k' = k[\text{catalyst}]^{0.94 \pm 0.11} [\text{acid}]^{0.52 \pm 0.03} [\text{MeOH}]^{0.53 \pm 0.05} [\text{CO}]^{0.65 \pm 0.03}$  for [CO] = 2.0 M; [acid] = 0.01 M; [Pd] = 0.001 M; [MeOH] = 3.1 M, the  $k$ -value can be calculated as  $k = 135 \pm 0.6 (\text{mol L}^{-1})^{3.85 \pm 0.24} \text{h}^{-1}$ .

### Effects of CO Pressure

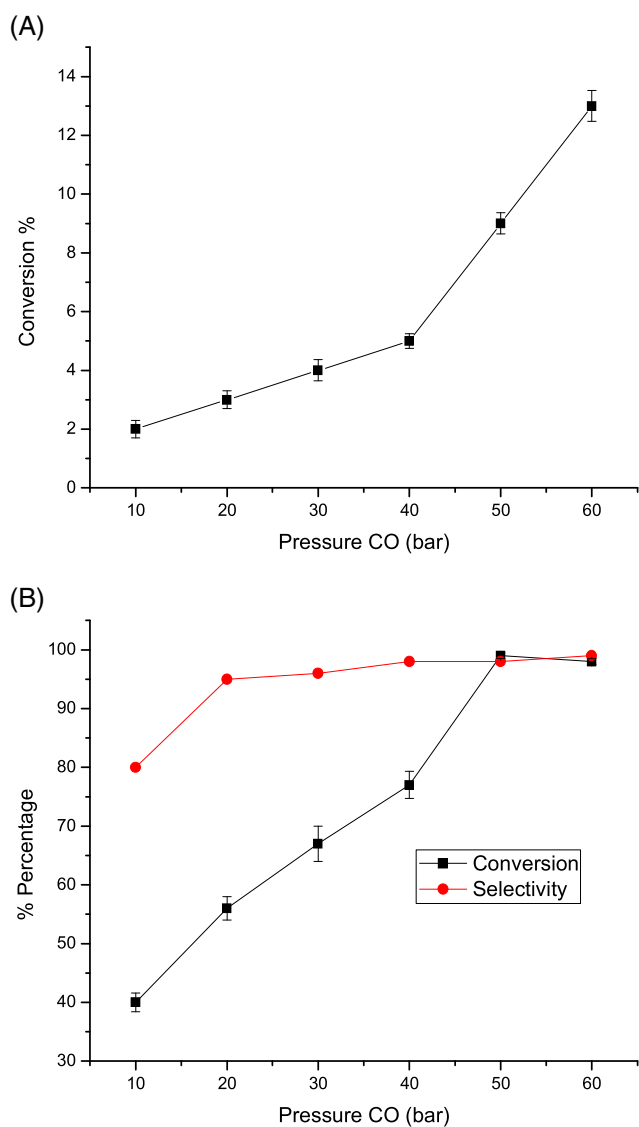
The results of the effect of CO pressure on conversion and regioselectivity are presented in Fig. 3(A,B). The figure shows that regioselectivity is over 80% in the whole range of CO pressure, but is increased with pressures over 20 bar. Above this value, high regioselectivities between 97% and 100% were observed for styrene between 1 h and 24 h of reaction time. Considering

Table 3. Determination of order $a$ of reaction in the substrate for methoxycarbonylation of styrene using the initial rate method				
Conversion (%) <sup>a</sup>	Initial rate ( $v_{\text{initial}}$ )	Styrene (M)	$\ln v_{\text{initial}}$	$\ln [\text{styrene}]$
4.3 ± 0.24	0.0172	0.4	-4.0628459	-0.9163
5.2 ± 0.25	0.0416	0.8	-3.1796551	-0.2231
5.5 ± 0.27	0.0715	1.3	-2.6380578	0.2624
6.0 ± 0.35	0.1020	1.7	-2.2827824	0.5306

$\Delta c/\Delta t = v_i$  constant = [CO], [MeOH], [*p*-toluenesulfonic acid], [catalyst],  
<sup>a</sup>mean of three experiments. Reaction time 1 h. Conversion confirmed using internal standard method.



**Figure 2.** Relationship between  $\ln v_{\text{initial}}$  vs.  $\ln$  [substrate concentration].



**Figure 3.** (A) Effect of CO pressure after 1 h and (B) after 24 h of reaction. Reaction conditions: Pd 0.02 mmol; *p*-toluenesulfonic acid:catalyst ratio = 10:1; substrate:catalyst ratio = 400:1; DCE 15 mL; methanol 3.1 M.

the CO pressure/reaction time relation, it is possible to conclude that over 50 bar the conversion does not increase significantly after 1 h of reaction, but after 24 h the methoxycarbonylation of styrene shows 100% conversion.

When the effect of the pressure of CO is studied (Fig. 3A,B), the conversion is linear with increasing pressure during the first hour of reaction. However, the conversion measured after 24 h shows that above 50 bar the conversion decreases. Nonlinearity is observed between conversion and the increase of pressure above 50 bar after 24 h.

Selectivity was maintained over 97% for the branched product (Fig. 3B). The kinetic parameter was calculated by using the initial rate method, obtaining the following order for  $P_{\text{CO}}$ :  $v = k [\text{CO}]^{0.65 \pm 0.03}$ . This result suggests that initial pressure is critical in order to obtain high conversion, and no linear effects were observed.

### Effect of *p*-Toluenesulfonic Acid Concentration

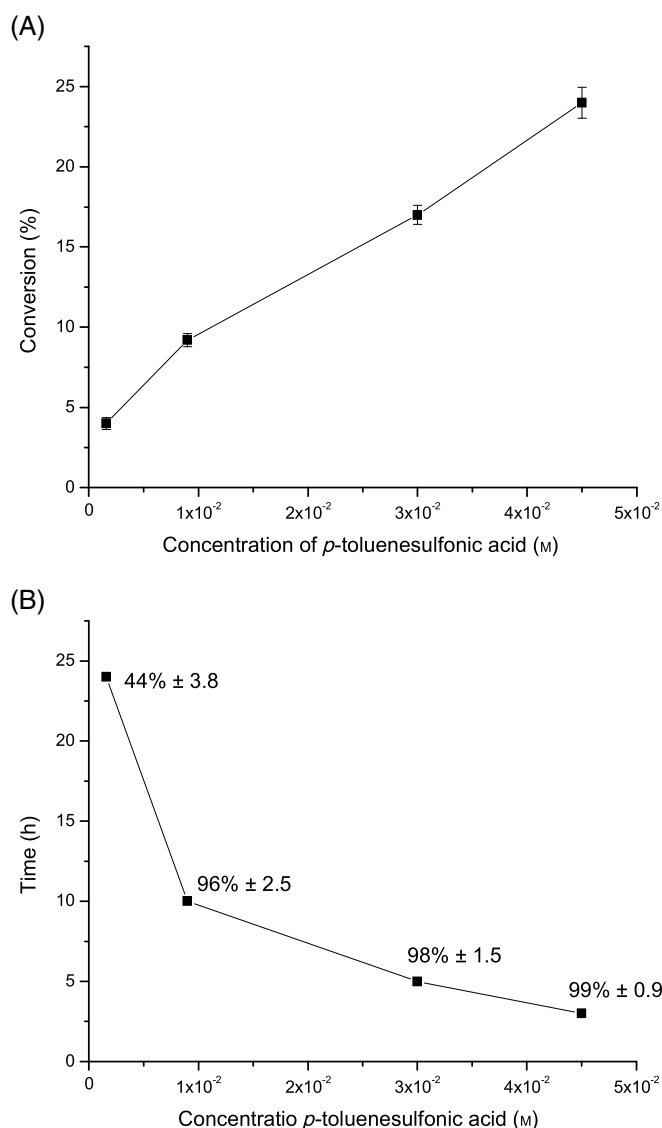
Fig. 4(A,B) shows the conversion and regioselectivity for different *p*-toluenesulfonic acid concentrations. The study was carried out over a range between 0.0016 M and 0.045 M *p*-toluenesulfonic acid. In this range, the level conversion in the methoxycarbonylation of styrene reaction was enhanced when the concentration of *p*-TsOH was increased. The conversion obtained between 1 h and 24 h of reaction suggests that the acid concentration is very important in the catalytic reaction. However, when using over 0.045 M of acid concentration, the conversion did not improve significantly. These results show that the Pd-hydride species could play a key role in the first steps of the catalytic cycle. The role of *p*-TsOH acid is to promote the formation of the Pd-hydride intermediate, which has been previously reported as key to the catalytic cycle of this reaction.<sup>[25–29]</sup>

Using the Initial rate method, the rate law obtained was  $v = k [p\text{-toluenesulfonic acid}]^{0.52 \pm 0.03}$ .

When conversion during the catalytic process was examined, in all cases the conversion obtained was 100%, but when the acid concentration was increased the maximum conversion was obtained in a shorter reaction time, as shown in Fig. 4(B). For example, when the acid concentration was 0.045 M, 100% conversion was obtained after only 3 h of reaction, but when the acid concentration was lower 100% conversion required a longer time of reaction. Thus, if an acid level of 0.0016 M is used, a reaction time of 24 h is required in order to reach 100% conversion.

### Palladium Concentration

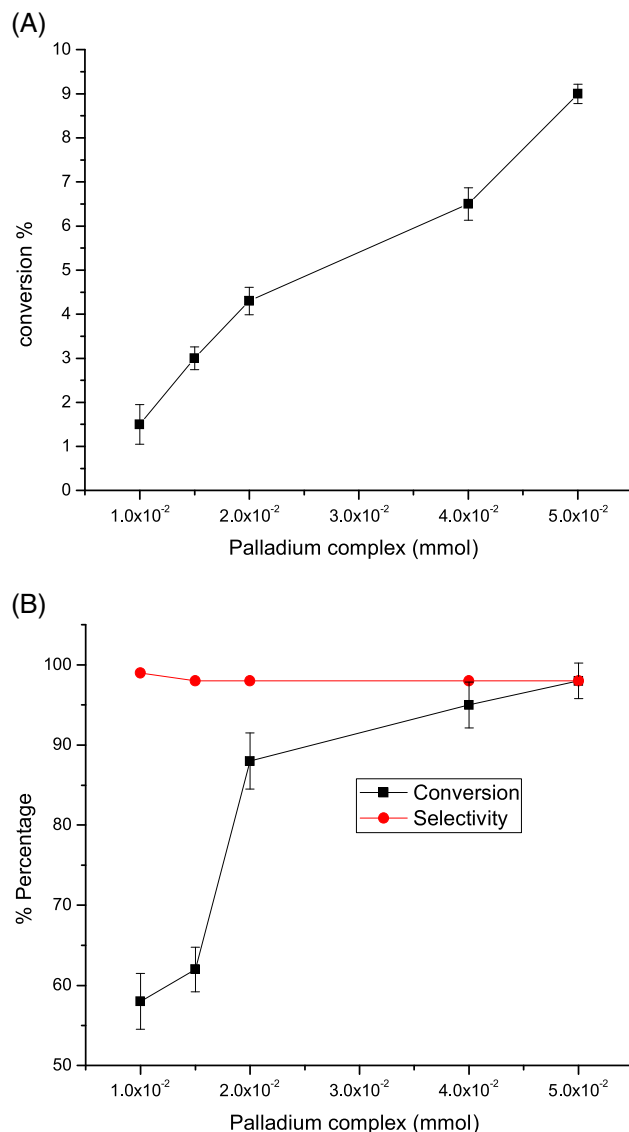
The results for the effect of the concentration of Pd(II) complex on the conversion and regioselectivity are presented in Fig. 5(A,B). Conversion in the methoxycarbonylation of styrene was higher when the palladium concentration was increased during the first hour of reaction. However, when the palladium concentration varied between 0.5 mM (0.01 mmol) and 1.0 mM (0.02 mmol) the effect was not clear during the first hour of reaction. On the other hand, after 6 h of reaction, the effect of palladium concentration was very important because significant levels of conversions were obtained with regioselectivity towards the branched product of about 98%. The kinetic parameter using the initial rate method allowed us to calculate the rate law, which was  $v = k [\text{catalyst}]^{0.94 \pm 0.11}$ .



**Figure 4.** (A) Effect of *p*-TsOH concentration after 1 h of reaction. (B) Effect of *p*-TsOH concentration in the maximum conversion in styrene methoxycarbonylation. Reaction conditions: Pd 0.02 mmol; *p*-toluenesulfonic acid 0.0016–0.045 M; substrate:catalyst ratio = 400:1; DCE 15 mL; methanol 3.1 M;  $P_{CO}$  = 50 bar.

### Effect of Styrene Concentration

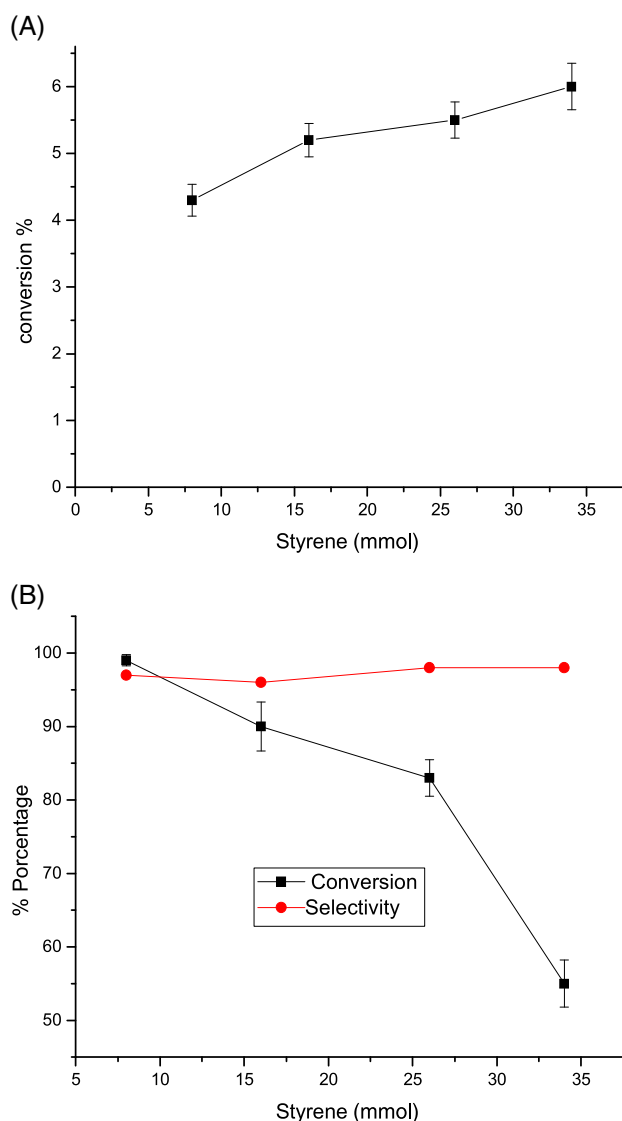
The results for the effect of styrene concentration on conversion and regioselectivity are shown in Fig. 6(A,B). During the first hours of reaction a linear effect between styrene concentration and conversion was observed. For a longer time of reaction, around 24 hours, no linear effect between styrene concentration and conversion was observed. Over 10 mmol styrene, the conversion did not improve significantly. This fact suggests that the palladium complex decomposes during the catalytic reaction, due probably to the fact that the high concentration of substrate generates a large amount of product, which tends to react with the catalyst to produce a poisoning effect, consequently decreasing the conversion. However, the regioselectivity of the catalytic process was maintained around 98% at 1 h and 95% at 24 h in all the ranges studied (400:1 to 1700:1). The kinetic parameter using the initial rate method made it possible to calculate the rate during the first hour of reaction:  $v = k [\text{substrate}]^{1.21 \pm 0.02}$ .



**Figure 5.** Effect of catalyst concentration in methoxycarbonylation olefin conversion and selectivity after (A) 1 h and (B) after 6 h of reaction. Conditions of reaction: substrate:catalyst ratio = 400:1; *p*-toluenesulfonic acid:catalyst ratio = 10:1; DCE 15 mL; methanol 3.1 M;  $P_{CO}$  = 50 bar.

### Effect of Methanol Concentration

The results of the effect of methanol concentration are summarized in Fig. 7(A,B). They indicate that the conversion and regioselectivity decreased when the methanol concentration was increased. Figure 7(A) shows the conversion and selectivity during the first hour of reaction. When the methanol concentration was increased beyond 12 M the activity decreased significantly, with low regioselectivity. The change in regioselectivity suggests a decomposition of the active species forming Pd(0). This behavior is more significant after 24 h of reaction. We have studied the methoxycarbonylation using different organic solvents, and in all cases the system was very sensitive to methanol concentration. This fact was confirmed by metallic palladium formation; however, using a low methanol concentration and a short reaction time (1 h), it was possible to obtain a rate law:  $V = k [\text{methanol}]^{0.53 \pm 0.05}$ . This result has to be carefully analyzed, due to the fact that the selectivity changed drastically in only 1 h of



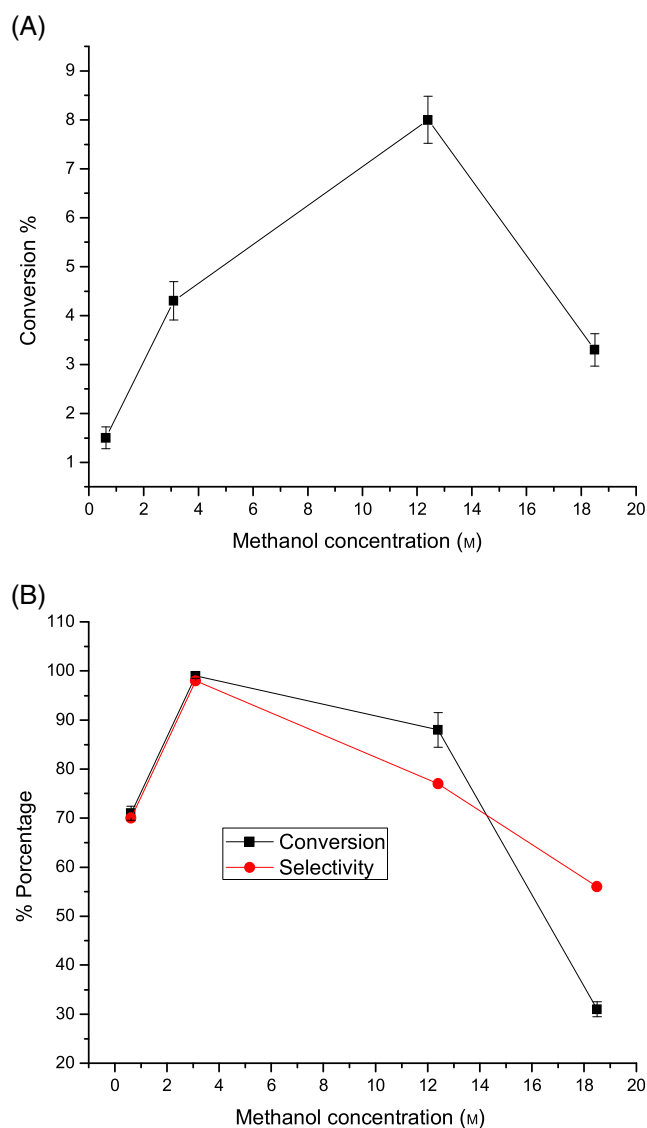
**Figure 6.** Effect of styrene concentration on the methoxycarbonylation reaction after (A) 1 h and (B) after 24 h of reaction. Reaction conditions: Pd 0.02 mmol; *p*-toluenesulfonic acid:catalyst 10:1; DCE 15 mL; methanol 3.1 M;  $P_{CO}$  = 50 bar.

reaction, which confirms the decomposition of palladium complex when the methanol concentration increased above 3 M.

This work has sought to optimize the main variables affecting methoxycarbonylation of olefins catalyzed by palladium(II) complex with naphthylphosphine ligands.

The reaction shows a nonlinear dependence on the acid concentration (Fig. 4A) since, when the acid concentration is doubled during the first hour of reaction, the conversion is increased, but it is not proportional to the amount of acid added. This is confirmed by the order of reaction obtained in the rate law.

Probably the excess of acid promotes the formation of a non-catalytic species or secondary undesirable reaction, which decreases the conversion rate achieved in the reaction. Moreover, both the CO and methanol drastically decreased the conversion at 24 h when the pressure (50 bar) and concentration (3 M) were increased. Under these conditions the formation of metallic palladium was observed, together with a decrease in the regioselectivity of the reaction, which is characteristic of the decomposition of the palladium catalyst in the reaction. This is



**Figure 7.** (A) Effect of methanol concentration on conversion and regioselectivity after 1 h of reaction. (B) Effect of methanol concentration on conversion and regioselectivity after 24 h of reaction. Reaction conditions: Pd 0.02 mmol; substrate:catalyst 400:1; *p*-toluenesulfonic acid:catalyst 10:1; DCE 15 mL;  $P_{CO}$  = 50 bar.

the reason why the reaction should be performed at shorter times in order to minimize this effect. Finally, the dependence between catalyst and substrate is close to first order, although this should be regarded with caution considering that, for high concentrations of substrate, the catalyst tends to decompose because the reaction product may react with palladium to form an inactive species. The results obtained indicate that the conversion and selectivity of the reaction increase when the concentration of substrate and catalyst increases, obtaining products (esters) with improved yields and with high selectivity up to a substrate:catalyst ratio of 400:1. On the other hand, the concentrations of *p*-toluenesulfonic acid, carbon monoxide and methanol must be handled with caution. The study shows that a pressure of 50 bar is optimal for the reaction. Above this value, a significant increase is not observed in the conversion and selectivity. The optimum concentration of acid to produce the best conversion and selectivity to the branched esters ranges from 0.030 to 0.045 M. In addition, the acid produces a significant effect on

reaction time (reductions achieved up to 3 h). Finally, the methanol concentration must not exceed 3 M. Above this concentration there is a substantial decrease in both activity and selectivity, since the catalyst under these conditions is decomposed by the action of methanol, drastically changing the efficiency of the reaction.

When the findings of our study are compared with those reported in the literature for reactions of olefin methoxycarbonylation, we can see that our results are better with respect to conversion times,<sup>[19,30]</sup> selectivity of the branched product<sup>[31]</sup> or relations of the substrate/catalyst used.<sup>[32]</sup>

## Conclusions

Palladium complexes containing naphthyl(diphenyl)phosphine derivatives have been synthesized and characterized.

The use of a palladium complex containing naphthylphosphine ligands as catalyst shows high activity and selectivity in the methoxycarbonylation reaction of different olefins. The best result was obtained in the methoxycarbonylation of styrene in only 6 h of reaction time.

The experimental rate law for the reaction was determined using the initial rate method:

$$v = 135 \pm 0.6 [\text{substrate}]^{1.21 \pm 0.02} [\text{catalyst}]^{0.94 \pm 0.11} \\ \times [\text{acid}]^{0.52 \pm 0.03} [\text{MeOH}]^{0.53 \pm 0.05} [\text{CO}]^{0.65 \pm 0.03}$$

## Acknowledgment

We thank Fondecyt-Chile for financial support provided by (Grant No. 1120149).

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