CATALYSIS BY METAL COMPLEXES 32

Series Editors C. Bianchini · D.J. Cole-Hamilton
P.W.N.M. van Leeuwen
Volume Editor C.S.J. Cazin

N-Heterocyclic Carbenes in Transition Metal Catalysis and Organocatalysis

Springer

N-Heterocyclic Carbenes in Transition Metal Catalysis and Organocatalysis

CATALYSIS BY METAL COMPLEXES

This book series covers topics of interest to a wide range of academic and industrial chemists, and biochemists. Catalysis by metal complexes plays a prominent role in many processes. Developments in analytical and synthetic techniques and instrumentation, particularly over the last 30 years, have resulted in an increasingly sophisticated understanding of catalytic processes.

Industrial applications include the production of petrochemicals, fine chemicals and pharmaceuticals (particularly through asymmetric catalysis), hydrometallurgy, and waste-treatment processes. Many life processes are based on metallo-enzyme systems that catalyse redox and acid-base reactions.

Catalysis by metal complexes is an exciting, fast developing and challenging interdisciplinary topic which spans and embraces the three areas of catalysis: heterogeneous, homogeneous, and metallo-enzyme.

Catalysis by Metal Complexes deals with all aspects of catalysis which involve metal complexes and seeks to publish authoritative, state-of-the-art volumes which serve to document the progress being made in this interdisciplinary area of science.

VOLUME 32:
***N*-HETEROCYCLIC CARBENES IN TRANSITION METAL CATALYSIS AND ORGANOCATALYSIS**

Volume Editor

Catherine S. J. Cazin
EaStCHEM School of Chemistry
University of St Andrews
St Andrews, KY16 9ST
United Kingdom

Catherine S. J. Cazin
Editor

N-Heterocyclic Carbenes in Transition Metal Catalysis and Organocatalysis

Springer

Editor
Catherine S. J. Cazin
EaStCHEM School of Chemistry
University of St Andrews
St Andrews, KY16 9ST
United Kingdom
cc111@st-andrews.ac.uk

ISBN 978-90-481-2865-5 e-ISBN 978-90-481-2866-2
DOI 10.1007/978-90-481-2866-2
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2010932004

Preface

The origins of amino carbenes as ligands can be traced back almost a century to the complex first synthesised by Tschugajeff (Chugaev). Interestingly, *N*-heterocyclic carbenes (NHCs) remained a lab curiosity until the mid-1990s. A few years later, this new class of ligands exploded in the literature, so much so that NHCs have become a ubiquitous class of ligands.

During the past decade, NHCs have been coordinated to virtually all transition metals (TM) and studied in numerous catalytic transformations, pushing back the frontiers of catalysis. In this regard, the most salient examples are found in olefin metathesis and cross coupling reactions, and more recently in organocatalysis.

The monograph commences with an introductory overview of NHCs, including a complete description of their steric and electronic properties, that shatters long-standing dogmas such as "phosphine mimicry" and "inexistent pi-acidity". This sets the stage for catalytic applications that are thoroughly discussed throughout eleven chapters. The penultimate chapter is devoted to decomposition pathways of TM-NHC systems. The closing chapter brings a unique industrial context to this book by describing applications of NHCs in industrial processes, a first of its kind.

In order to provide the reader with a *fresh* perspective on NHCs, the book has been assembled mainly by young emerging researchers, most of whom studied NHCs in undergraduate classes. This is therefore a perspective from a new generation of researchers that never considered NHCs as laboratory curiosities. A complementary perspective is brought by prominent, well-established academic researchers and an industrialist.

Believe it or not, I have been associated with NHCs in one form or another for the past eleven years. I went through it all, from the frustrations of tar-making to the distress of being *scooped* past tar-stage. I have even been told to give it all up. For some reason NHCs keep crossing my path, and I find them so intriguing that I keep coming back to them. This book has been an exciting project and I hope it will trigger activity from novices and provide inspiration to researchers already in the field.

St Andrews, UK
March 2010

Catherine S. J. Cazin

Contents

Contributors

Manuel Alcarazo
Max Planck Institut für Kohlenforschung, Kaiser Wilhelm Platz 1,
45470 Mülheim an der Ruhr, Germany
alcarazo@mpi-muelheim.mpg.de

Siegfried Blechert
Technische Universität Berlin, Institut für Chemie, Sekretariat C3,
Straße des 17, Juni 135 10623 Berlin, Germany
blechert@chem.tu-berlin.de

Oliver Briel
Umicore AG & Co. KG, Rodenbacher Chaussee 4, P.O. Box 1351,
63403 Hanau-Wolfgang, Germany
oliver.briel@eu.umicore.com

Luigi Cavallo
Dipartimento di Chimica, Università di Salerno, Via ponte don Melillo,
84084 Fisciano SA, Italy
lcavallo@unisa.it

Kingsley J. Cavell
School of Chemistry, Cardiff University, Main Building, Park Place,
CF10 3AT Cardiff, UK
Cavellkj@cf.ac.uk

Catherine S. J. Cazin
EaStCHEM School of Chemistry, University of St Andrews,
St Andrews, KY16 9ST, UK
cc111@st-andrews.ac.uk

Andreas A. Danopoulos
School of Chemistry, University of Southampton, Highfield SO17 1BJ, UK
ad1@soton.ac.uk

Reto Dorta
Organic Chemistry Institute, University of Zurich, Winterthurerstrasse 190,
8057 Zurich, Switzerland
dorta@oci.uzh.ch

Janis Louie
Department of Chemistry, University of Utah, Salt Lake City,
Utah 84112-0850, USA
louie@chem.utah.edu

David S. McGuinness
School of Chemistry, University of Tasmania, Private Bag 75, Hobart,
Tasmania 7000, Australia
David.McGuinness@utas.edu.au

Oscar Navarro
Department of Chemistry, University of Hawaii at Manoa, Honolulu,
Hawaii 96822, USA
oscarnf@hawaii.edu

Christian Slugovc
Institute for Chemistry and Technology of Materials (ICTM),
Graz University of Technology, 8010 Graz, Austria
slugovc@tugraz.at

Andrew D. Smith
EaStCHEM School of Chemistry, University of St Andrews,
St Andrews, KY16 9ST, UK
ads10@st-andrews.ac.uk

Adam Veige
Department of Chemistry, Center for Catalysis, University of Florida,
P.O. Box 117200, Gainesville, FL, USA
veige@chem.ufl.edu

Michael K. Whittlesey
Department of Chemistry, University of Bath, Claverton Down,
Bath BA2 7AY, UK
m.k.whittlesey@bath.ac.uk

Jonathan M. J. Williams
Department of Chemistry, University of Bath, Claverton Down,
Bath BA2 7AY, UK
j.m.j.williams@bath.ac.uk

Abbreviations

Å	angstrom(s)
AAA	Asymmetric Allylic Alkylation
acac	acetylacetonate
ACM	Asymmetric Cross-Metathesis
ADMET	Acyclic Diene Metathesis
AE	allyl ether
aNHC	*abnormally* bound NHC
ALTMET	Alternating Diene Metathesis Polycondensation
AM3	Amphidinol 3
Ar	aryl
AROCM	Asymmetric Ring Opening Cross Metathesis
AT	Advanced Technology
atm	atmosphere(s)
ATRP	Atom-Transfer Radical Polymerisation
av	average
BAr_4^F	tetrakis[3,5-bis(trifluoromethyl)phenyl]borate
BBN	borabicyclo[3.3.1]nonyl
$(Bcat)_2$	bis(catecholato)diboron
BDE	Bond Dissociation Energy
β-elim.	β-elimination
binap	2,2′-bis(diphenylphosphino)-1,1′-binaphthyl
bipy	2,2′-bipyridine
b:l	branched:linear ratio
$bmim^+$	1-*n*-butyl-3-methylimidazolium
bmiy	1-*n*-butyl-3-methylimidazolin-2-ylidene
Bn	benzyl
Boc	*tert*-butoxycarbonyl
$(Bpin)_2$	bis(pinacolato)diborane
Bu	butyl
^{t}Bu	*tert*-butyl
Bz	benzoyl

ºC	degrees Celsius
ca.	*circa*
CAAC	cyclic (alkyl)(amino)carbenes
cal	calorie(s)
cat.	catalyst
cf	*confer*
CM	Cross Metathesis
cm^{-1}	wavenumber(s)
COD	1,5-cyclooctadiene
COE	cyclooctene
Conv.	conversion
Cp	cyclopentadienyl
Cp*	1,2,3,4,5-pentamethylcyclopentadienyl
Cy	cyclohexyl
d	days
Δ	heat
dr	diastereomeric ratio
dba	dibenzylidene acetone
DBM	dibenzoylmethane
DBU	1,8-diazabicyclo[5.4.0]undec-7-ene
DBP	phenyldibenzophosphole
DCE	1,2-dichloroethane
de	diastereomeric excess
Dec	decyl
DFT	Density Functional Theory
DIBAL-H	di-*iso*-butylaluminium hydride
DIPEA	diisopropylethylamine (Hunig's base)
DMA	dimethylacetamide
DME	dimethoxyethane
DMF	dimethylformamide
DMI	1,3-dimethyl-2-imidazolidinone
dmpe	dimethylphosphinoethane
DMSO	dimethylsulphoxide
DPC	diphenyl carbonate
dppe	(diphenylphosphino)ethane
dppf	(diphenylphosphino)ferrocene
dppp	1,3-bis(diphenylphosphino)propane
dr	diastereomeric ratio
dvds	1,3-divinyltetramethyldisiloxane
dvtms	divinyltetramethylsiloxane
$E_{1/2}$	half-wave potential
E_{act}	activation energy
ECM	Enyne Cross Metathesis
EDA	ethyldiazoacetate

ee	enantiomeric excess
e.g.	for example
$emim^+$	1-ethyl-3-methylimidazolium
emiy	1- ethyl-3-methylimidazolin-2-ylidene
Ent	enantiomeric
equiv	equivalent
Et	ethyl
et al.	*et alii*
EWG	Electron Withdrawing Group
Fc	ferrocenyl
FDA	US Food and Drug Administration
g	gram(s)
GC	Gas Chromatography
gem	geminal
GSK	Glaxo Smith Kline
h	hour(s)
Hbbtm	*bis*-{benzothiazol-2-yl}methane
HBpin	pinacolborane
HCV	Hepatitis C Virus
Hex	hexyl
HMDS	hexamethyldisilazane
HNBR	Hydrogenated Nitrile Butadiene Rubbers
HOAt	1-hydroxy-7-azabenzotriazole
HOBt	hydroxybenzotriazole
Hz	Hertz
IAd	1,3-diadamantylimidazolium
ICy	*N,N'*-(dicyclohexyl)imidazol-2-ylidene
IDTB	*N,N'*-bis-[2,5-(di-*tert*-butyl)phenyl]imidazol-2-ylidene
i.e.	*id est*
IiPr	*N,N'*-(di-*iso*-propyl)imidazol-2-ylidene
IL	Ionic Liquid
Im	Imidazolium
IMe	*N,N'*-(dimethyl)imidazol-2-ylidene
IMes	*N,N'*-bis-[2,4,6-(trimethyl)phenyl]imidazol-2-ylidene
Inc.	Incorporated
IND	Investigational New Drug
IP	Intellectual Property
IPr	*N,N'*-bis-[2,6-(di-*iso*-propyl)phenyl]imidazol-2-ylidene
IR	Infrared
I*t*Bu	*N,N'*-(di-*tert*-butyl)imidazol-2-ylidene
ITM	1,3,4,5-tetramethylimidazol-2-ylidene
ITmt	*N,N'*-bis(2,2",6,6"-tetramethyl-*m*-terphenyl-5'-yl)imidazole-2-ylidene

ITol	*N,N'*-bis-(4-methylphenyl)imidazol-2-ylidene
J	coupling constant
J	joule(s)
k	kilo
L	litre(s)
Load.	loading
μ	micro
M	molar
M	metal
m	milli
m	*meta*
MAH	maleic anhydride
MALDI-TOF MS	Matrix-Assisted Laser Desorption Ionisation Time-Of-Flight Mass Spectrometry
MAO	methylaluminoxane
Me	methyl
Mes	mesityl (2,4,6-trimethylphenyl)
min.	minutes
MMA	methyl methacrylate
MMAO	modified methylaluminoxane
MOM	methoxymethylether
MS	Molecular Sieves
mV	millivolt
n	*normal*
nbd	norbornadiene
NHC	*N*-Heterocyclic Carbene
NMO	*N*-methylmorpholine-*N*-oxide
NMP	*N*-methyl-2-pyrrolidone
NMR	Nuclear Magnetic Resonnance
o	*ortho*
OAc	acetate
OTf	trifluoromethanesulfonate
p	*para*
PCBs	polychlorinated biphenyls
PCs	polycarbonates
PG	Protecting Group
Ph	phenyl
Piv	pivaloyl
POPs	Persistent Organic Pollutants
Pr	propyl
^{i}Pr	*iso*-propyl
Ph	phenyl

pin	pinacol
Piv	pivaloyl
PMP	*para*-methoxyphenyl
ppm	parts per million
psi	pound per square inch
quant.	quantitative
rac	racemic
RCM	Ring Closing Metathesis
R. E.	Reductive Elimination (Red. Elim.)
Ref	reference
REMP	Ring Expansion Metathesis Polymerisation
ROCM	Ring Opening Cross Metathesis
ROIMP	Ring Opening Insertion Metathesis Polymerisation
ROMP	Ring Opening Metathesis Polymerisation
RRM	Ring Rearrangement Metathesis
rt	room temperature
SEM	2-(trimethylsilyl)ethoxy-methyl
SICy	*N,N'*-(dicyclohexyl)imidazolidin-2-ylidene
SIEt	*N,N'*-(diethyl)imidazolidin-2-ylidene
SIMes	*N,N'*-bis[2,4,6-(trimethyl)phenyl]imidazolidin-2-ylidene
SIPr	*N,N'*-bis[2,6-(diisopropyl)phenyl]imidazolidin-2-ylidene
Substr.	substrate
syngas	synthesis gas $CO:H_2$ mixture
T	temperature
TASF	tris(dimethylamino)sulfonium difluorotrimethylsilicate
TBAF	tetra-*n*-butylammonium fluoride
TBDPS	*tert*-butyldiphenylsilyl
TBHP	*tert*-butyl hydroperoxide
TBS	*tert*-butylsilyl
TEP	Tolman Electronic Parameter
TES	triethylsilyl
Tf	trifluoromethanesulfonyl (triflyl)
TFA	trifluoroacetic acid
TFAA	trifluoroacetic anhydride
thf	tetrahydrofuran
TIMEN	tris[2-(3-alkylimidazol-2-ylidene)ethyl]amine
TM	Transition Metal
TMHD	2,2,6,6-tetramethyl-3,5-heptanedionate
tmiy	1,3,4,5-tetramethylimidazol-2-ylidene
TMPDA	tetramethylpropylenediamine
TMS	trimethylsilyl
TOF	Turnover Frequency
Tol	tolyl

TON	Turnover Number
TS	Transition State
Ts	*para*-toluenesulfonyl (tosyl)
ν_{av}	average value of stretching frequencies in IR
$\%V_{Bur}$	Percent Volume Buried

Chapter 1
N-Heterocyclic Carbenes: An Introductory Overview

Luigi Cavallo and Catherine S. J. Cazin

Abstract *N*-heterocyclic carbenes (NHCs) are probably the class of ligands that not only has attracted the most attention during the past decade, but also for which the greatest advances have been made. These include a wider availability, applicability and understanding. In this chapter, an overview of all aspects of NHCs is given, starting with an historical discussion that begins almost a century ago. An inventory of the structural diversity of NHCs found in the literature is given, followed by the nomenclature of NHCs and the trivial names used. A section is devoted to the synthetic strategies developed for the formation of NHC-precursors, NHC ligands and NHC-complexes. The most diagnostic spectroscopic features of NHCs and NHC complexes are listed as well as the manner in which NHCs are usually represented. NHCs have become indubitably one of the most important and unique class of ligands as they have very distinctive and interesting electronic and steric features. A large section of this chapter is hence devoted to the discussion of these features and presents the recent advances made for determination of NHC properties and their understanding.

1.1 Generalities

1.1.1 Historical Aspects

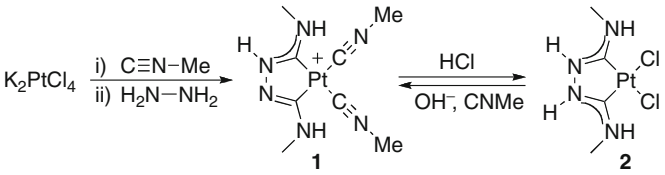
N-Heterocyclic carbenes (NHCs) have become an incontrovertible class of molecules for transition-metal- (TM) and organo-catalysis. Inception of the field dates back almost a century ago when Tschugajeff (Chugaev) and co-workers reacted

L. Cavallo (✉)
Dipartimento di Chimica, Università di Salerno, Via ponte don Melillo,
84084 Fisciano, SA, Italy
e-mail: lcavallo@unisa.it

C. S. J. Cazin (✉)
EaStCHEM School of Chemistry, University of St Andrews,
St Andrews, KY16 9ST, UK
e-mail: cc111@st-andrews.ac.uk

C. S. J. Cazin (ed.), *N-Heterocyclic Carbenes in Transition Metal Catalysis and Organocatalysis*, Catalysis by Metal Complexes 32,
DOI 10.1007/978-90-481-2866-2_1,

potassium tetrachloroplatinate with methyl isocyanide, followed by the addition of hydrazine [1, 2]. Contrarily to the authors' expectations, this reaction does not lead to a dimeric species composed of tetracyanide platinum moieties bridged by hydrazine molecules, but leads to a compound that is probably the first diamino carbene complex isolated in pure form. The structure of this salt **1**, and the one of its biscarbene derivative **2**, were only solved decades later (Scheme 1.1) [3–6]. It was later shown that this methodology is applicable to the synthesis of NHC complexes when functionalised isocyanides are used [7].



Scheme 1.1 Tschugajeff's (Chugaev) carbene complexes [1, 2]

In the early 1960s, Wanzlick pioneered investigations on NHCs [8]. This was followed by the first description of NHCs as ligands for metal complexes [9, 10]. However, it is only in the 1990s that this new class of ligands was brought under the spotlight. Firstly by Arduengo's seminal isolation and characterisation of a free NHC [11], secondly by the recognition that NHCs could act as promising ligands for homogeneous catalysts [12]. These reports ignited the curiosity of researchers as the possible role of NHCs as ligands was revealed, an interest that has seen an incredible research activity (Fig. 1.1).

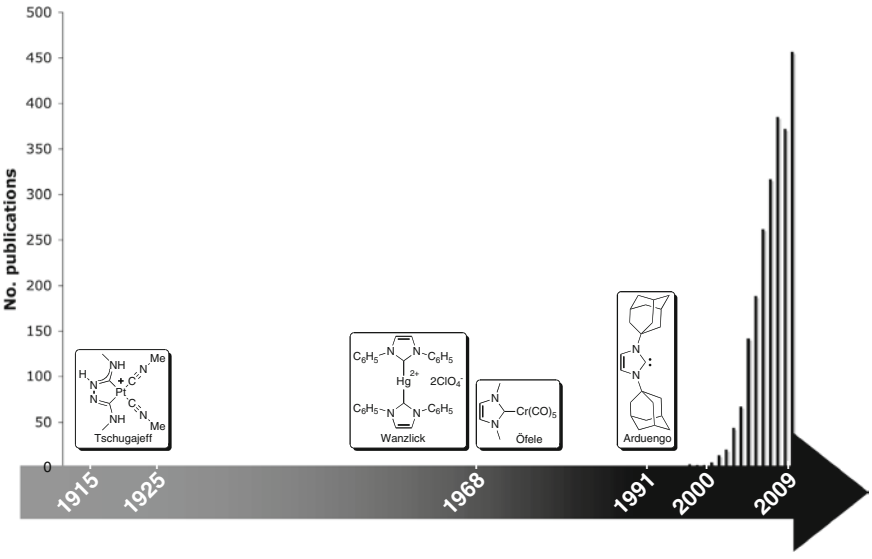


Fig. 1.1 Number of publications (*N-heterocyclic carbene* as research topic)

1.1.2 Structural Diversity of NHCs

At the origin of this abundance of publications on *N*-heterocyclic carbenes is the structural ligand diversity now available (Fig. 1.2). This developing area is noteworthy as most early developments were mainly focused on imidazolylidene and imidazolidinylidene NHC-types.

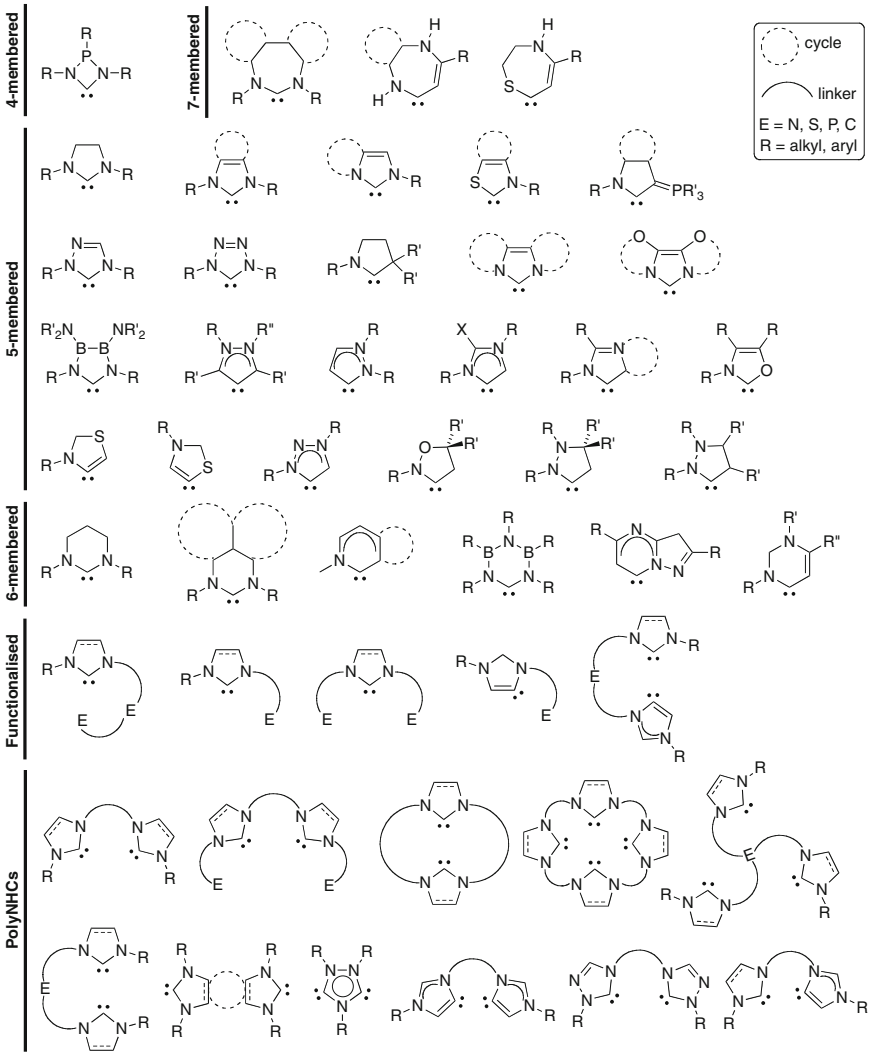


Fig. 1.2 Structural diversity of NHC ligands

This schematic overview of NHC ligands found in the literature shows that most are based on five-membered heterocyclic cores. The most common are listed in Section 1.1.3.

1.1.3 NHC Ligands: Nomenclature and Trivial Names

The most commonly encountered NHCs are those based on five-membered heterocycles. Figure 1.3 summarises these heterocycles and the associated name of the corresponding NHC.

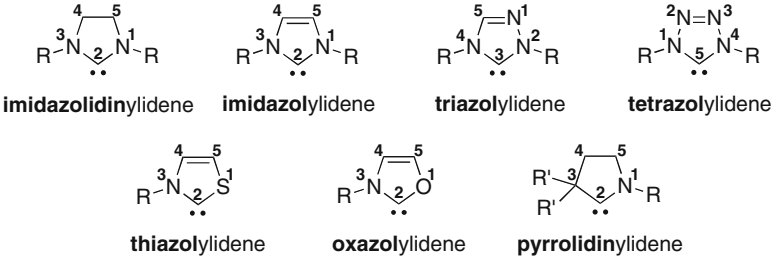


Fig. 1.3 Common five-membered heterocyclic carbenes

The most frequently encountered NHCs are all based on imidazole and imidazolidine. In Fig. 1.4 are presented the most commonly found examples with their associated acronym.

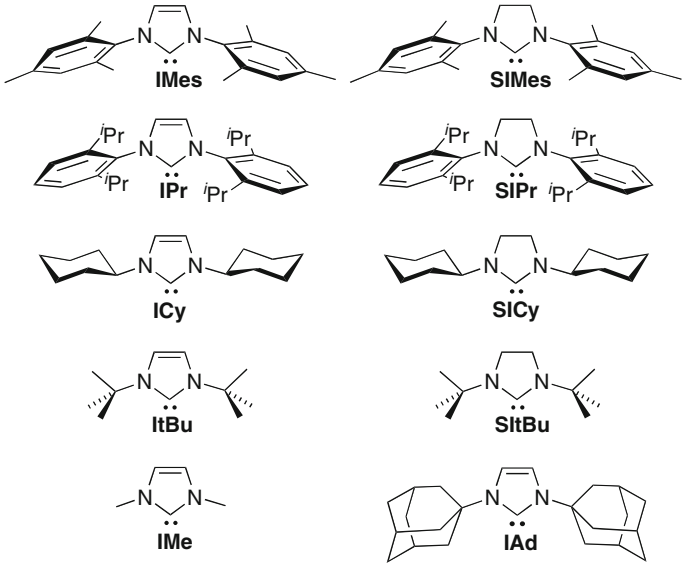


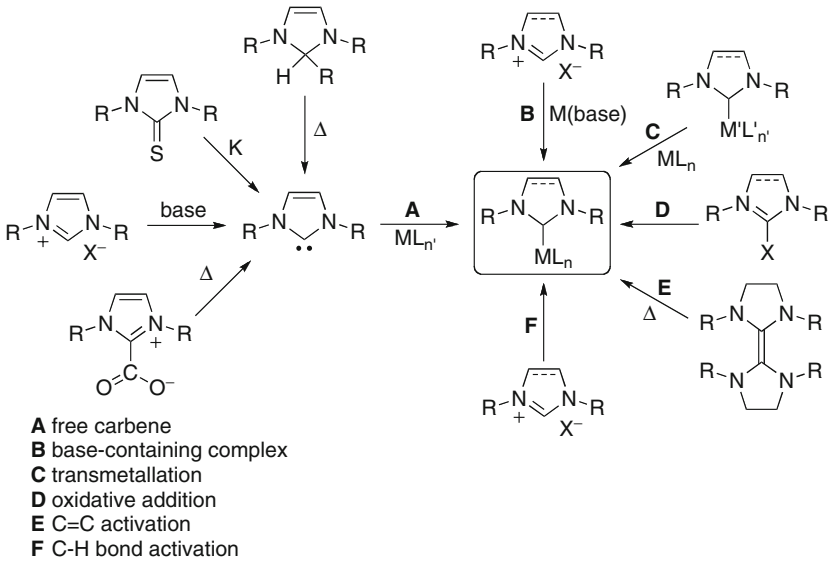
Fig. 1.4 Most common NHC ligands and their respective acronyms

Since Arduengo's first isolation of a free NHC (IAd) [11], a few others have been isolated and characterised. Despite the early assumption that bulky substituents on the nitrogen atoms were necessary in order to stabilise free NHCs, compounds

such as IMe have been found stable. However, depending on the class of NHCs, the isolation of the free ligand can be difficult or impossible. This is, for example, the case of NHCs based on imidazolidinylidene bearing small *N*-substituents as they dimerise to the corresponding tetraaminoethylene [13]. In order to overcome this limitation, alternate synthetic strategies have been developed for the formation of NHC complexes.

1.1.4 Synthesis of NHC Precursors, NHCs and Complexes

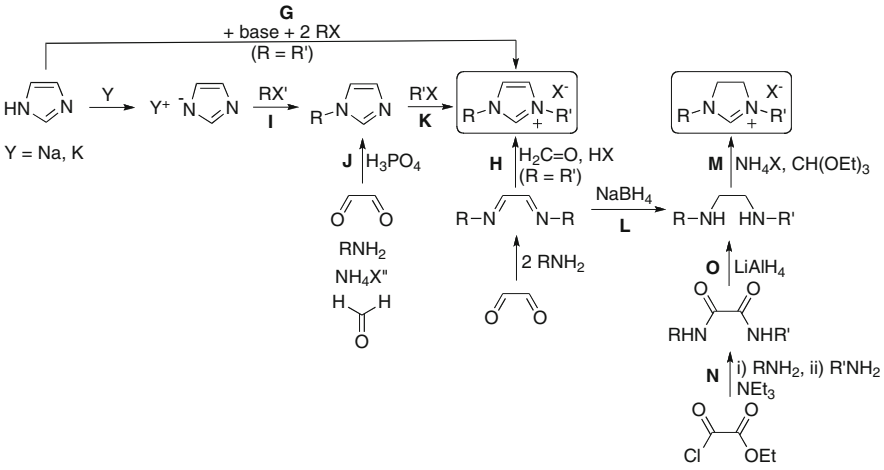
The main synthetic routes leading to the formation of NHC complexes are depicted in Scheme 1.2. The methodologies given are shown with imidazolidinylidene and imidazolylidene ligands, however, they are applicable to other NHCs [16, 17].



Scheme 1.2 Main synthetic strategies for the formation of NHC-complexes

The most often encountered routes are **A**, **B** and **C**. Route **A** consists of generating the free carbene (by deprotonation of the corresponding salt, by reductive desulfurisation or by thermal α-elimination from appropriate NHC precursors) followed by coordination to a metal centre (often with concomitant ligand displacement). Method **B** consists of using a metal precursor containing a base as ligand. The base deprotonates the imidazol(idin)ium salt, leading to the coordination of the NHC and of the counter-anion of the salt (if X is a coordinating anion). Method **C** employs a carbene transfer reagent (often a Ag-complex) that, by transmetallation, delivers

the NHC to the second metal. Methods **D** and **F** are less frequently encountered, they consist of a C–X or a C–H bond activation *via* oxidative addition. Route **E** is a possibility for the formation of imidazolidinylidene complexes by C=C bond activation of the dimerised imidazolidinylidene. Other routes that have not been depicted in Scheme 1.2 (because they are much less versatile) include the cycloaddition to Fischer carbenes and the intramolecular addition to a C≡N bond of coordinated isocyanides. The latter methodology is the intramolecular version of the Tschugajeff synthesis (Scheme 1.1) [7, 14, 15]. The most frequently encountered NHC-complexes are undoubtedly imidazolylidene and imidazolidinylidene due to the easy access of their precursors (imidazol(idin)ium salts). The most common routes for their synthesis are described in Scheme 1.3 [16, 17].

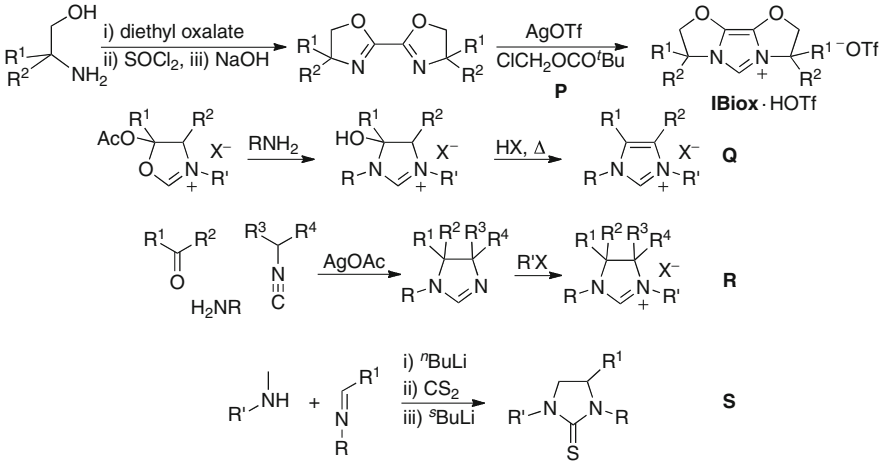


Scheme 1.3 Predominant routes to imidazolylidene and imidazolidinylidene precursors

Two types of imidazolium salts must be distinguished depending on the *N,N′*-substitution: symmetrically (R = R') and unsymmetrically substituted (R ≠ R') versions. For the first type (which is also the predominant one, see Fig. 1.4), two main strategies are viable: reaction of imidazole with RX in the presence of a base (**G**) or cyclisation of an α-diimine or diazobutadiene (obtained by the condensation of the amine with glyoxal) with formaldehyde in the presence of a Brønsted acid (**H**). On the other hand, the synthesis of unsymmetrically *N,N'*-substituted congeners is less straightforward as a functionalised imidazole has to be isolated prior to alkylation or arylation. Two main methods are available for imidazole functionalisation: deprotonation with metallic Na or K leading to an imidazolide (**I**) followed by reaction with RX; or reaction of glyoxal with a primary amine, an ammonium salt and formaldehyde (**J**). *N*-functionalised imidazole can then be alkylated or

arylated (**K**) to the imidazolium salt. Symmetrically *N,N'*-substituted imidazolidinium salts can be easily obtained by reduction of an α-diimine (**L**) followed by cyclisation using triethyl orthoformate in the presence of an ammonium salt (**M**). The same strategy is operative for the synthesis of unsymmetrically *N,N'*-substituted imidazolidinium salts (**M**, R ≠ R'). In such cases, the diamine is synthesised in two steps in order to introduce different *N,N'*-substituents: stepwise reaction of ethyl 2-chloro-2-oxoacetate with two primary amines leading to the corresponding oxalamide (**N**) followed by reduction to the diamine (**O**). Cyclisation (**M**) leads to the unsymmetrically *N,N'*-substituted imidazolidinium salt.

The methodologies described above lead to NHC precursors rather limited in terms of substitution at the four- and five-positions as their access is restricted to the accessibility of the appropriate diimine. As such substitutions are of great interest in particular for the design of asymmetric catalysts, routes to the synthesis of the NHC precursors have more recently been developed. Some of these approaches are described in Scheme 1.4.



Scheme 1.4 Synthetic pathways to NHC precursors with a substituted backbone (C^4 C^5)

The cyclisation of α-diimines can be efficiently performed using chloromethyl pivalate in the presence of silver triflate (**P**) [18]. This method is a good alternative to the use of formaldehyde (pathway **H**, Scheme 1.3) as it overcomes the problem of ring-closing of sterically hindered substrates encountered when using **H**. This method allowed Glorius and co-workers to introduce a new class of sterically demanding NHCs: the tricyclic Biox ligands. Imidazolium salts with substituted backbones can also be obtained by reaction of oxazolinium acetals with a primary amine, leading to hydroxylated imidazolidinium salts that lead to the imidazolium salt after elimination of water (**Q**) [19]. Imidazolidinium salts with a substituted backbone can be obtained by alkylation of the parent 2-imidazolidine [20]. The latter can be obtained by the reaction of an aldehyde with an amine and an isocyanide (**R**)

[21]. Imidazolidine-2-thiones functionalised on the four-position can be obtained by reaction of $HN(CH_3)R'$ with *n*-butyllithium, followed by addition of carbon disulfide. The lithium thicarbamate can then by further lithiated and cyclisation occurs upon reaction of this species with an imine (**S**) [22].

1.1.5 Spectroscopic Features of NHCs and Complexes

The most convenient tool for the characterisation of NHCs is NMR spectroscopy, in particular $^{13}C\{^1H\}$ NMR. As a case study, the carbenes IPr and SIPr, and their corresponding salts IPr·HCl and SIPr·HCl were chosen. As described above (Scheme 1.2), free carbenes are often obtained by deprotonation of the corresponding salt. The best diagnostic tool to observe the salt deprotonation, and thus indirectly monitor the carbene formation, is ^1H NMR spectroscopy, by means of the disappearance of the characteristic acidic proton resonance. The signal corresponding to the latter (H^2) is largely shifted downfield (typically 8–12 ppm) and disappears upon deprotonation (Fig. 1.5).

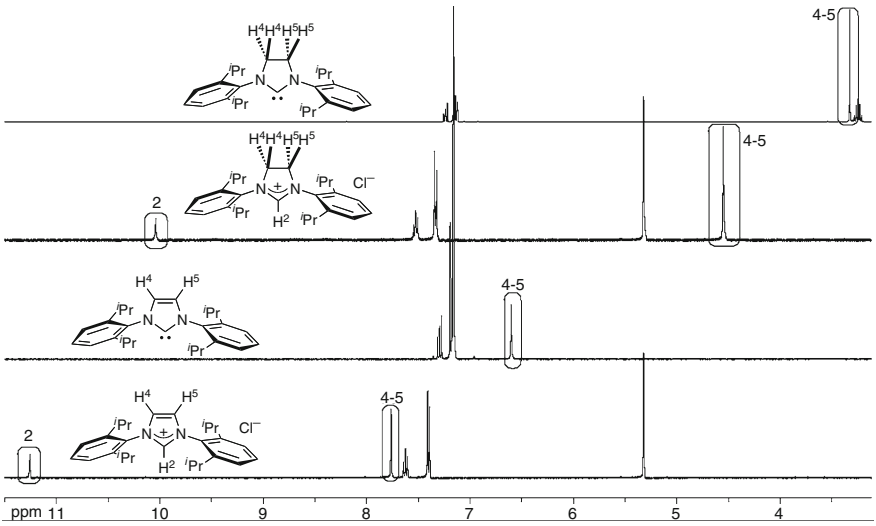


Fig. 1.5 ^1H NMR (CD_2Cl_2 – salt; C_6D_6 – free NHC) spectra of IPr, IPr·HCl, SIPr and SIPr·HCl

The carbene formation can be monitored by $^{13}C\{^1H\}$ NMR, as the carbene carbon atom of free NHCs has a signal significantly shifted downfield. Typically, the signal for the C^2 atom is found between 200 and 250 ppm for the free carbene, and between 130 and 160 ppm for the corresponding salt (Fig. 1.6) [23].

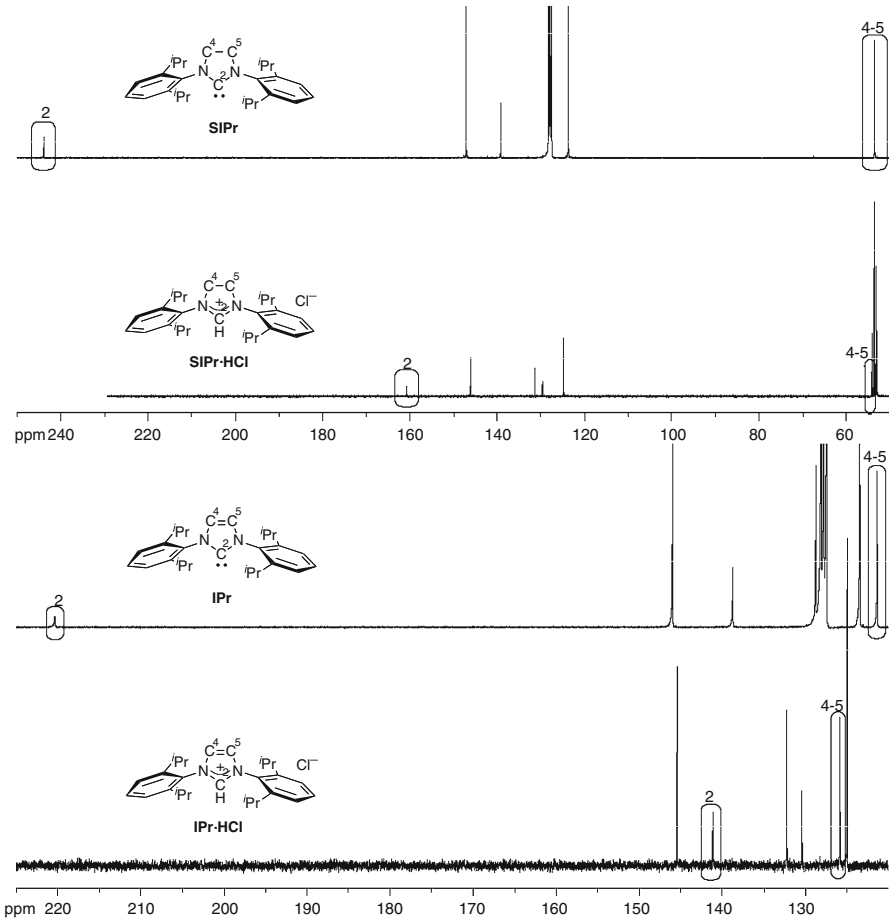


Fig. 1.6 $^{13}C\{^1H\}$ NMR (CD_2Cl_2 – salt; C_6D_6 – free NHC) spectra of IPr, IPr·HCl, SIPr and SIPr·HCl

Once coordinated to a metal centre, the signal corresponding to the carbene carbon atom is usually shifted upfield. The chemical shift of the carbene carbon atom (C^2) for a given metal in a given oxidation state is usually characteristic (Table 1.1).

Table 1.1 $^{13}C\{^{1}H\}$ NMR chemical shifts of the carbenic carbon atom C^2

Metal	Complex	δC^2 (ppm)	Solvent	Ref.
Ru(II)	$[RuHCl(CO)_2(IPr)_2]$	185.9	thf-d_8	[24]
	$[RuHCl(CO)(IPr)_2]$	195.6	thf-d_8	[24]
	$[RuHCl(CO)_2(SIPr)_2]$	193.0	thf-d_8	[24]
	$[RuHCl(CO)(SIPr)_2]$	201.0	thf-d_8	[24]
Rh(I)	[RhCl(COD)(IPr)]	187.7	C_6D_6	[25]
		$^{1}J_{Rh-C}$ = 53 Hz		
	$[RhCl(COE)(IPr)]_2$	181.7	C_6D_6	[26]
		$^{1}J_{Rh-C}$ = 64 Hz		
	$[Rh(OAc)(CO)(IPr)_2]$	190.6	$CDCl_3$	[27]
		$^{1}J_{Rh-C}$ = 44 Hz		
	[Rh(acac)(CO)(SIPr)]	210.75	$CDCl_3$	[28]
		$^{1}J_{Rh-C}$ = 54 Hz		
Rh(III)	$[RhCl(\eta^2\text{-}O_2)(IPr)_2]$	180.8	$C_6D_5CD_3$	[29]
		$^{1}J_{Rh-C}$ = 40 Hz		
Ir(I)	[IrCl(COD)(IPr)]	182.6	$CDCl_3$	[30]
	$[IrCl(CO)_2(IPr)]$	178.6	$CDCl_3$	[30]
	[IrCl(COD)(SIPr)]	209.5	$CDCl_3$	[30]
	$[IrCl(CO)_2(SIPr)]$	204.9	$CDCl_3$	[30]
Ir(III)	$[IrCl(\eta^2\text{-}O_2)(IPr)_2]$	167.4	C_6D_6	[31]
	$[IrCl(H)_2(IPr)(a\text{IPr})]$[a]	187.5 (IPr)	C_6D_6	[32]
		166.8 (*a*IPr)		
Ni(0)	$[Ni(CO)_3(IPr)]$	198.2	C_6D_6	[33]
	$[Ni(CO)_3(SIPr)]$	223.2	C_6D_6	[33]
Ni(II)	$[Ni(\eta^3\text{-}C_3H_5)Cl(IPr)]$	187.8	C_6D_6	[34]
	$[Ni(\eta^3\text{-}C_3H_5)(OH_2)(IPr)]^+[BAr_4^F]^-$	176.4	CD_2Cl_2	[35]
	$[Ni(\eta^3\text{-}C_3H_5)Cl(SIPr)]$	218.4	C_6D_6	[36]
Pd(0)	[Pd(dvtms)(IPr)]	200.8	thf-d_8	[37]
	$[Pd(IPr)_2]$	199.0	C_6D_6	[38]
	$[Pd(IPr)(PPh_3)]$	198.0	C_6D_6	[38]
		$^{2}J_{P-C}$ = 94 Hz		
	$[Pd(SIPr)(PPh_3)]$	218.1	C_6D_6	[38]
		$^{2}J_{P-C}$ = 86 Hz		
Pd(II)	$[Pd(\eta^3\text{-}C_3H_5)Cl(IPr)]$	188.5	C_6D_6	[39]
	$[Pd(\eta^3\text{-}2\text{-}MeC_3H_4)Cl(IPr)]$	189.6	C_6D_6	[40]
	$[PdCl_2(IPr)_2]$	172.5	$CDCl_3$	[41]
	$[PdCl_2(IPr)(PPh_3)]$	170.9	$CDCl_3$	[42]
		$^{2}J_{P-C}$ = 198 Hz		
	$[PdH_2(IPr)(PCy_3)]$	200.5	C_6D_6	[43]
		$^{2}J_{P-C}$ = 138 Hz		
	$[Pd(\eta^2\text{-}O_2)(IPr)(PCy_3)]$	192.0	C_6D_6	[43]
		$^{2}J_{P-C}$ = 16 Hz		
	$[Pd(\eta^3\text{-}C_3H_5)Cl(SIPr)]$	215.4	C_6D_6	[39]
Pt(0)	[Pt(AE)(IPr)]	187.5[b]	$CDCl_3$	[44]
	[Pt(dvtms)(IPr)]	186.4[b]	$CDCl_3$	[45]
	[Pt(dvtms)(SIPr)]	213.3[b]	$CDCl_3$	[45]

(continued)

Table 1.1 (continued)

Metal	Complex	δC^2 (ppm)	Solvent	Ref.
Pt(II)	[Pt(η^3-2-MeC_3H_4)Cl(IPr)]	180.8[b]	$CDCl_3$	[46]
	[$PtCl_2$(dmso)(IPr)]	147.4 $^1J_{Pt-C}$ = 1,479 Hz	$CDCl_3$	[47]
	[$PtCl_2$(dmso)(SIPr)]	174.4 $^1J_{Pt-C}$ = 1,373 Hz	$CDCl_3$	[47]
Cu(I)	[CuCl(IPr)]	182.3	$(CD_3)_2CO$	[48]
	[Cu(IPr)$_2$][BF_4]	177.4	$CDCl_3$	[49]
	[Cu(IPr)$_2$][PF_6]	178.4	$CDCl_3$	[49]
	[CuCl(SIPr)]	204.3	$CDCl_3$	[50]
	[Cu(SIPr)$_2$][BF_4]	201.4	$CDCl_3$	[51]
	[Cu(SIPr)$_2$][PF_6]	199.8	$CDCl_3$	[51]
Ag(I)	[AgCl(IPr)]	184.6 $^1J_{Ag-C}$ = 271 Hz $^1J_{Ag-C}$ = 235 Hz	$CDCl_3$	[52]
	[Ag(IPr)$_2$][PF_6]	183.6 $^1J_{Ag-C}$ = 211 Hz $^1J_{Ag-C}$ = 183 Hz	$CDCl_3$	[25]
	[AgCl(SIPr)]	207.7 $^1J_{Ag-C}$ = 253 Hz $^1J_{Ag-C}$ = 219 Hz	CD_2Cl_2	[52]
Au(I)	[AuCl(IPr)]	175.1	CD_2Cl_2	[53]
	[AuBr(IPr)]	179.0	$CDCl_3$	[54]
	[AuCl(SIPr)]	196.1	$CDCl_3$	[53]
	[AuBr(SIPr)]	199.0	$CDCl_3$	[54]
Au(III)	[$AuBr_3$(IPr)]	146.2	$CDCl_3$	[54]
	[$AuBr_3$(SIPr)]	174.1	$CDCl_3$	[54]

[a] *a*IPr = abnormal IPr (*i.e.* IPr bound through C^4)
[b] $^1J_{Pt-C}$ not observed

1.1.6 NHC Complexes: Representation and Convention

The standardised representation of NHC metal complexes is still not fully established, and different representations are used. Figure 1.7 summarises the representations found in the literature.

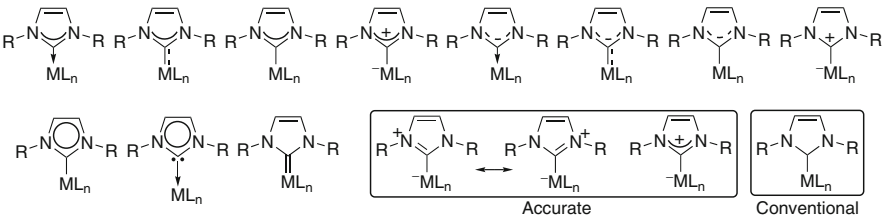


Fig. 1.7 Representations of NHCs found in the literature

Early representations exhibited a double bond between the metal centre and the carbene carbon atom. This was soon recognised as being a misleading representation as NHCs are two-electron donor ligands [55]. With respect to the disparity of representation still currently found in the literature, none is very accurate. The most accurate representation is the one displaying the charges [56], however, presumably for the sake of clarity, the most often encountered representation (conventional) does not contain any charge. It will also be the representation used throughout this book.

By convention, the carbenes displayed in Fig. 1.7 are "normal" NHCs as they are coordinated to the metal centre through the C^2 atom. By contrast, abnormal (also named non-classical or unusual) are those bound through the C^4 atom. Abnormal is also a term used for NHCs having a valence representation requiring additional charges. Remote is a term used to describe a carbene which does not have any heteroatom on the α-position to the carbenic carbon (Fig. 1.8) [57].

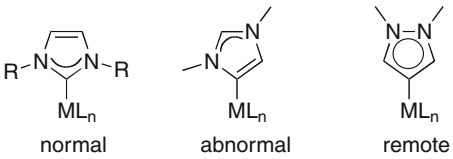


Fig. 1.8 Normal, abnormal and remote NHCs

As depicted above, there is a large variety of NHCs, and their access is relatively easy. This is a veritable advantage in the use of NHCs for homogeneous catalytic systems. However, it is probably their unique electronic and steric properties that make NHCs an exceptional class of molecules. These unique features are described in the following sections.

1.2 Electronic Properties of NHCs

NHCs can be classified as typical σ-basic/π*-acid ligands [58–61], whose electronics can be rationalised considering the Molecular Orbitals diagram presented in Fig. 1.9. The diagrams show the interaction of the basic imidazolidinylidene skeleton with a transition metal. The NHC presents a lone electrons pair in a high energy σ orbital, see Fig. 1.9a, which confers to NHCs a σ-donicity (basicity) clearly-stronger than that of even basic phosphines, such as PCy_3 [62, 63]. This key feature is accompanied by the presence of an empty low energy π* orbital, see Fig. 1.9b, which allows NHCs to act as acceptor of electron density from filled *d* orbitals of the metals (π-acidity) in a classical $d \rightarrow \pi^*$ back-donation scheme [64, 65]. Finally, with electron-deficient metals, NHCs can also engage in a $\pi \rightarrow d$ donation, in which electron density is donated from an appropriate combination of filled and empty π orbitals on the NHC, see Fig. 1.9c, to empty *d* orbitals of the metal (π-basicity) [66]. This picture of the M–NHC bonding is the result of years of research, since NHC ligands were initially considered to be pure σ-donors with insignificant π-acidity capability. Almost a decade later, seminal

reports [64, 65, 67, 68] clearly showed that NHCs can accept electron density from the metal into π* orbitals, and this contribution cannot be neglected. Finally, the π-donor capability of NHC ligands towards electron poor metals, which completes the picture, has been recognised only in the past few years [59, 60, 66, 69].

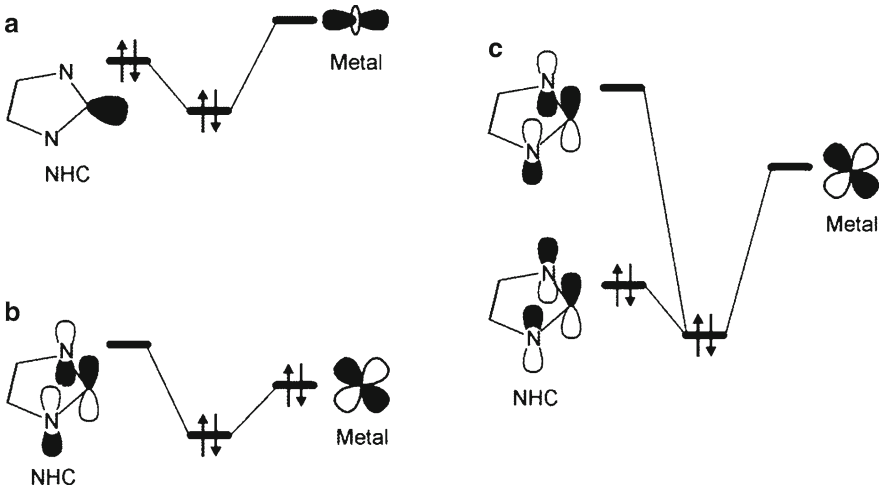


Fig. 1.9 Diagram illustrating the σ → *d* (**a**), the *d* → π* (**b**), and the π → *d* (**c**) bonding modes occurring between NHCs and transition metals

Different electronic properties of the NHC ligand can result in drastic consequences on the catalytic efficiency of the corresponding metal complexes. The key structural parameters that can be modified to tune the electronic properties in five-membered NHCs, shown in Fig. 1.10, are: (a) the NHC skeleton; (b) the nature of the substituents on the C^4 and C^5 carbon atoms of the NHC skeleton; (c) the *N*-substituents. To discuss these points, we will privilege studies focused on the [IrCl$(CO)_2$(NHC)] and [IrCl(cod)(NHC)] complexes (cod = 1,5-cyclooctadiene), since these two classes of compounds are gaining the status of model systems to investigate the stereoelectronic properties of NHC ligands [30, 70–75]. The former through the measurement of the average CO stretching frequency, ν_{av}, by IR spectroscopy [30, 70–74], the latter through the measurement of the redox potential, $E_{1/2}$, by cyclic voltammetry [18].

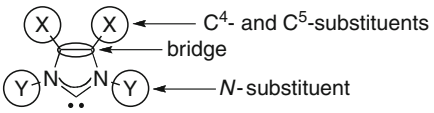


Fig. 1.10 Schematic illustration of the structural points whose modification can be used to tune the electronic properties of NHC ligands