Neutral palladium(II) complexes with P,N Schiff-base ligands: Synthesis, characterization and application as Suzuki—Miyaura coupling catalysts

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ABSTRACT

Palladium(II) complexes of the general formulae $[PdCl_2(P^\wedge N)]$ and $[Pd(Me)Cl(P^\wedge N)]$ were obtained from bidentate ligands bearing phosphine and imine donor groups. The complexes were shown to be highly active catalysts for the Suzuki—Miyaura cross-coupling reaction. The complexes are tolerant of a wide variety of reaction conditions such as solvent, choice of base as well as substituents on both arylboronic acids and aryl halides.

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1. Introduction

Transition metal-catalyzed C—C and C—X (X = heteroatom) bond forming reactions are a powerful synthetic tool in organic chemistry. In this regard, palladium complexes form some of the most versatile and useful catalysts in these organic trans-formations. The facile interchange between the two stable oxidation states, Pd(II) and Pd(0), and the compatibility of many palladium compounds with most functional groups, are mainly responsible for the rich chemistry enjoyed by palladium compounds [1]. This facile interchange between the Pd(II)/Pd(0) oxidation states is what most palladium-catalyzed C—C bond forming reactions such as ethylene oligo/polymerization reactions, Suzuki—Miyaura, Heck and Negishi coupling reactions rely on.

The most common Suzuki—Miyaura catalysts currently in use are phosphine complexes with strong P-donors, owing to the stability displayed by these complexes as well as the comparative ease with which their properties can be modified. The coupling pathway requires a sequential oxidative addition at an active Pd(0) by an aryl halide, activation and transmetallation with the organoborate substrate, and finally, reductive elimination to give the target product and regeneration of the active species [2]. As such, a pre-catalyst such as $Pd(PPh_3)_4$ would need to enter the catalytic cycle through two successive ligand dissociations to give the 14-electron catalytically active complex $Pd^0(PPh_3)_2$. Such low-valent, low-coordinate palladium complexes are known to be extremely unstable and their formation is energetically unfav-ourable. One of the main challenges facing these catalyst systems is therefore the facile decomposition and deactivation of such complexes, which can lead to poor catalyst performance [2] thereby making the use of high Pd loading (2—12 mol%) necessary [3—9]. It is therefore desirable to design catalysts that are both chemically stable and catalytically active. One way of achieving this is through the use of hemilabile supporting ligands.

The concept of hemilability was introduced in the 1970's by Rauchfuss [10,11] to describe multidentate ligands that 'would bind well enough to the metal centre to allow isolation of the complex, but would readily dissociate the hard end component thus gener-ating a vacant site for substrate binding' [12]. This is a particularly desirable characteristic for complexes which might have applica-tion in catalysis, and since the majority of metals used in such systems are middle or late transition metals, it is usually the soft donor atom which is continually bound to the metal centre [13]. An important property of these ligands is that they can stabilize metal

ions in a variety of oxidation states and geometries, which normally form during the catalytic cycle [10]. In addition, the hard donor sites are weakly coordinated to the soft metal centre, and can be easily dissociated in solution, affording a vacant site whenever demanded, whereas the chelate effect confers stability to the catalyst precursor in the absence of substrate [10] thereby preventing catalyst decomposition/deactivation.

Over the past few decades, interest in metal complexes of this type of ligands, which are essentially functionalized phosphine ligands, and their role in catalysis has been steadily growing as the different features associated with each donor atom confer unique properties to their metal complexes [13–16]. Unlike homo-donor chelate ligands, hetero-donor ligands have a distinct *trans* effect which can play a role in controlling the selectivity/activity, especially in co- and/or homo-polymerization processes [17]. The syntheses and reactivity/catalytic activity of complexes bearing hemilabile ligands of the type P^N [10,18] and P^O [19] have been widely reported.

Of these heterodentate ligands, those bearing phosphorus and nitrogen as their donor atoms have emerged as an important class of ligands [18]. The π-acceptor ability of the phosphine can stabilize a metal centre in a low oxidation state, while the nitrogen σ-donor ability makes the metal centre more susceptible to oxidative addition reactions. This electronic asymmetry can also be used to optimize a ligand for a particular reaction by appropriate choice of the nature of the donor atoms. For example, binding the phosphorus atom directly to a more electronegative atom such as oxygen or nitrogen [18,20] will reduce its electron donating capability while also enhancing its π-acceptor capacity. On the other hand, the presence of an imino rather than amino group will result in a nitrogen donor atom of greater δ-donating capabilities [18,21]. Moreover, these types of ligand allow modulation of the steric crowding around the metal centre through the simple variation of the substituents on the imine and phosphine groups [22]. Recent years have seen an increase in the amount of research on the synthesis and application of iminophosphine complexes as catalysts for coupling reactions and it has been found that these complexes show great promise [9,23–28].

We recently reported the use of well-defined neutral iminophosphine Pd(II) complexes in ethylene oligomerization reactions [29]. We, herein, report the use of these complexes with hemilabile iminophosphine ligands as pre-catalysts in Suzuki–Miyaura coupling reactions using low catalyst loadings under relatively mild reaction conditions. The tested complexes show tolerance of a wide variety of conditions, including different solvents, bases, substituents on both the phenylboronic acid and the aryl halides used.
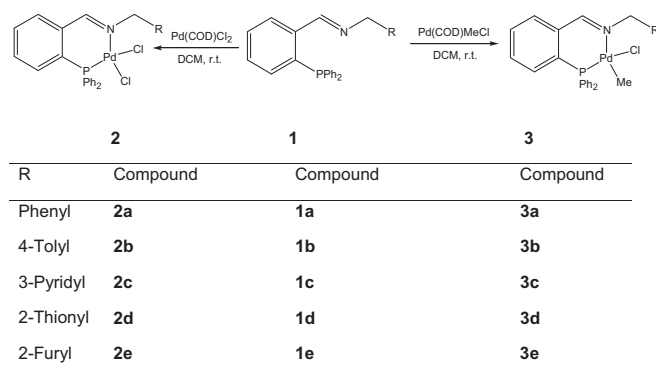
2. Results and discussion

2.1. Preparation of the iminophosphine ligands *1a–1e* and complexes *2a–2e*

We recently reported the preparation and characterization of the iminophosphine ligands **1a–1e** as well as their palladium dichloride complexes **2a–2e** and the activity of these complexes as pre-catalysts in ethylene oligomerisation reactions [29]. In this report, we present the preparation and characterization of analogous palladium chloromethyl complexes (**3a–3e**) based on the same ligands and investigate the application of both types of complexes in the Suzuki–Miyaura reaction (Scheme 1).

2.2. Preparation of the Pd(P^N)MeCl complexes *3a–3e*

The reaction of Pd(COD)MeCl with the appropriate iminophosphine ligands gave the desired palladium methylchloride

R	Compound	Compound	Compound
	2	**1**	**3**
Phenyl	**2a**	**1a**	**3a**
4-Tolyl	**2b**	**1b**	**3b**
3-Pyridyl	**2c**	**1c**	**3c**
2-Thionyl	**2d**	**1d**	**3d**
2-Furyl	**2e**	**1e**	**3e**

Scheme 1. Preparation of iminophosphine palladium dichloride (**2a–2e**) [29] and chloromethyl complexes (**3a–3e**).

complexes as air and moisture-stable crystalline solids in moderate to good yields (65–79%). Similar trends are observed in the characterization data of both the reported palladium dichloride [29] and palladium chloromethyl complexes (Table 1). In the ^{1}H NMR spectra of the chloromethyl complexes, the signals for the imine protons appear as singlets in the region δ 8.16–8.80 ppm (Table 1). Upon ligand coordination there is an upfield shift from δ 8.98–9.05 ppm (observed in the free ligand) and this upfield shift has been attributed to the conformational change that occurs in the ligand upon chelation [15,19,21d]. A similar trend was observed for the dichloride complexes, where an upfield shift of the signals for the imine protons to δ 8.52–8.84 ppm was observed [29]. As in the dichloride complexes, a downfield shift to δ 5.09–5.49 ppm is observed for the methylene protons (N-CH_2-R) upon chelation. A slightly bigger downfield shift (to δ 5.47–5.69 ppm) was observed for the same protons in the palladium dichloride complexes due to the deshielding that occurs for these protons when the adjacent imine group coordinates to the metal centre. The deshielding is, therefore, more significant for the palladium dichloride complexes as there is less electron density on the metal centre in the dichloride complexes due to the electronegative chlorido-ligands than there is in analogous palladium chloromethyl complexes. For both the dichloride and chloromethyl complexes, there is only a slight effect on the signals for the thiophenyl and furfuryl protons, indicating that these groups do not participate in coordinating to the metal centre. The signals for the methyl protons in Pd-Me appear as doublets in the region δ 0.21–0.61 ppm, with coupling constants of $^3J_{HP}$ = 2.4–3.2 Hz. As a result of the different *trans* influence of the two donor atoms in the ligands, the phosphine is expected to coordinate trans to the chloride. This coordination mode is demonstrated by the small coupling constants between the phosphorus and the Pd-Me protons [15,30–32].

In the ^{13}C NMR spectrum of the methylchloride complexes, the signals for the imine carbons are found in the region 162.4–164.7 ppm (Table 1). This is a downfield shift from 160.6 to 161.4 ppm observed for the free ligands, further confirming the coordination of the imine group to the metal centre [21d]. On the contrary, there is an upfield shift of 1.5–3.2 ppm with respect to the free ligand in the signals for the methylene carbons upon coordination to the metal centre [33]. The signals for the Pd-Me occur as a singlet at δ 0.62–2.9 ppm, which is comparable to similar complexes [30]. The downfield shift of the phosphine signals from −13.4 to −14.5 ppm in the free ligands to 37.4–38.3 ppm in the ^{31}P NMR spectra of the complexes reflects the coordination of the phosphine to the palladium [15,34–36]. This downfield shift is slightly more significant for the