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Synthesis, Characterization and Reactivity

Mousa, Abdelrazek

2018

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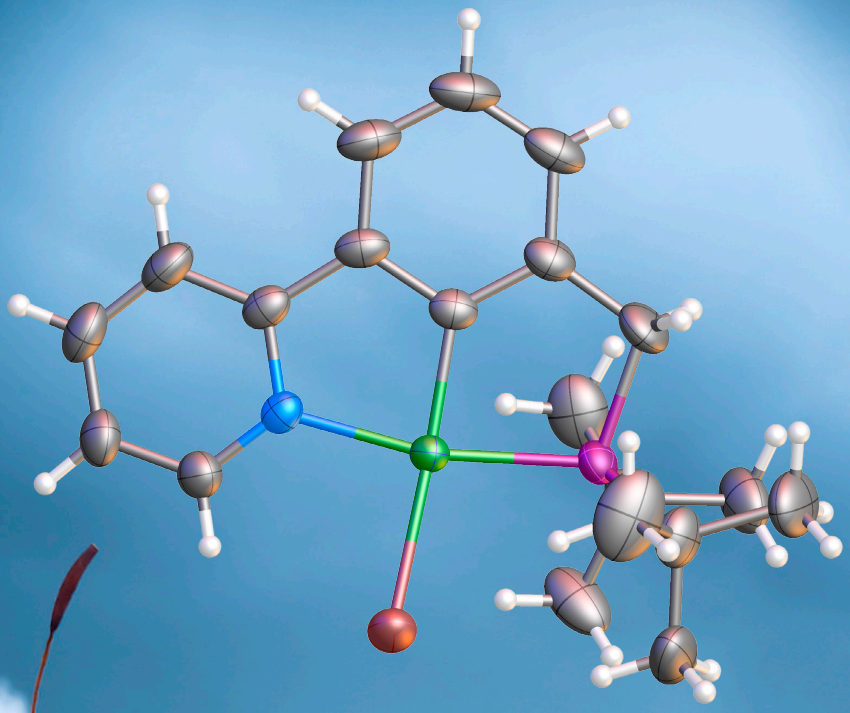

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Synthesis, Characterization and Reactivity

Abdelrazek H. Mousa

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To be defended at Hörsal Blå hallen, Ekologihuset. 17th December 2018 at 9.15 am.

Faculty opponent
Prof. Sascha Ott, Uppsala University, Sweden

Organization LUND UNIVERSITY	Document name **DOCTORAL DISSERTATION**
	Date of issue 2018-12-17
Author(s) Abdelrazek H. Mousa	Sponsoring organization

Unsymmetric PCN Pincer Palladium and Nickel Complexes. Synthesis, Characterization and Reactivity

Abstract

New palladium and nickel complexes based on unsymmetric PCN pincer ligands have been synthesized and fully characterized using different techniques. The substituents on the nitrogen side arm of the ligand have great influence on the cyclometallation and the reactivity of the new complexes particularly in case of nickel. The less sterically hindered PCN^{Me} ligand enabled formation of the trivalent nickel halide complexes through a straightforward reaction with anhydrous copper halide salts. The trivalent nickel halide complexes were isolated and characterized using EPR, magnetic moment and elemental analysis. The reactivity of the PCN nickel halide complexes in Kharasch addition was tested.

The PCN palladium and nickel complexes relevant to CO_2 insertion reactions were synthesized, and their reactivity towards CO_2 were investigated giving facile insertion reactions at room temperature in case of the hydroxo and amido complexes. Insertion of CO_2 into the nickel methyl bond was conducted under mild reaction conditions using the more electron donating and the sterically hindered $PCN^{i\text{-}Pr}$ ligand. Insertion of CO_2 into the palladium phenyl acetylide complex offered the corresponding hydrogen carbonate complex. Investigation of the identity of the later complex led to the development of catalytic decarboxylative cross coupling reaction.

A short synthetic route was developed to prepare the PCN^{Py} nickel complexes including pyridine as a nitrogen side arm. The new PCN^{Py} allowed C-H activation at room temperature and enhanced the stability of the alkyl nickel complexes. The PCN nickel complexes mediate the catalytic Kumada coupling reaction.

Key words: unsymmetric PCN; palladium; nickel; cyclometallation; carboxylation; cross coupling

Classification system and/or index terms (if any)

Supplementary bibliographical information		Language English
ISSN and key title		ISBN 978-91-7422-608-9 (Printed) ISBN 978-91-7422-609-6 (Digital)
Recipient's notes	Number of pages 186	Price
	Security classification	

Signature Abdelrazek Mousa Date 2018-11-09

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Cover by Paula Leckius & Abdelrazek H. Mousa

Faculty of Science, Department of Chemistry
Centre for Analysis and Synthesis (CAS), Lund University

ISBN 978-91-7422-608-9 (Printed)

ISBN 978-91-7422-609-6 (Digital)

Printed in Sweden by Media-Tryck, Lund University
Lund 2018

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Dedicated to

The soul of my father

The soul of my friend, Abdelrhman

The soul of my father in law

My family

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The current doctoral thesis is based on the following publications, referred to by their Roman numerals I-V

I. **Aromatic PCN Palladium Pincer Complexes. Probing the Hemilability through Reactions with Nucleophiles**

A. Fleckhaus, **A. H. Mousa**, N. S. Lawal, N. K. Kazemifar, O. F. Wendt. *Organometallics* **2015**, *34*, 1627-1634.

II. Aromatic PCN Pincer Palladium Complexes: Forming and Breaking C-C Bonds

A. H. Mousa, A. Fleckhaus, M. Kondrashov and O. F. Wendt. *Journal of Organometallic Chemistry* **2017**, *845*, 157-164.

III. Synthesis, Characterization and Reactivity of PCN Pincer Nickel Complexes

A. H. Mousa, J. Bendix, O. F. Wendt. *Organometallics* **2018**, *37*, 2581-2593.

IV. An electron Rich Unsymmetric PCN Pincer Nickel Complex Giving Facile Carboxylation Reaction of the Ni-Me Bond.

A. H. Mousa, O. F. Wendt. Manuscipt

V. Enhancing the Stability of Aromatic PCN Pincer Nickel Complexes by Incorporation of Pyridine as the Nitrogen Side Arm.

A. H. Mousa, , G. Isapour, O. F. Wendt. Manuscript

Publications not included in the current thesis

I. Synthesis and Characterisation of $POC_{sp3}OP$ Supported Ni(II) Hydroxo, Hydroxycarbonyl and Carbonate Complexes.

K. J. Jonasson, **A. H. Mousa**, and O. F. Wendt. *Polyhedron* **2017**, 14*3*, 132-137.

Contribution to the Publications

I. Reproduced most of the experimental work with full characterization except the kinetic work and assisted in writing the manuscript

II. Performed all the experimental work except two crystal structures and wrote the manuscript

III. Planned the project, performed all the experimental work except EPR and magnetic susceptibility and wrote the manuscript

IV. Planned the project, performed all the experimental work and wrote the manuscript

V. Planned the project, performed all the experimental work including the initial catalytic experiments, supervised and wrote the manuscript

Acknowledgment

First and foremost, I would like to praise and thank ALLAH, Almighty for giving me the strength and knowledge to do this work. Without his kindness and blessings, this work would not have been possible.

I would like to thank my supervisor Prof. Ola. F. Wendt for accepting me as a PhD student, introducing me to the fascinating world of pincer complexes, for his endless support during my PhD study and for the flexibility I got which enabled me to try different ideas. His office was always opened to answer my questions.

Special thanks go to André for teaching me the organometallic techniques and for useful discussions, which allowed me to gain more knowledge. I would like to thank Mike for his endless help I received. I used to jump to his office and ask him a lot of questions. Thanks for sharing your Strauss flask, which I really needed. I'm so grateful to Magnus, for his fruitful discussions and help with X-ray diffraction analysis. Unfortunately, I did not have time to carry out your gold work. I would also like to thank Klara for helping with NMR and high vacuum line.

Special thanks for the heterogeneous team at L14. Maitham, You inspired me! It was not easy for me to enter L14 after your graduation. The lab was so boring without your smile, your fruitful discussions, and motivation. Katya, thanks for your help and your sweet cake!. Sheetal, thanks for your support and your advice regarding the pregnancy of my wife. I really enjoyed work with all of you. I would also like to thank your collaborator, Payam, for the gifts he brought.

I'm so grateful to Alexy for nice discussions about science and life, sharing Knowledge, and proofreading my thesis. Hope our projects produce what we expect. I'm still optimistic regarding Mousa-Polukeev's catalyst ☺.

I would like to thank the former and the current members of OW's group: Sasha, Solomon, Nitish, Claudia, David, Dino, Rachael, Ruth #1, Irene, Fiona, Kristin, Saleh, Ali, Zarif, Volkan, Manoj, Yogesh, Cassandra, Nina, Sabitan, Roman, Josefine, Simon, Ruth #2 (done ☺).

Thanks to Michaela & Ghodsieh for helping me with my research.

I would like to thank Sven Lidin and his group members: Partha and Laura for helping with X-ray diffraction analysis.

Thanks to my co-supervisor Daniel Strand for helping me to update my PhD study plan smoothly and for his advice regarding the courses. I would also like to thank Kenneth for helping with this as well.

Thanks Karl-Erik for NMR discussions and table tennis games (I'm ready for the next game ☺).

Thanks Göran for helping with NMR experiments.

I would like to extend my appreciation to Bodil, Maria, and Katarina for facilitating administrative work, supplying chemicals and help with Klara system.

Thanks to all my colleagues and friends at CAS for the friendly atmosphere.

Special thanks for Said, Sami, Hafiz, Firas, Fiona, Mujtaba, Juliao, Mukul, Om, Jingwen, Magdalena, Jacov, Sofia, and Anita for fika times.

I would like to express my gratitude to Paula for helping me to produce the current thesis in such nice and beautiful form. I appreciate the time you spent and your patience.

Thanks to the Swedish Research Council, the Knut and Alice Wallenberg Foundation, and the Royal Physiographic Society in Lund for financial support.

I'm so grateful to Mohammed Reda and Mohammed Hagers for giving me the chance to continue my studies through the summer job I got during my master studies.

I would like to express my gratitude to the Egyptian friends at Lund: M. Abdellah (Welcome back), A. Fawzy, H. El-taliawy, W. Mobarak, M. Sayed (good luck with your parallel PhD defense), A. Mohsen, W. Awad, M. Fekry, A. Shokry (Welcome back), M. Elsokry, Hossam, Elsaid Younes, T. Dishisha, M. Ibrahim, M. Hamed, Islam, Abdo, Omar, Amr, Adel, Ali, Moataz ….

I'm so grateful to Eng. Kamal Elkazzaz who convinced my dad to let me travel abroad and complete my study.

My father, I wish that you were still alive. I miss you so much.

My mother, whatever I write to express my gratitude is nothing compared to your love and prayers.

I would like to thank my brothers and sisters for their support and help throughout my life. Special thanks for my brother Mohammed for his continuous support, encouragement, and prayers.

My lovely wife, Aya, without your support, patience, and love this would not have been possible. Now, I can stay at home during the weekend and take care of our lilla Sara ☺.

Popular Summary

Using transition metals in organic synthesis has led to the discovery of new reactions. These novel reactions have enabled different valuable transformations to take place through short synthetic routes and most importantly using a small amount of the metal. This small amount is called a catalytic amount and the metal which is in the form of a complex (with an array of groups of atoms bonded to the metal, so called ligands) is then known as a catalyst. Transition metal complexes have been extensively employed as catalysts to mediate many transformations. These transformations provide our society with useful things, e.g. pharmaceuticals to treat diseases for example cancer, killing a lot of people around the world, clean fuels to protect our planet from pollution and solar cells to provide a clean source of energy. All these useful things start in a small scale at laboratories in universities and companies and are then applied on a large scale in industry.

In general, an organometallic catalyst can be divided into two parts, the metal center and the surrounding inorganic or organic molecule or atom, the ligand. The ligand is responsible for tuning the electronic and steric properties of the catalyst. Changing the donor atoms of the ligand scaffolds greatly influences the catalytic activity. Different types of ligands have been used in combination with a variety of transition metals in order to prepare new catalysts. Palladium and nickel have gained a lot of interest in this respect. Also, monodentate and bidentate ligands (with one and two binding atoms, respectively) have been extensively employed with these metals because most of them are commercially available and easily accessible. However, these ligands do not always give stable complexes, which result in decomposition affecting the outcome of the catalytic process. This problem induced chemists to develop new type of ligands having a more robust interaction with the metal in a tridentate fashion (with three binding atoms). Indeed, complexes supported by tridentate ligands displayed unique reactivities compared to those including other ligands.

In the current thesis, we have designed and synthesized new palladium and nickel complexes containing tridentate PCN ligands (with phosphorus, carbon and nitrogen binding to the metal). Our choice of palladium and nickel is in line with their successful and great applications in catalysis. We used the new complexes in the activation of CO_2 and formation of new molecules, which are relevant to pharmaceuticals. Using different donor atoms were found to be very important to enhance the catalytic activities of these complexes.

Abbreviations

PCP	1,3-[(di-t-butylphosphino)methyl]benzene and its derivatives
NCN	1,3-[(dialkylamino)methyl]benzene and its derivatives
CCC	bis(diisopropylphenyl-benzimidazol-2-ylidene)phenyl
Me	Methyl
Et	Ethyl
***t*-Bu**	*tert*-butyl
***i*-Pr**	isopropyl
Cy	Cyclohexyl
NBS	*N*-Bromosuccinimide
AIBN	2,2-Azobis(2-methylpropionitrile)
DIBAL-H	Diisobutylaluminum hydride
DME	Ethylene glycol dimethyl ether
TFA	Trifluoroacetate
Py	Pyridine
DMAP	4-(Dimethylamino)pyridine
TMEDA	*N,N,N',N'*-Tetramethylethylenediamine
THF	Tetrahydrofuran
DCM	Dichloromethane
MeCN	Acetonitrile
MeOH	Methanol
NMR	Nuclear Magnetic Resonance
EPR	Electron Paramagnetic Resonance
GC	Gas Chromatography

1. Introduction

1.1. Pincer Complexes

The pioneering work of Moulton and Shaw on the metallation of the tridentate PCP ligand (Figure 1.1) with transition metal precursors of Pd, Pt, Ni, Rh and Ir generated a new class of organometallic complexes, which van Koten later named as pincer complexes.[1, 2] Such kind of organometallic complexes have unique structures and reactivities. They have received great attention resulting in fast development of their chemistry and consequently became one of the most dominant in the field of organometallic chemistry. They have been extensively employed in catalysis covering a broad area of applications.[3-14]

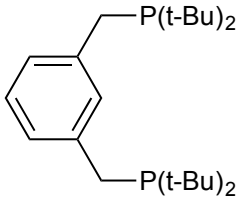


Figure 1.1. The first pincer ligand reported by Shaw.

The tridentate chelation of pincer ligands with the central metal produces two fused metallacycles sharing the bond between the central atom of the ligand (Y) and the metal center (M); M-Y bond (Figure 1.2). This strong chelation around the metal center provides high thermal stability and new reactivity for these complexes compared to other organometallic complexes. The name of the pincer ligand is derived from the three atoms chelating the metal, DYD in the general structure shown below. If spacer atoms (E) are incorporated in the ligand scaffold, the name expands to include these atoms as well and becomes DEYED, e.g. POCOP.[3, 5, 7]

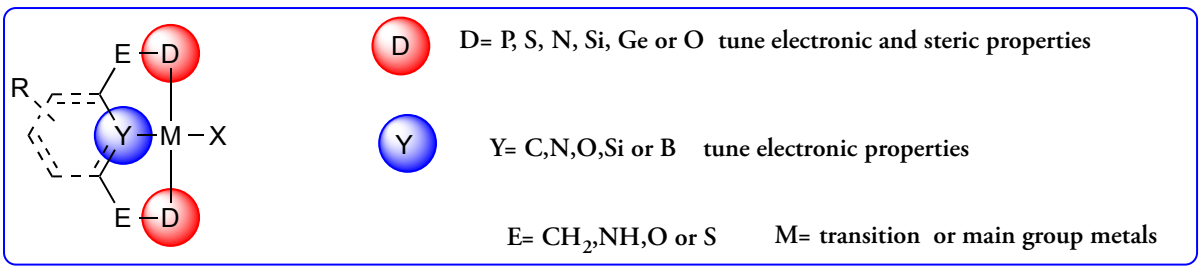


Figure 1.2. General structure for pincer complexes.

Changing the substituents on the side arms of the ligand architecture as well the ligand backbone plays an important role in adjusting the steric and electronic properties. Based on this modification, different kinds of pincer ligands have been synthesized which can be classified into symmetrical ligands, e.g. PCP[1, 15-18], NCN[19, 20], PNP[21-23], POCOP[24-31], PSiP[32-35], SCS[36-38], NN_2 [39-42] and unsymmetrical ones, e.g. PCN[43-49], PCO[50, 51], POCN[52-59]. More structures are shown in Figure 1.3.

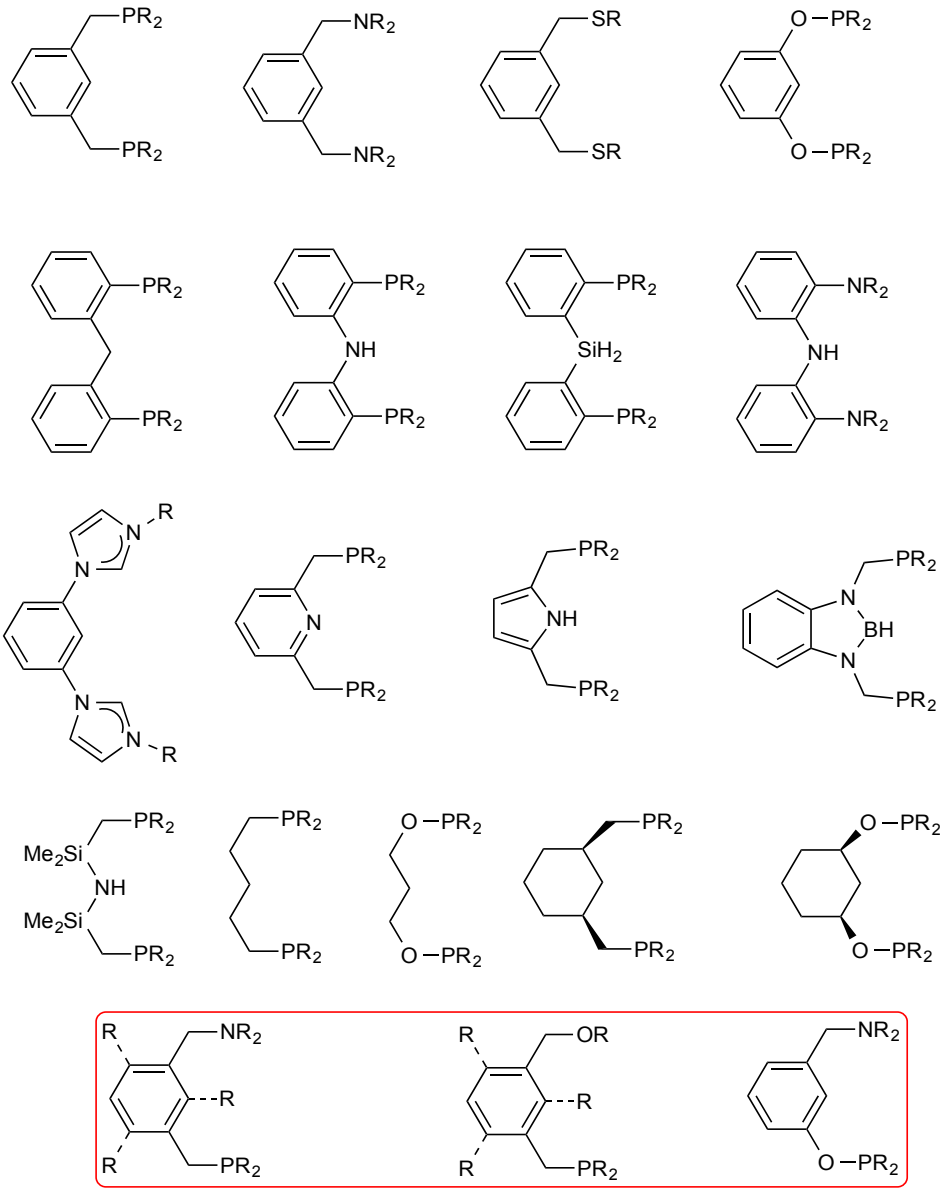
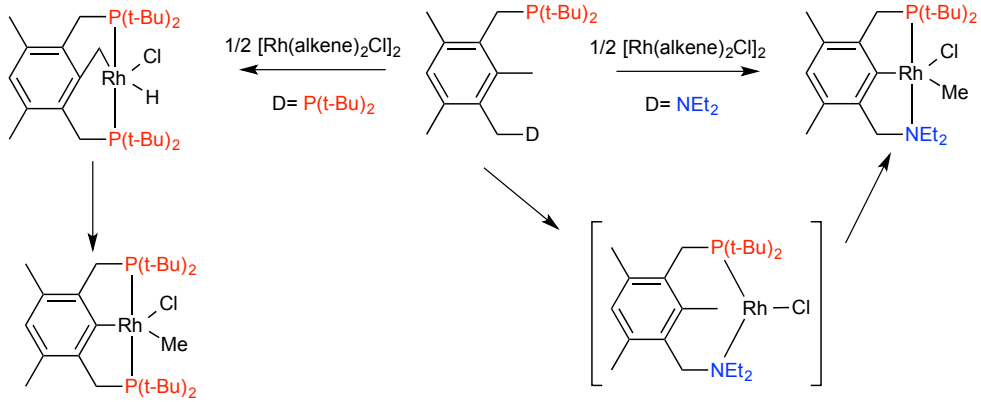


Figure 1.3. Different examples of pincer ligand structures.

Complexes based on symmetrical ligand structures are the most represented in the literature due to the short synthetic approaches used to prepare such type of complexes. On the other hand, complexes supported by unsymmetric pincer ligands are significantly less explored. Indeed, It was not until 1997 (more than 20 years after the first publication of Shaw) that the first example of unsymmetric pincer ligand, which includes mixed phosphine and amine side arms appeared in the literature.[43]

However, this unsymmetric ligand displayed a different reactivity compared to the symmetric PCP pincer ligand (Scheme 1.1). It enabled selective activation of the strong C_{sp2}-C_{sp3} bond upon metallation to a Rh(I) precursor. This unique reactivity for the PCN ligand was attributed to the small steric hindrance of the nitrogen side arm, which reduces the activation barrier of the C_{sp2}-C_{sp3} bond by allowing the Rh center to be directed closer to the C_{sp2}-C_{sp3} bond. In addition to this steric factor, the electronic effect should be considered as well since two different donor atoms are present on the side arms of the PCN ligand.[43, 60]



Scheme 1.1. C-C vs C-H bond activation.

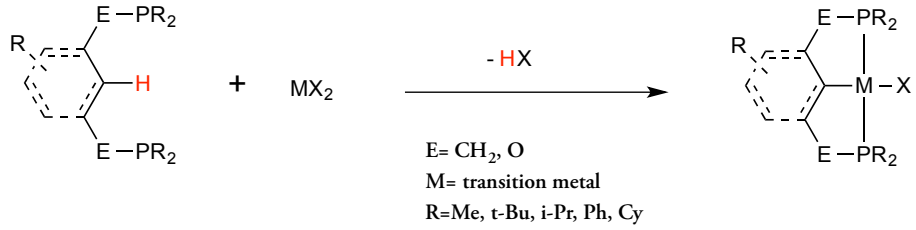
1.2. General Methods for Synthesis of Pincer Complexes

Different synthetic methods have been used to cyclometallate the pincer ligands with transition metal precursors.[3, 7, 61, 62] The donor atoms of the ligand scaffold together with the metal precursor determine the appropriate synthetic method in order to accomplish successful cyclometallation. These synthetic methods can be categorized as the following:

1.2.1. Direct Cyclometallation through C-H Bond Activation

Direct cyclometallation through C-H bond activation is the most common method, and it was first used by Shaw to cyclometallate the PCP ligand with a variety of late transition metal precursors e.g. Ni, Pd, Pt, Rh, and Ir producing the corresponding PCP pincer complexes.[1] Steric and electronic properties of the substituents on the phosphorus donor atoms affect the cyclometallation process as it was later observed that cyclometallation of the less sterically hindered and weakly electron withdrawing PCP^{Ph} pincer ligand happened under milder reaction conditions compared to the more bulky and electron donating $PCP^{t\text{-}Bu}$ pincer ligand.[16] It is believed that initial bidentate coordination of the phosphorus side arms of the pincer ligand with the

metal precursor takes place at the beginning to facilitate the intramolecular C-H bond activation and hence, achieve the cyclometallation.

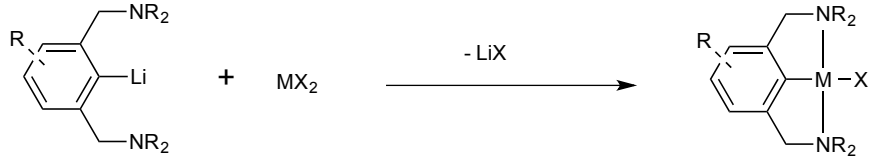


Scheme 1.2. Synthesis of pincer complexes through direct C-H activation.

The method is tolerant of different substituents on the phosphorus donor atoms, e.g. Me[15], i-Pr[17, 60, 63], Cy[64, 65](Scheme 1.2). Shaw also followed the same strategy to cyclopalladate the $SCS^{t\text{-}Bu}$ ligand, but in contrast to the PCP ligand, this method is not suitable for small substituents on the sulfur donor atoms, e.g. Me where extremely low yield was obtained in this case (< 10 %).[36, 37]

1.2.2. Transmetallation

Transmetallation was applied by van Koten to cyclometallate the NCN ligand where the direct cyclometallation is not favorable due to the weak interaction between the hard nitrogen atom and the metal center compared to the phosphorus one, which is considered as an important step to facilitate the C-H bond activation. Functionalization of the ligand precursors is required before the transmetallation takes place.[19, 20] Lithiation is the most common functionalization method used for this purpose and has been reported earlier by van Koten to prepare the NCN pincer complexes. Recently, the transmetallation method has been used to prepare the NN_2 pincer complexes.[39, 40]

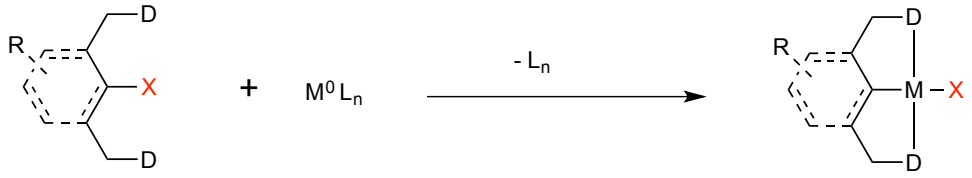


Scheme 1.3. Synthesis of pincer complexes through transmetallation.

1.2.3. Oxidative Addition

Carbon–halogen bond containing pincer ligands can be added to a low valent metal precursor resulting in oxidation of the metal center and formation of an M-halogen bond (Scheme 1.4).[66, 67] The method has been extended recently to include direct N-H or C-H oxidative addition of the pincer ligand to zero valent metal precursors subsequently forming the corresponding hydride complexes.[68-70] It is considered as a direct and clean method for synthesis of pincer hydride complexes which are

commonly prepared by metathesis reaction of pincer halide complexes with hydride sources, e.g. $NaBH_4$, $LiAlH_4$; in some cases, super hydride reagents, e.g. $LiEt_3BH$ are essential to carry out this transformation.[71]



X= Br, D= NR_2 (NCN), X=H,D=PR_2 (pyrrole based pincer ligand and PNP)

Scheme 1.4. Synthesis of pincer complexes through oxidative addition.

1.2.4. Transcyclometallation

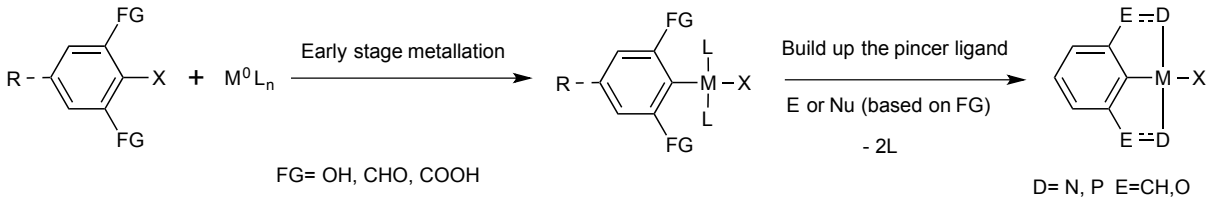
A cyclometallated ligand is replaced by stronger pincer ligand to form the desired pincer complex.[37, 72, 73] The initial work of transcyclometallation was published by Dupont and involved bidentate chelating ligands in the form of dimeric cyclometallated palladium complex. This novel synthetic method enabled the formation of the SCS^{Me} pincer palladium complex in 97 % yield compared to <10 % yield in case of using the direct C-H activation method described above.[37] Transition metal complexes based on NCN pincer ligand have shown to be suitable precursor for synthesis of the corresponding PCP pincer complexes through transcyclometallation method because the M-N bond is weak and easy to break (Scheme 1.5).[72, 73]

Scheme 1.5. Synthesis of pincer complexes through transcyclometallation.

1.2.5. Ligand Introduction Method

This novel method was developed by Uozumi initially to prepare chiral pincer palladium complexes bearing bulky pyrroloimidazolone side arms where the direct cyclometallation through C-H bond activation was unsuccessful in this case reflecting its synthetic limitation as already mentioned above.[74] The method involves an early stage reaction of a palladium (0) precursor with a functionalized aromatic ring to produce a palladium (II) complex through an oxidative addition reaction. Then the new complex reacts with an electrophile or nucleophile based on the nature of the functional groups in the 2-and 6-positions of the aromatic ring to build up the pincer scaffold and offer the desired pincer palladium complex (Scheme 1.6).[61, 62, 75] Using

this new synthetic approach allowed to prepare a wide variety of bulky NCN and POCOP pincer palladium complexes in high yields.[61, 62, 74]



Scheme 1.6. Synthesis of pincer complexes through ligand introduction method.

Frech introduced an elegant strategy to apply the ligand introduction method by using a Pd(II) precursor bearing two ligands of tri(piperidinyl)phosphine where piperidine serves as an internal base to facilitate the build up step of the pincer ligand after direct C-H palladation of resorcinol or 1,3-diaminobenzene.[76]

All the complexes included in the current thesis were obtained through the direct C-H bond activation method under mild reaction conditions. Incorporation of pyridine as the nitrogen side arm of the PCN ligand enabled room temperature cyclometallation process.

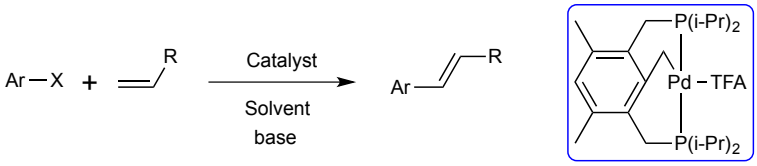
1.3. Application of Pincer Complexes in Catalysis

Transition metal pincer complexes have been used as catalysts to efficiently carry out different transformations both in organic and organometallic fields.[3-14, 77-80] Here we give some examples of the application of palladium and nickel pincer complexes in catalysis as it is relevant to the current thesis.

1.3.1. Palladium Pincer Complexes

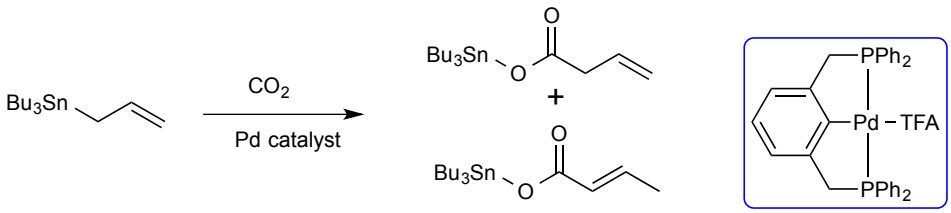
One of the most common applications of palladium complexes is cross coupling reactions.[81-87] Such type of reactions run under harsh reaction conditions, which are compatible with the high thermal stability of pincer complexes.[3-5, 7, 77, 79] Milstein found that $PCP^{i\text{-}Pr}$ pincer palladium complexes are efficient catalysts for Heck coupling reaction, particularly, the complex with central aliphatic carbon atom (Scheme 1.7). [88] This contribution established the first application of pincer palladium complexes in the area of cross coupling reactions. A catalytic cycle including Pd(II)/Pd(IV) was suggested based on the control experiments which rule out the participation of Pd(0) species in the mechanism. The high thermal stability of the catalyst under the harsh reaction conditions supported the suggested mechanism. Two years later, more efficient palladium catalyst having phosphinite pincer ligand was published by Shibasaki.[89] Inspired by these results, a large number of publications

have been reported covering this type of reaction, which helped to tune the catalytic activity and to provide more insight about the mechanism.[5, 7] The application of pincer palladium complexes extended further to include other cross coupling reactions, e.g. Suzuki-Miyaura, Stille and Sonogashira.[3-5, 7, 9, 13, 14, 77, 79]



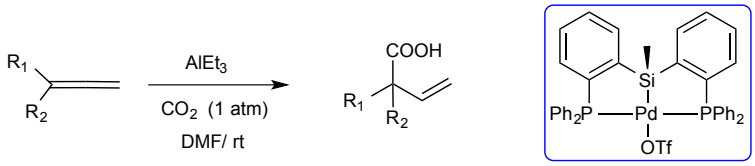
Scheme 1.7. Heck coupling reaction using PCP pincer palladium complex.

Another interesting research area where pincer palladium complexes have been employed is the stoichiometric and catalytic activation of CO_2.[90-97] Using PCP palladium complexes in the catalytic carboxylation of allyl stannanes offered only one regio isomer product compared to two isomers in case of $Pd(PPh_3)_4$ system (Scheme 1.8). The difference in the reaction outcomes was explained on the basis of the reaction mechanism. Low CO_2 pressure (4 atm) was used when pincer complex was employed as a catalyst.[91, 98]



Scheme 1.8. Catalytic carboxylation of allyl stannanes.

Catalytic hydrocarboxylation of allenes to the corresponding β,γ-unsaturated carboxylic acids was successfully achieved at room temperature (Scheme 1.9) using a PSiP palladium pincer complex. Iwasawa suggested a preliminary catalytic cycle including a PSiP palladium hydride complex formed *in situ* as a result of the transmetallation reaction of the OTf palladium complex with $AlEt_3$ to initially generate the pincer palladium ethyl complex which under fast β-hydride elimination offers the corresponding hydride complex. Insertion of allene to the hydride complex produces the allyl palladium complex. The latter, in a carboxylation reaction, produces β,γ-unsaturated carboxylate palladium complex which upon transmetallation with $AlEt_3$ gives β,γ-unsaturated carboxylate aluminum salt and regenerates the palladium hydride complex.[92]

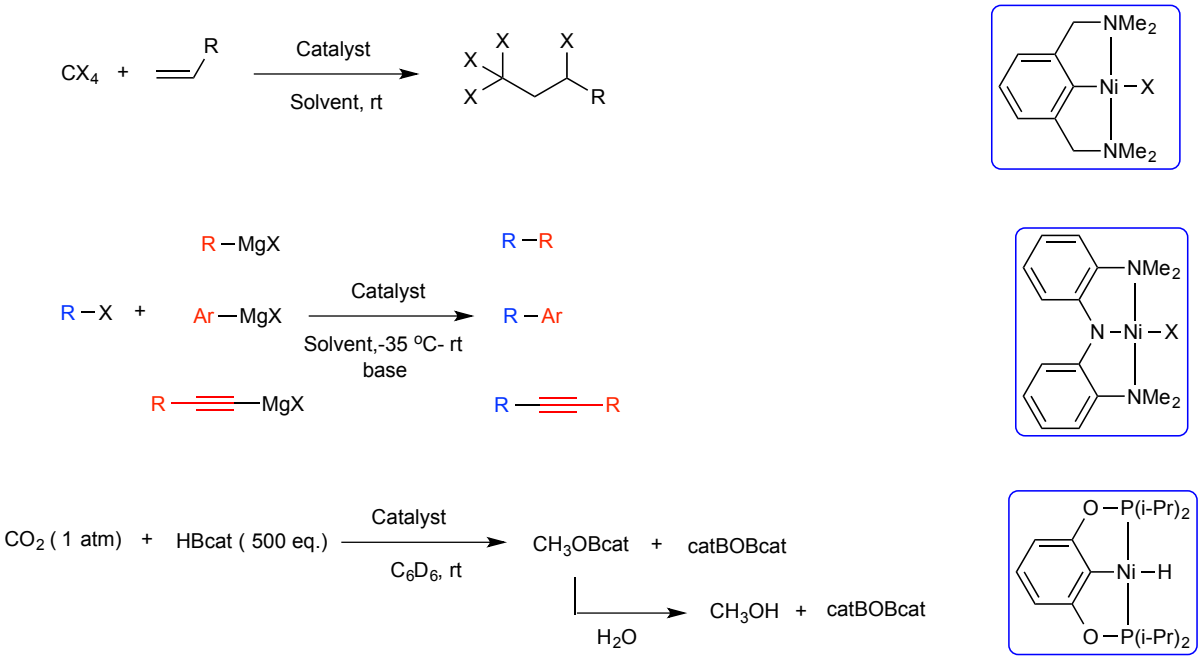


Scheme 1.9. Catalytic hydrocarboxylation of allenes.

More details about the mechanism supported by experimental evidence was published later by Hazari. He also found that $AlEt_3$ is crucial to achieve the hydrocarboxylation reaction and using pinacolborane HB(pin) as a reducing agent in the catalytic reactions did not produce the hydrocarboxylated product, but instead, hydroboration of CO_2 was observed. This led to the development of catalytic hydroboration of CO_2 using PSiP pincer palladium hydride complex as catalyst.[97]

1.3.2. Nickel Pincer Complexes

The NCN nickel pincer complexes reported by van Koten are considered the most efficient catalysts for Kharasch addition reaction of polyhalogenated hydrocarbons to olefins (Scheme 1.10). Using these complexes allowed for the formation of the 1:1 anti-Markovnikov adduct at room temperature within a short time.[99-101]



Scheme 1.10. Examples of nickel pincer complexes in catalysis.

As an alternative to the precious palladium catalysts, there is a great interest to apply earth abundant and inexpensive complexes in cross coupling reactions. Thus, nickel catalyzed cross coupling reactions have been developed.[102-105] In this regard, different types of nickel pincer complexes have been synthesized and their catalytic activities in cross coupling reactions specifically Kumada coupling reaction have been investigated. Among these complexes, the NN_2 pincer nickel complex (Nickamine) reported by Hu is known as an efficient catalyst mediating cross coupling reactions of different types of alkyl halides with Grignard reagents.[40-42, 106-114]

Another important application of nickel pincer complexes is the reduction of carbon dioxide to methanol using POCOP nickel pincer complexes developed by Guan.[115, 116] Nickel pincer complexes also have been used as catalysts for the reduction of carbonyl compounds.[71, 117-119]

1.4. Aim of the Thesis

(i) **Synthesis** of new unsymmetric aromatic PCN pincer ligands and study of their cyclometallation reactions with palladium and nickel precursors aiming to discover new reactivity patterns for these catalytically relevant metals through the difference in steric and electronic properties of the two different side arms of the PCN ligand.

(ii) **Study** of the catalytic activity of the new complexes in C-C bond formation reactions, e.g. decarboxylative cross coupling reaction for the PCN palladium pincer complexes, Kharasch addition and Kumada coupling reaction for the PCN nickel pincer complexes.

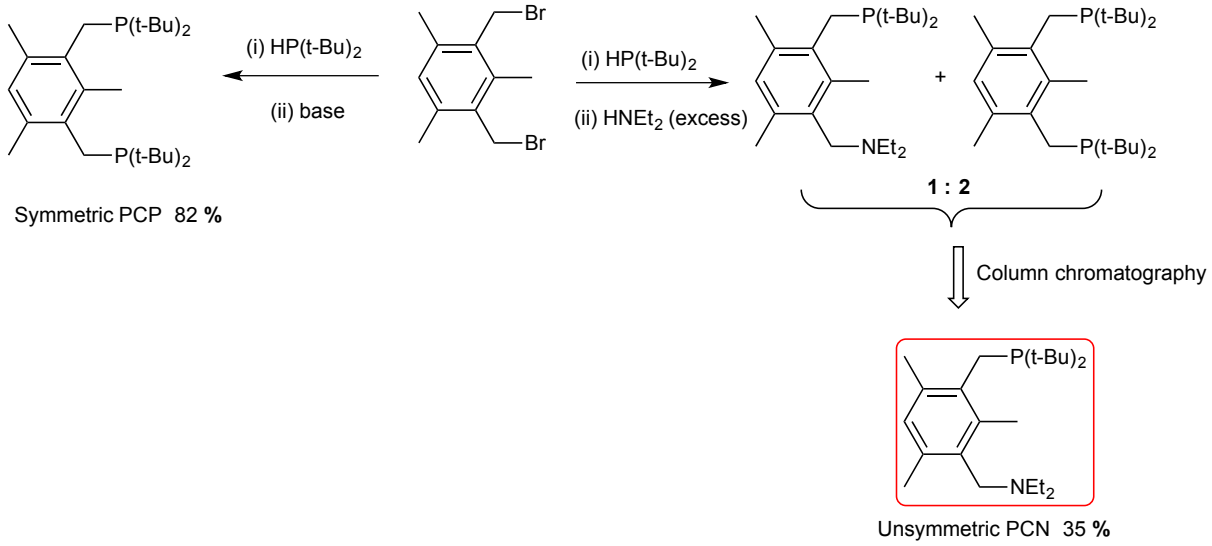
(iii) **Investigation** of the reactivity of the new complexes towards small molecules, e.g. CO_2.

(iv) **Development** of short synthetic route to prepare unsymmetric PCN pincer nickel complexes in order to provide an easy access to such complexes.

2. Unsymmetric PCN Pincer Ligands: Synthesis and Cyclometallation Reactions (Papers I-V)

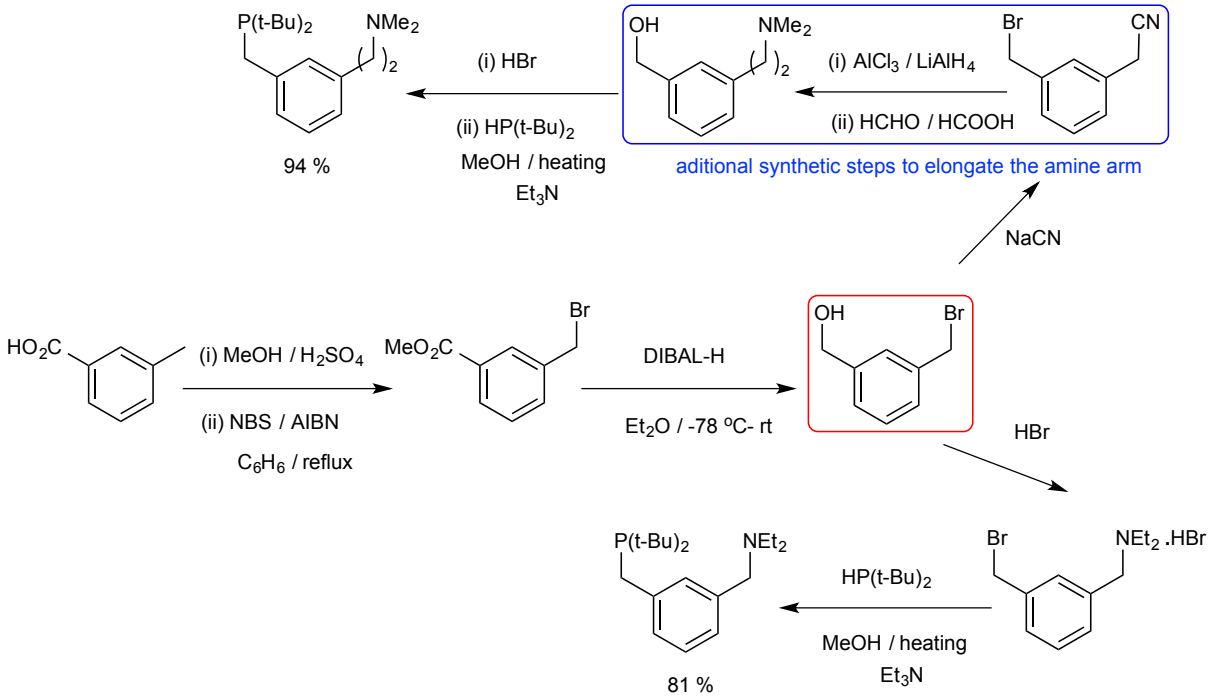
2.1. Introduction

As pointed out in the previous chapter, complexes based on unsymmetric pincer ligands are not so common in the literature.[120] This is due to the relatively long synthetic methods required to construct the two different side arms of the pincer ligand. However, the first unsymmetric aromatic pincer ligand was synthesized using a short synthetic procedure based on the same synthetic strategy employed to prepare the symmetric PCP ligand.[43, 60] Diethylamine was used to install the nitrogen donor arm of the ligand through a nucleophilic substitution reaction with the monophosphonium salt formed after the phosphination step and it also served as base to deprotonate the phosphonium salts. A low yield was obtained as a result of the concomitant formation of the symmetric PCP ligand (Scheme 2.1). The desired PCN ligand was successfully isolated using column chromatography. Despite the synthetic challenge, the unsymmetric PCN ligand offered superior reactivity compared to the symmetric PCP ligand as a model for activation of strong bonds.[43, 121, 122]



Scheme 2.1. Synthesis of unsymmetric PCN pincer ligand using the same synthetic strategy used for PCP ligand.

Later, Milstein developed a new synthetic approach to prepare the unsubstituted PCN ligand with a long amine arm (bearing two methylene groups as linker between the aromatic ring and the nitrogen donor atom). The new synthetic approach involved additional synthetic steps compared to the previously described one. However, these synthetic steps were required to prepare an unsymmetric ligand precursor in order to facilitate the introduction of the amine and phosphine donors and to avoid the contamination with the symmetric PCP pincer ligand. Furthermore, some of the synthetic steps were used to elongate the amine arm which are not necessary in case of using normal amine arm as it was reported later by the same group (Scheme 2.2). The new synthetic strategy allowed exclusive formation of the PCN ligands and achieved high yields.[44, 45]



Scheme 2.2. New synthetic approach to prepare unsymmetric PCN pincer ligands.

Elongation of the amine arm not only enhanced the hemilabile character of the PCN ligand, but also enabled formation of anionic dialkyl, diaryl, dihydride and alkyl hydride platinum complexes.[44, 123] These complexes displayed remarkable stability. Indeed, the anionic dihydride complex was isolated and characterized by X-ray crystallography. Switching back to the tridentate chelation of the PCN ligand can be achieved through the reaction of the anionic platinum complexes with electrophiles. Although hemilability of the long amine arm PCN ligand is crucial to stabilize the anionic complexes, other cases showed that hemilability can accelerate the decomposition of the unsymmetric pincer complexes.[45]

Despite the novel and the unique reactivities displayed by the unsymmetric PCN pincer complexes, such type of complexes were limited to Rh and Pt before this work.[43-45, 50, 123-129] There are many catalytic applications where these metals are not the

first choice. Therefore, it would be beneficial to incorporate unsymmetric PCN ligands with other catalytically relevant metals, e.g. Pd and Ni. In this respect, we were interested in designing new unsymmetric PCN ligands and studying their complexation reactions with palladium and nickel precursors to explore their chemistry and study their reactivities in stoichiometric and catalytic reactions.

The mixed PCN ligands are expected to combine the advantages displayed by both PCP and NCN pincer ligands which have been extensively studied (Figure 2.1). The presence of a phosphorus atom is useful to follow the reactions *in situ* using ^{31}P NMR spectroscopy to provide more details about any reactive intermediates which could be relevant to mechanistic studies. Furthermore, using bulky and electron donating substituents on the phosphorus donor atom can stabilize the new complexes against dimerization and decomposition as it was previously observed for the more electron deficient POCN complexes.[53]

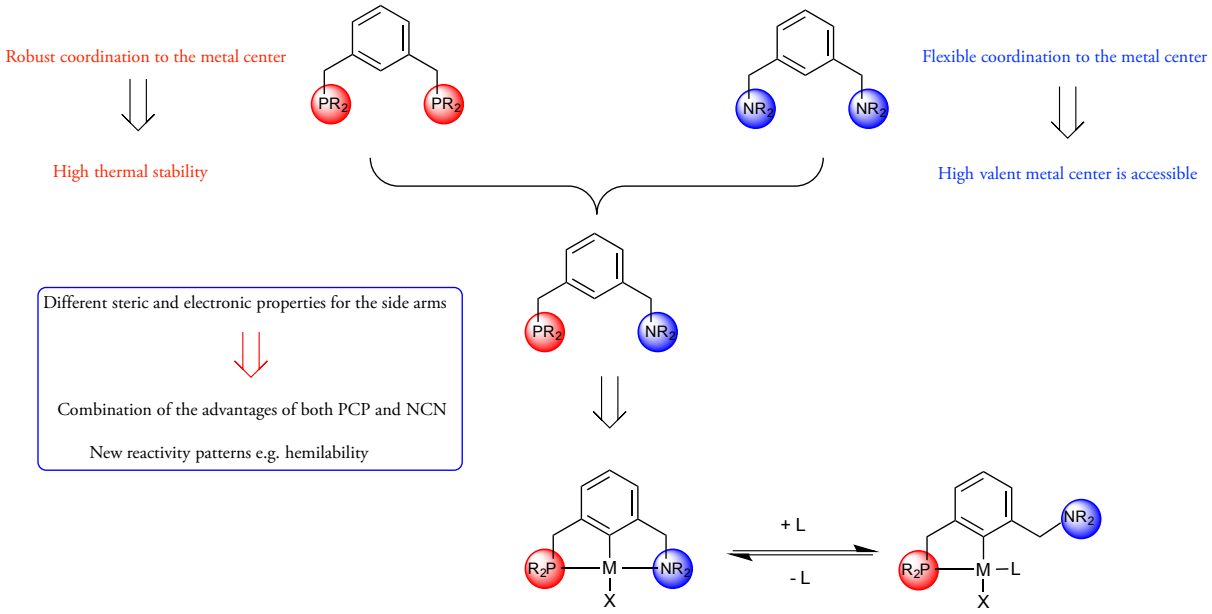
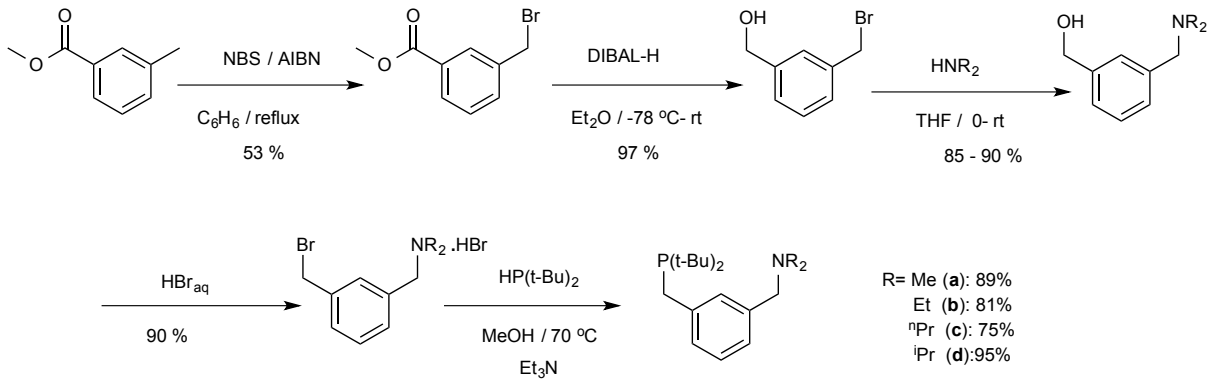


Figure 2.1. Symmetric PCP and NCN ligands against PCN ligand.

2.2. Synthesis of $^{t\text{-Bu}}$PCN^{R} Ligands

The synthesis of the new PCN ligands (**a-d**) was carried out according to the published procedures for the aforementioned $^{t\text{-Bu}}$PCN^{Et} ligand with a slight modification.[45] In general, the synthetic protocol includes installation of the amine arm followed by incorporation of the phosphine arm. More details about the synthesis of the PCN ligands are described in Scheme 2.3. The synthesis starts by radical bromination of the commercially available substrate, methyl-m-toluate, using NBS as a brominating agent and AIBN as initiator to produce the bromo benzyl derivative. Reduction of the ester group using DIBAL-H as a reducing agent produces

3-(bromomethyl) benzyl alcohol. Nucleophilic substitution reaction with a secondary amine enables the construction of the amine arm. The last two steps of the PCN ligand synthesis involve two subsequent nucleophilic substitution reactions (bromination and phosphination) to introduce the phosphine arm.



Scheme 2.3. Synthesis of PCN pincer ligands (**a**-**d**).

The new PCN ligands were obtained in excellent yields as colourless viscous liquids and were characterized using ^{1}H, ^{31}P and ^{13}C NMR spectroscopy. We succeeded to get crystal structures for two of the hydrobromide salts used to prepare the PCN ligands **a** and **d** and their molecular structures are shown in Figure 2.2.

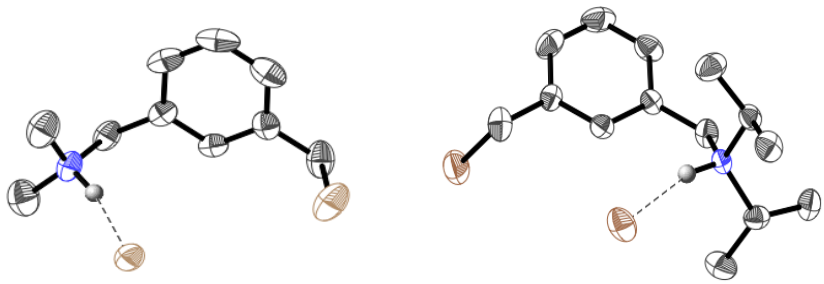
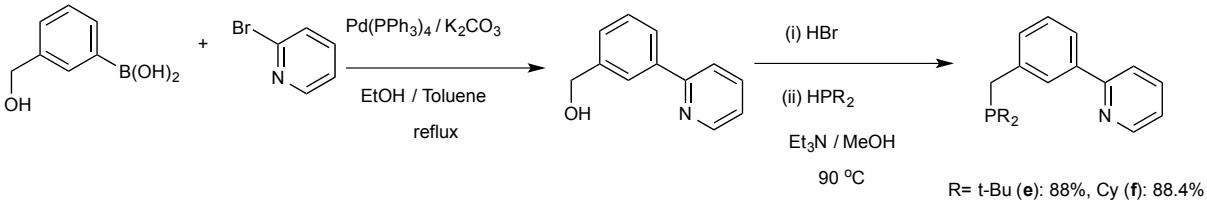


Figure 2.2. Molecular structures of the hydrobromide salts used to prepare PCN ligands (**a** and **d**).

2.3. Synthesis of $^{R}PCN^{Py}$ Ligands

Introduction of short synthetic methods to prepare unsymmetric pincer ligands is very important not only to give short access to such kind of relatively unexplored ligands to make them easily accessible but also for sustainability. Cross coupling reaction is the ideal choice to achieve this. In this regard, new $^{R}PCN^{Py}$ pincer ligands were synthesized through a straightforward synthetic approach using palladium catalyzed Suzuki coupling reaction. The nitrogen side arm, in this case, is readily available through one synthetic step.[130, 131]

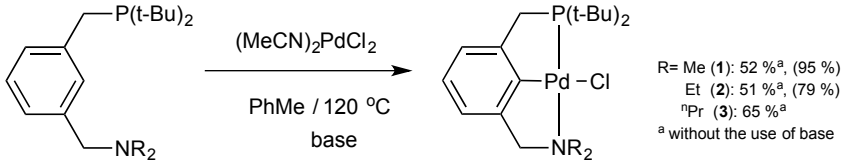


Scheme 2.4. Short synthetic route to prepare new PCN pincer ligands (**e** and **f**).

The new $^{R}PCN^{Py}$ ligands **e**[131] and **f** displayed a great difference in the ^{31}P chemical shift as a result of the difference in the electronic and steric properties of the tert-butyl and cyclohexyl groups.

2.4. Cyclometallation of $^{t\text{-}Bu}PCN^{R}$ Ligands with a Palladium Precursor

Cyclometallation of the PCN ligands (**a-c**) with $(MeCN)_2PdCl_2$ using the reaction conditions shown in Scheme 2.5 afforded the corresponding PCN palladium pincer complexes **1-3**. The yields of the new complexes were significantly enhanced in presence of base.



Scheme 2.5. Synthesis of PCN palladium pincer complexes**1-3.**

The tridentate chelation of the PCN ligands was initially established by NMR spectroscopy where the aromatic region for all the new complexes displayed only three integrated protons in the ^{1}H NMR spectra compared to four observed for their free PCN ligands.

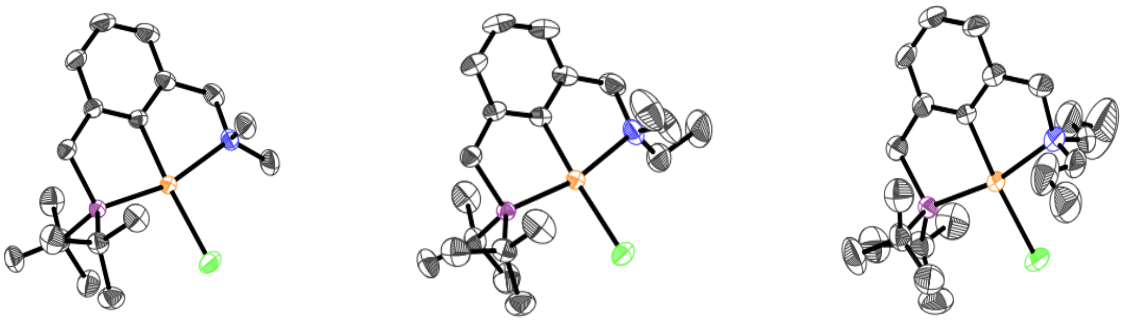
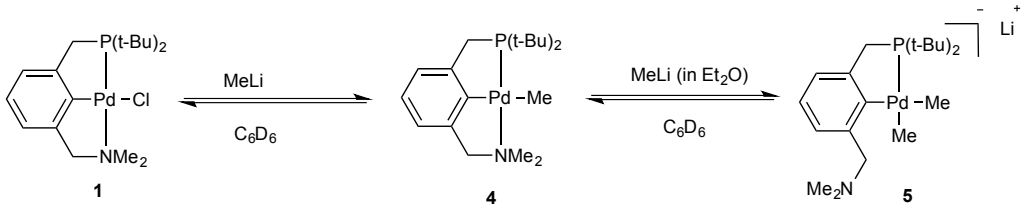


Figure 2.3. Molecular structures of PCN palladium complexes **1-3**.

There is a significant difference in the ^{31}P NMR chemical shift between complex **1**(δ= 93.8 ppm) and complexes **2** and **3** (δ= 90.8 and 91.0 ppm respectively). On the other hand, the difference between complexes **2** and **3** is small. The molecular structures of the new complexes were determined using X-ray diffraction and are shown in Figure 2.3.

2.5. Investigation the Hemilability Character of the PCN^{Me} Palladium Complex

We studied the reaction between the PCN^{Me} palladium complex **1** and MeLi as a strong nucleophile to investigate the hemilability of the amine arm (Scheme 2.6). Using C_6D_6 as a solvent enabled us to follow the progress of the reaction *in situ* using ^{1}H and ^{31}P NMR spectroscopy.



Scheme 2.6. Investigation of the hemilability character of complex **1**.

The ^{31}P NMR spectrum showed two signals upon addition of one equivalent of complex **1** to MeLi at 93.2 and 67.6 ppm and were assigned to the expected methyl complex and the bidentate dimethyl one respectively. Equilibrium between the two complexes was established based on the observation that only one signal corresponding to the methyl complex was recorded after keeping the reaction for a longer time. Adding excess of the MeLi led to complete conversion to the dimethyl complex. Both complexes were characterized *in situ* and all the attempts to isolate them were unsuccessful. Interestingly, this study reflects that hemilability of the PCN ligand can be achieved without further elongation of the amine arm.

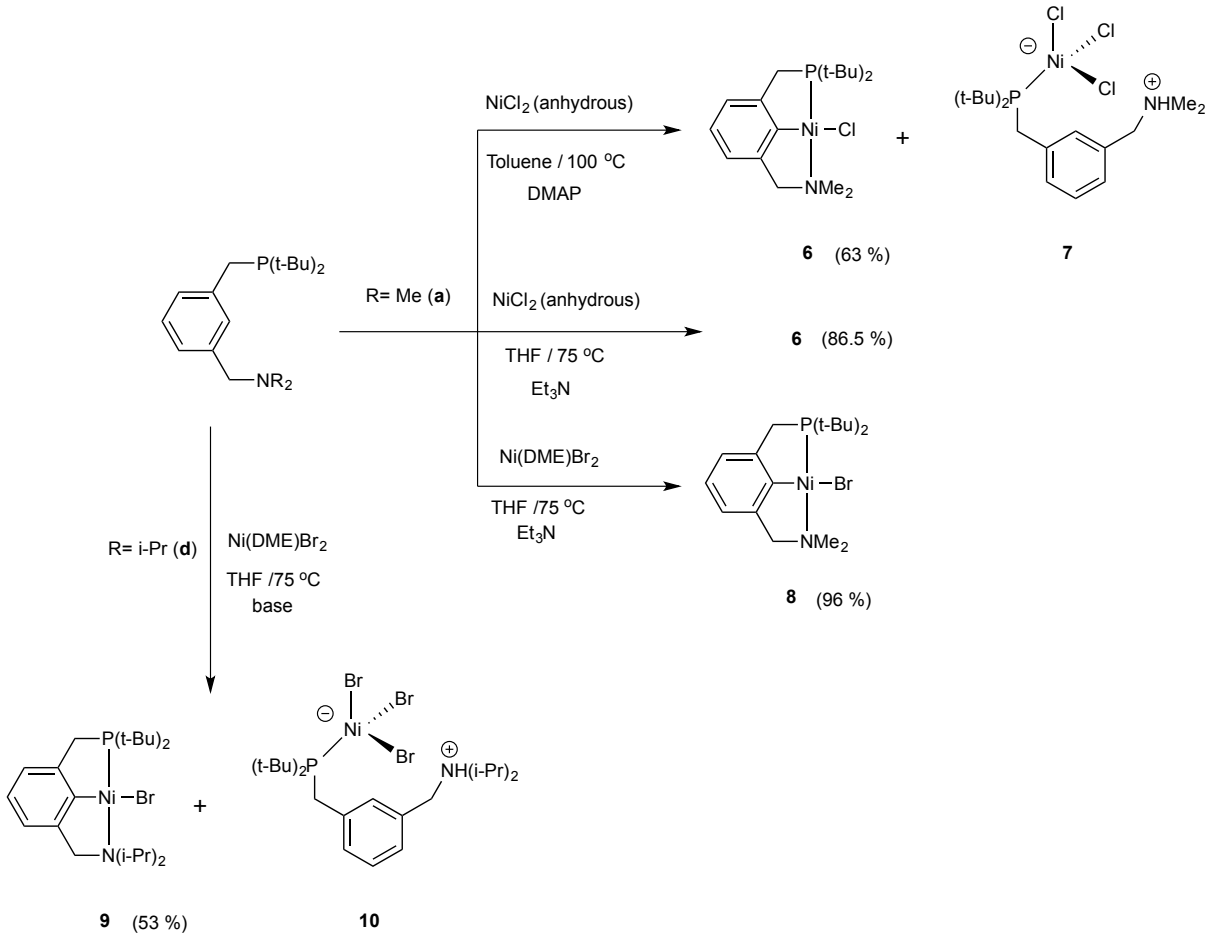
2.6. Nucleophilic Substitution Reaction with Iodide Ligand

The hemilability properties displayed by the amine arm of complex **1** encouraged us to study the nucleophilic substitution reaction of the chloride complexes **1-3** with sodium iodide as a weaker nucleophile aiming to find new mechanistic pathways for this reaction driven by hemilability. However, the kinetic experiments showed that

the solvent pathway is dominant over the direct one. The iodide complexes were synthesized and fully characterized by ^{1}H, ^{31}P, ^{13}C NMR spectroscopy, and X-ray diffraction.

2.7. Cyclometallation of PCN Ligands with Nickel Precursors

Reaction of the PCN ligand (**a**) with anhydrous $NiCl_2$ in toluene, as it is described in Scheme 2.7, produced the cyclometallated pincer complex **5** in 63 % yield. The moderate yield is due to the formation of a paramagnetic complex.



Scheme 2.7. Complexation of PCN ligands (**a** and **d**) with nickel precursors.

The identity of this paramagnetic complex was established by X-ray diffraction as a tetrahedral nickel complex incorporating the PCN ligand as a monodentate ligand (Figure 2.4). Further optimization of the reaction conditions involved the use of THF and Et_3N. This allowed the cyclometallation to take place under milder reaction

condition without formation of side products and achieved an 86.5 % yield of the desired pincer complex. Using (DME)$NiBr_2$ as nickel precursor offered the PCN nickel bromide complex **8** in 96 % yield.

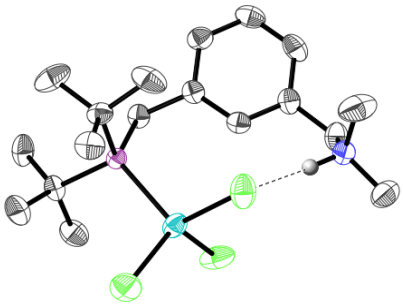


Figure 2.4. Molecular structures of the paramagnetic complex 7.

The new PCN nickel halide pincer complexes **6** and **8** were characterized by ^{1}H, ^{31}P, and ^{13}C NMR spectroscopy. Their molecular structures were confirmed by X-ray diffraction analysis (Figure 2.5). The purity of the new complexes was established by CHN analysis.

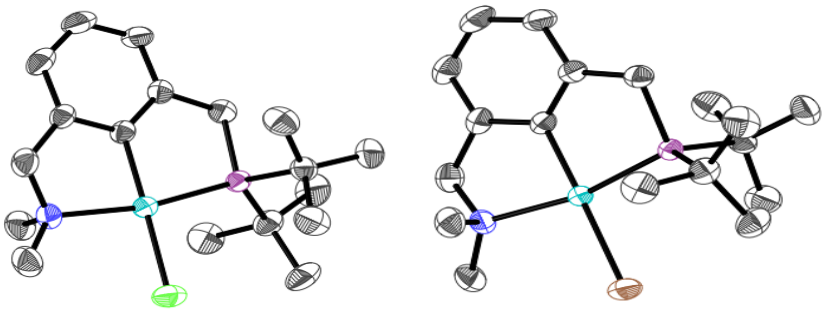


Figure 2.5. Molecular structures of PCN nickel halide complexes **6** and **8**.

In contrast to the PCN^{Me} ligand, the cyclometallation of the more electron donating and the sterically hindered $PCN^{i\text{-}Pr}$ ligand did not proceed smoothly. Moderate yield of the desired pincer complex was obtained in this case and using different bases, e.g. Et_3N, Et_2(i-Pr)N, K_2CO_3 did not improve the yield. The difference in the solubility between the two products enabled their separation. Complex **9** was obtained in pure form as it was confirmed by CHN analysis but the paramagnetic complex **10** was contaminated by the *in situ* generated salt. Both of the complexes offered single crystals suitable for X-ray diffraction analysis, which gave more insight about the geometry around nickel as it is shown in Figure 2.6. Attempt to convert complex **10** to the cyclometallated pincer complex **9** using DBU as a base was not successful and led to decomposition.

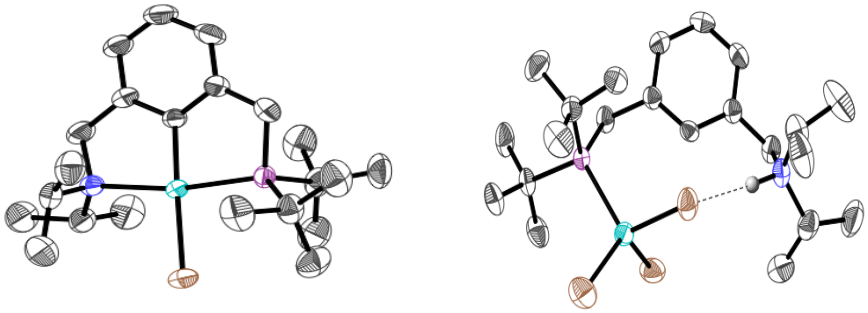
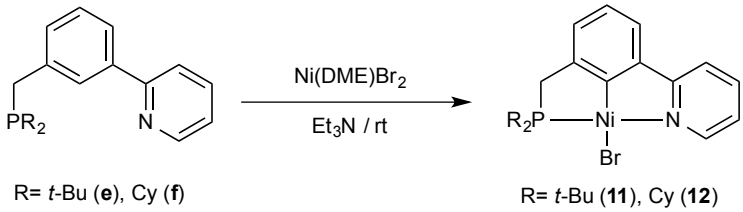


Figure 2.6. Molecular structures of nickel complexes **9** and **10**.

Cyclometallation of ligand (**e**) with (DME)$NiBr_2$ exclusively produced complex **11** at room temperature (Scheme 2.8). Similarly, the reaction of ligand (**f**) with the same nickel precursor gave complex **12**. The facile cyclometallation reactions can attribute to the strong coordination of the pyridine side arm to the nickel center compared to the previously discussed examples based on other nitrogen substituents.



Scheme 2.8. Synthesis of PCN nickel hydrocarbyl complexes.

Although facile cyclometallation of ligands **e** and **f** was achieved regardless of the substituents on the phosphorous donor, these substituents have great influence on the ^{31}P chemical shift.

The molecular structures of the complexes **11** and **12** were corroborated using X-ray diffraction (Figure 2.7).

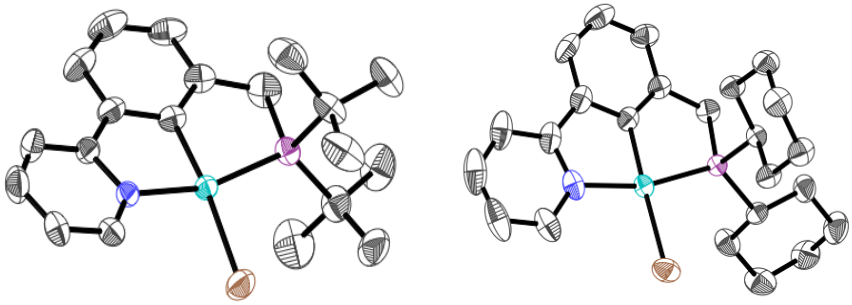
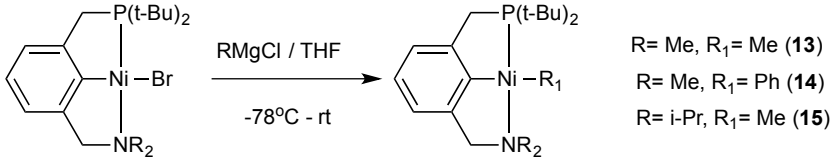


Figure 2.7. Molecular structures of nickel complexes **11** and **12**.

2.8. Reactivity towards Organometallic Reagents

Reaction of metal halide complexes with organometallic reagents, e.g. Grignard and organolithium reagents provides a straightforward synthetic approach to access the hydrocarbyl metal complexes. The hydrocarbyl metal complexes are important intermediates in cross coupling reactions and carboxylation reactions as well. The metal-carbon can be converted to other products. Surprisingly, there are no examples of unsymmetric aromatic pincer nickel hydrocarbyl complexes in the literature. Thus, we decided to prepare such kind of complexes and study their reactivity toward electrophiles which will be discussed later.



Scheme 2.9. Synthesis of PCN nickel hydrocarbyl complexes.

A small scale reaction of complex **8** with MeLi was carried out in a J. Young NMR tube. The reaction was monitored *in situ* using ^{31}P and ^{1}H NMR spectroscopy which confirmed the formation of the methyl complex as a single product. This result reflects the strong coordination of the amine arm to the nickel in contrast to the palladium system which displayed hemilability character and offered the anionic dimethyl PCN palladium complex. Unsuccessful isolation of the methyl complex led us to use MeMgCl instead, and in this case, the methyl complex was isolated and recrystallized from n-hexane. Single crystals suitable for X-ray diffraction experiment established its molecular structure as displayed in Figure 2.8.

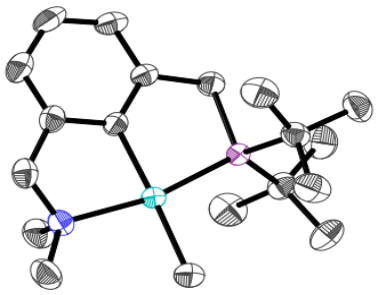


Figure 2.8. Molecular structure of complex **13**.

Similarly, the phenyl complex based on the same ligand and the methyl complex based on $PCN^{i\text{-}Pr}$ ligand were prepared. All the hydrocarbyl complexes are stable in the solid state.

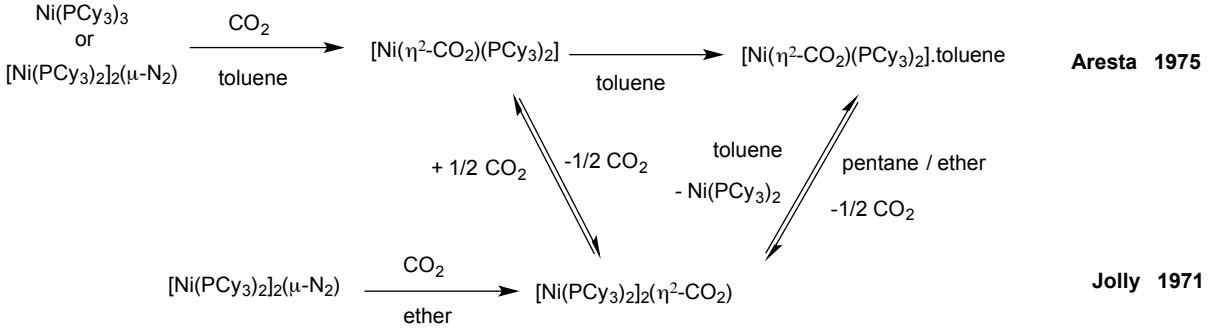
2.9. Conclusion

New unsymmetric PCN pincer ligands bearing different substituents on the nitrogen donor atom were synthesized, and their cyclometallation reactions with palladium and nickel were investigated. Using base was found to be important in order to enhance the cyclometallation reactions. In the case of nickel, paramagnetic side products were isolated and characterized by X-ray crystallography as tetrahedral nickel species. Using pyridine as a nitrogen side arm of the PCN ligand not only enabled short synthetic route but also produced the corresponding nickel complexes at room temperature. Nucleophilic substitution reaction of PCN palladium and nickel halide complexes with MeLi was used to investigate the hemilability of the amine arm. The formation of the corresponding anionic dimethyl complex was confirmed by NMR spectroscopy only in the case of palladium indicating a low hemilability for the PCN nickel complex.

3. Carboxylation Reactions (Papers II-IV)

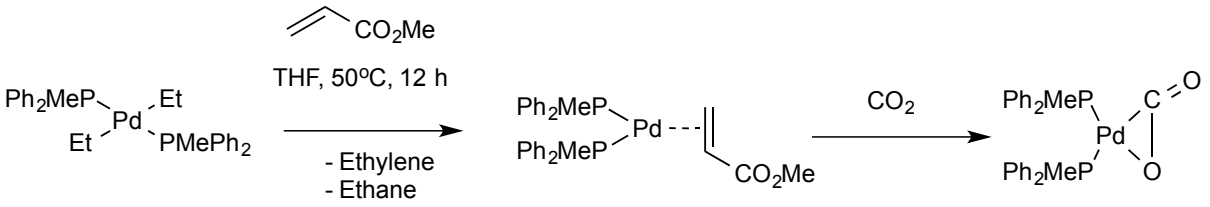
3.1. Introduction

Using inexpensive, abundant and non-toxic substrates to carry out important chemical transformations represents a key step towards sustainability. CO_2 has all these features, but it is a thermodynamically stable and kinetically inert molecule. One strategy to activate CO_2 is to use transition metal complexes. Earlier work included direct interaction of CO_2 with the metal center as a way to activate CO_2. This method is facilitated by using a weakly coordinated ligand to the metal center, typically N_2. In 1971, Jolly demonstrated that evaporating a toluene solution of the structurally characterized $[(PCy_3)_2Ni]_2(\mu\text{-}N_2)$ complex followed by dissolving it in ether and passing CO_2 into the resulting solution offered the dimeric $[(PCy_3)_2Ni]_2(\mu\text{-}CO_2)$ complex. However, the identity of this complex was suggested only based on the elemental analysis, IR-Spectroscopy and CO_2 displacement reactions.[132] Later, Aresta found that using the same complex or $Ni(PCy_3)_3$ gives a monomeric nickel complex upon reaction with CO_2. The structure of the resulting complex was confirmed using X-ray diffraction as $(PCy_3)_2Ni(\eta^2\text{-}CO_2)$.toluene.[133] Jolly investigated the reaction again where he published a comprehensive study showing the dynamic relation between the monomeric Aresta's complex and the dimeric one suggested during his initial work (Scheme 3.1). Furthermore, the crystal structure of the solvent-free monomeric complex was obtained through recrystallization of the dimeric complex from ether under a CO_2 atmosphere.[134]



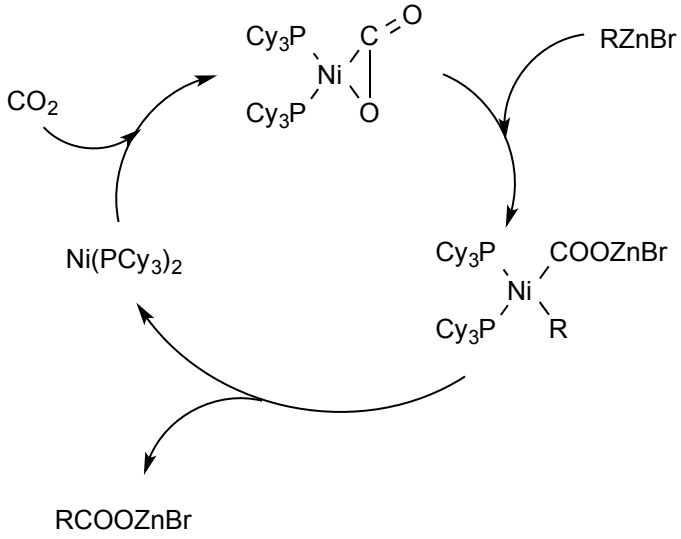
Scheme 3.1. Activation of CO_2 using nickel complexes.

The η^2 coordination mode of CO_2 is not limited to the nickel complexes of PCy_3 ligands. Nickel complexes including other alkyl phosphine ligands, e.g. n-Bu, Et displayed the same behavior.[135] Beck synthesized and structurally characterized the related $Ni(\eta^2\text{-}CO_2)(P(i\text{-}Pr)_3)_2$ complex.[136] The η^2 coordination of CO_2 extended further to involve nickel complexes supported by bidentate and tridentate phosphine ligands.[137-139] In contrast to the nickel complexes, the analogous $Pd(PCy_3)_2$ and $Pt(PCy_3)_2$ failed to offer the corresponding $M(\eta^2\text{-}CO_2)(PCy_3)_2$ complexes.[140] However, Yamamoto succeeded to prepare the $Pd(\eta^2\text{-}CO_2)(PMePh_2)_2$ complex using an alternative synthetic route based on a ligand substitution reaction (Scheme 3.2).[141]



Scheme 3.2. Synthesis of $Pd(\eta^2\text{-}CO_2)(PMePh_2)_2$ complex.

All the above-mentioned studies focused mainly on understanding the nature of the coordination of CO_2 to the metal center and the structures of the resulting complexes. However, integration of Aresta's type complexes into valuable catalytic reactions to make use of CO_2 as C1 building block in organic synthesis was reported by Dong.[142] The study included catalytic carboxylation of aryl and alkylzinc reagents to form the corresponding carboxylic acids using nickel and palladium complexes. $Pd(OAc)_2$ with electron rich phosphine ligands e.g PCy_3, $P(t\text{-}Bu)_2Me$ catalyzed the carboxylation reactions with low catalyst loading (1 mol %). Using $[(PCy_3)_2Ni]_2(\mu\text{-}N_2)$ enabled the catalytic carboxylation of β -hydrogen containing alkylzinc reagents. The suggested catalytic cycle with Aresta's complex is shown below (Scheme 3.3).



Scheme 3.3. Catalytic carboxylation of organozinc compounds.

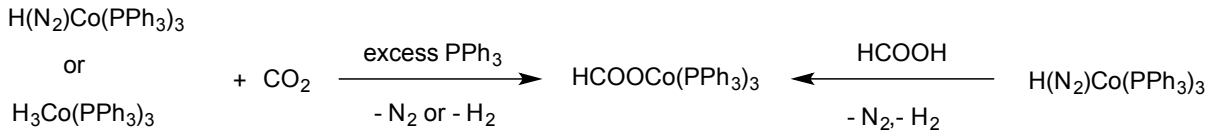
The first example of this reaction was published by Wendt where he reported the catalytic carboxylation of $ZnMe_2$ using PCP palladium pincer complexes as catalysts.[143] Other coordination modes of CO_2 to the transition metals are also reported. For example, Herskovitz published the $Rh(\eta^1\text{-}CO_2)Cl(diars)_2$ complex in which CO_2 adopts η^1 coordination mode through the carbon atom.[144] $Ru(\eta^1\text{-}CO_2)(bipy)_2CO$ reported by Tanaka displayed the same coordination mode.[145] All these examples include direct interaction of CO_2 with the metal center.

3.2. Insertion Reactions of CO_2 into M-L Bond

Insertion reactions of CO_2 into M-L bond (L= H, OH, NH_2, R) represents another strategy to activate CO_2 . Pincer based complexes have proved to be suitable platform to study such kind of insertion reactions in both stoichiometric and catalytic fashion. These insertion reactions can be classified into different categories

3.2.1. Insertion Reaction of CO_2 into M-H Bond

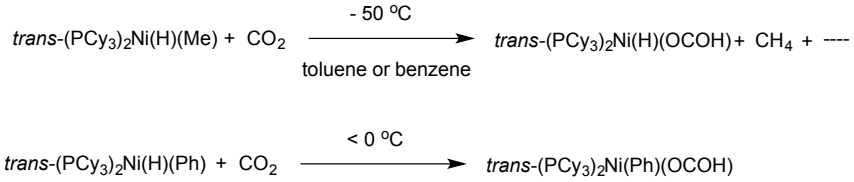
The normal insertion product of CO_2 into M-H bond is the formate adduct. This insertion reaction plays an important role in the catalytic hydrogenation of CO_2 to formic acid, formate, and methanol. Ikeda first reported the insertion reaction of CO_2 into the Co-H bond of the $H(N_2)Co(PPh_3)_3$ complex to produce the $HCOOCo(PPh_3)_3$ complex (Scheme 3.4). The same product was also obtained when $H_3Co(PPh_3)_3$ complex was used as a starting material with a concomitant evolution of H_2.[146] The identity of the insertion product was suggested based on IR spectroscopy and chemical reactions. Furthermore, reaction of the $H(N_2)Co(PPh_3)_3$ complex with HCOOH acid gave the insertion product as it was confirmed by IR spectroscopy and melting point.



Scheme 3.4. insertion of CO_2 into Co-H bond.

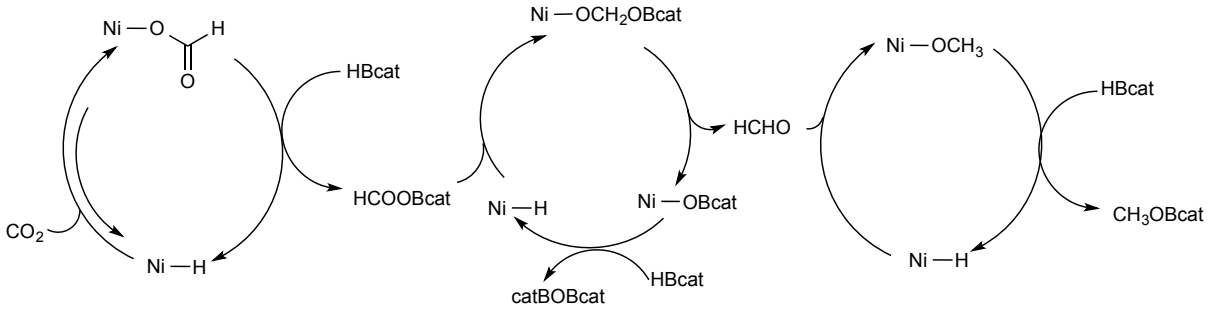
The insertion of CO_2 into the related complexes $H(N_2)Co(PR_3)_3$ and $H_3Co(PR_3)_3$ (R=$PhEt_2$ or Ph_2Et) were investigated by Gallo and offered the corresponding formate complexes, but they displayed lower stability and were difficult to isolate in a solid state form compared to the corresponding triphenylphosphine complexes. In contrast, the $HCo(L)_4$ complexes (L= $(PhO)_3P$, $(MeO)_3P$, $(EtO)_3P$, $(BuO)_3P$, $Ph(PhO)_2P$, $Ph(EtO)_2P$) did not react with CO_2 as a result of the low lability of the phosphite

ligands towards dissociation which is important for the insertion of the CO_2.[147] Insertion of CO_2 into the Ni-H bond was published by Darensbourg in 1987 where he found that the insertion reaction of CO_2 into the *trans-* $(PCy_3)_2Ni(Ph)(H)$ complex gives the *trans-* $(PCy_3)_2Ni(Ph)(OCOH)$ complex (Scheme 3.5).[148] Replacing the phenyl ligand with the methyl one of the starting material led to formation of the *trans-* $(PCy_3)_2Ni(H)(OCOH)$ complex together with methane and ethane. The expected insertion product *trans-* $(PCy_3)_2Ni(Me)(OCOH)$ was also observed and its identity was suggested based on NMR spectroscopy. The obtained results in case of the *trans-* $(PCy_3)_2Ni(Me)(H)$ complex can be attributed to the low thermal stability of this complex.



Scheme 3.5. insertion of CO_2 into Ni-H bonds.

The rigid tridentate chelation of the pincer ligand to the metal center enhanced the stability of the hydride complexes and allowed for the successful isolation and full characterization of these complexes including their molecular structures.[5, 71, 119] Among these complexes, (POCOP)Ni-H complex reported by Guan efficiently catalyzed the reduction of CO_2 to methanol using catecholborane as a reducing agent.[115] The catalytic cycles involved in this reduction are depicted in Scheme 3.6.

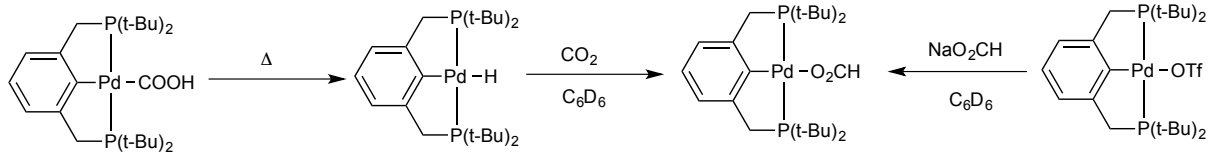


Scheme 3.6. Catalytic reduction of CO_2 using (POCOP)Ni-H as a catalyst.

More efficient catalyst can be obtained by changing the hydride ligand with thiolate and using isopropyl substituents on the phosphorus donor atoms of the POCOP ligand architecture.[149] Other related nickel pincer complexes were also used as catalysts for reduction of CO_2 .[150-152]

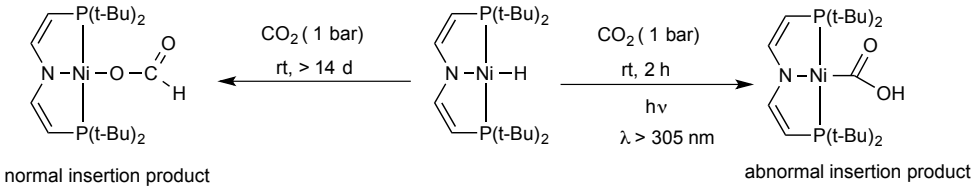
Wendt studied the reaction of CO_2 with the electron rich PCP palladium hydride complex giving the corresponding formate complex (Scheme 3.7).[90] The identity of the formate complex was established using NMR spectroscopy and through the reaction of the PCP palladium triflate with sodium formate. The formate complex

was also obtained through a decarboxylation reaction of the corresponding hydroxycarbonyl complex, but this process is slow.



Scheme 3.7. Insertion of CO_2 into the (PCP)Pd-H complex.

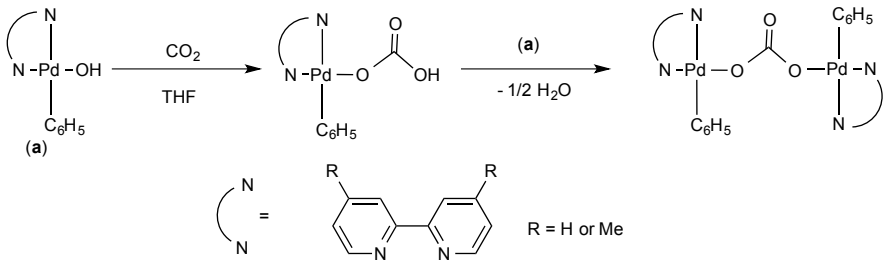
All the aforementioned examples displayed normal insertion of CO_2 into the metal hydride bond. More recently, Schneider published the first example of abnormal insertion of CO_2 into the Ni-H bond of the (PNP)Ni-H complex under photochemical reaction conditions (Scheme 3.8).[153] The normal insertion product was obtained through the reaction of the (PNP)Ni-H complex with CO_2 at room temperature, but the reaction was sluggish even at higher CO_2 pressure (10 bar). This is in contrast to the usually facile insertion reaction of CO_2 into M-H bond. The formation of the abnormal insertion product is induced by the photochemical N-H reductive elimination. In addition to the abnormal insertion product (70 % yield), the hydrocarbonate (PNP)Ni-OCO_2H complex (20 % yield) and the paramagnetic nickel(I) complex Ni(CO)(PNP) (trace quantities) were formed based on the NMR and EPR spectroscopy.



Scheme 3.8. Normal and abnormal insertion of CO_2 into the (PNP)Ni-H complex.

3.2.2. Insertion Reaction of CO_2 into M-OH Bond

Insertion of CO_2 into the terminal M-OH bond has been investigated. However, there are relatively few examples in the literature covering this topic as a result of the synthetic challenge of the terminal hydroxo complexes. The insertion product depends on the steric hindrance of the ancillary ligands coordinated to the metal center. Thus, the initial insertion product, the monomeric bicarbonate, can be converted into the dimeric carbonate product in the presence of small ancillary ligands (Scheme 3.9).[154]



Scheme 3.9. Reaction of CO_2 with less sterically hindered hydroxo complexes.

Wendt published the first structurally characterized monomeric bicarbonate palladium complex as a result of CO_2 insertion into terminal hydroxo palladium bond.[90] The analogous nickel complex was reported later by Hazari.[155] The successful isolation of these complexes is due to the steric bulkiness of the tridentate pincer ligand used to stabilize these complexes. Using less sterically hindered pincer structures enabled formation of both monomeric bicarbonate and dimeric carbonate complexes.[156] An interesting example reported by Holm included the reaction of CO_2 with anionic $[Ni^{II}(pyN_2^{R2})(OH)]^-$ complexes in DMF to produce the corresponding $[Ni^{II}(pyN_2^{R2})(OCO_2H)]^-$ complexes.[157, 158] The rate of the insertion reaction was calculated giving an extreme rapid insertion process in the range of the carbonic anhydrase enzyme.

3.2.3. Insertion Reaction of CO_2 into M-NH_2 Bond

Insertion of CO_2 into M-NH_2 bond is significantly less explored. Roundhill reported that the insertion of CO_2 into the Pt-NH_2 bond of the *trans*- $(PCy_3)_2Pt(Ph)(NH_2)$ complex depends on the solvent. In case of nonpolar solvent, the *trans*-$(PCy_3)_2Pt(Ph)(NHCO_2H)$ complex was formed while using a polar solvent offered the *trans*- $(PCy_3)_2Pt(Ph)(OCONH_2)$ complex.[159] The only example of insertion of CO_2 into M-NH_2 bond of pincer type complex was reported by Hazari giving the corresponding carbamate complex.[155] The lack of research on this topic could be attributed to the low stability and the high reactivity of the M-NH_2 bond.

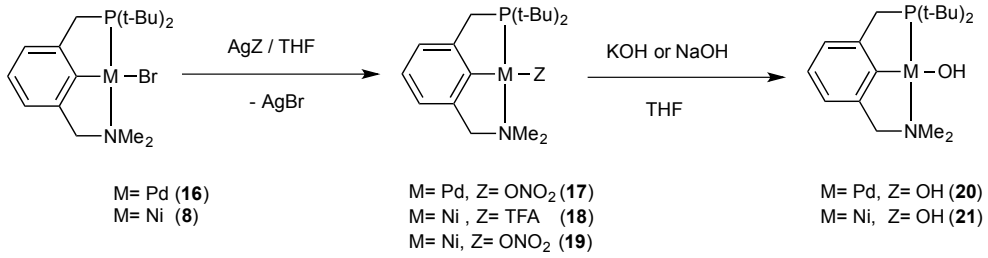
3.2.4. Insertion Reaction of CO_2 into M-C Bond

Insertion of CO_2 into an M-C bond is important because it generates new C-C bond using cheap and abundant feedstock. The resulting metal carboxylate fragment is prone to further functionalization due to the weak M-O bond of the insertion product. The C-based ligand greatly influences the insertion of CO_2. Facile insertion of CO_2 is known for M-C(allyl) bond while insertion of CO_2 into M-C(alkyl) is usually carried out under harsh conditions and long reaction times particularly for nickel complexes.[91-93, 96, 97, 143, 160-165] Darensbourg reported that carboxylation of Rh^I-C

(alkyl or aryl) bond can be achieved under mild reaction conditions and the insertion of CO_2 was facilitated by using electron rich Rh center.[166]

3.3. Reactivity of PCN Pincer Palladium and Nickel Complexes towards CO_2

Reactivity of pincer palladium and nickel complexes towards CO_2 is less explored, particularly, complexes based on unsymmetric ligand scaffolds. There is only one example involving the insertion of CO_2 into the unsymmetric PCO pincer palladium hydroxo complex.[51] In light of the lack of publications, we were interested to investigate the reactivity of our unsymmetric PCN palladium and nickel complexes towards CO_2. In order to achieve this, we first prepared the PCN palladium and nickel complexes relevant to this study. The PCN hydroxo complexes of palladium and nickel were synthesized using the same synthetic route employed to prepare the corresponding PCP pincer complexes that were previously reported (Scheme 3.10).[90, 167] Using a weakly coordinated ligand, e.g. ONO_2 or TFA is essential to facilitate the preparation of the hydroxo complexes. Other synthetic approaches suffer from long reaction times, low yield and formation of dimeric hydroxo complexes.[46, 51, 155, 168]



Scheme 3.10. Synthesis of PCN pincer palladium and nickle hydroxo complexes.

Molecular structures of the PCN palladium and nickel nitrate complexes, the precursors for the corresponding hydroxo complexes, display the same structural features (Figure 3.1).

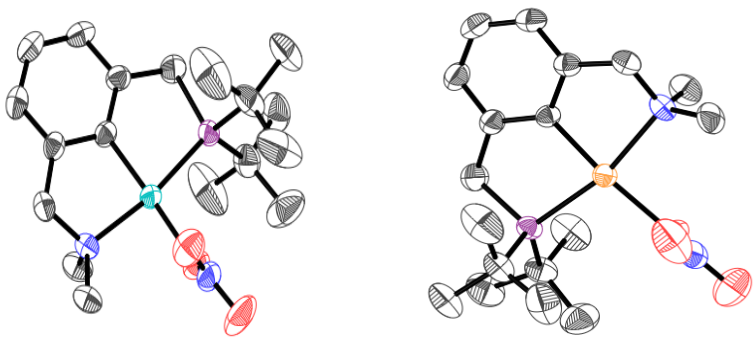


Figure 3.1. Molecular structures of the PCN pincer palladium and nickel nitrate complexes.

The new PCN palladium and nickel hydroxo complexes were characterized by NMR spectroscopy. A characteristic signal for the hydroxo ligand was observed at -1.32 and – 2.56 ppm in the ^{1}H NMR spectra for the palladium and nickel complexes respectively. The PCN palladium hydroxo complex was characterized by X-ray diffraction confirming its monomeric structure (Figure 3.2). Attempts to crystallize the corresponding nickel complex were not successful.

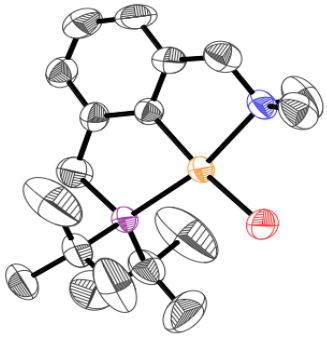
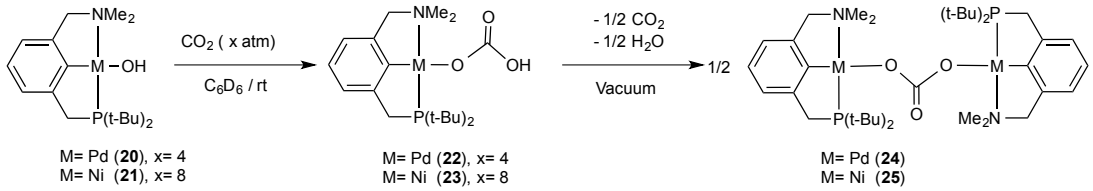


Figure 3.2. Molecular structure of complex **20**.

After we characterized the hydroxo complexes, we investigated their reactivities with CO_2 (Scheme 3.11). The carboxylation reactions were carried out using J. Young NMR tubes and monitored by NMR spectroscopy. Complete consumption of the hydroxo complexes was observed within minutes at room temperature for both palladium and nickel complexes based on NMR spectroscopy. The bicarbonate palladium complex was unambiguously confirmed using X-ray diffraction where the hydrogen carbonate ligand adopts η^1 coordination to the palladium center (Figure 3.3). The bicarbonate nickel complex was only stable under CO_2 pressure. Thus, it was characterized *in situ* using ^{1}H, $^{13}P\{^{1}H\}$, and $^{13}C\{^{1}H\}$ NMR spectroscopy. The hydrogen carbonate proton was observed as a broad singlet at 13.26 ppm and the hydrogen carbonate moiety displayed a singlet peak at 162.8 ppm in the $^{13}C\{^{1}H\}$ spectrum. Crystallization led to formation of the dimeric carbonate complex indicating the facile decarboxylation of the bicarbonate nickel complex.



Scheme 3.11. Reaction of CO_2 with the PCN pincer palladium and nickle hydroxo complexes.

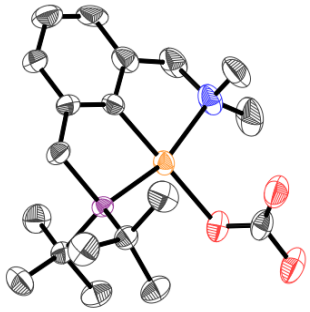


Figure 3.3. Molecular structure of complex **22**.

The obtained crystals were suitable for single X-ray diffraction analysis and helped to establish the structure of the complex (Figure 3.4).

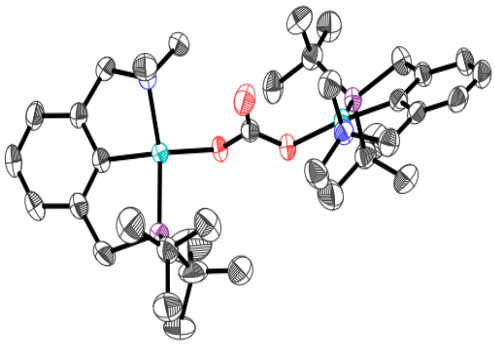
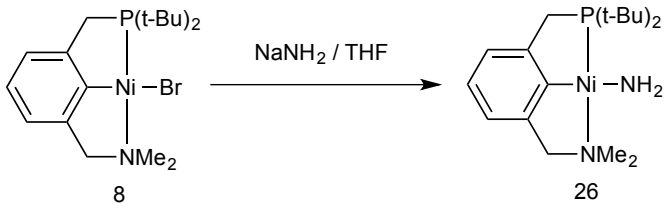


Figure 3.4. Molecular structure of complex **25**.

A salt metathesis reaction of the PCN nickel bromide complex with an excess of $NaNH_2$ produced the corresponding amido complex (Scheme 3.12). Although the synthesis of the amido complex is straightforward, extremely dry conditions need to be used. The complex is very hygroscopic and produces the corresponding hydroxo complex under wet conditions. This represents the first example of an amido nickel complex based on unsymmetric pincer ligand. In contrast to the PCN nickel amido complex, the synthesis of the analogous palladium complex was not successful.

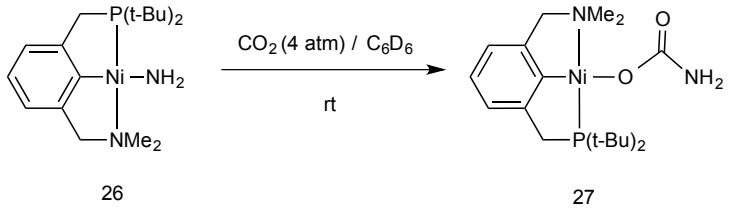


8 26

Scheme 3.12. Synthesis of PCN pincer nickel amido complex.

Having the amido complex in our hand, we decided to investigate the carboxylation reaction. The compex was pressurized with 4 atmosphere of CO_2 in C_6D_6 (Scheme 3.13). A new complex was formed according to the $^{31}P\{^1H\}$NMR spectrum which also displayed full consumption of the starting complex. The ^1H NMR spectrum displayed a distinct peak at 4.00 ppm with integration of two protons assigned to the carbamate protons. The carbamate group was observed as a sharp singlet at 162.9

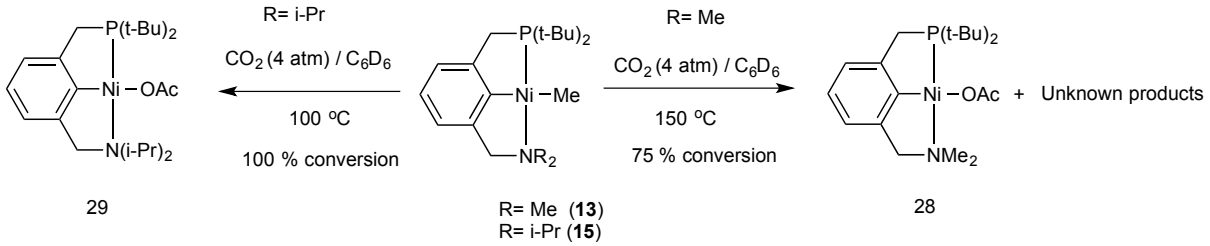
ppm in the $^{13}C\{^{1}H\}$NMR spectrum. A minor product was observed but establishing its identity was not successful.



26 27

Scheme 3.13. Reaction of CO_2 with the PCN pincer nickel amido complex.

Synthesis of the PCN nickel methyl complexes was described in the previous chapter. Carboxylation of the less sterically hindered methyl complex (**13**) offered the corresponding acetate complex under harsh reaction conditions, which allowed the formation of other unknown complexes. Only 75 % conversion was achieved after 6 days according to NMR spectroscopy. This result is in line with the previously reported nickel pincer examples, which also displayed sluggish reactivities with CO_2 indicating that carboxylation reaction of the nickel methyl bond is not easy. One way to enhance the carboxylation reaction is to increase the electron density on the metal center. In this context, we synthesized the more electron donating and the sterically demanded methyl complex (**15**), and we studied its reactivity with CO_2. Indeed, the carboxylation reaction took place under milder reaction condition as described in Scheme 3.14 and 100 % conversion was achieved in this case after 48 h. The obtained result is comparable to the reactivity reported for the symmetric PCP palladium methyl complex. However, nickel is more desirable because it is abundant and inexpensive.

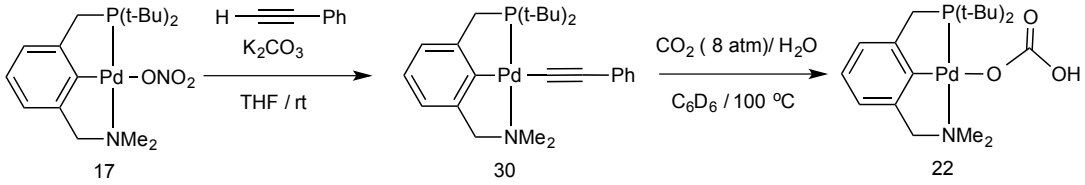


29 R= Me (**13**) R= i-Pr (**15**) 28

Scheme 3.14. Reaction of CO_2 with the PCN pincer nickel methyl complexes.

Reaction of the PCN palladium phenyl acetylide complex with CO_2 was also investigated (Scheme 3.15). The reaction was monitored using NMR spectroscopy. The extremely slow conversion of the starting complex induced us to repeatedly pressurize the J. Young NMR tube with CO_2. The product was identified as the bicarbonate PCN palladium complex. Conducting the carboxylation reaction under wet reaction conditions (adding two droplets of water) enhanced formation of the bicarbonate complex and enabled full conversion of the phenyl acetylide complex within 10 days compared to six months in the initial experiment. The formation of

the bicarbonate complex can be explained on the basis of the reaction of the *in situ* formed carbonic acid with the acetylide complex as it was previously reported for the bidentate palladium complexes L_2PdMe_2 (L_2 = TMEDA, dppe or MDC^{Mes}).[169, 170]



Scheme 3.15. Reaction of CO_2 with the PCN pincer palladium acetylide complex.

Our attempt to extend the scope of the carboxylation reaction of the PCN nickel complexes to include the insertion of CO_2 into a Ni-H bond, which is relevant to the catalytic reduction of CO_2, was hampered by the unsuccessful preparation of the PCN nickel hydride complexes. Neither PCN^{Me} nor $PCN^{i\text{-}Pr}$ nickel halide complexes offered the corresponding hydride complexes and instead the free PCN^{R} ligands were obtained with concomitant formation of a brown solution and a black precipitate.

3.4. Conclusion

The unsymmetric PCN pincer ligand architecture enabled the successful preparation and isolation of the terminal hydroxo palladium and nickel complexes. The PCN nickel amido complex was synthesized giving the first example of an unsymmetric amido pincer complex. The reactivity of the new hydroxo complexes towards CO_2 was investigated giving the corresponding bicarbonate complexes which further produced the dinuclear carbonate complexes upon decarboxylation. Insertion of CO_2 into the Ni-NH_2 offered the corresponding carbamate complex.

Increasing the electron donating and the steric hindrance of the PCN ligand was found to be crucial to enhance the carboxylation reaction of the Ni-Me bond.

The carboxylation of the PCN palladium phenyl acetylide complex offered the corresponding bicarbonate complex as a result of the reaction of the *in situ* formed carbonic acid with the phenyl acetylide complex.

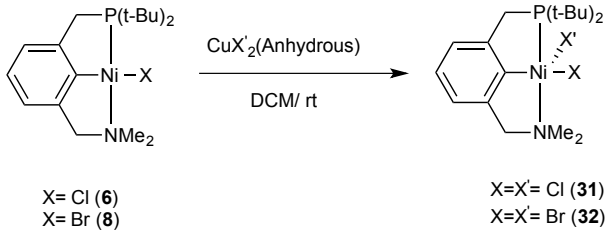
4. High Valent PCN Pincer Nickel Complexes (Papers III-IV)

4.1. Introduction

High valent organometallic complexes have been proposed as important intermediates in different catalytic reactions including cross coupling, C-H functionalization, and Kharasch addition reaction.[105, 111, 171-176] Isolation of these species is very important for the mechanistic studies and the systematic development of new catalysts. However, the high reactivity and the low thermal stability of these species in most of the cases impede their isolation and only allow *in situ* characterization using low temperature NMR or EPR measurements based on the magnetic properties of these elusive species.[177, 178] Using multidentate ligands improved this situation and helped to isolate and structurally characterize some of the catalytically relevant high valent organometallic complexes.[179-186] Among these multidentate ligands, NCN pincer ligand was first to demonstrate a remarkable ability in stabilizing high valent nickel (III) complexes, which displayed high thermal stability as a result of the unique tridentate chelation of the NCN pincer ligand to the nickel center.[187-190] Later, Zargarian reported that the $PC_{sp3}P$ pincer ligand also supports nickel (III) complexes and similarly, the electron deficient POCN ligands.[52, 57, 191, 192] However, the POCN nickel (III) complexes suffer from stability issue.[52, 57, 192] The outstanding ability of pincer ligands in stabilizing high valent metal centers extended further to involve isolation of the nickel (IV) complex based on the electron rich monoanionic bis (carbene) pincer ligand, ^{DIPP}CCC.[186] In contrast to the successful isolation of the nickel (IV) complex using a two-electron oxidant, the nickel (III) complex was not obtained despite using a variety of one-electron oxidants. In the current study, we were interested in investigating the possibility for formation of high valent nickel complexes based on the unsymmetric PCN ligand.

4.2. Oxidation of the PCN Nickel Halide Complexes

We initially carried out cyclic voltammetry measurements to check the possibility for formation of high valent PCN nickel complexes. The cyclic voltammetry measurements of the PCN^{Me} nickel (II) halide complexes showed that one electron oxidation process is indeed accessible for both the bromide and the chloride complexes. Irreversible oxidation waves were recorded at $E_{1/2}$= 0.797 and 0.837 V for the bromide and the chloride complexes respectively (Figure 4.1). In agreement with the obtained results, reaction of the PCN^{Me} nickel (II) halide complexes with anhydrous CuX_2 salts (X= Cl, Br) as oxidizing agents readily offered the corresponding PCN^{Me} nickel (III) dihalide complexes (Scheme 4.1). The oxidation reactions took place within seconds at room temperature with concomitant precipitation of CuX salts, which were removed through filtration over a short pad of Celite. Initial characterization of the new complexes using ^{1}H and $^{31}P\{^{1}H\}$ NMR spectroscopy gave no signal indicating their paramagnetic behavior.



Scheme 4.1. Oxidation of the PCN pincer nickel halide complexes.

Solid-state characterization using X-ray diffraction gave more details about the nature of coordination in these complexes. Complex **31** crystallized in the monoclinic crystal system having four molecules in the unit cell while complex **32** crystallized in the orthorhombic crystal system with eight molecules in the unit cell. A distorted square pyramidal geometry around the nickel center was confirmed for both of the complexes (Figure 4.2).

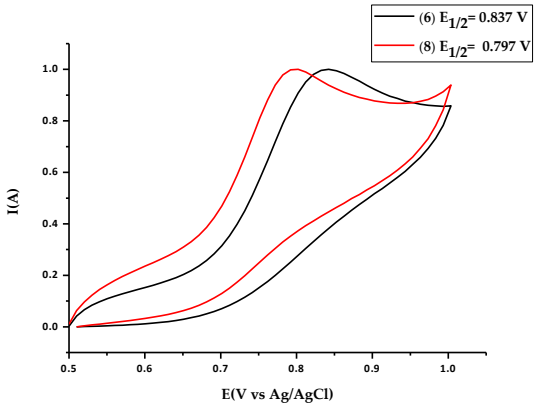


Figure 4.1. Cyclic voltammogram of 1mM solutions of complexes **6** and **8** in DCM containing 0.1M $(Bu_4N)PF_6$ at a scan rate of 0.1 V/s on a glassy carbon working electrode.

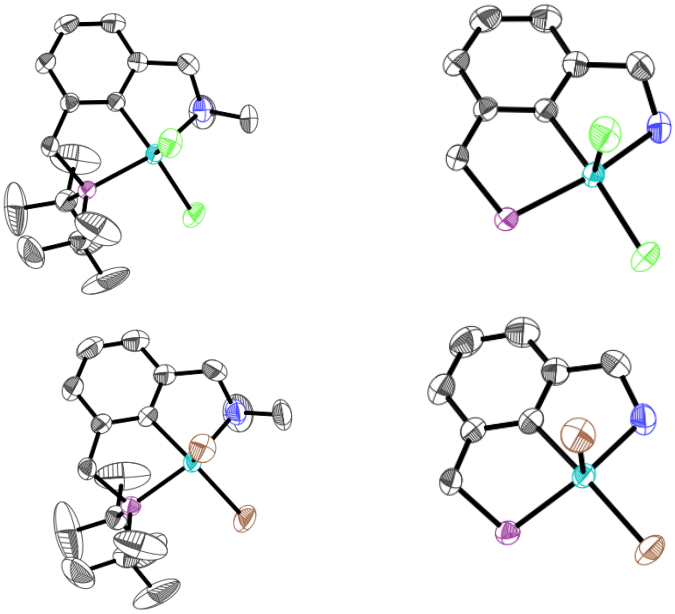


Figure 4.2. Molecular structures of complexes **31** and **32** (left). The substituents on the donor atoms have been omitted for clarity (right).

For complex **31**, the apical Ni-Cl1 bond is longer than Ni-Cl2 bond (2.2885 *vs.* 2.2498). The same trend was also observed for the Ni-Br bond lengths of complex **32**. This discrimination in the bond lengths of the halide ligands is due to the repulsive interaction between the single unpaired electron located in the d_z^2 orbital of the nickel center and the apical halide ligand, which locates on the same direction. Both of the complexes displayed a weak nonclassical hydrogen bond between the apical halide ligand and the meta C-H bond of the phenyl ring on a neighboring molecule (cf. Figure S26 for paper III). Magnetic susceptibility and magnetization measurement (Figure 4.3) of complex **32** in addition to the EPR spectroscopy measurements (Figure 4.4) confirmed the electronic structure for this complex as a low-spin d^7 system.

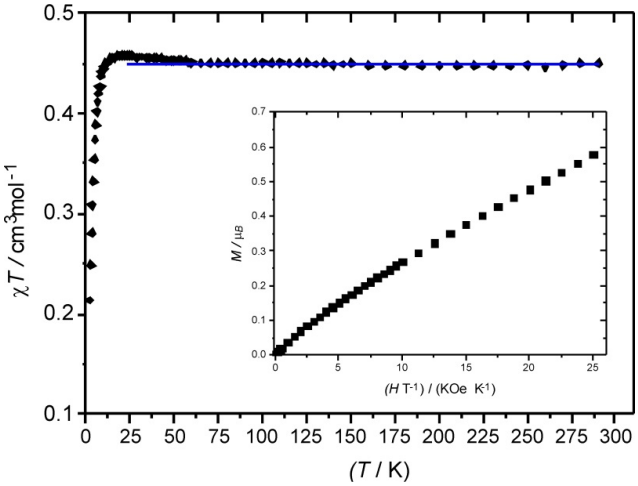


Figure 4.3. Magnetic susceptibility, represented by the χT product in the temperature range 2-300 K for complex **32**. The insert shows magnetization data for the same sample recorded at 2 K.

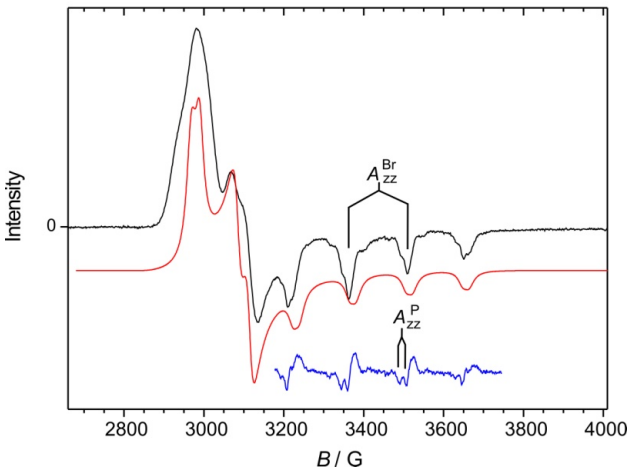


Figure 4.4. Experimental (black) and simulated (red) X-band EPR spectra of **32** in a frozen CH_2Cl_2/toluene (2:1) glass at T=20 K. The blue curve is the derivative of the experimental spectrum indicating super-hyperfine splitting also from coupling to one phosphorus nucleus. The spectrum was recorded with P = 6.325 mW; modulation amplitude = 3.0 G, modulation freq. = 100 kHz. Simulation parameters: g_1=2.301; g_2=2.208; g_3=2.000, $A^{Br}_{zz.}$ = 0.0132 cm^{-1}, $A^{P}_{zz.}$ = 0.0015 cm^{-1}, lorentzian derivative line shape, FWHH = 15.5 G.

Attempts to oxidize the $PCN^{i\text{-}Pr}$ nickel bromide complex were not successful probably due to the steric hindrance of the $PCN^{i\text{-}Pr}$ ligand. This is in agreement with the previous observation reported by van Koten for the symmetric NCN^{R} nickel complexes.

4.3. Kharasch Addition Reaction

Kharasch first reported that the addition of CCl_4 to olefins in the presence of peroxides as catalyst produce 1:1 anti-Markovnikov addition product.[193] The addition reaction takes place through a radical mechanism where peroxides act as initiator.[194-197] Other competing reactions, e.g. polymerization or telomerization during the propagation step are responsible for side product formation, which represents a drawback of using peroxides as catalyst. Using transition metal catalysts instead of peroxides helped to suppress the undesired side products and improve the selectivity. Among these complexes, nickel complexes supported by NCN pincer ligands are the most efficient catalyst.[99-101, 171] The polyhalogenated alkanes need to be used in large excess in order to promote 1:1 Kharasch addition. Using a stoichiometric amount of the polyhalogenated alkanes induces the controlled radical polymerization reaction of the olefin.

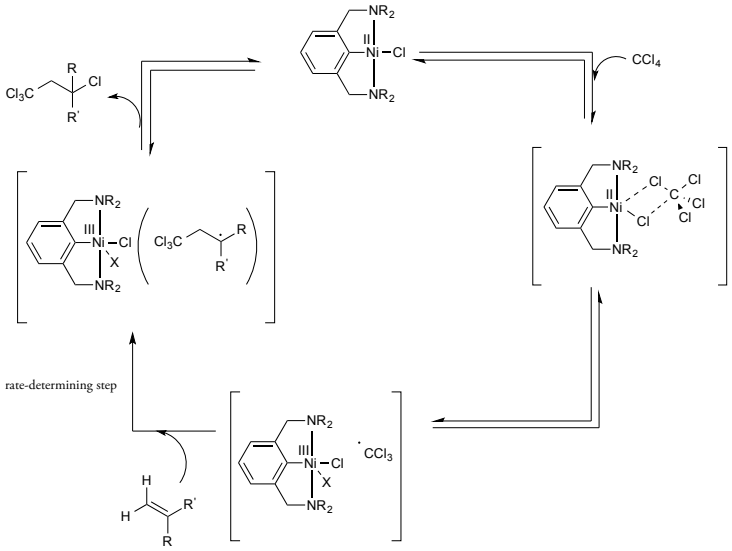
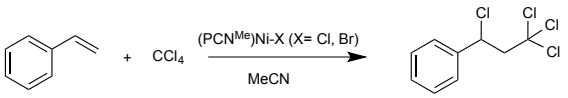


Figure 4.5. Catalytic cycle for Kharasch addition reaction of CCl_4 to olefins reported by van Koten.

Oxidation of Ni (II) to Ni (III) species is a key step in the catalytic cycle of Kharasch addition reaction of polyhalogenated hydrocarbons to olefins as it was investigated by van Koten (Figure 4.5).[101, 171] Therefore, the facile oxidation of the PCN^{Me} nickel halide complexes in our hand encouraged us to test their reactivities in Kharasch addition reaction. In order to compare the reactivities of our PCN nickel halide complexes with the state of art catalyst NCN nickel complex, we carried out the addition reaction of CCl_4 to styrene under the same reaction conditions reported by van koten.[101] However, at room temperature our PCN nickel halide complexes were not active. Changing the solvent from DCM to MeCN gave the same result. Conducting the catalytic reactions at 80-85 °C offered the 1:1 anti-Markovnikov product. 95% conversion was achieved in case of the bromo complex (TON= 293) while the chloro complex gave 87% conversion (Table 4.1).

Table 4.1. Catalytic Kharasch addition reaction of CCl_4 to styrene mediating with PCN nickel halide complexes



Entry	Catalyst	[Cat]/[Alkene] (%)	T (°C)	Conversion[a] (%)	Selectivity (%)
1	**6**	0.32	rt	0	
2	**8**	0.32	rt	0	
3	**6**	0.32	80-85	87	100
4	**8**	0.32	80-85	95	100
5[b]	**(NCN)NiBr**	0.32	rt	56	100
6[c]	**(POCN)NiBr**	2	80	95	100

Reaction conditions: CCl_4 (2.5 mL, 26 mmol), Styrene (0.8 mL, 7 mmol), (PCN) Ni-X (0.0227 mmol) and MeCN (3 mL).[a] Conversion was determined by ^1H NMR and GC-MS. [b] Conversion was determined after 1 h. [c] Conversion was determined after 18 h.

The obtained results together with the previously reported literature ones (which some of them are included in the above table) put our PCN nickel system in the following order of reactivity:

$$NCN > PC_{sp3}P > PCN > POCN$$

This arrangement is in agreement with the cyclic voltammetry measurements, which were used to assign the electron properties of these complexes.[52, 187, 191] The more readily the complex is oxidized, the more efficient it is in Kharasch addition.

4.4. Conclusion

Bench stable high valent nickel (III) complexes were readily synthesized and characterized in solid state using X-ray diffraction and CHN analysis. More insight about the electronic structure and the magnetic properties were established by EPR spectroscopy and magnetic moment measurement using the PCN dibromo complex as a case study. In line with the facile access of the trivalent PCN nickel complexes, the corresponding divalent complexes were employed in catalytic Kharasch addition reaction of CCl_4 to styrene showing high reactivity at mild reaction conditions in MeCN.

5. Catalytic Cross Coupling Reactions Using PCN Pincer Palladium and Nickel Complexes (Papers II & V)

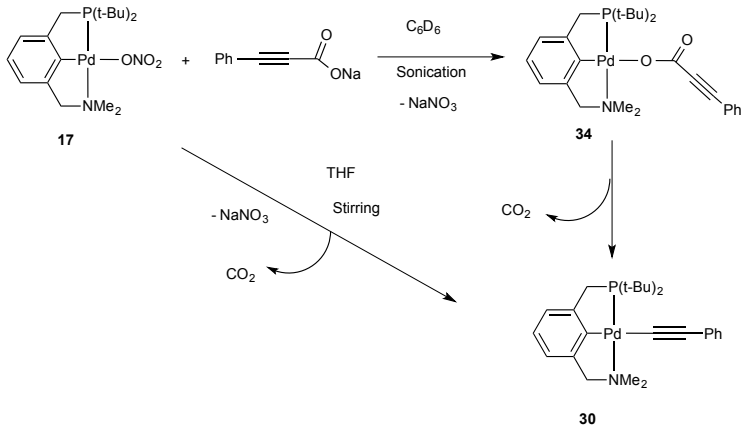
5.1. Introduction

There is no doubt that cross coupling reactions have become one of the most important and dominant synthetic tools in organic chemistry which have enabled facile access to complex molecules and a variety of pharmaceuticals.[81-83, 86, 198, 199] The great impact of these reactions was appreciated by the 2010 Nobel Prize in chemistry, which was awarded jointly to Richard F. Heck, Ei-ichi Negishi, and Akira Suzuki. Conventional cross coupling reactions involving Suzuki, Heck, Negishi, Kumada, Stille, and Sonogashira coupling use aryl or alkyl halides as an electrophilic partner and organometallic reagents as a nucleophilic partner. Transition metal catalyst combines these two fragments in order to achieve the cross coupling product through a cascade of organometallic reactions including oxidative addition, transmetallation, and reductive elimination. Palladium and nickel are extensively used in cross coupling reactions.[86, 105] In addition to these conventional cross coupling reactions, decarboxylative cross coupling reactions have been developed as a promising strategy which uses inexpensive and abundant carboxylic acid as one partner in the coupling reaction which generates the active species through *in situ* decarboxylation reaction.[200] In the current thesis, two methods were used to construct C-C bond. The first method is based on catalytic decarboxylative cross-coupling reactions mediated with PCN palladium complexes and the second one is catalytic Kumada-coupling reaction using PCN nickel complexes.

5.2. Catalytic Decarboxylative Cross Coupling Reactions

In our investigation to figure out the identity of the product of the reaction of CO_2 with the PCN palladium phenyl acetylide complex described in chapter 3, we studied

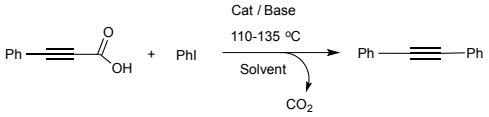
the reaction of the PCN palladium nitrate complex with sodium phenyl propiolate. The reaction was conducted at room temperature in THF. Surprisingly, the expected salt metathesis product, the PCN palladium phenyl propiolate complex, was not obtained and the PCN palladium acetylide was isolated as the sole product (Scheme 5.1).



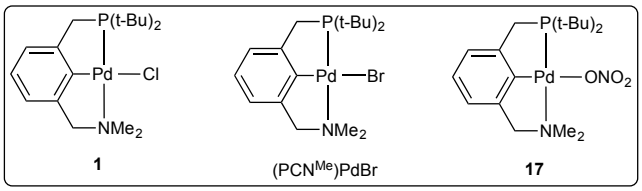
Scheme 5.1. Reaction of complex **17** with sodium phenyl propiolate.

To give more insight about the reaction, the above experiment was carried out in a J. Young NMR tube using C_6D_6 as a solvent. Following the reaction using ^{1}H and $^{31}P\{^{1}H\}$ NMR spectroscopy revealed formation of two new pincer complexes after five minutes of sonication. One of the two products was confirmed as the phenyl acetylide complex from independent synthesis, and the other is assigned as the phenyl propiolate. The phenyl propiolate complex disappeared during the course of the reaction and the phenyl acetylide complex was obtained as the final product. To make better use of this unexpected facile decarboxylation reaction of the phenyl propiolate sodium salt, we incorporated our PCN palladium complexes in catalytic decarboxylative cross coupling reactions with aryl halide. Thus, we carried out the reaction of phenyl propiolic acid with phenyl iodide in the presence of a catalytic amount of PCN palladium complexes. The catalytic reactions were optimized with respect to solvent, catalyst loading, base, reaction time and temperature (Table 5.1). A control experiment in the absence of the catalyst was initially carried out and displayed no product formation based on GC analysis. Using 0.5 % catalyst loading gave 4 % yield of the decarboxylative cross coupling product. To enhance the yield of the product, we increased the catalyst loading to 2.5 %. This helped to slightly increase the yield. Furthermore, using 10 equivalent of K_2CO_3 was found to be useful to increase the yield as well. Using a catalytic amount of CuI enhanced the yield significantly. To check the actual role of the CuI in the catalytic reaction, we carried out the reaction in absence of the palladium catalyst using the same catalytic amount of CuI employed in entry 11. No decarboxylative cross coupling product was observed in this case (entry 12). This result rules out the participation of the CuI in the cross coupling step under the employed reaction conditions.

Table 5.1. Screening optimal conditions for the decarboxylative cross coupling reaction of phenyl propiolic acid with PhI

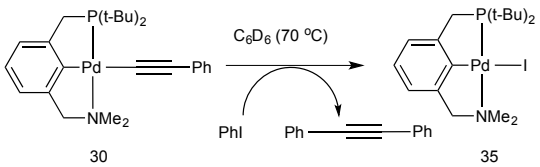


Entry	Catalyst	Catalyst loading (mol %)	T (°C)	t (h)	Base	Base(equiv)	Solvent	Yield (%)[a]
1	-	0	110	14	Cs_2CO_3	1.2	MeCN	0
2	**1**	0.5	110	14	K_2CO_3	1.2	THF	4
3	**1**	1	110	14	Cs_2CO_3	1.2	MeCN	2.7
4	**1**	2.5	110	48	LiO^{t}Bu	1.2	MeCN	3.3
5	**1**	2.5	135	48	TMEDA	1.2	MeCN	4.9
6	**17**	2.5	135	30	K_2CO_3	1.2	MeCN	9.5
7	**(PCN^{Me})PdBr**	2.5	135	30	K_2CO_3	1.2	MeCN	0
8	**1**	2.5	135	30	K_2CO_3	1.2	MeCN	9.1
9	**1**	2.5	135	48	K_2CO_3	1.2	MeCN	15.8
10	**1**	2.5	135	48	K_2CO_3	10	MeCN	23.2
11[b]	**1**	2.5	135	48	K_2CO_3	10	MeCN	54.4
12[c]	-	0	135	48	K_2CO_3	10	MeCN	3.3



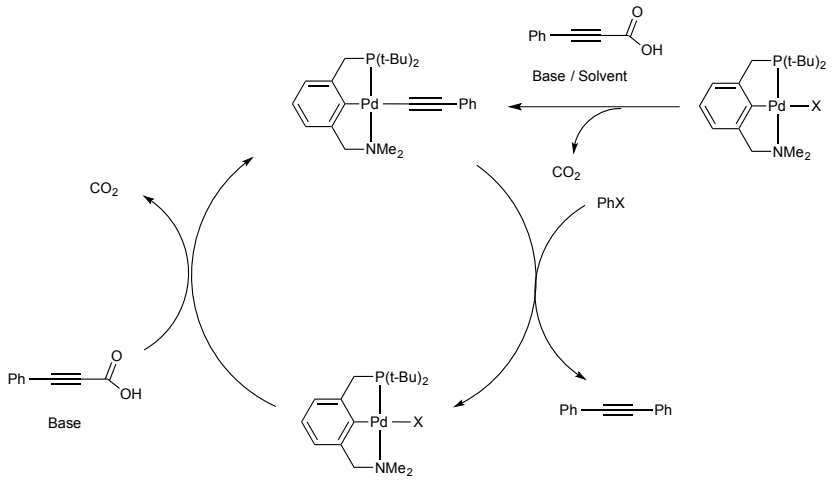
Reaction conditions: Phenylpropiolic acid (0.2 mmol), ArI (0.2 mmol), and solvent (3 mL).[a] The yield was determined as an average of two runs by GC based on a calibration curve of the product using decane as internal standard, [b] CuI (7.5 mol %) was used, [c] CuI (7.5 mol %) was used without palladium.

Further confirmation was obtained from the reaction of the PCN palladium phenyl acetylide and the PhI which produced the cross coupling product under mild reaction condition and more importantly in the absence of CuI (Scheme 5.2). The cross coupling product was confirmed using NMR spectroscopy and GC-MS analysis. Therefore, we suggest that CuI enhances the decarboxylation step by forming the cupper phenyl acetylide complex which subsequently reacts with the PCN palladium halide complex through a metathesis reaction to form the PCN palladium acetylide complex.



Scheme 5.2. Reaction of complex **30** with iodo benzene.

We suggest the catalytic cycle shown below (Scheme 5.3) based on the stoichiometric reactions previously discussed in this section which established the decarboxylation step and the cross coupling step.



Scheme 5.3. The suggested catalytic cycle for the decarboxylative cross coupling reaction of phenyl propiolic acid and PhI.

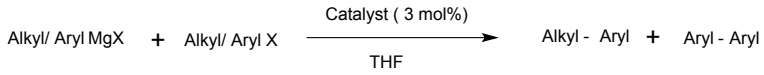
In contrast to the PCN palladium complexes, PCN nickel complexes displayed no reactivity in the catalytic decarboxylative cross coupling reactions.

5.3. Catalytic Kumada Coupling Reaction

Using nickel pincer complexes as catalysts to mediate Kumada coupling reaction allowed different types of electrophiles and a variety of Grignard reagents to successfully couple under mild reaction conditions.[111] We were interested in testing the reactivity of our PCN nickel complexes in Kumada coupling reaction aiming to discover new reactivity patterns based on the discrimination of the electronic and steric properties of the two different side arms of the PCN ligand. We started our catalytic reactions by studying the reaction of EtMgCl with PhI as an electrophilic coupling partner using 3 mol % catalyst loading (entry 1). GC analysis showed formation of the cross coupling product, ethylbenzene, in 15 % yield and the biphenyl as a homocoupling product in 8 % yield. Keeping the reaction for a longer time (entry 2) enhanced the yield of the cross coupling product. In order to suppress the formation of the homocoupling product, we reduced the temperature to 0 °C. However, in this case, the yield of the cross coupling product decreased as well. Using the alkyl partner as an electrophilic coupling partner gave an extremely low yield of the cross coupling product and concomitant enhancement of the homocoupling product was observed. The coupling of the PhCl with EtMgCl was not successful.

Both the pyridine and the dimethylamino based PCN nickel complexes (**11** and **8**) offered low reactivity in the coupling of alkyl/aryl halides with aryl/alkyl Grignard reagents, and other side products were observed.

Table 5.2. Optimization the reaction conditions of catalytic Kumada coupling reaction of aryl /alkyl halides and Et / PhMgCl



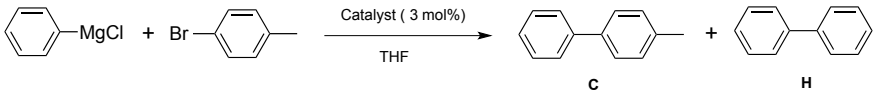
Entry	Alkyl/Aryl-X	Alkyl/Aryl-MgX	Catalyst	Solvent	T (°C)	t (h)	Yield[a] (%)	Yield[b] (%)
1	**PhI**	**EtMgCl**	**11**	THF	rt	7	15	8
2	**PhI**	**EtMgCl**	**11**	THF	rt	24	26	6
3	**PhI**	**EtMgCl**	**8**	THF	0	24	12	4
4	**PhI**	**EtMgCl**	**11**	THF	0	24	9	4
5	**n-BuBr**	**PhMgCl**	**8**	THF	rt	24	3	43
6	**n-BuBr**	**PhMgCl**	**11**	THF	rt	24	3	31
7	**n-BuBr**	**PhMgCl**	**8**	THF	0	7	0	27
8	**n-BuBr**	**PhMgCl**	**11**	THF	0	7	0	25
9	**PhCl**	**EtMgCl**	**8**	THF	rt	24	0	0
10	**PhCl**	**EtMgCl**	**11**	THF	rt	24	0	0

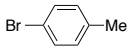
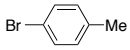
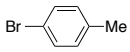
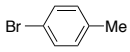
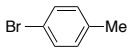
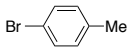
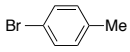
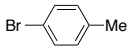
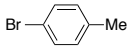
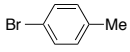
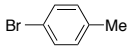
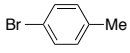
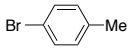
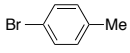
Reaction conditions: Aryl/Alkyl halide (0.25 mmol), R/ArMgCl (0.3 mmol), and solvent (3 mL).The yield was determined as an average of two runs by GC based on a calibration curve of the product using decane as internal standard.

However, complex **11** offered better yield than **8**. To investigate the difference in the reactivity between the two complexes, we decided to prepare the corresponding PCN nickel ethyl complexes anticipated to play an important role in this catalytic reaction. Thus, the reactions of the PCN nickel halide complexes (**11** and **8**) with EtMgCl were conducted aiming to produce the corresponding PCN nickel ethyl complexes (Scheme 5.4). In the case of complex **11**, the corresponding ethyl complex was successfully obtained and characterized in solution using NMR spectroscopy and in solid state using X-ray diffraction indicating its high thermal stability. However, complex **8** failed to give the corresponding ethyl complex and instead further decomposition was observed which extended beyond the expected β-hydride

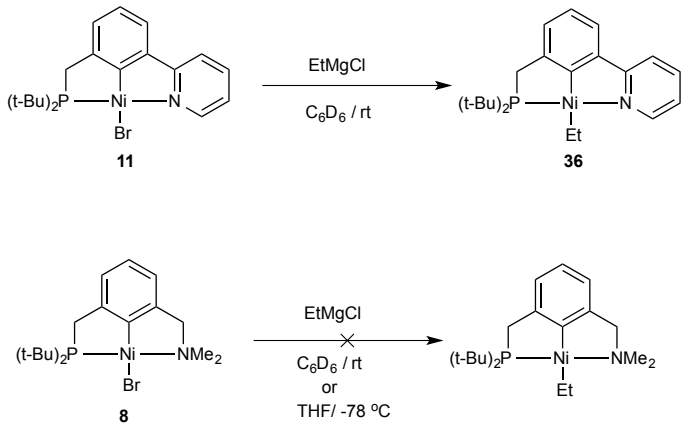
elimination product (PCN nickel hydride complex) to produce the free ligand and a black precipitate. This decomposition explains the low reactivity of complex **8**.

Table 5.3. Optimization the reaction conditions of catalytic Kumada coupling reaction of aryl halides and PhMgCl



Entry	Aryl-X	Aryl-MgX	Catalyst	T (°C)	t (h)	Additives	Additives (equiv.)	Yield (%) C	Yield (%) H
1		**PhMgCl**	**11**	rt	5			62	36
2		**PhMgCl**	**11**	rt	5	TMEDA	0.3	60	32
3		**PhMgCl**	**11**	rt	5	TMEDA	0.5	60	32
4		**PhMgCl**	**11**	rt	5	TMEDA	0.7	55	31
5		**PhMgCl**	**11**	rt	5	TMEDA	1	62	36
6		**PhMgCl**	**11**	rt	5	PPh_3	0.5	11	19
7		**PhMgCl**	**11**	rt	5	PPh_3	0.7	10	23
8		**PhMgCl**	**11**	rt	5	PPh_3	1	10	19
9[a]		**PhMgCl**	**11**	rt	5			41	33
10		**PhMgCl**	**11**	0	5			59	35
11		**PhMgCl**	**11**	-10	5			60	38
12		**PhMgCl**	**11**	-20	5			54	31
13		**PhMgCl**	**8**	rt	5			39	23
14		**PhMgCl**	**NCN^{Py}**	rt	5			47	27
14		**PhMgCl**	**11**	rt	5			60	
15		**PhMgCl**	**8**	rt	5			55	

Reaction conditions: Aryl halide (0.25 mmol), PhMgCl (0.3 mmol), and solvent (3 mL).The yield was determined as an average of two runs by GC based on a calibration curve of the product using mesitylene or decane as internal standard. [a] Toluene was used as solvent. Traces amount of 4,4'-dimethylbiphenyl was observed.



Scheme 5.4. Reaction of complexes **8** and **11** with EtMgCl.

Thus, we turned our attention to the coupling of aryl halide with aryl Grignard reagents as the expected PCN nickel aryl complexes are known to be more robust than the corresponding alkyl ones which are prone to β-hydride elimination decomposition pathway and in our hands we isolated this species as described in chapter 2. The reaction of the 4-bromotoluene with PhMgCl was used as a benchmark reaction to optimize the reaction conditions (Table 5.3). A control experiment was conducted in the absence of the catalyst showing no formation of the cross coupling product. Using 3 mol % catalyst loading gave 62 % of 4-methylbiphenyl as the cross coupling product and 36 % of the biphenyl as the homocoupling product of the PhMgCl. Also, traces of the 4,4'-dimethylbiphenyl was observed by GC and GC-MS. Full conversion of the aryl halide was confirmed as well after 5 h. Using TMEDA as an additive to improve the yield of the cross coupling product as it was previously reported by Hu[109] did not significantly change the ratio of the cross coupling and the homocoupling products. Using PPh_3 dramatically decreased the catalytic activity. Replacing THF by toluene did not improve the yield and instead led to decrease in the yield of the cross coupling product. Carrying out the catalytic reaction at low temperatures gave the same results we obtained at room temperature. Only at -20 ºC, a slight decrease in the yield was observed. Complex **11** gave better catalytic reactivity compared to complex **8** and NCN nickel complex described in paper **V** that is relevant to the current study. Formation of the homocoupling can be attributed to a radical mechanism. However, more time should be given to this promising project in order to improve the yield of the cross coupling product, expand the substrate scope and to give more insight about the mechanism.

5.4. Conclusion

A facile unexpected decarboxylation reaction of the sodium phenyl propiolate with the PCN palladium nitrate complex was exploited to employ our PCN palladium

complexes in the catalytic decarboxylative cross coupling reactions of the phenyl propiolic acid with phenyl iodide. In presence of catalytic amount of both the PCN palladium and CuI, a moderate yield of the decarboxylative cross coupling product was achieved. A mechanistic investigation confirmed that the PCN palladium complex is responsible for the cross coupling step and CuI only facilitates the decarboxylation step.

Preliminary results showed that PCN nickel pincer complexes catalyze Kumada coupling reaction of alkyl/aryl halides with alkyl/aryl Grignard reagents. The pyridine based PCN nickel complex displayed high reactivity. Full conversion of the aryl halide was achieved within five hours at room temperature. However, a significant amount of the homocoupling product was observed.

6. Perspective and Outlooks

The current thesis is devoted to the synthesis of new palladium and nickel complexes based on unsymmetric PCN pincer ligand scaffolds using a straightforward synthetic route facilitated by a direct C-H cyclometallation strategy. The choice of these two metals is in line with their widespread use in homogeneous catalysis.

In **Chapter 2**, we provided more details about the synthetic procedures used to prepare the new unsymmetric PCN ligands and their cyclometallation reactions. We also developed short synthetic method to give facile access to such kind of complexes. We succeeded to achieve high yield for the cyclometallated products using commercially available precursors.

Chapter 3 highlighted the ability of the PCN ligand in stabilizing elusive species, which are not very common in the literature. These complexes are essential for activating small molecules. However, a careful choice of the amine arm is vital to enhance the reactivity of these complexes towards small molecules, e.g. CO_2 as we described for the carboxylation reaction of the methyl complex. Mechanistic studies should be conducted in order to provide more insight about the facile insertion of CO_2 into the Ni-Me bond. Furthermore, this facile carboxylation reaction should be exploited catalytically.

Chapter 4 included more details about the successful synthesis of bench stable trivalent nickel complexes supported by the less sterically hindered PCN^{Me} ligand, including the electronic structures and the geometry of the isolated complexes. The factors affecting the oxidation reaction were investigated revealing that the steric factor is important. Furthermore, the catalytic activities of the PCN nickel halide complexes in Kharasch addition of CCl_4 to styrene were reported.

In **Chapter 5**, we discussed the catalytic applications of our PCN^{Me} palladium and nickel complexes in cross coupling reactions. The PCN palladium complexes enabled construction of the C-C bond through decarboxylative cross coupling strategy, which makes use of abundant, inexpensive and commercially available substrates. The easily accessible PCN^{Py} nickel complexes were employed in catalytic Kumada coupling reactions giving promising results. The time framework for this project was not enough to optimize the yield of the cross coupling product, try different substrates, and give more details about the mechanism. Therefore, future work should be carried out to study these issues.

7. References

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Printed by Media-Tryck, Lund 2018 NORDIC SWAN ECOLABEL 3041 0903

ISBN 978-91-7422-608-9

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