Palladium and rhodium allyl complexes in catalysis

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Chapter 10

New insights in the mechanism of the palladium catalyzed methoxycarbonylation of cinnamyl chloride.

Abstract

In this chapter, two mechanistic routes for the palladium catalyzed carbonylation of cinnamyl chloride are described, one associative and one insertion mechanism.

The associative mechanism was studied by the stepwise synthesis of potential intermediates at 1.2 bar of CO. After the formation of an intermediate [(η3-allyl)Pd(L)-CO][OTf]– complex (L is a monodentate ligand with a group 15 donor atom), the addition of methanol to the coordinated CO leads to the formation of a transient carboxymethoxy complex. Via reductive elimination of the η3-allyl and the carboxymethoxy group, the linear ester is formed. The catalytic carbonylation of cinnamyl chloride proceeds at room temperature and 1.2 bar of CO and requires the presence of a methoxide base. It was surprising to find an associative pathway for this reaction, since reported studies pointed to the insertion mechanism or disproved the occurrence of the associative mechanism.

When using a chloride counter ion instead of a triflate, insertion of the carbon monoxide in the Pd(η3-allyl) bond occurs at elevated pressure, forming an acyl complex. The insertion proved to be completely reversible. The ester product can be formed by reaction with methanol. The catalytic reaction via the insertion mechanism requires elevated pressures (>10 bar CO) and the absence of methoxide. The insertion mechanism was also studied using the bidentate P-N ligands POPyn (see chapter 6). When the chloride counterion was used, the acyl complexes could be isolated. For the POPyn modified complex, a crystal structure could be obtained in which the acyl group is located cis to the phosphorus. Interestingly, when acetate is used as the counterion also the analogous transient trans-P complex could be observed. Kinetic studies point out that the kinetic equation depends on the nature of the solvent. In all cases the catalytic reaction proceeds with a positive order in palladium, CO and the amine base.

Remarkably, for monodentate ligands, the catalytic carbonylation can proceed via both mechanisms. Which of the two prevails (association, insertion), depends on the ligand, the CO-pressure and whether methoxide or methanol is used.
Chapter 10

10.1 Introduction

As mentioned in chapter 1, the alkoxy carbonylation of dienes is a powerful tool in synthetic organic chemistry to form \( \beta \)-\( \gamma \) unsaturated esters (figure 1)[1]. These products can be used as intermediates in the synthesis of nylon-6 (figure 1).  

\[
\text{butadiene (A)} \quad \overset{\text{CO} + \text{CH}_3\text{OH}}{\longrightarrow} \quad \text{methyl 3-pentenoate (B)}
\]

\[
\text{nylon-6 (D)} \quad \overset{\text{Pd(}\eta^3\text{-allyl)}}{\longrightarrow} \quad \text{\varepsilon-caprolactam (C)}
\]

Figure 1: Use of the alkoxy carbonylation of butadiene in the synthesis of nylon-6.

Using butadiene as the substrate, research at DSM had shown the intermediacy of Pd(\( \eta^3 \)-allyl) complexes.[2] To obtain more insight in the carbonylation mechanism, we used the analogous allyl chlorides to obtain Pd(\( \eta^3 \)-allyl) complexes.

Carbonylation of allyl chlorides

Few studies have been reported concerning the carbonylation of allylic halides.[3a] In most cases a palladium catalyst is used for the alkoxy carbonylation of such substrates, although also rhodium or nickel based systems have been reported.[3b-c] Using palladium, the reaction proceeds under mild conditions and with a large tolerance for functional groups. The mechanism for the palladium system has been studied extensively by Yamamoto[4-a,4-c] and Milstein.[6a-7] As a model for the \( \eta^3 \)-allyl ligand the benzyl group was used, which can coordinate to palladium in an \( \eta^1 \)- or an \( \eta^3 \)-fashion (figure 2).[8]

\[
\text{Figure 2: } \eta^1 \text{-benzyl and } \eta^3 \text{-benzyl coordination of the benzyl group to palladium.}
\]
The mechanisms of the palladium catalyzed carbonylation.

Initially, two mechanisms have been proposed for the carbonylation reaction, a) an insertion pathway involving an acyl species in which the product-forming step is the alcoholysis of the Pd-acyl bond (figure 3) and b) an associative pathway involving a carbomethoxy intermediate, in which the product is formed by the reductive elimination of the π-allyl and the carbomethoxy group (figure 4).

Based on the studies using Pd-benzyl complexes as model systems, it was concluded that both the stoichiometric and the catalytic reaction proceed via an insertion pathway.

![Figure 3: Insertion pathway](image)

![Figure 4: Associative pathway](image)

Both because of the steric bulk of the phenyl group and because of the aromatic stabilization, the benzyl group will have a higher propensity to coordinate in the η¹-fashion than other allyl groups, such as cinnamyl (3-Ph-C₃H₅) or C₃H₅." Furthermore, in the studies mentioned, an excess of monodentate ligand was used (P/Pd > 1) which is known to stabilize the η¹-coordination thereby promoting the migratory insertion reaction of the Pd-(aliphatic carbon) σ-bond and CO, forming the Pd-C(O)CH₂Ph acyl species. The results obtained from these studies with the benzyl moiety may not be representative for an η¹-allyl group. Therefore we decided to perform mechanistic studies using complexes with a different allyl moiety and with only one equivalent of ligand per palladium. The use of the unsubstituted allyl ligand C₃H₅ proved not to be convenient, as (ligand)Pd(C₃H₅)X complexes were often found to be unstable. The slightly larger η³-C₃H₅ (crotyl group) is known to form several isomers, such as syn and anti complexes (see chapter 4), which complicates our mechanistic study. The 3,3-(CH₃)₂-C₃H₅ group may favor the η¹-isomer (figure 5) and thus is not a good model for an η³-allyl group either. We selected the η³-cinnamyl moiety for our studies, both because of the high stability of the complexes and the low tendency to form η¹-complexes.
Figure 5: Common η³-allyl moieties not used in this study.

Outline of this chapter

Using the η³-cinnamyl group, we studied systematically the possibilities of an associative and an insertion mechanism. We will evaluate the possible mechanisms using monodentate ligands and mixed bidentate ligands, both under high and low CO pressure.

Contrary to the reported studies, we will first show, that for some palladium complexes bearing one monodentate ligand, the alkoxy-carbonylation can proceed via the associative pathway. This mechanism was studied by the stepwise synthesis of intermediates and by performing catalytic reactions under a low pressure of CO.

Secondly, it will be shown that using the same ligands, the insertion pathway can be followed at elevated pressures. The insertion reaction proceeds for monodentate and bidentate P-N ligands. Also this mechanism was studied by the stepwise synthesis of intermediates and in addition, the kinetics of the catalytic reaction were studied by the variation of the concentrations of the various reactants.

10.2 Results and discussion: Associative mechanism, monodentate ligands

10.2.1 Synthesis of Pd complexes (1a-g) bearing monodentate ligands

To study the carbonylation mechanism of η³-cinnamyl complexes using monodentate ligands, we have prepared a series of (η³-cinnamyl)Pd(L)Cl complexes (figure 6, table 1) (1a-g). The used ligands are based on group 15 donor atoms and differ in steric and electronic properties.

The (cinnamyl)Pd(L)Cl complexes (1a-g) were prepared via reaction of the appropriate monodentate ligand with [(cinnamyl)PdCl]₂. The ¹H-NMR spectra showed sharp signals for all allylic protons. The coupling constant between Hc and Hd is relatively large (¹J(Hc-Hd) = 13 Hz) and indicates a trans configuration around the C2-C3 bond (see chapters 4-8). For the complexes containing a phosphorus ligand, a large coupling of phosphorus to Hd was observed (¹J(P-Hd) = 10 Hz), indicating that this proton is oriented trans to phosphorus. The chemical shifts of the signals of Ha-d do not differ much for the various ligands and it is concluded that
for all ligands, the phenyl group of the cinnamyl moiety is oriented trans to the ligand L, in a syn fashion with respect to the central allyl hydrogen He (figure 6) (see chapters 4-8).

![Figure 6: Numbering scheme of the cinnamyl moiety in the prepared complexes.](image)

Table 1: Numbering of complexes bearing monodentate ligands.

<table>
<thead>
<tr>
<th>Complex</th>
<th>L</th>
<th>Q</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>PCy₃</td>
<td>Cl</td>
<td>---</td>
</tr>
<tr>
<td>1b</td>
<td>PPh₃</td>
<td>Cl</td>
<td>---</td>
</tr>
<tr>
<td>1c</td>
<td>AsPh₃</td>
<td>Cl</td>
<td>---</td>
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<tr>
<td>1d</td>
<td>SbPh₃</td>
<td>Cl</td>
<td>---</td>
</tr>
<tr>
<td>1e</td>
<td>P(OPh)₃</td>
<td>Cl</td>
<td>---</td>
</tr>
<tr>
<td>1f</td>
<td>phosphorus-amidite *</td>
<td>Cl</td>
<td>---</td>
</tr>
<tr>
<td>1g</td>
<td>P(o-tolyl)₃</td>
<td>Cl</td>
<td>---</td>
</tr>
<tr>
<td>2a</td>
<td>PCy₃</td>
<td>MeCN</td>
<td>OTf</td>
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<td>PPh₃</td>
<td>MeCN</td>
<td>OTf</td>
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<td>OTf</td>
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<td>OTf</td>
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<td>MeCN</td>
<td>OTf</td>
</tr>
<tr>
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<td>P(o-tolyl)₃</td>
<td>MeCN</td>
<td>OTf</td>
</tr>
<tr>
<td>3a</td>
<td>PCy₃</td>
<td>CO</td>
<td>OTf</td>
</tr>
<tr>
<td>3b</td>
<td>PPh₃</td>
<td>CO</td>
<td>OTf</td>
</tr>
<tr>
<td>3c</td>
<td>AsPh₃</td>
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<tr>
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<td>SbPh₃</td>
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<td>OTf</td>
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<tr>
<td>3e</td>
<td>P(OPh)₃</td>
<td>CO</td>
<td>OTf</td>
</tr>
<tr>
<td>3f</td>
<td>phosphorus-amidite *</td>
<td>CO</td>
<td>OTf</td>
</tr>
<tr>
<td>3g</td>
<td>P(o-tolyl)₃</td>
<td>CO</td>
<td>OTf</td>
</tr>
</tbody>
</table>

*: see figure 7 for the structure of this ligand.
10.2.2 Reaction with CO

Treating 1a-g with 1.2 bar of CO resulted in a slight broadening of the \(^1H\)-NMR signals, but no new complexes were observed. Presumably, CO binds reversibly to complexes 1a-g, but the dynamic equilibrium strongly favors the \(\eta^3\)-cinnamyl)Pd(L)Cl complex (1a-g). Unfortunately, this could not be observed using IR spectroscopy.

To facilitate the binding of CO to these complexes, a vacant site was created by removal of the chloride by treatment with AgOTf. To stabilize the coordinatively unsaturated palladium, CH\(_3\)CN was added to occupy the vacant site (2a-g) (figure 8). In the absence of acetonitrile, the complexes were found to decompose to palladium metal within minutes. Complexes 2a-g are stable for a longer time, but decompose within hours after isolation. The \(^1H\)-NMR spectra of these cationic complexes are similar to those of the corresponding neutral complexes, which indicates that the orientation of the cinnamyl group is the same (syn trans P).

Upon treating these cationic complexes in chloroform with 1.2 bar of CO, the loosely bonded acetonitrile was easily replaced by CO and the light yellow solution of 2a-g turned colorless. Both IR and \(^{13}C\)-NMR spectroscopy (using \(^{13}CO\)) showed the formation of the novel [(cinnamyl)Pd(L)CO][OTf] complexes 3a-g. These complexes could not be isolated, but are stable for about one hour in solution (under an atmosphere of CO), before decomposing to palladium metal. The allyl region of the \(^1H\)-NMR spectra of these complexes is similar to those of the neutral complexes, indicating that also in this case, the phenyl group of the cinnamyl group is oriented syn-trans L.

![Figure 7: Structure of ligand f.](image)

![Figure 8: Synthesis scheme of [(cinnamyl)Pd(L)CO][OTf] 3a-g.](image)
The formation of complexes 3a-g is faster for the more basic ligands and the decomposition to palladium metal is slower. For these ligands, the stretching vibration of the coordinated CO in 3a-g was found at lower frequency (table 2). This is indicative of a more pronounced π-back donation from the palladium to the CO ligand, which can be explained by the higher electron density on the palladium. The enhanced π-back donation indicates a stronger bond between the palladium and the CO ligand, which may cause a higher stability of the complexes. The relatively high stability of other Pd-CO complexes with basic ligands has also been reported by Yamamoto, who used PMe3 for his mechanistic studies.[4,5,8]

Milstein and Yamamoto reported on the insertion mechanism, but unlike as in our studies they used at least two equivalents of ligand per palladium in their mechanistic studies.[4-8] The [(cinnamyl)Pd(L)CO][OTf] complexes showed no sign of insertion of CO, but the addition of an extra equivalent of PCy3-ligand to 3a, resulted in a new 13C resonance at 236 ppm, which was assigned to an acyl complex (see below) [4, 5, 7, 9, 26] (figure 9). The singlet resonance observed in the 31P-NMR spectrum suggests that both phosphorus ligands are magnetically equivalent, which can be explained by the formation of a complex bearing the two phosphines in a trans configuration.[4, 5]

Apparently, the non-coordinating counterion, the strong (η3-cinnamyl)-Pd bond (compared to the (η3-benzyl)-Pd bond) and an L / Pd ratio of 1 are crucial for the formation and relative stability of the [(cinnamyl)Pd(L)CO][OTf] complexes.

![Figure 9: Effect of addition of extra ligand to [(cinnamyl)Pd(PCy3)CO][OTf] (3a), L = PCy3.](image)

Table 2: Selected spectral data of the [(cinnamyl)Pd(L)CO][OTf] complexes (3a-g).  

<table>
<thead>
<tr>
<th>complex</th>
<th>L</th>
<th>δ(CO) NMR</th>
<th>ν (CO) IR</th>
</tr>
</thead>
<tbody>
<tr>
<td>3e</td>
<td>P(OPh)3</td>
<td>179.5</td>
<td>2133</td>
</tr>
<tr>
<td>3f</td>
<td>phosphorus-amidite *</td>
<td>179.4</td>
<td>2133</td>
</tr>
<tr>
<td>3b</td>
<td>PPh3</td>
<td>181.4</td>
<td>2125</td>
</tr>
<tr>
<td>3g</td>
<td>P(o-tolyl)3</td>
<td>n.d.</td>
<td>2123</td>
</tr>
<tr>
<td>3e</td>
<td>AsPh3</td>
<td>181.1</td>
<td>2123</td>
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<td>2115</td>
</tr>
<tr>
<td>3d</td>
<td>SbPh3</td>
<td>183.5</td>
<td>n.d.</td>
</tr>
</tbody>
</table>

n.d.: not determined

*: see figure 7 for the structure of this ligand
10.2.3 Reaction of [(cinnamyl)Pd(L)CO] complexes with nucleophiles.

To study the probability of an associative (carbethoxy) mechanism, the most readily formed and most stable cationic CO-complex, [(cinnamyl)Pd(PCy₃)CO][OTf] (3a), was treated with methanol at room temperature. According to ¹H-NMR several complexes were formed. The signals in the allyl region indicated the formation of a new (η³-cinnamyl)Pd(L) complex, which is assigned to the novel carbethoxy species 4a (see below). Yamamoto also studied the interaction of nucleophiles with (PMe₂)₂(benzyl-C(O))-Pd-CO. In contrast to our results it was found that alcohols only react via nucleophilic attack at the Pd-acyl group (methanolation),[⁴] whereas primary and secondary amines attack the coordinated CO, forming a Pd(amide) complex.

Addition of ammonium hydroxide at low temperature (-78° C) in methanol to [(cinnamyl)Pd(PCy₃)₁⁻¹⁻⁻⁻⁻CO][OTf] (3a) yielded the carbethoxy complex (4a) nearly quantitatively (figure 10, table 3). The ¹³C-NMR of this compound shows a resonance at 211.1 ppm (J_P,C = 23 Hz). This chemical shift is outside the normal range of Pd-CO or Pd-acyl type complexes, but it is similar to that of ((2S, 4S)-2, 4-bis-(diphenylphosphino)-pentane)Pd(Me)(COOMe) (δC = 214.4 ppm, J_P,C = 165 Hz).[¹⁴] The newly formed carbethoxy complex was stable at low temperature but upon heating to +10°C it decomposed to form the linear ester product and palladium metal.

The (η³-cinnamyl)Pd complexes (1-3) show a difference in the resonance of Hc and Hd larger than 0.5 ppm or show both resonances above 6 ppm (table 3, see also chapter 6). Therefore, the shifts of Hc (5.70 ppm) and Hd (5.60 ppm) of the [(cinnamyl)Pd(L)(C(O)OMe)] complex (4a) are not in agreement with a syn-trans-P orientation of the Ph group of the cinnamyl moiety (see chapter 6). Therefore it is proposed that the carbethoxy complex (4a) has the Ph group located syn-cis-P. The subsequent reductive elimination of the η³-cinnamyl and the carbethoxy group then yields the linear ester (E) (figure 11).

Figure 10: Synthesis scheme of [(cinnamyl)Pd(PCy₃)(C(O)OMe)] (4a), L = PCy₃.
Table 3: Chemical shifts of Hc and Hd in complexes of PCy₃ (1-4a), δ in ppm.

<table>
<thead>
<tr>
<th>complex</th>
<th>complex</th>
<th>Ha anti</th>
<th>Hb syn</th>
<th>Hc</th>
<th>Hd</th>
<th>P</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>X=Cl</td>
<td>2.64</td>
<td>3.28</td>
<td>5.80</td>
<td>5.20</td>
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<td>--</td>
</tr>
<tr>
<td>2a</td>
<td>X=OTf,</td>
<td>2.90</td>
<td>3.53</td>
<td>6.06</td>
<td>5.59</td>
<td>47.0</td>
<td>--</td>
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<tr>
<td></td>
<td>MeCN</td>
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<td></td>
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<tr>
<td>3a</td>
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<td>3.56</td>
<td>4.17</td>
<td>6.56</td>
<td>6.30</td>
<td>48.5</td>
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<td>4a</td>
<td>X=OMe,</td>
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<td></td>
<td></td>
<td></td>
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</tr>
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</table>

Figure 11: Reductive elimination of ester from [(cinnamyl)Pd(L)(C(0)OMe)].

The synthesis of carbomethoxy complexes (type 4) has been reported before. Milstein⁷ used Hg(C(0)OCH₃)₂ as a carbomethoxy-donor in the stoichiometric carbonylation of [(C₅H₅)PdCl]₂ and proposed a species of type 4 as an intermediate. Keim⁶ reported the preparation of (τ₃-C₅H₅-C(0)-Pd-C(0)-OR) via a one-pot procedure using [(τ₃-C₅H₅-C(0)-Pd-C(0)-OR)₂, two equivalents of PPh₃, and excesses of HC(0)OCH₃ and NaOMe. In contrast to our results, no reductive elimination to the linear ester was observed in these studies. Instead, a pathway was proposed involving an acyl group bonded to the carbomethoxy-Pd species (L₂(R-C(0)-Pd-C(0)-OR). Although the PPh₃-analogue of 4a may show different behavior than 4a itself, it cannot be ruled out that following the one-pot procedure a mixture of compounds was obtained. In contrast, the species 4a described in this chapter, was prepared via a stepwise route and does undergo reductive elimination to the ester.
10.2.4 Catalytic carbonylation at 1.2 bar CO

The ready formation of the carbomethoxy complex (4a) and the further reaction to the ester under mild conditions suggest that the catalytic carbonylation of cinnamyl substrates at 1.2 bar of CO at room temperature in organic solution is a feasible process. Indeed, the carbonylation of allyl halides under these conditions has been reported, but a two phase system was used, with potassium hydroxide as the nucleophile.\[6b, 15\]

To study the effect of the type of nucleophile on the reaction, experiments were carried out using both methoxide and hydroxide anions as the nucleophile. Sodium methoxide dissolved readily in the organic reaction medium (thf), but potassium hydroxide is much less soluble in organic solvents. Furthermore, the hydroxide anion proved to be too reactive and the direct nucleophilic attack on the allyl moiety leading to cinnamyl alcohol, prevailed over the carbonylation reaction. As a soluble alternative for KOH, we used NBu₄OH in a methanol solution.

![Figure 12: Products and side products of the carbonylation of cinnamyl chloride at room temperature and 1.2 bar of CO. The analogous side product cinnamyl alcohol is not formed.](image)

The use of cinnamyl triflate as the substrate resulted in a fast direct attack of the hydroxide or the methoxide on the cinnamyl and no carbonylation product could be observed (see chapters 4-8 for a discourse on nucleophilic attack on \(\eta^3\)-allyl complexes). The use of several other leaving groups instead of the triflate were examined (OAc, Br, Cl), but only cinnamyl chloride proved to be a suitable reagent for the carbonylation reaction, since the nucleophilic attack of hydroxide or methoxide is slow for this substrate.

The results of the catalytic carbonylation of cinnamyl chloride are presented in tables 4 and 5.
The mechanisms of the palladium catalyzed carbyonylation.

Table 4: Catalytic carbyonylation of cinnamyl chloride at room temperature and 1.2 bar of CO, using sodium methoxide, after 60 minutes. Substrate / Pd = 200, for further details: see experimental section.

<table>
<thead>
<tr>
<th>complex (L)</th>
<th>TOF*</th>
<th>conv. (%)</th>
<th>H (%)</th>
<th>G (%)</th>
<th>F (%)</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{1a (PCy}_3 )</td>
<td>132</td>
<td>66</td>
<td>5</td>
<td>5</td>
<td>9</td>
<td>82</td>
</tr>
<tr>
<td>( \text{1b (PPh}_3 )</td>
<td>16</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>75</td>
<td>13</td>
</tr>
<tr>
<td>( \text{1c(AsPh}_3 )</td>
<td>78</td>
<td>39</td>
<td>8</td>
<td>5</td>
<td>21</td>
<td>41</td>
</tr>
<tr>
<td>( \text{1d(SbPh}_3 )</td>
<td>80</td>
<td>40</td>
<td>8</td>
<td>5</td>
<td>18</td>
<td>70</td>
</tr>
</tbody>
</table>

*: in mole/mole/h, determined after 1 hour

Table 5: Catalytic carbyonylation of cinnamyl chloride at room temperature and 1.2 bar of CO, using NBu\(_4\)OH, after 60 minutes. Substrate / Pd = 200, for further details: see experimental section.

<table>
<thead>
<tr>
<th>complex (L)</th>
<th>TOF*</th>
<th>conv. (%)</th>
<th>H (%)</th>
<th>G (%)</th>
<th>F (%)</th>
<th>E (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{1a (PCy}_3 )</td>
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<td>68</td>
<td>28</td>
<td>25</td>
<td>3</td>
<td>44</td>
</tr>
<tr>
<td>( \text{1b (PPh}_3 )</td>
<td>52</td>
<td>26</td>
<td>19</td>
<td>19</td>
<td>38</td>
<td>23</td>
</tr>
<tr>
<td>( \text{1c(AsPh}_3 )</td>
<td>142</td>
<td>71</td>
<td>31</td>
<td>28</td>
<td>4</td>
<td>37</td>
</tr>
<tr>
<td>( \text{1d(SbPh}_3 )</td>
<td>184</td>
<td>92</td>
<td>24</td>
<td>22</td>
<td>1</td>
<td>53</td>
</tr>
</tbody>
</table>

*: in mole/mole/h, determined after 1 hour

Both the use of methoxide (table 4) and hydroxide/methanol (table 5), yields the linear trans ester E as the only carbyonylation product. This indicates that in both cases, methoxide is reacting. In addition, several other, non-carbonylation products are formed (F, G, H, figure 12). Remarkably, the possible side product cinnamyl alcohol (resulting from nucleophilic attack of OH\(_-\)) is not formed. Using NBu\(_4\)OH, both the conversion of cinnamyl chloride and the yield of the ester are higher than with NaOMe as the nucleophile, except when PCy\(_3\) is used. On the other hand, using NBu\(_4\)OH, also the relative amount of side products (G and H) formed is higher.

The formation of cinnamyl methyl ether (F) is not surprising and arises from nucleophilic attack of methanol or a methoxide anion on the \((\eta^3\text{-cinnamyl})\text{Pd}\) complex. The formation, however, of both allyl benzene (H) and \(\beta\text{-E-methyl styrene (G)}\) is remarkable. The ratio of allyl benzene (H) and methyl styrene (G) is approximately 1 for all ligands. The formation of these products occurs immediately after the start of the reaction and the amount does not increase in time. In the carbyonylation of allyl formates these products have also been observed, due to a decarbonylation of the formato group, giving a hydrido intermediate.\(^{41}\) Obviously, this mechanism cannot be operative in the present case.

The formation of allyl benzene (H) and \(\beta\text{-E-methyl styrene (G)}\) can be explained by the carboxmethoxy mechanism. The hydroxide that is present in the solution, may react with \([(\text{cinnamyl})\text{Pd(L)(CO)})][\text{Cl}]]\) (of the type 3a-d) to form \([(\text{cinnamyl})\text{Pd(L)(C(O)OH)}]\). Loss of CO\(_2\) then leads to the formation of a transient
[(cinnamyl)Pd(L)(H)] complex, which subsequently undergoes reductive elimination to form either allyl benzene H or ß-E-methyl styrene G. An analogous mechanism has been proposed for the hydroxycarbonylation of olefins. \(^{(21)}\) The feasibility of the reductive elimination of the allyl and the hydride from such palladium complexes is supported by theoretical studies (figure 13). \(^{(22)}\)

![Figure 13: Proposed mechanism of formation of allyl benzene and ß-E-methyl styrene.](image)

The initial formation of the carbonylation product E is much slower than the initial formation of G and H but the absolute amount of ester E steadily increases with conversion. The carbonylation proceeds fast for SbPh\(_3\) and slow for PPh\(_3\). As discussed above, the use of chloride as the counter ion leads to an equilibrium mixture of the CO-complexes (3a-g) with the starting complex (1a-g). Presumably, the (cinnamyl)Pd(L)Cl complex (1a-d) is the resting state of the catalyst. The CO-coordinated [(cinnamyl)Pd(L)CO][X] complexes (3a-g) are formed more readily and they are more stable for basic ligands, thereby increasing the concentration of the catalytically active species. This may be the cause of the higher overall reaction rate that is found for the basic ligands. This seems to be the major factor, although via increased \(\pi\)-back donation, the more basic ligands cause a higher electron density on the carbonyl ligand, which may decrease its reactivity towards nucleophiles.

Using the SbPh\(_3\) modified complex (1d) the carbonylation was also performed at 50 bar of CO, using NBu\(_4\)OH as the nucleophile. No significant difference was observed in rate and selectivity between the experiment at 50 bar CO and 1 bar CO, indicating that when NBu\(_4\)OH is used, the occurrence of the associative mechanism does not depend on the CO-pressure.

We propose that the following catalytic cycle is operative and can account for all the results (figure 14).

It is known, that the formation of the (\(\eta^3\)-cinnamyl)Pd complex 1 is a facile process (chapter 6, also 10.3). The next step is difficult and the dynamic equilibrium strongly favors complex 1. The rapid formation of ß-E-methyl styrene G and allyl benzene H shows that the next steps are easy for the hydroxide. The rate of reaction to form the ester E, however, is much lower. The difference between the reaction rate of the
The mechanisms of the palladium catalyzed carbonylation.

Hydroxide and the methoxide is either in the formation of 4 (from 3) or in the reductive elimination to form E (from 4). Our studies show that the reductive elimination proceeds rapidly at room temperature, leaving the reaction from 3 to 4 as the only candidate for the rate limiting step. More detailed kinetic studies are required to distinguish between these two steps.

Figure 14: Proposed catalytic cycle for the methoxy-carbonylation of cinnamyl chloride at 20 bar CO.

10.3 Results and discussion: Insertion mechanism

10.3.1 High pressure NMR using monodentate ligands

For the catalytic reaction at 1.2 bar of CO, cinnamyl chloride proved to be the only useful substrate and was used instead of cinnamyl triflate (section 10.2.4). Although the stepwise synthesis using the triflate complexes lead us to the discovery of the associative mechanism, we were interested in the reactivity of the chloride complexes towards CO. For these complexes, we were unable to observe CO-frequencies using infrared spectroscopy at 1.2 bar of CO (see section 4.2). We decided therefore, to study these complexes at various pressures of CO, using NMR spectroscopy. To this end, the (cinnamyl)Pd(L)Cl complexes (1a-d) were treated with 1.2 bar of CO. As expected, the chloride analogue of 3a-g ((cinnamyl)Pd(CO)Cl) could not be observed.
Raising the CO pressure to 20 bar and lowering the temperature to 233K resulted in the formation of a new complex. A characteristic pattern in the $^1$H-NMR spectrum was observed, showing Ha and Hb in the CH$_2$-unit around 4 ppm and the olefinic proton next to the phenyl as a doublet (figure 6). Furthermore, a resonance at 236 ppm in the $^{13}$C-spectrum indicated the formation of an acyl species (5a-b) (figure 15, table 6).[4, 5, 7, 9]

The starting $\eta^3$-cinnamyl and the acyl complex appeared to be in equilibrium. At low pressure and high temperature, the starting complex (cinnamyl)Pd(L)Cl (1a-b) was observed, whereas the acyl species was observed at low temperature and high pressure. No decomposition occurred during these NMR experiments and the formation of the acyl complex appeared to be completely reversible. After insertion of CO the formed acyl complex was found to be stable under the conditions used. Most likely, the vacant site created upon insertion will be occupied by a bridging chloride ligand, forming a dimeric complex (5a-b) (18b) (figure 16). In such a complex, the ligand and the carbonyl would be located cis to one another as in (POPy1)Pd(Cl)(C(O)cinnamyl) (13a, see below).

\[
\begin{align*}
\text{L} & \quad \text{Pd} \quad \text{Cl} \\
\text{Cl} & \quad \text{O} \\
\text{L} & \quad \text{Pd} \quad \text{O} \\
\end{align*}
\]

Figure 16: Proposed dimeric acyl species.

Several authors have reported on the reductive elimination of acid chloride from L$_2$Pd(acyl)Cl complexes.[18]

For the complexes studied in this chapter, however, no reductive elimination was observed.

To study the possible formation of the carboxethoxy intermediate (4a) from the acyl complex (5a), methanol was added to the solution, but no reaction occurred.

In contrast, the acyl species was not formed when the cationic [(cinnamyl)Pd(L)(MeCN)][OTf] complexes (2a-b) were used. The [(cinnamyl)Pd(L)CO][OTf] complexes (3a-b) were readily formed, but even raising the pressure of CO to as much as 50 bar did not result in the formation of the acyl complex (5a-b) (figure 15). Apparently, either an extra equivalent of ligand (see above) or a coordinating counterion are required to obtain acyl species.
The mechanisms of the palladium catalyzed carbonylation.

Figure 15: Observed species in HP-NMR using (cinnamyl)Pd(L,X) complexes.

Table 6: Distribution of (cinnamyl)Pd(L,X) complexes as observed using HP-NMR spectroscopy.

<table>
<thead>
<tr>
<th>L / X</th>
<th>Temperature (K)</th>
<th>p (bar)</th>
<th>% 1a/b (η³-allyl)</th>
<th>% 5a/b (acyl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCy₃</td>
<td>298</td>
<td>5</td>
<td>&gt;98</td>
<td>&lt;2</td>
</tr>
<tr>
<td>PCy₃</td>
<td>233</td>
<td>5</td>
<td>&gt;98</td>
<td>&lt;2</td>
</tr>
<tr>
<td>PCy₃</td>
<td>298</td>
<td>10</td>
<td>&gt;98</td>
<td>&lt;2</td>
</tr>
<tr>
<td>PCy₃</td>
<td>233</td>
<td>10</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>PCy₃</td>
<td>298</td>
<td>20</td>
<td>&gt;98</td>
<td>&lt;2</td>
</tr>
<tr>
<td>PCy₃</td>
<td>233</td>
<td>20</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>PCy₃ / OTf</td>
<td>298</td>
<td>50</td>
<td>&gt;98</td>
<td>&lt;2</td>
</tr>
<tr>
<td>PCy₃ / OTf</td>
<td>233</td>
<td>50</td>
<td>&gt;98</td>
<td>&lt;2</td>
</tr>
<tr>
<td>PPh₃</td>
<td>298</td>
<td>20</td>
<td>&gt;98</td>
<td>&lt;2</td>
</tr>
<tr>
<td>PPh₃</td>
<td>233</td>
<td>20</td>
<td>23</td>
<td>77</td>
</tr>
<tr>
<td>PPh₃</td>
<td>298</td>
<td>50</td>
<td>&gt;98</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>

10.3.2 High pressure NMR using bidentate PN ligands

In the previous paragraph describing the behavior of the complexes containing monodentate ligands, it was shown that an L/Pd ratio > 1 or a coordinating chloride counterion is needed to obtain acyl complexes. We therefore considered the use of hemilabile bidentate ligands. Since it is known\textsuperscript{[23]} that the use of dissymmetric ligands facilitates the CO-insertion, we decided to use the cinnamyl complexes of the ligands
Chapter 10

POPy1-3 (figure 17) (chapter 6), bearing the Ph group of the cinnamyl trans to phosphorus in the syn position.\(^{[16]}\)

![Figure 17: Used PN ligands, n=1: POPyl, n=2: POPy2, n=3: POPy3.](image)

Figure 17: Used PN ligands, n=1: POPyl, n=2: POPy2, n=3: POPy3.

![Figure 18: Reaction of complexes of type 12, as observed by HP-NMR.](image)

Figure 18: Reaction of complexes of type 12, as observed by HP-NMR.

Table 7: Numbering of complexes bearing POPyn ligands.

<table>
<thead>
<tr>
<th>Complex</th>
<th>Ligand</th>
<th>X</th>
<th>acyl complex?</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>11a</td>
<td>POPyl</td>
<td>OTf</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>11b</td>
<td>POPy2</td>
<td>OTf</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>11c</td>
<td>POPy3</td>
<td>OTf</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>12a</td>
<td>POPyl</td>
<td>Cl</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>12b</td>
<td>POPy2</td>
<td>Cl</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>12c</td>
<td>POPy3</td>
<td>Cl</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>13a</td>
<td>POPyl</td>
<td>Cl</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>13b</td>
<td>POPy2</td>
<td>Cl</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>13c</td>
<td>POPy3</td>
<td>Cl</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>14a</td>
<td>POPyl</td>
<td>OAc</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>14b</td>
<td>POPy2</td>
<td>OAc</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>15a1</td>
<td>POPyl</td>
<td>OAc</td>
<td>yes</td>
<td>minor</td>
</tr>
<tr>
<td>15a2</td>
<td>POPyl</td>
<td>OAc</td>
<td>yes</td>
<td>major</td>
</tr>
<tr>
<td>15b</td>
<td>POPy2</td>
<td>OAc</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>
Contrary to what was found for the complexes bearing monodentate ligands, treating the cationic (POPy1-3)Pd(η³-cinnamyl)OTf complexes (11a-c) with 1 bar of CO did not alter the NMR spectra. Raising the pressure to 50 bar, resulted in a slight broadening of the signals in the NMR spectra. No evidence was found, however, for coordination of CO to palladium or insertion of CO in the Pd-allyl bond. The ¹H-NMR spectrum shows that the pyridine functionality remained bonded to the palladium, thereby hampering the coordination of CO.

Since the presence of the nitrogen donor atom in the ligand did not result in the formation of the acyl complex, the corresponding chloride complexes 12a-c were prepared. The allyl signals in the ¹H-NMR spectra are broadened compared to the corresponding cationic complexes, indicating a lower barrier for the η¹-η¹ isomerization (see chapter 6). Recent EXAFS measurements show that the chloride counterion is at a large distance of the palladium, leaving the Pd-complex essentially cationic.¹¹ Again, treating these complexes with 1.2 bar of CO did not result in a reaction of the starting material.

Analogous to the complexes bearing monodentate ligands, NMR studies show that an increase of the CO pressure (> 5 bar) for the chloride containing complexes 12a-c resulted in the formation of the acyl complexes (13a-c) (figure 18, tables 7). The reaction proceeded smoothly for all three ligands, was irreversible for the POPy1 complex and was reversible for the POPy2 and the POPy3 complexes. It remains unclear, whether the different stabilities of 13a-c are only due to thermodynamic factors, or that kinetic factors may play a role as well. For instance, the low flexibility in the backbone of POPy1 may prevent rearrangements in the complex required for the reverse reaction.

The η³-allyl complexes of POPy2 and POPy3 (12b-c) and the newly formed acyl species (13b-c) are in equilibrium. At high temperature and low pressure, the η¹-allyl complexes (12b-c) are observed, whereas at low temperature and high pressure, the acyl complexes (13b-c) are observed. As was found for the monodentate ligands, also for the bidentate PN ligands, no reductive elimination of the acyl chloride was observed under these conditions.¹⁸

10.3.3 Effect of acetate as the counterion on acyl formation

As discussed in chapter 1, the use of leaving groups other than halogen atoms, is desirable for environmental reasons. Unfortunately, the catalytic carbonylation does not proceed for cinnamyl acetate (see below). To gain more insight in the origin of this inactivity of cinnamyl acetate, we studied the reactivity of the acetate complexes 14a-b towards CO.

The (POPy)n)Pd(cinnamyl)OAc complexes (14a-b) were prepared by treating 12a-b with AgOAc. The acetate complexes of monodentate ligands a-g (ligand)Pd(cinnamyl)OAc decomposed rapidly after formation to cinnamyl acetate and palladium metal, but the (POPy)n)Pd(cinnamyl)OAc complexes (14a-b) were found to be relatively stable. NMR spectroscopy showed that these complexes are very similar to the chloride analogues 12a-b.
The use of acetate instead of chloride as the counterion resulted in different behavior of the (POPyn)Pd(cinnamyl)OAc complexes (14a-b) upon reaction with CO. Pressurizing to 20 bar of CO at room temperature resulted in reductive elimination of cinnamyl acetate and decomposition to palladium metal. The propensity of (allyl)PdOAc type complexes to undergo reductive elimination in the presence of carbon monoxide has been described previously.\textsuperscript{[1b]} Below 273 K, the decomposition of 14a-b was slow and NMR-spectroscopy showed a $^{13}$C-resonance around 228 ppm, indicating the formation of the acyl species (15a-b) (table 8). In contrast to the chloride modified complexes, the (POPy2)Pd(cinnamyl)OAc (15b) complex slowly decomposed via reductive elimination to the linear anhydride (figure 19c) and palladium metal. This is in line with studies by Yamamoto, who reported on the reductive elimination of anhydrides from acyl-Pd-formato complexes.\textsuperscript{[4]}

Apparently, the use of cinnamyl acetate in the catalytic carbonylation is hampered by fast (direct or catalyzed) nucleophilic attack on the allyl and a relatively fast decomposition of the catalyst. EXAFS studies are being performed to gain more insight in the factors governing the decomposition of Pd(allyl) complexes (chapter 1).

![Figure 19 a-c: Reductive elimination of acyl complexes.](image)

For the POPy1 modified complex (15a), NMR-spectroscopy showed the presence of two acyl species in approximately a 3 / 2 (15a1/15a2) ratio, differing slightly in the chemical shift of $^{31}$P and $^{13}$C(O). Also in this case, slow decomposition occurred to the linear anhydride. Repeating the experiment with 5 bar instead of 20 bar of $^{13}$CO, again showed the two acyl species, but in a 1 / 5 (15a1/15a2) ratio. Lowering the temperature did not alter the ratio, but complex 15a1 disappeared upon raising the temperature to above 298 K. After completion of this reaction, lowering of the temperature did not alter the NMR-spectra, indicating
that the thermodynamically most stable isomer (15a2) had been formed. The $^{13}$C-NMR shift is close to that of the analogous chloride complex and 15a2 was assigned to the cis-acyl-P isomer (figure 20).

Table 8: Selected NMR data of the acyl complexes bearing PN ligands.

<table>
<thead>
<tr>
<th>complex</th>
<th>L</th>
<th>X</th>
<th>$\delta(^{13}\text{C-O})$/ppm</th>
<th>$\delta(^{31}\text{P})$/ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>13a</td>
<td>POPy1</td>
<td>Cl</td>
<td>226.5</td>
<td>119.9</td>
</tr>
<tr>
<td>13b</td>
<td>POPy2</td>
<td>Cl</td>
<td>229.6</td>
<td>106.7</td>
</tr>
<tr>
<td>13c</td>
<td>POPy3</td>
<td>Cl</td>
<td>227.5</td>
<td>118.9</td>
</tr>
<tr>
<td>15a1</td>
<td>POPy1</td>
<td>OAc</td>
<td>229.8</td>
<td>119.8</td>
</tr>
<tr>
<td>15a2</td>
<td>POPy2</td>
<td>OAc</td>
<td>231.9</td>
<td>123.5</td>
</tr>
<tr>
<td>15b</td>
<td>POPy2</td>
<td>OAc</td>
<td>228.0</td>
<td>106.8</td>
</tr>
</tbody>
</table>

These observations are in agreement with the proposed mechanism of the migratory insertion reaction.$^{23, 24}$ The dependence of the 15a1/15a2 ratio on the pressure can be explained by the relatively weak coordination of the acetate counterion. Under a high pressure of carbon monoxide, the CO may replace the acetate and retard the isomerization from 15a1 to 15a2. At a low CO pressure, the acetate is not replaced and the isomerization of 15a1 to 15a2 may be relatively fast.

10.3.4 Crystal structure of 13a

For POPy1, the CO-insertion reaction is not reversible under the applied conditions and complex 13a could be isolated. Recrystallization from CDCl$_3$ / hexane yielded colorless crystals suitable for structure determination by X-ray crystallography. As shown in the molecular plot (figure 21 and 22 and table 9), the acyl group is located cis to phosphorus, which is in agreement with the small P-C coupling constant ($J_{P-C}$ <
10 Hz) and with previous studies on (alkyl-C(O))-Pd(P-N) complexes that show that the acyl group is located cis to phosphorus.\[^{[17]}\]

The geometry around the central Pd-atom is square planar and the angles between the ligands are all close to 90°. The pyridine ring is rotated with respect to the coordination-plane and the Pd-P and Pd-N bonds are of almost equal length. The cinnamyl group is almost planar and points away from the palladium atom. The C=C double bond (C3-C4) and the phenyl rings on the phosphorus are at a distance of 4Å and are almost parallel.

Figure 21: X-ray crystal structure of 13a.

Figure 22: Line drawing and numbering scheme of the crystal structure of 13a.
The mechanisms of the palladium catalyzed carbonylation.

Table 9: Selected structural data of the crystal structure of 13a.

<table>
<thead>
<tr>
<th>Distance or angle</th>
<th>Value (distances in Å, angles in °)</th>
</tr>
</thead>
<tbody>
<tr>
<td>d(Pd-Cl)</td>
<td>2.348(3)</td>
</tr>
<tr>
<td>d(Pd-N)</td>
<td>2.210(5)</td>
</tr>
<tr>
<td>d(Pd-P)</td>
<td>2.215(2)</td>
</tr>
<tr>
<td>d(Pd-C(1))</td>
<td>1.972(6)</td>
</tr>
<tr>
<td>d(C(1)-O)</td>
<td>1.202(9)</td>
</tr>
<tr>
<td>d(C(1)-C(2))</td>
<td>1.580(13)</td>
</tr>
<tr>
<td>d(C(2)-C(3))</td>
<td>1.526(9)</td>
</tr>
<tr>
<td>d(C(3)-C(4))</td>
<td>1.305(11)</td>
</tr>
<tr>
<td>d(C(4)-C(ipso))</td>
<td>1.508(10)</td>
</tr>
<tr>
<td>(\angle) (Cl-Pd-N)</td>
<td>92.66(16)</td>
</tr>
<tr>
<td>(\angle) (N-Pd-P)</td>
<td>88.83(16)</td>
</tr>
<tr>
<td>(\angle) (P-Pd-C(1))</td>
<td>89.3(2)</td>
</tr>
<tr>
<td>(\angle) (C(1)-Pd-Cl)</td>
<td>89.4(2)</td>
</tr>
</tbody>
</table>

10.3.5 Discussion on the formation of cis-complexes

The reaction of (POPyn)Pd(Cl)(cinnamyl) complexes (12a-c) with CO resulted in the clean formation of the CO-inserted (POPyn)Pd(Cl)(C(O)cinnamyl) complexes (13a-c) with the phosphorus and the carbonyl functions cis to one another. This has been observed before for migratory insertion reactions in palladium complexes\(^{117, 23}\) (figure 23) but seems to contradict the Cossee mechanism\(^{24}\) which describes the acyl forming step as a migration reaction rather than a insertion reaction (see below).

The coalesced signals of Ha and Hb indicate that the well known \(\eta^1-\eta^1-\eta^3\) rearrangement readily occurs in the (POPyn)Pd(Cl)(cinnamyl) complexes (12a-c). In chapter 6 it was shown, that with the phenyl group of the cinnamyl trans to the phosphorus atom, the \(\eta^1-\eta^1-\eta^1\) rearrangement occurs via a selective cleavage of the Pd-allyl bond trans to the phosphorus atom, forming species 12-2 (figure 23). Consequently, the vacant site available for coordination of CO is trans to phosphorus. Migratory insertion via the Cossee mechanism, therefore, would yield the acyl group trans to phosphorus, instead of the observed cis arrangement. The trans-cis isomerization in such complexes is known to proceed easily and accounts for the observation the thermodynamic product only.\(^{23}\)

The \(\eta^1-\eta^1-\eta^3\) rearrangement, however, also takes place in the cationic complexes bearing a triflate counterion (11a-c). Even at a pressure of 50 bar, no insertion and no complexes other than (POPyn)Pd(cinnamyl)OTf (11a-c) could be observed. Apparently, the chloride counterion plays a crucial
role in the process of formation and / or stabilization of the acyl species (13). Several explanations may account for this behavior. First, the chloride may facilitate the isomerization from the trans-isomer to the cis-isomer. Thus, after formation of the kinetic trans-acyl complex, isomerization to the cis-isomer has to occur before “de-insertion” and dissociation of CO takes place. Second, the chloride counterion may be involved in a concerted mechanism, in which the CO coordinates and inserts in one step. This mechanism could proceed via either an $\eta^1$- or an $\eta^3$-complex.[25] Attempts to study the insertion pathway in an ($\eta^3$-C$_3$H$_5$)Pd(PH$_3$)(NH$_3$)Cl complex by molecular modeling have failed as a result of the strong interaction between the chloride and the cationic palladium center.

$\eta^1$-complex

In the $\eta^1$-complex (figure 24), the coordination of both Cl and CO to the palladium may cause the $\eta^3$-cinnamyl to rearrange to the $\eta^1$-cinnamyl. As the donor ligands will be located preferentially trans to the best π-acceptor ligands, the square pyramidal five coordinated transient complex depicted in figure 24 will be formed. The phosphorus and nitrogen donor atoms are cis to one another, the CO ligand is located trans to nitrogen and the $\eta^1$-allyl trans to phosphorus. Subsequent migratory insertion will directly yield the observed (POPyl)Pd(Cl)(C(O)cinnamyl) (13a) with the phosphorus and the carbonyl functions cis to one another.

$\eta^3$-complex

In an alternative mechanism, the cinnamyl remains bonded to the palladium in an $\eta^3$-fashion (figure 25). Upon coordination of CO and a weak coordination of Cl in the second coordination sphere, a concerted insertion of CO in the $\eta^3$-cinnamyl occurs. Because the CH$_2$-site of the cinnamyl is cis to phosphorus, the acyl will also be cis to phosphorus.

Figure 23 $\eta^3$ - $\eta^1$ rearrangement and CO insertion, according to the Cossee mechanism, for cationic complexes.
The mechanisms of the palladium catalyzed carbylation.

Figure 24: Proposed process for $\eta^3$-$\eta^1$-rearrangement and CO insertion, leading directly to the formation of 13a.

Figure 25: Proposed process for CO insertion in an $\eta^3$-complex.

10.3.6 Stoichiometric reactions of the acyl complex 13a

To study the reactivity of the acyl group, the isolated (POPyl)Pd(Cl)(C(O)cinnamyl) complex (13a) was subjected to stoichiometric reactions using various nucleophiles (figure 26). Reaction with methanol at room temperature resulted in slow formation of the linear ester. No evidence was found for the presence of other complexes such as a possible intermediate (POPyl)Pd(OCH$_3$)(C(O)cinnamyl) in which the chloride would be replaced by a methoxide (figure 27). When methanol was used in the presence of the base NEt$_3$, the methanolysis occurred instantaneously.

Piperidine reacted slowly with the acyl species to form the corresponding linear amide (K). The less nucleophilic amine p-toluidine, however, did not react at all. Because for the reaction of (POPyl)Pd(Cl)(C(O)cinnamyl) (13a) with methanol or piperidine no other intermediates than the acyl complex (13a) could be observed, it is concluded that both reactions take place via nucleophilic attack on the coordinated acyl group. Yamamoto suggested that Et$_2$NH might react via an associative mechanism rather than nucleophilic attack on the acyl group in (benzyl-C(O)-)Pd(CO)(PMe$_3$)$_2$ complexes. For the PN ligands studied in this chapter, however, no evidence for such an amidocarboxy Pd-(C(O)-NEt$_3$)-type intermediate was found.

Addition of a tertiary amine, NEt$_3$, resulted in the loss of CO and the known $\eta^3$-allyl complex 12a was formed quantitatively. The use of AgOTf had a similar effect; the chloride was abstracted and, as expected,
the cationic (POPy1)Pd(cinnamyl)OTf complex (11a) was formed. Apparently, the acyl decomposed via deinsertion to fill the vacant site. Thus, the more stable cationic complex (POPy1)Pd(cinnamyl)OTf complex (11a) was formed, which is known not to undergo CO-insertion (see above).

![Figure 26: Stoichiometric reactions of (POPy1)Pd(OCH3)(C(O)cinnamyl).](image)

![Figure 27: Possible mechanism of carbonylation via a Pd-OME intermediate (not observed).](image)

10.3.7 Catalytic carbonylation using PN ligands

The facile formation of the ester (E) from (POPy1)Pd(Cl)(C(O)cinnamyl) (13a) and methanol and NEt3 at room temperature, prompted us to study the catalytic carbonylation of cinnamyl chloride at room temperature and elevated pressure, using various solvents and various tertiary amines (tables 10 and 11). For comparison, the reactions were also performed using complex 1a (PCy3).
The mechanisms of the palladium catalyzed carbonylation.

Table 10: Results of catalytic carbonylation of cinnamyl chloride at 20 bar at room temperature, yields determined after 4 hours. Experimental details: see experimental section.

<table>
<thead>
<tr>
<th>L / amine</th>
<th>solvent</th>
<th>TOF(^a)</th>
<th>conversion (4 hours)</th>
<th>% ester (E)</th>
<th>% ammonium salt (AM)(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCy(_3) / NEt(_3)</td>
<td>thf</td>
<td>10</td>
<td>49</td>
<td>33</td>
<td>67</td>
</tr>
<tr>
<td>PCy(_3) / NEt(_3)</td>
<td>acetone</td>
<td>24</td>
<td>76</td>
<td>39</td>
<td>61</td>
</tr>
<tr>
<td>PCy(_3) / NEt(_3)</td>
<td>MeCN</td>
<td>23</td>
<td>100</td>
<td>32</td>
<td>68</td>
</tr>
<tr>
<td>POPy1 / NEt(_3)</td>
<td>MeCN</td>
<td>8</td>
<td>72</td>
<td>22</td>
<td>78</td>
</tr>
<tr>
<td>POPy2 / NEt(_3)</td>
<td>thf</td>
<td>22</td>
<td>36</td>
<td>8</td>
<td>92</td>
</tr>
<tr>
<td>POPy2 / NEt(_3)</td>
<td>MeCN</td>
<td>11</td>
<td>52</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>POPy3 / NEt(_3)</td>
<td>MeCN</td>
<td>55</td>
<td>100</td>
<td>37</td>
<td>63</td>
</tr>
<tr>
<td>POPy1 / DIPEA(^b)</td>
<td>MeCN</td>
<td>3</td>
<td>8</td>
<td>88</td>
<td>13</td>
</tr>
<tr>
<td>POPy2 / DIPEA(^b)</td>
<td>MeCN</td>
<td>21</td>
<td>39</td>
<td>87</td>
<td>13</td>
</tr>
<tr>
<td>POPy3 / DIPEA(^b)</td>
<td>MeCN</td>
<td>52</td>
<td>40</td>
<td>95</td>
<td>5</td>
</tr>
</tbody>
</table>

\(a\): initial Turn Over Frequency of substrate to ester in mole/mole/hour, determined after 60 minutes.
\(b\): N, N-di-isopropyl ethyl amine
\(c\): (cinnamyl)NR\(_3\)Cl

As was also found for the associative mechanism, the linear ester is the only carbonylation product. No formation of cinnamyl methyl ether (F) was observed, indicating that the carbonylation is faster than the nucleophilic attack of methanol on the Pd-allyl complex (table 10).

The only side product formed, (cinnamyl)NR\(_3\)Cl (AM), originates from nucleophilic attack of the tertiary amine on the allyl moiety. The absolute amount of ammonium salt formed depends on the ligand and increases in the following order: POPy2 < POPy1 < POPy3. This reaction is rather similar to the allylic alkylation reaction and the observed activity of the PN ligands with respect to the formation of the ammonium side product (AM) roughly corresponds to their activity in the allylic alkylation (see chapter 6).

The use of the bulkier amine DIPEA reduced the amount of ammonium salt formed and the ester was produced in nearly quantitative yield.

The catalytic carbonylation using piperidine as the nucleophile did not yield any carbonylation product; instead all cinnamyl chloride was converted to the corresponding amine (M), via the allylic amination reaction (figure 28).\(^{19}\)
Using PCy₃ as the ligand, the rate of the catalytic carbonylation at 20 bar (insertion mechanism) is much lower than for the carbonylation at 1.2 bar of CO with NBu₄OH (associative mechanism). This can be explained by a lower reactivity of methanol compared to methoxide towards the carbomethoxy species (if it would be formed at elevated pressures) and also by a low concentration of the acyl species (the equilibrium favors the η³-allyl).

Figure 28: Formation of allyl-amine using piperidine as the base.

10.3.8 Kinetics

To gain more insight in the mechanism of the carbonylation reaction and the origin of the different reaction rates found for the various ligands the kinetics of the reaction were studied. To this end, the reaction was performed with a systematic variation of the initial concentration of the reactants, using various solvents and various tertiary amines (table 11). Because of the stability of the intermediates in the catalytic reaction and their reversible formation, we were able to monitor the reaction by taking samples after releasing the pressure from the autoclave. After repressurizing, the reaction started again, without noticeable degradation of the catalyst (figure 29). At low conversion (below circa 60%) the reaction proceeded at the same rate, allowing for the reliable determination of the reaction orders for the reactants.
The mechanisms of the palladium catalyzed carbonylation.

Table 11: Kinetic data for the catalytic carbonylation of cinnamyl chloride to ester E.

\[ \text{d}[P]/\text{dt} = k_{\text{obs}} \left[ \text{Pd} \right]^p \left[ \text{cinnamyl chloride} \right]^q \left[ \text{MeOH} \right]^r \left[ \text{amine} \right]^s \left[ \text{CO} \right]^t. \]

Empty fields: order not determined.

Experimental details: see experimental section.

<table>
<thead>
<tr>
<th>L</th>
<th>base</th>
<th>solvent</th>
<th>( k_{\text{obs}}^{	ext{**}} ) ((10^{11}))</th>
<th>p</th>
<th>q</th>
<th>r</th>
<th>s</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCy3</td>
<td>NEt3</td>
<td>thf</td>
<td>5.6</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0-1*</td>
</tr>
<tr>
<td>PCy3</td>
<td>NEt3</td>
<td>acetone</td>
<td>13.0</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCy3</td>
<td>NEt3</td>
<td>MeCN</td>
<td>12.7</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POPy1</td>
<td>NEt3</td>
<td>MeCN</td>
<td>4.4</td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POPy2</td>
<td>NEt3</td>
<td>thf</td>
<td>12.2</td>
<td>0.5</td>
<td>0-1*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POPy2</td>
<td>NEt3</td>
<td>MeCN</td>
<td>6.1</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POPy3</td>
<td>NEt3</td>
<td>MeCN</td>
<td>30.6</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POPy1</td>
<td>DIPEA</td>
<td>MeCN</td>
<td>1.7</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POPy2</td>
<td>DIPEA</td>
<td>MeCN</td>
<td>1.2</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>POPy3</td>
<td>DIPEA</td>
<td>MeCN</td>
<td>28.9</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: not enough data points to determine the exact order.

**: in L\(^4\).mole\(^-2\).s\(^-1\).

Figure 29: Typical example demonstrating the stability of the catalyst: each point represents a sample taken after release of the pressure. Conditions of the experiment: 0.001 mmole of catalyst 1a, 1 mmole of methanol, 1 mmole of NEt3, 1 mmole of cinnamyl chloride, in acetonitrile at 20 bar of CO at 293K.

Under the used conditions, the reaction proceeded with a zero order dependence of both cinnamyl chloride and methanol concentration, whereas a positive order in CO concentration and a first order dependence on the palladium concentration were found. Intriguingly, the dependence of the rate of the reaction on the amine
concentration varies strongly for the different ligands and conditions. When using PCy$_3$ in thf, a first order dependence on the amine concentration is found, but in acetone and acetonitrile the observed order is 0.5 (figure 30). For the bidentate PN ligands, in all cases a broken order in the amine concentration was found. For NEt$_3$, the observed order varies with the ligand, between 0.3 and 0.7, but for the more bulky amine DIPEA, the observed order is 0.5 for all ligands within the window of concentrations studied. This half-order dependence might point to association-dissociation behavior. It is, however, not clear what the nature of the species involved is.

![Graph](image)

Figure 30: Typical example of the kinetic experiments. Each point represents the percentage of ester formed after 1 hour, using different concentrations of NEt$_3$. All kinetic experiments showed curves of product formation as displayed in the previous figure. The reaction conditions for the example of this graph are: 0.1-1.0 mmole of NEt$_3$, 0.005 mmole of complex 1a, 1.0 mmole of cinnamyl chloride, 1.0 mmole of MeOH, in acetone p.a. at 20 bar CO at 293K.

10.3.9 High pressure NMR of the reaction mixture of catalytic carbonylation at 20 bar CO.

For the PCy$_3$ complex 1a, the reaction was also followed using NMR spectroscopy. To this end, excesses of cinnamyl chloride, NEt$_3$ and methanol were used. After pressurizing to 20 bar, the tube was cooled in the NMR spectrometer. Some of the substrate was already converted to the ester, but the acyl complex could still be observed. In addition, several other complexes bearing $^{13}$CO were found in the reaction mixture. Two complexes showed resonances around 180 ppm, which is indicative of a Pd-CO complex (see section 4.2) and one resonance was found at 255 ppm, which is indicative of a palladium dimer containing a bridging carbonyl ligand.$^{[20]}$ Heating to room temperature resulted in a fast conversion of cinnamyl chloride to the ester (E). Unfortunately, as a result of broadened signals, the signal to noise ratio in the $^{31}$P and $^{13}$C-NMR
The mechanisms of the palladium catalyzed carbonylation.

spectra was too low to observe intermediate palladium complexes at room temperature. Repeating the experiment without added NEt$_3$ did not result in the formation of the ester. This is in agreement with the kinetic experiments, that showed a positive order in the amine concentration.

10.3.10 Discussion on the rate of the catalytic reaction

The results of the systematic variation of the initial concentrations of the substrates show that the overall kinetic equation is rather complicated. Compared to POPy1 and POPy2, the use of PCy$_3$ at 20 bar results in a similar reaction rate. The different rates for the various POPyn ligands are not easily explained, since several factors may influence the reaction rate.

The reaction rate increases from POPy1 to POPy3, resembling the bite angle trend observed for the alcoholysis of (acetyl)Pd(P-P) complexes.$^{[9a]}$ The kinetics, however, show a zero order dependency in methanol and a positive order in the amine. If the amine is involved in the alcoholysis, it follows the same reactivity pattern as the alcohol in the above mentioned studies. On the other hand, the amine may also be involved in stabilizing intermediate Pd clusters. For instance, Kurosawa reported cationic dimers, in which the allyl group acted as a bridge between the two palladium centers.$^{[27]}$ Although we have not yet observed Pd-clusters in the reaction mixtures, their formation cannot be ruled out. The dissociation of the amine from these dimeric complexes may be rate determining, leading to the observed rate equation.

Furthermore, the interactions between the formed H$^+$ and the amine may also influence the kinetics of the reaction. More studies are required to gain more insight in the catalytic cycle and in the observed differences in the rates of the catalytic reactions. Based on the results so far, we propose the following catalytic cycle for the carbonylation of cinnamyl chloride at elevated pressures of CO, using P-N ligands (figure 31).

![Proposed catalytic cycle for the methoxy-carbonylation of cinnamyl chloride at 20 bar CO using mixed bidentate P-N ligands.](image)

Figure 31: Proposed catalytic cycle for the methoxy-carbonylation of cinnamyl chloride at 20 bar CO using mixed bidentate P-N ligands.
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A transient Pd(P-N)\(^0\) complex reacts with cinnamyl chloride to form the corresponding (\(\eta^3\)-cinnamyl)Pd(P-N)Cl complex. Initially, the isomer bearing the phenyl group of the cinnamyl cis to the phosphorus will be formed (see also chapter 6), which after rearrangement yields the more stable complex 12. Insertion of CO occurs and initially the isomer bearing the acyl trans to the phosphorus will be formed. After rearrangement to the more stable isomer 13, the ester E will be formed via methanolysis of complex 13. The HCl, which is formed as a side product, will react with the amine base to form the corresponding ammonium salt.

10.4 Conclusions

To study the mechanism of the palladium catalyzed alkoxycarbonylation of cinnamyl chloride we have prepared several putative intermediates of the catalytic cycle, among which a new class of \([\eta^3\text{-cinnamyl}]\text{Pd(ligand)}\text{CO}[\text{OTf}]\) complexes (3). These palladium complexes react with a methoxide nucleophile to form \((\eta^3\text{-cinnamyl})\text{Pd(L)C(O)OMe}\) carbomethoxy complexes (type 4).

We have shown that two mechanistic pathways are possible for the palladium catalyzed methoxy carbonylation of cinnamyl chloride. Both mechanisms proceed at room temperature. The newly found carbomethoxy mechanism is favored at 1.2 bar of CO for complexes bearing a) an \(\eta^3\)-allyl moiety and b) one monodentate ligand. The acyl mechanism is favored only at higher pressures of CO and only for complexes bearing a) a coordinating counterion and b) more than one monodentate ligand or one bidentate P-N ligand.

The reagents determine the mechanism of the reaction. When monodentate ligands are used in combination with methoxide, the reaction proceeds via the carbomethoxy mechanism, both at high and low pressure. On the other hand, using methanol and amine, the reaction only proceeds via the acyl mechanism and a high CO-pressure is required.

Kinetic studies of the insertion reaction point out that the kinetic equation depends on the nature of the solvent. The catalytic reaction proceeds with a positive order in palladium, CO and the amine base.

Furthermore, we have shown for the insertion mechanism, that the catalyst remains stable after release of the CO-pressure. We expect that recycling of the catalyst is possible via anchoring the catalyst to a solid support and filtration of the reaction mixture.
The mechanisms of the palladium catalyzed carbonylation.

10.5 Experimental section

$^1$H and $^{13}$C-NMR (300 resp. 75 MHz, TMS, CDCl$_3$), $^{31}$P {$^1$H} (121.5 MHz external 85% H$_3$PO$_4$, CDCl$_3$) were recorded on a Bruker DRX-300 spectrometer.

The product distribution of the carbonylation reaction was measured by GC on an Interscience Mega2 apparatus, equipped with a DB1 column, length 30 m, inner diameter 0.32 mm, film thickness 3.0 µm, and a F.I.D detector.

10.5.1 General procedures

All experiments were carried out using standard Schlenk techniques. All solvents were freshly distilled prior to use. All reactions have been performed at room temperature (292 K). High pressure NMR experiments were carried out using a sapphire tube.

The Pd-complexes were prepared in CH$_2$Cl$_2$ from [(C$_9$H$_9$)$_2$Pd-μCl]$_2$ by adding 2 equiv. of ligand (i.e. one per palladium) and abstracting the chloride-atom using AgOTf (see chapter 4-8). The complexes were isolated in quantitative yield (microcrystalline powder) and were used as such in the alkylation reaction. The synthesis of the POPyn ligands has been described in chapter 6. The synthesis and characterization of 11a-c and 12c have been described in chapter 6. Ligand f was used by kind permission of Maarten Boele. All other ligands and reagents have been purchased from Aldrich.

10.5.2 Synthesis of palladium complexes

Typical procedures for the synthesis of the palladium complexes (procedures are the same for all ligands):

Type 1 (table 1) and 12 (table 7):
To a yellow solution of [(C$_9$H$_9$)$_2$Pd-μCl]$_2$ (100 mg, 193 µmole) in 20 mL of CH$_2$Cl$_2$ was added 101 mg (386 µmole) of PPh$_3$. After stirring for 30 minutes the solvent was evaporated and the complex was obtained quantitatively as a yellow microcrystalline solid.

Type 2 (table 1):
To a yellow solution (20 mL) of 1b in CH$_2$Cl$_2$ (201 mg, 386 µmole) was added 101.2 mg (39.0 µmole) of dry AgOTf. Upon addition, the color of the solution became light yellow and a fine white solid precipitates. After stirring for 3 minutes, 0.5 mL MeCN was added. The solution became even lighter yellow and the white powder changed to white flakes. After stirring for 15 minutes, active carbon was added to remove the excess of AgOTf. Filtration over cotton wool and evaporation of the solvent yielded a light yellow microcrystalline powder. The complexes should be stored at low temperature.
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Type 11 (table 7):
The procedure is analogous to the procedure for type 2 complexes, but no MeCN was added.

Type 3 (table 1):
CO was bubbled through a solution of 10 mg of 1b in CDCl₃. The light yellow solution turned colorless within one minute (within seconds for the more basic ligands). The product could not be isolated by either evaporation of the solvent or by precipitation using pentane or hexane.

Type 4 (table 3):
A solution of 10 mg of 3a in 0.6 mL of CDCl₃ was frozen at 195K and 0.1 ml of a 1.0 M solution of NBu₄OH in methanol was added and frozen as well. Slowly, the frozen solution was heated and upon melting, the solution was mixed thoroughly. Immediately, the tube was transferred to the precooled NMR spectrometer and complex 4a was characterized.

Type 5 (figure 15):
A solution of 20 mg of 1b in CDCl₃ was pressurized with CO to the appropriate pressure (10, 20, 50 bar).

Type 13 (table 7):
This procedure was performed similar to that of type 5, but alternatively, the pure acyl compound could also be obtained by preparation of the complex type 13(a and b) in an autoclave. Addition at high pressure of hexane (not pentane) via a pressurized addition vessel, led to the precipitation of the desired complex. The complex was isolated by removal of the solvent and slowly drying overnight (not evaporation in vacuo).

Type 14 (table 7):
Similar to type 11, but now AgOAc was used in place of AgOTf.

Type 15 (table 7):
Similar to type 13, but now complexes of type 14 were used as starting complexes.

10.5.3 Carbonylation reactions, low pressure

Standard conditions: 5 µmole of Pd complex of type 1, 1.0 mmole of cinnamyl chloride, 1.0 mmole of NaOMe or NBu₄OH, 0.2 mmole of para-methoxy-acetophenon (internal standard), total 5.0 mL of solvent (2.0 mL MeOH, 3.0 mL thf). The reactions were carried out under a CO atmosphere. Samples for GC were taken from the reaction mixture at regular time intervals. The samples were worked up by extraction (NH₄Cl in water / diethyl ether). After complete conversion, the catalyst decomposed to palladium metal.
10.5.4 Carbonylation reactions, high pressure

Standard conditions: 5 μmole of Pd complex of type 1 or 12, 1.0 mmole of cinnamyl chloride, 1.0 mmole of MeOH, 1.0 mmole of amine (NEt₃ or DIPEA), 0.2 mmole of decane (internal standard), total volume of solvent. Before the reactions were carried out, the air was removed from the dried stainless steel autoclave and replaced by CO. Samples for GC were taken (after pressure release) from the reaction mixture at regular time intervals, after which the reaction was started again by repressurizing. The samples were worked up by extraction (water / diethyl ether).

For the kinetic experiments, the amount of the reactants was varied systematically. In all cases, the total volume of the reaction mixture was 5.0 mL.

10.5.5 Characterization

**E (E-styrene-methyl-acetate):**

\(^1\)H: 3.22 (d, 2H, \(J = 7\) Hz, CH₂); 3.68 (s, 3H, CH₃); 6.25 (m, 1H, -CH=CH-Ph); 6.45 (d, 1H, 16 Hz, -CH=CH-Ph); 7.0-7.8 (m, 5H, aromatic)

**K (amide of E-styrene-acetic acid and piperidine):**

\(^1\)H: 1.6 (m, 6H, N-(CH₂-CH₃)₂); 3.10 (d, 2H, \(J = 7\) Hz, =CH-CH₂-C(=O)-); 6.31 (m, 1H, Ph-CH=CH-CH₂-C(=O)-); 6.48 (d, 1H, \(J = 16\) Hz, Ph-CH=CH-CH₂-C(=O)-); 7.2-7.9 (m, 5H, aromatic H)

ammonium salt of cinnamyl and NEt₃:

\(^1\)H: 1.23 (t, 9H, \(J = 7\) Hz, CH₃); 3.30 (q, 6H, \(J = 7\) Hz, N-CH₂-CH₃); 4.12 (d, 2H, \(J = 8\) Hz, -C(=O)-CH₂-); 6.05 (dt, 1H, \(J₁ = J₂ = 8\) Hz, \(J₃ = 16\) Hz, -CH=CH-Ph); 6.85 (d, 1H, \(J = 16\) Hz, -CH=CH-Ph); 7.15 (m, 3H, aromatic H); 7.30 (m, 2H, aromatic H)

\(^{13}\)C: 8.5; 53.4; 60.2; 114.3; 127.6; 129.1; 129.7; 135.0; 143.0

**1a (PCy₃)Pd(η¹-cinnamyl)Cl:**

\(^1\)H: 1.25 (br s, 12H, Cy-ring); 1.5 (br s, 6H, Cy-ring); 1.8 (br m, 12H, Cy-ring); 2.2 (q, 2.2, \(J₁ = 12\) Hz, \(J₂ = 12\) Hz, H on ipso carbon of Cy-ring); 2.65 (d, 1H, \(J = 11\) Hz, Ha); 3.28 (d, 1H, \(J₁ = 6\) Hz, Hb); 5.20 (dd, 1H, \(J₁ = 10\) Hz, \(J₂ = 13\) Hz, Hd); 5.81 (ddd, 1H, \(J₁ = 13\) Hz, \(J₁ = J₂ = 10\) Hz, Hc); 7.2-7.3 (m, 3H, aromatic); 7.50 (d, 2H, \(J = 8\) Hz, ortho-aromatic H)

\(^{31}\)P: 45.9 (s)

\(^{13}\)C \(\{\)H\): 26.5; 26.8; 27.3 (d, \(J = 11\) Hz); 27.9 (d, \(J = 11\) Hz); 30.6; 35.1 (d, \(J = 18\) Hz); 47.3; 100.8 (d, \(J = 26\) Hz); 110.0; 128.0; 128.3; 129.0; 129.4; 137.1

HR-MS (FAB): C₂₇H₄₂Pd⁺ requires m/z = 503.2059, found 503.2029 (loss of Cl).
2a (PCy₃)Pd(η¹-cinnamyl)(MeCN) OTf:

^1^H: overlap of 1.25 (br s); 1.27 (br s); 1.38 (br s) together 15H, Cy-ring; 1.7-1.9 (br m, 18H, Cy-ring); 2.02 (s, 3H, CH₃-CN); 2.90 (br d, 1H, J = 11 Hz, Ha); 3.53 (br d, 1H, J = 6 Hz, Hb); 5.59 (dd, 1H, J₁ = 8 Hz, J₂ = 13 Hz, Hd); 6.07 (ddd, 1H, J₁ = 13 Hz, J₂ = J₃ = 9 Hz, Hc); 7.4 (m, 3H, aromatic); 7.6 (d, 2H, J = 8 Hz, ortho-aromatic H)

^3^P: 47.0 (s)

3a (PCy₃)Pd(η¹-cinnamyl)(CO)OTf:

^1^H: 1.2-1.4 (br m, 15 H, Cy-ring); 1.7-2.2 (br m, 18 H, Cy-ring); 3.56 (d, 1 H, J = 13 Hz, Ha); 4.17 (d, 1H, J = 6 Hz, Hb); 6.3 (ddd, 1H, J₁ = 7 Hz, J₂ = J₃ = 9 Hz, Hd); 6.56 (br m, 1H, Hc); 7.4 (br m, 3H, aromatic); 7.78 (d, 2H, J = 8 Hz, ortho-aromatic H)

^3^P: 48.5 (s)

^1^C: 181.9

IR: 2115 cm⁻¹ (C=O)

4a (PCy₃)Pd(η¹-cinnamyl)(C(0)OMe):

^1^H: (signals of ammonium and Cy-rings omitted): 4.47 (dd, 1H, J₁ = J₂ = 12 Hz, Ha); 5.00 (dd, 1H, J₁ = J₂ = 10 Hz, Hb); 5.58 (ddd, 1H, J₁ = 8 Hz, J₂ = J₃ = 13 Hz, Hd); 5.72 (m, 1H, Hc); 7.0-7.4 (m, 5H, aromatic)

^3^P: 45.1 (d, J = 24 Hz)

^1^C: 211.0 (d, J = 23 Hz)

1b (PPh₃)Pd(η¹-cinnamyl)Cl:

^1^H: Ha and Hb overlap: 2.90 (d, 1H, J = 12 Hz, Ha); 2.95 (d, 1H, J = 6 Hz, Hb); 5.36 (dd, 1H, J₁ = 10 Hz, J₂ = 13 Hz, Hd); 6.01 (ddd, 1H, J₁ = 13 Hz, J₂ = J₃ = 10 Hz, Hc)

^3^P: 26.4 (s)

HR-MS (FAB): C₂₇H₂₄PPd⁺ requires m/z = 485.0650, found 485.0669 (loss of Cl⁻)

2b (PPh₃)Pd(η¹-cinnamyl)(MeCN)OTf:

^1^H: 1.84 (s, 3H, CH₃-CN); 3.13 (br, 1H, J = 9 Hz, Ha); 3.47 (br b, 1H, Hb); 5.97 (dd, 1H, J₁ = 13 Hz, J₂ = 9 Hz, Hd); 6.30 (ddd, 1H, J₁ = 13 Hz, J₂ = J₃ = 9 Hz, Hc); 7.2-7.5 (m, 18 H, aromatic); 7.71 (d, 2H, J = 5 Hz, ortho-aromatic H)

^3^P: 27.6 (s)
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3b (PPh₃)Pd(η⁳-cinnamyl)(CO)OTf:

H: 3.58 (br d, 1H, J = 11 Hz, Ha); 3.86 (br b, 1H, Hb); 6.44 (ddd, 1H, J₁ = J₂ = 10 Hz, J₃ = 9 Hz, Hd); 6.59 (br t, 1H, J₁ = J₂ = 11 Hz, Hc); 7.2-7.5 (m, 18 H, aromatic); 7.80 (d, 2H, J = 5 Hz, ortho-aromatic H)

P: 25.3 (s)

C: 181.4 (s)

IR: 2125 cm⁻¹ (C=O)

1c (AsPh₃)Pd(η⁴-cinnamyl)Cl:

H: 3.0-3.5 (br b, 2H, Ha + Hb); 5.20 (d, 1H, J = 12 Hz, Hd); 5.95 (ddd, 1H, J₁ = 12 Hz, J₂ = J₃ = 10 Hz, He); 7.2-7.6 (br m, 20 H, aromatic)

C: 56.5; 96.9; 109.8; 128.4; 128.7; 129.1; 129.4; 130.4; 130.6; 131.9; 134.0; 134.8; 136.9

HR-MS (FAB): C₂₇H₂₄AsPd⁺ requires m/z = 529.0129, found 529.0127 (loss of CI⁻).

2c (AsPh₃)Pd(η⁴-cinnamyl)(MeCN)OTf:

H: 1.90 (s, 3H, CH₃-CN); 3.18 (br b, 1H, Ha); 3.74 (br b, 1H, Hb); 5.92 (br b, 1H, Hd); 6.26 (br b, 1H, He); 7.2-7.8 (br b, 20 H, aromatic)

3c (AsPh₃)Pd(η⁴-cinnamyl)(CO)OTf:

H: 3.70 (br b, 1H, Ha); 4.16 (br b, 1H, Hb); 6.43 (ddd, 1H, J₁ = J₂ = 12 Hz, J₃ = 8 Hz, Hc); 6.67 (br b, 1H, Hd); 7.2-7.8 (br b, 20 H, aromatic)

C: 181.1

IR: 2123 cm⁻¹ (C=O)

1d (SbPh₃)Pd(η⁴-cinnamyl)Cl:

H: 3.00 (br b, 1H, Ha); 3.97 (br b, 1H, Hb); 5.24 (d, 1H, J = 12 Hz, Hd); 5.87 (ddd, 1H, J₁ = J₂ = 10 Hz, J₃ = 12 Hz); 7.2-7.6 (br m, 20 H, aromatic)

C: 56.5; 108.9; 128.3; 128.7; 129.3; 129.6; 130.4; 132.0; 136.5; 137.1

HR-MS (FAB): C₂₇H₂₄PdSb⁺ requires m/z = 575.8483, found 576.9933 (loss of Cl⁻).

2d (SbPh₃)Pd(η⁴-cinnamyl)(MeCN)OTf:

H: 2.01 (s, 3H, CH₃-CN); 3.20 (br b, 1H, Ha); 4.10 (br b, 1H, Hb); 4.60 (br b, 1H, Hd); 6.05 (br b, 1H, He); 6.8-7.8 (br m, 20 H, aromatic)

3d (SbPh₃)Pd(η⁴-cinnamyl)(CO)OTf:

H: 3.67 (br b, 1H, Ha); 4.52 (br b, 1H, Hb); 6.32 (ddd, 1H, J₁ = 13 Hz, J₂ = J₃ = 8 Hz, Hc); 6.62 (br b, 1H, Hd); 7.0-7.7 (br m, 20 H, aromatic)

C: 183.5 (s)
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1e (P(OPh)₃)Pd(η³-cinnamyl)Cl:

\[ ^1H: 2.00\ \text{(br d, 1H, } J = 10\ \text{Hz, } H_a) ; 3.18\ \text{(br b, 1H, } H_b) ; 5.00\ \text{(dd, 1H, } J_1 = 17\ \text{Hz, } J_2 = 13\ \text{Hz, } H_d) ; 5.25\ \text{(m, 1H, } H_c) ; 7.0-7.3\ \text{(m, 20 H, aromatic)} \]

\[ ^{31}P: 126.7\ \text{(s)} \]

1g (P(o-tolyl)₃)Pd(η³-cinnamyl)Cl:

\[ ^1H: 2.23\ \text{(s, 9H, } CH_3) ; 2.49\ \text{(br b, 1H, } H_a) ; 2.97\ \text{(br b, 1H, } H_b) ; 5.24\ \text{(dd, 1H, } J_1 = 11\ \text{Hz, } J_2 = 13\ \text{Hz, } H_d) ; 5.91\ \text{(edd, 1H, } J_1 = J_2 = 9\ \text{Hz, } J_3 = 13\ \text{Hz, } H_c) ; 6.6-7.8\ \text{(m, 17 H, aromaticH)} \]

\[ ^{31}P: 22.6\ \text{(br s)} \]

HR-MS (FAB): C₃₀H₃₀Pd⁺ requires m/z = 527.1120, found 527.1133 (loss of Cl⁻).

5a (PCy₃)Pd(C(O)-cinnamyl)Cl:

\[ ^1H: 1.0-2.0\ \text{(br m, 33 H, Cy-rings)} ; 3.8\ \text{(br d, 2H, } J = 5\ \text{Hz, } CH_2) ; 6.3\ \text{(d, 1H, } J = 18\ \text{Hz, } -CH=CH-Ph) ; 6.50\ \text{(m, 1H, } -CH=CH-Ph) ; 7.0-7.6\ \text{(br m, 5 H, aromatic)} \]

\[ ^{31}P: 41.3\ \text{(s)} \]

\[ ^{13}C: 236.0\ \text{(s)} \]

5a (PCy₃)Pd(C(O)-cinnamyl)OTf + extra PCy₃:

\[ ^1H: 1.0-2.0\ \text{(br m, 33 H, Cy-rings)} ; 3.8\ \text{(br d, 2H, } J = 5\ \text{Hz, } CH_2) ; 6.3\ \text{(d, 1H, } J = 18\ \text{Hz, } -CH=CH-Ph) ; 6.50\ \text{(m, 1H, } -CH=CH-Ph) ; 7.0-7.6\ \text{(br m, 5 H, aromatic)} \]

\[ ^{31}P: \text{several signals among which two singlets: 31.3 and 55.1} \]

\[ ^{13}C: 236.0\ \text{(s)} \]

5b (PPh₃)Pd(C(O)-cinnamyl)Cl:

\[ ^1H: 3.1\ \text{(br b, 2H, } CH_2) ; 5.63\ \text{(br b, } CH=CH-Ph) ; 6.08\ \text{(m, 1H, } -CH=CH-Ph) ; 7.0-7.6\ \text{(br m, 5 H, aromatic)} \]

\[ ^{31}P: 28.6\ \text{(s)} \]

\[ ^{13}C: 229.2\ \text{(s)} \]

12a (POPyl)Pd(η³-cinnamyl)Cl:

\[ ^1H: 2.77\ \text{(br b, 2H, } H_a + H_b) ; 4.93\ \text{(d, 2H, } J = 20\ \text{Hz, } O-CH_3) ; 5.17\ \text{(d, 1H, } J = 16\ \text{Hz, } H_d) ; 6.63\ \text{(ddd, 1H, } J_1 = 15\ \text{Hz, } J_2 = J_3 = 9\ \text{Hz, } H_c) ; 7.0-7.8\ \text{(m, 18 H, aromatic)} ; 9.6\ \text{(br b, 1H, ortho-pyridine)} \]

\[ ^{31}P: 134.6 \]

\[ ^{13}C: 25.6; 71.3; 72.0; 124.5\ \text{(d, } J = 149\ \text{Hz)} ; 125.9; 126.2; 128.7; 129.1; 129.2; 132.2; 132.4; 132.9; 133.4; 133.6; 134.5; 138.9; 139.4; 154.0; 154.6 \]

HR-MS (FAB): C₂⁵H₂₅NOPd⁺ requires 516.0709, found 516.0677 (loss of Cl⁻).

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**14a (POPy1)Pd(η^3-cinnamyl)OAc:**

1H: 2.07 (s, 3H, O2CCH3); 2.64 (br b, 2H, Ha+Hb); 4.95 (d, 2H, J = 20 Hz, O-CH2); 5.43 (d, 1H, J = 16 Hz, Hd); 6.41 (ddd, 1H, J1 = J2 = J3 = 7 Hz); 7.0-7.9 (m, 18H, aromatic); 9.2 (br b, 1H, ortho-pyridine)  

31P: 136.7

**12b (POPy2)Pd (η^3-cinnamyl)Cl:**

1H: 2.86 (d, 2H, J = 9 Hz, Ha+Hb); 3.25 (t, 2H, J = 6 Hz, -CH2-Ar); 4.32 (app q, 2H, J = 6 Hz, O-CH2); 5.34 (dd, 1H, J1 = 9 Hz, J2 = 14 Hz, Hd); 6.10 (ddd, 1H, J1 = J2 = 9 Hz, J3 = 14 Hz, Hc); 7.0-7.8 (m, 18 H, aromatic); 8.59 (d, 1H, J = 5 Hz, ortho-pyridine)  

31P: 121.9

HR-MS (FAB): C_{28}H_{27}NOOPd' requires m/z = 530.0865, found 530.0884 (loss of Cl).

**14b (POPy2)Pd (η^3-cinnamyl)OAc:**

1H: 1.97 (br s, 3H, O2CCH3); 2.80 (br b, 2H, Ha+Hb); 3.50 (br b, 2H, -CH2-Ar); 4.42 (br b, 2H, O-CH2); 5.78 (br m, 1H, Hd); 6.28 (br b, 1H, Hc)  

31P: 117.7

**13a (POPy1)Pd(^13C(O)cinnamyl)Cl:**

1H: 3.48 (d, 2H, J = 6 Hz, -C(O)-CH2-); 5.06 (d, 2H, J = 21 Hz, O-CH2); 5.88 (d, 1H, J = 16 Hz, -CH=CH-Ph); 6.20 (m, 1H, -CH=CH-Ph); 7.0-7.8 (br m, 18 H, aromatic); 9.38 (br b, 1 H, ortho-pyridine)  

31P: 119.9 (s)  

13C: 226.5 (d, J = 8 Hz)  

HR-MS (FAB): As a result of the loss of Cl', decomposition occurred in the spectrometer. M+ could not be observed, but the signal at m/z = 544.0669 corresponds to C_{28}H_{27}NOOPd', proving the existence of a Pd complex bearing two oxygen atoms (one of the ligand and one of the carbonyl).

**15a1 (POPy1)Pd(^13C(O)cinnamyl)OAc:**

1H: 2.18 (s, 3H, O2CCH3); 2.77 (br d, 2H, J = 7 Hz, -C(O)-CH2-); 5.10 (d, 2H, J = 19 Hz, O-CH2); 5.80 (d, 1H, J = 16 Hz, -CH=CH-Ph); 6.27 (m, 1H, -CH=CH-Ph); 7.0-7.8 (br m, 18 H, aromatic); 8.83 (br b, 1 H, ortho-pyridine)  

31P: 123.5  

13C: 231.9
15a2 (POPy1)Pd($^{[13]C(O)cinnamyl})OAc:

$^1$H: 2.24 (s, 3H, O-C(CH$_3$)$_3$); 4.69 (br d, 2H, J = 7 Hz, -C(O)-CH$_2$-); 4.96 (d, 2H, J = 21 Hz, O-CH$_2$); 5.65 (d, 1H, J = 16 Hz, -CH=CH-$^1$Ph); 6.27 (m, 1H, -CH=CH-$^1$Ph); 7.0-7.8 (br m, 18 H, aromatic); 9.30 (d, 1H, J = 5 Hz, ortho-pyridine)

$^{31}$P: 121.5

$^{13}$C: 229.8

13b (POPy2)Pd($^{[13]C(O)cinnamyl})Cl:

$^1$H: 3.51 (d, 2H, J = 7 Hz, -C(O)-CH$_2$-); 3.60 (br t, 2H, J = 5 Hz, -CH$_2$-Ar); 4.11 (dt, 2H, J = 14 Hz, J = 6 Hz, O-CH$_2$); 6.05 (d, 1H, J = 16 Hz, -CH=CH-$^1$Ph); 6.28 (m, 1H, -CH=CH-$^1$Ph); 7.0-7.7 (br m, 18 H, aromatic); 8.97 (d, 1H, J = 5 Hz, ortho-pyridine)

$^{31}$P: 107.4 (s)

$^{13}$C: 38.4; 56.3; 68.0; 124.2; 126.7; 127.8; 129.0; 129.5; 130.1; 131.6; 132.8; 137.2; 152.0; 158.1; 229.6 (d, J = 6 Hz)

15b (POPy2)Pd(C(O)cinnamyl)OAc:

$^1$H: 2.22 (d, 3H, J = 7 Hz, Pd-O$_2$C(CH$_3$)$_3$); 3.50 (br t, 2H, J = 4 Hz, -C(O)-CH$_2$- + -CH$_2$-Ar); 3.95 (br m, 2H, O-CH$_2$); 5.80 (d, 1H, J = 16 Hz, -CH=CH-$^1$Ph); 6.28 (m, 1H, -CH=CH-$^1$Ph); 7.0-7.7 (br m, 18 H, aromatic); 8.98 (d, 1H, J = 5 Hz, ortho-pyridine)

$^{31}$P: 106.8 (s)

$^{13}$C: 228.0 (s)

13c (POPy3)Pd(C(O)cinnamyl)Cl:

$^1$H: 1.94 (br b, 2H, -CH$_2$- + -CH$_2$-CH$_2$-); 3.41 (d, 2H, J = 7 Hz, -C(O)-CH$_2$-); 3.56 (br b, 4H, O-CH$_2$ + -CH$_2$-Ar); 6.06 (d, 1H, J = 16 Hz, -CH=CH-$^1$Ph); 6.29 (m, 1H, -CH=CH-$^1$Ph); 7.0-7.7 (br m, 18 H, aromatic); 8.37 (d, 1H, J = 5 Hz, ortho-pyridine)

$^{31}$P: 118.2 (s)

$^{13}$C: 227.5

10.5.6 Crystal structure determination of 13a:

C$_2$H$_5$ClNO$_2$PPd, M$_w$=580.3, triclinic, P $\overline{1}$, a=9.125(1), b=11.172(2), c=13.127(4)Å, $\alpha=79.68(2)$, $\beta=74.13(1)$, $\gamma=83.96(1)^\circ$, $V=1264.2(5)Å^3$, Z=2, D$_x = 1.52$ g cm$^{-3}$, $\lambda$(CuKα)=1.5418 Å, μ(CuKα)=76.94 cm$^{-1}$, F(000)=588, room temperature, Final R=0.069 for 5201 reflections.

A crystal with dimensions 0.35 x 0.45 x 0.50 mm approximately was used for data collection on an Enraf-Nonius CAD-4 diffractometer with graphite-monochromated CuKα radiation and $\omega$-2θ scan. A total of 5201 unique reflections was measured within the range -10≤h≤11, -13≤k≤13, 0≤l≤16. Of these, 5040 were above
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The significance level of $4\sigma(F_{\text{ref}})$ and were treated as observed. The range of $(\sin \theta)/\lambda$ was $0.040-0.630\,\text{Å}$ ($3.5^\circ \leq \theta \leq 76.1^\circ$). Two reference reflections ([2 2 1], [1 0 2]) were measured hourly and showed 5% decrease during the 83 h collecting time, which was corrected for. Unit-cell parameters were refined by a least-squares fitting procedure using 23 reflections with $40.04^\circ \leq \theta \leq 41.92^\circ$. Corrections for Lorentz and polarisation effects were applied. Absorption correction was performed with the program PLATON,[30b] following the method of North et al.[30a] using $\Psi$-scans of five reflections, with coefficients in the range 0.669-0.981. The structure was solved by the PATTY option of the DIRDIF99 program system.[29]

The hydrogen atoms were calculated and a riding model was used during refinement. Full-matrix least-squares refinement on $F^2$, anisotropic for the non-hydrogen atoms and isotropic for the hydrogen atoms, converged to $R=0.069$, $wR=0.075$, $(\Delta/\sigma)_{\text{max}}=0.03$, $S=1.5$. A weighting scheme $w=\left[7000. + 0.01*(\sigma(F_{\text{obs}}))^2 + 0.01/\sigma(F_{\text{obs}})\right]^{-1}$ was used. The secondary isotropic extinction coefficient[33-37] refined to $G=1181(30)$. A final difference Fourier map revealed a residual electron density between $-1.56$ and 2.04 eÅ$^{-3}$ in the vicinity of the Pd. Scattering factors were taken from Cromer and Mann,[30a] International Tables for X-ray Crystallography.[30b] The anomalous scattering of Pd, P and Cl was taken into account.[31] All calculations were performed with XTAL3.7[32], unless stated otherwise.

10.6 References


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[16] In chapter 6 we have found that on the timescale of the allylic alkylation the nitrogen functionality of the POPy ligands is not bonded to palladium in a hemilabile fashion. We were interested whether this would also apply for the conditions of the carbonylation reaction. Also in this chapter we found no evidence for a dissociation from palladium of the nitrogen functionality.


[25] A recent brief theoretical study by Yamamoto and coworkers points out that for cationic complexes an insertion mechanism involving a five-coordinated species is not feasible. Since the study is only
concerned with cationic complexes bearing one or two phosphorus atoms, this conclusion may not apply to the neutral complexes at hand:


