**Reactivity of acyclic diaminocarbene ligands**

Mikhail A. Kinzhalov\*,a and Konstantin V. Luzyanin\*,a,b

*a*Saint Petersburg State University, 7/9 Universitetskaya Nab., Saint Petersburg, 199034 Russia;   
e-mails: m.kinzhalov@spbu.ru

*b*Department of Chemistry, University of Liverpool, Crown Street, Liverpool L69 7ZD, United Kingdom; e-mail: konstantin.luzyanin@liverpool.ac.uk

**Abstract**

Acyclic diaminocarbenes (ADCs) are powerful ligands with a broad application scope in organometallic chemistry, catalysis, photophysics and crystal engineering. Although the preparation and application of metal-ADC species are discussed in many reports, the reactivity of ADC ligands is much less scrutinised. However, studies emerged indicate that ADC ligands, in particular, those prepared *via* the metal-mediated nucleophilic addition to isocyanides, can be further converted into various post-functionalised derivatives. In this review, we attempt for the first time to rationalise the most important reactivity modes of metal-ADC species reported up to date.

**Keywords**: acyclic diaminocarbene, carbene ligands, reactivity modes, metal complexes, deprotonation

**Contents**

1. Introduction

2. Reactivity of metal-ADC species

2.1 Brønsted acidity of ADC ligands and stabilisation of the hydrogen-bonded

carbene structures

2.2 Deprotonation of ADC species and the follow-up reactions

2.2.1 Deprotonation of ADC species and intramolecular metallation reactions

2.2.2 Intermolecular metallation of the deprotonated ADC derivatives

2.2.3 Intramolecular and intermolecular nucleophilic attack of the formamidinyl species derived from ADCs on the carbon atom in [M]-CNR and [M]-CO

2.3 Alkylation and acylation of ADC derivatives

2.3.1 Intermolecular alkylation of ADC derivatives

2.3.2Intramolecular alkylationand acylation of ADC derivatives

2.4 Reversible formation of metal-ADC species from isocyanide complexes and amines

2.5 Cleavage of the N–X bond within the carbene fragment

2.6 Oxidation of diaminocarbenes into carbodiimides

2.7 Displacement and re-coordination of ADC or corresponding formamidinyl ligands

3. Final remarks

**List of abbreviations**

ADC acyclic diaminocarbene

bipy 2,2′-bipyridine

Cy cyclohexyl

DMF *N*,*N*-dimethylformamide

DMSO dimethylsulfoxide

DNA deoxyribonucleic acid

dppe 1,2-*bis*(diphenylphosphino)ethane

dppm 1,1-*bis*(diphenylphosphino)methane

LiHMDS lithium *bis*(trimethylsilyl)amide

Mes 2,4,6-trimethylphenyl

NHC *N*-heterocyclic carbene

*p*ADC protic ADC

*p*NHC protic NHC

*p*-cym *p*-cymene (1-methyl-4-(propan-2-yl)benzene)

PS polystyrene

RT room temperature

*t*Bu *tert*-butyl

*n*Bu *n*-butyl

THF tetrahydrofuran

Xyl 2,6-dimethylphenyl

**1. Introduction**

Acyclic diaminocarbenes (ADCs) are powerful and persistent ligands with a broad scope of applications in organometallic chemistry (for the reviews in the field, see Refs. [[1-4](#_ENREF_1)]) and catalysis (for the reviews, see Refs. [[5-7](#_ENREF_5)]; for the recent applications, see Refs. [[8-17](#_ENREF_8)]). ADC derivatives are also examined for potential cytotoxicity in cancer research [[18-22](#_ENREF_18)], photophysical properties [[23-31](#_ENREF_23)], and in crystal engineering [[31-33](#_ENREF_31)]. Metal complexes with acyclic diaminocarbenes can be prepared *via* several synthetic strategies, including: (*i*) Direct Complexation of free carbene generated *via* the deprotonation *in situ* of the corresponding amidinium salt (**Scheme 1**, Route A), (*ii*) Oxidative Addition of the electron-rich metal centers into *C*-chloro -iminium and -formamidinium salts (Route B), and (*iii*) Nucleophilic Addition to metal-bound isocyanides (Route C) [[1](#_ENREF_1), [6](#_ENREF_6)].



**Scheme 1**. Routes to metal complexes with ADC ligands and representative nucleophiles used towards metal-bound isocyanides.

The last approach has been noticeably expanded in recent years, mostly by widening the scope of nucleophiles, *e.g.*, hydrazines, imines, hydrazides, hydrazones, amidines, imidines *etc*, used towards isocyanides bound to new metal centers, *e.g.*, AuI/III, MnI, ReI, Fe0, and others [[2](#_ENREF_2)]. Addition of monofunctional protic nucleophiles, *e.g.*, amines or hydrazones to metal-bound isocyanides generates monodentate protic *di*-*N*,*N*′,- or *tri*-*N*,*N*,*N*′-substituted diaminocarbenes, while addition of polyfunctional nucleophiles, *e.g.*, hydrazines or amidines, may lead to more complex products featuring chelating ADC ligands [[1](#_ENREF_1), [2](#_ENREF_2), [34](#_ENREF_34)]. Whereas the generation and application of metal-ADC are extensively reported and these species are assumed to be chemically stable [[5](#_ENREF_5), [6](#_ENREF_6)], a number of reports that emerged in the last decade indicate that ADC ligands can react further, furnishing various post-functionalised derivatives. The observed reactivity type is frequently related to the method of preparing the metal-ADC species and can only be observed in the course of that route or after its completion.

In this review, we reflect on the most important reactivity modes of metal-ADC species reported to date. Herein, the method of metal-ADC generation is discussed first, followed by the observed reactivity type for ADC species and the subsequent transformation of carbene derivative.

**2. Reactivity of metal-ADC species**

**2.1. Brønsted acidity of ADC ligands and stabilisation of the hydrogen-bonded**

**carbene structures**

Protic ADC ligands (*p*ADC), *i.e.* those featuring one or two NH (or one of them NH2) wingtips possess Brønsted acidity (**Figure 1**). 1H NMR spectra of *p*ADC complexes exhibit a characteristic resonance for the NH protons at lower-field (usually 5–11 ppm, **1**–**4**, **Figure 1**), that often disappears upon H−D exchange with deuterated solvent, *i.e.* CD3OD [[35](#_ENREF_35), [36](#_ENREF_36)] or D2O [[37](#_ENREF_37)]. Within the carbene moiety, the N(H)*aryl* group has usually more acidic character than the N(H)*alkyl* residue [[38](#_ENREF_38)], while for the bidentate Chugaev-type carbene ligands [[39](#_ENREF_39)], the “backbone” chelate-ring NHs are more acidic, than the exterior N(H)aryl [[24](#_ENREF_24)] or N(H)alkyl [[40-42](#_ENREF_40)] moieties.



**Figure 1**. Comparative Brønsted acidity of *p*ADC ligands. Acidic hydrogen atoms from ADC ligands are shown in blue and the moieties that influence their acidity are marked in red.

Electrophilicity and the Brønsted-acidity of NH hydrogens, as well as the presence of a lone pair of electrons on the nitrogen atoms of ADC moiety, explain why NH groups can act as both donors and acceptors of hydrogen bondings [[43](#_ENREF_43)]. Both *intra*- and *inter*molecular hydrogen bonds with ADC moieties are observed in solution and in the solid state. This acidity is frequently associated with the reversible deprotonation of ADC fragment leading to the formamidinyl derivatives [[40](#_ENREF_40), [44-46](#_ENREF_44)] (see section 2.2). Thus, for the gold(I)-ADCs **5** derived from the nucleophilic addition to 2-pyridyl isocyanide, the downfield shift of the NH resonance to δH *ca.* 12 ppm in solution 1H NMR confirms the existence of a strong intramolecular N–H···N hydrogen bonding between the NH proton of ADC moiety and the nitrogen atom of the 2-pyridyl group forming a six-membered cycle (**Figure 2**) [[33](#_ENREF_33), [47-51](#_ENREF_47)]. This hydrogen-bond-supported planar cyclic structure is observed in the solid state and is retained in solution, making these carbenes structurally related to NHCs [[49](#_ENREF_49)]. Similar hydrogen bonding is observed in palladium ADC complexes **6** generated upon the nucleophilic addition of an -aminoazaheterocycle to Pd(II)-bound isocyanides (**Figure 2**) [[52](#_ENREF_52)], and also in the iron ADC complexes **7** and **8** prepared *via* the insertion of iron center (in Fe3(CO)12 or Fe2(CO)9 clusters) into the C=X (S, Se) bond of thio- and selenoureas as reported by Shi and coworkers (**Figure 2**) [[37](#_ENREF_37)].



**Figure 2**. Gold [[33](#_ENREF_33), [47-51](#_ENREF_47)], palladium [[52](#_ENREF_52)] and iron [[37](#_ENREF_37)] hydrogen-bond-supported carbene species.

Intermolecular three-centered (bifurcated) hydrogen bonding (N−H···X···H−N, X = Cl, Br) HB with chloride [[12](#_ENREF_12), [53-56](#_ENREF_53)] and bromide [[32](#_ENREF_32)] in the outer coordination sphere were detected for the series of palladium-ADC complexes **9** (**Figure 3**). Kukushkin and coworkers demonstrated that Pd-ADC complexes **10** in CHCl3 solution exist as dimers stabilised by the bifurcated chalcogen−hydrogen bonding *μ*(S,N−H)Cl between two monomeric fragments [[52](#_ENREF_52)]. The capacity of *p*ADC species to behave as a H-bond donor was related to the cytotoxicity of their platinum(II) derivatives against cancer cells and its ability to interact with supercoiled DNA [[18](#_ENREF_18), [19](#_ENREF_19)].



**Figure 3**. Intermolecular three-centered (bifurcated) hydrogen bonding in the outer coordination sphere of palladium-ADC complexes [[12](#_ENREF_12), [32](#_ENREF_32), [53-55](#_ENREF_53)] and dimeric palladium-ADC structures stabilised by bifurcated chalcogen−hydrogen bonding *μ*(S,N−H)Cl [[52](#_ENREF_52)].

**2.2 Deprotonation of ADC ligands and the follow-up reactions**

*2.2.1 Deprotonation of ADC species and intramolecular metallation reactions*

Deprotonation of *p*ADCs typically generates the formamidinyl derivatives [[3](#_ENREF_3)], and those can exhibit strong nucleophilic properties leading to further reactions as described below. It was shown that deprotonation of ADC ligands represents an initial step leading to the generation of catalytically active species in the course of several cross-coupling reactions [[8](#_ENREF_8), [13](#_ENREF_13), [16](#_ENREF_16)].

Ruiz and coworkers reported that diaminocarbene ligands in the manganese(I) complexes **11** are easily deprotonated by an excess of KOH in CH2Cl2 to give the neutral formamidinyl complexes **12** in quantitative yields (**Scheme 2**) [[38](#_ENREF_38)]. Deprotonation of **11** to afford **12** occurs at the N(H)aryl moiety rather than in the N(H)Me fragment due to the more acidic character of the former. Deprotonation of **11** is shown to be fully reversible, and addition of one equivalent of HBF4 to **12** restores diaminocarbenes **11**.



**Scheme 2**. Reversible deprotonation of manganese(I) ADC complexes [[38](#_ENREF_38)].

Ko and coworkers described that rhenium(I) complexes with *C,N*-bidentate ADC ligand **13**–**15** derived from rhenium(I) isocyanide-carbonyl species and 2-aminopyridine can be deprotonated by the action of basic anions, *i.e.* fluoride, cyanide, acetate, and hydroxide giving neutral formamidinyl derivatives **16** (**Scheme 3**, a) [[26](#_ENREF_26)]. In the course of this reaction, the absorption properties of starting ADC complexes change in both the UV and the visible region of spectrum, and that can be used for the anion-sensing. Use of the less basic anions, *i.e.* chloride or bromide towards Re-ADC complexes **13**–**15**, does not lead to their deprotonation but to the hydrogen bonding of these anions with the protons located at *p*ADC (**17**, **Scheme 3**, b). The anion-binding affinity of complex **13** with carbonyl ancillary ligands is slightly higher than those of complexes **14** and **15** with isocyanide ligands. It could be explained by stronger π-accepting and electron withdrawing properties of ancillary CO ligands in **13**, that thereby enhance the acidity and anion-binding affinity of NH groups of the corresponding ADC species [[26](#_ENREF_26)].



**Scheme 3.** Anion binding properties of rhenium(I) ADC complexes [[26](#_ENREF_26)].

In the same study, deprotonated Re-ADC complexes were revealed to be capable of CO2 binding (**Scheme 4**) [[26](#_ENREF_26)]. The reaction between the deprotonated complex **15** and CO2 leads to *N*-carbamate anions in complex **18**. Those are stable under a CO2 environment and nonemissive in solution, in contrast to the blue-green phosphorescence observed for the starting complex **15** [[26](#_ENREF_26)].



**Scheme 4.** CO2-Binding by the deprotonated rhenium(I) ADC complexes [[26](#_ENREF_26)].

Che and coworkers reported that platinum(II) Chugaev-type ADC complexes **19** and **20**(ClO4) can be protonated using aqueous HBF4 to give *bis*ADC complexes **21**(BF4) and **22**(BF4)2 (**Scheme 5**, a) [[30](#_ENREF_30)]. Protonation of Chugaev-type ADC species leads to a dramatic change of their photophysical properties allowing for their application as potential pH-dependent luminescent chemosensors. Hence, protonation of carbene moiety with HBF4 induces a blue shift (∆λabs = *ca*. 70 nm) for the lowest energy absorption in the UV–vis spectra leading to a significant emission enhancement (*ca*. 12-fold for **1**; blue-shift with the ∆λmax = 48–59 nm). The observed high-energy emissions for **21**(BF4) and **22**(BF4)2 are assigned to the triplet intraligand excited state of *bis*(carbene) moiety [[30](#_ENREF_30)]. In the other study, Teets and coworkers reported that protonation of iridium(III) Chugaev-type ADC complexes **23** and **24** to give **25** and **26** leads to two-fold increase in quantum yield accompanied by a blue shift (∆λmax = *ca*. 30 nm)(**Scheme 5**, b) [[24](#_ENREF_24)].



**Scheme 5.** Protonation of platinum(II) [[30](#_ENREF_30)] and iridium(III) [[24](#_ENREF_24)] Chugaev-type ADC complexes.

Lentz and Marschall reported that reaction of *bis*(trifluoromethyl isocyanide) cobalt(I) complex **27** with secondary amines [R = Me, Et, ½ -(CH2)4-] in aqueous diethyl ether gives the five-membered cobaltaheterocycles **32** through the intermediate species **28**–**31** (**Scheme 6**) [[57](#_ENREF_57)]. ADC-species **28** initially formed are easily deprotonated by an excess of secondary amines followed by amination and hydrolysis of C–F bonds.



**Scheme 6**. Reaction of *bis*(trifluoromethyl isocyanide) cobalt(I) complex with secondary amines proceeds through the deprotonation of the initially formed ADC-species [[57](#_ENREF_57)].

Werner and coworkers described the preparation of metallacyclic cobalt(I) complexes **35**–**38** with deprotonated ADC species *via* the [2 + 2] cycloaddition of isocyanates and isothiocyanate to cobalt(I) isocyanide complexes **33** and **34** (**Scheme 7**) [[58](#_ENREF_58), [59](#_ENREF_59)]. Upon protonation with CF3CO2H, species **35** gives metallacyclic aminocarbene derivatives **39**; similar reactivity was observed for **37** and **38** [[58](#_ENREF_58)]. This process can be reversed by action of MeONa on complexes **39**, **41** and **42** restoring starting formamidimyl species **35**, **37** and **38**, respectively. On the contrary, metallacycle in complex **36** upon protonation suffers a ring opening to open-chain diaminocarbene derivative **40**. In the later study, complexes **35**, **37** and **38** were protonated by HBF4 to give complexes **39**, **41** and **42** withBF4– anion in the place of PF6– [[59](#_ENREF_59)].



**Scheme 7.** [2 + 2] Cycloaddition of isocyanates and isothiocyanate to cobalt(I)-isocyanides and the follow-up reversible deprotonation of ADC species [[58](#_ENREF_58), [59](#_ENREF_59)].

Werner and coworkers also described the preparation of metallacyclic cobalt(I) complexes **43** and **44** with deprotonated ADC *via* the [2 + 3] cycloaddition of benzoyl azide to cobalt(I) isocyanide complexes **33** and **34** (**Scheme 8**) [[60](#_ENREF_60)]. Upon protonation with CF3CO2H, species **43** and **44** are converted to the metallacyclic aminocarbene derivatives **45** and **46** [[60](#_ENREF_60)].



**Scheme 8.** [2 + 3] Cycloaddition of benzoyl azide to cobalt(I)-isocyanides and the follow-up protonation of deprotonated ADCs [[60](#_ENREF_60)].

*2.2.2 Intermolecular metallation of the deprotonated ADC derivatives*

Ruiz and coworkers described the reaction of manganese(I) ADC complexes **47** and **48** with stoichiometric [AuCl(PPh3)] in the presence of an excess of KOH to give heterobimetallic MnI/AuI complexes **55** and **56** (**Scheme 9**) [[61](#_ENREF_61), [62](#_ENREF_62)]. Upon reflux, **56** isomerise quantitively to **57**; isomers **56** and **57** differ by the location of Me and Ph substituents on the *N*-centers of ADC [[61](#_ENREF_61), [62](#_ENREF_62)]. Authors state that the reaction starts by the deprotonation of diaminocarbene moiety (complexes **49** and **50**), followed by the substitution of remaining NH proton by the isolobal [Au(PPh3)]+ fragment (complexes **51** and **52**), the transmetallation of the carbene carbon atom from manganese to gold center (complexes **53** and **54**), and the nucleophilic attack of a nitrogen atom onto a carbonyl ligand to furnish the carbamoyl derivatives **55** and **56** [[61](#_ENREF_61), [63](#_ENREF_63)]. Similar reactivity was observed for the iron(II) ADC complexes **58**–**60** upon reaction with [AuCl(PPh3)] under basic conditions leading to the heterobimetallic FeII/AuI species **61**–**63** (**Scheme 10**) [[64](#_ENREF_64)].



**Scheme 9.** Generation of the hetero*bi*metallic MnI/AuI complexes from manganese(I) ADC complexes[[61-63](#_ENREF_61)].



**Scheme 10**. Metallation reactions of iron(II) ADC complexes to lead to the heterobimetallic FeII/AuI species [[64](#_ENREF_64)].

Iron(II) ADC complex **64** can be converted to the *metalla*-*N*-heterocyclic carbenes through a four-step reaction pathway, as depicted in **Scheme 11** [[65](#_ENREF_65)]. Hence, the initial deprotonation of the complex **64** by KOH in CH2Cl2 generates the active formamidinyl derivative, that reacts further with [Ru(*p*-cym)Cl2]2 to give the heterobimetallic Ru/Fe complex **65**. This species formally bears a double deprotonated form of the diprotic diaminocarbene complex **64** bound to the ruthenium [Ru(*p*-cym)Cl]+ core in a chelating manner. A substitution reaction of the chloride ligand in **65** by isocyanide yields the cationic complex **66**, which is further transformed to **67** by treatment with HCl.



**Scheme 11.** Formation of *metalla*-N-heterocyclic carbene from iron(II) ADC complex [[64](#_ENREF_64), [65](#_ENREF_65)].

Crociani and coworkers reported that the palladium(II) ADC complex **68** containing ancillary *C*-metallated 2-pyridyl ligand upon deprotonation *in situ* reacted with ZnCl2 to give bimetallic Pd/Zn species **69** (**Scheme 12**) [[66](#_ENREF_66)]. The bimetallic species thus obtained possesses a six-membered ring with a boat conformation, formed by the Pt and Zn metal centers and two bridging 2-pyridyl and formamidinyl ligands.



**Scheme 12.** Reaction of the *in situ* deprotonated palladium(II) ADC complex bearing ancillary 2-pyridyl ligand with ZnCl2 [[66](#_ENREF_66)].

Espinet and coworkers reported that the deprotonation of the gold(I) ADC complex **70** with KOH leads to highly reactive formamidinyl derivative which trimerises spontaneously to the trimetallic species **71** (**Scheme 13**) [[33](#_ENREF_33)]. In both solution and the solid state, the structure of complex **71** possesses a trigonal prismatic arrangement of six metal atoms formed by gold-gold interactions between two gold triangles (n = 3 x 2). Complex **71** displays an intense phosphorescence (523 nm, lifetime 84 μs) attributed to the presence of gold-gold interactions.



**Scheme 13.** Trimerisation of the gold(I) formamidinyl derivative formed *in situ* upon deprotonation of gold(I) ADC complex with KOH [[33](#_ENREF_33)].

Balch and coworkers reported that the platinum Chugaev-type ADC complexes **72** upon deprotonation *in situ* reacted with TlNO3 to give the heterobimetallic Pt/Tl species **73** (**Scheme 14**) [[35](#_ENREF_35)]. For these complexes, the presence of weak interactions beyond the TlI··PtII bonds contributing to the solid-state structure was recognised. The bonding interactions between TlI and PtII metal centers result from a combination of metallophillic and Coulombic factors with an ionic component accounting for up to 87% of the bonding and covalent, metallophillic interaction contributing with the remaining 13% of the bond strength.



**Scheme 14.** Reaction of the *in situ* deprotonated platinum(II) Chugaev-type ADC complexes with TlNO3 [[35](#_ENREF_35)].

*2.2.3 Intramolecular and intermolecular nucleophilic attack of the formamidinyl species derived from ADCs on the carbon atom in [M]-CNR and [M]-CO*

Riera and Ruiz showed that the deprotonation of iron(II) ADC complexes **74** and **77** *in situ* with an excess of KOH or Et3N in CH2Cl2 generates *N*-nucleophilic center that subsequently attacks a secondary isocyanide ligand furnishing *C*,*C*’-chelating carbene(formamidinyl) derivatives **75** and **78** (**Scheme 15**) [[67](#_ENREF_67)]. Further deprotonation of **78** leads to *bis*(formamidinyl) derivatives **79**. Protonation of **75** with equimolar HClO4 in CH2Cl2 leads to the *C*,*C*’-chelating *bis*carbene species **76**. Complex **76** can be reversed to starting complex **74** by a sequential action of base and acid.



**Scheme 15.** Reversible deprotonation reaction of iron(II) ADC species [[67](#_ENREF_67)].

Iron(II) ADC complexes **80**–**82** displayed a reversible stepwise double deprotonation by KOH in CH2Cl2 and LiHMDS in THF (**Scheme 16**) [[64](#_ENREF_64)]. In the first step, complexes **80**–**82** reacted with KOH to give the corresponding formamidinyl derivatives resulting from the deprotonation of the NHR group (NHXyl group for R = Xyl or the NHMe group for R = Cy). In the case of L = CNR (complexes **81** and **82**), a subsequent nucleophilic attack of the imine group on an isocyanide ligand occurs to afford the neutral metallacyclic complexes **59** and **60** containing *C*,*C*’-chelating carbene(formamidinyl) ligands. Derivatives **58**–**60** can be easily reversed to their diaminocarbene precursors **80**–**82** by treatment with HClO4. The remaining NH group in **58**–**60** can be subsequently deprotonated by LiHMDS in THF leading to the anionic formamidinyl **83**, or the *bis*formamidinyl complexes **84** and **85** (**Scheme 16**) [[64](#_ENREF_64)]. In the case of L = CO (complex **58**), the double deprotonation reaction was followed by an intramolecular nucleophilic attack from either the NXyl group or the NMe group onto a vicinal carbonyl ligand. The anionic complexes **83**–**85** are highly hydroscopic and can be transformed into **58**–**60** even by moisture.



**Scheme 16**. Reversible stepwise double deprotonation reaction of iron(II) ADC complexes [[64](#_ENREF_64)].

It was reported that palladium(II)- and platinum(II)-diaminocarbenes **88** and **89**, generated by addition of α-amino azaheterocycles to arylisocyanide complexes **86** and **87**, can be deprotonated to give **90** and **91**. The latter species can behave as metal-containing nucleophiles and react further with an electrophilically activated isocyanide in starting **86** and **87** to furnish the binuclear diaminocarbene species **92** and **93** (**Scheme 17**) [[9](#_ENREF_9), [68-75](#_ENREF_68)].



**Scheme 17.** Prepared palladium(II) [[68-75](#_ENREF_68)] and platinum(II) [[9](#_ENREF_9), [73](#_ENREF_73)] ADC complexes and their coupling with an electrophilically activated isocyanide in *cis*-[MCl2(CNXyl)2] (M = PdII, PtII).

Diaminocarbene complexes **95** generated upon addition of α-amino azaheterocycles to palladium-bound cyclohexyl isocyanides **94**, do not react further with *cis*-[MCl2(CNR)2] [[72](#_ENREF_72)]. The reactivity difference between the aryl and cyclohexyl isocyanide palladium(II) complexes could be rationalised by the different acidity of the intermediate cationic *C,N-*chelated aminocarbene species **88** and **95**. For aryl isocyanides, aminocarbene complex **88** formed bears more acidic NH protons, and it is subject to a two-step deprotonation followed by the coupling with other CNR complex to furnish binuclear species **92** (**Scheme 17**). For the less acidic cyclohexyl isocyanide, diaminocarbene species **95** is subject to only one-step deprotonation giving complexes **96**, which are not involved in further reactions (**Scheme 18**).



**Scheme 18.** Reaction of palladium(II) cyclohexyl isocyanide complexes with α-amino azaheterocycles [[52](#_ENREF_52)].

**2.3 Alkylation and acylation of ADC derivatives**

**2.3.1 Intermolecular alkylation of ADC derivatives**

The N−H protons on diaminocarbene ligand can be readily alkylated by an appropriate electrophilic alkylating reagent. Thus, rhenium(I) ADC complex **15** was dialkylated upon action of dimethylsulfate under basic condition to give **97** as reported by Ko and coworkers (**Scheme 19**) [[26](#_ENREF_26)]. Authors described a pronounced red shift of the emission on going from ADC species **15** (547 nm) to methylated species **97** (672 nm). This is explained primarily by the steric repulsion due to installation of methyl groups, leading to a noncoplanar twisted diaminocarbene structure.



**Scheme 19.** Methylation of ADC ligand in the rhenium(I) complex [[26](#_ENREF_26)].

Werner and coworkers reported that cobalt(I) complexes **35**–**37** and **98** upon deprotonation can be methylated by "Meerwein salt" reagent (**Scheme 20**) [[58](#_ENREF_58), [59](#_ENREF_59)]. The derived alkylated products **99**–**101** are stable in solution and in the solid state and do not isomerise as the respective protonated species **144** and **147** (see section 2.5, Scheme 32). At the same time, methylation of complex **37** occurs simultaneously at one of the nitrogens of the aminocarbene moiety and the sulfur center giving new species **102** containing two distinct carbene fragments [[58](#_ENREF_58), [59](#_ENREF_59)].



**Scheme 20.** Methylation of the cobalt(I) formamidinyl complexes prepared *via* the *in situ* deprotonation of cobalt-ADCs [[58](#_ENREF_58), [59](#_ENREF_59)].

**2.3.2 Intramolecular alkylation and acylation of the ADC derivatives**

Saegusa and coworkers demonstrated that cyclisation (formally an intramolecular alkylation) of ADC ligand in the palladium(II) complexes **104**, generated by the nucleophilic addition of α-aminoacetal to PdII-ligated isocyanide in **103**, affords the NHC species **105** (**Scheme 21**, a) [[76](#_ENREF_76)]. This reaction proceeds in the presence of sulfuric (or *p*-toluenesulfonic) acid in CHCl3 at RT. Ko and coworkers extended this synthetic route to the synthesis of luminescent rhenium(I) NHC complexes **108** that are prepared starting from the corresponding isocyanide species **106** (**Scheme 21**, b) [[77](#_ENREF_77)]. Reaction is believed to proceed *via* the intermediate formation of the ADC species **107**. Hashmi and coworkers prepared catalytically active gold(I), palladium(II) and platinum(II) NHC complexes *via* the same approach [[78-83](#_ENREF_78)].



**Scheme 21**. Cyclisation of ADC ligand in palladium(II) [[76](#_ENREF_76)] and rhenium(I) [[77](#_ENREF_77)] complexes.

Reaction of coordinated isocyanides with haloamines represents a well-established method for the preparation of NHC derivatives, and it is extensively reviewed [[3](#_ENREF_3), [84-87](#_ENREF_84)]. Insofar as this process is related to the above-mentioned cyclisation of ADC derivatives, we provide herein a few representative examples. Hence, Michelin and coworkers described the reaction of palladium(II) and platinum(II) isocyanide complexes **109** and **110** with 2-bromoethylamine hydrobromide in the presence of *n*BuLi to give five-membered diaminocarbene derivatives **113** and **114** (**Scheme 22**, a) [[88](#_ENREF_88)]. The reaction proceeds through the initial formation of the ADC species **111** and **112** and the subsequent cyclisation. At the same time, iron(II) ADC complexes **116** and **117**, generated from the isocyanide complex **115** and 2-chloroethylamine or 3-chloropropylamine, give the NHC derivatives **118** and **119** only upon deprotonation by excess EtONa (**Scheme 22**, b) [[89](#_ENREF_89)].



**Scheme 22**. Intramolecular alkylation of ADC species to NHC derivatives [[88](#_ENREF_88), [89](#_ENREF_89)].

Hashmi and coworkers demonstrated that gold(I) isocyanide complexes **120** react with α-amino ester and 3-bromopropylamine to furnish five- and six-membered carbene complexes **122** and **124** (**Scheme 23**) [[90](#_ENREF_90), [91](#_ENREF_91)]. Reactions proceeds through the initial formation of ADC complexes **121** and **123** and the subsequent cyclisation *via* intramolecular acylation or alkylation.



**Scheme 23**. Cyclisation of metal-ADCs through intramolecular acylation or alkylation [[90](#_ENREF_90), [91](#_ENREF_91)].

Ruiz and coworkers reported on the cyclisation of ADC complexes **126** generated by the nucleophilic attack of propargylamine on manganese(I) isocyanide complexes **125** (**Scheme 24**) [[92](#_ENREF_92), [93](#_ENREF_93)]. ADC species **126** formed undergo an intramolecular hydroamination to give the cyclic carbene derivatives **127**, which are further transformed to NHC complexes **128** by an 1,3 proton shift from the endocyclic methylene group to the exocyclic one.



**Scheme 24**. Cyclisation of ADC ligands in manganese(I) complexes to give NHC [[92](#_ENREF_92), [93](#_ENREF_93)].

In the further study, it was reported that gold(I) ADC complex **129**, which is structurally related to **126**, cyclises to give the cyclic carbene **130** in the presence of NaH(**Scheme 25**) [[94](#_ENREF_94)].



**Scheme 25**. Cyclisation of ADC ligands in gold(I) complexes to NHCs [[94](#_ENREF_94)].

Above-mentioned examples for the addition of **-functionalised nucleophiles to metal-bound isocyanides illustrate the preparation of metal-NHCs from the corresponding metal-ADC species. This reactivity type for ADC complexes is therefore complementary to that of **-functionalised isocyanides, *e.g.* generation of gold-NHCs **132** *via* the cyclization of starting isocyanide species **131** (**Scheme 26**) [[95](#_ENREF_95), [96](#_ENREF_96)], and it was recently reviewed by Kuwata and Hahn as one of the synthetic routes to *p*NHC [[97](#_ENREF_97)].



**Scheme 26**. Cyclisation of metal-bound *β*-amino-functionalised isocyanides to give metal-NHCs.

**2.4 Reversible formation of metal-ADC species from isocyanide complexes and amines**

As far as the nucleophilic addition to isocyanides is concerned, several studies describe that this reaction might exhibit a reversible character. Thus, the addition of amine to an FeII-activated isocyanide leads to the monodentate ADC species **134** that exist in dynamic equilibrium with the starting isocyanide complex **133** (**Scheme 27**) [[98](#_ENREF_98), [99](#_ENREF_99)]. A similar reversibility was observed for the related RuII species [[100](#_ENREF_100)].



**Scheme 27.** Reversible formation of iron(II) and ruthenium(II) ADC complexes upon addition of amines to metal-bound isocyanides [[98-100](#_ENREF_98)].

Slaughter and coworkers described the dynamic equilibrium between the chelating *bis*(carbene)- **135** and the *mono*carbene-isocyanide **136** palladium(II) complexes (**Scheme 28**) [[101](#_ENREF_101)]. Steric repulsion between the backbone aryl groups in the carbene moieties is suggested as a likely cause of instability of the chelated ADC ligand leading to the ring opening. DFT calculations provided an estimate of 16 kcal mol–1 for the strain energy in the *bis*(ADC) ligand of **135**, that can be considered as an approximate upper limit of chelate ring steric strain that can be accommodated during ‘‘covalent self-assembly’’ of carbene ligand.



**Scheme 28.** Dynamic equilibrium between the chelating *bis*(carbene)- and the *mono*carbene-isocyanide palladium(II) complexes [[101](#_ENREF_101)].

Competitive cleavage of either C–NH2 or C–NHR bonds in the aminocarbene fragment was observed in iridium(III) ADC complexes **137** generated upon the nucleophilic addition of ammonia to Ir(III)-bound isocyanides (**Scheme 29**) [[102](#_ENREF_102)]. The reaction of **137** with a *weaker* organic base (*e.g.* *N*-methylmorpholine or triethanolamine) led to the cleavage of ADC ligand to isocyanide ligand in **138** and the elimination of NH3. In this case, the different acidity of CNH2 and CN(H)aryl groups are responsible for the observed reactivity: CN(H)aryl group more acidic and selective deprotonation by a weakorganic base, that is subsequently converted into **138**. The addition of a *stronger* base, *i.e.* Et3N or KOH to the aminocarbene species **137** results in the concurrent non-selective deprotonation of either NH2 or NH–Aryl moieties of the ADC leading to a mixture of **138** and **139**. When an excess of gaseous NH3 is used, the cleavage of ADC ligand proceeded *via* an alternative route furnishing cyanide species **139** and a substituted aniline. Insofar as the basicity of NH3 in organic solvents is comparable to that of Et3N, one can expect that the application of ammonia as a base should subsequently lead to a mixture of **138** and **139**. However, in this case, ammonia plays a dual role of a base and a nucleophile. As a base, NH3 converts **137** to a mixture of **138** and **139**, while as a nucleophile, it reacts with **138** to regenerate the starting complex **137**. As a result, when NH3 is used, the reaction proceeds until the full conversion of **137** to **139** is achieved. X-ray data for complex **137** show that the intramolecular repulsion between two ADC ligands, could contribute toward the cleavage of ADC ligands. It is worth noting that no follow-up transformation of the second ADC ligand present in **138** and **139** was observed.



**Scheme 29.** Competitive cleavage of either C–NH2 or C–NHR bonds in the aminocarbene fragment in iridium(III) ADC complexes [[102](#_ENREF_102)].

Fragmentation of diaminocarbene ligand to give metal-bound cyanide was reported by Che and coworkers who performed a photochemical reaction between platinum(II) ADC complex **140** and MeI [[29](#_ENREF_29)]. This reaction includes the oxidation of metal center and the fragmentation of diaminocarbene ligand to give a cyanide complex **141** (**Scheme 30**). Other fragmentation products were neither identified, nor suggested, and authors do not comment on a plausible mechanism of this process.



**Scheme 30.** Photochemical fragmentation of ADC ligand in platinum(II) complex [[29](#_ENREF_29)].

**2.5 Cleavage of the N–X bond within the carbene fragment**

Kukuskin and coworkers reported that palladium(II) binuclear diaminocarbene complexes **142**, which were generated by coupling of *cis*-[PdCl2(CNXyl)2] with 1,3-thiazol-2-amines (Y = CH) and 1,3,4-thiadiazol-2-amines (Y = N) can be subject to a reversible isomerisation giving a mixture of two isomeric binuclear diaminocarbene derivatives **142** and **143** (**Scheme 31**) [[70](#_ENREF_70), [74](#_ENREF_74)]. This isomerisation proceeds *via* the splitting of the Pd−N and C−N bonds of the aminocarbene fragment. Both isomeric structures **142** and **143** are held by intramolecular S···Cl (for kinetically controlled isomer **142**) or S···N (for thermodynamically controlled isomer **143**) chalcogen bonds and the energy difference between these noncovalent interactions is a driving force of isomerisation.

In contrast to the previous example, the binuclear species generated by using other α-amino azaheterocycles, *i.e.*, 1*H*-imidazol-2-amine, 4*H*-1,2,4-triazol-3-amine, 1*H*-tetrazol-5-amine, 1*H*-benzimidazol-2-amine, 1-methyl-1*H*-benzimidazol-2-amine, 1-ethyl-1*H*-benzimidazol-2-amine [[72](#_ENREF_72)], 2-aminopyridine [[68](#_ENREF_68)], and 2-aminoperazine [[69](#_ENREF_69)] are stable at RT or even upon reflux at C2H4Cl2 for 2 days, and they are not subject to isomerisation.



**Scheme 31.** Reversible regioisomerisation of binuclear diaminocarbene palladium(II) complexes accompanied with splitting the Pd−N and C−N bonds of the aminocarbene fragment [[70](#_ENREF_70), [74](#_ENREF_74)].

Werner and Strecker reported that cobalt(I) diaminocarbene complexes **144** can be subject to a reversible isomerisation giving a mixture of two isomeric diaminocarbene derivatives **144** and **147** (**Scheme 32**) [[59](#_ENREF_59)]. This reaction proceeds *via* splitting of the N−C bond of the aminocarbene fragment and formation of the corresponding intermediate species **145** and **146**.



**Scheme 32.** Reversible regioisomerisation of cobalt(I) diaminocarbene complexes accompanied with the splitting the C−N bond of the aminocarbene fragment [[59](#_ENREF_59)].

Fehlhammer and coworkers reported that amino(hydrazino)carbene complexes of сhromium(0) (**150**) and tungsten(0) (**151**), generated *in situ* by reaction of *N*-isocyanodialkylamine complexes [M(CO)5CNNR2] **148** and **149** [M = Cr, W; R = Et, *i*Pr, ½ ‑CH(Me)(CH2)3CH(Me)-] with secondary amines, are subject to N–N bond cleavage and C–N migration of the metal to give *N*-cyanamide species [M(CO)5NCNR’2] **152** and **153** (**Scheme 33**, a) [[103](#_ENREF_103)]. At the same time, the *N*-isocyanodialkylamine complexes of platinum(II) **154** react with an excess of secondary amines to give amine(guanidine)platinum(II) complexes *trans-*[PtI2(HNR’2)(HN=C(NR’2)2}] (**157**) [R’ = Et, ½ -(CH2)5-, ½ -(CH2)2O(CH2)2-] (**Scheme 33**, b) [[103](#_ENREF_103)]. It is likely that conversion of **154** to **157** proceeds through the initial formation of the metal-hydrazinocarbene species **155**, and subsequentlymetal-*N*-cyanamide species **156** that reacts further with an excess of amine. Noteworthy, similar amino(hydrazino)carbene complexes of сhromium(0) and tungsten(0) [M(CO)5{C(NHR’)NHNHR2}] [M = Cr, W]and platinum(II) *trans-*[PtI2(CNNR2){C(NHR’)NHNHR2}] generated by addition of primary amines to *N*-isocyanodialkylamine complexes are stable in the presence or the absence of amines [[104](#_ENREF_104)].



**Scheme 33.** Cleavage of N–N bond and C–N migration of the ADC complexes generated *in situ* by reaction of *N*-isocyanodialkylamine complexes of сhromium(0) and tungsten(0) and platinum(II) with secondary amines [[89](#_ENREF_89), [103](#_ENREF_103)].

Kostyuk, Biffis and coworkers described the coordination of ADC species **158** to a palladium(II) center leading to a mixture of *C*,*P*-chelated ADC derivatives **159** alongside *N*,*P*-chelated iminophosphane species **160**. The later derivative originates from the isomerization of ADC ligand, *viz*. 1,2-shift of the phosphanyl moiety from the N atom to the adjacent carbene (**Scheme 34**) [[105](#_ENREF_105), [106](#_ENREF_106)]. It was reported that the catalytic activity of iminophosphane complexes of the type **160** is superior to that of complexes with related *N*-phosphanyl diaminocarbene ligands **159** in the intermolecular catalytic hydroamination of alkynes with aromatic primary amines [[106](#_ENREF_106)]. Authors justify this by a lower stability of the carbene complexes **159** under the reaction conditions, leading to rapid catalyst decomposition [[106](#_ENREF_106)].



**Scheme 34.** Coordination of ADC species **158** to palladium(II) center leading to *C*,*P*-chelated ADC species **159** in a mixture with *N*,*P*-chelated iminophosphane species **160** [[105](#_ENREF_105), [106](#_ENREF_106)].

Yu and co-workers described the palladium-catalysed oxidative C−H imidoylation of *N*-methoxybenzamides **161** to 3-iminoisoindolin-1-ones **164** (**Scheme 35**). The mechanism proposed by the authors includes 1,3-acyl migration step in the acyclic diaminocarbene species **162** generated *in situ* to give an isomeric carbene derivative **163** [[107](#_ENREF_107)].



**Scheme 35**. 1,3-Acyl migration step in deprotonated acyclic diaminocarbene species generated *in situ* in the course of Pd-catalysed aerobic oxidative C−H imidoylation reactions [[107](#_ENREF_107)].

**2.6 Oxidation of diaminocarbenes into carbodiimides**

Saegusa and coworkers described the oxidation of palladium(II)-ADC complexes **165** with Ag2O to furnish the corresponding uncomplexed carbodiimide derivatives **166** (**Scheme 36**) [[108](#_ENREF_108)].



**Scheme 36.** Oxidation of palladium(II)-ADC complexes **165** with Ag2O to give uncomplexed carbodiimides [[108](#_ENREF_108)].

Slaughter and coworkers reported that palladium(II) *bis*(acyclic diaminocarbene) complex **167** is subject to a two-electron oxidation to the *bis*(amidine) complex **168** in air (**Scheme 37**) [[109](#_ENREF_109)]. Complex **168** can also be prepared upon oxidation of **167** with iodosobenzene [[109](#_ENREF_109)].



**Scheme 37.** Oxidation of palladium(II)-*bis*(ADC) species **167** to *bis*(amidine) complex **168** [[109](#_ENREF_109)].

Han and Huynh reported that reaction of the NHC–isocyanide palladium(II) complex **169** with 2,6-dimethylaniline leads to a mixture of NHC–ADC complex **170** and the uncomplexed *N,N’,N’*’-*tris*(2,6-dimethylphenyl)-guanidine (**171**) (**Scheme 38**) [[110](#_ENREF_110)].



**Scheme 38**. Oxidation of mixed palladium(II) NHC–ADC complex (**169**) to furnish uncomplexed *N*,*N*’,*N*’’-*tris*(2,6-dimethylphenyl)-guanidine **171** [[110](#_ENREF_110)].

Intramolecular oxidation of diprotic *p*ADC ligands in polystyrene-supported palladium(II) ADC complexes **172** in the presence of Et3N leads to the corresponding polystyrene-supported carbodiimide **174** and palladium nanoparticles (**Scheme 39**) [[8](#_ENREF_8)]. The reaction proceeds through the intermediate formation of formamidinyl derivative **173**. Short-lived gold(III) ADC complexes [AuCl3{C(NHNCPh2)NHR}] generated by addition of benzophenone hydrazone to the isocyanide ligand in [AuCl3(CNR)] in CDCl3 solution decompose in a similar way giving corresponding carbodiimide and gold nanoparticles [[111](#_ENREF_111)].



**Scheme 39.** Polystyrene-supported palladium(II) ADC complexes possessing two NH protons decompose *via* the carbene–carbodiimide path [[8](#_ENREF_8)].

Canovese and coworkers showed that mixed gold(III) ADC/isocyanide complex **176**, prepared *via* the oxidative addition of bromine to corresponding gold(I) species **175** decompose to gold(I) isocyanide complex [AuBr(CNXyl)] (**177**), uncomplexed *N*-(2,6-dimethylphenyl)piperidine-1-carbimidoyl bromide (**178**), and (2,6-dimethylphenyl)carbonimidic dibromide (**179**) (**Scheme 40**, a) [[112](#_ENREF_112)]. A related intramolecular oxidation was observed for the gold(III) monoADC complex **181** (**Scheme 40**, b) prepared by bromination of gold(I)-ADC complex **180** [[112](#_ENREF_112)]. At the same time, gold(III) *bis*ADC complex **183** that was generated upon bromination of gold(I)-ADC complex **182**,was stable under similar conditions (**Scheme 40**, c) [[112](#_ENREF_112)].



**Scheme 40.** Synthesis and decomposition of the gold(III) ADC complexes [[112](#_ENREF_112)].

Angelici and coworkers described the gold-catalysed coupling of isocyanides **184** with primary amines under an oxygen atmosphere leading to the carbodiimides **186** and H2O [[113](#_ENREF_113)]. Reaction of isocyanides and secondary amines with O2 in the presence of gold powder under similar conditions leads to the substituted ureas **187** (**Scheme 41**) [[114](#_ENREF_114)]. Formation of carbodiimides and ureas was proposed to proceed through a diaminocarbene intermediate **185** [[114](#_ENREF_114)]. It is known that oxygen is not absorbed by gold surface, therefore, strong electron donating ability of the diaminocarbene species is believed to be solely responsible for the observed reactivity.



**Scheme 41.** Oxidation of the gold acyclic diaminocarbene complexes prepared *in situ* with O2 to give carbodiimides (a) [[113](#_ENREF_113)] and ureas (b) [[114](#_ENREF_114)].

Ruiz and coworkers reported that ADC ligands in the manganese(I) complexes *fac*-[Mn{CNHR(NHMe)}(bipy)(CO)3](ClO4) (R = Ar **11**) can be selectively converted either to the free carbodiimides **190** (**Scheme 42**) or to the *N*-coordinated formamidines **203** and **204** (**Scheme 47**, section 2.7) [[62](#_ENREF_62), [115](#_ENREF_115)]. Treatment of the formamidinyl species **12** with Ag2O leads to conversion of the formamidinyl ligand to the unsymmetrically substituted carbodiimides **190** (**Scheme 42**) [[115](#_ENREF_115)]. This process occurs even for the sterically encumbered aromatic ADCs. Dialkyl carbodiimides (R = Alkyl) could not be prepared *via* this approach owing to the extreme propensity of the corresponding formamidinyl species **189** to protonation, leading to the diaminocarbene complexes **188** instead of oxidation.



**Scheme 42.** Oxidation of formamidinyl manganese(I) complexes with Ag2O to give carbodiimides [[115](#_ENREF_115)].

**2.7 Displacement and re-coordination of ADC or corresponding formamidinyl ligands**

Parks and Balch described the displacement of ADC ligands from the gold(I) ADC complexes **191** and **192** (**Scheme 43**) [[116](#_ENREF_116)]. Thus, the treatment of gold(I) ADC complexes **191** or **192** with two equivs of cyanide ion or triphenylphosphine results in the quantitative formation of *N*,*N*’-dimethylformamidine **193** or *N*,*N*,*N*’-trimethylformamidine **194**, respectively. With PPh3, the reaction requires several hours to reach completion at room temperature whereas the displacement with cyanide ion is essentially complete after five minutes. With MeNC, the reaction proceeds *via* the conversion of the gold(I) ADC complex **191** to diamidide **195** (**Scheme 43**) [[116](#_ENREF_116)].



**Scheme 43.** Displacement of formamidines from gold(I) ADC complexes [[116](#_ENREF_116)].

Minghetti and coworkers showed that reaction of gold(III) *bis*ADC complex **196** with triphenylphosphine leads to a displacement of both ADCs giving formamidine **197**; the gold(III) center is simultaneously reduced to gold(I) (**Scheme 44**) [[117](#_ENREF_117)].



**Scheme 44.** Displacement of formamidines from gold(III) ADC complexes [[117](#_ENREF_117)].

Michelin and coworkers reported that reaction of palladium(II) ADC complexes **198** with bidentate *P*-donors such as 1,2-*bis*(diphenylphosphino)ethane (dppe) and 1,1-*bis*(diphenylphosphino)methane (dppm) promotes the metal-carbene bond cleavage and the elimination of carbene ligand, yielding organic formamidines **199** alongside palladium-(dppm) species **200** (**Scheme 45**) [[44](#_ENREF_44)].



**Scheme 45.** Displacement of formamidines from palladium(II) ADC complexes [[44](#_ENREF_44)].

Ligand displacement from labile metal ions can be used for the catalytic preparation of formamidines from isocyanides and primary amines. Hence, the reaction between isocyanides and primary amines to give formamidines was shown to be catalysed by Cu+, Ag+, Zn2+, Cd2+, and Hg2+ and it proceeds *via* the *in situ* generation of the ADC species [[113](#_ENREF_113), [118](#_ENREF_118)].

Bertani and coworkers revealed that indium(I) ADC complexes **201** decompose by excess HCl to give corresponding formamidines **202** (**Scheme 46**) [[119](#_ENREF_119)].



**Scheme 46.** Displacement of formamidines from indium(I) ADC complexes [[119](#_ENREF_119)].

Ruiz and coworkers reported that ADC ligands in the manganese(I) complexes *fac*-[Mn{CNHR(NHMe)}(bipy)(CO)3](ClO4) (R = Ar **11**, Alk **188**) can be converted to *N*-coordinated formamidines **203** and **204** (**Scheme 47**) [[62](#_ENREF_62), [115](#_ENREF_115), [120](#_ENREF_120)]. Thus, the treatment of CH2Cl2 solution of **11** or **188** with catalytic amount of Ag2O leads to a quantitative conversion of carbene ligand to the corresponding formamidine. Complexes **203** and **204** prepared exist as a mixture of isomers due to coordination either through the NMe or the NR moiety. Conversion of diaminocarbenes to formamidines occurs only for the sterically unhindered aminocarbenes (R = Me, Bn, Ph, naphth-2-yl, 4-MeOC4H4); no reaction was observed with more sterically demanding 2,6-dimethylphenyl or 2-chloro-6-methylphenyl species.



**Scheme 47.** Isomerisation of ADC ligand to the corresponding formamidine, catalysed by Ag2O [[62](#_ENREF_62), [115](#_ENREF_115), [120](#_ENREF_120)].

Scherer, Herrmann and coworkers described the interconversion between *η*1- and *η*2‑bonded ADC ligand in chromium(0), molybdenum(0) and tungsten(0) complexes [[121](#_ENREF_121), [122](#_ENREF_122)]. The reaction of M(CO)5L complexes (M = Cr, L = diethyl ether **205**; M = Mo, L = THT **206**; M = W, L = THT **207**) with free acyclic diaminocarbenes gave the ADC complexes **209**–**211** (**Scheme 48**) [[121](#_ENREF_121), [122](#_ENREF_122)]. For chromium, reaction of **205** with ADCled to formation of chelating diaminocarbene complex **211** with the *η*2‑bonded ADC ligand [[122](#_ENREF_122)]; intermediate formation of *η*1-substituted-carbene species **208** was not detected. For molybdenum and tungsten, formation of the *η*1-substituted-carbene pentacarbonyl complexes **209** and **210** was observed [[121](#_ENREF_121)], and they are converted to the *η*2-bonded species **212** and **213** by loss of one CO ligand. In complexes **211**–**213**, the lone pairs of the nitrogen and the carbene carbon atom bound to metal contribute to stabilisation of the Lewis-acidic metal center. The *bis*(diisopropylamino)carbene ligand in complexes **211**–**213** is *η*2‑coordinated to the metals with a shorter metal-carbon bond and a longer metal–nitrogen bond.

**Scheme 48.** Reaction of free *bis*(diisopropylamino)carbene with a pentacarbonyl complexes and subsequent transformation of the ADC complexes to an imine species [[121](#_ENREF_121), [122](#_ENREF_122)].

The Cr–N bond in complex **211** can be easily cleaved resulting in a dynamic system at RT, where all alkyl substituents become equivalent in the 1H NMR spectrum [[122](#_ENREF_122)]; similar reactivity was not observed for **212** and **213**. Chromium complex **211** reacts with one equiv of CO to reform the *η*1-complex **208** [[122](#_ENREF_122)], whereas molybdenum and tungsten complexes **212** and **213** are converted into imine species **214** and **215** with elimination of propene [[121](#_ENREF_121)].

**3. Final remarks**

To conclude, acyclic diaminocarbenes are widely recognised as ancillary ligands with easily varied electronic and steric properties and many applications. In the course of this survey we showed that ADC metal complexes can exhibit a number of reactivity patterns and be converted into various functionalised derivatives. Reactivity modes of selected ADC ligand depend not only on the structure of the carbene fragment and metal complex itself, but also on the method of its generation. The majority of the reports reviewed involve the preparation of metal-ADC species *via* metal-mediated nucleophilic addition to isocyanides, and this route leads to the complexes with protic ADC ligands. As a result, these *p*ADC species can be subject to deprotonation paving the way for a number of intermolecular and intramolecular processes, including metallation, nucleophilic attack, alkylation, cyclisation and others. Furthermore, generation of metal-ADCs *via* nucleophilic addition to isocyanides in certain situations can be reversed to starting materials, *i.e.* through heating or photochemically. A better understanding of reactivity of metal-ADC species can be anticipated to aid structural elucidation, *e.g.* by ensuring more accurate assignment of carbene structure and their derivatives in solution using NMR and in solid-state by X-ray diffraction, to shed light on mechanisms of catalytic processes involving ADC-based catalysts, and to reveal unexpected applications of these unique compounds.

**Acknowledgments**

This work was supported by the Russian Foundation for Basic Research (project 18-33-20073 mol\_a\_ved). KVL additionally thanks the University of Liverpool for support. Authors are grateful to Dr. Matthew Pye for the constructive comments.

**References**

[1] J. Vignolle, X. Catton, and D. Bourissou, Stable noncyclic singlet carbenes, Chem. Rev., 109 (2009) 3333–3384, <https://dx.doi.org/10.1021/cr800549j>

[2] V.P. Boyarskiy, N.A. Bokach, K.V. Luzyanin, and V.Y. Kukushkin, Metal-Mediated and Metal-Catalyzed Reactions of Isocyanides, Chem. Rev., 115 (2015) 2698–2779, <https://dx.doi.org/10.1021/cr500380d>

[3] R.A. Michelin, A.J.L. Pombeiro, and M.F.C. Guedes da Silva, Aminocarbene complexes derived from nucleophilic addition to isocyanide ligands, Coord. Chem. Rev., 218 (2001) 75–112, <https://dx.doi.org/10.1016/S0010-8545(01)00358-7>

[4] K.V. Luzyanin, and A.J.L. Pombeiro, Carbene complexes derived from metal-bound isocyanides, in: V. Nenajdenko (Ed.) Isocyanide chemistry, Wiley-VCH, 2012, Ch. 15, pp. 531–550.

[5] L.M. Slaughter, Acyclic Aminocarbenes in Catalysis, ACS Catal., 2 (2012) 1802–1816, <https://dx.doi.org/10.1021/cs300300y>

[6] V.P. Boyarskiy, K.V. Luzyanin, and V.Y. Kukushkin, Acyclic diaminocarbenes (ADCs) as a promising alternative to N-heterocyclic carbenes (NHCs) in transition metal catalyzed organic transformations, Coord. Chem. Rev., 256 (2012) 2029–2056, <https://dx.doi.org/10.1016/j.ccr.2012.04.022>

[7] K.M.T. Mahmudov, V.Y. Kukushkin, A.V. Gurbanov, M.A. Kinzhalov, V.P. Boyarskiy, M.F.C. Guedes da Silva, and A.J.L. Pombeiro, Isocyanide metal complexes in catalysis, Coord. Chem. Rev., 384 (2019) 65–89, <https://dx.doi.org/10.1016/j.ccr.2019.01.002>

[8] V.N. Mikhaylov, V.N. Sorokoumov, D.M. Liakhov, A.G. Tskhovrebov, and I.A. Balova, Polystyrene-Supported Acyclic Diaminocarbene Palladium Complexes in Sonogashira Cross-Coupling: Stability vs. Catalytic Activity, Catalysts, 8 (2018) 141, <https://dx.doi.org/10.3390/catal8040141>

[9] J.C. Gee, B.A. Fuller, H.-M. Lockett, G. Sedghi, C.M. Robertson, and K.V. Luzyanin, Visible light accelerated hydrosilylation of alkynes using platinum–[acyclic diaminocarbene] photocatalysts, Chem. Commun., 54 (2018) 9450–9453, <https://dx.doi.org/10.1039/C8CC04287J>

[10] R.S. Chay, B.G.M. Rocha, A.J.L. Pombeiro, V.Y. Kukushkin, and K.V. Luzyanin, Platinum Complexes with Chelating Acyclic Aminocarbene Ligands Work as Catalysts for Hydrosilylation of Alkynes, ACS Omega, 3 (2018) 863–871, <https://dx.doi.org/10.1021/acsomega.7b01688>

[11] R.M. Islamova, M.V. Dobrynin, A.V. Vlasov, A.A. Eremina, M.A. Kinzhalov, I.E. Kolesnikov, A.A. Zolotarev, E.A. Masloborodova, and K.V. Luzyanin, Iridium(iii)-catalysed cross-linking of polysiloxanes leading to the thermally resistant luminescent silicone rubbers, Catal. Sci. Technol., 7 (2017) 5843–5846, <https://dx.doi.org/10.1039/C7CY02013A>

[12] V.N. Mikhaylov, V.N. Sorokoumov, K.A. Korvinson, A.S. Novikov, and I.A. Balova, Synthesis and Simple Immobilization of Palladium(II) Acyclic Diaminocarbene Complexes on Polystyrene Support as Efficient Catalysts for Sonogashira and Suzuki–Miyaura Cross-Coupling, Organometallics, 35 (2016) 1684–1697, <https://dx.doi.org/10.1021/acs.organomet.6b00144>

[13] S.A. Timofeeva, M.A. Kinzhalov, E.A. Valishina, K.V. Luzyanin, V.P. Boyarskiy, T.M. Buslaeva, M. Haukka, and V.Y. Kukushkin, Application of palladium complexes bearing acyclic amino(hydrazido)carbene ligands as catalysts for copper-free Sonogashira cross-coupling, J. Catal., 329 (2015) 449−456, <https://dx.doi.org/10.1016/j.jcat.2015.06.001>

[14] B.G.M. Rocha, E.A. Valishina, R.S. Chay, M.F.C. Guedes da Silva, T.M. Buslaeva, A.J.L. Pombeiro, V.Y. Kukushkin, and K.V. Luzyanin, ADC-metal complexes as effective catalysts for hydrosilylation of alkynes, J. Catal., 309 (2014) 79–86, <https://dx.doi.org/10.1016/j.jcat.2013.09.003>

[15] D.A. Khrakovsky, C. Tao, M.W. Johnson, R.T. Thornbury, S.L. Shevick, and F.D. Toste, Enantioselective, Stereodivergent Hydroazidation and Hydroamination of Allenes Catalyzed by Acyclic Diaminocarbene (ADC) Gold(I) Complexes, Angew. Chem. Int. Ed., 55 (2016) 6079-6083, <https://dx.doi.org/doi:10.1002/anie.201601550>

[16] M.A. Kinzhalov, K.V. Luzyanin, V.P. Boyarskiy, M. Haukka, and V.Y. Kukushkin, ADC-Based Palladium Catalysts for Aqueous Suzuki−Miyaura Cross-Coupling Exhibit Greater Activity than the Most Advantageous Catalytic Systems, Organometallics, 32 (2013) 5212–5223, <https://dx.doi.org/10.1021/om4007592>

[17] E.A. Valishina, M.F.C. Guedes da Silva, M.A. Kinzhalov, S.A. Timofeeva, T.M. Buslaeva, M. Haukka, A.J.L. Pombeiro, V.P. Boyarskiy, V.Y. Kukushkin, and K.V. Luzyanin, Palladium-ADC complexes as efficient catalysts in copper-free and room temperature Sonogashira coupling, J. Mol. Catal. A: Chem., 395 (2014) 162−171, <https://dx.doi.org/10.1016/j.molcata.2014.08.018>

[18] G. Alves, L. Morel, M. El-Ghozzi, D. Avignant, B. Legeret, L. Nauton, F. Cisnetti, and A. Gautier, A platinum Chugaev carbene complex as a potent anticancer agent, Chem. Commun., 47 (2011) 7830-7832, <https://dx.doi.org/10.1039/C1CC12228B>

[19] A. Gautier, and F. Cisnetti, Advances in metal–carbene complexes as potent anti-cancer agents, Metallomics, 4 (2012) 23-32, <https://dx.doi.org/10.1039/C1MT00123J>

[20] B. Bertrand, A.S. Romanov, M. Brooks, J. Davis, C. Schmidt, I. Ott, M. O'Connell, and M. Bochmann, Synthesis, structure and cytotoxicity of cyclic (alkyl)(amino) carbene and acyclic carbene complexes of group 11 metals, Dalton Trans., 46 (2017) 15875-15887, <https://dx.doi.org/10.1039/C7DT03189K>

[21] S. Montanel-Pérez, R.P. Herrera, A. Laguna, M.D. Villacampa, and M.C. Gimeno, The fluxional amine gold(iii) complex as an excellent catalyst and precursor of biologically active acyclic carbenes, Dalton Trans., 44 (2015) 9052-9062, <https://dx.doi.org/10.1039/C5DT00703H>

[22] M. Williams, A.I. Green, J. Fernandez-Cestau, D.L. Hughes, M.A. O'Connell, M. Searcey, B. Bertrand, and M. Bochmann, (C^Npz^C)AuIII complexes of acyclic carbene ligands: synthesis and anticancer properties, Dalton Trans., 46 (2017) 13397-13408, <https://dx.doi.org/10.1039/C7DT02804K>

[23] H. Na, P.N. Lai, L.M. Cañada, and T.S. Teets, Photoluminescence of Cyclometalated Iridium Complexes in Poly(methyl methacrylate) Films, Organometallics, 37 (2018) 3269-3277, <https://dx.doi.org/10.1021/acs.organomet.8b00446>

[24] H. Na, A. Maity, R. Morshed, and T.S. Teets, Bis-Cyclometalated Iridium Complexes with Chelating Dicarbene Ancillary Ligands, Organometallics, 36 (2017) 2965-2972, <https://dx.doi.org/10.1021/acs.organomet.7b00428>

[25] H. Na, and T.S. Teets, Highly Luminescent Cyclometalated Iridium Complexes Generated by Nucleophilic Addition to Coordinated Isocyanides, J. Am. Chem. Soc., 140 (2018) 6353-6360, <https://dx.doi.org/10.1021/jacs.8b02416>

[26] C.-O. Ng, S.-C. Cheng, W.-K. Chu, K.-M. Tang, S.-M. Yiu, and C.-C. Ko, Luminescent Rhenium(I) Pyridyldiaminocarbene Complexes: Photophysics, Anion-Binding, and CO2-Capturing Properties, Inorg. Chem., 55 (2016) 7969-7979, <https://dx.doi.org/10.1021/acs.inorgchem.6b01017>

[27] O. Crespo, M.C. Gimeno, A. Laguna, S. Montanel-Pérez, and M.D. Villacampa, Facile Synthesis of Gold(III) Aryl–Carbene Metallacycles, Organometallics, 31 (2012) 5520–5526, <https://dx.doi.org/10.1021/om300495u>

[28] S.-W. Lai, K.K. Cheung, M.C.W. Chan, and C.M. Che, [{Pt(CN)(C10H21N4)}6]: A Luminescent Hexanuclear Platinum(II) Macrocycle Containing Chelating Dicarbene and Bridging Cyanide Ligands, Angew. Chem. Int. Ed., 37 (1998) 182–184, <https://dx.doi.org/10.1002/(SICI)1521-3773(19980202)37:1/2><182::AID-ANIE182>3.0.CO;2-X

[29] S.-W. Lai, M.C.-W. Chan, K.-K. Cheung, and C.-M. Che, Carbene and Isocyanide Ligation at Luminescent Cyclometalated 6-Phenyl-2,2'-bipyridyl Platinum(II) Complexes: Structural and Spectroscopic Studies, Organometallics, 18 (1999) 3327-3336, <https://dx.doi.org/10.1021/om990256h>

[30] S.-W. Lai, M.C.W. Chan, Y. Wang, H.-W. Lam, S.-M. Peng, and C.-M. Che, Luminescent metal complexes derived from carbene and related ligands: tuning excited-state properties with metal–carbon multiple bonds, J. Organomet. Chem., 617-618 (2001) 133-140, <https://dx.doi.org/10.1016/S0022-328X(00)00723-3>

[31] C. Bartolome, M. Carrasco-Rando, S. Coco, C. Cordovilla, P. Espinet, and J.M. Martin-Alvarez, Gold(i)-carbenes derived from 4-pyridylisocyanide complexes: supramolecular macrocycles supported by hydrogen bonds, and luminescent behavior, Dalton Trans., 45 (2007) 5339−5345, <https://dx.doi.org/10.1039/b711430c>

[32] D.M. Ivanov, M.A. Kinzhalov, A.S. Novikov, I.V. Ananyev, A.A. Romanova, V.P. Boyarskiy, M. Haukka, and V.Y. Kukushkin, The H2C(X)–X•••X– (X = Cl, Br) Halogen Bonding of Dihalomethanes, Cryst. Growth Des., (2017) 1353–1362, <https://dx.doi.org/10.1021/acs.cgd.6b01754>

[33] C. Bartolomé, M. Carrasco-Rando, S. Coco, C. Cordovilla, P. Espinet, and J.M. Martín-Alvarez, Structural Switching in Luminescent Polynuclear Gold Imidoyl Complexes by Intramolecular Hydrogen Bonding, Organometallics, 25 (2006) 2700-2703, <https://dx.doi.org/10.1021/om0601753>

[34] M.A. Kinzhalov, and V.P. Boyarskii, Structure of isocyanide palladium(II) complexes and their reactivity toward nitrogen nucleophiles, Russ. J. Gen. Chem., 85 (2015) 2313–2333, <https://dx.doi.org/10.1134/S1070363215100175>

[35] J.R. Stork, M.M. Olmstead, J.C. Fettinger, and A.L. Balch, Metal−Metal Interactions in Thallium(I)/Platinum(II) Compounds Involving a Chelating Dicarbene and Various Auxiliary Ligands, Inorg. Chem., 45 (2006) 849-857, <https://dx.doi.org/10.1021/ic051252>+

[36] L. Biasiolo, G. Ciancaleoni, L. Belpassi, G. Bistoni, A. Macchioni, F. Tarantelli, and D. Zuccaccia, Relationship between the anion/cation relative orientation and the catalytic activity of nitrogen acyclic carbene–gold catalysts, Catal. Sci. Technol., 5 (2015) 1558-1567, <https://dx.doi.org/10.1039/C4CY01440E>

[37] Y.-C. Shi, S. Wang, and S. Xie, Syntheses, molecular structures, and self-assemblies of SFe3, S2Fe3, S3Fe5, SeFe3, and Se2Fe3 clusters with chelating diaminocarbenes, J. Coord. Chem., 68 (2015) 3852-3883, <https://dx.doi.org/10.1080/00958972.2015.1079312>

[38] J. Ruiz, and B.F. Perandones, Acyclic Diamino Carbene Complexes of Manganese(I): Synthesis, Deprotonation, and Subsequent Multiple Insertion Reaction of Alkynes, Organometallics, 28 (2009) 830-836, <https://dx.doi.org/10.1021/om800888r>

[39] L. Chugaev, M. Skanavy-Grigorieva, and A. Posniak, Über Die Hydrazin-Carbylamin-Komplexe des Platins, Zeitschrift für anorganische und allgemeine Chemie, 148 (1925) 37–42, <https://dx.doi.org/10.1002/zaac.19251480105>

[40] A.L. Balch, and J. Miller, Characterization of the complexes obtained from the addition of hydrazine to hexakis(methyl isocyanide)iron(II), J. Am. Chem. Soc., 94 (1972) 417-420, <https://dx.doi.org/10.1021/ja00757a019>

[41] A.L. Balch, and J.E. Parks, Platinum and Palladium Complexes Formed by Chelative Addition of Amines to Isocyanides, J. Am. Chem. Soc., 96 (1974) 4114–4121 <https://dx.doi.org/10.1021/ja00820a009>

[42] W.M. Butler, J.H. Enemark, J. Parks, and A.L. Balch, Chelative addition of hydrazines to coordinated isocyanides. Structure of Chugaev's red salt, Inorg. Chem., 12 (1973) 451-457, <https://dx.doi.org/10.1021/ic50120a042>

[43] S.A. Katkova, M.A. Kinzhalov, P.M. Tolstoy, A.S. Novikov, V.P. Boyarskiy, A.Y. Ananyan, P.V. Gushchin, M. Haukka, A.A. Zolotarev, A.Y. Ivanov, S.S. Zlotsky, and V.Y. Kukushkin, Diversity of Isomerization Patterns and Protolytic Forms in Aminocarbene PdII and PtII Complexes Formed upon Addition of N,N′-Diphenylguanidine to Metal-Activated Isocyanides, Organometallics, 36 (2017) 4145–4159, <https://dx.doi.org/10.1021/acs.organomet.7b00569>

[44] R.A. Michelin, R. Bertani, M. Mozzon, L. Zanotto, F. Benetollo, and G. Bombieri, Synthesis, structural properties, and reaction chemistry of hydrido alkyl diaminocarbene complexes of platinum(II). Cleavage of the metal-carbene and metal-alkyl bonds and synthesis of formamidines and cis hydrido carbene derivatives, Organometallics, 9 (1990) 1449–1459, <https://dx.doi.org/10.1021/om00119a015>

[45] T. Sawai, and R.J. Angelici, Ligand reactions of manganese carbonylisocyanide complexes with amines, J. Organomet. Chem., 80 (1974) 91-102, <https://dx.doi.org/10.1016/S0022-328X(00)87018-7>

[46] A.I. Moncada, S. Manne, J.M. Tanski, and L.M. Slaughter, Modular Chelated Palladium Diaminocarbene Complexes: Synthesis, Characterization, and Optimization of Catalytic Suzuki-Miyaura Cross-Coupling Activity by Ligand Modification, Organometallics, 25 (2006) 491–505, <https://dx.doi.org/10.1021/om050786f>

[47] Z. Ramiro, C. Bartolomé, and P. Espinet, Protection of the Gold(I) Catalyst by AsPh3 in Reactions of Enynes, Eur. J. Inorg. Chem., 2014 (2014) 5499-5506, <https://dx.doi.org/10.1002/ejic.201402744>

[48] Y.-M. Wang, C.N. Kuzniewski, V. Rauniyar, C. Hoong, and F.D. Toste, Chiral (Acyclic Diaminocarbene)Gold(I)-Catalyzed Dynamic Kinetic Asymmetric Transformation of Propargyl Esters, J. Am. Chem. Soc., 133 (2011) 12972-12975, <https://dx.doi.org/10.1021/ja205068j>

[49] C. Bartolome, M. Carrasco-Rando, S. Coco, C. Cordovilla, J.M. Martin-Alvarez, and P. Espinet, Luminescent gold(I) carbenes from 2-pyridylisocyanide complexes: Structural consequences of intramolecular versus intermolecular hydrogen-bonding interactions, Inorg. Chem., 47 (2008) 1616–1624, <https://dx.doi.org/10.1021/ic702201e>

[50] C. Bartolomé, Z. Ramiro, P. Pérez-Galán, C. Bour, M. Raducan, A.M. Echavarren, and P. Espinet, Gold(I) Complexes with Hydrogen-Bond Supported Heterocyclic Carbenes as Active Catalysts in Reactions of 1,6-Enynes, Inorg. Chem., 47 (2008) 11391-11397, <https://dx.doi.org/10.1021/ic801446v>

[51] C. Bartolomé, D. García-Cuadrado, Z. Ramiro, and P. Espinet, Synthesis and Catalytic Activity of Gold Chiral Nitrogen Acyclic Carbenes and Gold Hydrogen Bonded Heterocyclic Carbenes in Cyclopropanation of Vinyl Arenes and in Intramolecular Hydroalkoxylation of Allenes, Inorg. Chem., 49 (2010) 9758-9764, <https://dx.doi.org/10.1021/ic101059c>

[52] A.S. Mikherdov, A.S. Novikov, M.A. Kinzhalov, V.P. Boyarskiy, G.L. Starova, A.Y. Ivanov, and V.Y. Kukushkin, Halides Held by Bifurcated Chalcogen–Hydrogen Bonds. Effect of μ(S,N–H)Cl Contacts on Dimerization of Cl(carbene)PdII Species, Inorg. Chem., 57 (2018) 3420–3433, <https://dx.doi.org/10.1021/acs.inorgchem.8b00190>

[53] L. Zhang, W. Yu, C. Liu, Y. Xu, Z. Duan, and F. Mathey, The Chemistry of ortho-(Diarylphosphino)aryl Isocyanides, Organometallics, 34 (2015) 5697-5702, <https://dx.doi.org/10.1021/acs.organomet.5b00746>

[54] M.A. Kinzhalov, S.A. Timofeeva, K.V. Luzyanin, V.P. Boyarskiy, A.A. Yakimanskiy, M. Haukka, and V.Y. Kukushkin, Palladium(II)-Mediated Addition of Benzenediamines to Isocyanides: Generation of Three Types of Diaminocarbene Ligands Depending on the Isomeric Structure of the Nucleophile, Organometallics, 35 (2016) 218–228, <https://dx.doi.org/10.1021/acs.organomet.5b00936>

[55] M.A. Kinzhalov, A.S. Novikov, A.N. Chernyshev, and V.V. Suslonov, Intermolecular hydrogen bonding H···Cl− in the solid palladium(II)-diaminocarbene complexes, Z. Kristallogr. - Cryst. Mater., 232 (2017) 299–305, <https://dx.doi.org/10.1515/zkri-2016-2018>

[56] M.A. Kinzhalov, S.V. Baykov, A.S. Novikov, M. Haukka, and V.P. Boyarskiy, Intermolecular hydrogen bonding H···Cl in crystal structure of palladium(II)-bis(diaminocarbene) complex, Z. Kristallogr. - Cryst. Mater., 234 (2019) 155, <https://dx.doi.org/10.1515/zkri-2018-2100>

[57] D. Lentz, and R. Marschall, Reaktionen von (Pentamethylcyclopentadienyl)bis(trifluormethylisocyanid)cobalt mit Nucleophilen, Chem. Ber., 123 (1990) 467-470, <https://dx.doi.org/doi:10.1002/cber.19901230309>

[58] H. Werner, B. Heiser, and C. Burschka, Cycloadditionsreaktionen von Organometallkomplexen, I. Die Synthese viergliedriger Metalla-Heterocyclen durch [2 + 2]-Cycloaddition aus (Isonitril)cobalt-Komplexen und Isocyanaten sowie Isothiocyanaten, Chem. Ber., 115 (1982) 3069-3084, <https://dx.doi.org/10.1002/cber.19821150913>

[59] H. Werner, and B. Strecker, Cycloadditionsreaktionen von Organometallkomplexen.: XIII. Synthese und Reaktivität viergliedriger Cobalta-Heterocyclen aus C5H5Co(CNR)(PMe3) und Isocyanaten bzw. Isothiocyanaten sowie eine ungewöhnliche Fragmentierung des chiralen Isocyanid-Liganden (S)-CNCH(Me)Ph, J. Organomet. Chem., 413 (1991) 379-397, <https://dx.doi.org/10.1016/0022-328X(91)80064-Q>

[60] H. Werner, B. Heiser, and H. Otto, Cycloadditionsreaktionen von Organometallkomplexen, VII. Fünfgliedrige Cobalta-Heterocyclen durch [2 + 3]-Cycloaddition von Benzoylnitren an eine Co – CNR-Bindung, Chem. Ber., 118 (1985) 3932-3938, <https://dx.doi.org/doi:10.1002/cber.19851181006>

[61] J. Ruiz, L. García, B.F. Perandones, and M. Vivanco, A Fischer Carbene within an Arduengo Carbene, Angew. Chem. Int. Ed. , 50 (2011) 3010–3012, <https://dx.doi.org/10.1002/anie.201007937>

[62] J. Ruiz, L. García, M. Vivanco, Á. Berros, and J.F. Van der Maelen, Generating and Trapping Metalla-N-Heterocyclic Carbenes, Angew. Chem. Int. Ed. , 54 (2015) 4212–4216, <https://dx.doi.org/10.1002/anie.201411647>

[63] J. Ruiz, D. Sol, J.F. Van der Maelen, and M. Vivanco, Base-Promoted Transmetalation Reactions of Protic N-Heterocyclic Carbenes and Acyclic Diamino Carbenes from MnI to AuI: A Mechanistic Study, Organometallics, 36 (2017) 1035–1041, <https://dx.doi.org/10.1021/acs.organomet.7b00009>

[64] J. Ruiz, L. Garcia, M. Vivanco, D. Sol, and S. Garcia-Granda, Half-sandwich iron(ii) complexes with protic acyclic diaminocarbene ligands: synthesis, deprotonation and metalation reactions, Dalton Trans., 46 (2017) 10387-10398, <https://dx.doi.org/10.1039/C7DT02049J>

[65] J. Ruiz, L. Garcia, C. Mejuto, M. Vivanco, M.R. Diaz, and S. Garcia-Granda, Strong electron-donating metalla-N-heterocyclic carbenes, Chem. Commun., 50 (2014) 2129-2132, <https://dx.doi.org/10.1039/C3CC47987K>

[66] B. Crociani, F. Di Bianca, A. Fontana, E. Forsellini, and G. Bombieri, Nucleophilic attack at co-ordinated isocyanides promoted by the 2-pyridyl ligand, Dalton Trans., (1994) 407–414, <https://dx.doi.org/10.1039/DT9940000407>

[67] V. Riera, and J. Ruiz, Reactivity of cationic isocyanide iron(II) derivatives towards nucleophilic agents, J. Organomet. Chem., 384 (1990) 339–346, <https://dx.doi.org/10.1016/0022-328X(90)87126-X>

[68] A.G. Tskhovrebov, K.V. Luzyanin, F.M. Dolgushin, M.F.C. Guedes da Silva, A.J.L. Pombeiro, and V.Y. Kukushkin, Novel reactivity mode of metal diaminocarbenes: palladium(II)-mediated coupling between acyclic diaminocarbenes and isonitriles leading to dinuclear species, Organometallics, 30 (2011) 3362–3370, <https://dx.doi.org/10.1021/om2002574>

[69] M.A. Kinzhalov, K.V. Luzyanin, V.P. Boyarskiy, M. Haukka, and V.Y. Kukushkin, Coupling of C-amino aza-substituted heterocycles with an isocyanide ligand in palladium(II) complex, Russ. Chem. Bull., 62 (2013) 758–766, <https://dx.doi.org/10.1007/s11172-013-0103-4>

[70] A.S. Mikherdov, M.A. Kinzhalov, A.S. Novikov, V.P. Boyarskiy, I.A. Boyarskaya, D.V. Dar’in, G.L. Starova, and V.Y. Kukushkin, Difference in Energy between Two Distinct Types of Chalcogen Bonds Drives Regioisomerization of Binuclear (Diaminocarbene)PdII Complexes, J. Am. Chem. Soc., 138 (2016) 14129–14137, <https://dx.doi.org/10.1021/jacs.6b09133>

[71] A.S. Mikherdov, A.S. Novikov, M.A. Kinzhalov, A.A. Zolotarev, and V.P. Boyarskiy, Intra-/Intermolecular Bifurcated Chalcogen Bonding in Crystal Structure of Thiazole/Thiadiazole Derived Binuclear (Diaminocarbene)PdII Complexes, Crystals, 8 (2018) 112, <https://dx.doi.org/10.3390/cryst8030112>

[72] A.S. Mikherdov, M.A. Kinzhalov, A.S. Novikov, V.P. Boyarskiy, I.A. Boyarskaya, M.S. Avdontceva, and V.Y. Kukushkin, Ligation-Enhanced π-Hole···π Interactions Involving Isocyanides: Effect of π-Hole···π Noncovalent Bonding on Conformational Stabilization of Acyclic Diaminocarbene Ligands, Inorg. Chem., 57 (2018) 6722-6733, <https://dx.doi.org/10.1021/acs.inorgchem.8b01027>

[73] A.S. Mikherdov, Y.A. Orekhova, and V.P. Boyarskii, Formation of Homo- and Heteronuclear Platinum(II) and Palladium(II) Carbene Complexes in the Reactions of Coordinated Isocyanides with Aminothiazaheterocycles, Russ. J. Gen. Chem., 88 (2018) 2119-2124, <https://dx.doi.org/10.1134/s1070363218100158>

[74] A.S. Mikherdov, N.Y. Tiuftiakov, V.A. Polukeev, and V.P. Boyarskii, Coupling of Bis(xylylisocyanide) Palladium(II) Complex with 1,2,4-Thiadiazole-5-amines, Russ. J. Gen. Chem., 88 (2018) 713-720, <https://dx.doi.org/10.1134/s1070363218040151>

[75] C. Singh, A.P. Prakasham, M.K. Gangwar, and P. Ghosh, Binuclear Fused 5-membered Palladacycle and Palladium Complex of Amido-Functionalized N-heterocyclic Carbene Precatalysts for the One-Pot Tandem Hiyama Alkynylation/Cyclization Reactions, Chem. Select, 3 (2018) 9361-9367, <https://dx.doi.org/10.1002/slct.201801667>

[76] Y. Ito, T. Hirao, K. Tsubata, and T. Saegusa, A new preparation of imidazolidinylidene palladium(II) complexes, Tetrahedron Lett., 19 (1978) 1535-1538, <https://dx.doi.org/10.1016/S0040-4039(01)94597-6>

[77] C.-O. Ng, S.-M. Yiu, and C.-C. Ko, Synthesis, Characterization, and Photophysical Study of Luminescent Rhenium(I) Diimine Complexes with Various Types of N-Heterocyclic Carbene Ligands, Inorg. Chem., 53 (2014) 3022-3031, <https://dx.doi.org/10.1021/ic4028145>

[78] A.S.K. Hashmi, C. Lothschütz, C. Böhling, T. Hengst, C. Hubbert, and F. Rominger, Carbenes Made Easy: Formation of Unsymmetrically Substituted N-Heterocyclic Carbene Complexes of Palladium(II), Platinum(II) and Gold(I) from Coordinated Isonitriles and their Catalytic Activity, Adv. Synth. Catal., 352 (2010) 3001–3012, <https://dx.doi.org/10.1002/adsc.201000472>

[79] M.J. Spallek, D. Riedel, F. Rominger, A.S.K. Hashmi, and O. Trapp, Six-Membered, Chiral NHCs Derived from Camphor: Structure–Reactivity Relationship in Asymmetric Oxindole Synthesis, Organometallics, 31 (2012) 1127–1132, <https://dx.doi.org/10.1021/om201166b>

[80] C. Hubbert, M. Breunig, K.J. Carroll, F. Rominger, and A.S.K. Hashmi, Simple Synthesis of New Mixed Isocyanide-NHC-Platinum(II) Complexes and Their Catalytic Activity, Aust. J. Chem., 67 (2014) 469–474, <https://dx.doi.org/10.1071/CH13546>

[81] D. Riedel, T. Wurm, K. Graf, M. Rudolph, F. Rominger, and A.S.K. Hashmi, From Isonitriles to Unsaturated NHC Complexes of Gold, Palladium and Platinum, Adv. Synth. Catal., 357 (2015) 1515–1523, <https://dx.doi.org/10.1002/adsc.201401131>

[82] A. Zeiler, M. Rudolph, F. Rominger, and A.S.K. Hashmi, An Alternative Approach to PEPPSI Catalysts: From Palladium Isonitriles to Highly Active Unsymmetrically Substituted PEPPSI Catalysts, Chem. Eur. J., 21 (2015) 11065–11071, <https://dx.doi.org/10.1002/chem.201500025>

[83] P. Zargaran, T. Wurm, D. Zahner, J. Schießl, M. Rudolph, F. Rominger, and A.S.K. Hashmi, A Structure-Based Activity Study of Highly Active Unsymmetrically Substituted NHC Gold(I) Catalysts, Adv. Synth. Catal., 360 (2018) 106-111, <https://dx.doi.org/doi:10.1002/adsc.201701080>

[84] M.C. Jahnke, and F.E. Hahn, Complexes with protic (NH,NH and NH,NR) N-heterocyclic carbene ligands, Coord. Chem. Rev. , 293-294 (2015) 95-115, <https://dx.doi.org/10.1016/j.ccr.2015.01.014>

[85] V.P. Boyarskiy, K.V. Luzyanin, and V.Y. Kukushkin, Palladium-(acyclic diaminocarbene) species as alternative to palladium-(nitrogenheterocyclic carbenes) in cross-coupling catalysis, in: A.J.L. Pombeiro (Ed.) Advances in Organometallic Chemistry and Catalysis: The Silver/Gold Jubilee International Conference on Organometallic Chemistry Celebratory Book, John Wiley & Sons, Inc., New York, 2014, pp. 145–156.

[86] F.E. Hahn, and M.C. Jahnke, Heterocyclic Carbenes: Synthesis and Coordination Chemistry, Angew. Chem. Int. Ed., 47 (2008) 3122−3172, <https://dx.doi.org/10.1002/anie.200703883>

[87] U. Belluco, R.A. Michelin, R. Ros, R. Bertani, G. Facchin, M. Mozzon, and L. Zanotto, Synthesis of heterocyclic systems by activation of isocyanide, carbonyl, trifluoromethyl and nitrile ligands in platinum(II) and palladium(II) complexes, Inorg. Chem., 198-200 (1992) 883-897, <https://dx.doi.org/10.1016/S0020-1693(00)92434-4>

[88] R.A. Michelin, L. Zanotto, D. Braga, P. Sabatino, and R.J. Angelici, Transition-metal-promoted cyclization reactions of isocyanide ligands. Synthesis of cyclic diaminocarbenes from isocyanide complexes of palladium(II) and platinum(II) and x-ray structure of cis-Br2Pt[CN(C6H4-p-Me)CH2CH2N(H)](PPh3), Inorg. Chem., 27 (1988) 93-99, <https://dx.doi.org/10.1021/ic00274a020>

[89] I. Yu, C.J. Wallis, B.O. Patrick, P.L. Diaconescu, and P. Mehrkhodavandi, Phosphine-Tethered Carbene Ligands: Template Synthesis and Reactivity of Cyclic and Acyclic Functionalized Carbenes, Organometallics, 29 (2010) 6065-6076, <https://dx.doi.org/10.1021/om100841j>

[90] A.S.K. Hashmi, C. Lothschütz, K. Graf, T. Häffner, A. Schuster, and F. Rominger, A Short Way to Switchable Carbenes, Adv. Synth. Catal., 353 (2011) 1407–1412, <https://dx.doi.org/10.1002/adsc.201100183>

[91] T. Wurm, F. Mulks, C.R.N. Böhling, D. Riedel, P. Zargaran, M. Rudolph, F. Rominger, and A.S.K. Hashmi, Synthesis of Different Classes of Six-Membered Gold(I) NHC Complexes by the Isonitrile Route, Organometallics, 35 (2016) 1070–1078, <https://dx.doi.org/10.1021/acs.organomet.6b00023>

[92] J. Ruiz, G. García, M.E.G. Mosquera, B.F. Perandones, M.P. Gonzalo, and M. Vivanco, Generation of N-Heterocyclic Carbenes by Metal-Mediated Coupling of Propargylamine and Isocyanides, J. Am. Chem. Soc., 127 (2005) 8584-8585, <https://dx.doi.org/10.1021/ja042879e>

[93] J. Ruiz, B.F. Perandones, G. García, and M.E.G. Mosquera, Synthesis of N-Heterocyclic Carbene Complexes of Manganese(I) by Coupling Isocyanide Ligands with Propargylamines and Propargylic Alcohols, Organometallics, 26 (2007) 5687-5695, <https://dx.doi.org/10.1021/om700718x>

[94] J. Ruiz, L. García, D. Sol, and M. Vivanco, Template Synthesis, Metalation, and Self‐Assembly of Protic Gold(I)/(NHC)2 Tectons Driven by Metallophilic Interactions, Angew. Chem. Int. Ed. , 55 (2016) 8386-8390, <https://dx.doi.org/10.1002/anie.201603688>

[95] M. Giustiniano, A. Basso, V. Mercalli, A. Massarotti, E. Novellino, G.C. Tron, and J. Zhu, To each his own: isonitriles for all flavors. Functionalized isocyanides as valuable tools in organic synthesis, Chem. Soc. Rev., 46 (2017) 1295-1357, <https://dx.doi.org/10.1039/C6CS00444J>

[96] M. Tamm, and F. Ekkehardt Hahn, Reactions of β-functional phenyl isocyanides, Coord. Chem. Rev., 182 (1999) 175-209, <https://dx.doi.org/10.1016/S0010-8545(98)00233-1>

[97] S. Kuwata, and F.E. Hahn, Complexes Bearing Protic N-Heterocyclic Carbene Ligands, Chem. Rev., 118 (2018) 9642-9677, <https://dx.doi.org/10.1021/acs.chemrev.8b00176>

[98] W.P. Fehlhammer, A. Mayr, and G. Christian, Isonitrilsynthesen am Komplex VII. HX-Eliminierungen AUS carbenkomplexen des typs LnM–C(X)NHR. ZUR Umwandlung von Aryl-In Alkylisocyanidliganden über carbenzwischenstufen, J. Organomet. Chem., 209 (1981) 57–67, <https://dx.doi.org/10.1016/S0022-328X(00)88975-5>

[99] B.V. Johnson, and J.E. Shade, Trisubstituted diaminocarbene complexes of iron, J. Organomet. Chem., 179 (1979) 357–366, <https://dx.doi.org/10.1016/S0022-328X(00)91751-0>

[100] A.L. Steinmetz, and B.V. Johnson, Reactions of (.eta.5-cyclopentadienyl)ruthenium isocyanide complexes with primary and secondary amines, Organometallics, 2 (1983) 705–709, <https://dx.doi.org/10.1021/om00078a002>

[101] Y.A. Wanniarachchi, and L.M. Slaughter, Reversible Chelate Ring Opening of a Sterically Crowded Palladium Bis(acyclic diaminocarbene) Complex, Organometallics, 27 (2008) 1055–1062, <https://dx.doi.org/10.1021/om700866p>

[102] M.A. Kinzhalov, A.A. Eremina, A.S. Smirnov, V.V. Suslonov, V.Y. Kukushkin, and K.V. Luzyanin, Cleavage of acyclic diaminocarbene ligands at an iridium(III) center. Recognition of a new reactivity mode for carbene ligands, Dalton Trans., (2019) in press DOI:10.1039/C1039DT01138B, <https://dx.doi.org/10.1039/C9DT01138B>

[103] W.P. Fehlhammer, R. Metzner, and W. Sperber, Metallkomplexe funktioneller Isocyanide, XXIV. Reaktionen von N-Isocyandialkylamin-Metallkomplexen mit sekundären Aminen, Chem. Ber., 127 (1994) 829-833, <https://dx.doi.org/10.1002/cber.19941270507>

[104] W.P. Fehlhammer, R. Metzner, P. Luger, and Z. Dauter, Metal Complexes of Functional Isocyanides, XXV. Amino(hydrazino)carbene Complexes, Chem. Ber., 128 (1995) 1061-1068, <https://dx.doi.org/10.1002/cber.19951281102>

[105] A. Marchenko, G. Koidan, A. Hurieva, Y. Vlasenko, A. Kostyuk, and A. Biffis, Palladium(II) complexes with chelating N-phosphanyl acyclic diaminocarbenes: synthesis, characterization and catalytic performance in Suzuki couplings, Dalton Trans., 45 (2016) 1967–1975, <https://dx.doi.org/10.1039/C5DT02250A>

[106] A. Marchenko, G. Koidan, A. Hurieva, A. Kostyuk, D. Franco, M. Baron, and A. Biffis, PdII Complexes with N-(Diadamantylphosphanyl)diaminocarbene and Related Ligands: Synthesis and Catalytic Applications in Intermolecular Alkyne Hydroaminations, Eur. J. Inorg. Chem., 2018 (2018) 652-658, <https://dx.doi.org/10.1002/ejic.201701342>

[107] Y.-J. Liu, H. Xu, W.-J. Kong, M. Shang, H.-X. Dai, and J.-Q. Yu, Overcoming the limitations of directed C–H functionalizations of heterocycles, Nature, 515 (2014) 389, <https://dx.doi.org/10.1038/nature13885>

[108] Y. Ito, T. Hirao, and T. Saegusa, Synthetic reactions by complex catalysts. XXXVII. Novel and versatile method of carbodiimide synthesis oxidation of carbene palladium(II) complex with silver oxide, J. Org. Chem. , 40 (1975) 2981-2982, <https://dx.doi.org/10.1021/jo00908a038>

[109] Y.A. Wanniarachchi, and L.M. Slaughter, One-step assembly of a chiral palladium bis(acyclic diaminocarbene) complex and its unexpected oxidation to a bis(amidine) complex Chem. Commun., 31 (2007) 3294–3296, <https://dx.doi.org/10.1039/B703769D>

[110] Y. Han, and H.V. Huynh, Mixed carbene–isocyanide Pd(ii) complexes: synthesis, structures and reactivity towards nucleophiles, Dalton Trans., (2009) 2201-2209, <https://dx.doi.org/10.1039/B816471A>

[111] T.B. Anisimova, M.A. Kinzhalov, M.F.C. Guedes da Silva, A.S. Novikov, V.Y. Kukushkin, A.J.L. Pombeiro, and K.V. Luzyanin, Addition of N-nucleophiles to gold(iii)-bound isocyanides leading to short-lived gold(iii) acyclic diaminocarbene complexes, New J. Chem., 41 (2017) 3246–3250, <https://dx.doi.org/10.1039/C7NJ00529F>

[112] L. Canovese, F. Visentin, C. Levi, and C. Santo, Reactivity of cationic gold(I) carbene complexes toward oxidative addition of bromine, Inorg. Chem., 391 (2012) 141-149, <https://dx.doi.org/10.1016/j.ica.2012.05.020>

[113] M. Lazar, and R.J. Angelici, Gold Metal-Catalyzed Reactions of Isocyanides with Primary Amines and Oxygen:  Analogies with Reactions of Isocyanides in Transition Metal Complexes, J. Am. Chem. Soc., 128 (2006) 10613-10620, <https://dx.doi.org/10.1021/ja0618907>

[114] M. Lazar, B. Zhu, and R.J. Angelici, Non-nanogold Catalysis of Reactions of Isocyanides, Secondary Amines, and Oxygen to Give Ureas, J. Phys. Chem. C, 111 (2007) 4074-4076, <https://dx.doi.org/10.1021/jp070248b>

[115] J. Ruiz, D. Sol, M.A. Mateo, and M. Vivanco, Selective formation of formamidines, carbodiimides and formimidates from isocyanide complexes of Mn(i) mediated by Ag2O, Dalton Trans., 47 (2018) 6279-6282, <https://dx.doi.org/10.1039/C8DT01200H>

[116] J.E. Parks, and A.L. Balch, Gold carbene complexes: preparation, oxidation, and ligand displacement, J. Organomet. Chem., 71 (1974) 453–463,

[117] G. Minghetti, F. Bonati, and G. Banditelli, Carbene complexes of gold(III) and reactions of the coordinated ligand, Inorg. Chem., 15 (1976) 1718-1720, <https://dx.doi.org/10.1021/ic50161a051>

[118] L.V. Lavnevich, M.S. Avdontseva, M.A. Kinzhalov, and N.A. Bokach, Bisisocyanide complexes of Zn(II) halides: Synthesis, structure, and application in the catalysis of isocyanides reaction with secondary amines, Russ. J. Gen. Chem., 87 (2017) 1752–1758, <https://dx.doi.org/10.1134/S1070363217080199>

[119] R. Bertani, L. Crociani, G. D'Arcangelo, G. Rossetto, P. Traldi, and P. Zanella, Reactions of InMe3 with isocyanides in the presence of amines: chemical and mass spectrometric evidence of unprecedented insertion into InN bonds, J. Organomet. Chem., 626 (2001) 11-15, <https://dx.doi.org/10.1016/S0022-328X(01)00649-0>

[120] J. Ruiz, D. Sol, L. García, M.A. Mateo, M. Vivanco, and J.F. Van der Maelen, Generation and Tunable Cyclization of Formamidinate Ligands in Carbonyl Complexes of Mn(I): An Experimental and Theoretical Study, Organometallics, 38 (2019) 916-925, <https://dx.doi.org/10.1021/acs.organomet.8b00898>

[121] G.D. Frey, E. Herdtweck, and W.A. Herrmann, Structural investigations of metalcarbonyl complexes with acyclic diamino carbenes, J. Organomet. Chem., 691 (2006) 2465–2478, <https://dx.doi.org/https://dx.doi.org/10.1016/j.jorganchem.2006.01.033>

[122] M. Tafipolsky, W. Scherer, K. Öfele, G. Artus, B. Pedersen, W.A. Herrmann, and G.S. McGrady, Electron Delocalization in Acyclic and N-Heterocyclic Carbenes and Their Complexes:  A Combined Experimental and Theoretical Charge-Density Study, J. Am. Chem. Soc., 124 (2002) 5865–5880, <https://dx.doi.org/10.1021/ja011761k>