

# Fundamental Reactivity of the Metal-Carbon Bond in Cyclometalated PNC-Complexes

ACADEMISCH PROEFSCHRIFT

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**Linda Stéphanie Jongbloed**

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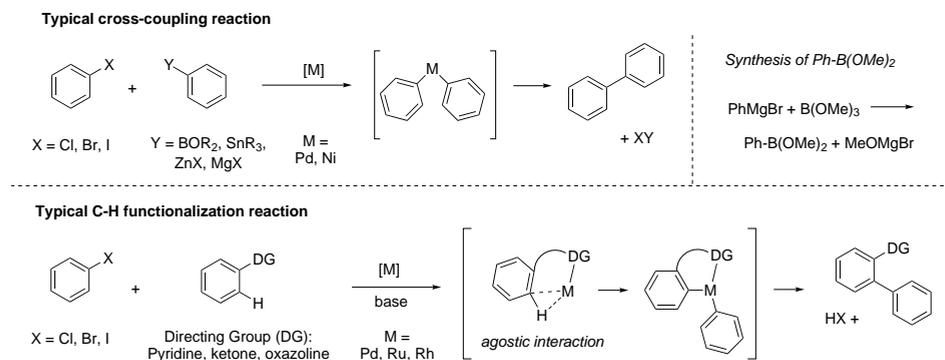
Summary

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# Summary

Catalysis plays an important role in the transformation to a sustainable society. Catalysts can offer a direct route to the formation of products in a selective and energy efficient way. By replacing stoichiometric reactions with catalytic processes, the amount of waste generated during the production of chemicals and materials can generally be reduced. In this context, one important type of homogeneous catalytic reaction that has recently attracted a lot of attention revolves around C-H functionalization reactions. In such a reaction, C-H bonds are transformed into C-C or C-heteroatom bonds, which are important transformations establishing the construction of larger molecules from simple building blocks. C-H functionalization is viewed as a green alternative to standard cross-coupling reactions, in which two activated carbon atoms are coupled, such as C-BOR<sub>2</sub>, C-SnR<sub>3</sub> and C-halogen substrates. This activation of carbon usually requires prefunctionalization of the substrate with reactive groups, which leads to waste production. In C-H functionalization reactions, the prefunctionalization step is not necessary, as C-H bonds are directly converted in a catalytic way.



Scheme S.1

Currently, most examples of mild and selective C-H functionalization require a directing group that can coordinate to the metal and bring one of the C-H bonds in close proximity of the metal. The formation of a M-C bond results in a cyclometalated intermediate. **Chapter 1** gives an overview on the different ways that a C-H bond can be activated. The types of directing groups that are generally used are discussed as well. The chapter also includes some examples of metal complexes that have an M-(C<sub>Ar</sub>-

H) interaction. Such interactions are considered to precede the actual C-H activation step by weakening the involved C-H bond. Finally, it is reviewed whether reversible cyclometalation (consecutive formation and cleavage of the M-C bond) in a ligand can account for bifunctional activation of substrates and cooperative catalysis.

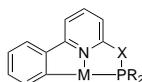
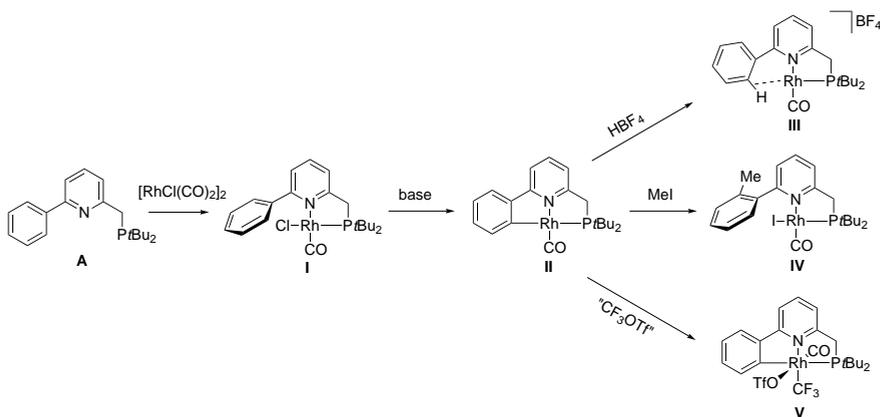


Figure S.1

The research described in this thesis aims to provide a fundamental understanding of C-H activation and M-C bond reactivity in complexes based on the novel *P,N,C*-ligands shown in Figure S.1. When the M-C bond is formed, these ligands bind to the metal in a tridentate way and can be described as pincer ligands. Pincer ligands with a phenyl-ring in the central position (ECE, E = P, N, S or O) are very common and they undergo facile metalation of the C-H bond due to the encumbering effect of the ligand structure. Pincer ligands with a phenyl-ring in the flanking position are uncommon.



Scheme S.2

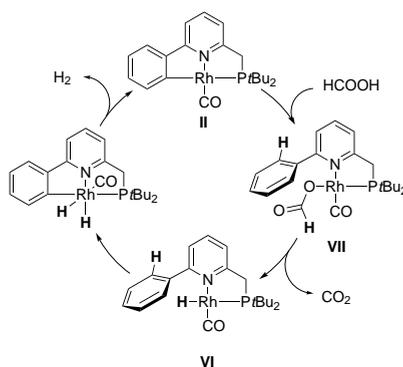
In **Chapter 2**, the synthesis of ligand **A** ( $X = \text{CH}_2$ ) is described. This ligand can be coordinated to  $[\text{Rh}-\mu\text{-Cl}(\text{CO})_2]_2$  to form square planar  $\text{Rh}^{\text{I}}$  complex **I** (Scheme S.2). Facile C-H metalation to form complex **II** can be achieved in the presence of a weak base, KOAc, and this process presumably follows a concerted-metalation-deprotonation pathway. Addition of a strong base, KOtBu, results in fast C-H metalation and DFT calculations and deuteration studies indicate that this reaction follows a different mechanism. Initial deprotonation of the relatively acidic  $-\text{CH}_2\text{P}$  backbone occurs to form a dearomatized intermediate, which is very unstable and forms the thermodynamically more stable cyclometalated complex **II** at RT.

The formation of the  $\text{Rh}^{\text{I}}\text{-C}$  bond is reversible, which was proven by reacting complex **II** with HCl. Addition of another strong acid,  $\text{HBF}_4$ , resulted in the cationic complex **III**, with  $\text{BF}_4^-$  acting as a non-coordinating counterion. In the solid state structure, the

vacant site at the metal is occupied by a C-H bond of the ligand. DFT calculations show that the Rh-(C-H) interaction is weak and can not be classified as agostic. This was also observed experimentally in solution, as low temperature NMR experiments show that the phenyl-ring can still rotate freely at  $-90^{\circ}\text{C}$ .

The  $\text{Rh}^{\text{I}}\text{-C}$  bond can also be cleaved by addition of MeI to complex **II**, which results in the formation of a  $\text{C}_{\text{Ph}}\text{-CH}_3$  bond in complex **IV**. Low temperature-experiments show that this reaction occurs *via* a  $\text{Rh}^{\text{III}}(\text{CH}_3)(\text{I})$  intermediate that is formed by oxidative addition of MeI to  $\text{Rh}^{\text{I}}$ . At RT, C-C reductive elimination is instantaneous. This was not the case for the more challenging C- $\text{CF}_3$  bond formation from  $\text{Rh}^{\text{III}}$ -complex **V**, which is stable at RT.

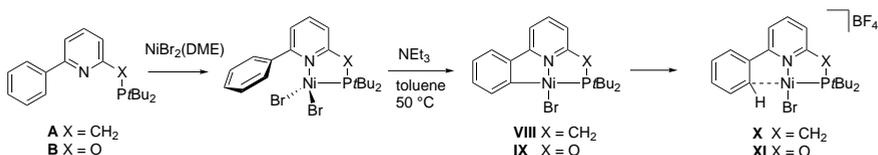
In **Chapter 3**, it was explored whether the reversibility of cyclometalation of Rh-complex **II** could be used to activate E-H bonds in a bifunctional manner. It was found that the  $\text{Rh}^{\text{I}}$  could only be cleaved by relatively acidic substrates such as trifluoromethylsulfonamide and thiols. Heterolytic splitting of  $\text{H}_2$  could not be achieved and DFT calculations pointed out that the cyclometalated complex **II** is 7.6 kcal/mol more stable than the putative Rh-hydride complex **VI**. This finding made us wonder whether complex **II** could serve as a catalyst for the reverse, dehydrogenation, reaction.



Scheme S.3: One of the two possible catalytic cycles for the dehydrogenation of HCOOH to H<sub>2</sub> and CO<sub>2</sub>. This pathway shown here is based on a mechanism involving reversible cyclometalation.

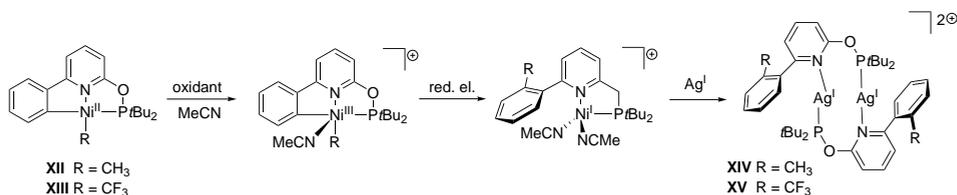
It was discovered that complex **II** indeed catalyzes the base-free dehydrogenation of formic acid (HCOOH) to H<sub>2</sub> and CO<sub>2</sub> (Scheme S.3). The activity of the catalyst is modest compared to other TM-catalysts (TOF = 169 h<sup>-1</sup>), but the catalyst is stable for at least eight consecutive runs. Furthermore, this is the first example of base-free dehydrogenation of HCOOH with a Rh<sup>I</sup> catalyst. DFT calculations indicate that a mechanism *via* reversible cyclometalation is viable, but that it most likely competes with a non-bifunctional pathway that exhibits almost identical overall energetics. DFT calculations also pointed out that concerted H<sup>+</sup>/H<sup>-</sup> abstraction from HCOOH is not possible because the HCOOH-hydride could not approach Rh due to the filled d<sub>z<sup>2</sup></sub> orbital. Because of this, both mechanisms have the same rate determining step that involves β-hydrogen elimination from the intermediate with a coordinated formate-fragment (**VII**).

In **Chapter 4**, a challenging C-H metalation at Ni<sup>II</sup> is reported. In addition to ligand **A**, ligand **B** (X = O) is synthesized as a complementary ligand with a different electronic structure and an unreactive oxygen linker between the pyridine and phosphine. For both ligands, easy cyclometalation was observed to NiBr<sub>2</sub>(DME) to form complexes **VIII** and **IX**, but only when the reaction was carried out in toluene with NEt<sub>3</sub> as the base (Scheme S.4). Intriguingly, neither NaOAc, the preferred base in many C-H metalation reactions, nor strong bases did result in clean formation of complexes **VIII** and **IX**.



Scheme S.4

The Ni-C bond in complexes **VIII** and **IX** react with HBF<sub>4</sub> to form complexes **X** and **XI**, which have a similar M-(C-H) interaction as observed in Rh-complex **III**. The complexes are unstable and give ill-defined NMR spectra suggesting paramagnetism in solution. When the cationic complexes are reacted with a base (NEt<sub>3</sub>), immediate cyclometalation is observed, indicating a more acidic C-H bond in these cationic species compared to the neutral dibromo analogues. A combination of ELF and QAIM calculations demonstrate that the interaction between the Ni-center and the C-H can be best described as an anagostic Ni<sup>II</sup>- $\eta^1$ -C interaction. This conclusion is based on the presence of weak bonding between Ni and C without a clear bonding between Ni and H. The interaction is slightly stronger for complex **XI** possibly originating from the more electron-withdrawing character of the phosphinite ligand.



Scheme S.5

In **Chapter 5**, the studies are reported that investigate whether C-C bond formation could be achieved as easily for these Ni-complexes as was found for Rh-complex **IV** (Chapter 2). Because the formation of Ni<sup>IV</sup>-alkyl intermediates is considered difficult and the reductive elimination from Ni<sup>IV</sup>-alkyl species was found not to occur in these systems, the study focused on C-C bond formation from Ni<sup>III</sup> intermediates. The synthesis of Ni-complexes **XII** and **XIII** is reported, which contain alkyl groups as the fourth ligand. Based on literature examples, Ni-CF<sub>3</sub> complex **XIII** was expected to be stable in the higher oxidation state. However, with a combination of spectroscopic techniques it was proven that both complexes easily undergo oxidation-induced C<sub>sp<sup>2</sup></sub>-C<sub>sp<sup>3</sup></sub> bond formation. In the presence of Ag<sup>I</sup>, transmetalation from Ni<sup>I</sup> to Ag<sup>I</sup> is observed, leading

to complexes **XIV** and **XV**. Unfortunately, the Ni<sup>III</sup> intermediate could not be detected in any of the experiments.

This thesis describes the coordination chemistry and reactivity of *P,N,C*-ligands **A** and **B** in Rh<sup>I</sup> and Ni<sup>II</sup> complexes. The strong *P,N*-chelation to the metal brings the *ortho*-C-H of a flanking phenyl ring in proximity of the metal, which results in facile C-H activation in both metal complexes. Although the M-C bond is easily formed, it is still reactive in presence of acids. Rh-complex **II** is an active catalyst for the dehydrogenation of formic acid, in which the reversible M-C bond formation can play a role. Furthermore, reactions with HBF<sub>4</sub> show that M-(C-H) interactions can be formed for this ligand structure, although the interactions are weak. It was also shown that the M-C bond is susceptible to C<sub>sp<sup>2</sup></sub>-C<sub>sp<sup>3</sup></sub> bond formation from the metals in higher oxidation states. The obtained insights on the C-H activation, especially with simple Ni<sup>II</sup>-precursors, could possibly lead to the development of C-H functionalization methodologies involving a broader substrate scope. Finally, these initial results into the possibility of reversible M-C bond formation in cyclometalated complexes as a design concept for cooperative catalysis are deemed to provide a basis for further exploration of this strategy using both noble and base metals for a variety of reactions.