# Nickel N-heterocyclic carbene complexes in homogeneous catalysis

Berding, J.

## Citation

Berding, J. (2009, October 8). *Nickel N-heterocyclic carbene complexes in homogeneous catalysis*. Retrieved from https://hdl.handle.net/1887/14048

# Chapter 8

## Summary, general discussion and outlook

## 8.1 Summary

### 8.1.1 Introduction

Even though the extraordinary chemistry of N-heterocyclic carbenes (NHCs) has been under investigation for about forty years, only in the past decade the field has come to full development. First regarded as a laboratory peculiarity, NHCs are now known as stable, economically attractive, and highly versatile ligands in a wide range of homogeneous catalytic applications. Although initially NHCs were mostly investigated as phosphane analogues for ruthenium and palladium catalyzed reactions, numerous unprecedented transformations have been disclosed using NHC complexes of these and many other transition metals. In this regard, nickel-NHC complexes have only been used in a relatively small number of catalytic reactions. The aim of the research described in this thesis was to prepare nickel-NHC complexes, with an emphasis on chelating ligands, and to use these complexes in a variety of homogeneous catalytic reactions.

In Chapter 1, first an overview of the electronic and steric properties of N-heterocyclic carbenes and the corresponding transition-metal complexes is given. This is followed by a summary of the various methods for the preparation of NHCs and their complexes. The chapter is concluded with a summary of the catalytic reactions in which transition-metal NHC complexes have played a role, with an emphasis on nickel NHC complexes.

### 8.1.2 Silver complexes of N-heterocyclic carbene

The transmetalation of NHCs from silver(I) to other transition metals has been shown to be an efficient way for the preparation of transition-metal NHC complexes. For this reason, attempts to obtain silver(I) NHC complexes were undertaken, which ultimately resulted in the determination of the solid-state structure of a dimer of a silver(I) bromide complex of a monodentate NHC, as described in Chapter 2. Surprisingly, using a nearly identical synthetic route, a significantly different crystal structure had been obtained by another research group.[1] In this case the solid-state structure comprised of a mononuclear silver(I) bromide complex with two monodentate NHCs. Several studies, including NMR and crystallization studies, were undertaken to determine the structure of the complex in solution and to elucidate why two different solid state structures could be obtained using nearly identical reaction conditions. It was finally concluded that the isolation of the [$(NHC)_2AgBr$] structure must be serendipitous. Moreover, a new classification of all known solid-state structures of silver NHC complexes was introduced. In addition, the silver(I) NHC complex was used to obtain the corresponding nickel(II) dihalide complex, demonstrating the feasibility of transmetalation of monodentate NHCs from silver(I) to nickel(II).

### 8.1.3 Nickel N-heterocyclic carbene complexes in homogeneous catalysis

#### *General*

A number of nickel-NHC complex-catalyzed reactions was introduced in Chapter 1. The aim of this research was to extend and improve the use of nickel NHC complexes in homogeneous catalytic reactions. Ultimately, the use of nickel NHC complexes was successfully studied for three types of catalysis: the hydrosilylation of internal alkynes, the Kumada cross coupling of aryl halides with an aryl Grignard reagent, and the vinyl polymerization of norbornene.

#### *Monodentate NHC ligands - Hydrosilylation*

The synthesis of a variety of nickel(II) dihalide complexes of monodentate N-heterocyclic carbenes bearing small substituents is described in Chapter 3. These complexes were used as catalysts in the hydrosilylation of internal alkynes, which is an important route toward vinylsilanes. The majority of investigations concerning catalytic hydrosilylation reported to date focus on terminal alkynes and often use precious metals as catalyst. In the study described in this thesis, the active catalyst is a nickel(0) species, which is generated *in situ* by a reaction of the nickel(II) NHC precursor complex with diethylzinc. Using a protocol in which the catalyst is activated before the reagents are added, two of the $Ni(NHC)_2I_2$ complexes were found to be active catalysts for the hydrosilylation of 3-hexyne with triethylsilane; full conversion was reached within 60 minutes at 5 mol% catalyst loading at 50 °C. The (*E*)-product, in which the hydrogen and the silane are located on the same face of the double bond, is obtained selectively in all cases.

As the NHCs in this catalytic system are only coordinated as a monodentate ligand, there is a possibility that the ligand dissociates, possibly leading to free nickel metal or nanoparticles. To be sure that the observed catalytic activity is not the result of any heterogeneous nickel species, two tests to distinguish between homogeneous and heterogeneous catalysis were performed. First, all catalytic runs were repeated with 100 equivalents of mercury present, as this is a known poison for heterogeneous catalysts. Second, the catalyst concentration was varied, as in a homogeneous system the catalytic activity should increase linearly with catalyst concentration, while for a heterogeneous system this is not the case. The results of both tests clearly showed that the active catalyst must be a homogeneous species.

#### *Chelating NHC ligands - Kumada cross coupling*

Early attempts to isolate *cis*-chelating bisNHC nickel dihalide complexes were unsuccessful and in stead yielded dicationic homoleptic tetracarbene complexes,[2] or intractable mixtures.[3] The only *cis*-[(bisNHC)$NiX_2$] complex was reported in the literature was prepared from a rigid, cyclic bisimidazolium salt, in which the two imidazolium rings are connected by two $C_4$ bridges.[4] The synthesis and characterization of a number of nickel(II) dihalide complexes of bidentate benzimidazole-based bisNHC ligands is described in Chapter 4. The reason why it is possible to obtain these complexes with benzimidazole-based carbenes, while with imidazole-based carbenes the synthesis failed, remains to be elucidated. Nonetheless, the solid-state structures of four of these complexes were determined by single-crystal X-ray diffraction, providing evidence for the proposed square-planar *cis*-geometry. In addition, two nickel complexes with a macrocyclic bisNHC ligand were successfully prepared.

The novel nickel bisNHC complexes were investigated for their catalytic activity in the Kumada cross coupling of aryl chlorides and bromides with phenyl magnesium chloride at room temperature. This reaction is an effective and economically attractive route for the synthesis of C–C coupled diaryls, even though it lacks a high functional group tolerance. With the exception of the complexes bearing cyclic bisNHC ligands, all complexes are moderately to highly active in this reaction. The most efficient catalyst for both aryl halides found in this study is a benzyl-substituted nickel bisNHC complex, giving full conversion of 4-chloroanisole in less then 14 h, with a selectivity of 99% to the desired product 4-methoxybiphenyl with 3 mol% catalyst loading, and full conversion of 4-bromoanisole in 75 min, with a selectivity of 82%, under the same conditions. Furthermore, it was observed that the catalytic activity of the nickel complexes is dependent on the bulk of the substituents on the bisNHC ligand: in the case of the 4-bromoanisole the rate decreased with an increase in bulk, while with 4-chloroanisole the rate increased with more bulky ligands. From this it was concluded that the rate-determining step of the catalytic cycle is dependent on the leaving group of the starting material.

It is interesting to mention that, simultaneous with and independent from the publication of the work on nickel bisNHC complexes in the Kumada coupling described in Chapter 4, the group of Huynh also reported the synthesis, crystal structure and use of the nickel(II) dibromide complex bearing a methyl substituted, propanediyl-bridged bisNHC ligand (**3a**) in the same reaction.[5] In addition, they attempted to obtain the analogous complex using a methylene bridged bisbenzimidazolium salt. In this case, however, a dicationic nickel complex with two chelating bisNHC ligands was obtained, probably due to the smaller chelate ring of the methylene bridged ligand, compared to the propylene bridged one. In contrast to the work described in Chapter 4, in which a range of different complexes is tested with one substrate, Huyhn *et al.* used complex **3a** to cross-couple a variety of aryl halides with phenyl or *p*-tolyl magnesium bromide. Good to excellent yields are obtained of the desired products, using 1 mol% catalyst, after reacting for 12 h at room temperature. In addition, it is reported that the homoleptic bis(bisNHC) nickel complex and a nickel dihalide complex with two monodentate benzimidazole-based NHC ligands are able to catalyze the coupling, although they are less active than complex **3a**. Unfortunately, the evolution of products was not followed in time, and side products are not reported, so no conclusions about the "true" catalytic activities with these substrates may be drawn.

The continuing search for an efficient Kumada coupling catalyst is described in Chapter 5. It was decided to attempt to synthesize nickel complexes bearing chelating NHC ligands, in which the NHC is functionalized with an anionic donor moiety. Based on the complexes introduced by Liao *et al.*,[6] a number of complexes bearing amido- and benzimidazolato-functionalized NHCs were prepared and characterized by single-crystal X-ray diffraction. Surprisingly, these complexes are highly active in the Kumada coupling of 4-chloroanisole with phenylmagnesium chloride, under the conditions used in Chapter 4. The benzimidazolato-functionalized complex shows the highest activity and efficacy in this reaction reported to date, yielding the desired product in quantitative yields within 30 min, even with only 1 mol% catalyst loading. In addition, the less reactive 4-fluoroanisole could be coupled quantitatively in 150 min, under the same conditions. It is proposed that the high rate of these catalysts may be explained by a cooperative interaction between the anionic N-donor side group, magnesium halide, and the substrate, allowing for faster oxidative addition of the substrate to the nickel center.

### *DFT studies*

To conclude the investigations into the nickel-catalyzed Kumada coupling an attempt was undertaken to rationalize the results of the catalytic experiments described in Chapter 4. Using density functional theory (DFT), the complete catalytic cycle of this reaction using a nickel bisNHC complex was calculated. The results of these quantum-chemical calculations are presented in Chapter 6 and show the feasibility of the generally accepted cycle, which consists of oxidative addition of the aryl halide, transmetalation of the halide and the second aryl with the Grignard reagent, and reductive elimination of the coupling product. The oxidative addition was shown to start with coordination of the aryl halide to the starting Ni(0) species, followed by insertion of the nickel center into the C–X bond to give a *cis*-coordinated nickel(II) species. In the second step, the arylmagnesium chloride is coordinated between the nickel-bound aryl and halide and, following a transition state comprising a 4-membered Ni–C–Mg–X ring, the new aryl group and the halide exchange positions. This leads to an MgXCl moiety, located between two nickel-coordinated aryl rings, which dissociates. In the third step, the two remaining aryl groups form a C–C bond, following a three-membered transition state, and the coupled product dissociated to yield the starting nickel(0) species.

In addition to the cycle leading to the desired product, a route was proposed, starting from an intermediate of the transmetalation sequence, which would effectively lead to scrambling of the aryl rings of the two starting materials. This route excellently explains all sideproducts observed in the experimental studies.

The calculated energy profile of the full catalytic cycle shows barriers of nearly equal magnitude for all three steps of the cycle, which is consistent with the change in rate-determining step when changing leaving groups. Unfortunately, this also hampers a clear cut conclusion about the exact rate-determining step under experimental conditions.

### *Vinyl polymerization of norbornene*

The last type of homogeneous catalysis under experimental investigation in this research is the vinyl polymerization of norbornene, which is presented in Chapter 7. Due to their good thermal resistance and transparency, polynorbornenes are of interest for a number of optical and electronic applications and their catalytic synthesis has been reported with numerous nickel complexes with N, O, and P-donor ligands. Only two examples of nickel NHC complexes in this reaction are known, and it was decided to investigate the activity of complexes of the three types described in Chapters 3-5, *i.e.* a complex with monodentate NHC ligands, two complexes with a chelating bisNHC ligand, and two complexes with anionic bidentate N-donor functionalized NHC ligands.

Activated by a relatively low 500-fold excess of methylaluminoxane (MAO) the three complex types showed good to high activity, over a range of temperatures in dichloromethane or 1,2-dichloroethane. The polymeric products were shown by IR spectroscopy and NMR spectrometry be of the vinyl-polymerized type and were of high molecular weight and narrow polydispersity (as determined with size exclusion chromatography). Of the three types of catalysis under investigation, the N-donor functionalized complexes were the least active, while the highest activity of $2.6 \times 10^7$ g/(mol cat)·h was obtained with the small diiodidobis(1,3-dimethylimidazol-2-ylidene)nickel(II).

## 8.2 Concluding remarks and outlook

The aim of the research described in this thesis was to design and prepare nickel complexes with N-heterocyclic carbene ligands and to use these complexes in homogeneous catalysis. The fact that three distinct types of nickel-NHC complexes could be obtained and used in three very different types of catalysis is a clear demonstration of the great flexibility of NHCs and the potential of their complexes as versatile, stable and efficient homogeneous catalysts in a wide range of reactions. Even though the present research was mainly curiosity-driven, the results may lead to more efficient, economically attractive, and environmentally friendly catalytic processes. For instance, if the precious metals (Pd, Pt, Rh) generally used in catalysis could be replaced by nickel, if phosphane ligands with their elaborate synthesis could be replaced by NHCs, or if C–C couplings reactions have only magnesium salts as byproducts this would save costs and avoid environmentally unfriendly chemicals.

Research is never finished and many research areas have not been explored in the work described in this thesis. A few subjects involving nickel NHC complexes which may be of interest for future investigations are listed below.

In the hydrosilylation of alkynes described in Chapter 3, only two symmetric alkynes were used as substrates. It should be interesting to see the regioselectivity of the catalyst in the case of an asymmetric internal alkyne. It is expected that the shape and size of the NHC ligand will have a large influence on this selectivity.

In the studies on the Kumada cross coupling described in Chapter 4 and 5, the catalysts have only been tested against 4-haloanisoles. It should be very exciting to see how these catalysts perform with more challenging substrates, especially the highly efficient N-donor functionalized complexes of Chapter 5. Relevant challenges are ortho-substituted aryl halides, heteroaryl halides and Grignard reagents, and polyhalogenated aromatic rings. A major limitation of the Kumada cross coupling is the poor functional-group tolerance, which may be addressed by using highly active nickel NHC complexes. For instance, the coupling to cyanoaryl halides would lead to cyanobiphenyl molecules, which are relevant for drug synthesis. In addition, the cross coupling of alkyl and aryl reagents would worthwhile to investigate.

The nickel-catalyzed vinyl-polymerization studies on norbornene described in Chapter 7, although preliminary, clearly show that next to the often used polydentate N, O and P-donor ligands, mono- and bidentate NHC ligands may be used for this type of reaction as well. The real benefit of nickel NHC complexes should be made clear by testing them against less strained olefins and using them in the preparation of copolymers.

The catalytic processes under investigation in this research have all been reported in the literature before, using other types of catalyst. A larger challenge would be to actually find a novel catalytic process, for which the NHC ligand is an essential component of the catalytic system and for which other ligand types are unsuitable. Especially in catalytic reactions in which the metal center would benefit from elevated electron density, such as those involving an oxidative addition, NHCs may prove to be of importance. In that respect, the use of NHC ligands with anionic side groups should be investigated further. If the mechanism proposed in Chapter 5 is indeed correct, the use of such ligands in catalysis should be very beneficial for all kinds of reactions involving oxidative additions of aryl or alkyl halides, as the anionic side group has interaction with the substrate or leaving group, while the NHC ensures stable coordination of the ligand.

Although not directly applicable to the catalytic reactions under study in this thesis, the use of chiral substituents on the NHC ligands may lead to stereoselective synthesis. Some examples of chiral NHC ligands in homogeneous catalysis have started to emerge, leading to good enantioselectivities in a number of cases.[7]

Even though the field of N-heterocyclic carbenes has only come to full activity in the last decade, a vast amount of exciting and promising applications in homogeneous catalysis has already been disclosed. The work described in this thesis has extended the field with some highly active catalysts, and has provided insight in the versatile chemistry of nickel N-heterocyclic carbene complexes.

## 8.3 References

(1) Newman, C. P.; Clarkson, G. J.; Rourke, J. P. *J. Organomet. Chem.* **2007**, *692*, 4962.
(2) Herrmann, W. A.; Schwarz, J.; Gardiner, M. G.; Spiegler, M. *J. Organomet. Chem.* **1999**, *575*, 80.
(3) Douthwaite, R. E.; Green, M. L. H.; Silcock, P. J.; Gomes, P. T. *Organometallics* **2001**, *20*, 2611.
(4) Baker, M. V.; Skelton, B. W.; White, A. H.; Williams, C. C. *J. Chem. Soc.-Dalton Trans.* **2001**, 111.
(5) Huynh, H. V.; Jothibasu, R. *Eur. J. Inorg. Chem.* **2009**, 1926.
(6) Liao, C. Y.; Chan, K. T.; Chang, Y. C.; Chen, C. Y.; Tu, C. Y.; Hu, C. H.; Lee, H. M. *Organometallics* **2007**, *26*, 5826.
(7) Douthwaite, R. E. *Coord. Chem. Rev.* **2007**, *251*, 702.