Palladacycles: synthesis and catalysis
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Chapter 1

General Introduction

1.1 Coordination and Organometallic complexes

Organometallic and coordination chemistry are two domains of chemistry that are complementary. Coordination complexes consist of one or more metals centres surrounded by ligands, organic or inorganic, ions or molecules, that can have an independent existence. The organometallic chemistry is defined as the chemistry of compounds containing metal–carbon bond, however, in general manner this term is attributed to the chemistry made of organic transformations assisted by metals.¹

The rise of the modern organometallic chemistry occurred in the 50’s, after the discovery of the ferrocene (1951) by Pauson²ᵃ and Miller²ᵇ and the elucidation of its structure (1952) by Wilkinson²ᶜ and Fischer²ᵈ. However, it is in 1757 that the origin of the organometallic chemistry can be traced back when Cadet de Gassicourt discovered the “Cadet’s fuming liquid” which was a mixture of cacodyl oxide and tetramethylidarsine during his work on ink made of cobalt salts containing arsenic.¹ᶜ,⁴

The first organometallic complex containing a transition metal was a π complex synthesized by Zeise (1827).⁵ Two decades later Frankland prepared a series of air sensitive metal–alkyl complexes i.e.: ZnEt₂ (1849), HgMe₂ (1852),⁶ which have been used to synthesize various main group organometallic compounds as the organochlorosilanes of Friedel and Crafts (1863).⁷

\[
\begin{align*}
\text{(a) } \text{As}_2\text{O}_3 + 4 \text{MeCO}_2\text{K} & \rightarrow [(\text{AsMe}_2)_2\text{O}] + [\text{Me}_2\text{As-AsMe}_2] + ... \\
\text{(b) } \left[\begin{array}{c}
\text{Cl} \\
\text{Cl} \\
\end{array}\right] \text{Pt} \left[\begin{array}{c}
\text{Cl} \\
\text{Cl} \\
\end{array}\right] \rightarrow \text{K}^+ \\
\text{(c) Fe} \\
\text{Fe}\end{align*}
\]

Scheme 1-1. (a) Reaction leading to the “fuming liquid of Cadet”; (b) Zeise’s salt; (c) Ferrocene of Pauson followed by the ferrocene of Wilkinson and Fischer.
1.2 Metallacyclic and Cyclometallated Compounds of the Transition Elements

1.2.1 Metallacyclic compounds

A metallacycle can be defined as “a carbocyclic system with one or more atoms replaced by a transition metal”.\(^8\) This definition means that metallacycle should be restricted to those compounds, of type I, that have the transition metal atom incorporated in the ring via two carbon–metal $\sigma$-bonds, and therefore excludes simple complexes containing chelating PP, NN ligands, cyclometallated complexes and any other cyclic complex in which the metal is bound to a heteroatom.

The first metallacyclic complex was prepared by Tipper\(^9\) in 1955 (Scheme 1-2). He treated hexachloroplatinic acid with cyclopropane in acetic anhydride to give a compound of formula $[\text{PtCl}_2(\text{C}_3\text{H}_6)]_n$. The complex was later shown to be a chloride bridged tetramer,\(^10\) with a structure analogous to Pt(IV) alkyls, in which platinum has inserted into the cyclopropane ring and not a dimeric structure analogous to Zeise’s dimer, as it was initially suggested.

However, despite their discovery in the mid-fifties, metallacyclic compounds did not become intensively studied until their role in catalysis was appreciated. It is in the 1970s that the metallacyclic compounds of the transition elements have been the subject of considerable research as it was recognised that they were playing an important role in a number of catalytic reactions, e.g. alkene metathesis,\(^11\) isomerization of strained carbocyclic rings,\(^12\) cycloaddition of alkenes,\(^13\) oligomerization of dienes\(^14\) and in polymerisation reactions.\(^15\)
1.2.2 Cyclometallated compounds

Cyclometallated compounds can be defined as being metallacyclic compounds in which a carbon atom is substituted by a heteroatom Y directly bound to the metal through a two electrons lone pair. Cyclometallated complexes of the type II, in which Y is typically a Lewis base and the chelate ring generally possesses three to seven members, with the five-membered ring being most prevalent. Precious metals are most common, although other transition metals can cyclometallate. Cyclometallated complexes of the type III, result of an hydrogen transfer from a coordinated ligand to a metal atom.

\[
\begin{align*}
\text{II} & \quad \text{CM} \quad Y \\
\text{III} & \quad \text{CM} \quad \text{H}
\end{align*}
\]

It is in the mid sixties that the first cyclometallated complexes were prepared by Cope et al.\textsuperscript{16} by reacting aromatic azo compounds and potassium tetrachloroplatinate(II) or palladium(II) dichloride. However, two years before a cyclopentadienyl nickel compound with similar azobenzene ligand was obtained by Dubeck et al.\textsuperscript{17} but they assigned the wrong structure to this compound as they proposed that the N=N double bond was \(\pi\) coordinated to nickel (Scheme 1-3). The first report of metal insertion in a C–H bond, leading to cyclometallated complexes of the type III, was made in a bis dimethylphosphinoethane (dmpe) complex of ruthenium [Ru(dmpe)\textsubscript{2}], yielding a [HRu(CH\textsubscript{2}PMe(CH\textsubscript{2})\textsubscript{2}PMe\textsubscript{2})(dmpe)] complex.\textsuperscript{18}

\[
\begin{align*}
(a) & \quad \text{(a) Cycloplatinated and cyclopalladated complexes of Cope.}^{16} \\
(b) & \quad \text{(b) Cyclopentadienyl azobenzene nickel compound of Dubeck.}^{17} \\
(c) & \quad \text{(c) Formation of a cycloruthenated complex by insertion into a C–H bond of a methyl group of the coordinated ligand.}
\end{align*}
\]

Despite the fact that the cyclometallation reactions under C–H activation have been known for more than thirty years\textsuperscript{19} and represent one of the best developed
areas of organometallic chemistry, it is only almost two decades later that L. Lewis disclosed the discovery that cycloruthenated compounds displayed enhanced catalytic activity. Thus, olefin hydrogenation\textsuperscript{20a} and the double alkylation of phenol with ethylene selectively in the ortho positions were performed with an ortho-ruthenated phosphite complex.\textsuperscript{20b}

1.3 Formation of Palladacyclic Compounds

1.3.1 Insertion into C–C bonds

Oxidative addition of a C–C bond of cyclopropane to a metal centre provides a facile synthesis of metallacyclic complexes of a variety of transition metals. Regarding the group 10 of transition metal, most of the studies refer to the insertion of a metal in cyclopropane derivatives leading to metallocyclobutane.\textsuperscript{21} The C–C bond cleavage of carbocyclic rings larger than cyclopropane or cyclopropene is less common, although it is known that cyclobutene derivatives can undergo this reaction. As may be expected, reactions with palladium are much less common than for platinum due to the fact that palladium is less able to accept electron density from the ring. Contrary to the reaction with Pt(II), in which an electrophilic attack on the organic ring has been proposed, the Pd\textsuperscript{0} behaves as a nucleophilic moiety. Hence it is found that palladium will only insert into cyclopropanes containing good electron withdrawing substituants. Lenarda et al.\textsuperscript{22} have demonstrated the formation of palladacyclobutanes 1 from tetracyanocyclopropane and tetrakis(triphenylphosphine)palladium (0), the latter inserting into the C–C bond containing the CN substituants (Scheme 1-4). Further investigations of tetrakis(triphenylphosphine)palladium(0) insertion into cyclopropene has led to the preparation of an unstable palladacyclobuta[b]naphthalene 2\textsuperscript{23} product illustrated in Scheme 1-4.

![Scheme 1-4. Formation of palladacyclobutane derivatives via oxidative addition of C–C bond.](image-url)
1.3.2 Reaction with dilithio and di-Grignard reagents

The most frequently synthesized palladacycles by transmetalation reaction are the five-membered rings, although in principle any ring size can be obtained. Reaction of 1,4-dilithiobutane with $[\text{PdCl}_2(\text{dppe})]^{24a,b}$ at -70°C leads to the formation of the palladacyclopentane 3 (Scheme 1-5). This compound is thermally very stable considering that it contains $\beta$-hydrogen atoms available for hydride elimination and decomposes in about 12 hours in toluene whereas $[\text{Pd}(n\text{Bu})_2(\text{dppe})]$ decomposes in about 1 hour. The use of the $\alpha,\alpha$-xylil di-Grignard reagent with $[\text{PdCl}_2(\text{PMe}_3)_2]$ yielded the formation of benzo[c]palladacyclopentene 4$^{25}$ (Scheme 1-5).

![Scheme 1-5. (3) Palladacyclopentane obtained by reaction of 1,4-dilithiobutane$^{24}$ and (4) benzo[c]palladacyclopentene synthesized from $\alpha,\alpha$-xylil di-Grignard reagent.$^{25}$]

1.3.3 Palladacycles derived from homocoupling reactions of alkynes or alkenes

Reactions of metal complexes with alkenes giving metallacycloalkanes, or alkynes giving metallacycloalkadienes represent the most common and useful methods for synthesis of metallacyclic compounds. In the 1970s a series of palladacyclopentadienes has been made by Maitlis et al.$^{26}$ and Ishii et al.$^{27}$ using a zerovalent palladium starting material. Thus, reaction of dibenzylideneacetonepalladium, $[\text{Pd(dba)}_2]$ or $[\text{Pd}_2(\text{dba})_3]$, with dimethyl-2-butynedioate (dmbd) at room temperature led to the formation of 5 which forms adducts 6 with either monodentate or bidentate donor ligands (Scheme 1-6). The quantitative oxidative-addition/coupling toward palladium(0) olefin complexes requires the electron-deficiency of the alkyne. Fewer examples are known of reactions with alkynes leading to palladacyclopentadienes$^{28,29,30}$ as palladium generally prefers to form monoalkyne complexes which tend to be inert to further acetylenic attack. This method of synthesis yields almost exclusively five membered ring systems.
Scheme 1-6. Formation of palladacyclopentadienes from dmbd reported 1970s.

Besides electron deficiency, structural strain can also lead to the activation of an unsaturated molecule towards the cycloaddition reaction, i.e. the cycloaddition of cyclopropene derivatives (Scheme 1-7) on the in situ generated [Pd(PR₃)₂][31] and the regioselective oxidative cyclization of C₂-symmetrical, chiral cyclopropene derivatives on [Pd₂dba₃.CHCl₃].[32]

Scheme 1-7. (a) Cycloaddition of cyclopropene by Binger et al.[31] (b) Formation of trans-5-palladatricyclo[4.1.0.0²,4]heptanes described by Hashmi et al.[32]

1.3.4 Palladacycles derived from heterocoupling reactions of unsaturated molecules or polyalkene or polyalkyne reactions

During their studies on co-cycloaddition of methoxyallene and dimethyl-2-butynedioate (dmbd) on a diazadiene palladium(0) fragment to form tetrahydronaphthalene derivatives, tom Dieck et al. noticed that the use of allenic ethers with better leaving groups was not resulting in improved yields but instead in the formation of stable palladacyclopentenes 7 (Scheme 1-8).[33a] The formation of palladacyclopentene 8 from dmbd and alkene was also successful, however, a considerable excess of alkene was necessary to compete with the oxidative coupling reaction of the second molecule of dmbd.[33b]
Yamamoto et al.\textsuperscript{34} and Canovese et al.\textsuperscript{35} recently reported the synthesis of palladacyclopentadienyl derivatives from diyne diester. In both cases, the formation of a bicyclopalladacycle is observed as illustrated in Scheme 1-9.

Scheme 1-8. Palladacyclopentene resulting of the heterocoupling reaction of dmbd with allenic ethers and dmbd with alkene.

Scheme 1-9. Palladacyclopentadienyl derivatives issued of (a) flexible\textsuperscript{34} and (b) rigid\textsuperscript{35} diyne diester.

1.3.5 Formation of palladacycles via palladacyclization reactions

Metallacyclization involving coordinated ligands has been known for a long time (1970s)\textsuperscript{19a} but it is only few years later that its application to hydrocarbyl systems has been recognized. Cyclization can be observed via oxidative addition to a distal C–H bond of functionalized alkyl groups. This reaction has been observed in palladium complexes by Clarke et al.\textsuperscript{36} whereby dimethyl 3-oxoglutarate reacts with the zerovalent complex [PdL\textsubscript{4}] (L = PPh\textsubscript{3}) to give 9. One decade later, Trost investigated...
the scope and reactivity of the complexes obtained from reaction of Pd\(^0\) with 1-acetoxy-3-(trimethylsilyl)propanone 10 and suggested that the Pd\(^0\) would be at the origin of a Brook rearrangement to form the silyl enol ether 11 and after a catalytic oxidative addition into the allyl acetate, the acetate-induced desilylation would form palladacyclobutanone 12 (Scheme 1-10).\(^{37}\)

![Scheme 1-10. Palladacyclobutanones described by Clark et al. 9\(^{36}\) (L = PPh\(_3\)) and Trost 12 (L = PPh\(_3\), P(C\(_2\)H\(_5\))\(_3\)).\(^{37}\)](image)

Thermal palladacyclization was observed from dialkyl complex, palladacyclobutane has been prepared by intramolecular C–H insertion reaction of the corresponding dineopentyl palladium complex [Pd(CH\(_2\)CMe\(_3\))\(_2\)(PPh\(_3\))\(_2\)].\(^{38}\)

Electrophilic palladacyclization is an electrophilic substitution at the unactivated ortho aromatic carbon, the reaction being favored by the presence of electron-donating substituents on the aromatic ring (para to the palladium-carbon bond to be formed) of the open precursor.\(^{39}\) The reaction corresponds to activation of a usually inert aromatic C–H bond \(i.e.\) Catellani and co-workers have showed that the ring closure readily occurs under very mild conditions with arylnorbornylpalladium complexes (Scheme 1-11),\(^{39,40}\) that is probably favored by the previous coordination of the aromatic ring to the metal which provides the right steric arrangement.\(^{41,42}\)

![Scheme 1-11. Palladacyclization of arylnorbornylpalladium via activation C–H (L = mono- or bidentate nitrogen ligands or PPh\(_3\)).](image)
1.4 Formation of Cyclopalladated Compounds

The vast majority of these complexes possess anionic four-electron (bidentate) or six-electron (tridentate) donor ligands, with five-membered nitrogen-containing rings being the most common (Scheme 1-12). In syntheses prior to 1980, the C-donor was sp²-hybridized and primarily part of an aromatic ring, nowadays cyclopalladated compounds are known, for nearly all classes of ligands using different methods of preparation⁴³ and to be formed by a variety of mechanisms.⁴⁴a Their synthesis is facile and it is possible to modulate their electronic and steric properties simply by changing (i) the size of the metallacyclic ring (3-10 membered), (ii) the nature of the metallated carbon atom (aliphatic, aromatic, vinylic, etc.), (iii) the type of donor group L (N-, P-, S-, O containing group, etc.) and its substituents (alkyl, aryl, etc.), or (iv) the nature of the X ligands (halide, triflate, or solvent, i.e. THF, H₂O). These factors determine whether the complex is dimeric, monomeric, neutral, or cationic. This flexibility confers a plethora of potential applications upon this class of compounds.

Scheme 1-12. General cyclopalladated complexes structures (with L = donor and Y = linker group), cyclopalladated complexes (IV and VI), symmetric pincer type cyclopalladated complexes⁴⁵ (IV and V), dissymmetric pincer type cyclopalladated complexes (VII and VIII).

1.4.1 Cyclopalladation by orthopalladation and similar reactions

Cyclopalladation or bis-cyclopalladation was successfully used as early as 1965 for the complexation of Pd with C=N ligands,¹⁶ and 1976 for the complexation of Pd with P=C=P ligands.⁴⁶

The direct cyclopalladation, promoted by the chelate effect, is the most simple and there has been a considerable interest in the synthesis of these cyclopalladated complexes. This allows the use of simple organic starting materials and hence is
much more economic than those reactions that require the use of expensive and air-sensitive organometallic precursors (e.g., RLi). The classical methods are the use of tetrachloropalladated salts with base\textsuperscript{47} or palladium acetate in acetic acid, benzene or toluene.\textsuperscript{48}

The cyclopalladation also termed orthopalladation means usually an intramolecular coordination of donor groups on the ligand precursor prior to formation of the Pd–C σ bond (Scheme 1-13).\textsuperscript{19a,2} This method of cyclopalladation is quite similar to the palladacyclization of the arylnorbornylpalladium complexes\textsuperscript{39,40} represented in Scheme 1-11.

\begin{center}
\textbf{Scheme 1-13.} Proposed mechanism for the cyclopalladation of aromatic ligand, \textit{i.e.} the azobenzene ligand of Cope\textsuperscript{16}.
\end{center}

\subsection{1.4.2 Cyclopalladation via oxidative addition}

In contrast to direct cyclometallation, oxidative addition to carbon–halogen bonds has hardly been explored, presumably because C–H activation has been a successful method for complexation. This method is used to generate cyclopalladated complexes which are not usually accessible by direct C–H bond activation, \textit{i.e.} the syntheses of three-membered ring cyclopalladated compounds [(PPh\textsubscript{2}R)\textsubscript{2}Pd(CH\textsubscript{2}SR')Cl],\textsuperscript{49a} by oxidative addition of R'SCH\textsubscript{2}Cl to [Pd(PPh\textsubscript{2}R)\textsubscript{4}] and the formation of four-membered ring cyclopalladated compounds (Scheme 1-14).\textsuperscript{49b}
Scheme 1-14. (a) Formation of the unfavourable four-membered cyclopalladated complex.49b (b) Chemoselective palladation of the bifunctional pincer N–C–N ligand.50

The method might become more important when further functionalization on the ligand is required. Van Koten achieved the chemoselective palladation on pincer ligand at the Caryl–I or Caryl–Br bonds (Scheme 1-14).50 In this way a series of bis-cyclopalladated complexes were prepared that have a second functional group available for further reactions such as a second metallation in order to obtain (hetero)bimetallic complex.

1.4.3 Cyclopalladated compounds formed by transmetallation reaction

The transmetallation methodology involves in most cases organolithium or organomercury as transmetallating agents and is often-used to achieve bis-cyclopalladation. Similarly to the oxidative addition, the transmetallation could be used to generate cyclopalladated complexes which are not usually accessible by direct C–H bond activation, i.e. it has been used for the bis-cyclopalladation of N–C–N pincer ligands.51 The lithiation of P–C–P or N–C–N pincer ligands has been studied and the use of an aryl halide precursor improves the selectivity, since Li/halide exchange is quantitative. In case of P–C–P pincer ligand, methyl substituants, on the phosphorus atoms, have to be used to prevent an isomerization into benzylolithium (Scheme 1-15).52
Scheme 1-15. Lithiation of $N^\cdot C(H \text{ or } X)$ (N and P(C(H or X) (P = copers ligands.

The formation of [Pd(C(N)(C'(L'))] (with L' = N or O), an other type of bis-cyclopallated compound, is easily realized by reacting organolithium or organomercury compounds (Li–C'(L’ or HgCl–C'(L’)) with halogen dimer cyclopalladated complex (Scheme 1-16).53,54

The synthesis of planar chiral cyclopalladated complexes containing the Cr(CO)3 moiety via transmetallation with organomercury compounds has been explored by Berger et al. since the cyclopalladation under C–H bond activation yielded irreversibly to the decomposition in Cr0 (Scheme 1-16).54

Scheme 1-16. Synthesis of the chiral planar palladacycle 14 and of the bimetallic heteroleptic cis bis-chelated Pd(II) complex 15 by a transmetallation reaction of the orthomercurated 2-[tricarbonyl($^6$-phenyl)chromium]pyridine.54
1.4.4 Cyclopalladated compounds formed by transcyclometallation reaction

Accordingly, transcyclometallation describes the substitution of one cyclometallated ligand by another one without the formation of significant and detectable amounts of purely inorganic compounds (dissociated metal salts). Transcyclometallation reactions were initially investigated with bidentate coordinating ligands, but the concept has subsequently been extended also to terdentate-binding pincer ligands. Preliminary results included the reaction of the pincer ligand precursor $S\cdot C(H)\cdot S$ with half an equivalent of the chloro-bridged cyclopalladated dimer of $N,N$-dimethylbenzylamine 13 which afforded the biscyclopalladated palladium complex $[PdCl(S\cdot C\cdot S)]$ 16 and the free $N,N$-dimethylbenzylamine (Scheme 1-17).

![Scheme 1-17. Transcyclo-
Scheme 1-18. (a) Alkoxy palladation and allylamine or thioether leading to cyclopalladated complexes. (b) Trans-carbopalladation of alkene.

1.4.5.2 Trans-chloropalladation of heterosubstituted alkynes

The reaction of propargyl amines and thioethers with [Li₂PdCl₄] occurs readily to afford exclusively the air-stable five-membered cyclopalladated compounds containing a palladium–vinyl bond resulting formally from the trans nucleophilic addition of the chlorine anion onto the C≡C bond (Scheme 1-19). This method tolerates a variety of alkyne functional groups (amines, pyridine, thioethers, phosphines, and phosphinites) and allows the preparation of palladacycles containing various metalate ring sizes.

Thus the reaction of [Li₂PdCl₄] with hetero-substituted alkynes Me₂NCH₂C≡CCH₂CH₂L (L = S-t-Bu, NMe₂, PPh₂, and OPPh₂) affords the “pincer” cyclopalladated compounds (Scheme 1-19). This chloropalladation reaction is an interesting method for the generation of unsymmetrical pincer type cyclopalladated complexes. The following mechanism was proposed, the chloropalladation reaction proceeds through the coordination of only one donor group followed by coordination of the C≡C bond to the palladium. Selective intermolecular chloride nucleophilic addition on this activated triple bond affords the more thermodynamically stable cyclopalladated ring. Finally, coordination of the second donor group to the Pd centre yields the “pincer” palladacycles.
1.5 Palladacyclic and Cyclopalladated Compounds in Catalysis

1.5.1 Palladacyclic compounds

Palladacyclic compounds are most of the time intermediate species in catalytic processes\textsuperscript{59} such as palladium-mediated cycloaddition reactions. Palladacycles are key intermediates in other types of palladium-catalyzed reactions, such as coupling reactions via C–H activation and the intramolecular Stille reaction but they are also assumed to be intermediates in Heck type cyclization reactions when the crucial reaction step, the \( \beta \)-hydrogen elimination, is inhibited.\textsuperscript{60} They can be formed in the course of a sequence by C–H activation of usually inert groups, by oxidative coupling and they can also be demolished in the course of the same reaction sequence during which they have been formed. The cyclopalladation of alkyl(aryl) ligands is frequently invoked in palladium-catalyzed cyclization reaction.\textsuperscript{61}

1.5.1.1 Palladacycles as intermediates: 6-membered rings and larger rings

The typical reaction that 6-membered rings and larger palladacycles with two carbon-palladium \( \sigma \) bonds undergo is reductive elimination, e.g. the synthesis of the indolo[2,3-a]carbazole alkaloid ring system present in several active molecules such as arcyriaflavin A and the potent antitumor agent rebeccamycin (Scheme 1-20).\textsuperscript{62} This is a facile process, thus explaining why it is difficult to detect these reactive intermediates.
Scheme 1-20. The polyannulation reaction, leading to the indolo[2,3-a]carbazole alkaloid ring system, is assumed to proceed via a palladacycloheptatriene.

For some palladium-catalyzed reactions their role as key intermediates is based on compelling mechanistic considerations (e.g. for the intramolecular Stille coupling reaction). Intramolecular palladium-catalyzed processes that involve a sequence of oxidative addition at aryl or vinyl halides, followed by a transmetallation step, generally proceed via palladacycles. This type of processes have found widespread application in the synthesis of naturally occurring macrocycles. An intramolecular Stille coupling reaction was the key step in the synthesis of (S)-zearalenone, a macrocyclic lactone (Scheme 1-21).\(^6^3\)

For some other reactions the presence of 6-membered rings and larger palladacycles as intermediates has to be regarded as a working hypothesis that is challenged by alternative mechanistic explanations.

Scheme 1-21. Oxidative addition of the supported Pd\(^0\) catalyst to the aryl iodide bond, and transmetallation with the vinylstannane, to give the 15-membered palladacycle which lead, after reductive elimination and deprotection to (S)-zearalenone.
1.5.1.2 Palladacycles as intermediates: 5-membered rings and smaller rings

No matter how 6-membered rings and larger palladacycles are formed, they generally undergo a facile reductive elimination. 5-Membered palladacycles behave differently; the formation of 4-membered rings via reductive elimination is unfavourable and restricted to special cases. Instead, 5-membered palladacycles can react with a second equivalent starting material, or with added reagents resulting in domino processes\textsuperscript{64} \textit{i.e.} [2+2+2] cycloaddition reaction\textsuperscript{61a,65} such as cyclo- and cyclocotrimerization of acetylenes,\textsuperscript{26a,28,34,66} arynes,\textsuperscript{67} or dimerization-carbostannylation of alkynes.\textsuperscript{68}

\begin{center}
\includegraphics[width=\textwidth]{scheme22.png}
\end{center}

\textbf{Scheme 1-22.} Treatment of 1,6-enyne in presence of palladacyclopentadiene 17a and tri-o-tolylphosphite and dimethyl-2-butynedioate (dmbd) leads to vinylcyclopentene 18.\textsuperscript{61b,69}

The three-membered organopalladium intermediates, resulting from the oxidative coupling of Pd\textsubscript{0} complexes with C=C or C≡C bonds of alkenes, alkynes, allenes, conjugated dienes, and other C–C multiple bonds including even arenes, are involved or suggested in various process such as oligomerization reaction of conjugated diene via the production of a bis(allyl)palladium\textsuperscript{70} or in the conversion of enynes into vinylcyclopentene derivatives\textsuperscript{69} (Scheme 1-22).

1.5.1.3 Palladacycles as catalysts

Thermodynamic, as well as kinetic stability is necessary for palladacycles to be applicable as catalysts. 5-Membered palladacycles that fulfil these requirements are
the derivatives of the polymeric tetrakis(alkoxycarbonyl)palladacyclopentadiene (TCPC) 17, and the chiral palladatricycloheptane THC-catalysts$^{32a}$ (see (b) Scheme 1-7). Reductive elimination is unfavourable in both cases. The polymeric pre-catalysts TCPC 17 required an activation such as the addition of a ligand to break down the insoluble polymer to create the active specie. Trost has reported that ene-diyne [2+2+2] cycloaddition with an electron-deficient alkyne, leading to cyclohexadiene derivatives such as 19, is catalyzed by 17a in presence of tri-o-tolylphosphite (Scheme 1-23).$^{71}$ In contrast, with the TCPC catalyst 17b that achieved an intramolecular enyne metathesis.$^{72}$ Other reactions of [2+2+2] cycloaddition catalyzed by TCPC type of catalyst have been reported such as co-cyclotrimerization of various alkynes,$^{28}$ of acetylenes with alkenes.$^{8a}$

Scheme 1-23. (a) The polymeric tetrakis(alkoxycarbonyl)palladacyclopentadienes 17.
(b) The ene-diyne [2+2+2] cycloaddition with dmbd catalyzed by 17a.$^{71}$

Other reactions catalyzed by TCPC derivatives are cycloaddition reactions with intermediary palladadienes,$^{73}$ three-component synthesis of conjugated dienes,$^{74}$ the dimerization of allenyl ketones leading to functionalized furans,$^{75}$ hydrostannation of cyclopropene$^{76}$ and in Stille cross-coupling reaction.$^{77}$

1.5.2 Cyclopalladated compounds

Cyclopalladated complexes are amongst the most active catalysts in Heck-type carbon–carbon bond formation and related carbon–heteroatom bond forming reactions.$^{78,45c}$ Heck type reactions are generally believed to work via a Pd(0)/Pd(II) catalytic cycle.$^8$ Starting with cyclopalladated pre-catalyst in the oxidation state +II a reduction step prior to catalysis would be necessary.
Scheme 1-21. Reduction of the Herrmann’s cyclopalladated catalyst to Pd⁰ species.

In the cases of the Stille, Grignard, Negishi and Suzuki-Miyaura cross coupling reactions, the reduction mechanism of the Herrmann’s palladacycle into a catalytically active Pd⁰ species has been elucidated by Hartwig 79 and extended by Böhm 80 (Scheme 1-21). Regarding the Mizoroki-Heck reaction a Pd(II)/Pd(IV) cycle was initially proposed since the cyclopalladated catalyst was recovered unchanged in good yield at the end of the reaction. 78a However, after these initial speculations, all experimental evidence available to date speaks against such Pd(II)/Pd(IV) cycle. 81 It is now accepted that in most of the cases, the catalytically active species involved in these reactions are based on Pd⁰ and that the reaction proceeds through a Pd(0)/Pd(II) catalytic cycle. 82, 83

How act the cyclopalladated compounds in Mizoroki-Heck reaction? Consorti et al. described their C⁻N cyclopalladated pre-catalyst as a reservoir of the catalytically active Pd⁰ species, i.e. Pd colloids, or highly active forms of low ligated Pd⁰ species, 84 and Herrmann and co-workers described a cyclometallated anionic palladium(0) as the catalytically active species (Scheme 1-22) assuming the reduction of the dimeric pre-catalyst without cleavage of the metallacycle. 83

Scheme 1-22. Reduction of the Herrmann’s pre-catalyst without rupture of the carbon–palladium bond.
1.6 Aim and Outline of this Thesis

The research described in this thesis ranges from the study of the formation of palladacycles and cyclopalladated complexes (Chapters 2, 3 and 4) and the investigation of their catalytic properties (Chapters 3 and 4) to the study of the cyclic palladium(0)-complexes, containing chelating \( \alpha \)-diimines ligands, in catalytic semi hydrogenation of allenes to (Z)-alkenes (Chapter 5).

In Chapter 2 the synthesis of palladacyclopentadienes complexes from \([\text{Pd(dba)}_2]\) and dissymmetric electron-poor alkynes, such as methyl phenylpropynoate, methyl (4-methoxyphenyl)propynoate and methyl (4-nitrophenyl)propynoate with various bidentate \(N\)-ligands, 2,2'-bipyridine, 1,10-phenanthroline, tetramethylenediamine and bis(arylimino)acenaphthene is presented. X-ray crystal structures of dissymmetric and symmetric palladacyclopentadienes have been obtained. The regioselectivity and the stability of these complexes will be presented.

The kinetics, mechanistic aspects and the scope of the three-components synthesis of conjugated dienes from alkyne catalyzed by \([\text{Pd(bis(arylimino)acenaphtene)(CCOOME)}_4]\) are described in Chapter 3. Based on the experiments, a general mechanism is proposed for this catalytic formation of dienes.

Chapter 4 deals with the synthesis and characterization of cyclopalladated and cycloplatinated complexes of the type \([\text{M(C\`N)(LL)}]^+\) \((\text{C\`N} = \text{N,N-dimethylbenzylamine or benzo[h]quinoline and LL = 4,4'-bis(tert-butyl)-2,2'-bipyridine or bis(diphenylphosphino)ethane). X-ray crystal structure determinations of complexes have been determined. The complexes have been employed as pre-catalyst in the Sonogashira cross-coupling reaction and the results will be describer. The tentatives about the preparation of cyclopalladated complex of type \([\text{Pd(C\`N)L}_n]^-\) and the use of biphosphinine as ligand to stabilize such anionic zerovalent palladium complex will be discussed.
In the Chapter 5 the palladium complexes of the type \([\text{Pd}(\text{bis}(\text{arylimino})\text{acenaphthene})(\eta^2\text{-alkene})]\), containing electron-poor alkenes, have been employed as pre-catalysts for the reaction of hydrogenation of different functionalized allenes. The results will be discussed and from these experiments a plausible reaction mechanism will be proposed.

1.7 References


