NOVEL REACTIVITY OF SILVER ISOCYANIDE COMPLEXES AND PALLADIUM BIS(ACYCLIC DIAMINOCARBENES) AS CATALYST FOR THE NAZAROV CYCLIZATION

By

ANTHEA JACINTA MIRANDA

Bachelor of Science in Chemistry
St. Xavier's College
Mumbai, India
2001

Master of Science in Chemistry
University of Mumbai
Mumbai, India
2004

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Dissertation Approved:

Dr. LeGrande Slaughter
Dissertation Adviser

Dr. Warren T. Ford

Dr. Richard Bunce

Dr. Allen Apblett

Dr. Aihua Xie

Dr. A. Gordon Emslie
Dean of the Graduate College

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CHAPTER I

INTRODUCTION

Carbenes are highly reactive species with no charge. They have a divalent carbon atom with two unshared electrons. They can exist in the singlet state or the triplet state (Figure 1.1).[1] The most common and widely studied carbene is dichlorocarbene, which is formed by the alkaline hydrolysis of chloroform.[2] In 1862, Geuther was the first to propose that dichlorocarbene can exist as a reactive intermediate, however, it was only in 1954 that this was confirmed, when Doering and co-workers synthesized dichlorocarbene and trapped the intermediate by an addition reaction to cyclohexene to generate the cyclopropane derivative (Scheme 1.1).[2, 3]

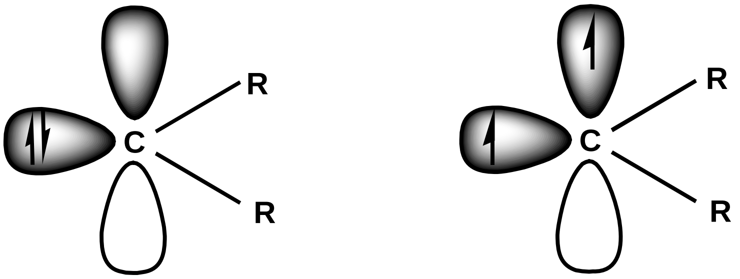
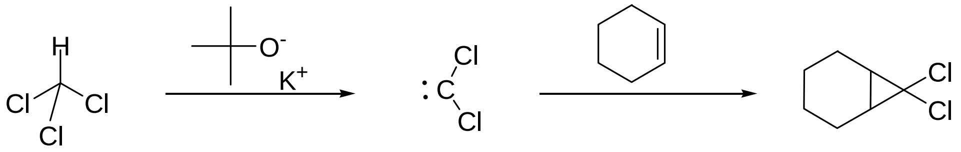


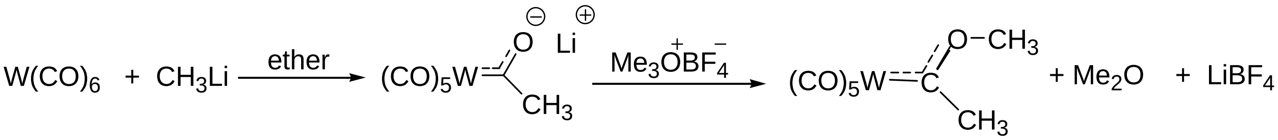
Figure 1.1. Singlet and Triplet carbenes. Adapted from Reference 1.



Scheme 1.1. Synthesis of dichlorocarbene by the deprotonation of chloroform and generation of a cyclopropane derivative. Adapted from Reference 2.

Types of Carbene ligands

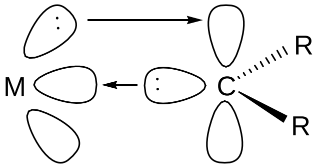
Classically, carbene ligands have been broadly classified into two categories, namely the Fischer carbenes and the Schrock carbenes. N-heterocyclic carbenes or NHCs have only been recognized as being different in recent years. In 1964, Fischer and Maasböl synthesized a stable tungsten carbene complex.[4] Fischer carbene complexes can be synthesized by treating metal hexacarbonyl with phenyllithium or methyllithium in ether followed by alkylation with Me_3OBF_4 (Scheme 1.2).[5] Fischer carbene complexes are typically electron rich, late transition metal complexes in low oxidation states such as Fe(0), Cr(0), W(0) etc. The carbene ligands generally have π-donor substituents like methoxy or dimethylamino attached to carbon.[1]



Scheme 1.2. Synthesis of the first Fischer carbene complex. Adapted from Reference 5.

Bonding in Fischer carbene complexes takes place by the σ donation of electrons from the sp^2 orbital of the singlet carbene carbon to the empty d orbitals of the metal.

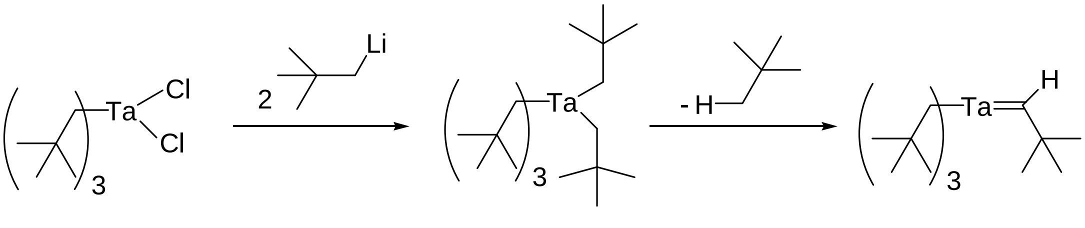
Some π back donation is possible from the metal to the carbene empty p orbital; however, it is usually considered minor, almost negligible. Due, to this, Fischer carbenes are formally electrophilic in nature.[1]



Fischer carbene

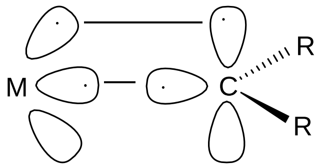
Figure 1.2. Electron donation in Fischer carbene complexes. Adapted from Reference 1.

The second category of carbene ligands is called the Schrock carbenes. These carbenes ligands are also commonly called alkylidenes.[1] Schrock carbene complexes are typically early transition metal complexes in high oxidation states like Ta(V), Ti(IV). These complexes have no π donor substituents and usually have only alkyl groups.[1] The first Schrock carbene complex was formed as a result of treatment of $Ta[CH_2C(CH_3)_3]_3Cl_2$ with two equivalents of neopentyl lithium to obtain $Ta[CH_2C(CH_3)_3]_3[CHC(CH_3)_3]$. This compound was thought to be formed by α-hydrogen abstraction from a neopentyl group leading to the formation of the Ta(V) alkylidene complex (Scheme 1.3).[6]



Scheme 1.3. Synthesis of Schrock carbene complex. Adapted from Reference 6.

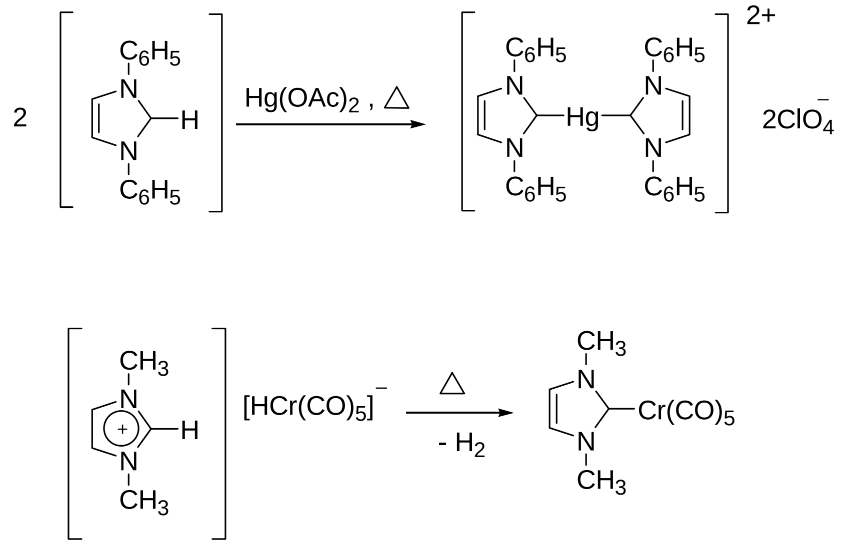
Bonding in these complexes takes place by the interaction between the unpaired electrons on the triplet carbene carbon and two unpaired electrons on the metal resulting in the formation of two covalent bonds; therefore the carbene is formally a -2 ligand. These bonds can be viewed as being polarized towards the carbon atom, as carbon is more electronegative than the metal. Hence, these carbene ligands are considered nucleophilic in nature (Figure 1.3.).[1]



Schrock carbene

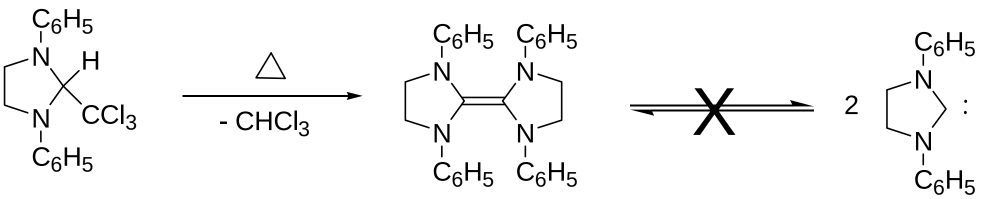
Figure 1.3. Electron donation in a Schrock carbene complex. Adapted from Reference 1.

The third category of carbene ligands are called the N-heterocyclic carbenes which are commonly abbreviated as NHCs. NHCs were not used in catalysis until after Arduengo's isolation of the free carbene. They were very little studied from 1968-1971.[7,8] Independent reports by Öfele and Wanzlick introduced complexes containing N-heterocyclic carbenes as ligands. In 1968, Wanzlick and Schönherr, synthesized an NHC complex by treating 1,3-diphenylimidazolium perchlorate with mercury(II) acetate in DMSO and formed the corresponding carbene complex (Scheme 1.41). A similar route was used to synthesize a Cr(NHC) complex by deprotonation of the imidazolium cation with a carbonylmetalate as shown in Scheme 1.4**.**



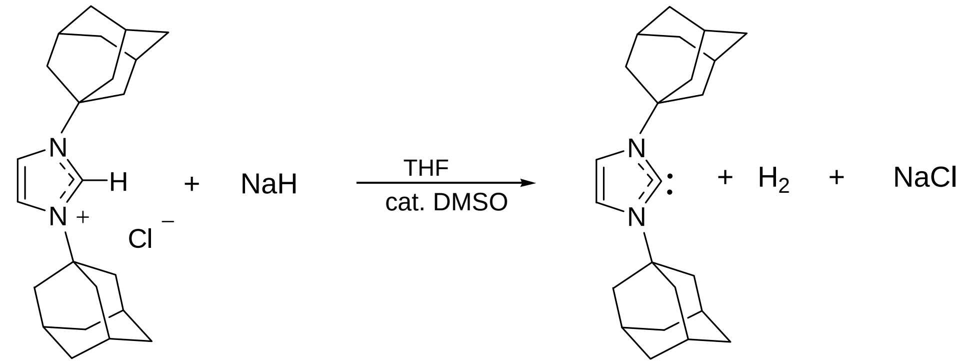
Scheme 1.4. NHC complexes of Wanzlick and Öfele. Adapted from References 7 and 8.

During initial attempts to synthesize on NHC by Wanzlick and co-workers in early 1960, it was thought that the thermal elimination of chloroform from 2-trichloromethyl dihydroimidazoles would form the free carbene, however the resultant product formed was a dimer (Scheme 1.5).[9] It was only later in 1991, when Arduengo synthesized and isolated the first stable crystalline carbene by the treatment of 1,3-di-adamantylimidazolium cation with sodium hydride and catalytic DMSO in THF to form the free carbene (Scheme 1.6).[10] The sodium hydride deprotonated DMSO to form the dimsyl anion which served as a base.



Scheme 1.5. Formation of enetetramine from imidazolidine. Adapted from Reference 9.

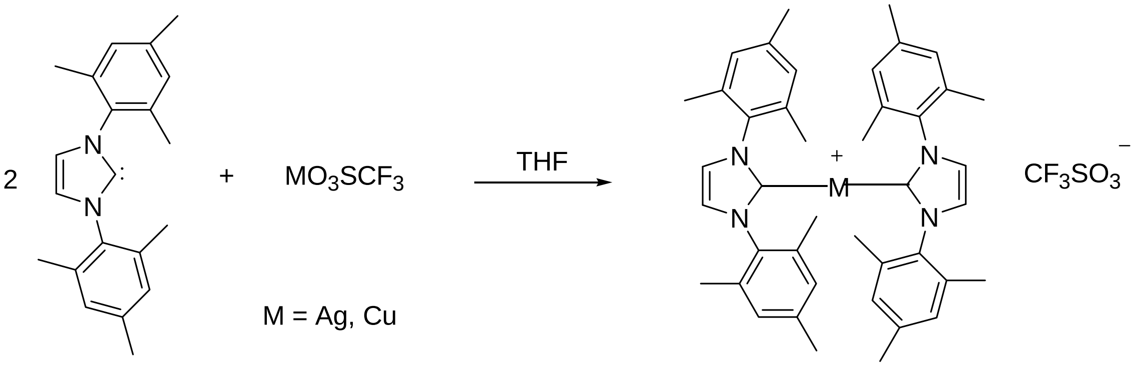
This report was significant as it demonstrated that the first stable free carbene could be formed in good yield and was stable up to 240 °C without decomposition. This carbene, however, was unstable in the presence of oxygen. The unique stability of NHCs was initially attributed to the presence of steric bulk, shielding the carbene carbon; however, later Arduengo and co-workers synthesized 1,3,4,5-tetramethylimidazol-2-ylidene by deprotonation of the corresponding imidazolium chloride showing that a non hindered carbene could also be stable.[11,12]



Scheme 1.6. Arduengo’s stable carbene synthesis. Adapted from Reference 10.

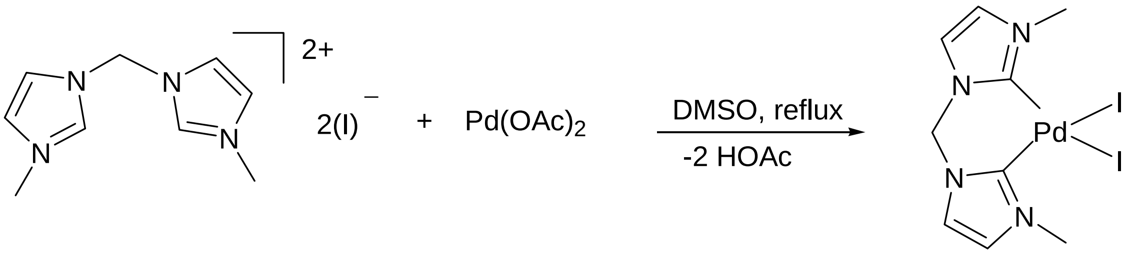
Since Arduengo’s discovery of free NHC ligands; numerous reports on methods for synthesizing NHC metal complexes have appeared. These reports most commonly use the reaction between metal precursors and free carbenes. Catalytic systems containing NHC ligands have been known to promote several transformations such as the Suzuki coupling, hydrosilylation of alkenes and olefin metathesis to name a few. This is proposed to be due to the fact that NHC ligands have strong σ donating abilities,[13] with the result that they show favorable properties compared with phosphine ligands in forming strong stable metal carbene complexes. In addition to strong bonds, these NHC ligands show high temperature stability over 140 °C under harsh catalytic conditions.[14]

Metal NHC complexes can be synthesized via many routes. The most widely studied among these is the treatment of free carbenes with metal salt precursors. This method has been primarily used to synthesize monodentate NHC complexes. In 1993, Arduengo and co-workers, synthesized homoleptic Ag(I) and Cu(I) carbene complexes by the treatment of free 1,3-dimesitylimidazol-2-ylidene with the corresponding metal triflate (M = Ag, Cu) (Scheme 1.7.).[15]



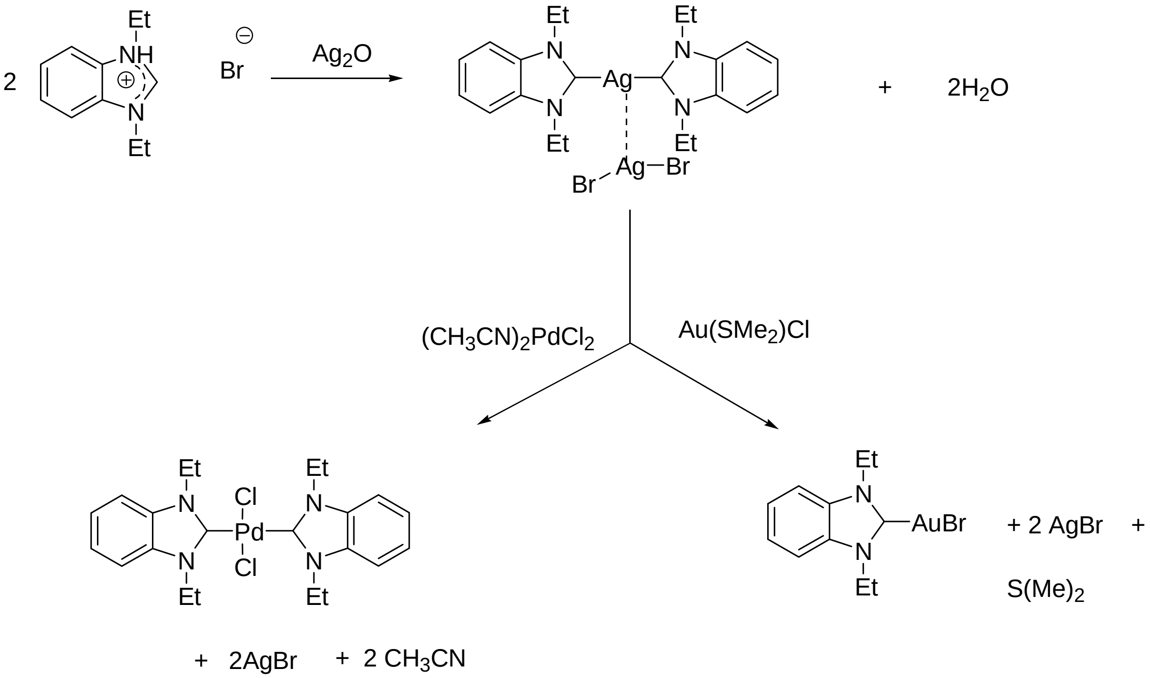
Scheme 1.7. Homoleptic carbene complexes of Ag and Cu. Adapted from Reference 15.

Chelating bis(NHC) complexes have been known nearly as long as monodentate NHCs, though they have not been extensively used in catalysis.[15] The most common route to synthesize chelating bis(NHC) complexes is by direct reaction between two equivalents of an *N*-alkylimidazole and the desired alkyl halide.[16] In 1995, Herrmann and co-workers synthesized the first chelating bis(NHC) complex by treatment of 3,3'-dimethyl-1,1'-methylenedimidazoliumdiodide with $Pd(OAc)_2$ (Scheme 1.8).[17] The palladium bis(NHC) complex was stable to heat, air and moisture. It was also used as a catalyst in the Heck coupling reaction of substituted aryl halides.[16]



Scheme 1.8. Synthesis of chelating bis(NHC) complex. Adapted from Reference 17.

Lin and co-workers synthesized an Ag(I) carbene complex by the treatment of 1,3-diethylbenzimidazolium bromide with 0.5 equivalents of Ag_2O to form the silver(Et_3-Bimy) [Et_3-Bimy = 1,3-diethylbenzimidazol-2-ylidene] complex with the $[AgBr_2]^-$ anion co-ordinated by a short Ag(I)-Ag(I) contact (Scheme 1.9).[18] This silver (I) complex was successfully used to transfer the carbene to the catalytically active metals palladium and gold by treatment with $(CH_3CN)_2PdCl_2$ and $Au[S(CH_3)_2]Cl$ respectively. To exclude the $[AgBr_2]^-$ anion, the complex was treated with Ag_2O in a 4:1 ratio to give $[Ag(Et_2\text{-}Bimy)_2]PF_6$. The Ag-NHC complex showed a sharp signal with no Ag-$C_{carbene}$ coupling by ^{13}C NMR spectroscopy which was described as fluxional behavior.



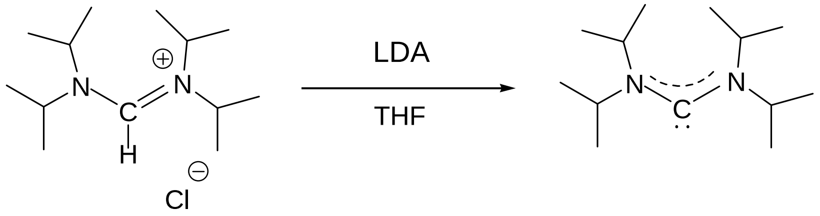
Scheme 1.9. Synthesis of a labile Ag(I) NHC complex followed by carbene transfer to Pd and Au. Adapted from Reference 18.

Acyclic diaminocarbenes

Acyclic diaminocarbenes (ADCs) (Figure 1.4) have generated less attention than the N-heterocyclic carbene ligands even though they show several advantages. Although ADCs are similar to NHCs electronically, very few reports exist in literature on their use as ancillary ligands in catalysis. Some of these advantages include easy synthesis by deprotonation by formamidinium salt precursors, larger N-C-N angles that could increase effective steric bulk at the metal center and higher basicity which makes ADCs potentially stronger σ donor ligands than NHCs.[19,20,21]

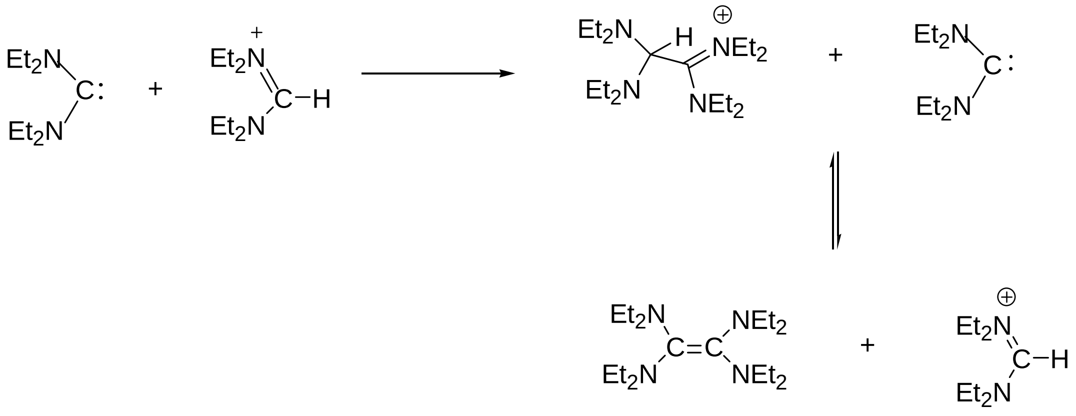
Figure 1.4. N-heterocyclic carbene (NHC) and acyclic diaminocarbene (ADC). Adapted from Reference 19.

Alder and co-workers in 1996 synthesized and isolated bis(diisopropylamino)-carbene. (*N*,*N*,*N*',*N*'-tetraisopropylformamidinylidene) by the treatment of the corresponding formamidinium chloride with lithium diisopropylamide in THF.[22] The resulting diaminocarbene was stable in solution and as a solid (it could be sublimed), but was sensitive to moisture (Scheme 1.10)



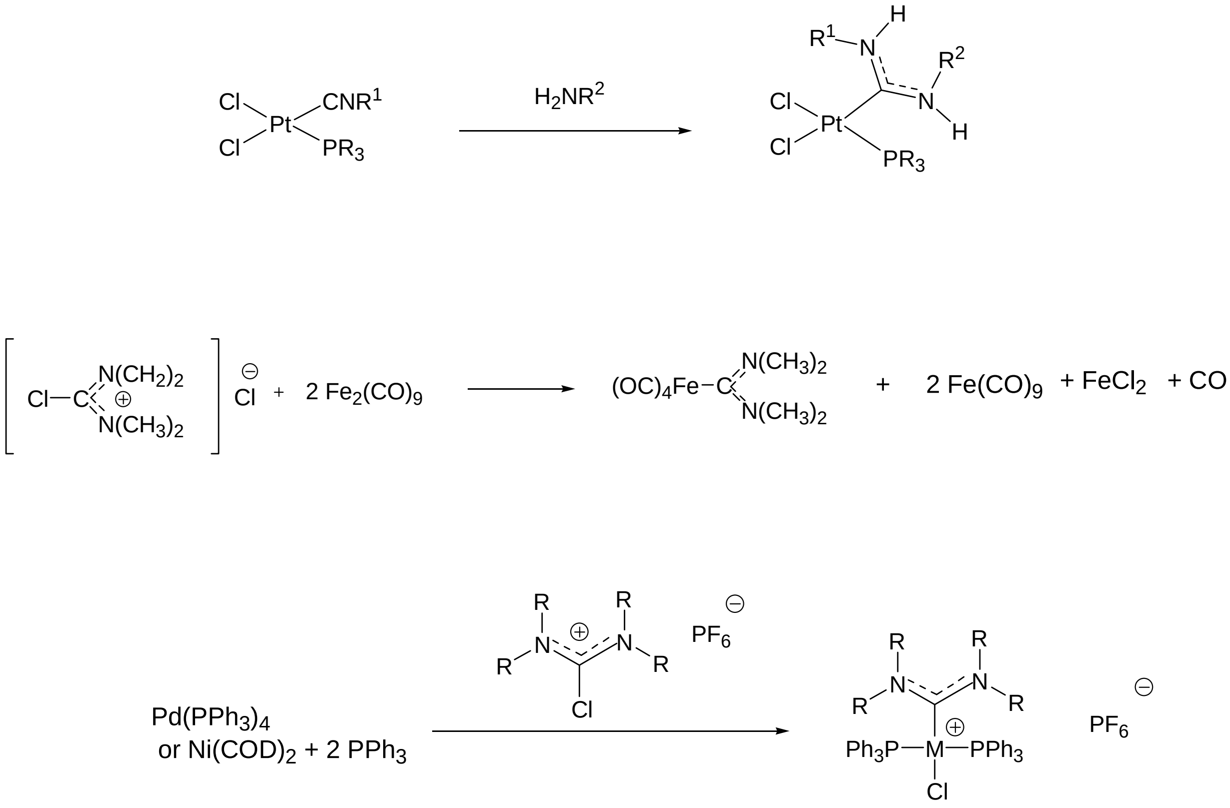
Scheme 1.10. Synthesis of the first free ADC synthesized by Alder. Adapted from Reference 22.

Later, in 2004, Alder and co-workers synthesized bis(diethylamino)carbene by the treatment of its corresponding amidinium salt with lithium diisopropylamide in THF (Scheme 1.11).[23] This diaminocarbene was found to dimerize to tetraaminoethane dimers by the reaction of the free carbene with the formamidinium precursor ion. Although dimerization can be successfully avoided by increasing steric bulk, it poses a potential drawback in the development synthetic routes to metal ADC complexes that proceed via the free carbene.[24]



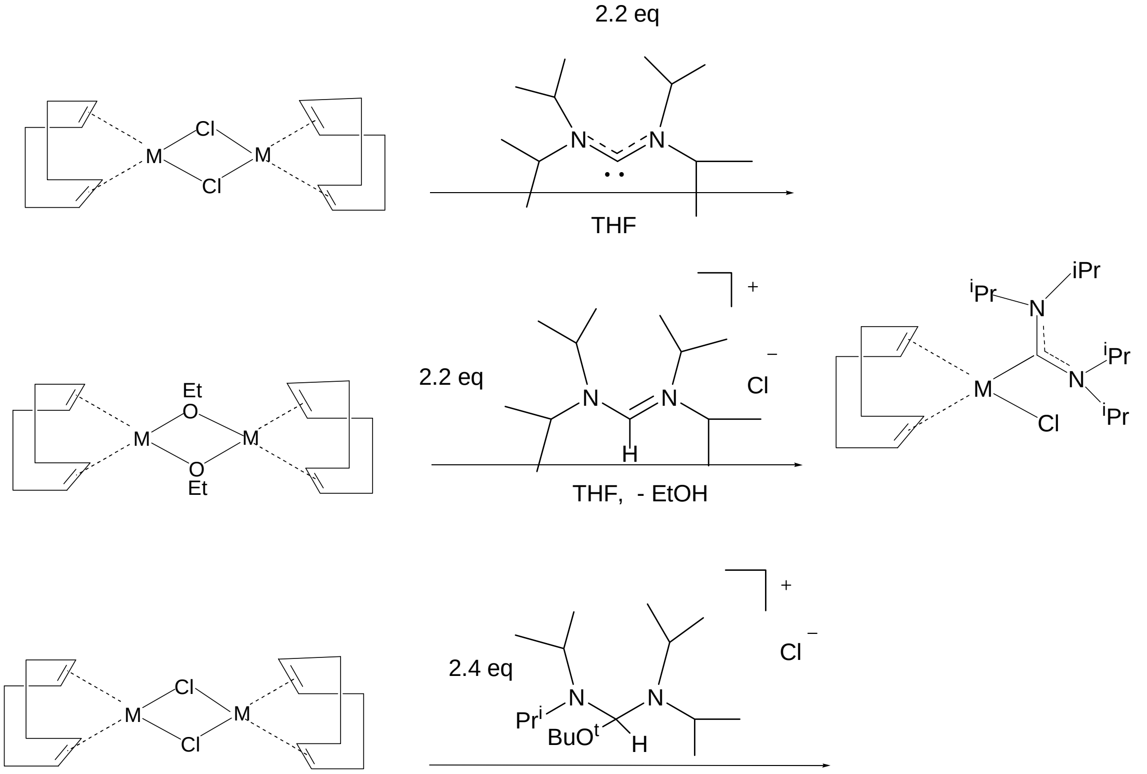
Scheme 1.11. Dimer formation from bis(diethylaminocarbene). Adapted from Reference 23.

Some of the earliest methods to generate ADC include reports by Badley and co-workers, where platinum ADCs were formed by attack at co-ordinated isocyanide ligands on Pt(II) by a secondary amine.[25] Another early route involved formation of an Fe bis(dimethylaminocarbene)complex by the reaction of the chloroformamidinium chloride with $Fe_2(CO)_9$.[26] However, these routes were never generalized to a range of metals. More recently, Fürstner and co-workers devised a synthetic procedure wherein 2-chloroamidinium salts oxidatively added to Pd(0) and Ni(0) complexes to form the corresponding Pd(II) and Ni(II) ADC complexes (Scheme 1.12).[27] The only drawback of this method was that it could not be applied to other catalytically important metals like Rh, Co and Fe.[28] In an attempt to synthesize chelated metal ADC complexes in a similar manner as NHCs, Hermann and co-workers were unsuccessful in synthesizing a chelated Rh bis(ADC) complex by treating an ethoxy bridged Rh dimer with free bis(formamidinium) salt.[29]



Scheme 1.12. Different routes to metal ADC complexes. Adapted from References 25, 26 and 27.

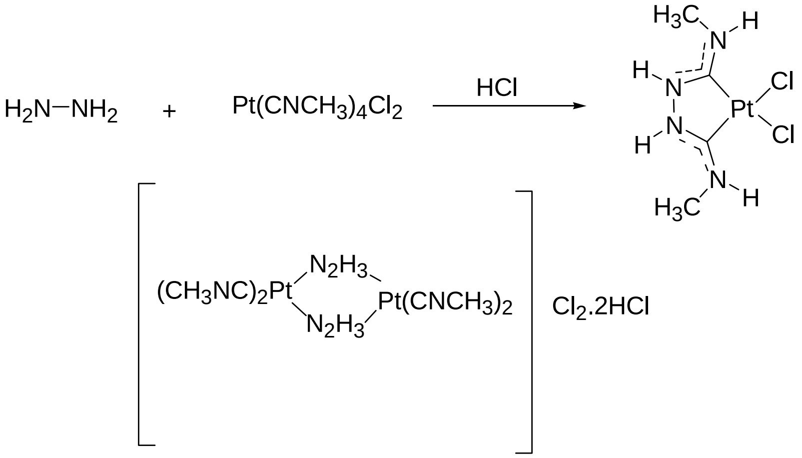
Hermann and co-workers later synthesized and characterized bis(diisopropylamino)carbene complexes of Rh(I) and Ir(I) using three different routes (Scheme 1.12). These involved (1) treatment of $[M(COD)Cl]_2$ (M=Rh, Ir) where (COD=1,5-cyclooctadiene) with free diisopropylamino carbene in THF; (2) *in situ* deprotonation of the formamidinium chloride by an ethoxy-bridged metal dimer which acted as an internal base and deprotonated the formamidinium chloride;[30] and (3) treatment of an alcohol adduct of the formamidinium salt with the metal precursor dimer to form the corresponding metal bis(diisopropylamino)carbene complexes (Scheme 1.13).



Scheme 1.13. Synthetic routes to metal ADC complexes of M = Rh and Ir. Adapted from Reference 30.

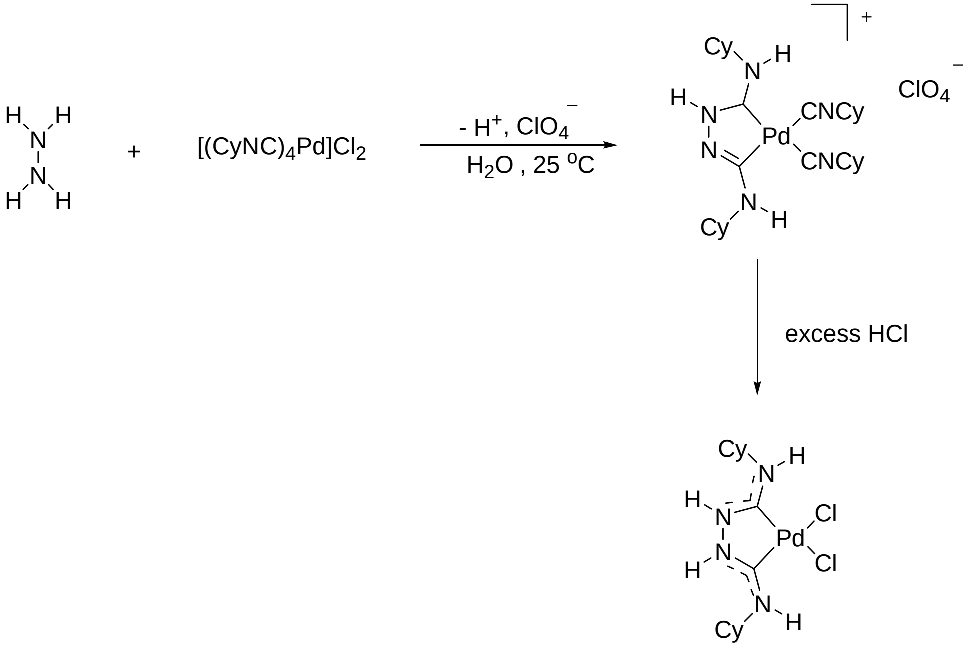
In an effort to study electronic properties of the bis(diisopropylcarbene) ligand, Herrmann and co-workers synthesized a Rh(I) dicarbonyl complex. In view of the fact that carbon monoxide is an excellent IR probe, CO stretching frequencies of ADC complexes *vs* saturated and unsaturated NHCs were found and compared. Based on the CO stretching frequencies, it was inferred that the bis (diisopropylcarbene) ligand was in fact a stronger σ donor compared to the saturated and unsaturated NHC ligands. Surprisingly, this result would also indicate that ADC could replace the traditional phosphine ligand in Grubbs Ru metathesis catalyst, but on treatment of Grubbs' 1st generation catalyst with free acyclic diaminocarbene, no activity was detected.[30]

In 1915 Chugaev, formed bidentate platinum diaminocarbenes by the reaction of hydrazine with platinum bound isocyanides (Scheme 1.14).[31,32] However, at the time, they were not recognized as carbenes. They were only characterized by Burke and co-workers and Rouschias and Shaw in 1970.[33-36]



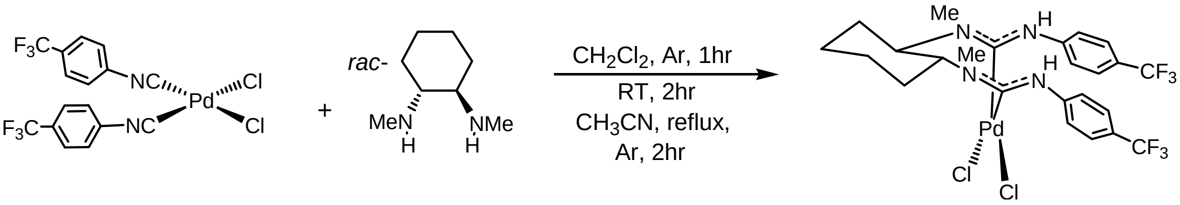
Scheme 1.14. Synthesis of Chugaev's platinum dicarbene complex with the original proposed incorrect structure. Adapted from References 35 and 36.

Addition of protic amines to metal bound isocyanides to form acyclic carbenes have been extensively studied for Pt(II) and Pd(II).[37,38] This approach has also been extended to form carbenes of Fe(II) and Ru(II).[39,40] The mechanism of such a reaction can be described in two steps. First, the attack of the amine nitrogen to the isocyanide carbon occurs, followed by proton transfer to form the carbene product. In 2005, Slaughter and co-workers synthesized Chugaev-type chelating palladium dicarbene complexes by varying the electronic groups on the hydrazine and/or isocyanide backbone and tested these catalysts for the Suzuki coupling reaction (Scheme 1.15).[41-43] The first example was readily synthesized by the treatment of hydrazine hydrate with [Pd(CNCy)$_4$]Cl$_2$, which was generated in situ by the treatment of $PdCl_2$ and cyclohexylisocyanide. These reactions involved the addition of the hydrazine across the C≡N bonds in the isocyanides to generate carbenes.[44] Due to the use of the bifunctional amine hydrazine, chelating dicarbenes were formed.

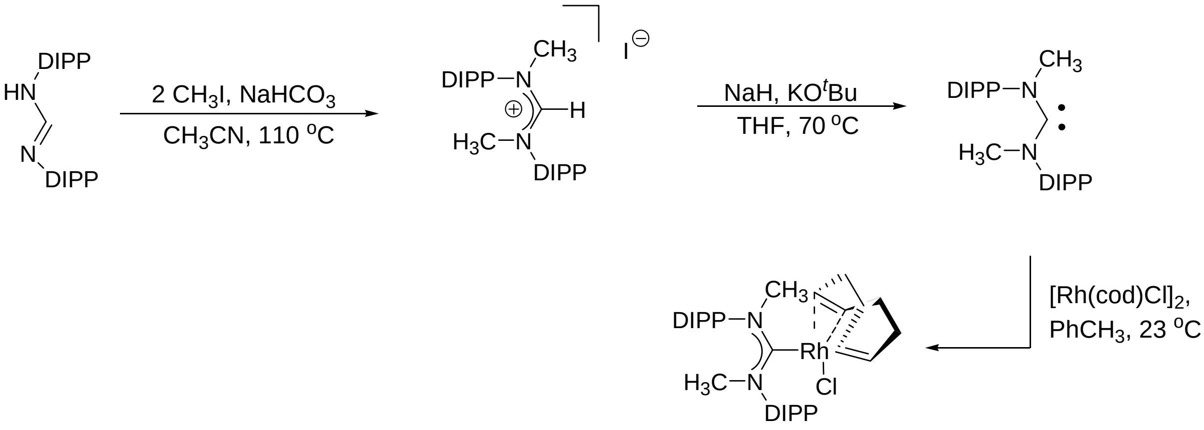


Scheme 1.15. Synthesis of Chugaev-type palladium dicarbene complexes. Adapted from Reference 42.

Since then, several syntheses of metal ADC complexes with catalytic potential have appeared. A chiral palladium bis(ADC) complex was synthesized by Slaughter and co-workers by the reaction between a *p*-trifluoromethylphenyl isocyanide palladium precursor and a chiral diamine (Scheme 1.16).[45] This complex was synthesized with the objective that the trifluoromethyl group would be sufficiently electron withdrawing to decrease the electron density at the palladium center, hence favoring it to be a suitable pre-catalyst for electrophilic reactions such as the aza Claisen rearrangement.[46] This was the first example of a chiral ADC complex. In 2007, Bielawski and co-workers, synthesized a Rh(I) ADC complex by the treatment of the corresponding free ADC ligand with $[Rh(cod)Cl]_2$ (Scheme 1.17). The objective of their work was to synthesize ADC complexes with the standard deprotonation routes and to understand the different conformations in ADC complexes with respect to the N-substituents.[47] According to their studies, they found two inequivalent sets of methyl protons, which led to the conclusion that the *N*-aryl substituents adopted a pseudo-*trans* conformation. Downfield shifts were observed for the carbene carbon signal of the Rh(I) ADC complex, which was consistent with the reports by Hermann and co-workers.

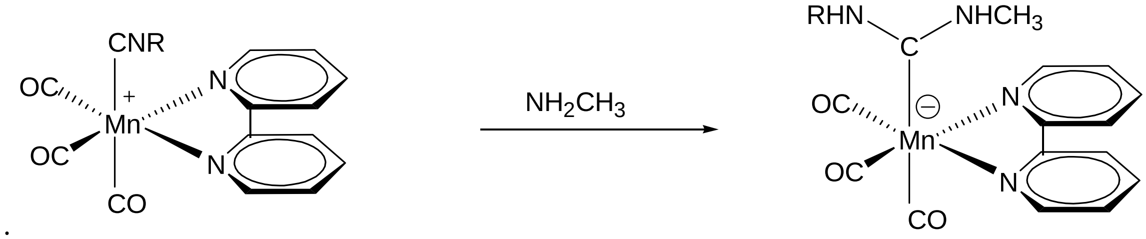


Scheme 1.16. Synthesis of chiral ADC complex. Adapted from Reference 45.



Scheme 1.17. Synthesis of Rh(I) ADC complex by the treatment of free ADC with Rh[(cod)Cl]$_2$ formed by the treatment of substituted foramidinium salts. Adapted from Reference 47.

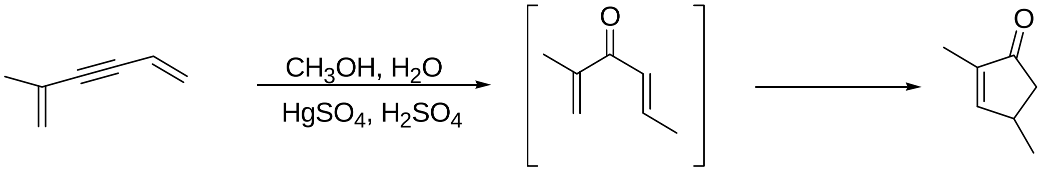
A more recent report was published in 2009 by Ruiz and co-workers in which Mn(I) ADC complexes were synthesized by the reaction of gaseous methylamine with[Mn(CNR)(CO)$_3$bipy]$^+$ where R = phenyl, 2-naphthyl, xylyl and 2-chloro-6-phenyl (Scheme 1.18).[48] These Mn(I) ADC complexes were found to deprotonate easily into formamidinyl derivatives. These derivatives inserted alkynes into the metal carbon bond. Interestingly, in comparison with reports published by Alder and Hermann on the observed basicity of the ADC ligands by comparing IR stretching frequencies of carbonyl complexes of Ir(I) and Rh(I), IR Studies of Bielawski's Rh(I) ADC complex and Ruiz's Mn(I) ADC complexes, indicated that the ADC ligands were less basic ligands compared to diisopropylcarbene as evidenced by the high CO stretching frequency.



Scheme1.18. Synthesis of Mn(I) ADC complex formed by the attack of methylamine on a Mn(I) isocyanide complex. Adapted from Reference 48.

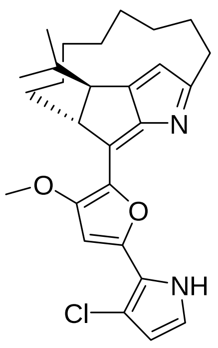
Nazarov cyclization

The origin of the Nazarov cyclization began with the initial discovery by Ivan Nazarov while he was studying the acid catalyzed hydration of dienynes (Scheme 1.19).[49]

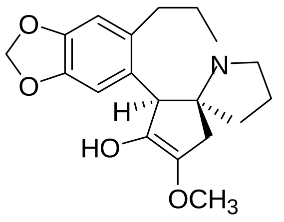


Scheme 1.19. Acid-catalyzed hydration of dienynes discovered by Ivan Nazarov. Adapted from Reference 49.

The Nazarov cyclization has received much attention in recent years due to several advantages. Among these advantages, this reaction generates two or more stereocenters in a single step. The cyclopentenones that are formed as a result occur in many natural products. Roseophilin and Cephalotaxine (Figure 1.5) are among some of the natural products that have been successfully synthesized by the Nazarov cyclization.[50,51]



Roseophilin



Cephalotaxine

Figure 1.5. Roseophilin and Cephalotaxine. Adapted from References 50 and 51.

The Nazarov cyclization is a 4π electrocyclic reaction that converts divinyl ketones to cyclopentenones with the generation of two or three stereocenters in a single step. Lewis acids such as $AlCl_3$ and BF_3 are commonly employed as catalysts. The Lewis acid serves an important function of binding with both the carbonyl oxygen atom and an alkoxy group at the α position when present.[52] An alkoxy group (-OR) in the α position is thought to promote the cyclization reaction due to the fact that electron density will increase at the terminal position, lowering the activation barrier for cyclization to form the desired cyclopentenone product.[52]

In addition, studies of substrates with electron-donating substituents at the C2 position and electron-withdrawing substituents at the C4 positions indicated an increase in the cyclization rate, thereby leading to a polarized divinyl ketone system (Figure 1.6).[53,54] Interest in Lewis Acid effects on the Nazarov cyclization date back to the work of Denmark[55,56] and co-workers, in which the effects of α and β substituents on the Nazarov cyclization of various silicon directed divinyl ketones were investigated. They found that stoichiometric $FeCl_3$ gave a relatively low yield of the desired cyclized product. Later, reports by West and co-workers highlighted the use of $SnCl_4$, $FeCl_3$ and $BF_3.OEt_2$ used in Nazarov cyclization reactions.[57-59]

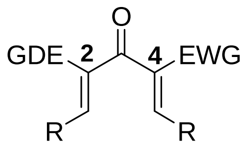


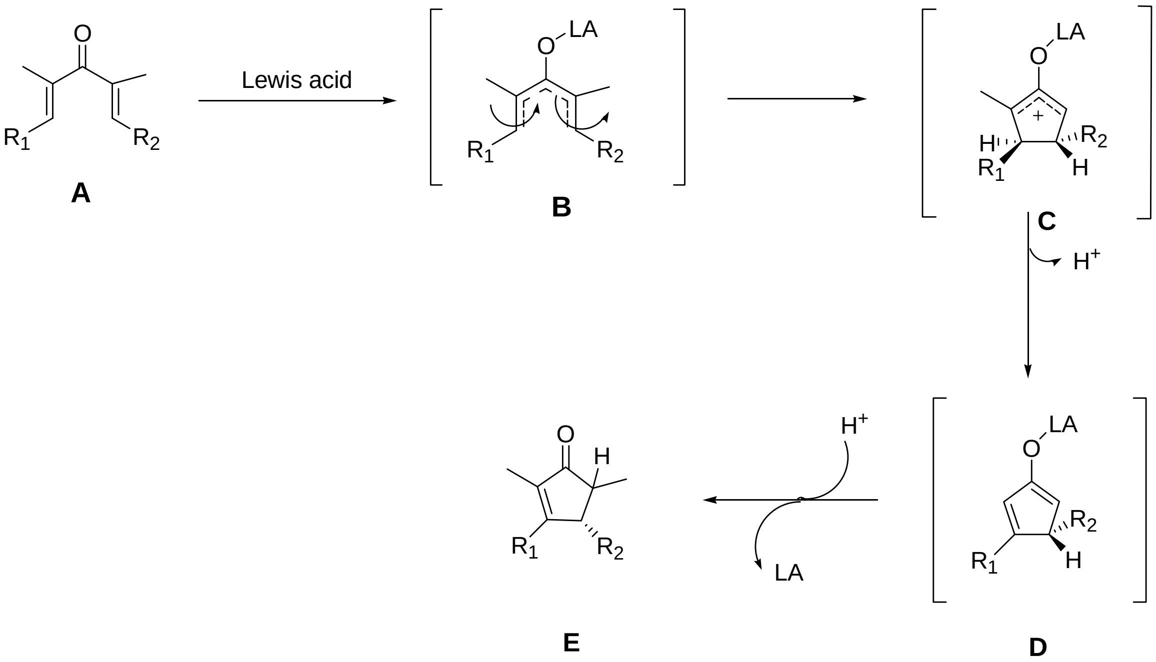
Figure 1.6. Polarized divinyl ketone. Adapted from Reference 52.

The Nazarov cyclization is comprised of the following steps:

a) Binding of the Lewis acid by either one-point binding to the carbonyl oxygen atom or two-point binding of the carbonyl oxygen atom and the α alkoxy group of substrate **A** to form cyclopentadienyl cation **B**.

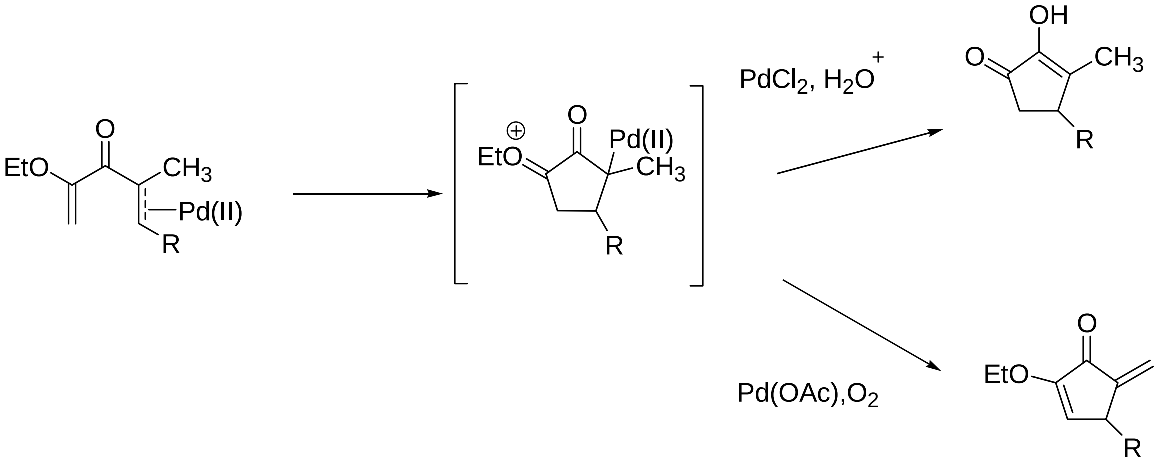
b) Conrotatory ring closure of **B** to give the oxyallyl cation **C** with an anti relationship of the groups R_1 and R_2.

c) Deprotonation of **C** to give an enolate **D** followed by reprotonation and subsequent release of the Lewis acid to give the cyclized product **E** (Scheme 1.20).



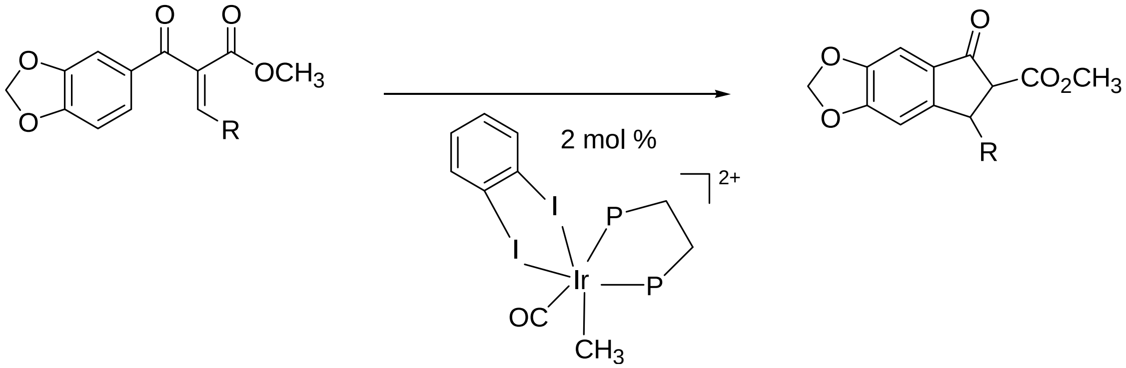
Scheme 1.20. General mechanism of the Nazarov cyclization. Adapted from Reference 52.

Work by Tius and co-workers demonstrated that Pd(II) complexes could direct Nazarov cyclizations in polarized divinyl ketones, even though Pd(II) is thought to activate olefins rather than the carbonyl oxygen atom.[60] Interestingly, Tius found that by the use of either $PdCl_2(MeCN)_2$ and $Pd(OAc)_2$, two mechanisms operate yielding two different atypical Nazarov cyclized products(Scheme 1.21).



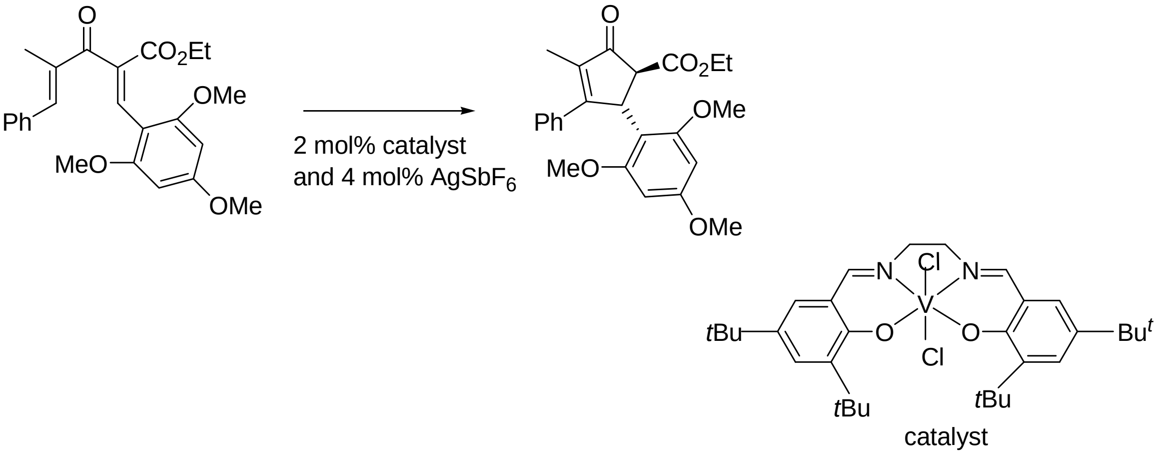
Scheme 1.21. Unusual products obtained by Pd(II) catalysis of the Nazarov reaction. Adapted from Reference 60.

Intrigued by the use of cationic metal complexes for catalysis and C-H bond activation, Frontier and co-workers found that a dicationic Ir(III) $BAr^F{}_4$ complex afforded the Nazarov cyclized product of polarized divinyl ketones substrates as shown in Scheme 1.22.[61,62] They found that the o-diiodobenzene was a weakly co-ordinating ligand which provided two labile sites which could easily co-ordinate with the diketones of the substrate, affording cyclization.



Scheme 1.22. Nazarov cyclization using Ir(III) $BAr^F{}_4$ complex. Adapted from Reference 62.

Togni synthesized a V(IV) salen dichloride catalyst which was capable of forming a dicationic species by treatment with silver tetrafluoroborate(Scheme 1.23). This catalyst was chosen because it could have stronger binding due to the two available co-ordination sites with the two carbonyl oxygen and also a dicationic species would be more reactive in solution than the dichloride catalyst itself.[63] However, a chiral version of the V(IV) salen dichloride catalyst gave no enantioselectivity. Togni later used a Ni(II) PIGIPHOS catalyst system and achieved enantiomeric excesses up to 88% ee with the same substrate as shown in Scheme 1.23.[64]



Scheme 1.23. Nazarov cyclization using a V(IV) salen dichloride catalyst. Adapted from Reference 64.

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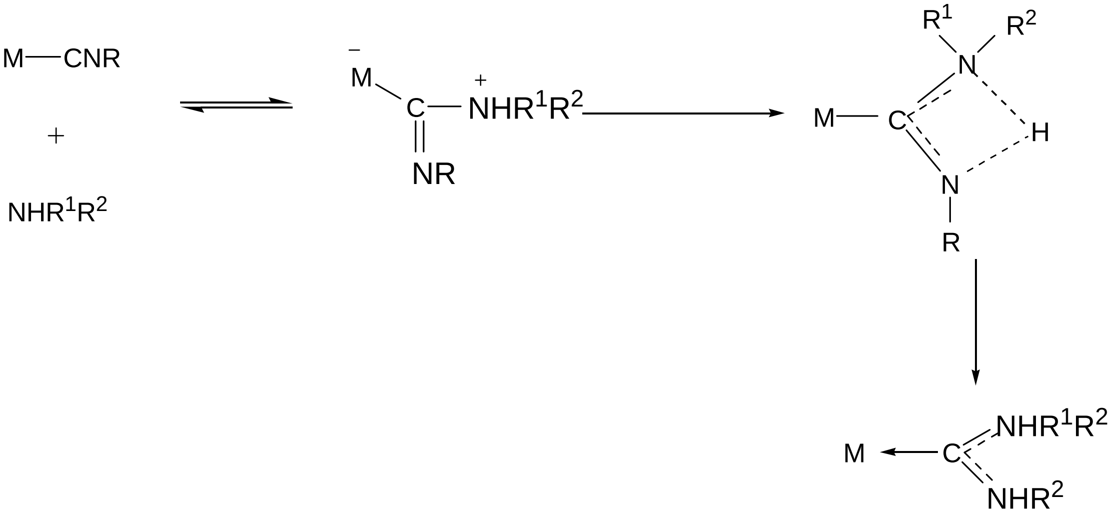
CHAPTER II

SYNTHESIS AND CHARACTERIZATION OF SILVER ISOCYANIDE COMPLEXES AND UNEXPECTED FORMATION OF A SILVER BIS(AMIDINE) COMPLEX

Introduction

N-heterocyclic carbene ligands (NHCs) have been widely used in numerous catalytic reactions such as the Heck Reaction and the Suzuki coupling.[1] Since the report by Arduengo and co-workers in 1993 on the synthesis of homoleptic Ag(I) and Cu(I) NHC complexes, many methods for the synthesis of metal NHC complexes have appeared in literature.[2] Some of these methods include treatment of the carbene precursors with a corresponding silver salt;[3] deprotonation of the imidazolium salts with basic silver reagents like Ag_2O, AgOAc[4], or other silver salts.[5] Alternatively, metal carbenes can be synthesized by the treatment of metal bound isocyanide precursors with protic amines or alcohols.[6] Electrophilic metals in positive oxidation states, such as Pd(II), Pt(II) and Ag(I) often make ligands susceptible to attack from nucleophiles.[7,8] This method has been successfully adapted to the synthesis of Au(I), Pd(II), Pt(II), Fe(II) and Ru(II) carbene complexes.[6,9a,9b]

The reaction occurs in two steps: the first step involves the nucleophilic attack of the amine on the isocyanide carbon, followed by proton transfer to give the carbene complex (Scheme 2.1).[6] Au(I) carbene complexes can be readily synthesized by the treatment of bis(isocyanide)Au(I) complexes with amines.[10] However,this methodology has not been used to synthesize acylic silver(I) diaminocarbene complexes. In an earlier report, Wang and Lin had shown that silver NHC complexes can be efficient carbene transferring agents to catalytically active metals such as Pd(II) and Au(I).[11] This methodology also extended to a chelated Ag bis(NHC) complex which was used as a carbene transferring agent by Wanniarachchi and co-workers.[12]



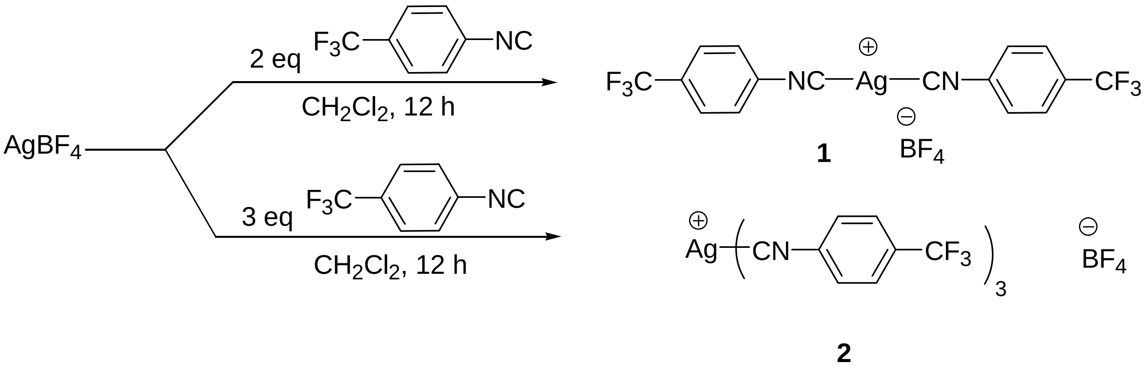
Scheme 2.1. General scheme for carbene formation by the reaction between metal bound isocyanide complex and secondary amine. Adapted from Reference 6.

Hence, in an effort to synthesize novel ligands for catalyst design, the synthesis of silver(I) carbene complexes by the nucleophilic attack of protic amines on silver(I) isocyanide complexes was pursued. The next goal was to use these silver(I) carbene complexes as carbene transferring agents to catalytically active metals like Pd(II) and Rh(I).

Results and Discussion

Silver (I) Isocyanide complexes

The first step involved in planned synthesis of the silver(I) carbene complexes was the synthesis of the silver isocyanide precursors. Silver(I) isocyanide complexes can be readily synthesized by the treatment of various silver salts with two or three equivalents of the respective isocyanides to afford silver(I) isocyanide complexes. The silver isocyanide complexes were synthesized by treating silver tetrafluoroborate with two equivalents of *para*-trifluoromethylphenyl isocyanide to form silver(I) bis (isocyanide) complex **1** after stirring in dry dichloromethane overnight (Scheme 2.2). After filtering the solution over Celite®, diethyl ether was added to precipitate out the complex as white crystals. The silver(I) tris(isocyanide) complex **2** was synthesized in the same manner as described above but using three equivalents of ligand. Both, the silver(I) bis(isocyanide) and tris(isocyanide) complexes were light sensitive, hence they were stored in a dark place. They showed high stability at room temperature and were soluble in solvents like dichloromethane and acetonitrile but insoluble in solvents such as ether and hexanes. The ^{1}H NMR spectra of complexes **1** and **2** in CD_3CN showed two sets of doublets corresponding to the aryl protons with chemical shifts ranging from 7.24 to 7.99 ppm.



Scheme 2.2. Synthesis of silver (I) bis(isocyanide) and silver (I) tris(isocyanide) complexes.

The infrared stretching frequencies of complexes **1**, **2** and the free isocyanide are shown in Table 2.1. Complexes **1** and **2** showed characteristic isocyanide stretching frequencies of 2200 and 2190 cm^{-1}, which is in the expected range for the stretching frequencies of terminal isocyanide ligands.[13,14] The isocyanide stretching frequency for the free *para*-trifluoromethylphenyl isocyanide was at 2120 cm^{-1}. The difference between the isocyanide stretches of complexes **1** and **2** and that of the free isocyanide is defined as Δν. A positive value of Δν should effectively indicate increased bond order and strong donation from carbon to silver with little or no backbonding.[15]

Table 2.1. Infrared data of complexes **1**, **2** and free isocyanide.

Complex	ν (NC, cm-1)	Δ ν (NC, cm-1)
Free CF_3-Ph-NC	2120	-
1	2200	80
2	2190	70

The ^{13}C NMR data for free *para*-trifluoromethyl phenyl isocyanide and complexes **1** and **2** were taken in CD_2Cl_2 and are shown in Table 2.2. Both complexes **1** and **2** showed large quartets for the CF_3 group at 123 ppm with a coupling of $^1J_{C-F}$ = 272 Hz, as well as for the *para* carbons which appeared at 133 ppm with a coupling of $^2J_{C-F}$ = 33 Hz and *meta* carbons which appeared at 127 ppm with a coupling of $^3J_{C-F}$ = 3.4 Hz.[16] The isocyanide carbon was not observed in either of the two complexes. The isocyanide carbon was not visible even after collecting data on a 600 MHz NMR instrument.

Table 2.2. ^{13}C NMR spectral data for complexes **1** and **2** and free isocyanide.

Complex	^{13}C NMR (δ ppm)
Free CF_3-Ph-NC	167.8 (broad singlet, *ipso*); 131.5 (q, Ar *para*, $^2J_{C-F}$ = 33.3 Hz); 129.8(m, ArN*C*); 127.4(s, Ar *ortho*); 127.1(q, Ar *meta*, J_{C-F} = 3.6 Hz); 123.7(q, CF_3, J_{C-F} = 272 Hz).
1	145.8(broad singlet, *ipso*); 133.7(q, Ar *para*, $^2J_{C-F}$ = 33 Hz); 128.4(s, Ar *ortho*); 127.5(q, Ar *meta*, J_{C-F} = 4.2 Hz); 123.3(q, CF_3, J_{C-F} = 272 Hz)
2	150.6(br singlet, *ipso*), 133.2(q, Ar *para*, $^2J_{C-F}$ = 33 Hz); 127.9(s, Ar *ortho*); 127.4(q, Ar *meta*, J_{C-F} = 3.4 Hz); 123.4(q, CF_3, J_{C-F} = 272 Hz).

X-ray quality crystals of complex **1** were grown by the slow diffusion of cyclohexane into a chlorobenzene solution of complex **1**. According to the X-ray crystal structure in Figure 2.1, complex **2** is a two-coordinate silver (I) complex with a distorted linear geometry. The C(2)-Ag(1)-C(1) angle deviated by about 11^o from linearity. This was attributed to the weak interaction between the silver atom and the two fluorine atoms of the tetrafluoroborate anion. The Ag(1)-F(11) and Ag(1)-F(12) interactions caused the bending in the molecule. Even though complex **2** is slightly bent, the infra-red spectrum of complex **2** still shows a single isocyanide peak, instead of two as expected for a nonlinear molecule. It is possible that the second peak is weak and hence cannot be seen in the infrared spectrum. These weak Ag-F interactions could be considered as electrostatic interactions as the Ag(1)-F(11) distance was of the order of 2.9-3.0 Å. A Similar Ag-F interaction was observed by Cheung and co-workers in a silver(I) bis(isocyanide) complex derived from the reaction between silver tetrafluoroborate and 4-isocyano-3,5-diisopropylbenzonitrile.[17] This was also observed by Yamamoto and co-workers in a silver(I) bis(isocyanide) complex formed by the reaction between silver hexafluorophosphate and bulky 2,4,6-*tert*-butylphenyl isocyanide.[18] The Ag-C distances [2.066(4), 2.074(4) Å] in complex **2** were in good agreement with Ag-C distances found in silver(I) bis(isocyanide) complexes synthesized by Cheung and Yamamoto.

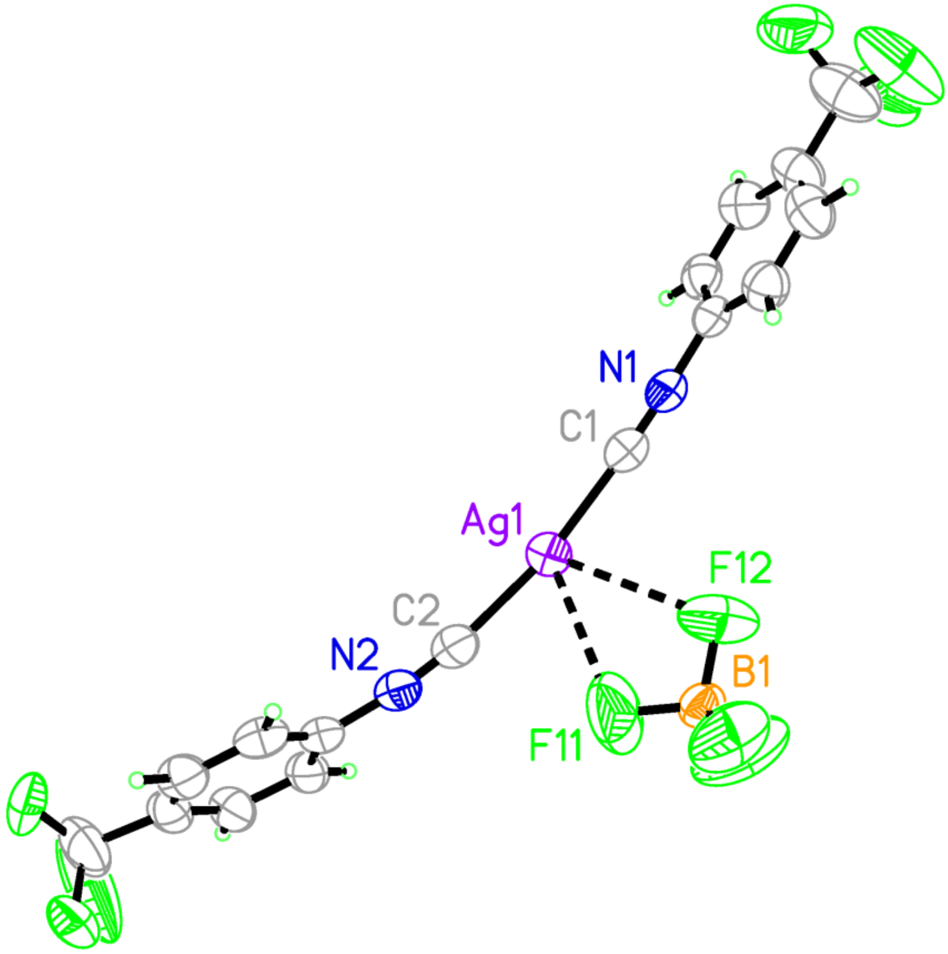


Figure 2.1. Molecular structure of complex **1** with 50% probability ellipsoids.

Table 2.3. Selected bond lengths (Å) and bond angles (^{o}) of complex **1**.

	Bond Lengths (Å)
Ag(1)-C(1)	2.066(4)
Ag(1)-C(2)	2.074(4)
C(1)-N(1)	1.146(5)
C(2)-N(2)	1.136(5)
Ag(1)-F(11)	2.949(4)
Ag(1)-F(12)	3.059(4)

	Bond Angles (^{o})
C(1)-Ag(1)-C(2)	169.33(15)
C(1)-Ag(1)-F(12)	78.13(12)
C(2)-Ag(1)-F(11)	70.92(12)
C(1)-Ag(1)-F(12)	78.13(12)
F(11)-Ag(1)-F(12)	41.60(8)
N(1)-C(1)-Ag(1)	177.3(3)
N(2)-C(2)-Ag(1)	173.0(3)

Table 2.4. Crystal data and structure refinement details for complex **1**.

Empirical Formula	$C_{16}H_8AgF_{10}N_2$
Formula weight	536.92

Temperature	170 (2) K
Wavelength	0.71073 Å
Crystal system	Triclinic
Space group	$P_{\bar{1}}$
Unit cell dimensions	a = 10.9549(7) Å alpha = 69.541(3) ^{o}
	b = 11.9048(8) Å beta = 77.206(3) ^{o}
	c = 16.1257(11) Å gamma = 88.374(3) ^{o}
Volume, Z	1918.7 (2) Å^{3}, 4
Density (calculated)	1.859 Mg/m^{3}
Reflections collected	25600
Independent reflections	7701 (R_{int} = 0.0441)
Final R indices [I>2σ (I)]	R1 = 0.0357, wR2 = 0.0942
R indices (all data)	R1 = 0.0427, wR2 = 0.1005

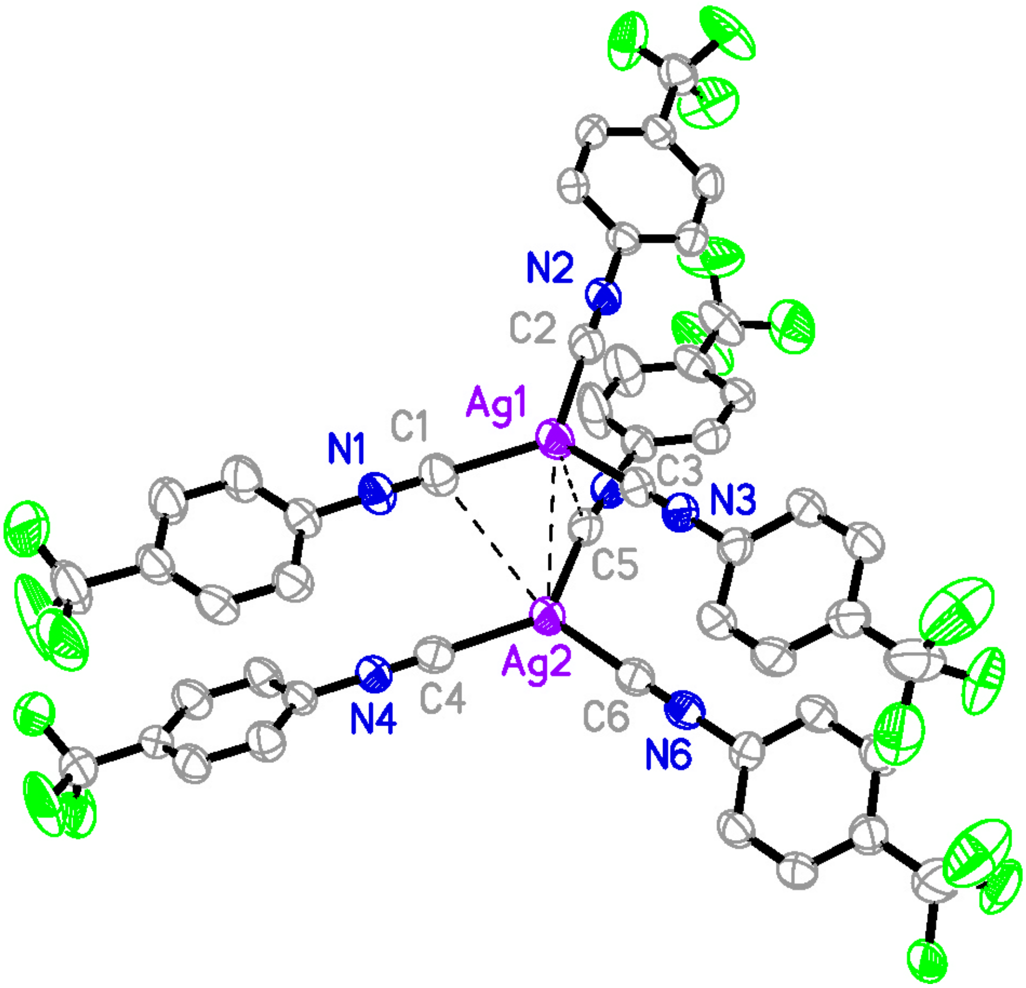


Figure 2.2. Molecular structure of complex **2** with 50% probability ellipsoids.

X-ray quality crystals of complex **2** were grown by the slow diffusion of cyclohexane into chlorobenzene solution of complex **2** (Figure 2.2). There are two weak associated molecules in the asymmetric unit. Complex **2** showed an interesting but weak argentophilic interaction between Ag(1) and Ag(2) and was the first structurally characterized example of a silver tris(isocyanide) complex. The first published example of a silver tris(isocyanide) complex was isolated by Figueroa and co-workers.[19] The Ag(1)-Ag(2) contact in complex **3** (3.35 Å) was shorter than twice the sum of the van der Waals radii, which for silver is 3.40Å.[11,20] Evidence for closed shell d^{10} metals such as gold[21] does exist in literature but is relatively rare for silver.[22] Also there is a short Ag(2)-C(1) distance of 3.42 Å which possibly could be an η^2 donation from the Ag(1)-C(1) bond to Ag(2).

Table 2.5. Selected bond lengths (Å) and bond angles (°) of complex **2**.

	Bond Lengths (Å)
Ag(1)-C(1)	2.156(4)
Ag(1)-C(2)	2.165(4)
Ag(1)-C(3)	2.153(4)
Ag(2)-C(1)	3.417(4)
Ag(2)-C(4)	2.164(4)
Ag(2)-C(6)	2.152(4)
C(1)-N(1)	1.142(4)
C(2)-N(2)	1.143 (4)
Ag(1)-Ag(2)	3.3543(4)

	Bond Angles (^{o})
C(1)-Ag(1)-C(2)	121.80(12)
C(3)-Ag(1)-C(2)	119.21(12)
C(1)-Ag(1)-C(3)	117.66(12)
N(1)-C(1)-Ag(1)	172.1(3)
N(2)-C(2)-Ag(1)	178.8(3)
N(3)-C(3)-Ag(1)	176.7(3)

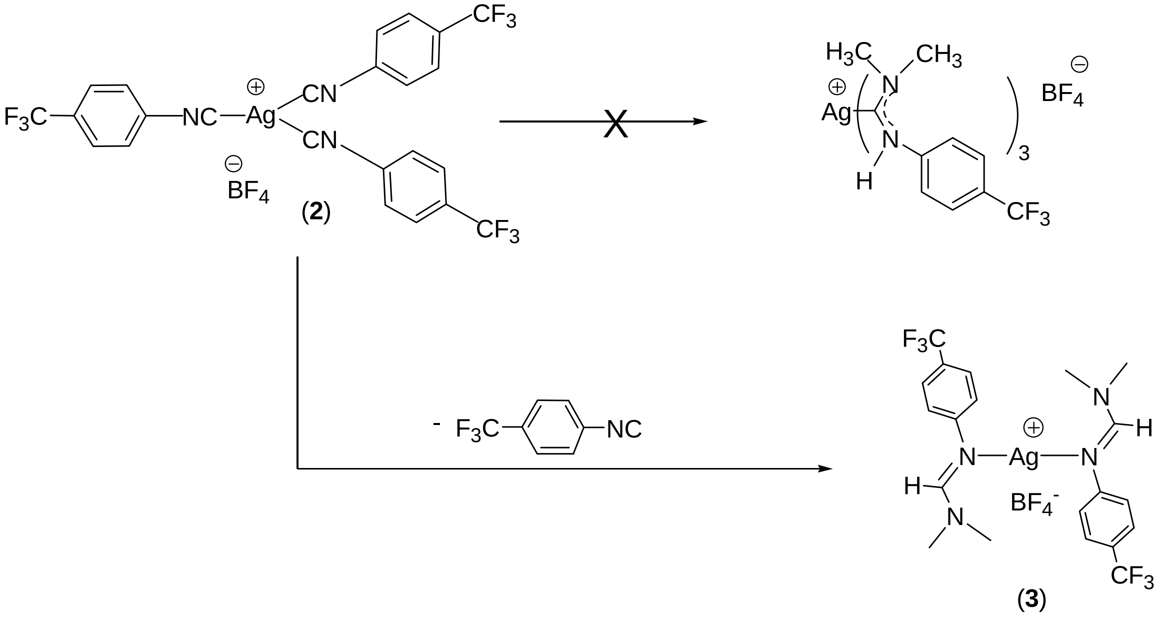
Table 2.6. Crystal data and structure refinement details for complex **2**.

Empirical Formula	$C_{24}H_{12}AgF_{13}N_3$
Formula weight	708.05

Temperature	170 (2) K	
Wavelength	0.71073 Å	
Crystal system	Triclinic	
Space group	$P_{\bar{1}}$	
Unit cell dimensions	a = 13.6975 (7) Å	alpha = 114.525(3) ^{o}
	b = 15.5457(7) Å	beta = 95.479 (3) ^{o}
	c = 15.7790 (8) Å	gamma = 113.992 (3) ^{o}
Volume, Z	2694.8 (3) Å^3, 4	
Density (calculated)	1.776 Mg/m^3	
Reflections collected	30632	
Independent reflections	9318 (R_{int} = 0.0716)	
Final R indices [I>2σ (I)]	R1 = 0.0466, wR2 = 0.1157	
R indices (all data)	R1 = 0.0978, wR2 = 0.1319	

Attempt to synthesize silver(I) diaminocarbene from the silver isocyanide precursors.

Attempts were made to synthesize silver carbene complexes, by treatment of complex **2** with three equivalents of dimethylamine in dichloromethane overnight. At the end of 12 hours, the solvent was removed and the residue was triturated with ether to form white crystals of complex **3,** which are highly light sensitive and turn pale brown with time (Scheme 2.3.). This complex was soluble in solvents like dichloromethane and acetonitrile and insoluble in ether and hexanes. The ^{1}H NMR spectrum of complex **3** in CD_3CN showed the presence of a downfield NH signal at 7.72 ppm, consistent with the formation of a carbene complex. It also showed two doublets at 7.57 and 7.23 ppm, corresponding to the aryl protons and a broad doublet at 3.20 ppm for the two methyl groups as shown in Figure 2.3.



Scheme 2.3. Attempted synthesis of Ag-diaminocarbene and formation of silver(I) bis amidine.

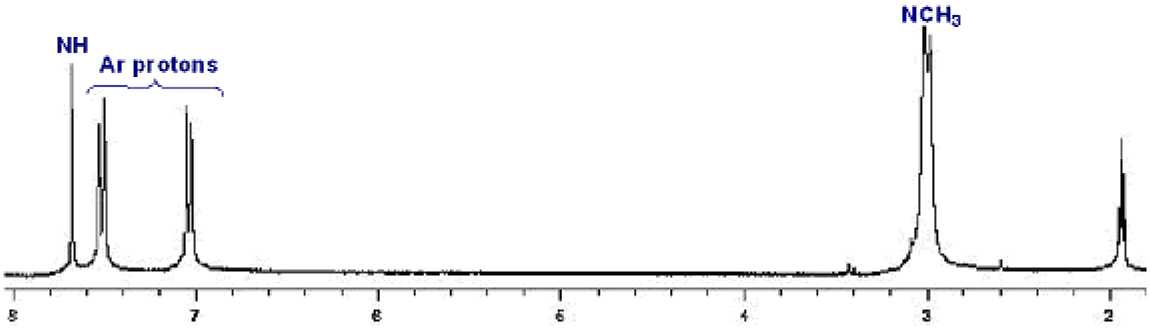


Figure 2.3. ^{1}H NMR spectra of complex **3** in CD_3CN.

The ^{13}C NMR spectrum of complex **3** was taken in CD_3CN. Complex **3** did not show the characteristic downfield carbene carbon signals in the 180-200 ppm range, instead showing a strong signal at 158.2 ppm. It also showed a quartet for the *meta* carbon at 127 ppm with the characteristic coupling constant $J_{C\text{-}F}$ = 3.6 Hz and a singlet for the *ortho* carbon. It also showed a quartet for the CF_3 carbon with a large coupling constant of 272 Hz, but did not show the *para* carbon.[15] It also showed a weak ipso signal at 145.5 ppm. Two signals for the methyl groups were observed at 43.3 and 34.8 ppm. A diagnostic method to identify non labile silver–carbon bonds in silver (NHC) complexes was by ^{13}C NMR identification of Ag-C coupling constants.[5,11] For this purpose, a low temperature NMR experiment was set up with a sample of complex **3** dissolved in CD_2Cl_2 and the temperature set to -90 ^{o}C, to observe any silver carbon coupling($^1J^{107}{}_{Ag\text{-}C}$; $^1J^{109}{}_{Ag\text{-}C}$). At lower temperatures there would be lesser exchange of any labile Ag-C bonds, and hence silver carbene coupling may be observed. However at -90 ^{o}C, weak Ag-C coupling was observed with coupling constants of 419 and 455 Hz.

X-ray quality crystals of complex **3** were grown by the slow diffusion of *n*-hexane into a concentrated dichloromethane solution of complex **3**. The X-ray crystal structure indicated that complex **3** was indeed not a carbene complex, but a silver(I) bis(amidine) complex. The signal at 158.2 ppm was found to be in good agreement with the CH signal for dimethylformamide, which appears at 163 ppm.[23] The X-ray crystal structure of complex **3** showed a slightly bent N(1)-Ag(1)-N(2) angle that deviated by about 9^o from linearity. The C(2)-N(2) and C(1)-N(1) bond lengths of 1.298(7) Å and 1.318(7) Å were consistent with the expected range of a C=N bond.[24] Catalytic formation of formamidines generated by the reaction between isocyanides and primary amines have been known to be catalyzed by group 11 metals such as Cu^+, Ag^+, Zn^{2+}, Cd^{2+} and Hg^{2+}.[25] The mechanism for the amidine formation from complex **2** would probably start with the loss of one of the isocyanide molecules to form the silver bis isocyanide complex followed by attack of the secondary amine to form the amidine. However, density functional calculations (Dr. Thomas Cundari, UNT, Texas) reveal that silver bis(isocyanide) complex **1** is more reactive than the silver tris(isocyanide) complex **2**. Figure 2.4 shows the LUMO of the silver bis(isocyanide) complex **1** and silver tris(isocyanide) complex **2**. According to the DFT calculations, the LUMO of the complex **1** was found to be 0.5 eV lower than that of complex **2**, which would suggest that silver bis(isocyanide) complex **1** should be a better electrophile or more reactive for the nucleophilic attack of dimethyl amine than complex **2.** However**,** complex **1** gives no reaction with dimethylamine.

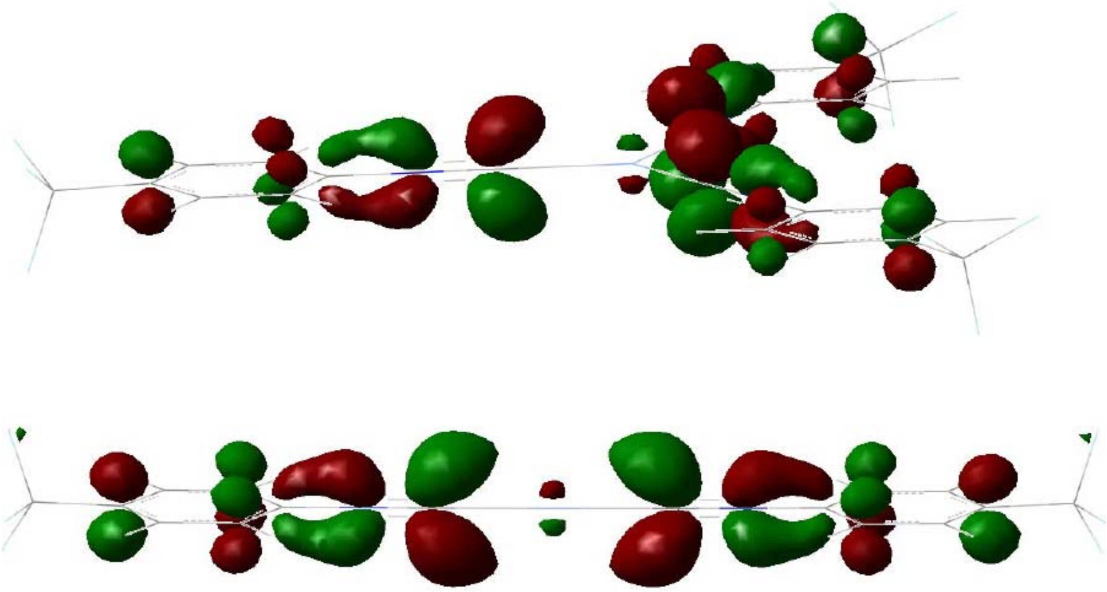


Figure 2.4. LUMO of silver bis(isocyanide) complex **1** and silver tris(isocyanide) complex **2**.

Carbene complexes of Au have been known to undergo displacement in the presence of ligands to form corresponding amidines.[26,27] An attempt to transfer the amidine ligand of complex **3** to rhodium was unsuccessful upon treatment of complex **3** with $[Rh(COD)Cl]_2$(COD=1,5-cyclooctadiene), no reaction was observed. This reaction was carried out by treating 0.5 equivalents of $[Rh(COD)Cl]_2$ with one equivalent of complex **3** in dichloromethane at 60 °C in a sealed ampoule for 2 hours.

NMR tubes reaction were carried out by treating silver(I) tris isocyanide complex **3** with two equivalents of dimethylamine in CD_2Cl_2 in an attempt to understand whether there was rapid exchange between ligands of the silver bis(amidine) and the isocyanide. The NMR indicated a one set of aryl protons (doublets) for the silver (I) bis amidine and a multiplet which corresponded to free or complexed silver isocyanide with integration ratios of 1:4 for aryl protons for the silver bis(amidine) to the complexes or free isocyanide. It also showed a broad singlet for the two methyl groups on the silver bis(amidine). It was unclear whether the isocyanide multiplet corresponded to either free or complexed silver isocyanide or if the silver remains labile between the free isocyanide and the complexed form. The reaction was carried out in an NMR tube by treating silver(I) tris isocyanide complex **3** with one equivalent of dimethylamine in CD_2Cl_2. After 10 min at room temperature, the NMR spectrum indicated one set of aryl protons (doublets) for the silver(I) bis amidine. It also showed a multiplet corresponding to free or complexed silver isocyanide. The integration ratios observed for aryl protons of the silver bis(amidine) to that of the complexed or free isocyanide was 1:4. It showed a multiplet at 7.80 ppm for the aryl protons of the free complexed isocyanide and a set of doublets for the aryl protons of the silver(I) bis(amidine) at 7.52 and 7.12 ppm respectively. It also showed a singlet for the CH for the amidine at 7.61 ppm and a broad singlet for the two methyl groups on the silver bis(amidine) at 3.03 ppm. This reaction was monitored again after 1 hour intervals for four hours and the above ratio remained unchanged. NMR tube reactions were also carried out by treating silver(I) tris isocyanide complex **3** with one equivalent of diisopropyl amine in CD_2Cl_2 in order to observe whether any silver bis(amidine) was formed. After 5 minutes of reaction time, no signals corresponding to the silver bis(amidine) were observed. The NMR spectrum also showed a multiplet corresponding to the aryl protons at 7.80 ppm, a septet for the isopropyl CH at 3.08 ppm, a broad singlet for the NH at 2.04 ppm and a doublet for the methyl groups at 1.15 ppm. However, after two hours, signals corresponding to the silver bis(amidine) and free or complexed isocyanide were observed. The NMR spectrum also showed a multiplet corresponding to the aryl protons of the free or complexed isocyanide at 7.80 ppm, a singlet for the CH of the amidine at 7.70 ppm, a set of doublets corresponding to the aryl protons of the silver(I) bis(amidine) at 7.47 and 6.97 ppm respectively. The ratio of the aryl protons of the silver bis(amidine) to that of the free or complexed isocyanide was 1:3 which remained unchanged even after four hours.

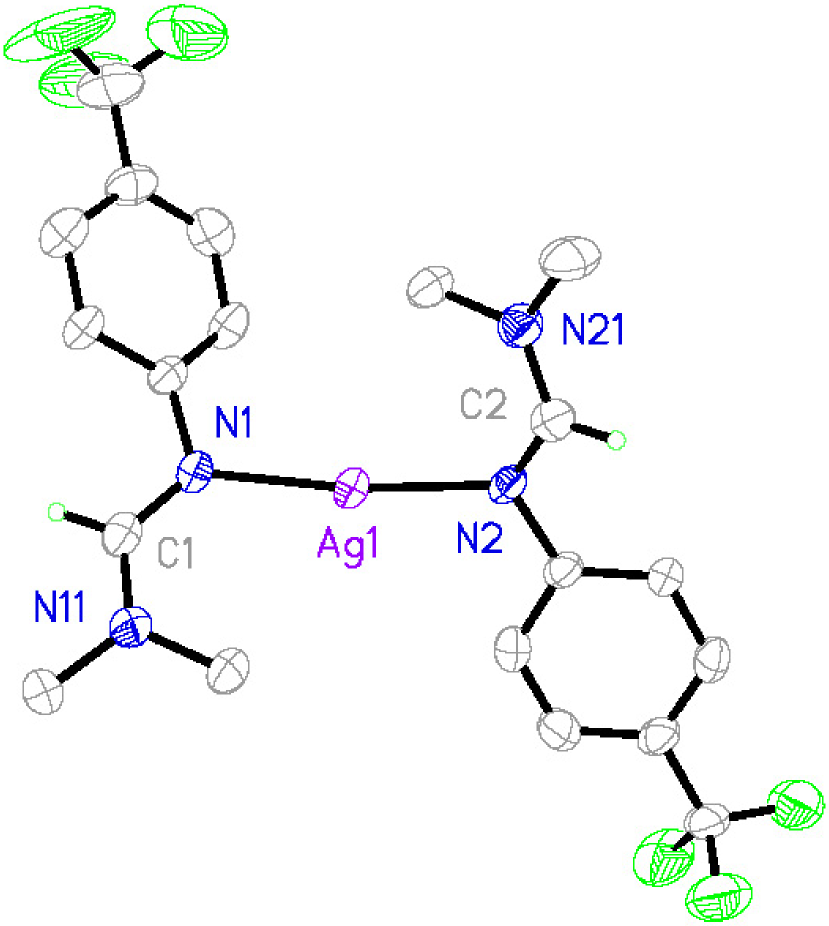


Figure 2.4. Molecular structure of silver(I) bis amidine complex **3** with 50% probability ellipsoids.

Table 2.7. Selected bond lengths (Å) and bond angles (^{o}) of complex **3**.

	Bond lengths (Å)
Ag(1)-N(1)	2.151(4)
Ag(1)-N(2)	2.140(4)
C(1)-N(1)	1.318(7)
C(2)-N(2)	1.298(7)
C(1)-N(11)	1.325(7)
C(2)-N(21)	1.345(7)
	Bond angles (^{o})
N(2)-Ag(1)-N(1)	171.47(17)
C(1)-N(1)-Ag(1)	130.4(4)
C(2)-N(2)-Ag(1)	121.8(4)
N(1)-C(1)-N(11)	125.9(5)

Table 2.8. Crystal and structure refinement data for complex **3**.

Empirical Formula	$C_{30}H_{33}AgBF_{13}N_6$
Formula weight	843.30
Temperature	115 (2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	$P2_1/_c$
Unit cell dimensions	a = 14.011 (2) Å alpha = 90 ^{o}
	b = 16.045 (2) Å beta = 104.560 (8) ^{o}
	c = 22.712 (3) Å gamma = 90 ^{o}
Volume, Z	4941.7 (12) Å^3, 4
Density (calculated)	1.133 Mg/m^3
Reflections collected	25994
Independent reflections	26007 (R $_{int}$ = 0.0000)
Final R indices [I>2σ (I)]	R1 = 0.0840, wR2 = 0.2784
R indices (all data)	R1 = 0.1723, wR2 = 0.3388

Summary and Conclusions:

Novel silver (I) isocyanide complexes were synthesized by the reaction between silver tetrafluoroborate and *para*-Trifluoromethylphenyl isocyanide. Silver (I) bis (isocyanide) complex displayed an unusual Ag-F interactions due to which the molecule was bent. The silver(I) tris(isocyanide) complex was the first report of a three coordinate silver complex that showed a weak but evident argentophilic interaction with a short Ag-Ag contact of 3.3Å, which is slightly shorter than the sum of the van der waals radius for silver. In an attempt to synthesize the acyclic silver(I) carbene complex by reaction between silver(I) tris(isocyanide) and dimethyl amine, silver(I) bis amidine complex was generated instead. Low temperature NMR studies in CD_2Cl_2 indicated the presence of labile $Ag-C_{carbene}$ bonds due to lack of observed $Ag-C_{carbene}$ coupling. Attempts to transfer the amidine ligand from the silver(I) bis amidine complex **3** to rhodium using $[Rh(COD)Cl]_2$ failed.

Experimental

Diethyl ether was dried by refluxing over sodium-benzophenone ketyl and distilled prior to use. Dichloromethane (Pharmco) was purified by washing with concentrated sulphuric acid and sodium bicarbonate, predried with anhydrous $CaCl_2$, and then refluxed overnight with P_2O_5. CD_3CN was purified by stirring over activated 4 Å molecular sieves followed by distillation under vacuum and storage in an air free glove box. *para*-Trifloromethylphenyl isocyanide was synthesized by the Hoffman Carbylamine raction.[28]

^1H NMR spectra were recorded on Varian 300 MHz and 400 MHz spectrometers, with chemical shifts in ppm, multiplicity reported as (s = singlet, d =doublet) and coupling constants recorded in Hz. ^{13}C NMR spectra were recorded on a Varian 400 and 600 MHz spectrometers, with chemical shift in ppm. Elemental analyses were performed by Desert Analytics Laboratory, Tucson, AZ, USA and Midwest Microlabs, Indianapolis, IN, USA. Infrared (IR) spectra were recorded were recorded from Nujol mulls on a Nicolet Protégé 460 FT–IR spectrometer. Data collection for determining X-ray crystal structures of complexes **1, 2** and **3** was done on a Bruker Apex II diffractometer using MoKα (λ = 0.71073 Å) radiation. The X-ray crystal structures were solved using the SHELXTL system and were refined by full matrix least squares on F^2 using all reflections.[29,30]

Synthesis of silver bis(isocyanide)[$C_{16}H_8F_{10}BN_2Ag$] (1). To a stirred solution of silver tetrafluoroborate (0.0542 g, 0.278 mmol) in about 10 mL of dry dichloromethane was added *para*-Trifluoromethylphenyl isocyanide (0.100 g, 0.584 mmol). The resultant solution was stirred in the dark for 12 hours. The solution was filtered over Celite® followed by washing with dry dichloromethane. The solution volume was reduced to half, and dry diethyl ether was added to precipitate complex **1** as white crystals. These crystals were washed with dry ether and dried under vacuum overnight. (0.102 g, 68 %). Complex **1** was light sensitive, hence had to be stored in the dark. ^{1}H NMR (300 MHz, CD_3CN): Anal. Calcd for $C_{16}H_8F_{10}N_2Ag$: C, 35.78, H, 1.50, N, 5.22. Found: C, 35.79, H, 1.46, N, 5.07 %.

Synthesis of silver tris(isocyanide)[$C_{24}H_{12}BF_{13}N_3Ag$] (2). To a stirred solution of silver tetrafluoroborate (0.0907 g, 0.46 mmol) in about 10 mL of dry dichloromethane was added *para*-Trifluoromethylphenyl isocyanide (0.239 g, 1.38 mmol). The resultant solution was stirred in the dark for 12 hours. The solution was filtered over Celite® followed by washing with dry dichloromethane. The solution volume was reduced to half and dry diethyl ether was added to precipitate complex **2** as white crystals. These crystals were washed with dry ether and dried under vacuum overnight. (0.242 g, 74 %). Complex **2** was light sensitive, hence had to be stored in the dark. ^{1}H NMR (300 MHz, CD_3CN): δ 7.86 (2H, d, Ar, *J*=9.9 Hz), 7.75 (2H, d, Ar, *J*=8.1 Hz). Anal. Calcd for $C_{24}H_{12}F_{13}N_3Ag$: C, 40.70, H, 1.71, N, 5.93. Found: C, 40.86, H, 1.59, N, 5.95 %.

Synthesis of silver bis(amidine)[$C_{20}H_{22}BF_{10}N_4Ag$] (3). To a stirred solution of complex **2** (0.118 g, 0.166 mmol) in dry dichloromethane in a swivel frit was added dimethylamine as a 2.0M solution in THF (249 μL, 0.498 mmol) under argon. The resultant solution was allowed to stir overnight at RT. After 12 h, the solution volume was reduced and triturated with dry diethyl ether to form an off white precipitate. The precipitate was washed with dry diethyl ether and dried under vacuum for two hours (0.0712 g, 68%). Complex **3** was light and moisture sensitive and hence had to be stored in the dark in an air free glove box. ^{1}H NMR (300 MHz, CD_3CN): δ 7.68 (1H, s, *C*H), 7.51 (2H, d, Ar, *J*=9 Hz), 7.03 (2H, d, Ar, *J*=8.7Hz), 3.00 (6H, d, N*C*H_3). ^{13}C NMR (101 MHz, CD_2Cl_2): δ 158.2 (s, *C*H amidine), 145.5 (s, Ar *ipso*), 127 (q, Ar *meta*, $^3J_{CF}$= 3.6 Hz), 124.2 (q, *C*F_3, $^1J_{CF}$= 272 Hz), 123.1(s, Ar *ortho*), 43.3 (s, N*C*H_3), 34.8 (s, N*C*H_3). Anal. Calcd for $C_{20}H_{22}BF_{10}N_4Ag$: C, 38.3, H, 3.54, N, 8.93. Found: C, 38.46, H, 3.69, N, 8.67 %.

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CHAPTER III

SYNTHESIS OF BIS(ARYL ISOCYANIDE) PALLADIUM COMPLEXES AND CHIRAL PALLADIUM BIS(ACYCLIC DIAMINOCARBENE) COMPLEXES

Introduction

Acyclic diaminocarbenes, or ADCs, have been studied less extensively than the N-heterocyclic carbenes, or NHCs. Since Alder's discovery of a stable diaminocarbene formed by the deprotonation of a formamidinium chloride salt by lithium diisopropylamide (LDA) in THF, most synthetic routes to ADCs have utilized the free carbenes.[1-5] ADCs have higher proton affinity[1] and are therefore stronger bases. Palladium complexes of ADCs have been successfully used as catalysts for the Suzuki coupling and the Sonogashira reactions.[6] However, relatively few reports exist in literature on the utilization of ADCs as ancillary ligands.[1,6] The most historically common route to ADCs involve the attack of protic amines on metal bound isocyanides complexes to generate carbene ligands.[7-10] The first example of such a process was reported by Chugaev in 1915, by the treatment of hydrazine with tetrakis(methyl isocyanides) platinum(II).[11,12] However, the complex was not identified as a carbene until much later when the structure was determined by Balch and Shaw in 1970.[13]

Early examples of reactions between metal bound isocyanides and amines have been studied by Balch,[14] Badley[15] and Uguagliati.[7] Although chelating Chugaev-type bis(ADCs) have been less studied than monodentate ADCs, recently, a series of Chugaev type carbene complexes were synthesized via the treatment of different palladium isocyanides complexes with hydrazines.[16] These complexes were found to be moderate catalysts in Suzuki-Miyauru cross coupling reaction.[17] Moreover, these Chugaev type palladium carbene complexes were air and moisture stable. This approach was recently extended to chiral palladium ADC complexes by the treatment of bis(trifluoromethylphenyl isocyanide) palladium dichloride with chiral diamines by Wanniarachchi and co-workers.[18] These complexes were successfully used as precatalysts for enantioselective aza-Claisen rearrangements.[19]

Results and Discussion

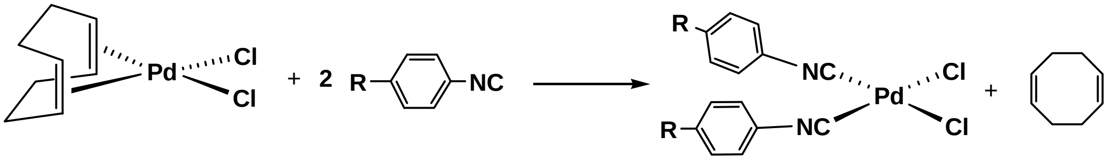
The goal of this work was to synthesize a series of palladium(II) bis(aryl isocyanide) dichloride complexes, and to use them as precursors for electronically tunable bis(ADC) complexes. The palladium(II) bis(aryl isocyanide) dichloride complexes served as precursors to synthesize palladium(II) bis(ADC) dichloride complexes via nucleophilic addition of diamines. Electron-donating and electron-withdrawing isocyanides were chosen in order to synthesize a range of bis(ADC) ligands with varying donor strengths .

The reaction between the palladium(II) bis(aryl isocyanide) dichloride complexes and *rac*-*N*,*N*-dimethylcyclohexanediamine led to the formation of a series of palladium(II) acyclic diaminocarbenes complexes. Full characterization of the palladium(II) bis(aryl isocyanide) dichloride complexes and the palladium(II) bis(ADC) complexes was carried out by ^{1}H NMR, ^{13}C NMR, IR spectroscopy and X-ray crystallography.

Series of palladium (II) bis (arylisocyanide) complexes

Synthesis

A general synthetic procedure was developed to synthesize a series of palladium (II) bis(aryl isocyanide) complexes. This involved the addition of two equivalents of the aryl isocyanide to a stirred solution of (1,5-cyclooctadiene)palladium dichloride. Hexanes and/or ether were used to precipitate and wash the products, which were dried in vacuo. Isocyanides with different electron-donating and electron-withdrawing groups including phenyl isocyanide, *p*-tolyl isocyanide, *p*-methoxyphenyl isocyanide, *p*-fluorophenyl isocyanide and 2,6-xylyl isocyanide were used to form the corresponding palladium bis(aryl isocyanide) dichloride complexes **4-8** (Scheme 3.1).



4-8

4 (R = H)
5 (R = CH_3)
6 (R = OCH_3)
7 (R = F)
8 (xylyl)

Scheme 3.1. Synthesis of bis(aryl isocyanide) palladium dichloride complexes **4-8.**

Table 3.1 shows the synthetic yields of the palladium bis(aryl isocyanide) complexes obtained from this reaction. These complexes were formed in yields ranging between 61-79 %. All of the palladium bis(aryl isocyanide) complexes were stable under air, hence could be stored at room temperature on the bench top. Complexes **4-7** (R = H**,** CH_3, OCH_3, F) were soluble in dichloromethane, acetonitrile, and dichlorobenzene and insoluble in hexanes, diethyl ether and cyclohexane. Complex **8** (xylyl) was sparingly soluble in dichloromethane and chloroform and insoluble in hexanes and diethyl ether.

Table 3.1. Synthetic yields of bis(arylisocyanide) palladium dichloride complexes.

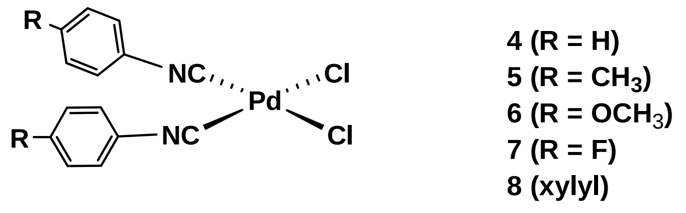
R	**Compound**	**Yield (%)**
H	**4**	77
CH_3	**5**	75
OCH_3	**6**	61
F	**7**	79
xylyl	**8**	80

Spectroscopic studies

The palladium(II) bis(aryl isocyanide) complexes showed a *cis* configuration of the two isocyanide ligands. Table 3.2 shows the ^1H NMR data of palladium bis(aryl isocyanide) dichloride complexes. The ^1H NMR data of complex **4** in CD_3CN displayed two multiplets in the ratio of 2:3, corresponding to the phenyl protons. Complexes **5-6** in CD_3CN exhibited two doublets corresponding to the aryl protons and singlets corresponding to the methyl and methoxy signals respectively. Complex **7** in CD_3CN

showed two multiplets corresponding to the aryl protons. Complex **8** in $CDCl_3$ showed a doublet and a triplet corresponding to the aryl protons and a singlet corresponding to the methyl protons.

Table 3.2 ^{1}H NMR spectral data for palladium(II) bis(aryl isocyanide) dichloride complexes.

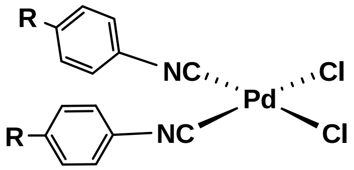


4-8

Compound	Solvent	Aromatic protons	R
4	CD_3CN	7.64-7.57 (2H, m), 7.57-7.53 (3H, m)	-
5	$CDCl_3$	7.52 (d, 2H, *J* = 8.4 Hz), 7.34 (d, 2H, *J* = 8.8 Hz)	2.41 (s, 3H, CH_3)
6	CD_3CN	7.57 (d, 2H, *J* = 8.7 Hz), 7.03 (m, 2H)	3.83 (s, 3H, OCH_3)
7	CD_3CN	7.69 (m, 2H,), 7.28 (m, 2H,)	-
8	$CDCl_3$	7.29-7.25 (t, 1H), 7.13 (d, 2H, 8Hz)	2.45 (s, 6H)

The ^{13}C NMR data for the palladium(II) bis(aryl isocyanide) complexes are shown in Table 3.3. The isocyanide carbon resonance was visible only for complexes **4** and **7** and appeared as a broad singlet between 119-129 ppm. Complex **7** displayed aryl *para*, *meta* and *ortho* signals at 160 ppm, 114 ppm and 126 ppm with coupling constants of $^1J_{C\text{-}F} = 254$ Hz, $^2J_{C\text{-}F} = 24$ Hz and $^3J_{C\text{-}F} = 9$ Hz respectively.[20] The ^{13}C NMR spectra also showed characteristic signals corresponding to the phenyl carbons in the range from 114-164 ppm. Complex **8** displayed *ortho*, *meta* and *para* signals at 137, 131 and 129 ppm, but did not show any ipso or isocyanide signal even after collecting data the 600 MHz NMR instrument.

Table 3.3. ^{13}C NMR spectral data for palladium (II) bis (aryl isocyanide) dichloride complexes.



4 (R = H)
5 (R = CH$_3$)
6 (R = OCH$_3$)
7 (R = F)
8 (xylyl)

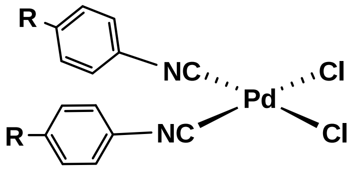
4-8

Compound	**Solvent**	**Isocyanide and aryl signals**	**R**
4	CD_3CN	δ 131.9 (Ar *para*), 130.1(Ar *ortho*), 127.1 (Ar *meta*), 125.5 (*C*NAr), 124.4 (Ar *ipso*)	H
5	CD_2Cl_2	δ 143.1 (Ar *para*), 130.6 (Ar *ortho*), 126.8 (Ar *meta***),** Ar *ipso* and *C*NAr not detected.	21.5 (CH_3)
6	CD_3CN	δ 162.7 (Ar *par*a), 129.7 (Ar *ortho*), 116.1 (Ar *meta*), ipso and *C*NAr not detected	56.6 (OCH_3)
7	CD_2Cl_2	160.2 (Ar *para*, $^1J_{CF} = 254$ Hz); 114.8 (Ar meta , $^2J_{CF} = 24$ Hz); 126.9 (Ar *ortho* , $^3J_{CF} = 9$ Hz), 122.0 (Ar *ipso*), 119.1 (*C*NAr)	F
8	$CDCl_3$	137.0 (Ar *para*); 131.7 (Ar *meta*); 129.1 (Ar *ortho*), *ipso* and *C*NAr not detected.	19.4 (CH_3)

Table 3.4 shows infrared spectral data for the palladium(II) bis(aryl isocyanide) dichloride complexes and free isocyanides. Complexes **4-8** show characteristic isocyanide CN stretching bands in the range of 2200-2400 cm^{-1}. The isocyanide CN stretching frequencies of complexes **4-8** are higher than those of the free isocyanides,

indicating strong σ donation from the coordinated isocyanide carbon to the palladium center and little or no π-backbonding. The higher Δν CN value indicates the electrophilic nature of the isocyanide carbons which in turn should correlate with their ability to undergo nucleophilic attack by protic amines.[21,22]

Table 3.4. Infrared spectral data for palladium(II) bis(aryl isocyanide) dichloride complexes.



4 (R = H)
5 (R = CH_3)
6 (R = OCH_3)
7 (R = F)
8 (xylyl)

4-8

Compound	ν CN (cm^{-1})	Free isocyanide ν CN (cm^{-1})	Δν CN (cm^{-1})
4	2254, 2224 Average = 2239	2123	116
5	2253, 2228 Average = 2240	2121	120
6	2239, 2219 Average = 2229	2120	109
7	2240, 2227 Average = 2234	2122	111.5
8	2227, 2211 Average = 2219	2124	95

X-ray quality crystals were grown of complexes **4-8** either by the slow diffusion of *n*-hexane into a dichloromethane solution of the complex, or by the slow diffusion of cyclohexane into a chlorobenzene solution of the complex. Complexes **4-8** displayed C_1

symmetry according to their X-ray crystal structure, except complex **5** which had C_S symmetry. Figures 3.1-3.8 show the X-ray crystal structures of complexes **4** to **8**. While growing X-ray quality crystals of complex **4** by slow diffusion of *n*-hexane into a concentrated solution of complex **4** in dichloromethane, two polymorphs of complex **4** were formed in the same vial. The two polymorphs were yellow needle-like crystals and large colorless blocks. Figure 3.1 shows a single molecule of complex **4** (needle-like crystals). On further analysis, it was found that the yellow needles **4a** exhibited Pd···Pd interaction with a Pd···Pd distance of 3.24 Å and vacant channels. This was attributed to the fact that the crystals of complex **4** (polymorph **4a**) stacked in an alternate manner due to the π-π interactions of the phenyl rings of the isocyanide ligands. This in turn minimized the repulsion between the ligands due to which they stacked one on top of each other to make effective Pd···Pd contact (Figure 3.2).[23] No Pd···Pd chains were observed with the colorless blocks polymorph **4b**. They existed as isolated dimers with a Pd···Pd distance of 3.40 Å (Figure 3.3). In an effort to understand what factors would influence the growth of the two different polymorphs, crystals of complex **4** were grown in the slow diffusing solvent combination of cyclohexane and chlorobenzene. On diffusing cyclohexane into a concentrated solution of complex **4** dissolved in chlorobenzene, only irregular polyhedral blocks of the second polymorph **4b** were obtained. These blocks did not show any Pd···Pd chain formation. Based on this result, it was inferred that upon employing the dichloromethane/ *n*-hexane solvent combination, crystals containing Pd···Pd metallophilic interactions were formed as a result of rapid crystal growth. In contrast, the use of the cyclohexane/ chlorobenzene solvent combination, more efficiently packed crystals were formed which contained no Pd···Pd chains or metallophilic interaction.[23]

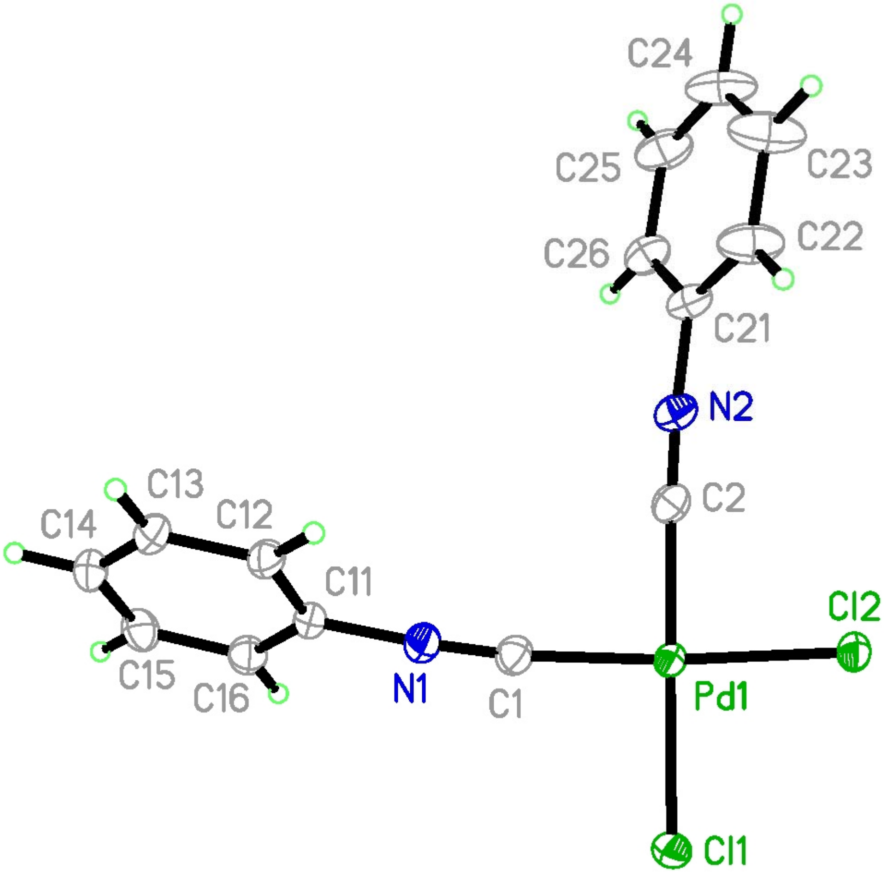


Figure 3.1. Molecular structure of complex **4** (polymorph **4a**) with 50 % probability ellipsoids.

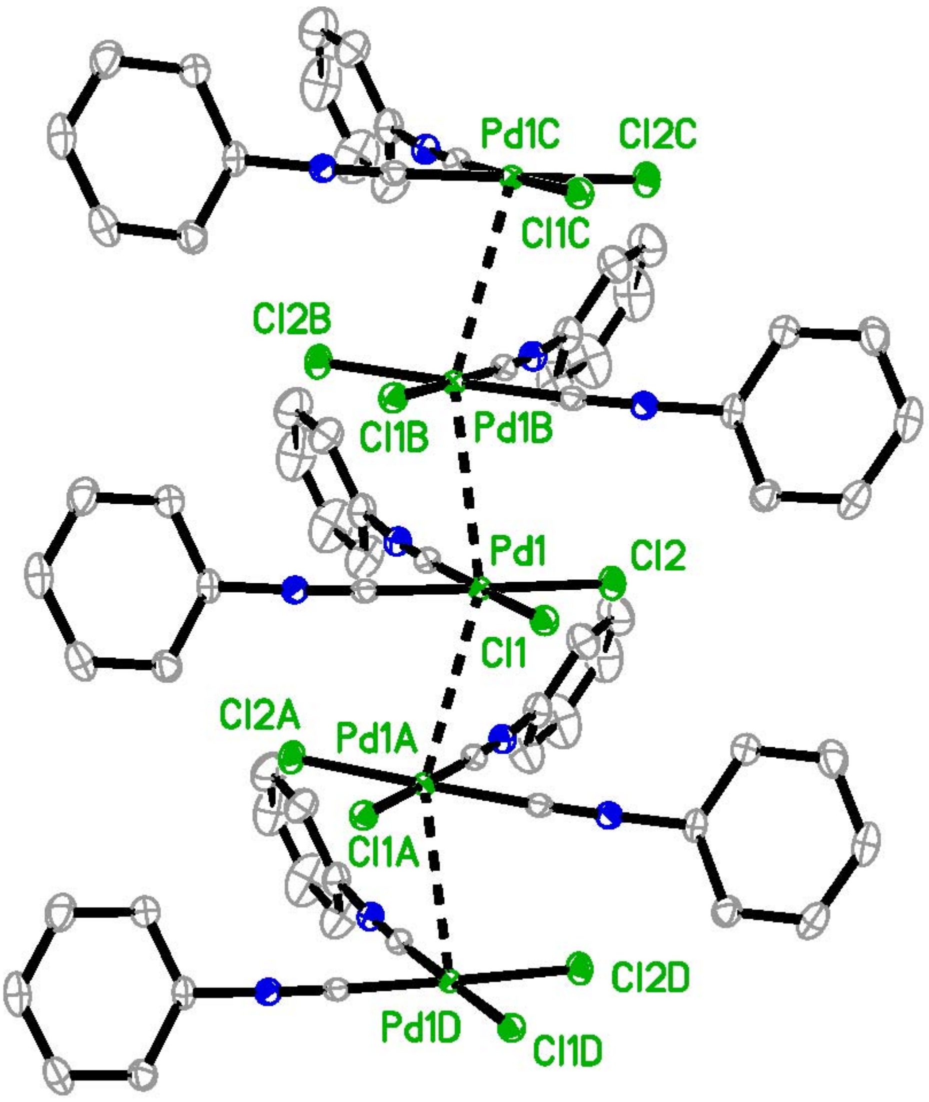


Figure 3.2. Stacked palladium bis(phenyl isocyanide) dichloride molecules in polymorph **4a** displaying Pd···Pd metallophilic interaction with a Pd···Pd distance of 3.2370(3) Å.

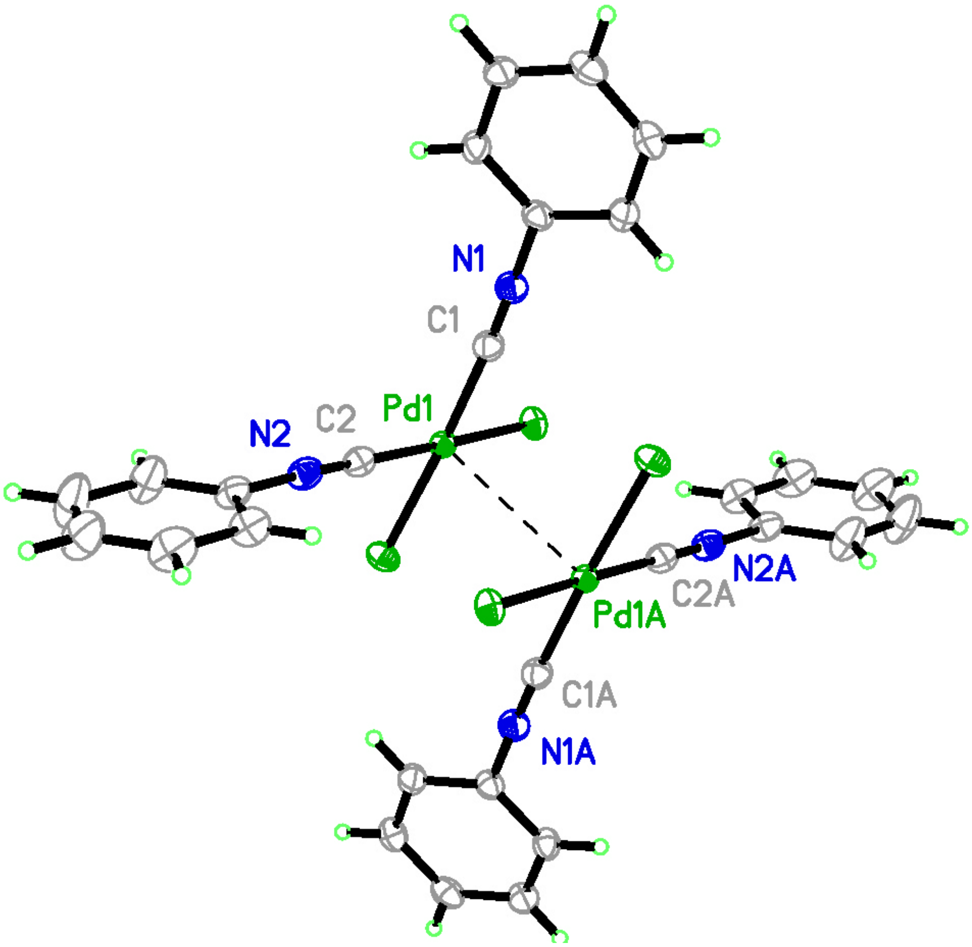


Figure 3.3. Isolated dimers of palladium bis(phenyl isocyanide) dichloride formed by the slow diffusion of cyclohexane into a concentrated solution of complex **4** dissolved in chlorobenzene in polymorph **4b** [Pd1···Pd1A = 3.3986(4)Å].

Table 3.5. Selected bond lengths (Å) and bond angles (°) of polymorph **4a.** [Needles]

	Bond Lengths (Å)
Pd(1)-C(1)	1.938 (3))
Pd(1)-C(2)	1.940(3)
C(1)-N(1)	1.137(4)
C(2)-N(2)	1.143(4)
Pd(1)-Pd(1A)	3.2370(3)

	Bond Angles (°)
C(2)-Pd(1)-C(1)	89.76(12)
N(1)-C(1)-Pd(1)	177.7(3)
C(2)-Pd(1)-Cl(1)	177.94(9)
C(2)-Pd(1)-Cl(2)	89.34(9)
N(2)-C(2)-Pd(1)	177.6 (3)

Table 3.6. Crystal data and structure refinement details of polymorph **4a**. [Needles]

Empirical Formula	$C_{14}H_{10}Cl_2N_2Pd$
Formula weight	383.54
Temperature	115(2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	$P2_1/c$
Unit cell dimensions	*a* 16.1828 (4) Å alpha = 90 $^{\mathrm{o}}$
	b = 15.0511 (4) Å beta = 93.1640 (10) $^{\mathrm{o}}$
	c = 6.34840 (10) Å gamma = 90 $^{\mathrm{o}}$
Volume, Z	1543.92 (6) Å^3, 4
Density (calculated)	1.650 Mg/m^3
Reflections collected	44661
Independent reflections	6922 (R_{int} = 0.0364)
Final R indices [$I>2\sigma(I)$]	R1 = 0.0255, wR2 = 0.0741
R indices (all data)	R1 = 0.0303, wR2 = 0.0763

Table 3.7. Selected bond lengths (Å) and bond angles (^{o}) of polymorph **4b** [blocks].

	Bond Lengths (Å)
Pd(1)-C(1)	1.9386(12)
Pd(1)-C(2)	1.9355(13)
C(1)-N(1)	1.1443(16)
C(2)-N(2)	1.1443(17)
Pd(1)-Pd(1A)	3.3986(4)

	Bond Angles (^{o})
C(2)-Pd(1)-C(1)	89.34(5)
N(1)-C(1)-Pd(1)	174.11(12)
C(2)-Pd(1)-Cl(1)	178.26(4)
C(2)-Pd(1)-Cl(2)	86.55(4)
N(2)-C(2)-Pd(1)	177.04(11)

Table 3.8. Crystal data and structure refinement details of polymorph **4b**. [Block shaped]

Empirical Formula	$C_{14}H_{10}Cl_2N_2Pd$
Formula weight	383.54
Crystal system	Monoclinic
Temperature	115(2) K
Wavelength	0.71073 Å
Space group	$P2_1/c$
Unit cell dimensions	a = 9.9103 (14) Å alpha = 90 ^{o}
	b = 11.8010 (17) Å beta = 101.841 (6) ^{o}
	c = 12.7677 (18) Å gamma = 90 ^{o}
Volume, Z	1461.4 (4) Å^3, 4
Density (calculated)	1.743 Mg/m^3
Reflections collected	26004
Independent reflections	5578 (R_{int} = 0.0382)
Final R indices [I>2σ(I)]	R1 = 0.0183, wR2 = 0.0440
R indices (all data)	R1 = 0.0214, wR2 = 0.0454

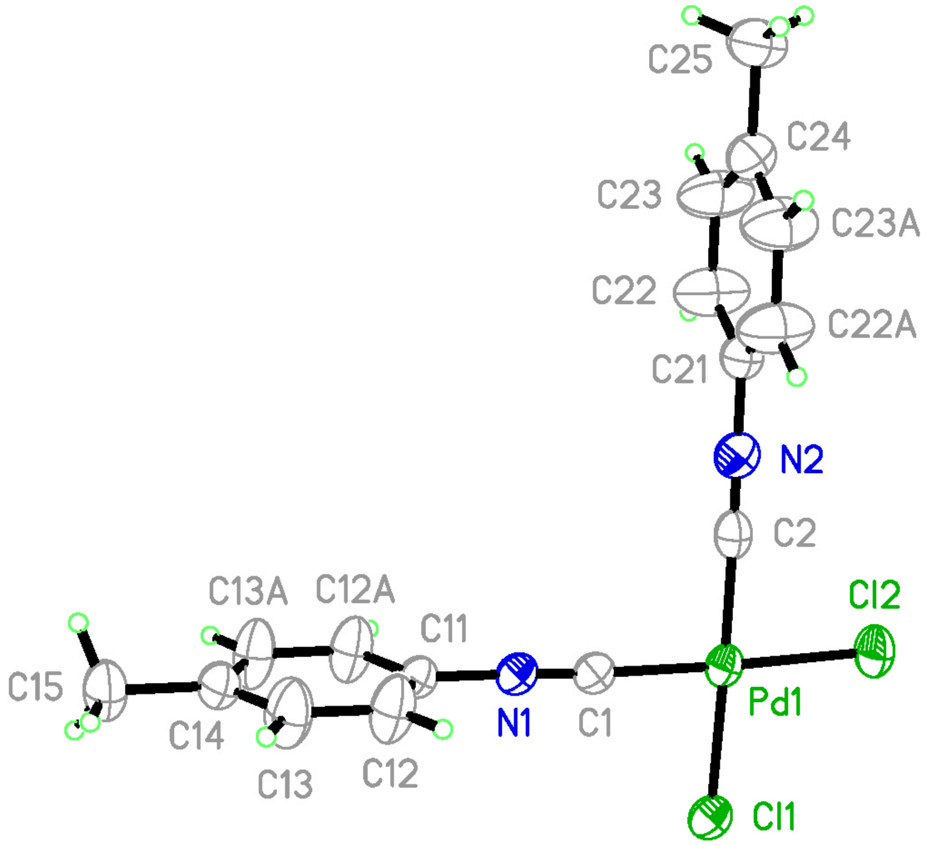


Figure 3.4. Molecular structure of complex **5** with 50 % probability ellipsoids.

Crystals of complex **5** were grown by the slow diffusion of cyclohexane into a concentrated solution of complex **5** dissolved in chlorobenzene. The crystals grew as yellow rods. In complex **5**, crystals were found to stack in a similar manner as complex **4**, showing a Pd···Pd interaction of 3.34063(12) Å (Figures 3.4-3.5).

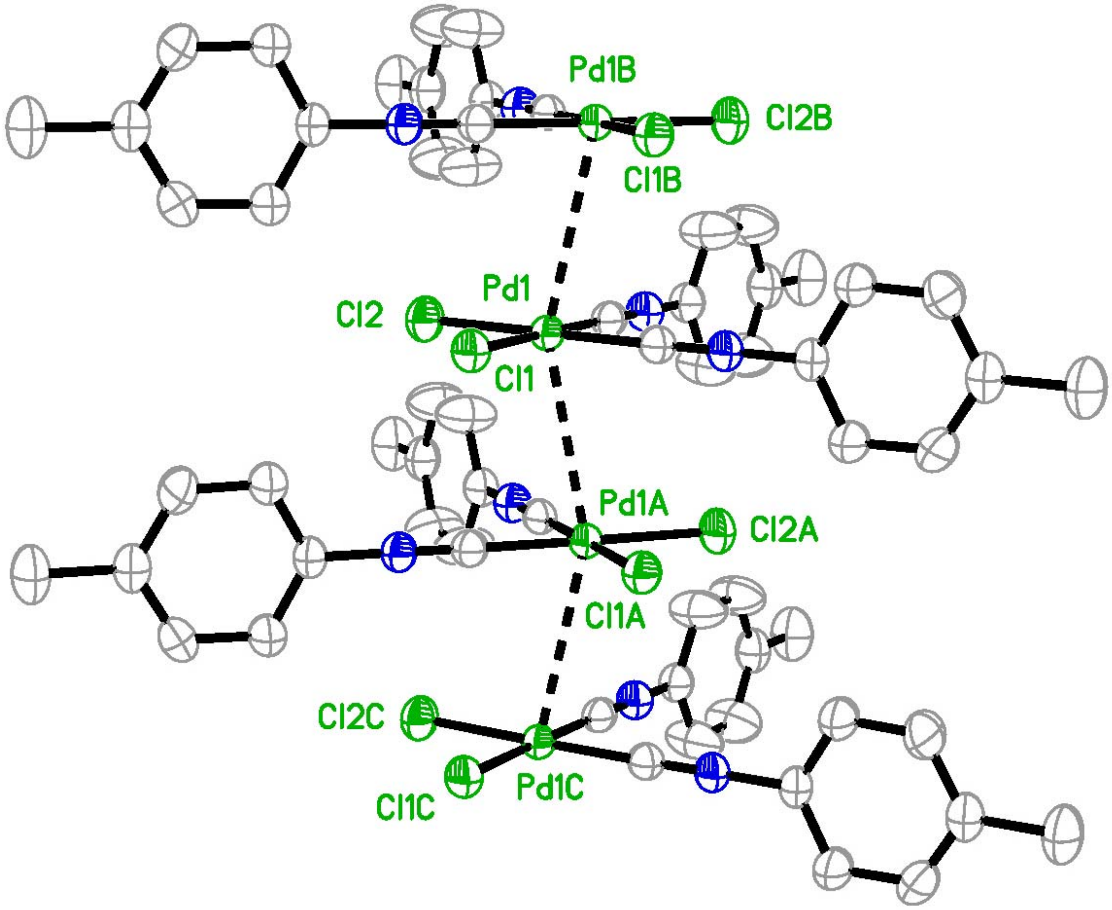


Figure 3.5. Stacked crystals of complex **5** with a Pd···Pd interaction of 3.34063(12) Å.

Table 3.9. Selected bond lengths (Å) and bond angles(^{o}) of complex **5**.

	Bond Lengths (Å)
Pd(1)-C(1)	1.938 (5)
Pd(1)-C(2)	1.934 (5)
C(1)-N(1)	1.132 (5)
C(2)-N(2)	1.145 (6)
Pd(1)-Pd(1A)	3.34063 (12)
	Bond Angles (^{o})
C(2)-Pd(1)-C(1)	89.52 (16)
N(1)-C(1)-Pd(1)	177.4 (4)
C(2)-Pd(1)-Cl(1)	178.58 (12)
C(2)-Pd(1)-Cl(2)	88.19 (12)
N(2)-C(2)-Pd(1)	178.9 (11)

Table 3.10. Crystal data and structure refinement details of complex **5**.

Empirical Formula	$C_{16}H_{14}Cl_2N_2Pd$
Formula weight	411.59
Temperature	298 (2) K
Wavelength	0.71073 Å
Crystal system	Tetragonal
Space group	*P*4/*mnc*
Unit cell dimensions	*a* = 24.5268 (2) Å alpha = 90 ^{o}
	b = 24.5268 (2) Å beta = 90 ^{o}
	c = 6.5445 (1) Å gamma = 90 ^{o}
Volume, Z	3936.94 (8) Å^3, 8
Density (calculates)	1.389 Mg/m3
Reflections collected	21135
Independent reflections	2661 (R_{int}= 0.0309)
Final R indices [I>2σ(I)]	R1= 0.0397, wR2 = 0.0979
R indices (all data)	R1= 0.0515, wR2 = 0.1024

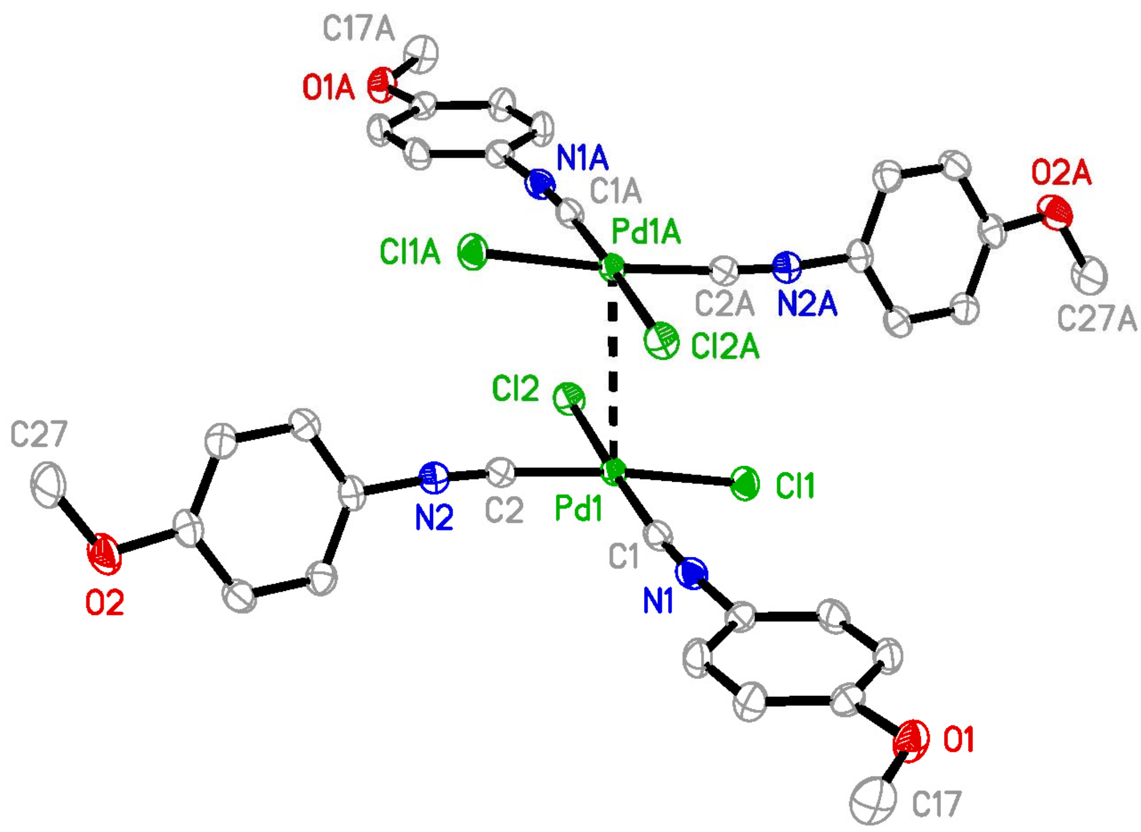


Figure 3.6. Molecular structure of complex **6** with 50 % probability ellipsoids.

X-ray quality crystals of complex **6** were grown by the slow diffusion of *n*-hexane into a concentrated solution of complex **6** dissolved in dichloromethane. These crystals grew as pale yellow rods. Figure 3.6 shows the dimers of complex **6** with a Pd···Pd interaction of 3.4643(3) Å with no extended chains.

Table 3.11. Selected bond lengths (Å) and bond angles (^{o}) of complex **6**.

	Bond Lengths(Å)
Pd(1)-C(1)	1.923(2)
Pd(1)-C(2)	1.949(2)
C(1)-N(1)	1.143(2)
C(2)-N(2)	1.142(3)
Pd(1)-Pd(1A)	3.4643(3)
	Bond Angles (^{o})
C(2)-Pd(1)-C(1)	91.12(8)
N(1)-C(1)-Pd(1)	174.81 (18)
C(2)-Pd(1)-Cl(1)	174.51(6)
C(2)-Pd(1)-Cl(2)	90.97(6)
N(2)-C(2)-Pd(1)	175.36(17)

Table 3.12. Crystal data and structure refinement details of complex **6**.

Empirical Formula	$C_{16}H_{14}Cl_2N_2O_2Pd$
Formula weight	443.59
Crystal system	Triclinic
Temperature	115(2) K
Wavelength	0.71073 Å
Space group	$P\bar{1}$
Unit cell dimensions	*a* = 12.2899 (3) Å alpha = 96.317 (1) ^{o}
	b = 12.3550 (3) Å beta = 104.314 (1) ^{o}
	c = 14.1451 (3) Å gamma = 118.329 (1) ^{o}
Volume, Z	1765.62 (8) Å^3, 4
Density (calculated)	1.669 Mg/m^3
Reflections collected	25068
Independent reflections	8490(R_{int} = 0.0256)
Final R indices [I>2σ(I)]	R1 = 0.0225, wR2 = 0.0503
R indices (all data)	R1 = 0.0301, wR2 = 0.0534

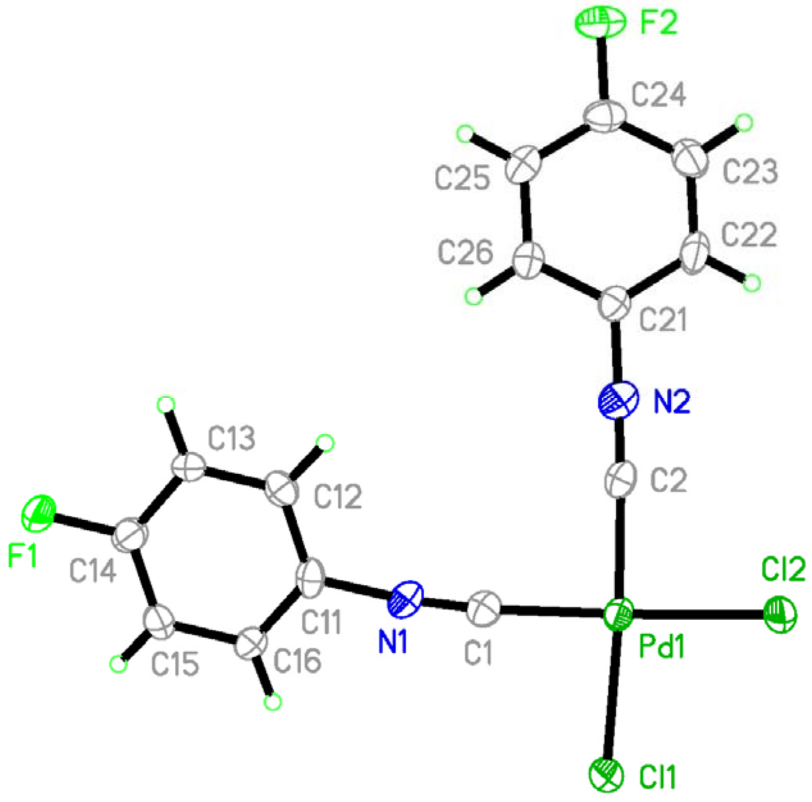


Figure 3.7. Molecular structure of complex **7** with 50 % probability ellipsoids.

X-ray quality crystals of complex **7** were grown by the slow diffusion of *n*-hexane into a concentrated solution of complex **7** dissolved in dichloromethane. These crystals grew as colorless rods. These crystals showed some stacking producing a dimer of dimers (Figure 3.7).

Table 3.13. Selected bond lengths (Å) and bond angles (^{o}) of complex **7**.

	Bond Lengths (Å)
Pd(1)-C(1)	1.941(8)
Pd(1)-C(2)	1.932(8)
C(1)-N(1)	1.130(10)
C(2)-N(2)	1.145(10)
Pd(1)-Pd(2)	3.3659(8)
	Bond Angles (^{o})
C(2)-Pd(1)-C(1)	89.0(3)
N(1)-C(1)-Pd(1)	175.0(8)
C(2)-Pd(1)-Cl(1)	175.8(2)
C(2)-Pd(1)-Cl(2)	89.1(2)
N(2)-C(2)-Pd(1)	177.7(8)

Table 3.14. Crystal and structure refinement data for complex **7**.

Empirical Formula	$C_{14}H_8Cl_2F_2N_2Pd$
Formula weight	419.52
Temperature	115(2)
Wavelength	0.71073 Å
Crystal system	Triclinic
Space group	$P\bar{1}$
Unit cell dimensions	*a* = 9.5569(4) Å alpha = 97.089 (3) ^{o}
	b = 13.2609 (5) Å beta = 94.043 (2) ^{o}
	c = 24.5769 (11) Å gamma = 104.483 (2) ^{o}
Volume, z	2976.0 (2) Å ^{3}, 8
Density (calculated)	1.873 Mg/m^3
Reflections collected	36222
Independent reflections	16700 (R_{int} = 0.0455)
Final R indices [$I>2\sigma>(I)$]	R1 = 0.0484, wR2 = 0.1261
R indices (all data)	R1 = 0.0566, wR2 = 0.1298

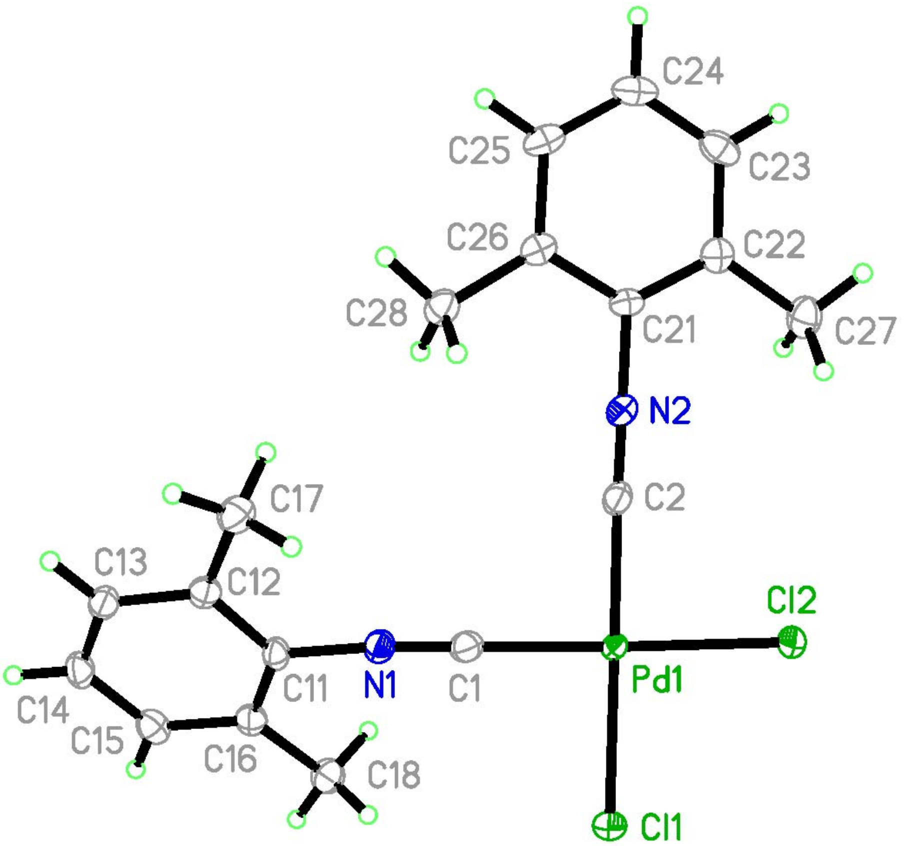


Figure 3.8. Molecular structure of complex **8** with 50 % probability ellipsoids.

X-ray quality crystals of complex **8** were grown by the slow diffusion of *n*-hexane into chloroform. These crystals were obtained as colorless blocks with no Pd···Pd interaction (Figure 3.8). Crystal growth was done by Ilya Sluch.

Table 3.15. Selected bond lengths (Å) and bond angles (^{o}) for complex **8**.

	Bond Lengths (Å)
Pd(1)-C(1)	1.9333(14)
Pd(1)-C(2)	1.9307(13)
C(1)-N(1)	1.1459(18)
C(2)-N(2)	1.1444(18)
	Bond Angles (^{o})
C(2)-Pd(1)-C(1)	91.42(5)
N(1)-C(1)-Pd(1)	177.81(12)
C(2)-Pd(1)-Cl(1)	93.336(12)
C(2)-Pd(1)-Cl(2)	87.12(4)
N(2)-C(2)-Pd(1)	175.91(12)

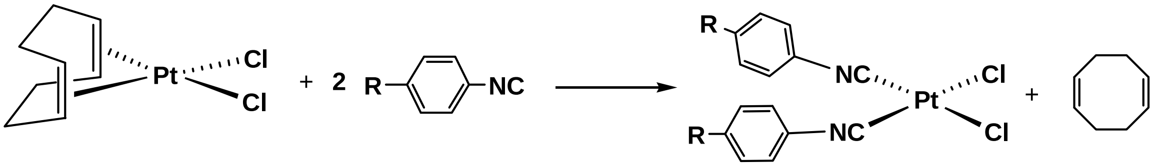
Table 3.16. Crystal data and structure refinement details of complex **8.**

Empirical Formula	$C_{18}H_{18}Cl_2N_2Pd$
Formula weight	439.64
Temperature	115(2) K
Wavelength	0.71073 Å
Crystal system	Triclinic
Space group	$P\bar{1}$
Unit cell dimensions	a = 8.0383(1) Å alpha = 85.4011(4) ^{o}
	b =10.4097(1) Å beta = 80.3707(5) ^{o}
	c =10.7831(1) Å gamma = 87.6240(5)^{o}
Volume, Z	886.353(16) Å^3, 2
Density (calculated)	1.647 Mg/m^3
Reflections collected	14163
Independent reflections	4363 (R_{int} = 0.0182)
Final R Indices [$I>2\sigma(I)$]	R1= 0.0158, wR2 = 0.0399
R indices (all data)	R1= 0.0166, wR2 = 0.0404

Series of platinum(II) bis(arylisocyanide) complexes

Synthesis

The platinum(II) bis(aryl isocyanide) complexes were synthesized using the same method as that described for the palladium(II) bis(arylisocyanide) complexes. This involved the addition of two equivalents of aryl isocyanide to a stirred solution of (1, 5-cyclooctadiene)platinum dichloride. Hexanes and/or ether were used to precipitate and wash the products followed by drying under vacuo. Isocyanides with different electron-donating and electron-withdrawing isocyanides such as phenyl isocyanide, *p*-tolyl isocyanide, *p*-methoxyphenyl isocyanide, *p*-fluorophenyl isocyanide, *p*-trifluoromethylphenyl isocyanide and 2,6-xylyl isocyanide were used to form the corresponding platinum bis(aryl isocyanide) dichloride complexes **9-14** (Scheme 3.2).



9-14

9 (R = H)
10 (R = CH_3)
11 (R = OCH_3)
12 (R = CF_3)
13 (R = F)
14 (xylyl)

Scheme 3.2. Synthesis of bis (aryl isocyanides) platinum dichloride complexes **9-14.**

Table 3.17 shows the synthetic yields of the platinum bis(aryl isocyanide) complexes obtained from the above reaction. These complexes were formed in yields ranging between 72-89 %. All of the platinum bis(aryl isocyanide) complexes were stable under air, hence could be stored at room temperature on the bench top. Complexes **9** to **14** were soluble in dichloromethane, acetonitrile, and dichlorobenzene and insoluble in hexanes, diethyl ether and cyclohexane.

Table 3.17. Synthetic yields of bis(arylisocyanide) platinum dichloride complexes.

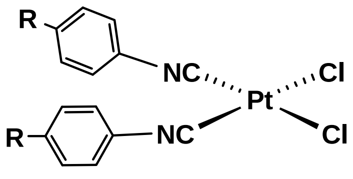
R	Compound	Yield (%)
H	**9**	77
CH_3	**10**	83
OCH_3	**11**	79
CF_3	**12**	89
F	**13**	72
xylyl	**14**	85

Spectroscopic studies

The platinum(II) bis(aryl isocyanide) complexes show a *cis* configuration of the two isocyanide ligands. Table 3.18 shows the ^1H NMR spectral data of platinum bis(aryl isocyanide) dichloride complexes. The ^1H NMR data of complex **9** in CD_3CN showed two multiplets in the ratio of 2:3 corresponding to the phenyl protons. Complexes **10-11** in CD_3CN showed two doublets corresponding to the aryl protons and singlets corresponding to the methyl and methoxy signals respectively. Complexes **12-13** in

CD_3CN showed two multiplets corresponding to the aryl protons. Complex **14** in $CDCl_3$ showed a triplet and a doublet corresponding to the aryl protons and a singlet corresponding to the methyl protons.

Table 3.18. ^{1}H NMR spectral data for platinum (II) bis (aryl isocyanides) dichloride complexes.



9-14

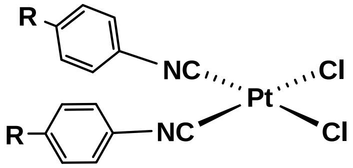
9 (R = H)
10 (R = CH_3)
11 (R = OCH_3)
12 (R = CF_3)
13 (R = F)
14 (xylyl)

Compound	Solvent	Aromatic H	R
9	CD_3CN	7.64-7.57 (2H, m), 7.57-7.53 (3H, m).	H
10	CD_3CN	7.39 (d, 2H, *J*=8.4 Hz), 7.25 (2H, d, *J*=6.9 Hz)	2.40 (s, CH_3)
11	CD_3CN	7.56 (2H, d, *J*=9 Hz), 7.02 (2H, d, *J*=9 Hz)	3.83 (s, OCH_3)
12	CD_3CN	7.75 (2H, d, *J*=9 Hz), 7.71 (2H, d, *J*=9 Hz)	CF_3
13	CD_3CN	7.69 (m, 2H), 7.27 (m, 2H)	F
14	$CDCl_3$	7.29-7.25 (t, 1H), 7.13 (d, 2H, 8Hz)	2.45 (s, 6H)

The ^{13}C NMR data for the platinum(II) bis(aryl isocyanide) complexes are shown in Table 3.19. The isocyanide carbon resonance was visible for all complexes and appeared as a broad singlet between 118-129 ppm. Complex **12** displayed quartets for the aryl *para* and *meta* signals at 132 ppm and 128 ppm, respectively, with coupling constants $^2J_{C\text{-}F}$ = 33 Hz and $^3J_{C\text{-}F}$ = 4.1 Hz. It also displayed C-F coupling of 272 Hz at

124 ppm characteristic of the CF_3 functional group. Complex **13** displayed aryl *para* and *meta* signals at 164 ppm, 114 ppm and 126 ppm with coupling constants $^1J_{C\text{-}F}$ = 254 Hz, $^2J_{C\text{-}F}$ = 23.8 Hz and $^3J_{C\text{-}F}$ = 9.5 Hz, respectively.[20] The ^{13}C NMR spectra also showed characteristic resonances corresponding to the phenyl carbons in the range from 111-164 ppm. Table 3.20 shows infrared absorptions for the platinum(II) bis(aryl isocyanide) dichloride complexes. Complexes **9-14** displayed characteristic isocyanides CN stretching bands in the range of 2200-2400 cm^{-1}. The isocyanides CN stretching frequencies of complexes **9-14** are higher than those of the free isocyanides indicating strong σ donation from the co-coordinated isocyanides carbon to the platinum center and little or no π-backbonding.

Table 3.19. ^{13}C NMR data for platinum (II) bis (aryl isocyanides) dichloride complexes.

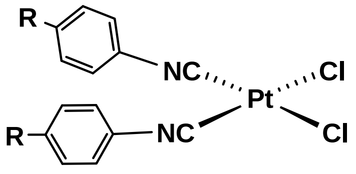


9-14

9 (R = H)
10 (R = CH_3)
11 (R = OCH_3)
12 (R = CF_3)
13 (R = F)
14 (xylyl)

Compound	Solvent	Isocyanide and aromatic carbons	R
9	CD_2Cl_2	131.5 (Ar *para*), 130.1 (Ar *ortho*), 127.1 (Ar *meta*), 126.0 (*C*NAr), 113.7 (Ar *ipso*).	H
10	CD_3CN	142.5 (s, Ar *para*), 130.4 (s, Ar *ortho*), 126.9 (s, Ar *meta*), 123.2 (broad s, *C*NAr), 111.9 (broad s, Ar *ipso*)	20.6 (CH_3)
11	CD_2Cl_2	161.5 (s, Ar *para*), 128.8 (s, Ar *ortho*), 118.2 (s, *C*NAr), 115.1 (s, Ar *meta*), 111.2 (m, Ar *ipso*)	55.7 (OCH_3)
12	CD_3CN	132.9 (q, $^2J_{CF}$ = 33.3 Hz, Ar *para*), 129.9 (m, *C*NAr), 129.1 (s, Ar *ortho*), 128.0 (q, $^3J_{CF}$ = 4.1 Hz, Ar *meta*), 124.3 (q, $^1J_{CF}$ = 272 Hz, CF_3), 116.0 (m, Ar *ipso*)	CF_3
13	CD_3CN	163.6 (d, $^1J_{CF}$ = 254 Hz, Ar *para*), 129.6 (d, $^3J_{CF}$ = 9.5 Hz, Ar *ortho*), 122.3 (*C*NAr), 117.3 (d, $^2J_{CF}$ = 23.8 Hz, Ar *meta*), 113.6 (m, Ar ipso).	F
14	$CDCl_3$	137.0 (Ar *para*); 131.7 (Ar *meta*); 129.1 (Ar *ortho*)	19.4 (CH_3)

Table 3.20. Infrared spectral data for platinum(II) bis(aryl isocyanide) dichloride complexes.



9-14

9 (R = H)
10 (R = CH_3)
11 (R = OCH_3)
12 (R = CF_3)
13 (R = F)
14 (xylyl)

Compound	**ν CN (cm^{-1})**	**Free isocyanide ν CN (cm^{-1})**	**Δν CN (cm^{-1})**
9	2254, 2214 Average = 2234	2123	111
10	2255, 2217 Average =2236	2121	115
11	2236, 2215 Average =2226	2120	106
12	2242, 2206 Average =2224	2120	104
13	2252, 2218 Average = 2235	2122	113
14	2229, 2200 Average = 2215	2124	91

X-ray quality crystals of complexes **9-14** were grown either by the slow diffusion of dry *n*-hexane into dry dichloromethane solutions or by diffusion of cyclohexane into chlorobenzene or *o*-dichlorobenzene solutions. The crystal structures of complexes **9-14** indicated a *cis* configuration of the two isocyanides ligands. Interestingly, when crystals of complex **9** were grown by the slow diffusion of *n*-hexane into a concentrated solution of complex **9** in dichloromethane, yellow rods were obtained (Figure 3.9). On crystallographic analysis, these yellow rods displayed stacked platinum chains with Pt···Pt distance being 3.25Å which is represented as polymorph **9a** (Figure 3.10).[20] These complexes stacked in such a way that the steric repulsion between ligands was minimized, and the Pt···Pt contact between the resultant stacks was increased. Also, the phenyl rings in these ligands were found to stack one on top of each other and hence displayed π-π stacking interactions. This type of packing also led to the formation of channels parallel to the Pt···Pt chains, which were about 3.0-4.0 Å wide.[23] A combination of the Pt···Pt metallophilic interaction and π-π stacking interactions gave rise to luminescence in complex **9**. The yellow rods of complex **9** displayed bright orange luminescence under UV light with emission maxima at 657 nm.[23] On slow diffusion of cyclohexane into a concentrated solution of complex **9,** block shaped crystals were formed which was represented as polymorph **9b.** X-ray analysis of the blocks indicated the presence of a dimer with a Pt···Pt distance of 3.4 Å with no extended Pt···Pt chain formation (Figure 3.11). A similar conclusion was deduced for palladium complex **4**. Rapid crystal growth took place to give rise to infinite Pt···Pt chains with the fast diffusing solvent combination like dichloromethane/ *n*-hexane while with the slower diffusing solvent combination, non-luminescent dimers were observed.

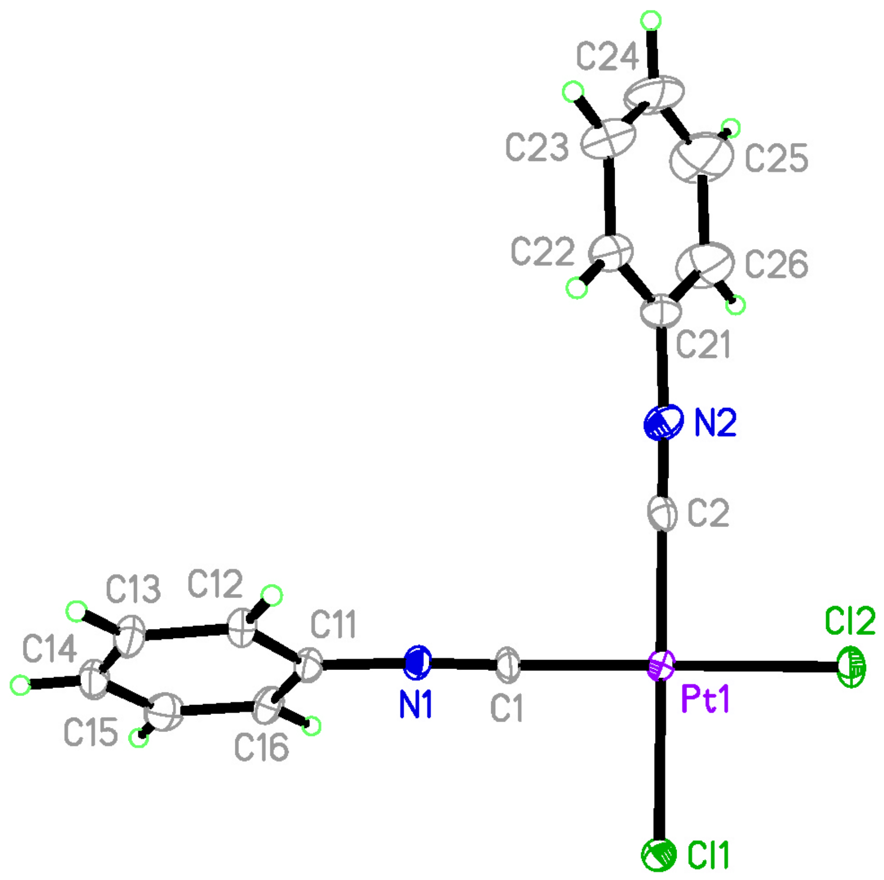


Figure **3.9.** Molecular structure of polymorph **9a** with 50 % probability ellipsoids.

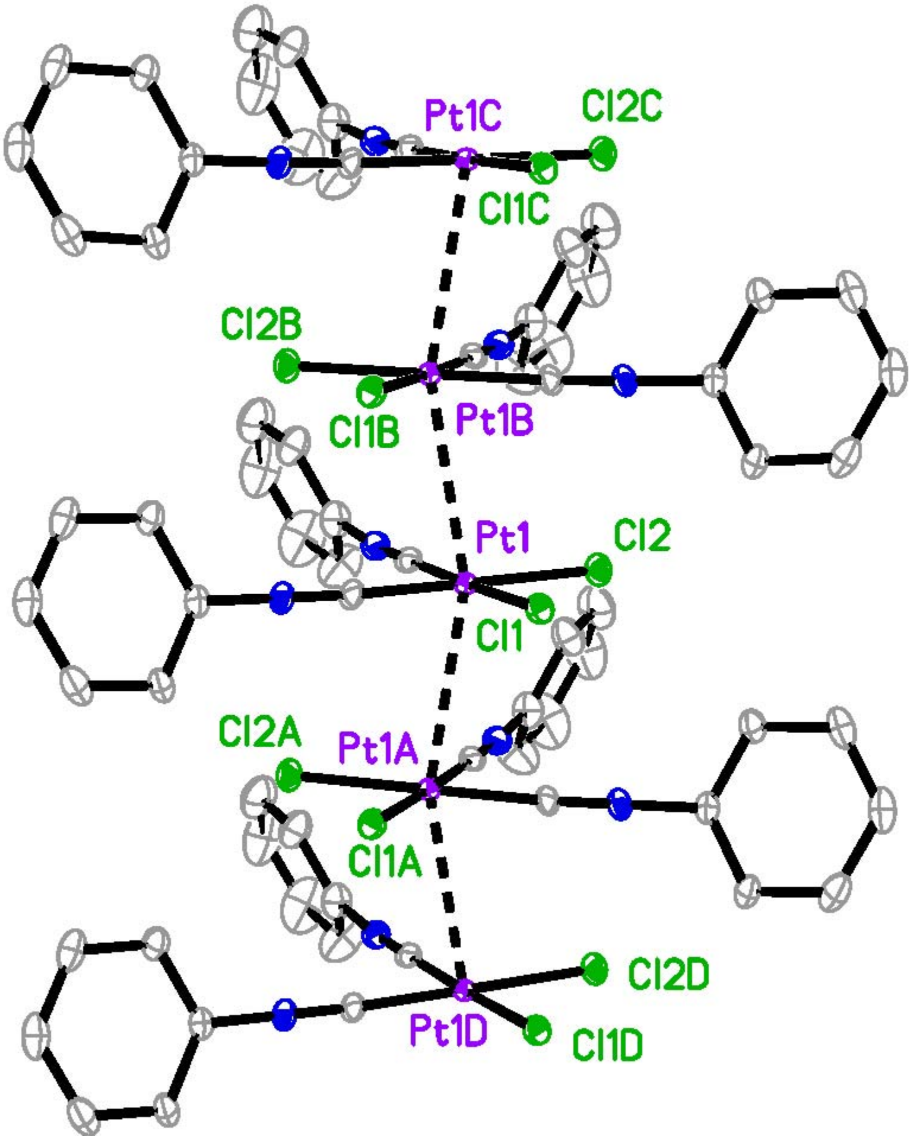


Figure 3.10. Stacked platinum bis(phenylisocyanide) dichloride molecules of polymorph **9a** displaying Pt···Pt metallophilic interactions with a Pt···Pt distance of 3.2455(3) Å.

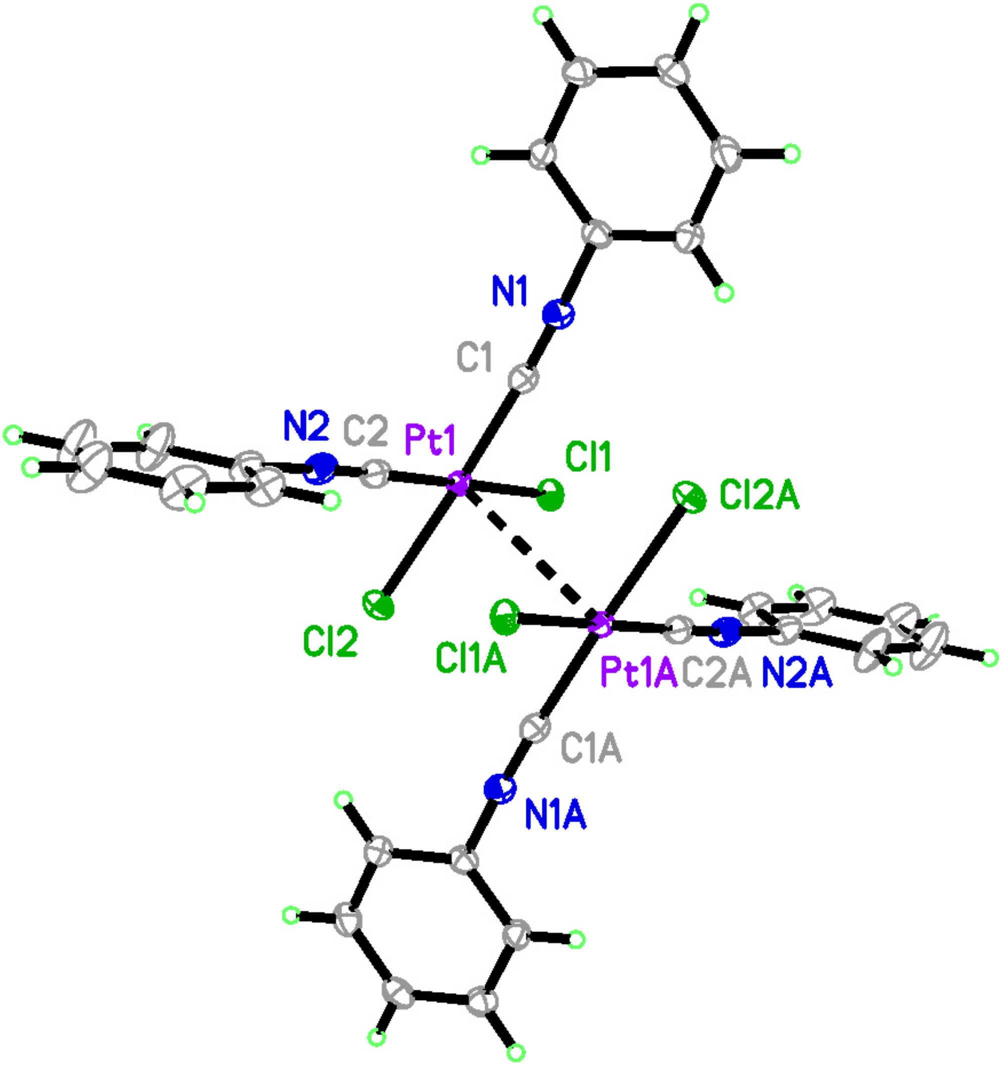


Figure 3.11. Isolated dimers of polymorph **9b** formed by the slow diffusion of cyclohexane into a chlorobenzene solution [Pt1···Pt1A 3.4001(2) Å].

Table 3.21. Selected bond lengths (Å) and bond angles (°) for polymorph **9a**.

	Bond Lengths(Å)
C(1)-N(1)	1.140(8)
C(2)-N(2)	1.160(9)
Pt(1)-C(2)	1.903(7)
Pt(1)-C(1)	1.919(6)
Pt(1)-Cl(1)	2.3172(15)
Pt(1)-Cl(2)	2.3247(17)
Pt(1)-Pt(1A)	3.2455(3)

	Bond Angles (°)
C(2)-Pt(1)-C(1)	90.7(3)
N(1)-C(1)-Pt(1)	177.5(7)
Cl(1)-Pt(1)-Cl(2)	90.08(6)
N(2)-C(2)-Pt(1)	179.5(7)

Table 3.22. Crystal data and structure refinement details for polymorph **9a (**yellow needles**)**.

Empirical Formula	$C_{14}H_{10}Cl_2N_2Pt$
Formula weight	472.23
Temperature	115(2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	$P2_1/c$
Unit cell dimensions	a = 16.2461 (12) Å alpha = 90 ^{o}
	b = 14.9863 (11) Å beta = 93.225 (5) ^{o}
	c = 6.3995 (11) Å gamma = 90 ^{o}
Volume, Z	1555.6 (5) Å^3, 4
Density (calculated)	2.016 Mg/m^3
Reflections collected	19947
Independent reflections	6319 (R_{int} = 0.0444)
Final R indices [I>2σ (I)]	R1 = 0.0343, wR2 = 0.0956
R indices (all data)	R1 = 0.0423, wR2 = 0.0989

Table 3.23 Selected bond lengths (Å) and bond angles (^{o}) for polymorph **9b (**block shaped crystals**)**.

	Bond Lengths (Å)
C(1)-N(1)	1.147(3)
C(2)-N(2)	1.150(3)
Pt(1)-C(2)	1.908(2)
Pt(1)-C(1)	1.911(2)
Pt(1)-Cl(1)	2.3228(5)
Pt(1)-Cl(2)	2.3162(4)
Pt(1)-Pt(1A)	3.40009(15)

	Bond Angles (^{o})
C(2)-Pt(1)-C(1)	90.07(9)
N(1)-C(1)-Pt(1)	174.9(2)
Cl(1)-Pt(1)-Cl(2)	91.119(17)
N(2)-C(2)-Pt(1)	177.79(18)

Table 3.24 Crystal data and structure refinement details for complex **9b (**block shaped crystals**).**

Empirical Formula	$C_{14}H_{10}Cl_2N_2Pt$
Formula weight	472.23
Temperature	115(2) K
Wavelength	0.71073 Å
Crystal system	Monoclinic
Space group	$P2_1/c$
Unit cell dimensions	a = 9.90160 (10) Å alpha = 90 ^{o}
	b = 11.7921 (2) Å beta = 102.2590 (10) ^{o}
	c = 12.7424 (2) Å gamma = 90 ^{o}
Volume, Z	1453.89 (4) Å^3, 4
Density (calculated)	2.157 Mg/m^3
Reflections collected	23873
Independent reflections	5500 (R_{int} = 0.0272)
Final R indices [I>2σ (I)]	R1 = 0.0189, wR2 = 0.0405
R indices (all data)	R1 = 0.0228, wR2 = 0.0415

X-ray quality crystals of complex **10** were grown by the slow diffusion of cyclohexane into a chlorobenzene solution (Figures 3.12-3.13). These crystals were observed as yellow rods with a similar stacked formation as complex **9** and were found to be luminescent at 25 °C.

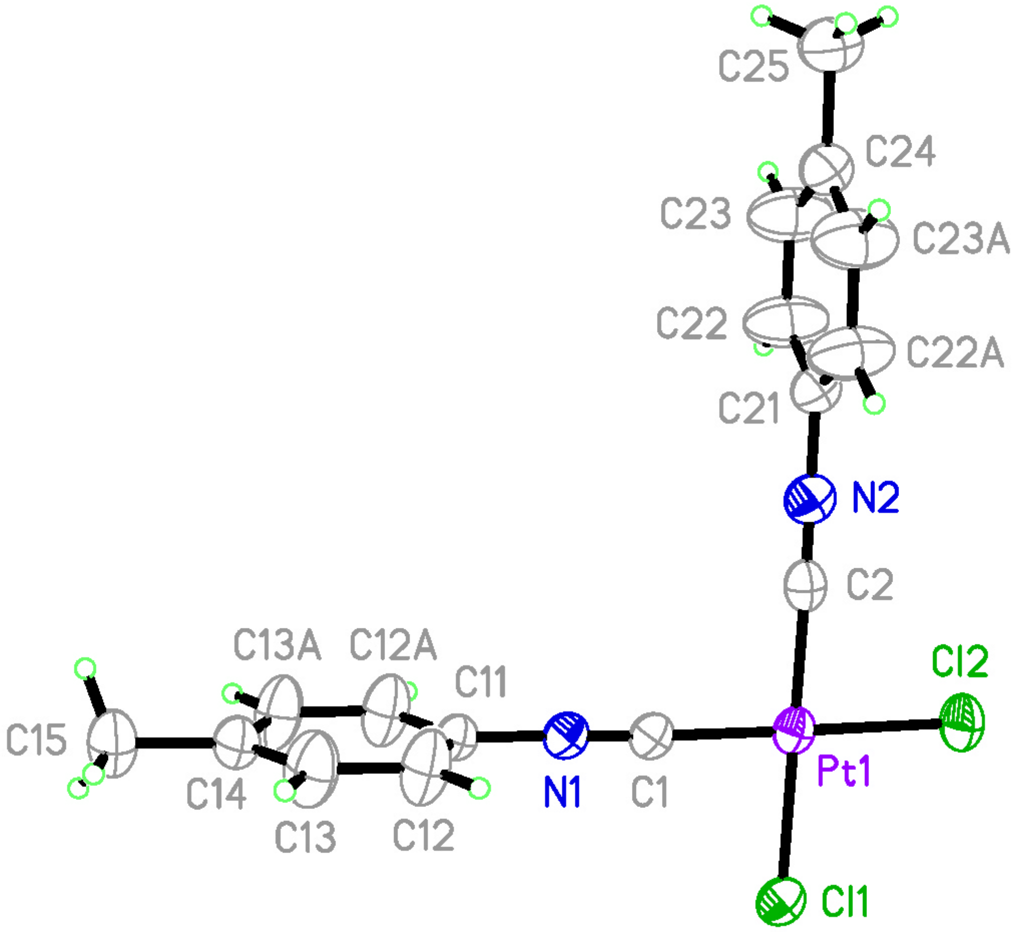


Figure 3.12. Molecular structure of complex **10** with 50 % probability ellipsoids.

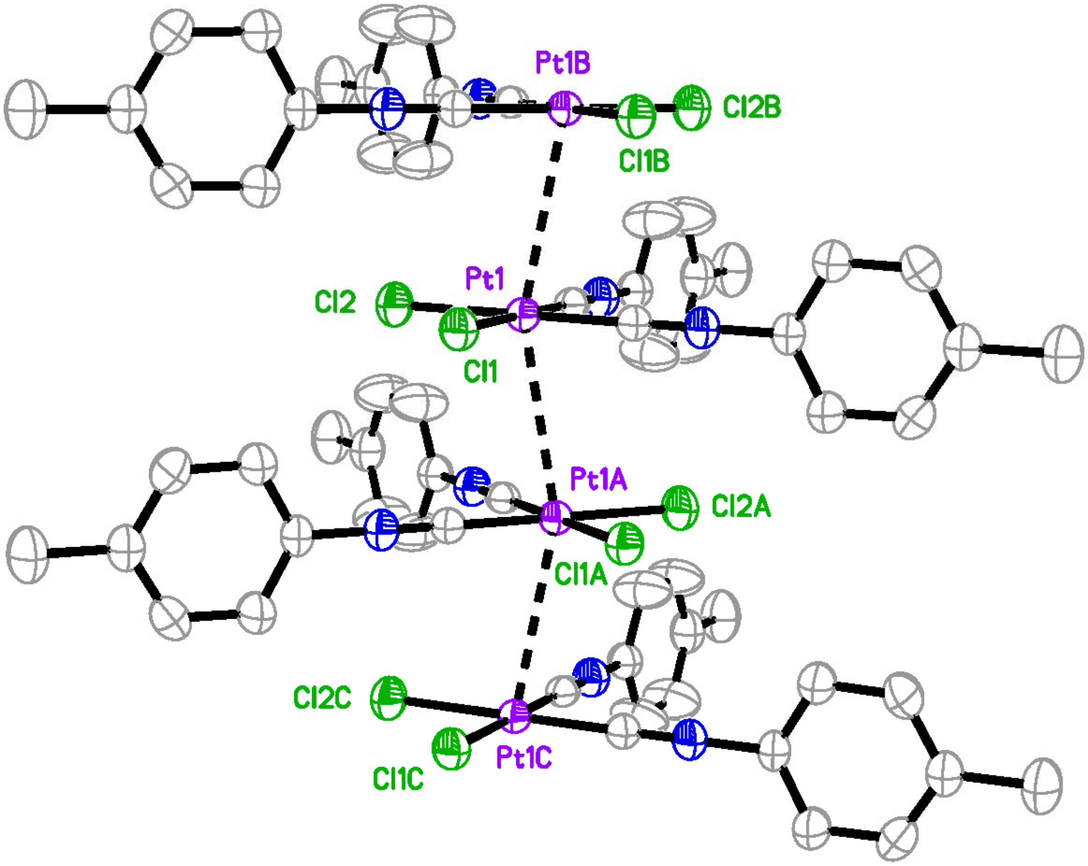


Figure 3.13. Stacks of complex **10** showing Pt···Pt interactions [Pt···Pt distance 3.3393(1)Å].

Table 3.25. Selected bond lengths (Å) and bond angles (^{o}) for complex **10**.

	Bond Lengths (Å)
C(1)-N(1)	1.130(5)
C(2)-N(2)	1.127(6)
Pt(1)-C(2)	1.919(5)
Pt(1)-C(1)	1.917(5)
Pt(1)-Cl(1)	2.3145(11)
Pt(1)-Cl(2)	2.3224(11)
Pt(1)-Pt(1A)	3.3393(1)
	Bond Angles (^{o})
C(2)-Pt(1)-C(1)	90.49(17)
N(1)-C(1)-Pt(1)	177.7(4)
Cl(1)-Pt(1)-Cl(2)	91.23(4)
N(2)-C(2)-Pt(1)	178.8(4)

Table 3.26. Crystal data and structure refinement details for complex **10.**

Empirical Formula	$C_{16}H_{14}Cl_2N_2Pt$
Formula weight	500.28
Temperature	298(2) K
Wavelength	0.71073
Crystal system	Tetragonal
Space group	$P4/_{\mathrm{mnc}}$
Unit cell dimensions	*a* = 24.5366 (1) Å alpha = 90 ^{o}
	b = 24.5366 (1) Å beta = 90 ^{o}
	c = 6.5728 (1) Å gamma = 90 ^{o}
Volume, Z	3957.12 (6) $Å^3$, 8
Density (calculated)	1.679 Mg/m^3
Reflections collected	31545
Independent reflections	2043 (R_{int} = 0.0315)
Final R indices [I>2σ(I)]	R1 = 0.0188, wR2 = 0.0453
R indices (all data)	R1 = 0.0260, wR2 = 0.0470

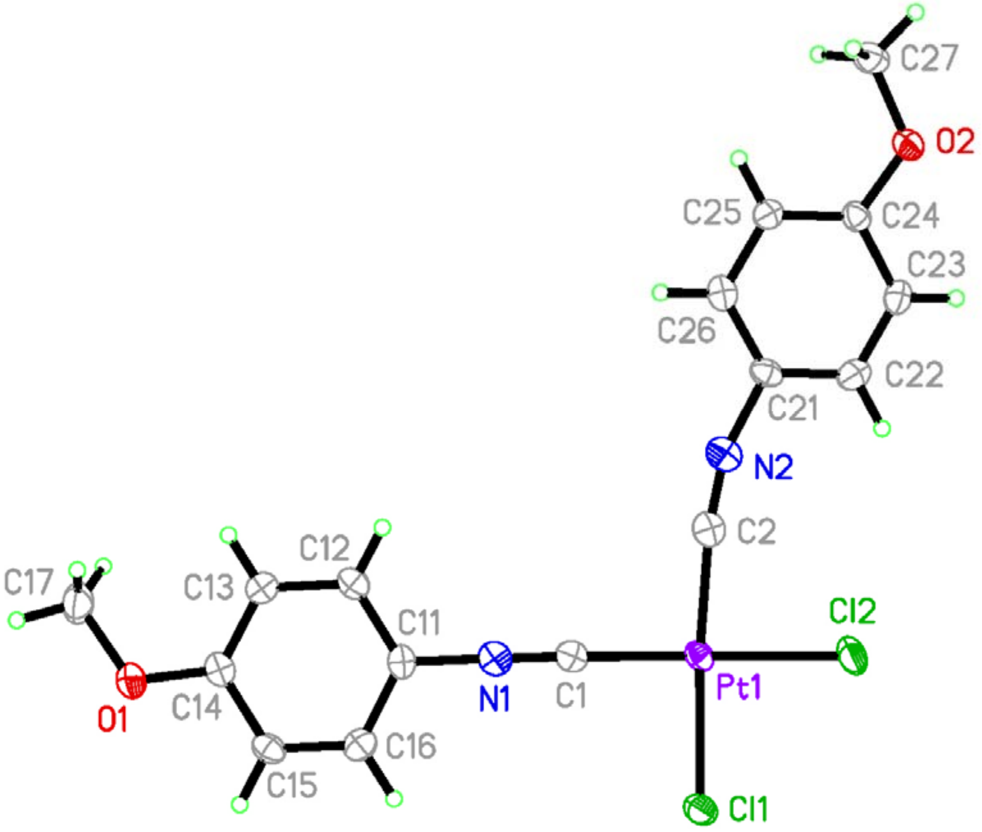


Figure 3.14. Molecular structure of complex **11** with 50 % probability ellipsoids.

X-ray quality crystals of complex **11** were grown by the slow diffusion of cyclohexane into a concentrated solution of complex **11** dissolved in *o*-dichlorobenzene, and also by the slow diffusion of *n*-hexane into a concentrated solution of **11** in dichloromethane. A single unit of complex **11** is shown in Figure 3.14. In both cases, complex **11** existed as isolated dimers with *o*-dichlorobenzene or dichloromethane trapped in the crystal lattice (Figures 3.15-3.16). The *o*-dichlorobenzene solvate (**11a**) showed a Pt···Pt distance of 3.24612(11)Å, whereas the dichloromethane solvate (**11b**) showed a Pt···Pt distance of 3.49599(14)Å .

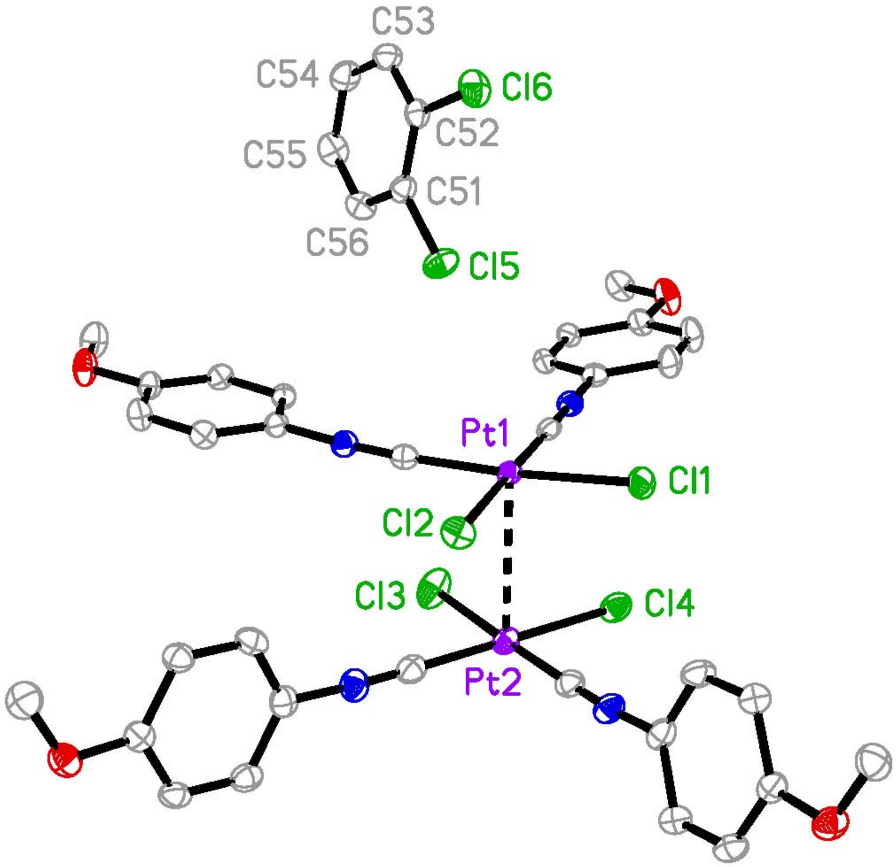


Figure 3.15. Dimers of complex **11** displaying Pt···Pt distance of 3.24612(11) Å with a molecule of *o*-dichlorobenzene trapped in the crystal lattice (**11a**).

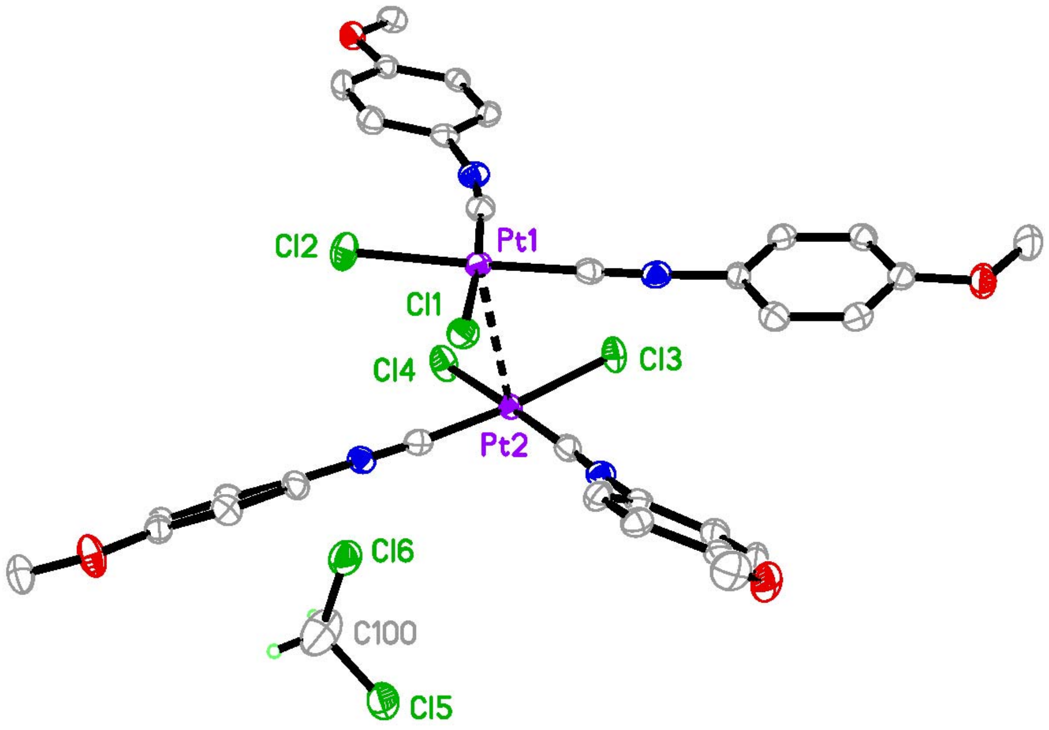


Figure 3.16. Dimers of complex **11** displaying Pt···Pt distance of 3.49599(14) Å with a molecule of dichloromethane trapped in the crystal lattice (**11b**).

Table 3.27. Selected bond lengths (Å) and bond angles (°) for complex **11a** (*o*-dichlorobenzene, cyclohexane).

	Bond Lengths(Å)
C(1)-N(1)	1.143(3)
C(2)-N(2)	1.143(3)
Pt(1)-C(2)	1.914(2)
Pt(1)-C(1)	1.909(2)
Pt(1)-Cl(1)	2.3182(5)
Pt(1)-Cl(2)	2.3076(5)
Pt(1)-Pt(2)	3.24612(11)

	Bond Angles (°)
C(1)-Pt(1)-C(2)	89.96(8)
N(1)-C(1)-Pt(1)	178.81(6)
Cl(1)-Pt(1)-Cl(2)	91.290(19)
N(2)-C(2)-Pt(1)	176.21(18)

Table 3.28. Crystal data and structure refinement for complex **11a (***o*-dichlorobenzene, cyclohexane**).**

Empirical Formula	$C_{19}H_{16}Cl_3N_2O_2Pt$
Formula weight	605.78
Temperature	115(2) K
Wavelength	0.71073 Å
Crystal system	Triclinic
Space group	$P\bar{1}$
Unit cell dimensions	*a* = 13.2283 (2) Å alpha = 107.146(1) ^{o}
	b = 13.9112 (2) Å beta = 101.539 (1) ^{o}
	c = 14.4607 (21) Å gamma = 118.042(1) ^{o}
Volume, Z	2055.44(7) Å^3 , 4
Density (calculated)	1.958 Mg/m^3
Reflections collected	48699
Independent reflections	10180 (R_{int} = 0.0286)
Final R indices [I>2σ (I)]	R1 = 0.0159, wR2 = 0.0354
R indices (all data)	R1 = 0.0183, wR2 = 0.0361

Table 3.29. Selected bond lengths (Å) and bond angles (^{o}) for complex **11b** **(**dichloromethane, *n*-hexane**)**

	Bond Lengths (Å)
C(1)-N(1)	1.149(3)
C(2)-N(2)	1.147(3)
Pt(1)-C(2)	1.911(3)
Pt(1)-C(1)	1.914(3)
Pt(1)-Cl(1)	2.3160(7)
Pt(1)-Cl(2)	2.3143(6)
Pt(1)-Pt(2)	3.49599(14)

	Bond Angles (^{o})
C(1)-Pt(1)-C(2)	94.25(11)
N(1)-C(1)-Pt(1)	177.6(2)
Cl(1)-Pt(1)-Cl(2)	89.14(2)
N(2)-C(2)-Pt(1)	172.3(2)

Table 3.30 Crystal data and structure refinement for complex **11b** (dichloromethane, *n*-hexane)

Empirical Formula	$C_{16.50}H_{15}Cl_3N_2O_2Pt$
Formula weight	574.74
Temperature	115(2) K
Wavelength	0.71073 Å
Crystal system	Triclinic
Space group	$P\bar{1}$
Unit cell dimensions	*a* = 8.9518 (1) Å alpha = 113.331(1) ^{o}
	b = 15.3609 (2) Å beta = 97.016 (1) ^{o}
	c = 15.4429 (3) Å gamma = 100.525(1) ^{o}
Volume, Z	1872.06 (5) Å^3 , 4
Density (calculated)	2.039 Mg/m^3
Reflections collected	52148
Independent reflections	10028 (R_{int} = 0.0330)
Final R indices [I>2σ (I)]	R1 = 0.0186, wR2 = 0.0374
R indices (all data)	R1 = 0.0271, wR2 = 0.0398

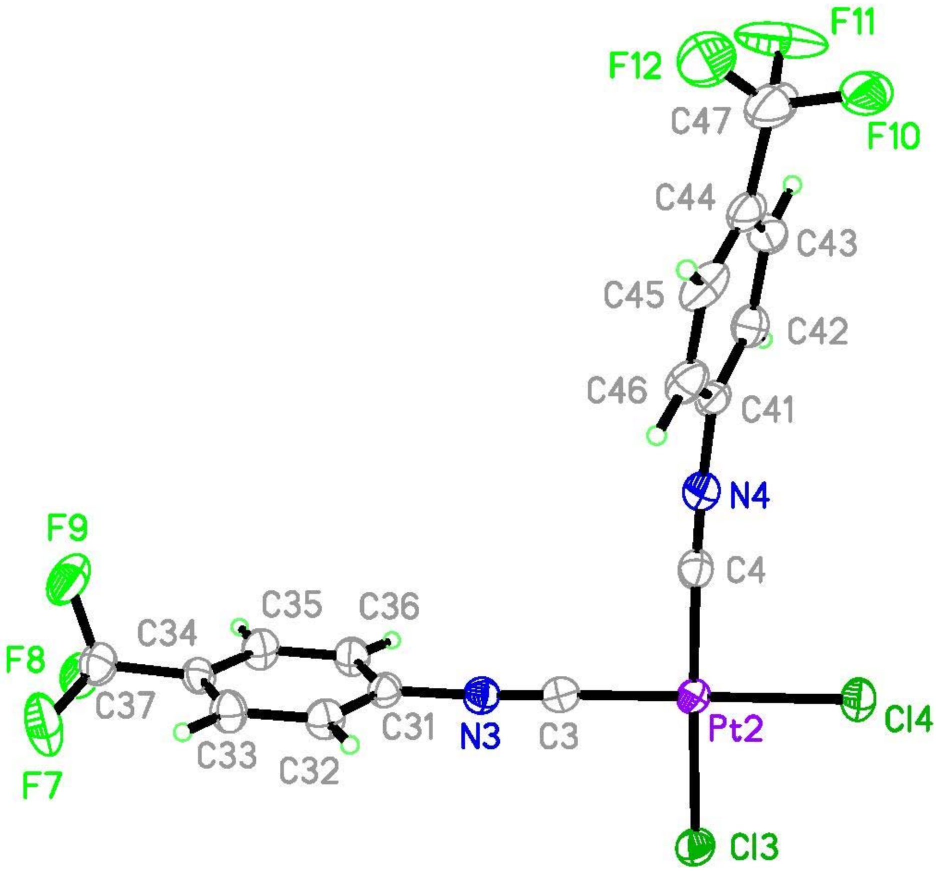


Figure 3.17. Molecular structure of complex **12** with 50 % probability ellipsoids.

X-ray quality crystals of complex **12** were grown by the slow diffusion of cyclohexane into a concentrated solution of complex **12** in chlorobenzene. Only single, translucent, block-like crystals were observed. A single unit of complex **12** is shown in Figure 3.17. This complex existed as isolated dimers with a Pt···Pt distance of 3.5359 Å as shown in Figure 3.18.

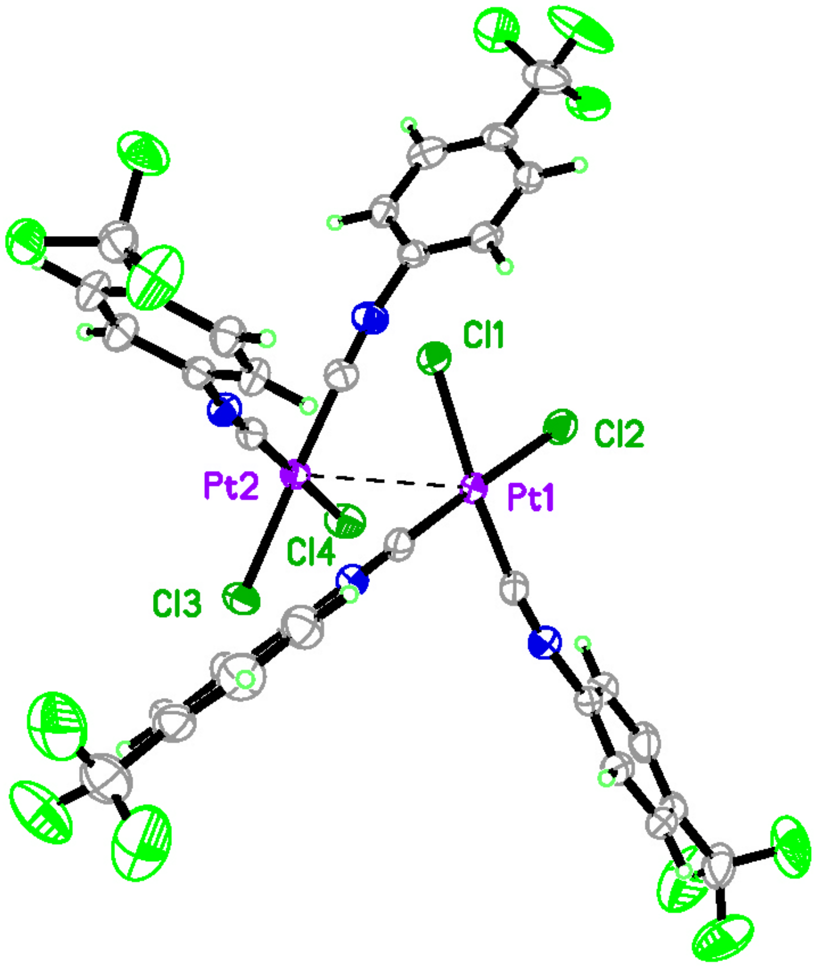


Figure 3.18. Dimer of complex **12** displaying Pt1···Pt2 distance of 3.5359(2) Å.

Table 3.31. Selected bond lengths (Å) and bond angles (^{o}) for complex **12**.

	Bond Lengths (Å)
C(1)-N(1)	1.144(4)
C(2)-N(2)	1.145(5)
Pt(1)-C(2)	1.905(4)
Pt(1)-C(1)	1.917(4)
Pt(1)-Cl(1)	2.3110(8)
Pt(1)-Cl(2)	2.3142(9)
Pt(1)-Pt(2)	3.5359(2)
	Bond Angles (^{o})
C(2)-Pt(1)-C(1)	92.57(15)
N(1)-C(1)-Pt(1)	178.0(3)
Cl(1)-Pt(1)-Cl(2)	89.94(3)
N(2)-C(2)-Pt(1)	173.1(3)

Table 3.32. Crystal data and structure refinement details for complex **12**.

Empirical Formula	$C_{16}H_8Cl_2F_6N_2Pt$	
Formula weight	608.23	
Temperature	115(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	$P2_1/c$	
Unit cell dimensions	a = 14.2940 (9) Å	alpha = 90 ^{o}
	b = 17.9417 (11) Å	beta = 93.597 (4) ^{o}
	c = 14.7000 (9) Å	gamma = 90 ^{o}
Volume, Z	3762.5(4) Å^3 , 8	
Density (calculated)	2.147 Mg/m^3	
Reflections collected	43604	
Independent reflections	9320 (R_{int} = 0.0323)	
Final R indices [I>2σ (I)]	R1 = 0.0218, wR2 = 0.0496	
R indices (all data)	R1 = 0.0288, wR2 = 0.0527	

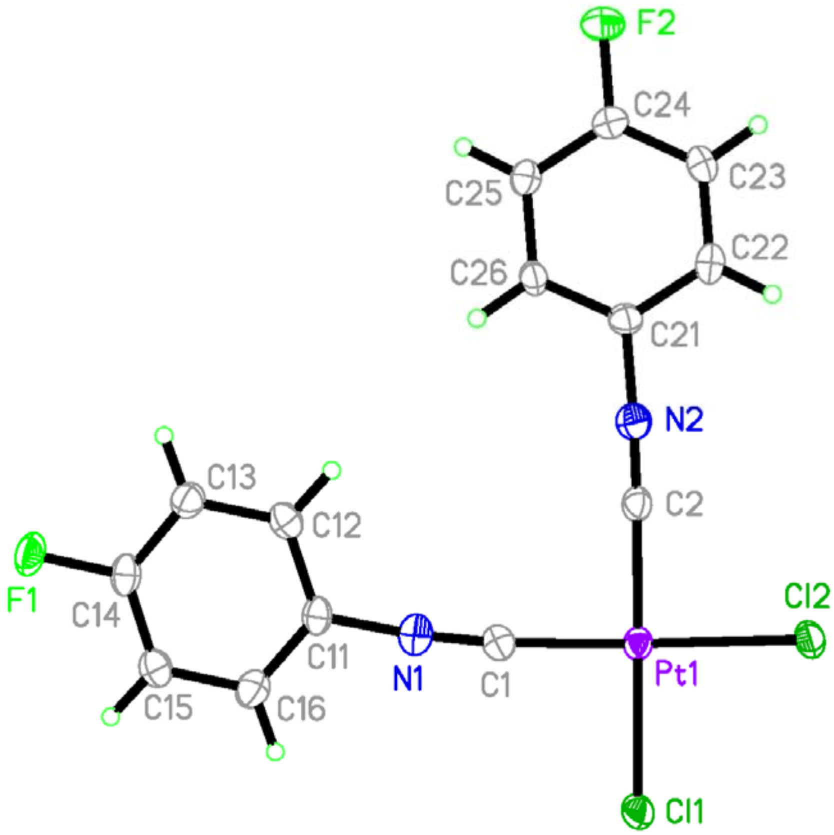


Figure 3.19. Molecular structure of complex **13** with 50 % probability ellipsoids.

X-ray quality crystals of complex **13** were grown by the slow diffusion of *n*-hexane into a concentrated solution of complex **13** in dichloromethane. A single unit of complex **13** is shown in Figure 3.19. The crystal structure displayed dimer of dimers, with a Pt···Pt distance of [Pt(1)-Pt(2) and Pt(1A)-Pt(2A)= 3.3747Å] for each dimer, while a longer Pt···Pt distance of 3.7858(4) Å connecting the two dimers as shown in Figure 3.20.

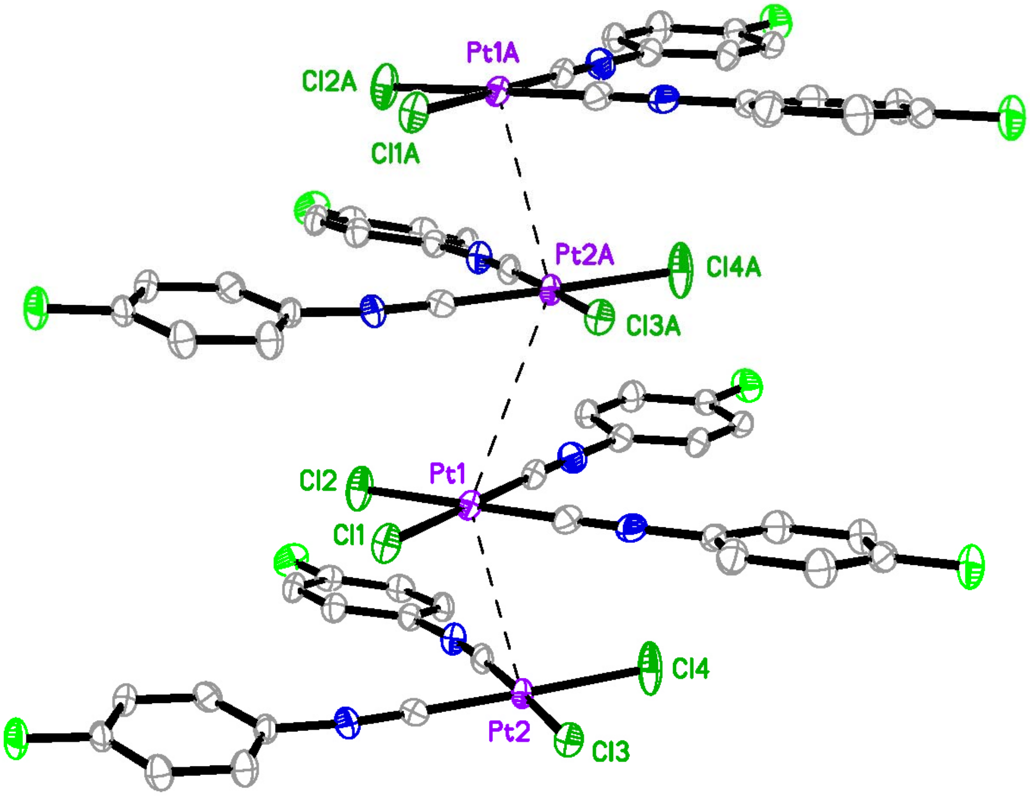


Figure 3.20. Stacks of dimers of complex **13** where [Pt(1)-Pt(2) and Pt(1A)-Pt(2A)= 3.3747 Å] for each dimer, while a longer Pt···Pt distance of 3.7858(4) Å connecting the two dimers.

Table 3.33. Selected bond lengths (Å) and bond angles (^{o}) for complex **13**.

	Bond Lengths(Å)
C(1)-N(1)	1.150(8)
C(2)-N(2)	1.137(8)
Pt(1)-C(2)	1.913(6)
Pt(1)-C(1)	1.911(6)
Pt(1)-Cl(1)	2.3111(16)
Pt(1)-Cl(2)	2.3284(15)
	Bond Angles (^{o})
C(2)-Pt(1)-C(1)	89.7(3)
N(1)-C(1)-Pt(1)	174.5(6)
Cl(1)-Pt(1)-Cl(2)	91.91(6)
N(2)-C(2)-Pt(1)	178.2(6)

Table 3.34. Crystal data and structure refinement details for complex **13.**

Empirical Formula	$C_{14}H_8Cl_2F_2N_2Pt$	
Formula weight	508.21	
Temperature	115(2) K	
Wavelength	0.71073 Å	
Crystal system	Monoclinic	
Space group	$P2_1/c$	
Unit cell dimensions	a = 6.7933 (2) Å	alpha = 90 °
	b = 18.2047 (5) Å	beta = 90.084 (4) °
	c = 24.2898 (6) Å	gamma = 90 °
Volume, Z	3003.92(14) Å^3, 8	
Density (calculated)	2.247 Mg/m^3	
Reflections collected	63428	
Independent reflections	7427 (R_{int} = 0.0563)	
Final R indices [I>2σ (I)]	R1 = 0.0278, wR2 = 0.0722	
R indices (all data)	R1 = 0.0291, wR2 = 0.0727	

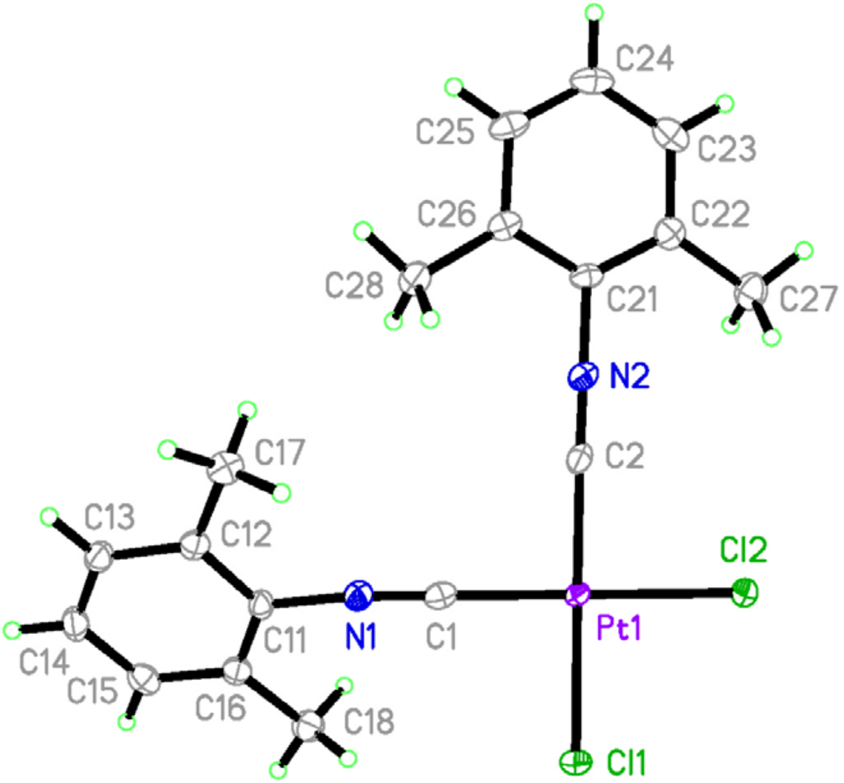


Figure 3.21. Molecular structure of complex **14** with 50% probability ellipsoids.

X-ray quality crystals of complex **14** were grown by the slow diffusion of *n*-hexane into a concentrated solution of complex **14** in chloroform. These crystals grew as colorless blocks and showed no Pt···Pt interactions. A single unit of complex **14** is shown in Figure 3.21. Crystal growth was done by Ilya Sluch.

Table 3.35. Selected bond lengths (Å) and bond angles (°) for complex **14**.

	Bond Lengths (Å)
C(1)-N(1)	1.148(3)
C(2)-N(2)	1.153(3)
Pt(1)-C(2)	1.905(2)
Pt(1)-C(1)	1.912(2)
Pt(1)-Cl(1)	2.3193(5)
Pt(1)-Cl(2)	2.3179(5)
	Bond Angles (°)
C(2)-Pt(1)-C(1)	91.79(8)
N(1)-C(1)-Pt(1)	179.31(19)
Cl(1)-Pt(1)-Cl(2)	91.446(18)
N(2)-C(2)-Pt(1)	179.31(19)

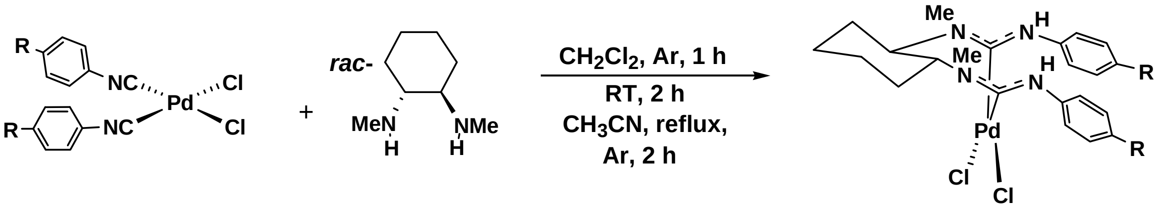
Table 3.36. Crystal data and structure refinement details for complex **14.**

Empirical Formula	$C_{18}H_{18}Cl_2N_2Pt$
Formula weight	528.33
Temperature	115(2) K
Wavelength	0.71073 Å
Crystal system	Triclinic
Space group	$P\bar{1}$
Unit cell dimensions	*a* = 8.0404 (2) Å alpha = 85.111(1)°
	b = 10.4016 (3) Å beta = 80.174 (1) °
	c = 10.8137 (3) Å gamma = 87.225(1) °
Volume, Z	887.35(4) $Å^3$, 2
Density (calculated)	1.977 Mg/m^3
Reflections collected	19552
Independent reflections	4379 (R_{int} = 0.0274)
Final R indices [I>2σ (I)]	R1 = 0.0139, wR2 = 0.0336
R indices (all data)	R1 = 0.0147, wR2 = 0.0339

Having synthesized the precursor palladium(II) bis(aryl isocyanide) dichloride complexes **4**-**8** and their platinum analogues, the next objective was to synthesize the palladium biscarbenes by reaction with a chiral diamine.

Chiral bis(carbene) palladium dichloride complexes:

The chiral bis(ADC) palladium complexes were synthesized by treating one equivalent of precursors **4**-**7** in dry dichloromethane with one equivalent of (*rac*)-*N*, *N*'-dimethyl-1,2-diaminocyclohexane in 4 mL of dry dichloromethane.[18] The amine was added to the precursor via a syringe pump under argon at the rate of 4 mL/ hour. The reaction mixture was stirred for an additional two hours at room temperature. Then, the solvent was stripped under vacuum, and the residue was dried for approximately thirty minutes. The yellow residue was then treated with dry acetonitrile and refluxed for two hours under argon, after which time a white precipitate began to form. The white solid was filtered and washed with dry acetonitrile and dry ether, followed by drying overnight under vacuum (Scheme 3.3).



4-7

15-18

15 (R = H)
16 (R = CH_3)
17 (R = OCH_3)
18 (R = F)

Scheme 3.3. General synthesis of chiral bis(carbene) palladium complexes **15-18** from reaction between bis(aryl isocyanide) palladium dichloride precursors **4-7** and the chiral diamine.

The chiral bis(carbene) palladium complexes **15-18** were white solids with synthetic yields ranging from 58-74 %. Table 3.37 shows the yields of the chiral bis(carbene) palladium complexes obtained from this reaction.

Table 3.37. Percentage yields of chiral bis(carbene)palladium dichloride complexes.

R	**Compound**	**Yield (%)**
H	**15**	63
CH_3	**16**	65
OCH_3	**17**	58
F	**18**	74

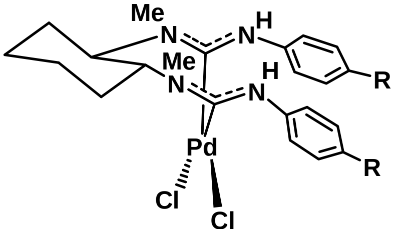
All of the chiral bis(carbene) palladium complexes **15-18** were stable in the presence of air and could be stored at room temperature. These complexes were only soluble in dimethyl sulfoxide and methanol. Complex **8** did not give any bis(carbene) product on syringe addition of the diamine. This may be due to the bulky methyl groups located *ortho* to the isocyanide group which could hinder the attack of the amine. The effect of ortho substitution could decrease the rate of the reaction, sufficiently to give no reaction.[24] Among the platinum(II) bis(aryl isocyanide) complexes **9-14**, complexes **10** and **12** formed the bis(carbene) complex. However, there were significant impurities in the NMR spectrum as well as problems in isolating the two complexes.

Spectroscopic studies

Table 3.38 shows the ^{1}H NMR data of chiral bis(carbene) palladium dichloride complexes. The ^{1}H NMR in wet DMSO-d_6 showed two different NH peaks that range between 8.66-9.35 ppm for complexes **15-18**. There were also two different NCH_3 peaks that range between 8.66-9.35 ppm for complexes **15-18,** indicating C_1 symmetry in the structure. The aryl protons appeared as doublets in the range of 6.64-8.00 ppm for complexes **15-18,** with the exception of complex **18** that exhibited multiplets. The cyclohexane methylene groups appeared as doublets or multiplets in the range of 1.41-2.25 ppm.

Table 3.39 shows ^{13}C NMR data of complexes **15-18** in wet DMSO-d_6. Complexes **15-18** displayed carbene carbon signals in the range from 183-190 ppm. Complexes **15-18** displayed aromatic carbon signals in the range from 112.4-159.7 ppm. Complex **18** displayed typical C-F couplings for the aromatic carbons, which appeared as doublets. Complex **18** displayed aryl *para*, *meta* and *ortho* signals at 159 ppm, 114 ppm and 126 ppm with coupling constants $^1J_{C\text{-}F}$ = 241 Hz, $^2J_{C\text{-}F}$ = 22 Hz and $^3J_{C\text{-}F}$= 8.2 Hz respectively.[20] The ^{1}H NMR data of the crude platinum bis(carbene) dichloride derived from complex **12** gave a similar pattern as the palladium bis(carbene) dichloride complexes, with doublets for the aryl protons in the range from 7.09-8.26 ppm. Two NH signals were observed between 9.06-9.68 ppm. The two NCH_3 signals were observed at 3.13 and 3.15 ppm, while the cyclohexane methylene groups appeared as doublets and multiplets in the range of 1.45-2.26 ppm. Complex **12** could not be isolated from the reaction mixture. According to the crude ^1H NMR spectrum of complex **12**, the desired platinum bis(carbene) dichloride complex was formed in 77% yield. The ^1H NMR spectrum of complex **10** was messy making integration difficult.

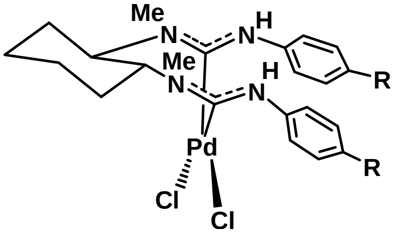
Table 3.38. ^{1}H NMR spectral data of chiral bis(carbene) palladium dichloride complexes.



15 (R = H)
16 (R = CH$_3$)
17 (R = OCH$_3$)
18 (R = F)

Complex	NH	Aryl protons	^{c}Hex ipsoCH	NCH$_3$	^{c}Hexyl –CH$_2$ /R
15 (R = H)	9.35, 8.77	8.00 (d, 2H, *J* = 6.4 Hz), 7.31 (d, 2H, *J* = 7.9 Hz), 7.24 (d, 2H, *J* = 7.9 Hz), 6.94-6.93 (m, 2H**)**	7.48-7.42 (m, 1H), 3.61-3.56 (m,1H)	3.13 (s, 3H), 3.04 (s, 3H)	2.25-2.23 (m, 1H), 2.12-2.10 (m, 1H), 1.92-1.84 (m, 4H), 1.51-1.41 (m, 2H)
16 (R = CH$_3$)	9.29, 8.70	7.83 (d, 2H, *J* = 7.9 Hz), 7.19 (d, 2H, *J* = 7.9 Hz), 6.97 (d, 2H, *J* = 7.6 Hz), 6.64 (d, 2H, *J* = 7.9Hz)	7.46-7.41 (m, 1H), 3.59-3.54 (m, 1H)	3.10 (s, 3H), 3.01 (s, 3H)	2.09-2.06 (m, 1H), 1.91-1.84 (m, 4H), 1.50-1.42 (m, 2H); 2.33 (s, 3H, CH$_3$), 2.21 (s, 3H, CH$_3$)
17 (R = OCH$_3$)	9.23, 8.66	7.85 (d, 2H, *J* = 8.7 Hz), 7.17 (d, 2H, *J* = 9.3 Hz), 6.74 (d, 2H, *J* = 8.7 Hz), 6.64 (d, 2H, *J* = 7.9 Hz)	7.44-7.38 (m, 1H), 3.55-3.48 (m, 1H)	3.08 (s, 3H), 2.98 (s, 3H)	2.23-2.19 (m, 1H), 2.10-2.06 (m, 1H), 1.90-1.83 (m, 4H); 1.50-1.43 (m, 2H), 3.77 (s, 3H, OCH$_3$), 3.68 (s, 3H, OCH$_3$)
18 (R = F)	9.35, 8.79	7.97-7.93 (m, 2H), overlapping ^{c}Hex CH, 7.45-7.39 (m, 3H), 6.98-6.94 (m, 2H), 6.72-6.67 (m, 2H).	3.58-3.52 (m, 1H)	3.11 (s, 3H), 3.05 (s, 3H)	2.24-2.21 (m, 1H), 2.11-2.08 (m, 1H), 1.91-1.84 (m, 4H), 1.51-1.41 (m, 2H).

Table 3.39. ^{13}C NMR spectral data of chiral bis(carbene) palladium dichloride complexes.



15 (R = H)
16 (R = CH_3)
17 (R = OCH_3)
18 (R = F)

Complex	Carbene	Aryl carbons	NCH_3	^{c}Hex/R
15 (R = H)	183.7, 190.0	140.7 (Ar para), 139.8 (Ar para), 128.3 (Ar meta), 127.5 (Ar meta), 125.2 (Ar meta), 124.3 (Ar meta), 123.6 (Ar ortho)	67.6, 66.3	31.6, 30.9, 29.9, 25.3, 24.6
16 (R = CH_3)	183.6, 189.7	138.3 (Ar para), 137.5 (Ar para), 134.0 (Ar ipso), 133.2 (Ar ipso), 128.7 (Ar meta), 127.9 (Ar meta), 123.8 (Ar ortho), 123.4 (Ar ortho)	67.6, 66.3	40.1, 31.6, 30.9, 30.0, 25.3, 24.6, 20.5 (CH_3).
17 (R = OCH_3)	183.7, 189.8	156.7 (Ar para), 156.1(Ar para), 133.9 (Ar ipso), 133.1 (Ar ipso), 125.5 (Ar ortho), 125.0 (Ar ortho), 113.3 (Ar meta), 112.4 (Ar meta)	67.6, 66.1	54.9 (OCH_3), 54.7 (OCH_3), 40.1, 31.6, 30.7, 30.0, 25.4, 24.7.
18 (R = F)	184.4, 189.8	159.7 (d, Ar para,$^{1}J_{CF}$ = 241.1 Hz), 159.3 (d, Ar para, $^{1}J_{CF}$ = 241.1 Hz), 137.2 (Ar ipso), 136.4 (Ar ipso), 126.0 (d, Ar ortho, $^{3}J_{CF}$ = 8.2 Hz), 125.3 (d, Ar ortho, $^{3}J_{CF}$ = 8.7 Hz), 114.8(d, Ar meta, $^{2}J_{CF}$ = 22.4 Hz), 113.9(d, Ar meta, $^{2}J_{CF}$ = 22.4 Hz),	67.6, 66.3	31.4, 30.9, 29.9, 25.3, 24.6.

X-ray quality crystals were grown for complex **16** ($R=CH_3$) by the slow evaporation of a concentrated solution of complex **16** in wet methanol. The X-ray structure indicates that complex **16** has C_1 symmetry (Figure 3.22). Complex **16** deviated from the C_2 symmetry of the chiral diamine precursor forming a rigid chelate ring. The Pd-$C_{carbene}$ bond distances for Pd(1)-C(2) and Pd(1)-C(1) were found to be 2.381(17)Å and 2.417(17) Å which were in agreement with expected values for palladium bis(acyclic diaminocarbene) complexes.[18] The N-C-N bond angles of N(1)-C(1)-N(3) and N(2)-C(2)-N(4) were found to be 116.5(6)^o and 115.5(6)^o consistent with the N-C-N bond angles in known ADC complexes of Rh synthesized by Hermann.[25]

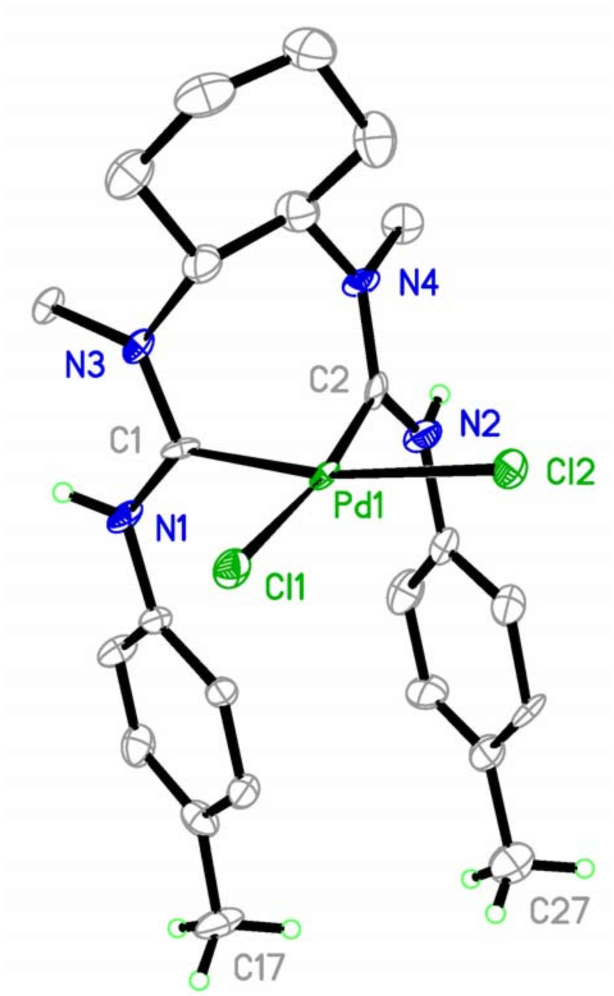


Figure 3.22. Molecular structure of complex **16** with 50 % probability ellipsoids.

Table 3.40. Selected bond lengths (Å) and bond angles (^{o}) of complex **16**.

	Bond Lengths (Å)
C(1)-N(1)	1.342(8)
C(2)-N(2)	1.345(9)
C(1)-N(3)	1.340(8)
C(2)-N(4)	1.346(9)
Pd(1)-Cl(1)	2.417(17)
Pd(1)-Cl(2)	2.381(17)

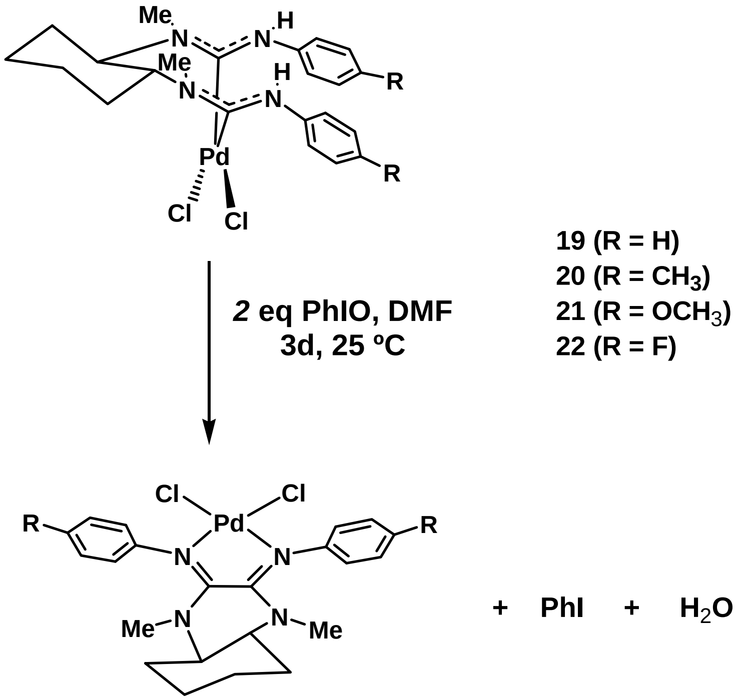
	Bond Angles (^{o})
C(2)-Pd(1)-C(1)	81.7(3)
N(3)-C(1)-N(1)	116.5(6)
N(2)-C(2)-N(4)	115.5(6)
Cl(2)-Pd(1)-Cl(1)	91.97(6)
C(2)-Pd(1)-Cl(1)	171.8(2)
C(1)-Pd(1)-Cl(1)	169.16(19)

Table 3.41. Crystal data and structure refinement details for complex **16**.

Empirical Formula	$C_{27}H_{44}Cl_2N_4O_3Pd$
Formula weight	649.96
Crystal system	Triclinic
Temperature	115(2) K
Wavelength	0.71073 Å
Space group	$P\bar{1}$
Unit cell dimensions	a = 7.9947(8) Å alpha = 100.398(8) ^{o}
	b = 14.0154(15) Å beta = 92.567(7) ^{o}
	c = 14.2150(15) Å gamma = 105.132(7) ^{o}
Volume, Z	1505.2(3) $Å^3$, 2
Density (calculated)	1.434 Mg/m^3
Reflections collected	12800
Independent reflections	5274 (R_{int} = 0.0881)
Final R indices [I>2σ(I)]	R1 = 0.0625, wR2 = 0.1334
R indices (all data)	R1 = 0.1095, wR2 = 0.1517

Stability of ADC complexes and syntheses of palladium bis(amidine) dichloride complexes 19-22

One of the major disadvantages of some palladium bis(ADC) complexes is their tendency for decomposition to the corresponding palladium bis(amidines). This was first observed by Wanniarachchi and co-workers on leaving the palladium bis(ADC) derived complex (R=CF_3) under air in dry DMSO for 30 days, during which time the compound slowly oxidized to the bis(amidine).[18] Similar observations were made on leaving analogous ADC complexes **15-18** in air in approximately 1 mL of dry DMSO, mixtures of red and translucent crystals were obtained. Long red fine fibers were obtained for complexes **19** (R = H); mixture of short red fibers and colorless block shaped crystals for complex **20** (R = CH_3), transluscent blocks for complex **21** (R = OCH_3) and colorless block shaped crystals were obtained for complex **22** (R = F). Unfortunately, these crystals were not suitable for X-ray analysis. The palladium bis(amidine) complexes were quantitatively prepared by treatment with iodosobenzene, which is an oxidizing agent. The reaction proceeded with formal loss of two NH atoms to form the bis(amidine) complexes (Scheme 3.3). Table 3.42 shows the percent yields of the palladium bis(amidine) dichloride complexes. High insolubility of complexes **19-22** made it impossible to get any spectroscopic data. All complexes **19**-**22** were formed as powders. However, these complexes have been characterized by elemental analyses. The elemental analyses of complexes **20**-**22** were within expected range, but the analysis for complex **19** was not within acceptable range.



Scheme 3.4. Formation of chiral bis(amidine) palladium dichloride complexes **19-22**.

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Table 3.42. Percent yields of palladium bis(amidine) dichloride complexes **19-22.**

R	Compound	Time to form the crystals	Color and type of crystals	Yield (%)
H	**19**	3 days	red short needles	49
CH_3	**20**	7 days	red needles and transluscent blocks	54
OCH_3	**21**	9 days	transluscent blocks	52
F	**22**	7 days	transluscent needles and blocks	50

Summary and Conclusions

A series of palladium bis(aryl isocyanide) dichloride and platinum(II) bis(arylisocyanide) dichloride complexes were synthesized in good yields by altering the substituents on the aryl ring with a range of electron-donating and electron-withdrawing groups. These complexes were highly air stable and could be readily used as precursors to synthesize the palladium bis(carbene) complexes. The palladium bis(carbene) complexes were synthesized by a general method which involved slow addition of the chiral amine to a solution of the precursor palladium bis(arylisocyanide) complexes. These palladium bis(carbene) complexes were found to be air stable as solids. A significant drawback, however lies in the solution instability of these palladium bis(carbene) complexes. They slowly oxidized to the corresponding palladium bis(amidine) dichloride complexes in the presence of oxygen in DMSO solutions and could be more rapidly oxidized by iodosobenzene. Of all the platinum bis(aryl isocyanide) complexes, only complex **12** formed a bis(carbene) complex with impurities but could not be isolated in pure form. Polymorph **4a** showed an interesting Pd···Pd interaction with a Pd···Pd distance of 3.24 Å and vacant channels. Polymorph **9a** showed Pt···Pt interactions with a Pt···Pt distance of 3.25 Å which led to Pt···Pt metallophilic interaction and orange luminescence under UV light.

Experimental

General considerations. All syntheses were performed under air unless otherwise noted. Phenyl isocyanide, *para*-tolyl isocyanide, *para*-methoxyphenyl isocyanide, *para*-fluorophenyl isocyanide and *para*-trifluoromethylphenyl isocyanide were synthesized by the Hoffmann carbylamine reaction.[26] Pd(COD)Cl_2[27] and Pt(COD)Cl_2[28] (COD=1,5-cyclooctadiene) and iodosobenzene[29] were synthesized using literature procedures. **Caution:** Isocyanides are vile smelling liquids that must be used in well ventilated fume hoods. Solvents for synthesis were purified as follows. Dichloromethane (Pharmco) was purified by washing with concentrated sulphuric acid and sodium bicarbonate, predried over anhydrous $CaCl_2$ and then refluxed overnight with P_2O_5. Hexanes, cyclohexane and diethyl ether were dried by refluxing over sodium-benzophenone ketyl and distilled prior to use. Chlorobenzene and o-dichlorobenzene were used as received. NMR solvents were purified as follows. CD_2Cl_2 (Cambridge Isotope laboratories, Inc, 99.9%) was dried over degassed 4Å molecular sieves and stored over P_2O_5, while CD_3CN (Cambridge Isotope laboratories, Inc, 99.8%) was used as received. DMSO-d_6 was dried by stirring over activated 4Å molecular sieves followed by distillation under vacuum and storage in an air free glove box.

^{1}H NMR spectra were recorded on Varian 300 MHz, 400 MHz and 600 MHz spectrometers, with chemical shifts in ppm, multiplicity reported as (s = singlet, d = doublet, t = triplet, m = multiplet) and coupling constants recorded in Hz. ^{13}C NMR spectra were recorded on Varian 400 MHz and 600 MHz spectrometers, with chemical shifts in ppm. Elemental analyses were performed by Desert Analytics Laboratory, Tucson, AZ, USA and Midwest Microlabs, Indianapolis, IN, USA. Infrared (IR) spectra were recorded as Nujol mulls on a Nicolet Protégé 460 FT–IR spectrometer. Data collection for determining X-ray crystal structures of complexes **4-14** and **16** was done on a Bruker Apex II diffractometer using MoKα (λ = 0.71073 Å) radiation. The X-ray crystal structures were solved using the SHELXTL system and were refined by full matrix least squares on F^2 using all reflections.[30,31]

Synthesis of (R=H) **[Pd($C_{14}H_{10}N_2$)Cl_2] (4).** Phenyl isocyanide (158 μL, 1.50 mmol) was added to a stirred solution of (COD)$PdCl_2$ (0.204 g, 0.714 mmol) in 10 mL of dry dichloromethane. The resulting green solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes resulted in the formation of a yellow precipitate, which was collected by filtration, washed with hexanes and anhydrous diethyl ether and dried in vacuo overnight (0.212 g, 77 %). Anal. Calcd for $C_{14}H_{10}N_2Cl_2Pd$: C, 43.82, H, 2.63, N, 7.34. Found: C, 44.07, H, 2.77, N, 7.26 %.

Synthesis of (R=CH_3) **[Pd($C_{16}H_{14}N_2$)Cl_2] (5).** *para*-tolyl isocyanide (0.052 g, 0.42 mmol) was added to a stirred solution of (COD)$PdCl_2$ (0.058 g, 0.20 mmol) in 10 mL of dry dichloromethane. The resulting green solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes resulted in the formation of a yellow precipitate, which was collected by filtration, washed with hexanes and anhydrous diethyl ether and dried in vacuo overnight (0.062 g, 75 %). Anal. Calcd for $C_{16}H_{14}N_2Cl_2Pd$: C, 46.67; H, 3.42; N, 6.86. Found: C, 46.70; H, 3.65, N, 6.68 %.

Synthesis of (R=OCH_3) **[Pd($C_{16}H_{14}N_2O_2$)Cl_2] (6).** *para*-methoxyphenyl isocyanide(0.091 g, 0.68 mmol) was added to a stirred solution of (COD)$PdCl_2$ (0.093 g, 0.32 mmol) in 10 mL of dry dichloromethane. The resulting yellow solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes and anhydrous diethyl ether resulted in the formation of a yellow crystalline precipitate which was collected by filtration, washed with dry hexanes and dry diethyl ether and dried in vacuo overnight (0.088 g, 61 %). Anal. Calcd for $C_{16}H_{14}N_2O_2Cl_2Pd$: C, 43.30, H, 3.18, N, 6.31. Found: C, 43.01, H, 3.30, N, 6.07 %.

Synthesis of (R=F) **[Pd($C_{14}H_8N_2F_2$)Cl_2] (7).** *para*-fluorophenyl isocyanide(0.166 g, 1.37 mmol) was added to a stirred solution of (COD)$PdCl_2$ (0.186 g, 0.654 mmol) in 10 mL of dry dichloromethane. The resulting yellow solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes and dry diethyl ether resulted in the formation of a crystalline yellow precipitate which was collected by filtration, washed with dry hexanes and dry diethyl ether and dried overnight in vacuo (0.216 g, 79 %). Anal. Calcd for $C_{14}H_8N_2F_2Cl_2Pd$: C, 40.06, H, 1.92, N, 6.67. Found: C, 40.26, H, 2.14, N, 6.60 %.

Synthesis of (xylyl) **[Pd($C_{18}H_{18}N_2$)Cl_2] (8).** 2,6-Dimethylphenyl isocyanide (0.117 g, 0.892 mmol) was added to a stirred solution of (COD)$PdCl_2$ (0.127 g, 0.444 mmol) in 10 mL of dry dichloromethane. The resulting green solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes resulted in the formation of a yellow precipitate, which was collected by filtration, washed with hexanes and anhydrous diethyl ether and dried in vacuo overnight (0.116 g, 80 %). Anal. Calcd for $C_{18}H_{18}N_2Cl_2Pd$: C, 49.1, H, 4.13, N, 6.37. Found: C, 48.72, H, 4.14, N, 6.52 %.

Synthesis of (R=H) **[Pt($C_{14}H_{10}N_2$)Cl_2] (9).** Phenyl isocyanide (84.2 µL, 0.800 mmol) was added to a stirred solution of (COD)$PtCl_2$ (0.150 g, 0.400 mmol) in 10 mL of dry dichloromethane. The resulting green solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes resulted in the formation of a yellow precipitate, which was collected by filtration, washed with hexanes and anhydrous diethyl ether and dried in vacuo overnight (0.146 g, 77 %). Anal. Calcd for $C_{14}H_{10}N_2Cl_2Pt$: C, 35.60, H, 2.14, N, 5.93. Found: C, 35.72, H, 2.25, N, 5.90 %.

Synthesis of (R=CH_3) **[Pt($C_{16}H_{14}N_2$)Cl_2] (10)** *para*-Tolyl isocyanide (0.086 g, 0.764 mmol) was added to a stirred solution of (COD)$PtCl_2$ (0.137 g, 0.364 mmol) in 10 mL of dry dichloromethane. The resulting green solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes resulted in the formation of a yellow precipitate, which was collected by filtration, washed with hexanes and anhydrous diethyl ether and dried in vacuo overnight (0.152 g, 83 %). Anal. Calcd for $C_{16}H_{14}N_2Cl_2Pt$: C, 38.41; H, 2.82; N, 5.60. Found: C, 39.14; H, 3.05; N, 5.54 %.

Synthesis of (R=OCH_3) **[Pt($C_{16}H_{14}N_2O_2$)Cl_2] (11).** *para*-Methoxyphenyl isocyanide (0.0438 g, 0.327 mmol) was added to a stirred solution of (COD)$PtCl_2$ (0.0587 g, 0.156 mmol) in 10 mL of dry dichloromethane. The resulting yellow solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes and anhydrous diethyl ether resulted in the formation of a yellow crystalline precipitate which was collected by filtration, washed with dry hexanes and dry diethyl ether and dried in vacuo overnight (0.066 g, 79 %). Anal. Calcd for $C_{16}H_{14}N_2O_2Cl_2Pt$: C, 36.1, H, 2.65, N, 5.26. Found: C, 35.60, H, 2.55, N, 5.09 %.

Synthesis of (R=CF$_3$) **[Pt($C_{16}H_8N_2F_6$)Cl$_2$] (12).** *Para*-Trifluoromethylphenyl isocyanide (0.096 g, 0.53 mmol) was added to a stirred solution of (COD)PtCl$_2$ (0.100 g, 0.267 mmol) in 10 mL of dry dichloromethane. The resulting green solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes and anhydrous diethyl ether resulted in the formation of a yellow crystalline precipitate which was collected by filtration, washed with dry hexanes and dry diethyl ether and dried in vacuo overnight (0.1442 g, 89 %). Anal. Calcd for $C_{16}H_8N_2F_6Cl_2Pt$: C, 31.59; H, 1.33; N; 4.61. Found: C, 31.63; H, 1.47; N, 4.61 %.

Synthesis of (R=F) **[Pt($C_{14}H_{18}N_2F_2$)Cl$_2$] (13).** *para*-Fluorophenyl isocyanide (0.102 g, 0.847 mmol) was added to a stirred solution of (COD)PtCl$_2$ (0.151 g, 0.403 mmol) in 10 mL of dry dichloromethane. The resulting yellow solution was allowed to stir for 10 minutes at room temperature. Dropwise addition of dry hexanes and dry diethyl ether resulted in the formation of a crystalline yellow precipitate which was collected by filtration, washed with dry hexanes and dry diethyl ether and dried overnight in vacuo (0.148 g, 72 %). Anal. Calcd for $C_{14}H_{18}N_2F_2Cl_2Pt$: C, 33.1, H, 1.58, N, 5.51. Found: C, 33.06, H, 1.65, N, 5.51 %.

Synthesis of (xylyl) **[Pt($C_{18}H_{18}N_2$)Cl_2]** (**14**). 2,6-Dimethylphenyl isocyanide (0.085 g, 0.651 mmol) was added to a stirred solution of (COD)$PtCl_2$ (0.121 g, 0.325 mmol) in 10 mL of dry dichloromethane. The resulting green solution was allowed to stir for 10 minutes at room temperature. Drop wise addition of dry hexanes resulted in formation of a yellow precipitate, which was collected by filtration, washed with hexanes and anhydrous diethyl ether and dried in vacuo overnight (0.146 g, 85 %). Anal. Calcd for $C_{18}H_{18}N_2Cl_2Pt$: C, 40.91, H, 3.43, N, 5.32. Found: C, 40.43, H, 3.40, N, 5.37 %.

Synthesis of (R=H) **[Pd($C_{22}H_{28}N_4$)Cl_2] (15):** To a stirred solution of complex **4** (0.120 g, 0.313 mmol) in dry dichloromethane, *rac*-*N*,*N*-dimethylcyclohexane diamine (50 μL, 0.31 mmol) was added via a syringe pump at the rate of 4 mL/ hour under the flow of argon. The solution was allowed to stir for an additional 2 h at room temperature, over which the pale yellow precipitate appeared. The solvent was removed using a rotary evaporator followed by drying under vacuum for about 30 min. The yellow residue was then dissolved in approximately 10 mL of dry acetonitrile and the resultant solution was refluxed for about 2 h under a flow of argon. A white precipitate formed which was then filtered, washed with dry acetonitrile and dry ether and subsequently dried overnight under vacuum (0.103 g, 63 %). Anal. Calcd for $C_{22}H_{28}N_4Cl_2Pd$: C, 50.23; H, 5.37; N; 10.65. Found: C, 50.14; H, 5.25; N, 10.33 %.

Synthesis of (R=CH_3) **[Pd($C_{24}H_{32}N_4$) Cl_2] (16):** To a stirred solution of complex **5** (0.037 g, 0.089 mmol) in dry dichloromethane, *rac-N*, *N*-dimethylcyclohexane diamine (14 μL, 0.089 mmol) was added via a syringe pump at the rate of 4 mL/ hour under a flow of argon. The solution was allowed to stir for an additional 2 h at room temperature, over which time a pale yellow precipitate appeared. The solvent was removed using a rotary evaporator followed by drying under vacuum for about 30 min. The yellow residue was then dissolved in approximately 10 mL of dry acetonitrile and the resultant solution was refluxed for about 2 h under a flow of argon. A white precipitate formed which was then filtered, washed with dry acetonitrile and dry ether and subsequently dried overnight under vacuum (0.033 g, 65 %). Anal. Calcd for $C_{24}H_{32}N_4Cl_2Pd$: C, 52.02; H, 5.83; N; 10.11. Found: C, 51.80; H, 5.67; N, 10.04 %.

Synthesis of (R=OCH_3) **[Pd($C_{24}H_{32}N_4O_2$)Cl_2] (17):** To a stirred solution of complex **6** (0.083 g, 0.19 mmol) in dry dichloromethane, *rac-N*, *N*-dimethylcyclohexane diamine (29 μL, 0.19 mmol) was added via a syringe pump at the rate of 4 mL/hour under the flow of argon. The solution was allowed to stir for an additional 2 h at room temperature at which a pale yellow precipitate appeared. The solvent was removed using a rotary evaporator followed by drying under vacuum for about 30 min. The yellow residue was then dissolved in approximately 10 mL of dry acetonitrile and the resultant solution was refluxed for about 2 h under the flow of argon. A white precipitate formed which was then filtered, washed with dry acetonitrile and dry ether and subsequently dried overnight in vacuo (0.063 g, 58 %). Anal. Calcd for $C_{24}H_{32}N_4O_2Cl_2Pd$: C, 49.19; H, 5.52; N; 9.56. Found: C, 48.60; H, 5.40; N, 9.32 %.

Synthesis of (R=F) **[Pd($C_{22}H_{26}N_4F_2$)Cl_2] (18):** To a stirred solution of complex **7** (0.069 g, 0.163 mmol) in dry dichloromethane, *rac-N*, *N*-dimethylcyclohexane diamine (26 μL, 0.163 mmol) was added via a syringe pump at the rate of 4 mL/hour under the flow of argon. The solution was allowed to stir for an additional 2 h at room temperature at which a pale yellow precipitate appeared. The solvent was removed using a rotary evaporator followed by drying under vacuum for about 30 min. The yellow residue was then dissolved in approximately 10 mL of dry acetonitrile and the resultant solution was refluxed for about 2 h under a flow of argon. A white precipitate formed which was then filtered, washed with dry acetonitrile and dry ether and subsequently dried overnight under vacuo (0.068 g, 74 %). Anal. Calcd for $C_{22}H_{26}N_4F_2Cl_2Pd$: C, 47.01; H, 4.67; N; 9.97. Found: C, 46.95; H, 4.50; N, 9.93 %.

Synthesis of palladium bis(amidine)complex (R=H) **[Pd($C_{22}H_{26}N_4$)Cl_2](19):** Bis(carbene) palladium dichloride complex **15** (0.0823 g, 0.16 mmol) and iodosobenzene (0.069 g, 0.312 mmol) were added to a sealable J Young NMR tube. Anhydrous DMF (1.2 ml) was added under nitrogen. The NMR tube was sealed and allowed to react at room temperature on a shaker under nitrogen for three days. The resultant orange solution was filtered under air, washed with dry dichloromethane and wet DMF and dried overnight under vacuo to give an orange powder (0.042 g, 49 %). The resultant complex formed was an orange powder. Anal. Calcd for $C_{22}H_{26}N_4Cl_2Pd$: C, 50.43; H, 5.00; N; 10.69. Found: C, 47.87; H, 5.41; N, 10.08 %.

Synthesis of palladium bis(amidine)complex (R=CH_3) **[Pd($C_{24}H_{30}N_4$)Cl_2](20):** Bis(carbene) palladium dichloride complex **16** (0.0794 g, 0.143 mmol) and iodosobenzene (0.0631 g, 0.28 mmol) were added to a sealable J Young NMR tube. Anhydrous DMF (1.2 mL) was added under nitrogen. The NMR tube was sealed and allowed to react at room temperature on a shaker under nitrogen for three days. The resultant orange solution was filtered under air, washed with dry dichloromethane and wet DMF and dried overnight under vacuo to give an orange powder (0.043 g, 54 %). Anal. Calcd for $C_{24}H_{30}N_4Cl_2Pd$: C, 52.23; H, 5.47; N; 10.15. Found: C, 51.90; H, 5.71; N, 9.84 %.

Synthesis of palladium bis(amidine)complex (R=OCH_3) **[Pd($C_{24}H_{30}N_4O_2$)Cl_2] (21):** Bis(carbene) palladium dichloride complex **17** (0.099 g, 0.17 mmol) and iodosobenzene(0.0743 g, 0.34 mmol) were added to a sealable J Young NMR tube. Anhydrous DMF (1.2 mL) was added under nitrogen. The NMR tube was sealed and allowed to react at room temperature on a shaker under nitrogen for three days. The resultant orange solution was filtered under air, washed with dry dichloromethane and wet DMF and dried overnight under vacuo to give a white powder (0.0521 g, 52 %). Anal. Calcd for $C_{24}H_{30}N_4O_2Cl_2Pd$: C, 49.37; H, 5.17; N; 9.59. Found: C, 49.07; H, 5.05; N, 9.50 %.

Synthesis of palladium bis(amidine)complex (R=F) **[Pd($C_{22}H_{24}N_4F_2$)Cl_2] (22):** Bis(carbene) palladium dichloride complex **18** (0.155 g, 0.26 mmol) and iodosobenzene (0.1212 g, 0.55 mmol) were added to a sealable J Young NMR tube. Anhydrous DMF (1.2 mL) was added under nitrogen. The NMR tube was sealed and allowed to react at room temperature on a shaker under nitrogen for three days. The resultant orange solution was filtered under air, washed with dry dichloromethane and wet DMF and dried overnight under vacuo (0.0771 g, 50 %). Anal. Calcd for $C_{22}H_{24}N_4F_2Cl_2Pd$: C, 47.19; H, 4.32; N; 10.00. Found: C, 46.88; H, 4.44; N, 9.93 %.

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CHAPTER IV

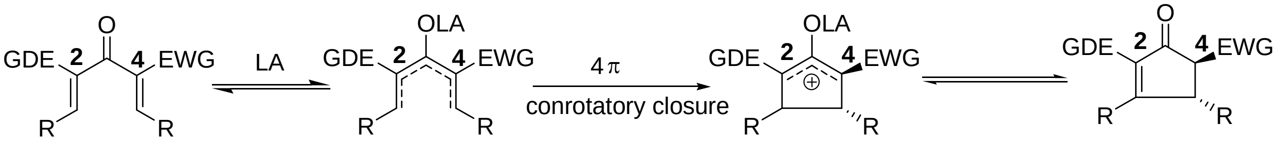
DICATIONIC DERIVATIVES OF CHIRAL PALLADIUM BIS(ACYCLIC DIAMINO CARBENE) COMPLEXES: EVALUATION OF DONOR ABILITIES IN METHYL ISOCYANIDE ADDUCTS AND CATALYTIC NAZAROV CYCLIZATION IN ACETONITRILE ADDUCTS.

Introduction

N-heterocyclic carbene ligands (NHCs) have been widely used in catalysis due to their higher binding energies compared to phosphines as well as the high air and thermal stability of NHC complexes.[1] NHC-containing catalysts have also been found to tolerate different functional groups and can often be used at ambient temperatures.[1] Nolan and co-workers studied NHC binding energies by calorimetry studies of NHC binding to the Cp*RuCl fragment. It was observed that NHC-Ru binding energies for some of the complexes were 10 kcal/mol greater than phosphine-Ru binding energies.[2] Another common method used to study sigma donation in metal complexes is infrared spectroscopy. A common IR probe for this purpose is a CO ligand.[3,4] CO ligands are known to be both strong sigma donors and strong π acceptors.[5] In a CO bound metal complex, the CO stretching frequency typically decreases relative to free CO, primarily due to π backbonding which reflects the donor ability of the ligand trans to it. This phenomenon is defined as trans influence, which is the ability of a ligand to weaken the bond trans to itself.[6] Instead of using CO as a probe ligand in our studies, methyl isocyanide was used in order to prevent any contribution from π back bonding.

Methyl isocyanide is known to be a strong sigma donor with much weaker π back bonding than CO.[7] Electrophilic catalytic reactions are promoted by electrophilicity at the metal center. The Nazarov cyclization is one example of an electropilic reaction catalyzed by Lewis acidic metal centers such as Pd(II) species, $Cu(OTf)_2$ and $AlCl_3$.[8] The Nazarov cyclization converts divinyl ketones to cyclopentenones by a 4π conrotatory ring closure.

The Nazarov cyclization is a long known reaction, however recently it has drawn much attention due to new catalytic systems and improved selectivity.[9-12] The Nazarov cyclization is of great significance as it forms two stereocenters in the final cyclopentenone product in one step. Roseophilin, a common antibiotic, has also been synthesized via the Nazarov reaction.[13] The mechanism of the catalytic Nazarov cyclization involves the binding of the Lewis acid catalyst to the oxygen of the dienone followed by conrotatory ring closure to form the cyclopentenone (Scheme 4.1).[8] Reports by Frontier and co-workers have shown that electron-donating groups at the C2 position and electron withdrawing groups at the C4 position increase cyclization rates due to a "polarized" divinyl ketone system.[13] Among some of the recent efforts to develop catalytic systems, Togni has been investigating the Nazarov cyclization by using a V(IV) salen dichloride catalyst with the use of silver additives such as $AgSbF_6$ to generate a catalytically active dicationic species.[9] This system afforded the diastereomeric product in 94 % yield. He was however unable to get any enantioselective separation by using a chiral V(IV) catalyst system. Later, in a study of the same substrate Togni was successful in achieving enantioselectivity of up to 88 % in the desired Nazarov product by using 10 mol % of a dicationic Ni(II) PIGIPHOS (PIGIPHOS=(Bis{(S)-1-[(R)-2-diphenylphosphino)ferrocenyl]ethyl}-cyclohexylphosphine) catalyst system.[14] With the goal of improving upon the activity and selectivity of known catalyst systems, a series of novel dicationic palladium bis(acyclic diaminocarbene) bis(acetonitrile) complexes were synthesized and used as catalysts for the Nazarov reaction.



"polarized" divinyl ketone

LA: Lewis acid; EDG: Electron donating group; EWG: Electron withdrawing group

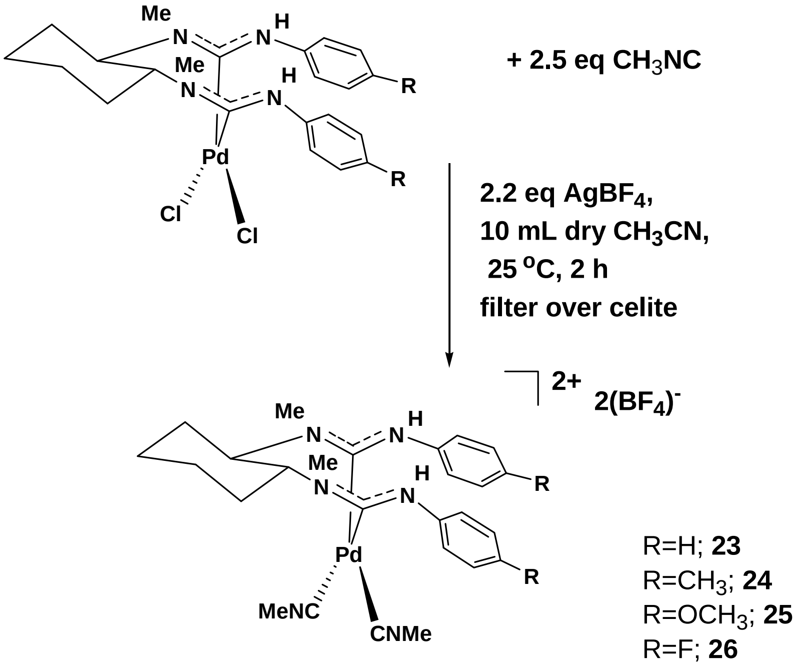
Scheme 4.1. The mechanism of Nazarov cyclization. Adapted from references 10 and 13.

Results and Discussion

Trans Influence studies: The goal of this project was to evaluate the sigma donor abilities of a series of differently substituted bis(ADC) ligands using methyl isocyanide as an IR probe. This was carried out by synthesizing methyl isocyanide adducts of a series of palladium bis(ADC) dications. The sigma donation was evaluated using the difference, Δν, between the average C≡N IR stretching frequency of each of the palladium bis(ADC) complexes and that of free methyl isocyanide. Hence, a high value of Δν would indicate strong sigma donation from the methyl isocyanide and weak donation from the bis(ADC) ligand due to weak trans influence. Having evaluated the sigma donating ability of the bis(ADC) ligands, the next objective was to test the activity of the palladium bis(ADC) complexes towards Nazarov cyclization and to correlate activity with the Δν parameter. Since the palladium bis(ADC) complexes were to be used as precatalysts by treating them with silver salts to generate catalytically active cationic species in solution, the effect of silver salts on the rate of cyclization was also studied by ^{1}H NMR spectroscopy.

Palladium bis(ADC) methyl isocyanide dications derived from *rac* palladium bis(ADC) dichloride complexes

The methyl isocyanide adducts of palladium bis(ADC) dications **23-26** were synthesized by treating each of the palladium bis(ADC) dichloride complexes **15-18** and with an excess of methyl isocyanide in dry acetonitrile for about two hours followed by treatment with silver tetrafluoroborate to generate the methyl isocyanide adducts with abstraction of silver chloride (Scheme 4.2). The silver chloride was removed by filtration through Celite® under nitrogen, followed by treatment with dry ether to furnish complexes **23-26**. Complexes **23-26** were formed as white crystals in yields ranging from 57-64 %. All of these complexes displayed high sensitivity to air and moisture and were thus stored under nitrogen in an air-free glove box.

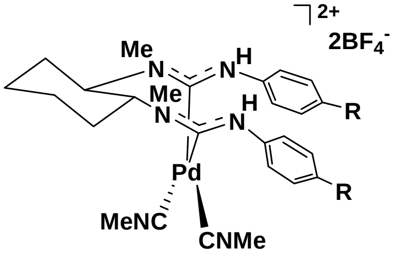


Scheme 4.2. Synthesis of [palladium bis(ADC)(MeNC)$_2$][BF$_4$]$_2$ derivatives from complexes **15-18**.

These complexes were soluble in DMSO and acetonitrile. The ^{1}H NMR spectral data for complexes **23**-**26** in dry DMSO-*d*$_6$ are shown in Table 4.1. The ^{1}H NMR spectra of complexes **23-26** showed two distinct NH signals in the range of 9.68-10.22 ppm and two distinct NCH$_3$ signals in the range of 3.11-3.62 ppm, both indicative of C_1 symmetry similar to the starting palladium bis(ADC) dichloride complexes **15-18.** Aryl proton signals were observed as doublets or multiplets in the range of 6.52-7.62 ppm.

The ^{13}C NMR data for complexes **23**-**26** in DMSO-*d*$_6$ are shown in Table 4.2. The ^{13}C NMR spectra of all these complexes showed two distinct carbene carbon signals in the range of 180.5-186.5 ppm. In the case of complexes **23** and **25**, no signal was observed for the *C*NCH$_3$ group, however it was observed for complexes **24** and **26**. Complex **26** showed doublets for the *para* and *meta* aryl carbons with C-F coupling constants of 23 Hz and 8 Hz corresponding to the ${}^{2}J_{C\text{-}F}$ and ${}^{3}J_{C\text{-}F}$ coupling constants respectively.[15] It also showed a doublet with a large coupling for the C-F carbon of 244 Hz, which was within the expected range.[15] An unusual observation is that the carbene carbon chemical shift showed no correlation with the electron donating groups and the electron withdrawing groups. For example, the carbene carbon stretches of complex **24** (R=CH_3) and **25** (R=OCH_3) were unchanged with respect to each other. Also, the chemical shifts of the carbene carbon in complex **26** (R=F) are slightly upfield compared to those of complexes **24** and **25** despite the fact F is electron withdrawing. The carbene carbon chemical shifts for complex **27** (R=CF_3) synthesized by Slaughter and co-workers was at 187.1 ppm and 181.8 ppm respectively.[16] The primary reason to study complex **27** was to compare the bis(ADC) with other chelate ligand types.

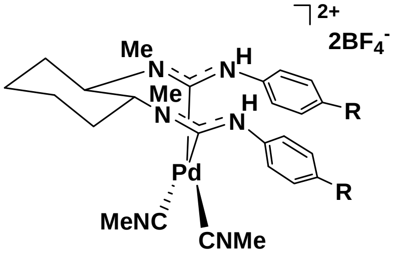
Table 4.1. ^{1}H NMR spectral data of chiral bis(ADC) palladium bis(methylisocyanide) dications.



23 R=H
24 R=CH$_3$
25 R=OCH$_3$
26 R=F

Complex	NH	Aryl	^{c}Hex	NCH$_3$	CH$_3$NC	^{c}Hex-CH$_2$	R
23 (R=H)	10.22 (s, 1H), 9.79 (s, 1H)	7.62-7.53 (m, 3H), 7.43 (d, 2H, *J*=7.2 Hz), 7.20-7.17 (m, 1H), 7.02-6.98 (m, 2H), 6.74 (d, *J*=7.6 Hz)	5.44-5.39 (m, 1H), 3.84-3.78 (m, 1H)	3.17 (s, 3H), 3.13 (s, 3H)	3.64 (s, 3H), 3.25 (s, 3H)	2.34-2.32 (m, 1H), 2.14-2.11 (m, 1H), 1.92-1.75 (m, 3H), 1.51-1.39 (m, 2H), 1.24-1.16 (m, 1H)	-
24 (R=CH$_3$)	10.15 (s, 1H), 9.70 (s, 1H)	7.38 (d, 2H, *J*=7.9 Hz), 7.30 (d, 2H, *J*=8.3 Hz), 6.78 (d, 2H, *J*=8.4 Hz), 6.61(d, 2H, *J*=7.9 Hz)	5.42-5.37 (m, 1H), 3.82-3.78 (m, 1H)	3.17 (s, 3H), 3.11 (s, 3H)	3.65 (s, 3H), 3.22 (s, 3H)	2.33-2.30 (m, 1H), 2.12-2.10 (m, 1H), 1.92-1.75 (m, 4H), 1.51-1.38 (m, 2H), 1.23-1.14 (m, 1H)	2.45 (s, 3H, CH$_3$), 2.23 (s, 3H, CH$_3$)
25 (R=OCH$_3$)	10.05 (s, 1H), 9.68 (s, 1H)	7.33 (d, 2H, *J*= 8.4 Hz), 7.14 (d, 2H, *J*=8.8 Hz), 6.66 (d, 2H, *J*=7.6 Hz), 6.52 (d, 2H, *J*=8 Hz)	5.41-5.37 (m, 1H), 3.79-3.77 (1H, m)	3.24 (s, 3H), 3.20 (s, 3H)	3.86 (s, 3H), 3.10 (s, 3H)	2.32-2.30 (m, 1H), 1.87-1.75 (m, 4H), 1.50-1.38 (m, 2H), 1.20-1.17 (m,, 1H)	3.77 (s, 3H), 3.70 (s, 3H)
26 (R=F)	10.17 (s, 1H), 9.77 (s, 1H)	7.47-7.45 (m, 4H), 6.86-6.83 (m, 4H)	5.39 (m, 1H), 3.82 (m, 1H)	3.62 (s, 3H), 3.11 (s, 3H)	3.32 (s, 3H), 3.11 (s, 3H)	2.30-2.27 (m, 1H), 2.08-2.03 (m, 1H), 1.84-1.72 (m, 2H), 1.48-1.34 (m, 3H), 1.19-1.16 (m, 1H)	-

Table 4.2. ^{13}C NMR spectral data of chiral bis(ADC) palladium bis(methylisocyanide) complexes.



23 R=H
24 R=CH$_3$
25 R=OCH$_3$
26 R=F

Complex	Carbene	Aryl	^{c}Hex	CH$_3$NC	NCH$_3$	R
23 (R=H)	185.8, 180.6	141.4 (para), 139.0 (para), 129.7 (meta), 128.8 (meta), 128.0 (ipso), 127.0 (ipso), 126.6 (ortho), 123.9 (ortho)	40.8, 32.7, 31.5, 30.4, 29.4, 29.3	24.5 (**C**H$_3$NC), 24.2 (**C**H$_3$NC), ***C***NMe not detected	66.7, 66.3	-
24 (R=CH$_3$)	185.8, 180.5	139.7 (ipso), 138.1 (ipso), 137.2 (ortho), 136.9 (ortho), 130.8 (meta), 129.7 (meta), 127.1 (para), 124.5 (para)	33.4 , 32.1, 31.3, 31.1, 30.1 , 30.1, 29.9	127.1 (***C***NCH$_3$), 125.7 (***C***NCH3), 25.1 (CN***C***H$_3$), 24.9 (CN***C***H$_3$)	67.4, 66.9	21.3 (CH$_3$), 21.2 (CH$_3$)
25 (R=OCH$_3$)	185.8, 180.4	159.2 (ipso), 158.3 (ipso), 135.1 (meta), 132.6 (meta), 128.7 (para), 126.3 (para), 115.3 (ortho), 114.2 (ortho)	41.3, 33.4, 32.0, 31.1, 30.2, 29.9	25.2 (CN***C***H$_3$), 24.9 (CN***C***H$_3$), ***C***NMe not detected	67.2, 66.8	56.2 (OCH$_3$), 55.7 (OCH$_3$)
26 (R=F)	δ 185.8, 180.6	161.6 (para, d, $^{1}J_{CF}$=245 Hz), 159.9 (para, d, $^{1}J_{CF}$=245 Hz), 137.9 (ipso), 135.6 (ipso), 128.9 (ortho, d, $^{3}J_{CF}$=8 Hz), 126.4 (ortho, d, $^{3}J_{CF}$=8 Hz), 116.4 (meta, d, $^{2}J_{CF}$=22 Hz), 115.3 (meta, d, $^{2}J_{CF}$=22 Hz)	40.8, 32.7, 31.5, 30.4, 29.5, 29.2	24.4 (**C**H$_3$NC), 24.2 (*C*H$_3$NC), 125.2 (***C***NCH$_3$), 124.0 (***C***NCH3)	66.6, 66.2	-

Complexes **23-25** showed a similar pattern in the ^{1}H NMR spectra for the aryl protons. Complex **26** showed two multiplets instead of four sets of doublets. This was possibly due to coupling with fluorine atoms. Crystals of complex **26** were grown by the slow diffusion of diethyl ether into an acetonitrile solution under nitrogen, as this complex was air sensitive. The crystal structure shown in Figure 4.2 indicated that the complex had C_1 symmetry consistent with that of the starting racemic palladium bis(ADC) dichloride. These crystals grew as colorless blocks. The seven-membered chelate ring was slightly twisted, which made the structure deviate from the C_2 symmetry of the starting diamine precursor. The isocyanide triple bond lengths were in agreement with the C≡N bonds and were found to be 1.138(16) Å and 1.139(14) Å respectively.[17]

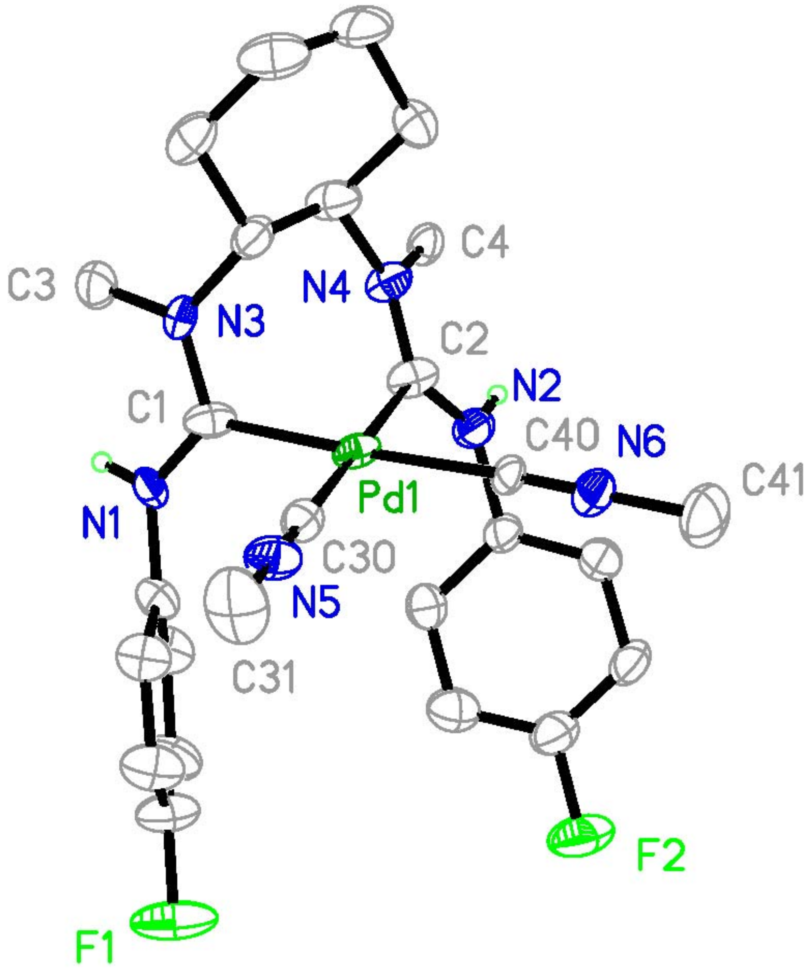


Figure 4.1. Molecular structure of complex **26** with 50 % probablilty ellipsoids. The BF_4^- anion is omitted for clarity.

Table 4.3. Selected bond lengths (Å) and bond angles (^{o}) for complex **26.**

	Bond Lengths (Å)
C(1)-N(1)	1.303(13)
C(2)-N(2)	1.314(14)
C(30)-N(5)	1.138(16)
C(40)-N(6)	1.139(14)
Pd(1)-C(30)	1.985(12)
Pd(1)-C(40)	2.010(10)
Pd(1)-C(1)	2.044(12)
Pd(1)-C(2)	2.048(12)

	Bond Angles (^{o})
C(30)-Pd(1)-C(40)	85.9(4)
C(1)-Pd(1)-C(2)	86.1(4)
N(1)-C(1)-N(3)	117.0(11)
N(2)-C(2)-N(4)	117.7(11)

Table 4.4. Crystal data and structure refinement details for complex **26.**

Empirical Formula	$C_{30}H_{38}B_2F_{10}N_8Pd$
Formula weight	828.70
Temperature	115(2) K
Wavelength	0.71073
Crystal system	Monoclinic
Space group	$P2_1/_n$
Unit cell dimensions	a = 10.4107 (9) Å, alpha = 90 ^{o}
	b = 16.8248 (14) Å, beta = 90.766(6) ^{o}
	c = 20.8388 (16) Å, gamma = 90 ^{o}
Volume, Z	3649.8 (5) Å^3, 4
Density (calculated)	1.508 Mg/m^3
Reflections collected	39132
Independent reflections	9390 (R_{int} = 0.0531)
Final R indices [I>2σ(I)]	R1 = 0.1020, wR2 = 0.2689
R indices (all data)	R1 = 0.1170, wR2 = 0.2810

The IR stretching frequencies for each of the complexes **23-27** are shown in Table 4.5. As indicated, the IR stretching frequencies for methyl isocyanide in each of these complexes was greater than the stretching frequency for free methyl isocyanide (2160 cm^{-1}). An important observation was made while comparing the IR stretching frequencies of complexes **23-27**. In theory, upon going from electron donating groups like $–OCH_3$, $-CH_3$ to electron withdrawing groups like $–CF_3$ and –F, one would expect weaker electron donation to the metal center, in effect more σ donation from the methyl isocyanide in accordance with trans influence, which should result in lesser values for Δν of the complexes **25** to **23** and higher Δν values for complex **27** to **26**. However, the values indicated in Table 4.5 show no correlation with the expected trend, thus suggesting that the different substituents have almost no effect on the donating ability of the bis(ADC) ligand itself.

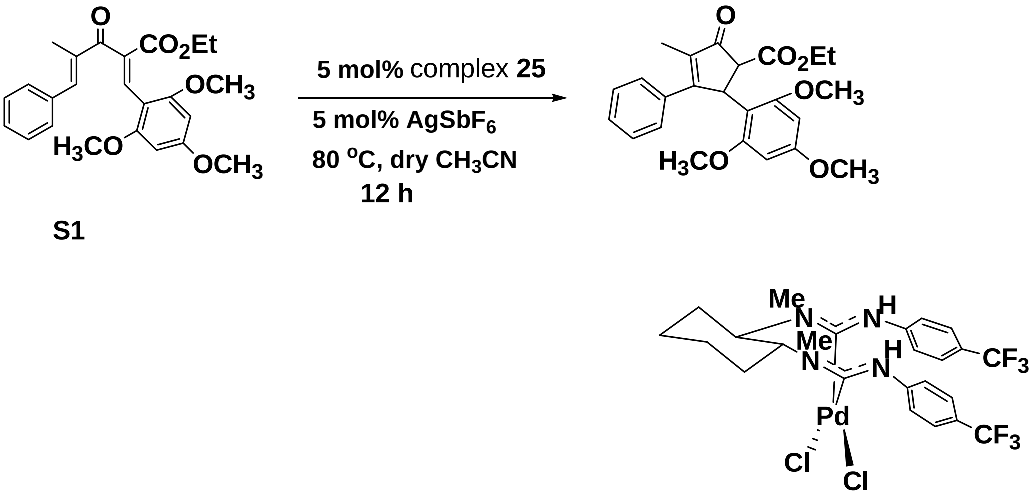
Table 4.5. Infrared spectral data for bis(ADC) palladium bis(methylisocyanide) dications.

R	Complex	ν NC (cm^{-1})	Δ ν NC (cm^{-1})
-	Free CH_3NC	2160	-
H	**23**	2266	106
CH_3	**24**	2268	108
OCH_3	**25**	2274	114
F	**26**	2267	107
CF_3	***27**	2271	111

* Yoshitha Wanniarachchi

Nazarov cyclization

The Nazarov substrate chosen for this study was ethyl-4-methyl-3-oxo-5-phenylpent-4-enoate due to the fact that the presence of electron-donating groups such as methyl, and electron-withdrawing groups such as ethoxy ester in the α position are known to facilitate cyclization. Another consideration is that the palladium catalyst could potentially bind to two oxygen atoms in a bidentate manner.[8] The Nazarov cyclization has been studied by Togni and co-workers by using a Vanadium(IV) salen dichloride catalyst and silver hexafluoroantimonate as an additive.[9] The Nazarov substrate was synthesized using published procedures by Aggarwal and Togni.[9, 18] Initial studies on this substrate used 5 mol% of palladium bis(ADC) dichloride complex **17a** with 5 mol% of $AgSbF_6$ added in dry acetonitrile at 80 ^{o}C to generate a catalytically active species in solution (Scheme 4.3). Complex **17a** was the first chiral palladium ADC complex synthesized by Slaughter and co-workers.[19] The formation of the desired Nazarov cyclized product as a single diastereomeric product was confirmed by ^{1}H NMR spectroscopy. Some of the other Nazarov substrates that were synthesized were ethyl 2-(4-methoxybenzylidene)-4-methyl-3-oxo-5-phenylpent-4-enoate and ethyl benzylidene-4-methyl-3-oxo-5-phenyl-4-pentenoate. These substrates failed to give any reaction with the palladium bis(carbene) catalyst.



S1

***17a**

Scheme 4.3. Initial test with palladium bis(ADC) dichloride complex **17a** as catalyst.

Despite Togni's use of $AgSbF_6$ to generate a catalytically active species, the ability of silver salts to solely act as catalysts has not been studied. In an effort to study the catalytic activity of silver salts with no added palladium catalyst in the cyclization of the substrate, NMR scale reactions were set up in CD_2Cl_2 with hexamethyl disiloxane (HMDS) as an internal standard. These reactions were typically set up under a nitrogen atmosphere, by adding the substrate followed by a silver salt in dry distilled CD_2Cl_2 in a J Young tube. These J Young tubes were then immersed in an oil bath set at 35 ^{o}C overnight and were monitored by ^{1}H NMR spectroscopy. Table 4.6 shows the effect of silver salts on the cyclization of substrate **S1**. As a control, an NMR tube reaction with substrate in dry CD_2Cl_2 was set up to ensure no cyclization was afforded at 35 ^{o}C in the absence of silver. These reactions were set up under nitrogen by adding the substrate and silver salt to dry CD_2Cl_2 in J Young NMR tubes. As observed in Table 4.6, when $AgBAr^F_4$ is used, the cyclized product was formed in 66 % yield. BAr^F_4 [tetrakis(bis-3,5-trifloromethyl phenyl) borate] is a non-coordinating anion. When AgOTf was used, the cyclized product was formed in 81 % yield and when $AgSbF_6$ was used, 99 % of the cyclized product was formed with respect to HMDS as the internal standard. In order to deviate from Togni's use of the added silver salts and eliminate the interference from silver in the reaction, dicationic palladium bis(ADC) complexes were synthesized and used as catalysts.

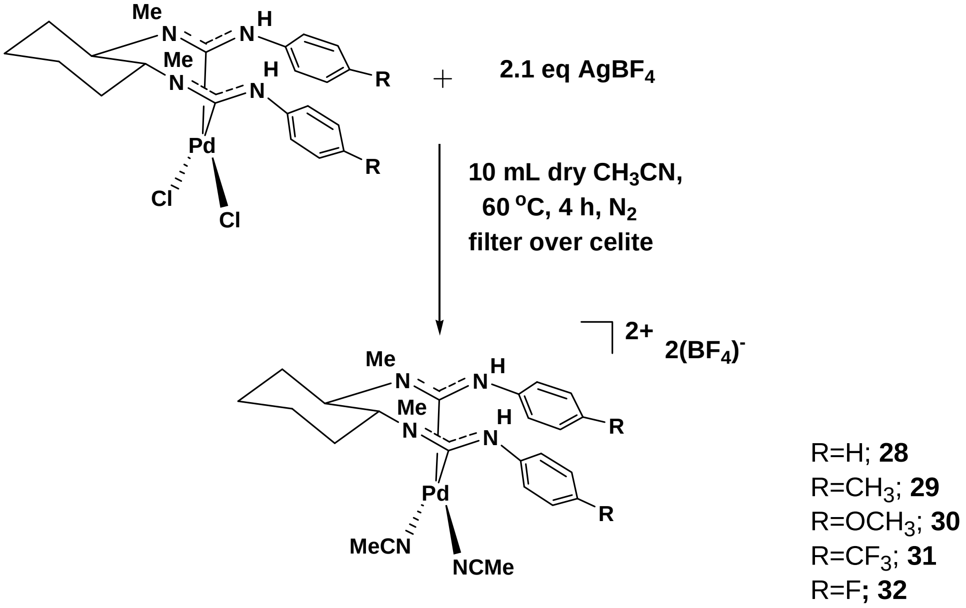
Table 4.6. Effect of silver salts on the Nazarov cyclization of substrate **S1**.

Rxn	AgX	Cat: Sub	% yield *
1	-	CTRL	
2	BAr^F_4	1:20	66
3	OTf	1:20	81
4	SbF_6	1:20	99

* Percent yields determined with respect to external standard hexamethyl disilazane (HMDS).

Dicationic palladium bis(ADC) bis(acetonitrile) complexes derived from *rac*-palladium bis(ADC) complexes

With the goal of making silver free precatalyts, dicationic Pd(II) bis(ADC) bis(acetonitrile) adducts were synthesized by treatment of each of complexes **15-18** and **17a** with two equivalents of silver tetrafluoroborate in dry acetonitrile at 60 °C for four hours under nitrogen (Scheme 4.4). The residual silver chloride was removed by filtration over Celite® under nitrogen and dry ether was used to precipitate out the complexes as the tetrafluoroborate salts. Complexes **28-32** were formed in yields ranging from 64-78 % and displayed high sensitivity to air and moisture. They were thus stored and used under nitrogen. These complexes were soluble in acetonitrile, dimethyl sulfoxide and dichloromethane.

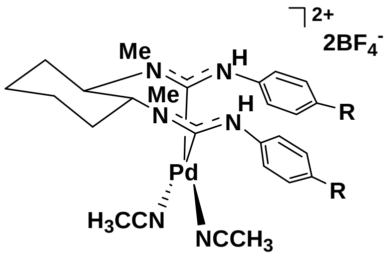


Scheme 4.4. Synthesis of [palladium bis(ADC)(MeCN)$_2$][(BF$_4$)$_2$] from complexes **15-18** and **17a**.

Table 4.7 shows the ^{1}H NMR data for complexes **28-32** in DMSO-*d*$_6$. The ^{1}H NMR data of complexes **28-32** indicated two distinct NH signals in the range of 9.23-10.06 ppm and two distinct NCH$_3$ signals in the range of 3.10-3.26 ppm. These complexes showed doublets and multiplets for the aryl signals in the range of 6.53 -7.87 ppm. All of the complexes **28-32** showed a singlet at 2.06 ppm which corresponded to the acetonitrile methyl protons.

The ^{13}C NMR data for complexes **28**-**32** in DMSO-*d*$_6$ are shown in Table 4.8. The ^{13}C NMR data indicate two distinct carbene carbon signals in the range of 172.1- 184.1 ppm and two distinct NCH$_3$ signals in the range of 66.5-67.4 ppm indicative of C_1 symmetry. The aryl protons exhibit signals in the range of 113.3–160.7 ppm. Complex **31** shows quartets arising from the coupling of the –CF_3 group with the *para and meta* carbons with values of 33 Hz and 3.4 Hz corresponding to the $^2J_{C\text{-}F}$ and $^3J_{C\text{-}F}$ coupling constants, respectively.[15] It also showed a large quartet for the CF_3 carbon at 123 ppm with a coupling constant of 272 Hz. Complex **32** shows the presence of doublets arising from the coupling of the –F group with the *meta* and *ortho* carbons with values of 22 Hz and 8.6 Hz corresponding to the $^2J_{C\text{-}F}$ and $^3J_{C\text{-}F}$ coupling constants respectively. It also showed a large doublet which corresponded to the C-F carbon with a coupling constant of 244 Hz. In most cases, acetonitrile signals for the $\mathit{C}H_3$ and $CH_3\mathit{C}N$ were observed for complexes **28**-**32** with values ranging from 1.10-1.16 ppm for $\mathit{C}H_3CN$ and 118.1 for the $CH_3\mathit{C}N$ groups respectively.

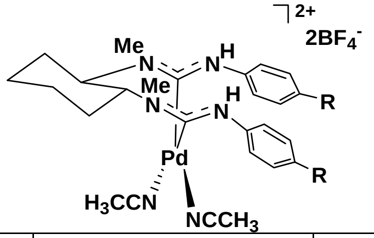
Table 4.7. ^{1}H NMR spectral data of chiral bis(ADC) palladium bis(acetonitrile) dications.



R=H, **28**
R=CH_3, **29**
R=OCH_3, **30**
R=CF_3, **31**
R=F, **32**

Complex	NH	Aryl	^{c}Hex	NCH_3	CH_3CN	^{c}Hex-CH_2	R
28 (R=H)	9.92 (1H, s), 9.36 (1H, s)	7.59-7.46 (5H, m), 7.14-6.99 (5H, m)	6.88-6.831 (1H, m), 3.85-3.80 (1H, m)	3.22 (3H, s), 3.14 (3H, s)	2.06 (6H, s)	2.46-2.44 (1H, m), 2.25-2.23 (1H, m), 1.99-1.86 (3H, m), 1.65-1.62 (1H, m), 1.48-1.37 (2H, m)	-
29 (R=CH_3)	9.80 (1H, s), 9.23 (1H, s)	7.38 (2H, d, *J*= 8.4 Hz), 7.24 (2H, d, *J*=8.4 Hz), 6.90 (2H, d, *J*= 7.6 Hz), 6.73 (2H, d, *J*= 7.9 Hz),	6.79 (1H, m), 3.78-3.72 (1H, s)	3.15 (3H, s), 3.07 (3H, s)	2.02 (6H, s)	1.96-1.81 (4H, m), 1.59-1.56 (1H, m), 1.43-1.32 (2H, m)	2.45 (3H, s, CH_3), 2.19 (3H, s, CH_3)
30 (R=OCH_3)	9.79 (1H, s), 9.24 (1H, s)	7.44 (2H, d, *J*= 8.7 Hz), 7.05 (2H, d, *J*=8.7 Hz), 6.94 (2H, d, *J*= 7.9Hz), 6.53 (m, 2H, *J*= 8.3Hz)	6.80 (1H, m), 3.74 (1H, m)	3.17 (3H, s), 3.10 (3H, s)	2.06 (6H, s)	2.48-2.42 (1H, m), 2.23-2.20 (1H, m), 1.99-1.94 (2H, m), 1.89-1.85 (1H, m), 1.63-1.60 (1H, m), 1.47-1.35 (2H, m)	3.85 (s, 3H, OCH_3), 3.70 (3H, s, OCH_3),
31 (R=CF_3)	10.06 (1H, s), 9.59 (1H, s)	7.87 (2H, m, *J*=8.79 Hz), 7.80 (2H, m, Ar), 6.85-6.80 (m, 3H, Ar),	7.07(1H, m), 3.82-3.77(1H, m)	3.26 (3H, s), 3.18 (3H, s)	2.06 (6H, s)	2.27-2.23 (1H, m), 2.01-1.99 (2H, s), 1.88 (1H, m), 1.69-1.66 (1H, m), 1.48-1.46 (2H, m)	-
32 (R=F)	9.86(1H, s), 9.34(1H, s)	7.56-7.52 (2H, m), 7.33-7.29 (2H, m), 7.07(2H, overlapping ^{c}Hex CH and aryl), 6.85-6.80 (2H, m)	7.07 (1H, m, overlapping aryl), 3.82-.3.77 (1H, m)	3.20 (3H, s), 3.11 (3H, s)	2.06 (6H, s)	2.24-2.22 (1H, m), 1.98-1.93 (2H, m), 1.89-1.86 (1H, m), 1.65-1.62 (1H, m), 1.49-1.41 (2H, m)	-

Table 4.8. ^{13}C NMR spectral data of chiral bis(ADC) palladium bis(acetonitrile) dications.

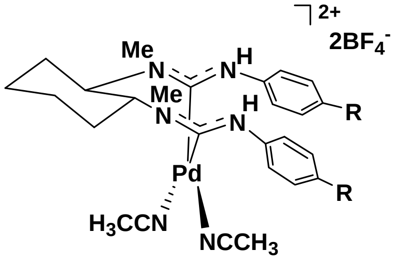


R=H, **28**
R=CH_3, **29**
R=OCH_3, **30**
R=CF_3, **31**
R=F, **32**

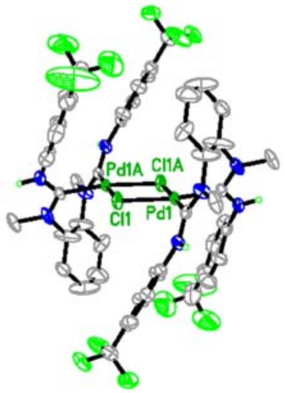
Complex	Carbene	Aryl	^{c}Hex	CH_3CN	NCH_3	R
28 (R=H)	180.5, 172.2	140.1 (ipso), 139.2 (ipso), 129.6 (ortho), 128.6 (ortho), 127.2 (para), 125.9 (para), 125.0 (meta), 123.3 (meta)	41.7, 33.4, 31.8, 29.4, 25.0, 24.3	118.1 (NCCH$_3$), 1.16 (NCCH$_3$)	66.9, 66.7	-
29 (R=CH_3)	180.4, 172.1	137.6 (ipso), 136.7 (ipso), 136.4 (para), 135.1 (para), 129.9 (ortho), 128.8 (ortho), 124.8 (meta), 123.2 (meta)	41.5, 33.3, 31.7, 29.4, 25.1, 24.3	118.1 (NCCH$_3$), 1.1 (NCCH$_3$)	66.9, 66.6	20.6 (CH$_3$), 20.5 (CH$_3$)
30 (R=OCH_3)	184.1, 180.4	158.1 (ipso), 157.1 (ipso), 133.1 (meta), 132.2 (meta), 126.5 (para), 124.9 (para), 114.5 (ortho), 113.3 (ortho)	41.3, 33.3, 31.6, 29.4, 25.1, 24.3	118.1 (NCCH$_3$), 1.1 (NCCH$_3$)	66.8, 66.5	55.4 (OCH_3), 55.0 (OCH_3)
31 (R=CF_3)	180.3, 172.8	143.7 (ipso), 143.0 (ipso), 126.9 (q, para, $^2J_{CF}$=33.3 Hz), 126.6 (q, meta, $^3J_{CF}$=3.6 Hz), 123.0 (q, CF_3, $^1J_{CF}$=272 Hz)	42.0, 33.2, 32.2, 29.3, 24.9, 24.3	118.1 (NCCH$_3$), 1.15 (NCCH$_3$),	67.4, 66.8	-
32 (R=F)	180.3, 172.6	160.7 (d, ipso, $^1J_{CF}$=244 Hz), 159.9 (d, ipso, $^1J_{CF}$=243 Hz), 136.5 (para), 135.7 (para), 126.8 (d, meta, $^3J_{CF}$=8.2 Hz), 125.8 (d, meta, $^3J_{CF}$=8.1 Hz), 116.1 (d, ortho, $^2J_{CF}$=22.4 Hz), 114.9 (d,ortho, $^2J_{CF}$=22.4 Hz),	41.4, 33.2, 31.8, 29.4, 25.0, 24.4	1.1 (NCCH$_3$)	67.0, 66.6	-

Having synthesized the bis(acetonitrile) adducts of the Pd(II) bis(ADC) complexes; NMR scale studies were performed to test the activity of these catalysts towards the cyclization of Nazarov substrate **S1**. The yields obtained from NMR scale reactions and isolated products are reported in Table 4.9. The NMR scale reactions were carried out in dry CD_2Cl_2 by treating the substrate with 5 mol% of each of the complexes **29-33** at 35 °C. Racemic palladium $BAr^F{}_4$ dimer complex **33** was synthesized by treating one equivalent of chiral bis(carbene) dichloride with one equivalent of $AgBAr^F{}_4$ and was used to study the effect of a single charge per palladium atom.[20] The dimer was previously used to study aza-Claisen rearrangement reactions catalyzed by a chiral palladium bis(ADC) **17a** complex published in our group.[19] The reactions were monitored by ^1H NMR spectroscopy every 30 minutes and percent yields were calculated with respect to the internal standard HMDS. Entries **5-9** in Table 4.9 indicated formation of the desired Nazarov cyclized product in yields ranging from 73-91 % within 10 min to 1h. The NMR spectra of each of these reactions also indicated a possible cyclic enol by-product.[9] This by-product was also observed and isolated by Togni for the same substrate. Attempts were made to isolate this by-product by filtering each of these CD_2Cl_2 solutions through a thin bed of silica in a glass frit, followed by washing with acetonitrile and dichloromethane. The orange solution volume was reduced to a small extent, which instantaneously formed a yellow crystalline solid. The ^1H NMR spectra of these yellow crystals indicated the sole formation of the cyclopentenone product as a diastereomer thus suggesting that the by-product may be stable only in solution (Scheme 4.5). These reactions were also carried out at 35 °C in sealed glass ampoules sealed under nitrogen. On completion of the reaction, the resultant solution was filtered through a thin bed of silica, and washed with dichloromethane and acetonitrile followed by reducing the solvent to half its volume. On reducing the volume, yellow crystalline products were obtained in all cases and were found to be pure by ^{1}H NMR spectroscopy.

Table 4.9. Catalytic activity of palladium bis(ADC) bis(acetonitrile) complexes in the Nazarov cyclization of substrate S1.

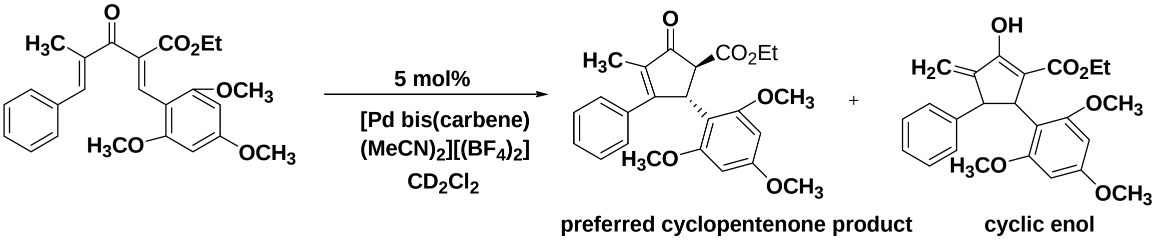


R=H; **28**
R=CH$_3$; **29**
R=OCH$_3$; **30**
R=CF$_3$; **31**
R=F**; 32**



33
*(CF$_3$) rac-Pd(BArF$_4$)dimer
Yoshitha Wanniarachchi

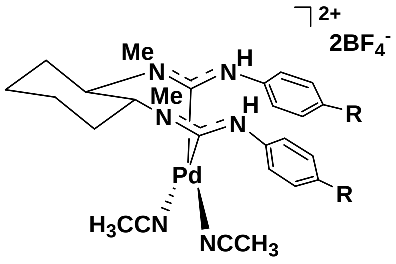
Rxn	Catalyst (R)	Cat:Sub	Time (min)	NMR yields (%)	Isolated yields (%)
5	CH$_3$	1:20	60	82	85
6	OCH$_3$	1:20	60	73	68
7	CF$_3$	1:20	10	84	75
8	F	1:20	60	81	84
9	*(CF$_3$) rac-Pd(BAr$^{F}_{4}$)dimer	1:20	10	91	89



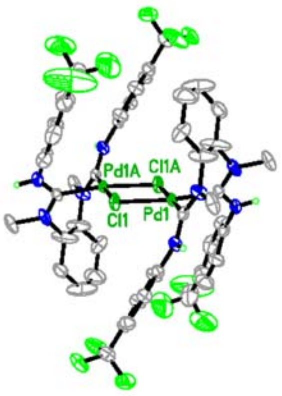
Scheme 4.5. Observed by-product formation from NMR tube reactions.

Gas Chromatography (GC) was also used to monitor the Nazarov cyclization reactions in an effort to rapidly test different catalyst loadings. For this purpose, reactions were set up in 1 mL glass vials fitted with teflon screw caps and a magnetic stir bar. The reactions were done by adding the substrate, catalyst and the internal standard diethylene diglycol ether (DEGDBE) under nitrogen. The solvent dichloromethane was added in a separate 1 mL glass vial fitted with a teflon screw cap. Solvent was added to the first vial and the reaction was started. After regular intervals, a known aliquot was injected into a methyl isocyanide solution in dichloromethane. The methyl isocyanide served to deactivate the catalyst and stop the reaction. Since reaction completion times had already been determined by ^{1}H NMR spectroscopy, the same times were used to stop monitoring the reaction by GC. Tables 4.10–4.12 show the results obtained for the different catalyst loading studies. Entries **10-14** show the yields of product formed with the different palladium bis(ADC) bis(acetonitrile) adducts, while entry **15** showed the activity of a dimeric analogue complex **33**. Entries **13** and **15** formed the cyclized products within 20 min in 93 % yield and 10 minutes in 94 % yield respectively. This could be reasoned by the fact that, in complexes **13** and **15** where R = CF_3, the trifluoromethyl groups was sufficiently electron withdrawing to make the palladium center electrophilic, increasing the cyclization rate. Entries **10-12** and **14** formed the cyclized product within 60 min in yields ranging from 70-84 %. Another important observation can be inferred by the trend in Table 4.10. According to the expected trend, it might be thought that the catalyst with less electron donation to the metal center would facilitate cyclization compared to one with more electron donation. According to Table 4.10, no such trend was observed indicating almost no dependence on the aryl substitution patterns of the palladium ADC ligands. However, this conclusion is based solely on yields.

Table 4.10. Effect of catalyst structure and loading on the Nazarov cyclization with 5 mol % catalyst.



R=H; **28**
R=CH_3; **29**
R=OCH_3; **30**
R=CF_3; **31**
R=F**; 32**



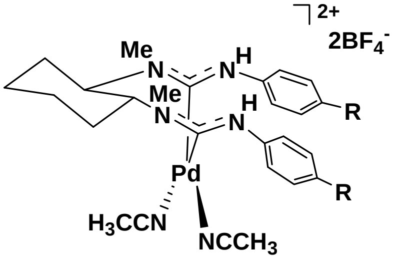
33

*(CF_3) rac-Pd($BArF_4$)dimer
Yoshitha Wanniarachchi[19]

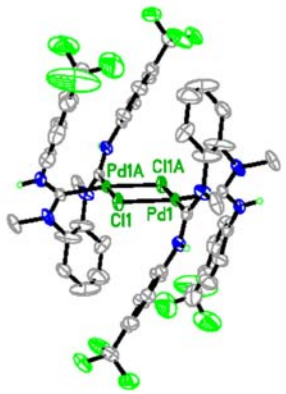
Rxn	Catalyst	% yield of cyclized product (GC)	Time (min)
10	-H	70	60
11	$-CH_3$	72	60
12	$-OCH_3$	83	60
13	$-CF_3$	93	20
14	-F	84	30
15	rac- $PdBAr^F_4$ dimer	94	10

Table 4.11 shows the effect of catalyst variation with 2 mol% catalyst loading. Entries **16-18** show that as we go from complex **27-29,** where R = H**,** R = CH_3 and R = OCH_3 there is an increase in activity upon decreasing loading from 5 mol% to 2 mol%. However, in the case of complexes **31** and **32 (**entries **19** and **20)**, where R = CF_3 and R = F, and in case of complex **33**, the palladium BAr^F_4 dimer, there is a decrease in the catalytic activity as observed in Table 4.11.

Table 4.11. Effect of catalyst structure and loading on the Nazarov cyclization with 2 mol % catalyst.



R=H; **28**
R=CH_3; **29**
R=OCH_3; **30**
R=CF_3; **31**
R=F**; 32**



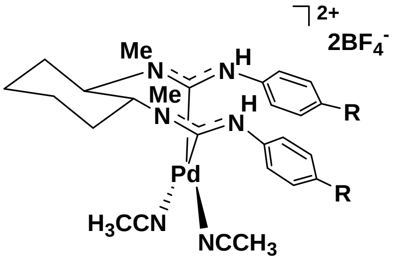
33
*(CF_3) rac-Pd($BArF_4$)dimer
Yoshitha Wanniarachchi[19]

Rxn	Catalyst	% yield cyclized product (GC)	Time (min)
16	-H	72	60
17	$-CH_3$	96	60
18	$-OCH_3$	87	60
19	$-CF_3$	81	30
20	-F	83	35
21	rac- $PdBAr^F_4$ dimer	89	10

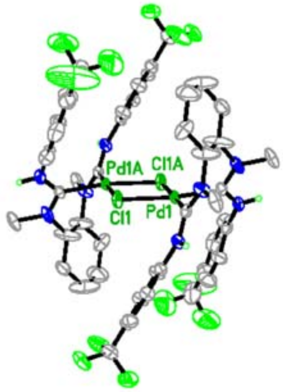
Table 4.12 shows the effect of catalyst variation with 0.5 mol % catalyst loading. In an effort to further examine catalyst activity, studies were carried out with 0.5 mol % catalyst loading. As we go to a lower catalyst loading of 0.5 mol %, when R = H and R = CH_3, there was no increase observed in the yield of the final product. However, when R = OCH_3 and R = CF_3, increase yields were observed. In case of the palladium BAr^F_4 dimer

complex **33**, the yield of the final product was increased from 2 mol % to 0.5 mol% catalyst loading.

Table 4.12. Effect of catalyst structure and loading on the Nazarov cyclization with 0.5 mol % catalyst.



R=H; **28**
R=CH_3; **29**
R=OCH_3; **30**
R=CF_3; **31**
R=F**; 32**



33

*(CF_3) rac-Pd($BArF_4$)dimer
Yoshitha Wanniarachchi[19]

Rxn	Catalyst	% yield of cyclized product (GC)	Time (min)
22	-H	73	240
23	$-CH_3$	96	180
24	$-OCH_3$	89	300
25	$-CF_3$	95	75
26	-F	79	20
27	*rac*- $PdBAr^F_4$ dimer	80	75

The Hammett equation is a qualititative tool used to explain the relationship between substituent groups and chemical properties.[21] A substituent group on a phenyl ring could impart two types of effects, namely resonance and inductive effects. The observed reactivity of the palladium bis(ADC) bis(acetonitrile) complexes **28**-**32** showed no correlation with the Hammett constant σ. The greater the positive value of the Hammet constant σ, the greater is the electron withdrawing nature of the aryl substituent. According to the values in Table 4.12 for the bis(ADC) complex having R = CF_3 (σ = 0.53), lower electron donation to the metal may be the cause for the high yield of the cyclopentenone product. When R = CH_3, R = OCH_3, and R = H, the yields are comparatively less when compared to R = CF_3 but still relatively high. When R = F (σ = 0.15), the yield of the cyclopentenone product decreases, which maybe due to deactivation of the catalyst. This agrees with the previous observation that the carbene complexes did not show the expected trend with respect to the carbene carbon signals in the ^{13}C NMR as in Table 4.2. In the case of electron-donating groups, the carbene carbons were expected to be more shielded as compared to the electron-withdrawing groups which were expected to be more deshielded, but this was not observed.

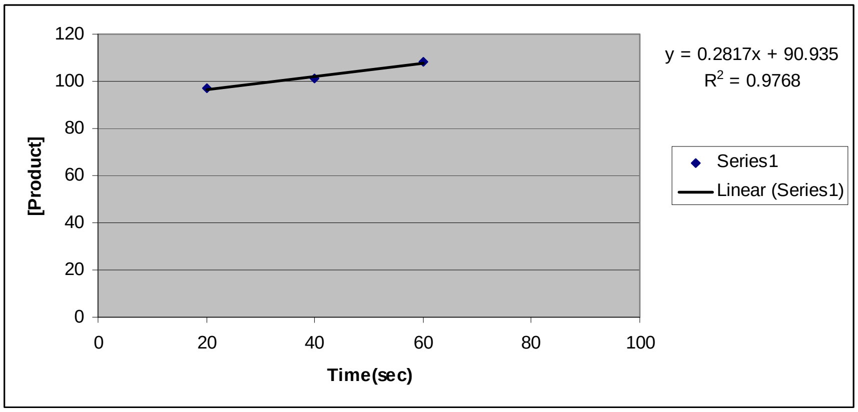
Table 4.13. Effect of substituents on the Hammett constant.

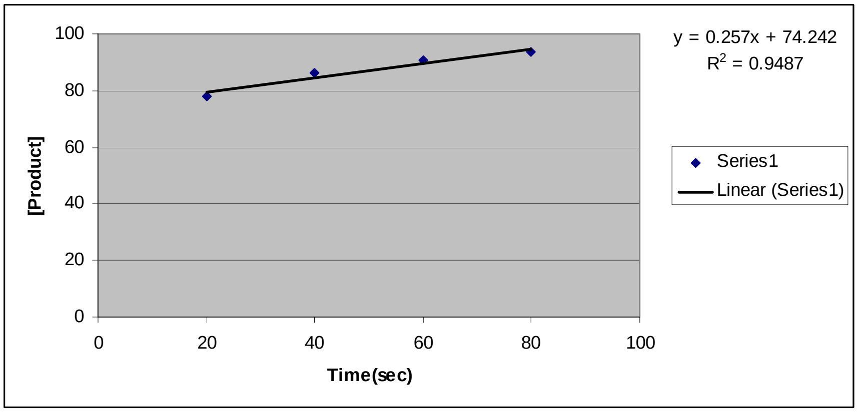
Complex	R	^{13}C of carbene (δ ppm)	Hammet σ parameter for R^{**}	% cyclopentenone product (5 mol % catalyst)
15	-H	190.1, 183.7	0	70 (60min)
16	$-CH_3$	189.7, 183.6	-0.14	72 (60 min)
17	$-OCH_3$	189.8, 183.7	-0.12	83 (60 min)
17a*	$-CF_3$	190.3, 184.4	0.53	93 (20 min)
18	-F	189.8, 184.4	0.15	84 (30 min)

17a* Yoshitha Wanniarachchi[18]
$\log K/K_o = \sigma\rho$
$^{**}\sigma$ =pKa(benzoic acid) – pKa(substituted benzoic acid) when $\rho=1$
K= acid dissociation constant of substituted benzoic acid
K_o= acid dissociation constant of benzoic acid
σ = substituent constant
ρ = sensitivity of the reaction to substituent effects

Attempts were made to measure the rates of reaction with the different catalysts using a low catalyst loading of 0.1 mol% at room temperature and in an ice bath at 0 °C. This was carried out by dissolving a known amount of catalyst in dichloromethane in a volumetric flask under nitrogen, and withdrawing a fixed volume of the solution in one vial. In a second vial, a weighed amount of the substrate, internal standard DEGDBE (diethylene glycol dibutyl ether) and dichloromethane were added under nitrogen. Both of the vials were placed in an ice bath to equilibrate for 15 minutes. After this time, the catalyst solution was added to the vial that contained the substrate and internal standard.

Aliquots of the resultant solution were injected into a methyl isocyanide solution in dichloromethane after regular 20 second intervals. A plot of product concentration versus time was made for the four catalysts (R = CH_3, R = OCH_3, R = CF_3, R = F). Figure 4.2 shows a plot of product concentration versus time at room temperature with catalyst **29** (R = CH_3). According to the plot, a steep increase was observed within the first twenty seconds which was also observed at 0 ^{o}C for catalysts **28**, **29** and **30** while catalysts **31** and **32** showed a steep decrease. Shown below are the plots of product concentration versus time at room temperature with catalysts **28**, **29**, **30, 31 and 32**.





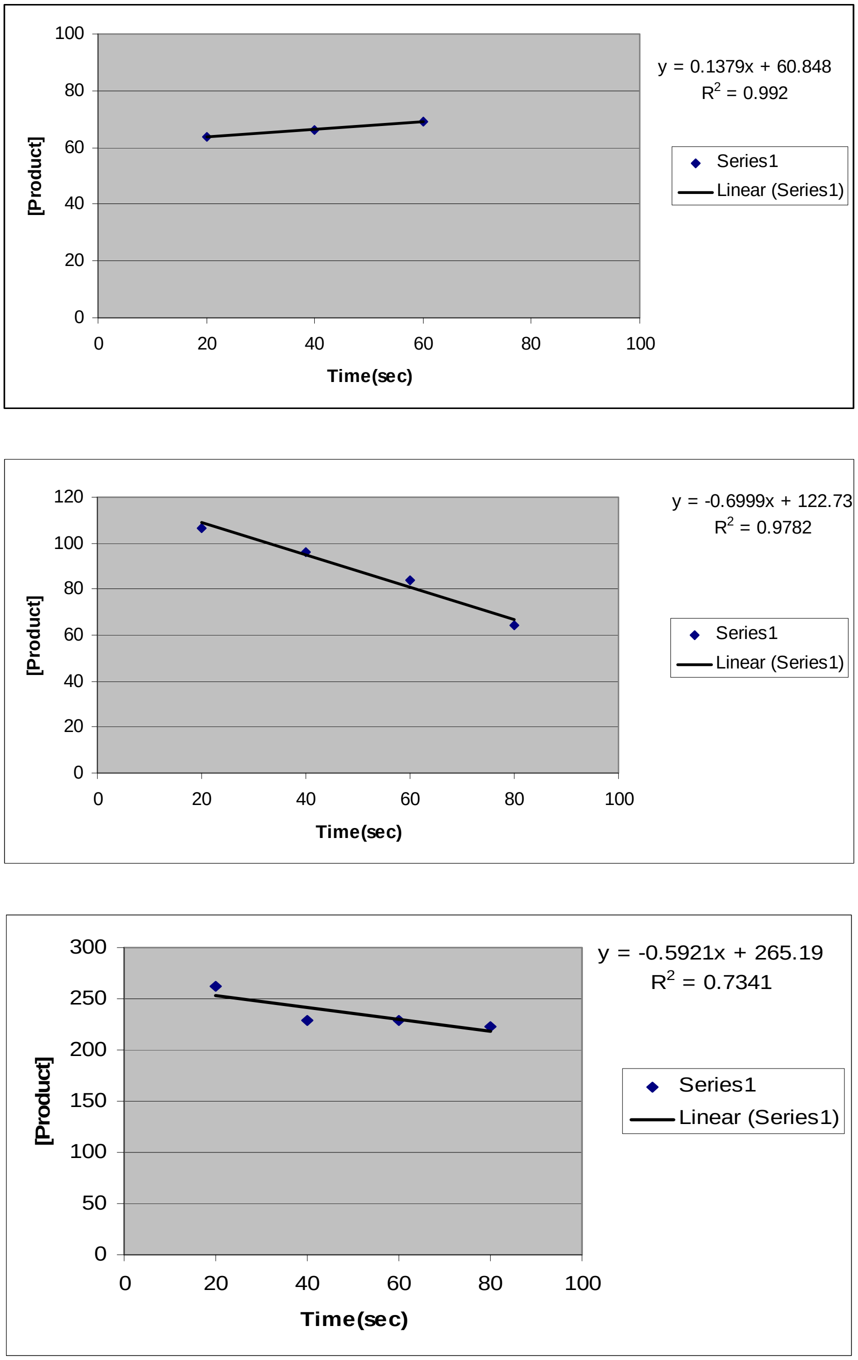


Figure 4.3. Plots of product concentration vs time in seconds for Nazarov cyclization of **S1** with catalyst **28**, **29**, **30**, **31**, **32**.

Enantioselective reactions:

In order to study enantioselectivity in the Nazarov cyclization, enantiomerically pure (1*R*,2*R*)-*N*,*N*'-dimethyl-1,2-diaminocyclohexane derived palladium bis(ADC) bis(acetonitrile) adduct was synthesized using the same procedure in Scheme 4.4. Before running the sample obtained from the enantiomerically pure catalyst, a racemic Nazarov cyclized product sample was run in order to assign the peak retention times from the two different enantiomers. For this purpose, a 2-mg sample of pure cyclized Nazarov product was dissolved in a 70:30 *n*-hexane/ *i*PrOH to make a solution of roughly 1000 ppm.[14] The racemic sample was run on a Beckman System Gold HPLC equipped with a 25-cm Chiralpak AD-H column and UV detector (254 nm) with sample injections of 20 μL. Since the chiral HPLC column was unable to differentiate between the two enantiomers, hence the sample has been sent to Dr. Tanski (Vassar College, New York) for chiral GC analysis.

Summary and Conclusions

In an attempt to study the σ donating ability of the ADC ligands, methyl isocyanide adducts of the palladium bis(ADC) dichloride complexes were synthesized. Taking into consideration that methyl isocyanide should serve solely as a σ donor, trans influence studies were carried out using infrared spectroscopy by comparing the IR stretches of the methyl isocyanide adducts with that of free methyl isocyanide. The IR studies did not show the expected trend, wherein, lesser electron donating groups like –H, -CF_3 and –F would donate to a lesser extent, hence the IR stretch of methyl isocyanide would be greater than in the case of a stronger electron donating groups like –CH_3 and –

OCH_3. Due to the apparent weak electron donation of the bis(ADC) ligands, these complexes served as attractive candidates for the Nazarov cyclization. Initial studies carried out in the presence of 5 mol% of the palladium bis(ADC) dichloride complex and $AgSbF_6$ indicated the formation of the cyclized product. However, to eliminate possible interference of silver salts and increase solubility of the palladium bis(ADC) complexes acetonitrile adducts were synthesized and tested for catalytic activity . Catalyst loading studies were carried out using gas chromatography. It was observed that catalyst **31** and **33** showed high activity at high catalyst loading of 5 mol% while catalyst **29-31** showed high catalyst activity at lower catalyst loading of 2 mol % and 0.5 mol%. Therefore, differences in catalytic activity may depend on subtle electronic effects that are difficult to assess experimentally.

Experimental

General considerations. All syntheses were performed under air unless otherwise noted. Acetonitrile (Pharmco) was pre-dried over anhydrous $CaCl_2$ for 2-3 hours and refluxed over CaH_2 overnight under nitrogen followed by distillation. Dichloromethane (Pharmco) was purified by washing with concentrated sulphuric acid and sodium bicarbonate, predried with anhydrous $CaCl_2$, and then refluxed overnight with P_2O_5. Hexanes and diethyl ether were dried by refluxing over sodium-benzophenone ketyl and distilled prior to use. NMR solvents were purified as follows. CD_2Cl_2 (Cambridge Isotope laboratories, Inc, 99.9%) was dried over degassed 4 Å molecular sieves and stored over P_2O_5. DMSO-d_6 was dried by stirring over activated 4 Å molecular sieves followed by distillation under vacuum and storage in an air free glove box. Methyl isocyanide[22] and $AgBAr^F_4$ [silver tetrakis(bis-3,5-trifloromethyl phenyl)borate] were synthesized using published procedures.[23]

^1H NMR spectra were recorded on Varian 300 MHz and 400 MHz spectrometers, with chemical shifts reported in ppm, multiplicity reported as (s = singlet, d = doublet, t = triplet, m = multiplet) and coupling constants recorded in Hz. ^{13}C NMR spectra were recorded on Varian 400 MHz and 600 MHz spectrometers, with chemical shifts in ppm. Elemental analyses were performed by Desert Analytics Laboratory, Tucson, AZ, USA, and Midwest Microlabs, Indianapolis, IN, USA. Infrared (IR) spectra were recorded were recorded as Nujol mulls on a Nicolet Protégé 460 FT–IR spectrometer. Data collection for determining X-ray crystal structure of complexes **26** was done on a Bruker Apex II diffractometer using MoKα ($\lambda = 0.71073$ Å) radiation. The X-ray crystal structures were solved using the SHELXTL system and refined by full matrix least squares on F^2 using all reflections.[24, 25]

(*rac*) palladium(II) bis(ADC) bis(methylisocyanide)complex derived from (*rac*) palladium bis(ADC) dichloride complex [R = H](23)

To a solution of (±)-**15** (0.117 g, 0.22 mmol) in 10 mL dry distilled acetonitrile, methyl isocyanide (31 μL, 0.55 mmol) was added. After stirring at room temperature for 1 h, the white precipitate changed to a clear solution. To this solution, $AgBF_4$ (0.0905 g, 0.46 mmol) was added. This solution was allowed to stir for an additional 2 hours at room temperature. The reaction mixture was filtered through Celite® under nitrogen, followed by layering of diethyl ether to afford white crystals of complex **23**. The crystals were filtered and dried overnight in vacuo. Yield: 89 mg, 57 %. Anal. Calcd for $C_{26}H_{34}N_6B_2F_8Pd$: C, 43.94; H, 4.83; N, 11.83 %. Found: C, 43.10; H, 4.45; N, 11.48 %.

(*rac*) palladium(II) bis(ADC) bis(methylisocyanide)complex derived from (*rac*)-palladium bis(ADC) dichloride complex [R = CH_3]**(24)**

To a solution of (±)-**16** (0.0503 g, 0.09 mmol**)** in 10 mL dry distilled acetonitrile, methyl isocyanide (13 µL, 0.22 mmol) was added. After stirring at room temperature for 1 h, the white precipitate changed to a clear solution. To this solution, $AgBF_4$ (0.0371 g, 0.19 mmol) was added. This solution was allowed to stir for an additional 2 hours at room temperature. The reaction mixture was filtered through Celite®under nitrogen, followed by layering of diethyl ether to afford white crystals of complex **24**. The crystals were filtered and dried overnight in vacuo (41 mg, 62 %). Anal. Calcd for $C_{28}H_{38}N_6B_2F_8Pd$: C, 45.52; H, 5.19; N, 11.38 %. Found: C, 45.68; H, 5.17; N, 11.26 %.

(*rac*) palladium(II) bis(ADC) bis(methylisocyanide)complex derived from (*rac*)-palladium bis(ADC) dichloride complex [R=OCH_3] (25)

To a solution of (±)-**17** (0.0897 g, 0.15 mmol**)** in about 10 mL dry distilled acetonitrile, methyl isocyanide (23 µL, 0.38 mmol) was added. After stirring at room temperature for 1 h, the white precipitate changed to a clear solution. To this solution, $AgBF_4$ (0.0625 g, 0.32 mmol) was added. This solution was allowed to stir for an additional 2 hours at room temperature. The reaction mixture was filtered through Celite®under nitrogen, followed by layering of diethyl ether to afford white crystals of complex **25**. The crystals were filtered and dried overnight in vacuo (75 mg, 64 %). Anal. Calcd for $C_{28}H_{38}N_6O_2B_2F_8Pd$: C, 43.62; H, 4.98; N, 10.91 %.Found: C, 43.84; H, 5.02; N, 10.76 %.

(*rac*) palladium(II) bis(ADC) bis(methylisocyanide)complex derived from (*rac*)-palladium bis(ADC) dichloride complex [R=F](26)

To a solution of (±)-**18** (0.1021 g, 0.18 mmol) in about 10 mL dry distilled acetonitrile, methyl isocyanide (26 μL, 0.45 mmol) was added. After stirring at room temperature for 1 h, the white precipitate changed to a clear solution. To this solution, $AgBF_4$ (0.0742 g, 0.38 mmol) was added. This solution was allowed to stir for an additional 2 hours at room temperature. The reaction mixture was filtered through Celite®under nitrogen, followed by layering of diethyl ether to afford white crystals of complex **26**. The crystals were filtered and dried overnight in vacuo (88 mg, 62 %). Anal. Calcd for $C_{26}H_{32}N_6B_2F_{10}Pd$: C, 41.82; H, 4.32; N, 11.25 %. Found: C, 40.75; H, 4.26; N, 10.83 %.

(*rac*) palladium(II) bis(ADC) bis(acetonitrile) complex derived from (*rac*) palladium bis(ADC) dichloride complex [R=H] (28)

To a stirred solution of (±)-**15** (0.137 g, 0.26 mmol) in about 10 mL of dry acetonitrile was added $AgBF_4$ (0.106 g, 0.54 mmol) under nitrogen. The solution was stirred for 4 h hours at 60 °C in an oil bath. The reaction mixture was filtered over Celite®under nitrogen followed by layering with dry ether to afford white crystals of complex **28**. The crystals were filtered, washed with dry ether and dried in vacuo (128 mg, 61 %). Anal. Calcd for $C_{26}H_{32}B_2F_8N_6Pd$: C, 43.94; H, 4.82; N, 11.82 %. Found: C, 44.07; H, 4.99; N, 11.74 %.

(*rac*) palladium(II) bis(ADC) bis(acetonitrile) complex derived from (*rac*) palladium bis(ADC) dichloride complex [R=CH_3]**(29)**

To a stirred solution of (±)-**16** (0.1651 g, 0.29 mmol) in about 10 mL of dry acetonitrile was added $AgBF_4$ (0.1218 g, 0.62 mmol) was added under nitrogen. The solution was stirred for 4 h at 60 °C in an oil bath. The reaction mixture was filtered over Celite® under nitrogen followed by layering with dry ether to afford white crystals of complex **29**. The crystals were filtered, washed with dry ether and dried overnight in vacuo (141.3 mg, 64 %). Anal. Calcd for $C_{28}H_{38}B_2F_8N_6Pd$: C, 45.52; H, 5.18; N, 11.37. %. Found: C, 45.24; H, 5.13; N, 10.99 %.

(*rac*) bis(ADC) palladium(II) bis(acetonitrile) complex derived from (*rac*) palladium bis(ADC) dichloride complex [R=OCH_3]**(30)**

To a stirred solution of (±)-**17** (0.1616 g, 0.27 mmol) in about 10 mL of dry acetonitrile was added $AgBF_4$ (0.1127g, 0.57 mmol) under nitrogen. The solution was stirred for 4 h at 60 °C in an oil bath. The reaction mixture was filtered over Celite®under nitrogen followed by layering with dry ether to afford white crystals of complex **30**. The crystals were filtered, washed with dry ether and dried overnight in vacuo (139 mg, 65 %). Anal. Calcd for $C_{28}H_{38}B_2F_8N_6O_2Pd$: C, 43.63; H, 4.97; N, 10.90 %. Found: C, 43.87; H, 5.13; N, 10.58 %.

(*rac*) palladium(II) bis(ADC) bis(acetonitrile) complex derived from (*rac*) palladium bis(ADC) dichloride complex [R=CF_3] **(31)**

To a stirred solution of (±)-**17a** (0.1616 g, 0.27 mmol) in about 10 mL of dry acetonitrile was added $AgBF_4$ (0.1127 g, 0.57 mmol) under nitrogen. The solution was stirred for 4 h at 60 °C in an oil bath. The reaction mixture was filtered over Celite®under nitrogen followed by layering with dry ether to afford white crystals of complex **31**. The crystals were filtered, washed with dry ether, and dried overnight in vacuo (154 mg, 79 %). Anal. Calcd for $C_{28}H_{32}B_2F_{14}N_6Pd$: C, 39.72; H, 3.81; N, 9.92%. Found: C, 39.68; H, 3.92; N, 9.67 %.

(*rac*) palladium(II) bis(ADC) bis(acetonitrile) complex derived from (*rac*) palladium bis(ADC) dichloride complex [R= F]**(32)**

To a stirred solution of (±)-**18** (0.137 g, 0.26 mmol) in about 10 mL of dry acetonitrile was added $AgBF_4$ (0.106 g, 0.54 mmol) under nitrogen. The solution was stirred for 4 h at 60 °C in an oil bath. The reaction mixture was filtered over Celite®under nitrogen followed by layering with dry ether to afford white crystals of complex **32**. The crystals were filtered, washed with dry ether and dried overnight in vacuo (126 mg, 69 %). Anal. Calcd for $C_{26}H_{32}B_2F_{10}N_6Pd$: C, 41.82; H, 4.32; N, 11.25%. Found: C, 42.04; H, 4.24; N, 11.36 %.

Ethyl-4-methyl-3-oxo-5-phenyl-2-(2,4,6-trimethoxybenzylidene)pent-4-enoate (**S1**)

Nazarov substrate **S1** was synthesized using published procedure by Aggarwal[10] and Togni.[9] The first step involved the synthesis of ethyl-4-methyl-3-oxo-5-phenyl-4-

pentenoate. This was carried out by treating alpha-methylcinnamic acid with oxalyl chloride in dichloromethane with a few drops of dimethyl formamide at 0 ^{o}C for 3 h to form the corresponding acid chloride. Ethyl acetate was treated with lithium diisopropylamide generated in situ by *n*-butyl lithium and diisopropylamine in dry THF at -78 ^{o}C. The acid chloride is then added to the above solution forming the product of the first step. The second step involved a Knoevenagel condensation reaction between ethyl-4-methyl-3-oxo-5-phenyl-4-pentenoate and 2,4,6-trimethoxy benzaldehyde in the presence of catalytic amounts of acetic acid and piperidine in a Dean Stark Apparatus to afford substrate **S1**.

Other Nazarov substrates:

Ethyl-2-(4-Methoxybenzylidene)-4-methyl-3-oxo-5-phenyl-4-pentenoate and ethyl benzylidene-4-methyl-3-oxo-5-phenyl-4-pentenoate were also synthesized using a procedure similar to that used to prepare **S1.**

Attempted syntheses of other Nazarov substrates:

Ethyl-4-methyl-3-oxo-5-phenyl-1,4-pentadiene, 1-(5,6-dihydro-4H-pyran-2-yl)-2-methyl-3-phenylpropenone and 4,5-dimethyl-2-ethoxy-3-oxo-1,4-pentadiene:

Ethyl-4-methyl-3-oxo-5-phenyl-1,4-pentadiene, 1-(5,6-dihydro-4H-pyran-2-yl)-2-methyl-3-phenylpropenone and 4,5-dimethyl-2-ethoxy-3-oxo-1,4-pentadiene were synthesized using a published procedure by Tius.[11] The synthesis involved two steps. In the first step, one equivalent of tiglic acid or alpha-methyl cinnamic acid was treated with two equivalents of oxalyl chloride at 0 ^{o}C for 3 h at room temperature. The corresponding solution was then dried under vacuum to remove the excess oxalyl chloride. The resultant solution was then treated with one equivalent of triethylamine followed by one equivalent of morpholine to furnish the corresponding morpholine enamide and solid triethylaminehydrochloride which was removed by filtration. The second step involved the reaction between the corresponding morpholine enamide with ethyl vinyl ether or 2,4-dihydropyran under argon atmosphere.[11] Although this reaction formed the substrate, the yields were as low as 30 %. This reaction was repeated several times and was scaled upto twice etic procedure to observe any improvement in the yield, but there was no conceivable difference. The above reaction was repeated by drying and distilling the starting materials using activated molecular sieves with no observable difference.

4-benzylidene-4-methyl-3-oxo-5-phenyl-4-pentenoic acid ethyl ester:

The synthesis of 4-benzylidene-4-methyl-3-oxo-5-phenyl-4-pentenoic acid ethyl ester was carried out using published procedure by Aggarwal.[10] The first step involved the synthesis of 4-methyl-3-oxo-5-phenyl-4-pentenoic acid ethyl ester. The second step involved a Knoevenagel condensation reaction between the ester in the first step and benzaldehyde to form the desired substrate in the presence of $TiCl_4(thf)_2$ (thf = tetrahydrofuran) formed in situ by the reaction between $TiCl_4$ and tetrahydrofuran. Treatment of the ester with benzaldehyde gave no reaction as indicated by the ^1H NMR data. This reaction was not successful using isolated $TiCl_4(thf)_2$ as well.[12]

Synthesis of ethyl-4-methyl-3-oxo-2-(2,4,6-trimethoxybenzylidene)pent-4-enoate:

The first step involved the drop wise addition of methacryoyl chloride to one equivalent of potassium monoethyl malonate in acetonitrile at 0 °C. After 30 minutes, one equivalent of anhydrous magnesium chloride and triethylamine were added to the reaction mixture and the reaction mixture was stirred for five hours at room temperature. The solution was made acidic by addition of 1M hydrochloric acid, and ethyl acetate was added. The organic phase was separated, washed with water and sodium bicarbonate. It was further dried over anhydrous magnesium sulphate and concentrated on a rotary evaporator to form ethyl-4-methyl-3-oxo-4-pentenoate. The potassium monoethyl malonate was synthesized by refluxing diethyl malonate with potassium hydroxide in ethanol for 24 h followed by work up.[26] The second step involved a Knoevenagel condensation between the product from the first step and 2,4,6-trimethoxy benzaldehyde in dry benzene with acetic acid and piperidine in a Dean Stark Apparatus.[8]

Synthesis of 1-(5,6-Dihydro-4H-pyran-2-yl)-3-phenyl-propenone :

The first step involved the synthesis of 1-(5,6-Dihydro-4H-pyran-2-yl)-3-phenyl-prop-2-en-1-ol.[27] This involved the treatment of dihydropyrone with *tert*-butyl lithium at -78 °C followed by addition of cinnamaldehyde. The reaction was kept at 0 °C and quenched with water followed by work up. The crude orange oil was then purified by column chromatography. The second step involved the oxidation of the above product with activated MnO_2.

General procedure for catalytic Nazarov cyclization reactions

Palladium bis(ADC) bis(acetonitrile) complex (1 eq), internal standard DGDBE (15 μL) and Nazarov substrate (**S1**, 0.100g) were added to a glass vial with 1 mL of dry dichloromethane under nitrogen. The vial was kept at room temperature and after appropriate time intervals, 10 μL of reaction mixture was withdrawn and added to 190 μL of methyl isocyanide in dichloromethane. Methyl isocyanide served to deactivate the catalyst. The solution was filtered through glass microfiber and further analyzed by GC. In the case of lower catalyst loading, 10 mg of each of the corresponding catalysts **28-32** were dissolved in dry dichloromethane to give a stock solution, and appropriate aliquots were withdrawn and dried in vacuo for 30 minutes. To these vials, 0.100 g substrate, 15 μL of internal standard DGDBE and 1 mL of dry dichloromethane were then added.

(1*R*,2*R*) palladium(II) bis(ADC) bis(acetonitrile) complex derived from (1*R*,2*R*) palladium bis(ADC) dichloride complex [R=CF_3]

(1*R*,2*R*) palladium(II) bis(ADC) bis(acetonitrile) complex was synthesized using the same method as that described for complex **31** in this chapter. This complex was isolated as a white crystalline powder with a yield of 76 %. The analytical data matched the racemic complex **31**. Anal. Calcd for $C_{28}H_{32}B_2F_{14}N_6Pd$: C, 39.72; H, 3.81; N, 9.92 %. Found: C, 39.68; H, 3.92; N, 9.67 %.

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VITA

Anthea Jacinta Miranda

Candidate for the Degree of

Doctor of Philosophy

Dissertation: NOVEL REACTIVITY OF SILVER ISOCYANIDE COMPLEXES AND PALLADIUM BIS(ACYCLIC DIAMINOCARBENES) AS CATALYSTS FOR THE NAZAROV CYCLIZATION.

Major Field: Chemistry

Biographical:

Personal Data: Born in Bombay, India on July 22, 1981 daughter of (late) Jeanette and Louis Miranda. Married to Lawrence Wilfred Barretto on December 29, 2007.

Education: Received Bachelor of Science Degree in Chemistry from St. Xavier's College in 2001. Received Master's of Science Degree in Chemistry from the University of Mumbai in 2004.

Experience: Employed by Oklahoma State University, Department of Chemistry as a graduate teaching assistant from 2004-2009.

Professional Memberships: American Chemical Society, Inorganic Division

Name: Anthea Miranda Date of Degree: December, 2009

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: NOVEL REACTIVITY OF SILVER ISOCYANIDE COMPLEXES AND PALLADIUM BIS(ACYCLICDIAMINOCARBENES) AS CATALYSTS FOR THE NAZAROV CYCLIZATION

Pages in Study: 189 Candidate for the Degree of Doctor of Philosophy

Major Field: Chemistry

Scope and Method of Study: Inorganic Chemistry

Findings and Conclusions:

N-heterocyclic carbenes (NHCs) have been widely used in catalysis since the discovery of the first stable carbene by Arduengo in 1991. Acyclic diaminocarbenes (ADCs) have been studied very little, even though they have similar electronic stabilization as the NHCs. The first research goal was to synthesize silver(I) acyclic carbenes by the nucleophilic attack of dimethyl amine on isocyanide bound silver precursors. However, on treating silver(I) tris isocyanide with dimethyl amine, an unexpected silver(I) bis(amidine) complex was formed instead of the silver(I) tris carbene. The second research goal was to synthesize palladium bis(ADC) complexes via a general route by the nucleophilic attack of a chiral diamine on palladium bound isocyanide precursors. With a goal to study the donor ability of these palladium bis(carbene) complexes trans influence studies were carried out using methyl isocyanide as a probe by comparing the stretching frequencies using infrared spectroscopy. Dicationic bis(acetonitrile) adducts were synthesized and used as precatalysts in the electrocyclic Nazarov cyclization. The cyclization reactions were monitored by gas chromatography with catalyst loadings of 5 mol% to 0.5 mol %.

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