

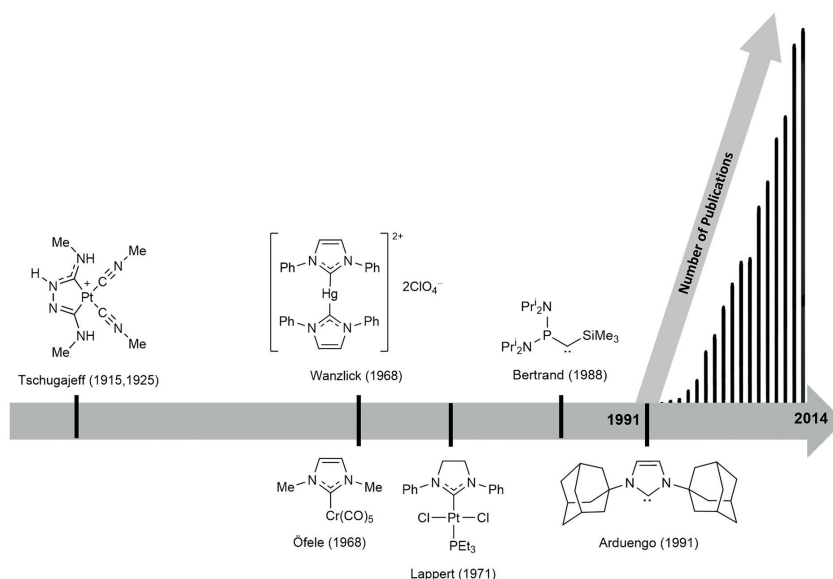
Abstracts

p 1

1.1.1 Historic Perspectives on Carbenes

F. Nahra and C. S. J. Cazin

This chapter provides a brief overview of the historical development of N-heterocyclic carbenes, from inception to isolation of the first stable aminocarbene, followed by the early applications of N-heterocyclic carbene–metal complexes as catalysts.



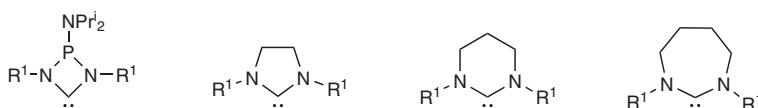
Keywords: N-heterocyclic carbenes • stable carbenes • metal–carbene complexes • ligands • catalysts

p 5

1.1.2 Types of N-Heterocyclic Carbenes

C. Segarra and M. Albrecht

This chapter discusses the different types of N-heterocyclic carbenes (NHCs) and is organized according to ring size. The terminology for describing NHCs as normal or abnormal (mesoionic) and remote or nonremote is outlined. The pertinent properties of these different NHCs are compiled, in particular the ^{13}C NMR spectroscopic and crystallographic parameters, as well as steric and electronic effects, which provides insights into the donor properties of the various classes of NHCs.

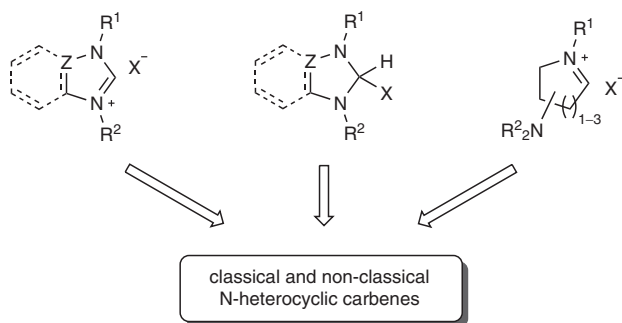


Keywords: N-heterocyclic carbenes • normal carbenes • abnormal carbenes • mesoionic • remote carbenes • nonremote carbenes • imidazolylienes • triazolylienes • pyrazolylienes • cyclic alkyl(amino)carbenes • pyrimidylidenes • pyridylidenes

1.1.3 Synthesis of N-Heterocyclic Carbenes and Their Precursors

H. V. Huynh and D. Yuan

An overview of common methodologies for the preparation of free N-heterocyclic carbenes (NHCs) and their respective precursors is given. In addition to classical five-membered NHCs, examples of less-explored non-classical NHCs, including mesoionic and ring-expanded species, are also described. Experimental procedures reported in the primary literature are included for selected key compounds.

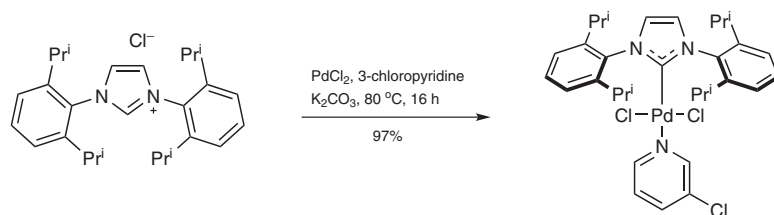


Keywords: N-heterocyclic carbenes • carbene dimers • carbene precursors • azolium salts • cyclic thioureas

1.1.4 Synthesis of N-Heterocyclic Carbene Complexes

M. Ruamps, G. Lavigne, and V. César

This chapter describes the main synthetic pathways to access N-heterocyclic carbene-metal complexes. Routes covered include the complexation of free carbenes, metal-induced decomposition of carbene adducts, in situ generation of carbenes in the presence of metals, transmetalation, and templated synthesis from isocyanides.

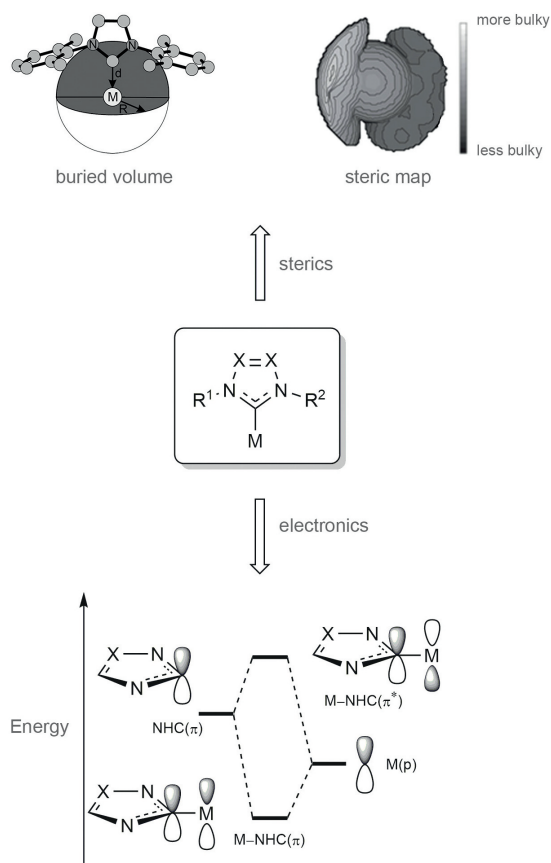


Keywords: N-heterocyclic carbenes • carbenes • complexes • heterocycles • deprotonation • transmetalation • isocyanides • template synthesis

1.1.5 Quantifying Steric and Electronic Properties of N-Heterocyclic Carbenes

S. V. C. Vummaleti, L. Falivene, and L. Cavallo

This chapter gives an overview of the most-used methods to evaluate the steric and electronic properties of N-heterocyclic carbenes (NHCs). Quantification of these properties allows for a straightforward and quantitative comparison between different NHCs, allowing for a more enlightened selection of the appropriate carbene for any given application.

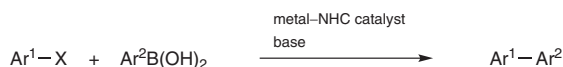


Keywords: buried volume • density functional theory • electronic properties • N-heterocyclic carbenes • NMR methods • paramagnetic shielding • steric maps • steric properties

1.2.1 Suzuki–Miyaura Coupling

M. J. Chetcuti

The Suzuki–Miyaura reaction of an organoboronic acid (usually an arylboronic acid) with an organo halide (typically an aryl halide) to generate a new C–C bond is one of the most valuable methods for C–C bond formation. Since the ascension of N-heterocyclic carbenes (NHCs) to occupy the position of key ligands in the repertoire of synthetic organometallic chemists, metal complexes based on these ligands have become important as catalysts for the Suzuki–Miyaura reaction. Most metal–NHC complexes used for Suzuki–Miyaura coupling are based on palladium, but an increasingly important contribution is being played by nickel-based complexes. This chapter reviews the state of the art of Suzuki–Miyaura coupling reactions catalyzed by metal–NHC complexes, with a focus on systems with broad applicability, and especially those that can be applied to “difficult” reactions such as the coupling of aryl chlorides or sterically hindered substrates. The relatively undeveloped fields of asymmetric Suzuki–Miyaura reactions and Suzuki–Miyaura reactions in water, both catalyzed by metal–NHC complexes, are also covered.



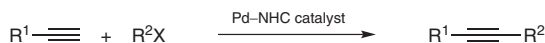
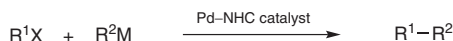
Keywords: Suzuki–Miyaura coupling · N-heterocyclic carbenes · palladium catalysis · nickel catalysis · biaryls · aryl halides · boronic acids · asymmetric synthesis · aqueous media

p 141

1.2.2 Cross-Coupling Reactions Other Than Suzuki–Miyaura Coupling

M. Ogasawara

Cross coupling between a main-group organometallic nucleophile and an organic electrophile is one of the most powerful C–C bond-forming reactions in modern organic synthesis. Various palladium–N-heterocyclic carbene (NHC) complexes have been utilized in a wide range of cross-coupling reactions. The palladium–NHC systems outperform the classical palladium–phosphine catalysts in many cases, and they have solved several long-standing limitations of the classical cross-coupling protocols. This chapter covers cross couplings mediated by palladium–NHC complexes in which the nucleophile is an organomagnesium (Kumada–Tamao–Corriu coupling), an organozinc (Negishi coupling), an organotin (Stille coupling), an organosilicon (Hiyama coupling), or an organolithium, as well as Sonogashira-type couplings of alkynes.



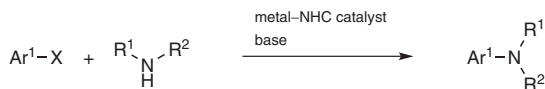
Keywords: cross coupling · N-heterocyclic carbenes · palladium catalysis · organomagnesium · Kumada–Tamao–Corriu coupling · organozinc · Negishi coupling · organotin · Stille coupling · organosilicon · Hiyama coupling · organolithium · Sonogashira coupling

p 161

1.2.3 The Buchwald–Hartwig Reaction

A. R. Martin

This chapter covers the use of N-heterocyclic carbenes as ligands in the Buchwald–Hartwig reaction. The most efficient and convenient palladium- and nickel-based catalytic systems able to promote the C–N bond formation between various amines and (het)aryl halides or pseudohalides are reviewed.



Keywords: N-heterocyclic carbenes · palladium · nickel · C–N bond formation · Buchwald–Hartwig coupling · aryl halides · hetaryl halides · pseudohalides · trifluoromethanesulfonates · 4-toluenesulfonates · pivalates · phosphates · carbamates · sulfamates · amines

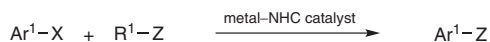
p 183

1.2.4 C–O, C–S, and C–B Bond Formation

T. O. Ronson and I. J. S. Fairlamb

This chapter describes the formation of C–O, C–S, and C–B bonds mediated by N-heterocyclic carbene based transition-metal catalysts. These reactions represent efficient and

economical methods to prepare aryl ethers, phenols, sulfides (thioethers), aryl sulfoxides, and aryl boronates, all of which are important as synthetic intermediates or target compounds in natural product and materials chemistry. The transformations can be mediated by a range of metals including palladium, copper, nickel, and zinc, and the chapter is arranged accordingly.



X = I, Br, Cl; Z = OR², SR², BR²₂; metal = Pd, Cu, Ni, Zn

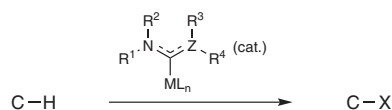
Keywords: N-heterocyclic carbenes • C—O bond formation • C—S bond formation • C—B bond formation • ethers • phenols • sulfides • sulfoxides • boronates • aryl halides • thiols • cross coupling • palladium • copper • nickel • zinc

p 199

1.3 C—H Bond Functionalization

M. Elie, J.-L. Renaud, and S. Gaillard

This chapter deals with C—H bond functionalization catalyzed by N-heterocyclic carbene transition-metal complexes. The C—H bond functionalizations have been classified with respect to the hybridization of the carbon atom and the reaction type.



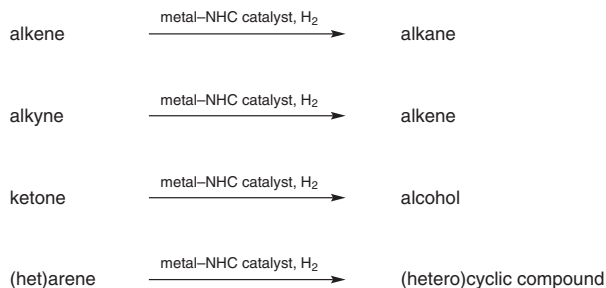
Keywords: C—H bonds • metal–carbene complexes • ligands • imidazoles • imidazolylidenes • N-heterocyclic carbenes

p 261

1.4.1 Hydrogenation

Y. Makida and R. Kuwano

From the viewpoint of atom economy and cost efficiency, hydrogenation is an ideal way to reduce various multiple bonds. In this chapter, some methods are described for the hydrogenation of alkenes, alkynes, carbonyls and related compounds, and (het)arenes using homogeneous metal–N-heterocyclic carbene (NHC) catalysts. Moreover, this section also covers enantioselective hydrogenations in which chiral NHCs are employed as ligands.



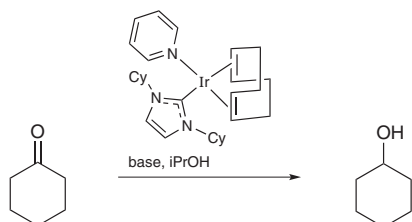
metal = Ru, Rh, Ir, Ni, Pd, etc.; NHC = IPr, SIPr, IMes, SIMes, ICy, etc.

Keywords: hydrogenation • partial hydrogenation • asymmetric hydrogenation • transition-metal catalysts • carbene ligands • alkenes • alkynes • ketones • arenes • hetarenes • heterocycles • N-heterocyclic carbenes

1.4.2 Transfer Hydrogenation

M. K. Whittlesey

The chapter describes the use of N-heterocyclic carbene (NHC) complexes of *d*-block metals for the transfer hydrogenation of C=O, C=C, C≡C, and C=N bonds, and nitro groups. Emphasis is placed on the most active metal–NHC combinations and those that incorporate valuable properties, including ease of use and inexpensive starting materials. The source of hydrogen is in most cases propan-2-ol, but formic acid/formate salts are also used.

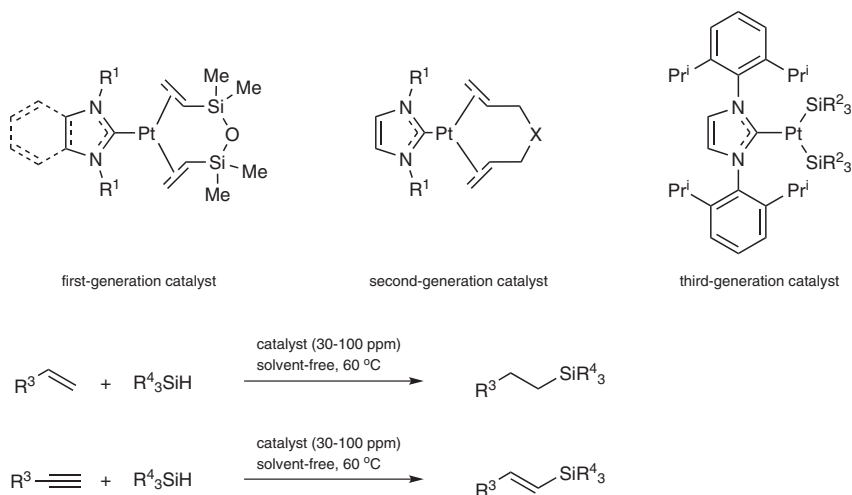


Keywords: N-heterocyclic carbenes • ruthenium • rhodium • iridium • ketones • aldehydes • alkenes • alkynes • imines • transfer hydrogenation • asymmetric hydrogenation

1.4.3 Hydrosilylation

L. Baudrenghien and I. E. Markó

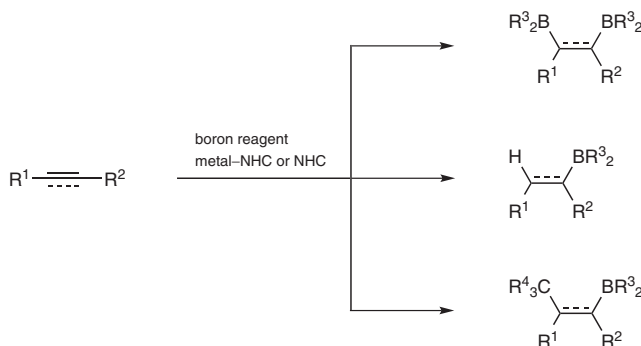
Hydrosilylation of alkenes and alkynes, promoted by various generations of now commercially available (or easily formed) platinum–N-heterocyclic carbene complexes, enables efficient access to valuable silanes. Under optimal conditions, this process constitutes an atom economical, solvent-free, green process yielding terminal alkylsilanes and β -(*E*)-vinylsilanes in a rapid, efficient, and selective manner.



Keywords: N-heterocyclic carbenes • hydrosilylation • alkenes • alkynes • alkylsilanes • vinylsilanes • platinum • siloxanes

1.4.4 Catalytic Boron Addition Reactions*A. B. Cuenca and E. Fernández*

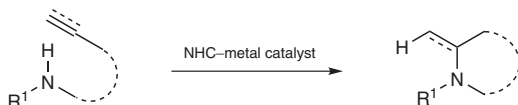
The use of N-heterocyclic carbenes (NHCs) in metal-mediated and metal-free catalytic borylation reactions is described. Special emphasis is given to the activation mode of the borane reagent by a metal–NHC complex or an NHC itself, as well as its influence on the delivery of the boryl moiety onto unsaturated substrates to generate a C–B bond efficiently and selectively. Asymmetric induction can be achieved in borylation reactions using chiral N-heterocyclic carbenes and a detailed range of examples is highlighted.



Keywords: N-heterocyclic carbenes • borylation • C–B bonds • selectivity • hydroboration • diboration • carboboration • alkenes • alkynes • carbonyl compounds • imines

1.4.5 Hydroamination*P. R. Payne and M. R. Gagné*

Hydroamination, the addition of an N–H moiety across carbon–carbon unsaturation, is an attractive, atom-economical methodology for the synthesis of nitrogen-containing compounds. N-Heterocyclic and cyclic (alkyl)(amino)carbenes have been applied as supporting ligands for the synthesis of catalysts capable of mediating both inter- and intramolecular (cyclization) reactions with alkynes, allenes, and activated alkenes.

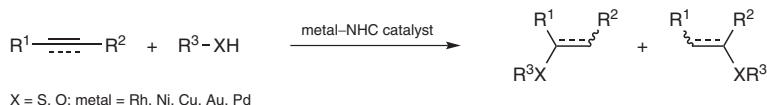


Keywords: catalytic hydroamination • C–N bond formation • N-heterocyclic carbenes • cyclic (alkyl)(amino)carbenes • nitrogen heterocycles • pyrrolidines • piperidines • amines • imines • enamines • quinolines • 1,2-dihydroquinolines • benzo[*b*][1,4]diazepines

1.4.6 Hydrothiolation, Hydroalkoxylation, and Hydroaryloxylation

P. de Frémont

Hydrothiolation, hydroalkoxylation, and hydroaryloxylation reactions of carbon–carbon triple or double bonds, which belong to the broader family of hydroelementation reactions, conveniently lead to the formation of vinyl sulfides, alkyl sulfides, vinyl ethers, or alkyl ethers. Well-defined complexes of late transition metals with N-heterocyclic carbene ligands can efficiently promote these reactions under milder conditions and with better stereo- and regiocontrol compared to other methods employing free radicals or strong acids/bases.

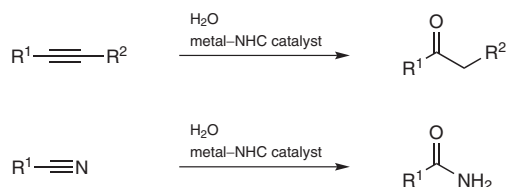


Keywords: hydrothiolation • hydroalkoxylation • hydroaryloxylation • alkenes • alkynes • allenes • ethers • thioethers • sulfides • nickel • rhodium • copper • gold • palladium • N-heterocyclic carbenes

1.4.7 Hydration

A. Biffis and C. Tubaro

The application of metal–N-heterocyclic carbene (NHC) complexes as catalysts for the addition of water to multiple bonds in organic substrates is reviewed. Protocols for general and efficient reactions of this kind under mild conditions have been developed, in particular with gold–NHC complexes as catalysts for the hydration of alkynes, which have raised the appeal of this methodology among synthetic organic chemists.

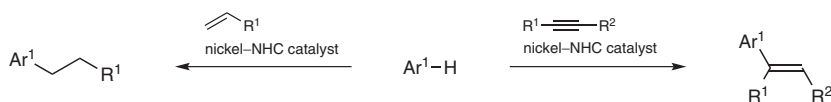


Keywords: hydration • alkynes • nitriles • allenes • catalysts • N-heterocyclic carbenes • gold

1.4.8 Hydroarylation

Y. Nakao

This chapter describes the hydroarylation and hydrohetarylation of alkenes and alkynes catalyzed by nickel–N-heterocyclic carbene complexes.

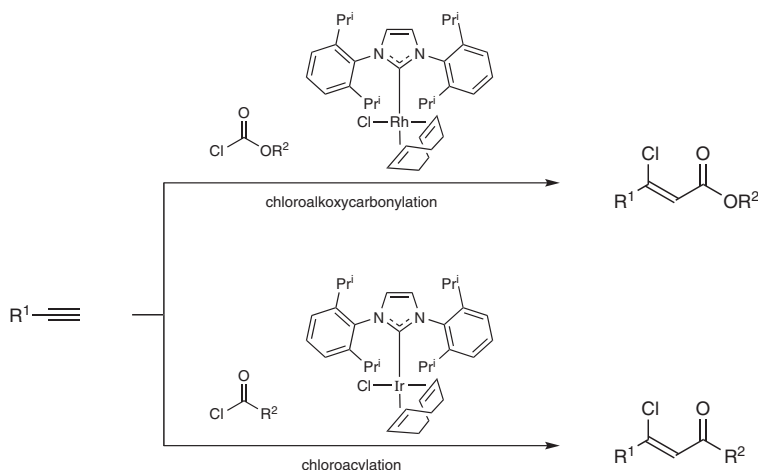


Keywords: nickel • hydroarylation • hydrohetarylation • alkynes • alkenes • N-heterocyclic carbenes

1.4.9 Chloroacylation and Chloroalkoxycarbonylation of Alkynes

D. N. Lastovickova, A. J. Teator, and C. W. Bielawski

Transition metal–N-heterocyclic carbene (NHC) complexes catalyze a broad range of chloroalkoxycarbonylation and chloroacylation reactions, while simultaneously suppressing undesirable side-reaction pathways. A rhodium–NHC complex facilitates the chloroalkoxycarbonylation of alkynes via the direct addition of chloroformates to give substituted 3-chloroacrylates. Similarly, an iridium–NHC complex enables the chloroacylation of alkynes with acid chlorides to generate β -chloro- α,β -unsaturated ketones. Both of the aforementioned transformations result in high product conversions and excellent degrees of regio- and stereoselectivity, with the *Z*-isomer often being observed as the major or only product. Iridium–NHC catalyzed chloroacylations are also utilized in the synthesis of 2,5-disubstituted furans from alkynes and acid chlorides.

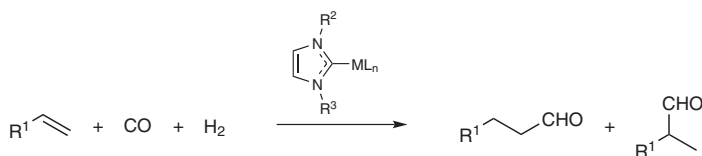


Keywords: chloroalkoxycarbonylation • chloroacylation • chloroesterification • catalysis • N-heterocyclic carbenes • carbenes • rhodium • iridium • β -chloro- α,β -unsaturated ketones • chloroacrylates • furans

1.4.10 Hydroformylation

A. M. Trzeciak

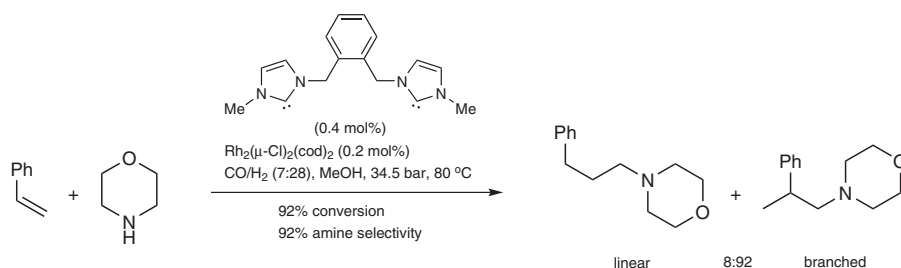
Hydroformylation of alkenes is one of the most important catalytic industrial processes performed in a homogeneous system. During hydroformylation, aldehydes are formed from alkenes and syngas (a mixture of hydrogen and carbon monoxide) in the presence of a metal complex, usually based on rhodium or cobalt. In this chapter, the catalytic application of metal complexes with N-heterocyclic carbene (NHC) ligands in hydroformylation is discussed.



Keywords: hydroformylation • homogeneous catalysis • metal–carbene complexes • N-heterocyclic carbenes • rhodium catalysis

1.4.11 Hydroaminomethylation*P. Kalck and M. Urrutigoity*

Rhodium complexes of the form $\text{Rh}(\text{Cl})(\text{NHC})(\text{cod})$ (NHC = N-heterocyclic carbene), bearing a monocarbene ligand, are efficient catalyst precursors for the synthesis of a variety of amines from alkenes through the hydroaminomethylation reaction. Starting from styrene, styrene derivatives, or other alkenes, this tandem reaction involves a hydroformylation reaction, the condensation of the produced aldehyde with a primary or secondary amine, and the hydrogenation of the resulting imine/enamine to give the expected amine. High conversion rates and chemoselectivities are obtained. Under a medium pressure of carbon monoxide/hydrogen, the active species $\text{Rh}(\text{H})(\text{NHC})(\text{CO})_2$ is presumably formed, which coordinates the alkene. High regioselectivity for the linear amine is obtained for terminal alkenes. Interestingly, high yields of the branched amine are obtained from styrene and its derivatives using a bis-carbene ligand, which should produce the $\text{Rh}(\text{H})(\text{CO})(\text{NHC})_2$ active species. The absence of decoordination of the NHC ligand allows the use of a stoichiometric carbene/rhodium ratio in catalysis.



Keywords: rhodium–carbene catalysts • alkenes • hydroaminomethylation • amines • selectivity • N-heterocyclic carbenes