Mechanistic study on the coupling reaction of aryl bromides with arylboronic acids catalyzed by (iminophosphine)palladium(0) complexes. Detection of a palladium(II) intermediate with a coordinated boron anion

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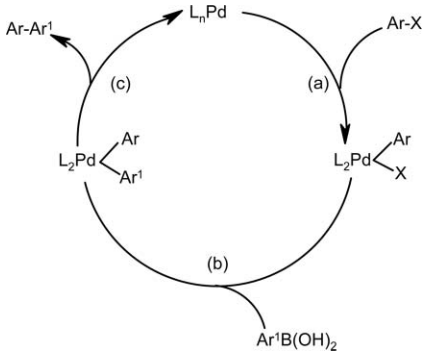
The complexes [Pd(η^2-dmfu)(P–N)] [P–N = 2-(PPh_2)C_6H_4-1-CH=NR, R = C_6H_4OMe-4; $CHMe_2$; $C_6H_3Me_2$-2,6; $C_6H_3(CHMe_2)$-2,6] react with an excess of $BrC_6H_4R^1$-4 (R^1 = CF_3; Me) yielding the oxidative addition products [PdBr($C_6H_4R^1$-4)(P–N)] at different rates depending on R [C_6H_4OMe-4 > $C_6H_3(CHMe_2)$-2,6 > $CHMe_2$ ≈ $C_6H_3Me_2$-2,6] and R^1 (CF_3 ≫ Me). In the presence of K_2CO_3 and activated olefins (ol = dmfu, fn), the latter compounds react with an excess of 4-$R^2C_6H_4B(OH)_2$ (R^2 = H, Me, OMe, Cl) to give [Pd(η^2-ol)(P–N)] and the corresponding biaryl through transmetallation and fast reductive elimination. The transmetallation proceeds *via* a palladium(II) intermediate with an O-bonded boron anion, the formation of which is markedly retarded by increasing the bulkiness of R. The intermediate was isolated for R = $CHMe_2$, R^1 = CF_3 and R^2 = H. The boron anion is formulated as a diphenylborinate anion associated with phenylboronic acid and/or as a phenylboronate anion associated with diphenylborinic acid. In general, the oxidative addition proceeds at a lower rate than transmetallation and represents the rate-determining-step in the coupling reaction of aryl bromides with arylboronic acids catalyzed by [Pd(η^2-dmfu)(P–N)].

Introduction

The palladium-catalyzed cross-coupling between organic electrophiles and organoboron compounds (Suzuki–Miyaura reaction) is a very efficient and widely used method for the formation of carbon–carbon bonds.[1] In particular, when aryl halides and arylboronic acids are used, the reaction yields biaryls,[1,2] which are important intermediates for the synthesis of more complex molecules widely used as pharmaceuticals, agrochemicals or advanced materials.

The commonly accepted mechanism of this reaction involves an initial oxidative addition of the aryl halide to a palladium(0) species, followed by transfer of the aryl group from the boronic acid to the palladium(II) centre (transmetallation) and eventually by reductive elimination to give the biaryl product and regenerate the catalytically active palladium(0) species (Scheme 1).[3]

The key step of the catalytic cycle is represented by the particular type of transmetallation, step (b), because the oxidative addition, step (a), and reductive elimination, step (c), are also commonly found in other catalytic reactions leading to carbon–carbon bond formation, *e.g.* the coupling of organic electrophiles with organostannanes (Stille reaction).[4] In spite of its importance, the mechanism of the transmetallation step is not completely clear. In aqueous alkaline solutions, the transmetallation was proposed to proceed through the interaction of the hydroxoboronate anion $Ar^1B(OH)_3^-$ with the oxidative addition product [PdX(Ar)(L_2)].[3]



Scheme 1

An alternative mechanism involves the reaction of the arylboronic acid with the complex [Pd(OR)(Ar)(L_2)] *in situ* formed by ligand exchange between [PdX(Ar)(L_2)] and the base RO^- (alkoxide, hydroxide or carboxylate anion).[3]

Following our studies on the catalytic activity of the zerovalent complexes [Pd(η^2-dmfu)(P–N)] [dmfu = dimethyl fumarate; P–N = 2-(PPh_2)C_6H_4-1-CH=NR, R = alkyl or aryl group],[5] we have recently reported that these complexes are quite efficient catalysts (or catalyst precursors) in the coupling of arylboronic acids with aryl bromides (turnover numbers of up to 10^5 h^{-1} in anhydrous toluene at 110 °C, in the presence of K_2CO_3).[6] With a suitable choice of the reaction conditions, an almost complete conversion of the substrates to biaryls can be obtained also when deactivating groups are present on the aryl bromide. These results prompted us to carry out a mechanistic investigation of the fundamental steps of the catalytic cycle of Scheme 1 in order to achieve a better understanding of (i) the factors which affect the

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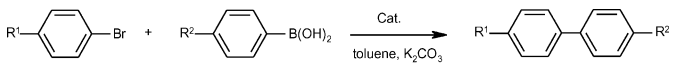
reaction rates and (ii) the mechanism of the transmetallation step, because the formation of the anion $Ar^1B(OH)_3^-$ or the complex $[Pd(OR)(Ar)(L)_2]$ can hardly occur under the catalysis conditions used.

Results and discussion

The model reaction chosen for the mechanistic study is reported in eqn (1):



$R^1 = CF_3$, Me

R^2 = Cl, H, Me, OMe

(1)

The zerovalent complexes [Pd(η^2-ol)(P–N)] [ol = dimethyl fumarate (dmfu) or fumaronitrile (fn); P–N = iminophosphine] used as catalysts are shown in Scheme 2. Where possible, the reactions of the single steps of the cycle in Scheme 1 have been carried out in dry toluene (or toluene-d_8) at 90 °C in a N_2 atmosphere under pseudo-first-order conditions, generally using a palladium complex/reactant molar ratio of 1:10 with an initial palladium complex concentration of 1×10^{-2} mol dm^{-3}. The progress of the reactions was monitored by IR spectroscopy in the range 2400–1500 cm^{-1} and by ^{31}P NMR spectroscopy.

Step (a): oxidative addition

The reactions studied are summarized in Scheme 3.

With a ten-fold excess of $BrC_6H_4R^1$-4, the completion times of Table 1 were evaluated by IR and ^{31}P NMR spectra at different times.

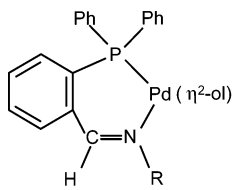
For the dmfu complexes **1a–4a**, the progress of the reaction was indicated by the increasing intensity of the ν(C=O) band of free dmfu at 1725 cm^{-1} and the concomitant decreasing intensity of the ν(C=O) band the η^2-bound dmfu at 1685 cm^{-1}. For the fn complex **5a**, the decreasing intensity of the ν(C≡N) band of the η^2-bound olefin at 2203 cm^{-1} was monitored. In the ^{31}P NMR spectra, the $\delta(^{31}P)$ singlet of the starting complexes **1a–4a** (in the range 19.3–23.2 ppm) progressively disappears with concomitant formation of the $\delta(^{31}P)$ singlet of the products **1b–5b** in the range 20.7–28.0 ppm. Even though the reactions are accompanied by a slight decomposition to palladium metal, the completion times evaluated from IR data are very close to those obtained from ^{31}P NMR spectra.

Table 1 Completion times for reaction (2) of Scheme 3[a]

Complex	Aryl bromide	Product	Completion time
1a	$BrC_6H_4CF_3$-4	**1b**	*ca.* 15 min
2a	$BrC_6H_4CF_3$-4	**2b**	*ca.* 55 min
2a	BrC_6H_4Me-4	**5b**	*ca.* 7 h
3a	$BrC_6H_4CF_3$-4	**3b**	*ca.* 60 min
4a	$BrC_6H_4CF_3$-4	**4b**	*ca.* 35 min
5a	$BrC_6H_4CF_3$-4	**1b**	*ca.* 20 h

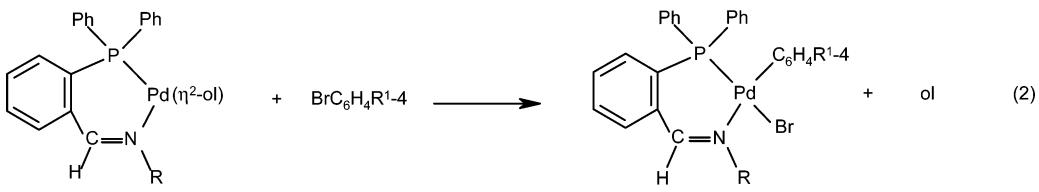
[a] For a molar ratio **1a–5a**/aryl bromide of 1:10 in toluene at 90 °C.

As expected, in the reactions of **2a** with $BrC_6H_4R^1$-4 the rate decreases considerably on going from $R^1 = CF_3$ to R^1 = Me in agreement with a lower electrophilic character of the C–Br carbon atom. The rate of the oxidative addition of $BrC_6H_4CF_3$-4 to complexes **1a–5a** depends essentially on the electronic and steric properties of the imino nitrogen substituent R and on the π-accepting properties of the olefin as it decreases in the order **1a** > **4a** > **2a** ≈ **3a** ≫ **5a**. This trend closely parallels that found for the analogous oxidative additions of $IC_6H_4CF_3$-4: **1a** > **2a** ≫ **5a**.[7] From a kinetic study of the latter reactions,[7] this trend was rationalized in terms of electronic effects which reduce the electron density on the central metal and increase the strength of the Pd–olefin and Pd–N bonds, on the basis of the following



R	ol		
C_6H_4OMe-4	dmfu	:	**1a**
$CHMe_2$	dmfu	:	**2a**
$C_6H_3Me_2$-2,6	dmfu	:	**3a**
$C_6H_3(CHMe_2)_2$-2,6	dmfu	:	**4a**
C_6H_4OMe-4	fn	:	**5a**

Scheme 2



1a - 5a

1b: R = C_6H_4OMe-4 $R^1 = CF_3$

2b: R = $CHMe_2$ $R^1 = CF_3$

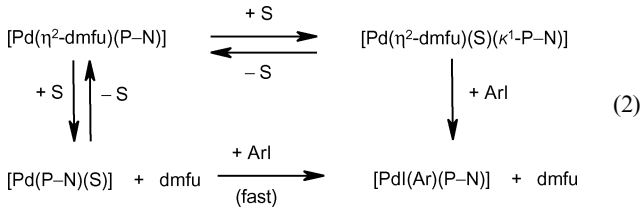
3b: R = $C_6H_3Me_2$-2,6 $R^1 = CF_3$

4b: R = $C_6H_3(CHMe_2)_2$-2,6 $R^1 = CF_3$

5b: R = $CHMe_2$ $R^1 = CH_3$

Scheme 3

mechanism:



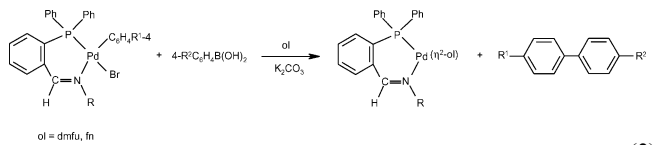
(2)

where S is a solvent molecule and [Pd(η²-dmfu)(S)(κ¹-P–N)] is an intermediate containing a P-monodentate iminophosphine. From the data presented it can be seen that steric effects are also important, but a clear trend cannot be recognized. As a matter of fact, for the complexes **1a**, **3a** and **4a**, containing N–aryl substituents, the rate decreases on going from **1a** (R = C_6H_4OMe-4) to **3a** (R = $C_6H_3Me_2$-2,6), *i.e.* with increasing the steric bulk of the N–aryl group, and this effect can be understood on the basis of the proposed mechanism which involves a solvent assisted rupture of the Pd–olefin and Pd–N bonds. By contrast, an increased rate is observed on going from **3a** to **4a** [R = $C_6H_3(CHMe_2)_2$-2,6] where the steric requirements of the N–aryl group are further increased. In a possible rationalization, this may be attributed to an intramolecular steric clash between the isopropyl groups and dmfu which would favour the olefin dissociation and/or the Pd–N bond breaking. However, this explanation needs to be confirmed by further kinetic measurements.

All the complexes **1b–5b** have been isolated and characterized (see Experimental). These palladium(II) derivatives may exist as two geometrical isomers depending on the relative position of the bromide and aryl ligands. The available spectroscopic data indicate the presence of a major isomer (*ca.* 96%) and of a minor one for **4b** and of a single isomer for the other complexes. A single isomer is also observed for the chloride analogues [PdCl($C_6H_4R^1$-4)(P–N)] [P–N = 2-(PPh_2)C_6H_4-1-CH=NCHMe$_2$; R^1 = CF_3 (**2c**), Me (**5c**)] which can be prepared by different methods (see Experimental). According to X-ray structural analyses of the related compounds [PdI(Ph)(P–N)] [P–N = 2-(PPh_2)C_6H_4-1-CH=NR; R = Me, Et],[8] a configuration with the aryl ligand *trans* to the imino nitrogen is proposed for the predominant isomer in the above complexes of the type [PdX(Ar)(P–N)] (X = Cl, Br). The assignment is further supported by the low-frequency values of the ν(Pd–Cl) bands of **3c** and **5c** at 284 and 270 cm^{-1}, respectively, indicating that the chloride ion is *trans* to a ligand of high *trans* influence such as the phosphorus atom of the iminophosphine.[9]

Steps (b) and (c): transmetallation and reductive elimination

In dry toluene, the complexes **1b–5b** react with arylboronic acids in the presence of an activated olefin and anhydrous K_2CO_3 according to eqn (3):



(3)

Despite the presence of solid K_2CO_3, the progress of the reactions can be followed by IR and ^{31}P NMR spectroscopy in toluene and toluene-d_8, respectively.

The completion times (Table 2) are not influenced by the nature of the olefin nor by its concentration: for **2b**, the reaction goes to completion in *ca.* 20 min when a **2b**/ol molar ratio of 1 : 1.5 is used with ol = dmfu or fn, and also when the molar ratio **2b**/ol is increased to 1 : 10. For this reason and for the greater thermal stability of the complexes [Pd(η²-fn)(P–N)] towards decomposition, fumaronitrile was used as the olefin in reaction (3). A comparison of the completion times of Table 2 with those of Table 1 shows that the oxidative addition is generally the rate-determining step in the catalytic cycle of reaction (1) under the experimental conditions of this work, the only exception being the coupling of $BrC_6H_4CF_3$-4 with 4-$ClC_6H_4B(OH)_2$ when **2a** is used as catalyst.

Table 2 Completion times for reaction (3)[a]

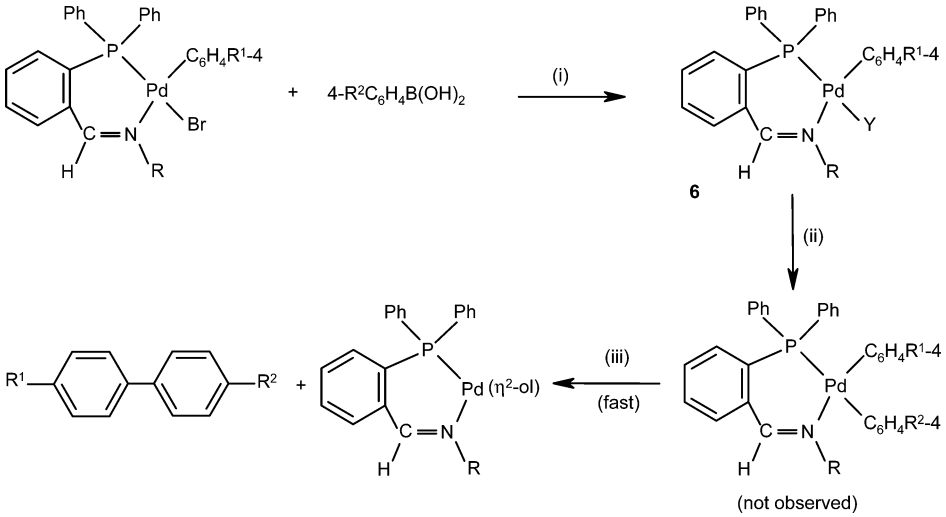
Complex	R	R^1	R^2	ol	T/min
1b	C_6H_4OMe-4	CF_3	H	fn	*ca.* 5
2b	$CHMe_2$	CF_3	H	dmfu	*ca.* 20
2b	$CHMe_2$	CF_3	H	fn	*ca.* 20
2b	$CHMe_2$	CF_3	Me	fn	*ca.* 7
2b	$CHMe_2$	CF_3	OMe	fn	< 5
2b	$CHMe_2$	CF_3	Cl	fn	> 90
3b	$C_6H_3Me_2$-2,6	CF_3	H	fn	*ca.* 35
4b	$C_6H_3(CHMe_2)_2$-2,6	CF_3	H	fn	*ca.* 30
5b	$CHMe_2$	Me	H	fn	*ca.* 40

[a] For initial mixtures **1b–5b**/4-$R^2C_6H_4B(OH)_2$/K_2CO_3/ol in a 1 : 10 : 20 : 1.5 molar ratio at 90 °C in toluene.

As commonly accepted,[3] the formation of the biaryl and the complex [Pd(η²-ol)(P–N)] occurs through aryl transfer from the boronic acid to the palladium(II) centre of **1b–5b** (transmetallation) to give a labile intermediate [Pd($C_6H_4R^1$-4)($C_6H_4R^2$-4)(P–N)]. The subsequent reductive elimination of the biaryl generates a coordinatively unsaturated Pd(P–N) fragment which is stabilized by η²-coordination of the olefin. During our experiments, however, signals stemming from an intermediate of the type [Pd($C_6H_4R^1$-4)($C_6H_4R^2$-4)(P–N)] were never detected in the ^{31}P NMR spectra of the reaction mixtures. This implies that reductive elimination and olefin coordination are much faster than transmetallation. By contrast, the ^{31}P NMR spectra shows the initial formation of a palladium(II) intermediate containing a coordinated boron anion which undergoes the transmetallation step (see later). Thus, the overall reaction (3) consists of at least three consecutive steps as shown in Scheme 4.

The formation of an intermediate of the type **6** is particularly evident in the reaction of **2b** with $PhB(OH)_2$. At 25 °C and with a **2b**/$PhB(OH)_2$ molar ratio increasing from 1 : 3 to 1 : 10, the ^{31}P NMR spectra at different times show the progressive decrease of the δ(^{31}P) singlet of **2b** at 27.7 ppm and the simultaneous increase of the δ(^{31}P) singlet of **6** at 33.2 ppm [spectrum (a) of Fig. 1].

The rate of step (i) in Scheme 4 increases with increasing concentration of the arylboronic acid, and is also influenced by the steric requirements of the imino group R and by the electronic properties of the *para* substituent R^1 on the aryl ligand. The latter effect is observed in the spectrum (b) of Fig. 1. Under the same experimental conditions, in the reaction **5b**/$PhB(OH)_2$/K_2CO_3/dmfu (1 : 5 : 10 : 1.5 molar ratio) the intermediate of type **6** is formed more slowly (*ca.* 50% after 30 min from mixing of the reactants). Thus, the rate of step (i) decreases on going from **2b** (R^1=CF_3) to **5b** (R^1 = Me), *i.e.* when the electron-withdrawing CF_3 substituent on the aryl ligand is replaced by the



Scheme 4 (i) + K_2CO_3 − KBr, nucleophilic substitution; (ii) transmetallation; (iii) reductive elimination and olefin coordination; Y = boron anion (see further).

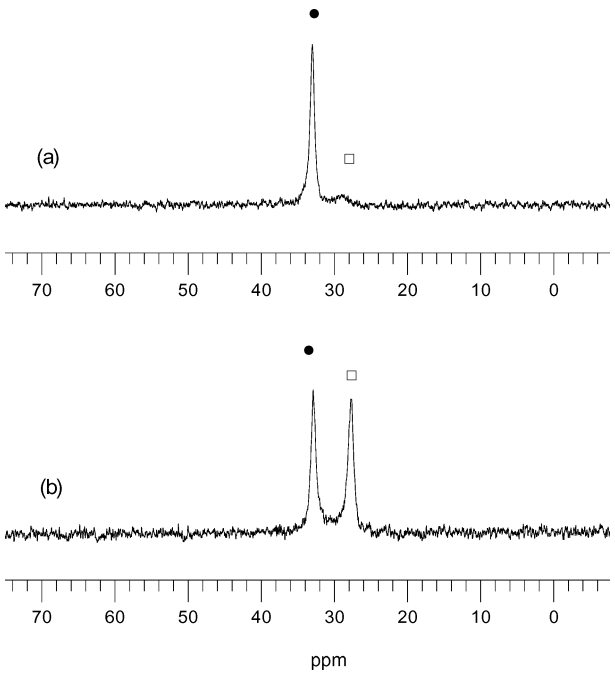


Fig. 1 (a) ^{31}P NMR spectrum of the reaction mixture **2b**/$PhB(OH)_2$/K_2CO_3/dmfu (1 : 5 : 10 : 1.5 molar ratio) in toluene-d_8 at 25 °C after 25 min from mixing of the reactants: ● signal of the intermediate **6**, □ signal of the starting complex **2b**. (b) ^{31}P NMR spectrum of the reaction mixture **5b**/$PhB(OH)_2$/K_2CO_3/dmfu (1:5:10:1.5 molar ratio) in toluene-d_8 at 25 °C after 25 min from mixing of the reactants: ● signal of the intermediate **6**, □ signal of the starting complex **5b**.

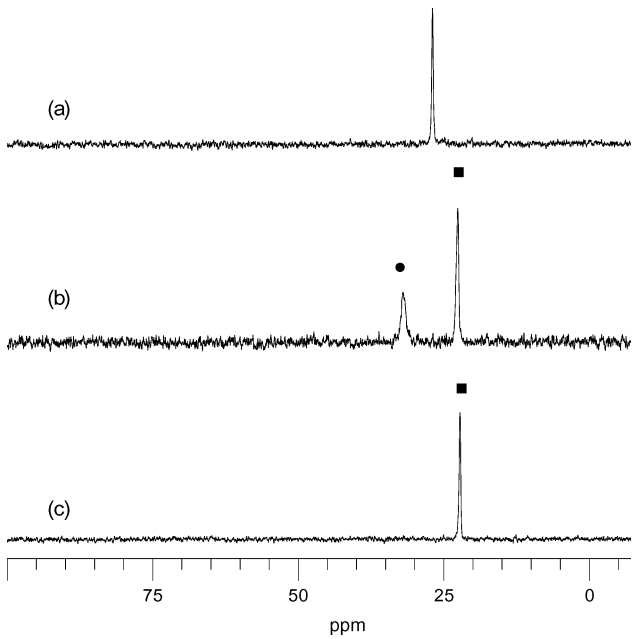


Fig. 2 (a) ^{31}P NMR spectrum of complex **2b** in toluene-d_8 at 90 °C. (b) and (c) ^{31}P NMR spectra of the reaction mixture **2b**/$PhB(OH)_2$/K_2CO_3/fn (1 : 10 : 15 : 1.5 molar ratio) in toluene-d_8 at 90 °C after 8 and 25 min, respectively, from the mixing of the reactants: ● signal of the intermediate **6**, ■ signal of the product [Pd(η^2-fn)(P–N)].

electron-donating Me group. At 90 °C and with a complex/aryl boronic acid molar ratio of 1 : 10, the formation of **6** is relatively fast in the reaction of **1b** (R = C_6H_4OMe-4) with $PhB(OH)_2$ and in the reactions of **2b** (R = $CHMe_2$) with 4-$R^2C_6H_4B(OH)_2$ (R_2 = H, Me, OMe, Cl). As can be seen in the spectra (a) and (b) of Fig. 2, the starting complex **2b** has completely disappeared after 8 min from the mixing of the reactants.

In the reactions of **3b** (R = $C_6H_3Me_2$-2,6) and **4b** [R = $C_6H_3(CHMe_2)_2$-2,6] with $PhB(OH)_2$, the intermediate of the type **6** is not observed during the course of reaction (3). In the ^{31}P NMR spectra of the reaction mixture at different times (Fig. 3), the decreasing $\delta(^{31}P)$ singlet of the starting complex and the increasing $\delta(^{31}P)$ singlet of the zerovalent product [Pd(η^2-fn)(P–N)] are the only observed signals throughout.

This can be ascribed to a marked rate decrease of step (i) relative to the subsequent step (ii) brought about by the greater steric hindrance towards nucleophilic substitution of the bromide ligand exerted by the bulkier N–aryl groups. From the present data it appears that formation of the intermediate **6** [step (i)] is rate-determining in reaction (3) of **3b** or **4b** with $PhB(OH)_2$, whereas transmetallation [step (ii)] is rate-determining in reaction (3) of

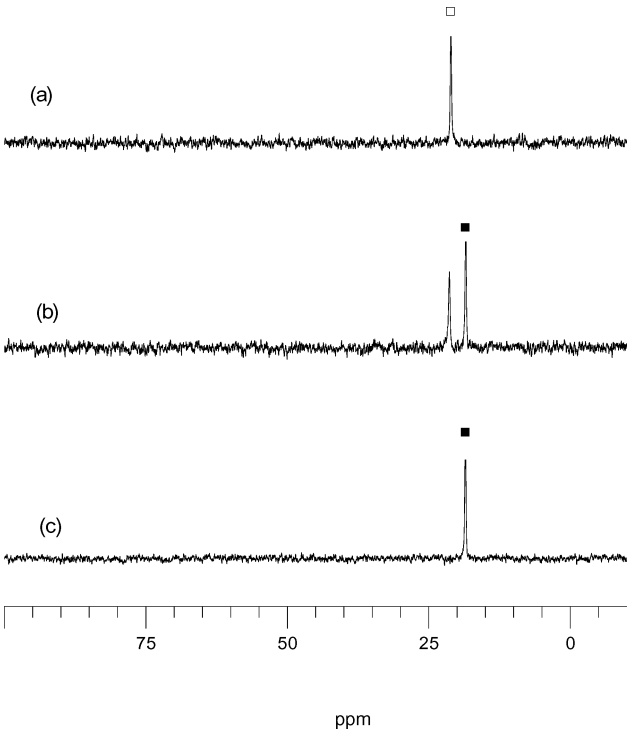


Fig. 3 (a) ^{31}P NMR spectrum of complex **3b** in toluene-d_8 at 90 °C. (b) and (c) ^{31}P NMR spectra of the reaction mixture **3b**/PhB(OH)$_2$/K_2CO_3/fn (1 : 10 : 15 : 1.5 molar ratio) in toluene-d_8 at 90 °C after 12 and 35 min, respectively, from the mixing of the reactants: □ signal of the starting complex **3b**, ■ signal of the product [Pd(η^2-fn)(P–N)].

1b with PhB(OH)$_2$ or of **2b** with 4-R^{2}C$_6$H$_4$B(OH)$_2$ (R^2 = H, Me, OMe, Cl). In the latter cases, the completion times of Table 2 give a measure of the reaction rates for the transmetallation step (ii). It is interesting to note that under comparable steric requirements the rate increases with increasing electron-withdrawing properties of the imino substituent R [**1b** (R = C$_6$H$_4$OMe-4) > **2b** (R = CHMe$_2$)] and with increasing electron-donating properties of the 4-R^2 group on the arylboronic acid.

Characterization of the intermediate 6b

The intermediate **6b** was isolated as an off-white microcrystalline solid from the reaction of **2b** with PhB(OH)$_2$ in the presence of K_2CO_3 (see Experimental). Unfortunately, the crystals proved unsuitable for X-ray analysis. Therefore, the caracterization is essentially based on elemental analysis, IR and multinuclear (^{1}H, ^{31}P, ^{11}B, ^{19}F) NMR spectra along with FAB mass spectra. The available data suggest a structure containing an O-bonded boron anion formed by a diphenylborinate anion associated with a molecule of phenylboronic acid (structure **I** of Fig. 4) or by a phenylboronate anion associated with a molecule of diphenylborinic acid (structure **II** of Fig. 4).

The IR spectrum in the solid and in $CHCl_3$ solution show the presence of different OH groups. In the solid, the ν(OH) vibrations are detected as a rather sharp band at 3627 cm^{-1} and as a much broader band at 3430 cm^{-1}, while a sharp band at 3596 cm^{-1} and a broader band at 3410 cm^{-1} are observed in solution. This pattern clearly indicates the presence of OH groups with the H atom not involved in hydrogen-bonding (higher frequency band) and OH groups with the H atom involved in hydrogen-bonding (lower frequency band). The integration of the ^{1}H NMR spectrum ($CDCl_3$) in the range 8.2–6.8 ppm gives a value of 35 in good agreement with the number of the phenyl and N=CH protons (34) resonating in that range. Significant structural information is afforded by the MS spectrum where the peaks at *m/z* 105 and 165 are assigned to the ions [PhBOH]$^+$ and [Ph$_2$B]$^+$, respectively, and the cluster of peaks centered at *m/z* 688 is assigned to the ion [Pd(OBPh)(C$_6$H$_4$CF$_3$-4)(P–N)]$^+$ [P–N = 2-(PPh$_2$)C$_6$H$_4$-1-CH=NCHMe$_2$]. Furthermore, clusters of peaks centered at *m/z* 436, 582 and 598 are also observed and assigned to the ions [Pd(P–N)]$^+$, [Pd(C$_6$H$_4$CF$_3$-4)(P–N)]$^+$ and [Pd(OH)(C$_6$H$_4$CF$_3$-4)(P–N)]$^+$, respectively.

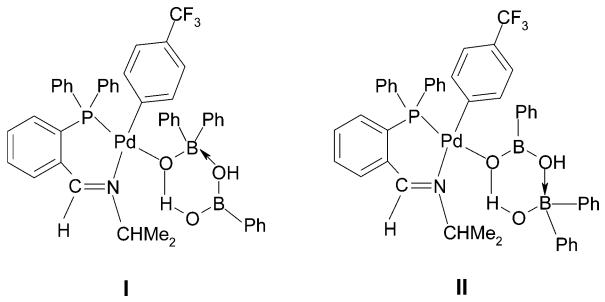


Fig. 4 Proposed structures for the intermediate **6b**.

In the temperature range −35 ÷ + 25 °C, the ^{19}F and ^{31}P NMR spectra show the presence of a sharp singlet only, while the ^{1}H NMR spectra are characterized by a single set of resonances. Accordingly, the intermediate **6b** may exist in solution either with a single structure or with both structures **I** and **II** in a fast interconversion (on the NMR timescale). Furthermore, in the ^{1}H NMR spectra the methyl protons of the N–CHMe$_2$ group appear as a single doublet indicating that the coordination plane around the palladium centre acts as a time-averaged symmetry plane[10] for the whole molecule, in accord with the proposed structures. The ^{11}B NMR spectrum of **6b** in Fig. 5 shows two broad signals at 31.8 and 7.4 ppm, which become somewhat sharper at higher temperatures.

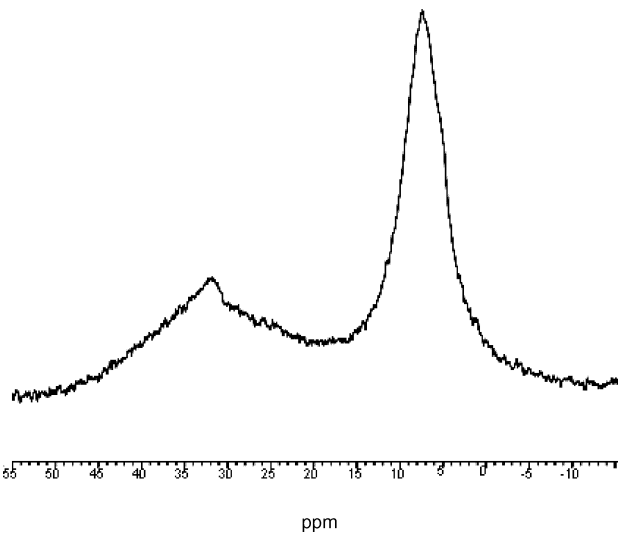


Fig. 5 ^{11}B NMR spectrum of **6b** in $CDCl_3$ at −10 °C.

From chemical shift considerations, the signal at 31.8 ppm is assigned to a three-coordinate ^{11}B centre whereas that at 7.4 ppm is assigned to a four-coordinate ^{11}B centre.[11]

If our formulation is correct, the presence of the Ph_2BO unit in the structures of the intermediate **6b** implies that a Ph/OH exchange has occurred between two $PhBO_2$ moieties in the course of the reaction [step (i) of Scheme 4]. We have therefore studied the interaction of $PhB(OH)_2$ with anhydrous K_2CO_3 in toluene-d_8 [spectra (a) and (b) of Fig. 6].

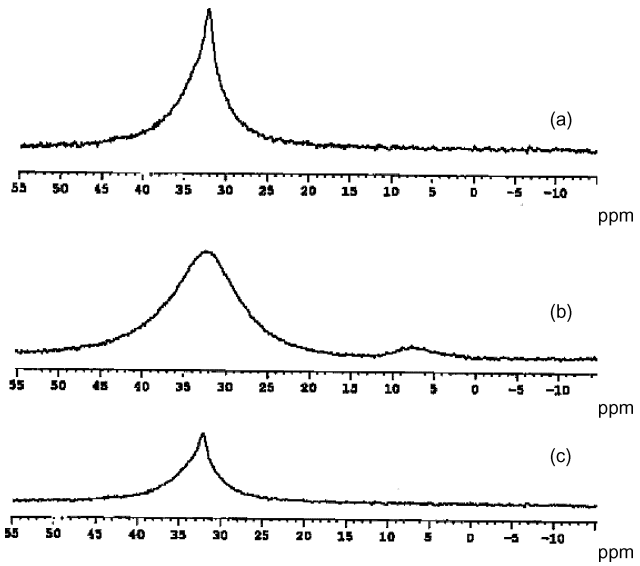


Fig. 6 ^{11}B NMR spectra of $PhB(OH)_2$ at 25 °C: (a) in toluene-d_8; (b) in toluene-d_8 saturated with anhydrous K_2CO_3; (c) in $CDCl_3$.

As can be seen, in the presence of K_2CO_3 the signal of the phenylboronic acid at 32.0 ppm considerably broadens and a new broad resonance appears at 7.4 ppm suggesting that a four-coordinate boron anion is formed. From the close similarity in the ^{11}B chemical shifts, it is likely that such an anion is also present in the structure of **6b**.

In the intermediate, the boron anion is weakly bound to the metal centre as it can be completely displaced by chloride anions [reaction (1) of scheme 5].

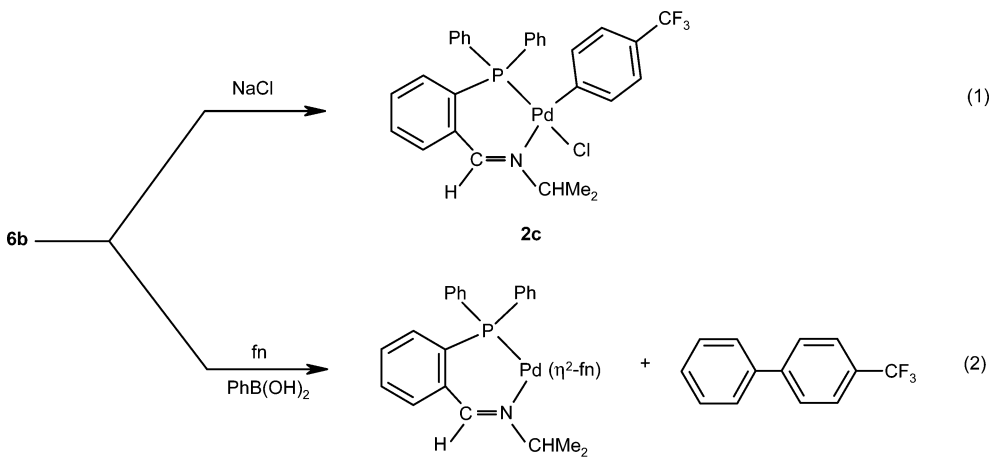
The intermediacy of **6b** in the catalytic cycle is confirmed by the reaction (2) of Scheme 5, which occurs in *ca.* 20 min when the complex is heated at 90 °C in toluene in the presence of fumaronitrile and $PhB(OH)_2$ with a **6b**/$PhB(OH)_2$/fn molar ratio of 1 : 7 : 1.5 [*cf.* the completion time of *ca.* 20 min for the reaction (3) of **2b**, under comparable experimental conditions].

Conclusion

From the present mechanistic study it appears that in the cross-coupling of arylboronic acids with aryl bromides catalyzed by [Pd(η^2-ol)(P–N)] the oxidative addition of the aryl bromide is generally the rate-determining step of the catalytic cycle. Thus, the greater catalytic activity displayed by the zerovalent complexes with ol = dmfu and with an imino N–aryl group of low steric requirements, such as Ph and C_6H_4OMe-4,[6] can be related to the higher rates of their reactions with ArBr. The oxidative addition products [PdBr(Ar)(P–N)] react with arylboronic acids in the presence of K_2CO_3 and of an activated olefin yielding the corresponding biaryls and regenerating the starting complexes [Pd(η^2-ol)(P–N)] by transmetallation followed by fast reductive elimination and η^2-coordination of the olefin. The transmetallation step proceeds through the intermediacy of a complex containing an O-bonded boron anion which is formulated as an arylboronate anion associated with a molecule of diarylborinic acid and/or a diarylborinate anion associated with a molecule of arylboronic acid.

Experimental

^1H, ^{31}P and ^{19}F NMR spectra were recorded on a Bruker AM400 spectrometer operating at 400.13, 161.98 and 376.50 MHz, respectively. The ^{11}B NMR spectra were recorded on a Bruker AMX300 spectrometer operating at 96.25 MHz. Chemical shifts are reported in ppm downfield from $SiMe_4$ for ^1H, from H_3PO_4 as external standard for ^{31}P, from $CFCl_3$ as external standard for ^{19}F and from $BF_3{\cdot}Et_2O$ as external standard for ^{11}B. The spectra were run at 25 °C except when noted. IR spectra were recorded on a Perkin–Elmer 983G spectrophotometer. The FAB mass spectra in a matrix of 3-nitrobenzyl alcohol were obtained with a VG Quattro Micromass spectrometer. All the



Scheme 5

reactions were carried out under N_2. Toluene was distilled from sodium/benzophenone and methanol was dried over magnesium turnings.[12] The aryl bromides $BrC_6H_4R^1$-4 (R^1 = CF_3, Me), the arylboronic acids 4-$R^2C_6H_4B(OH)_2$ (R^2 = H, Me, OMe, Cl), the olefins dmfu and fn, and the anhydrous potassium carbonate are commercially available and were used without further purification. The complexes [Pd(η^2-ol)(P–N)] (**1a–5a**) were prepared as reported in the literature.[5c,13]

Synthesis of [PdBr($C_6H_4R^1$-4)(P–N)] (1b–5b)

The complex [Pd(η^2-dmfu)(P–N)] **1a–4a** (0.5 mmol) and the aryl bromide $BrC_6H_4CF_3$-4 (1.13 g, 5 mmol) were dissolved in toluene (50 cm^3). The mixture was heated at 110 °C (5 min for **1a** and **4a**, 10 min for **2a** and **3a**) and then rapidly cooled at room temperature to minimize decomposition. The solvent was removed at reduced pressure and the solid residue was extracted with CH_2Cl_2 (2 × 20 cm^3). After addition of activated charcoal and filtration, the solution was evaporated to about 3 cm^3. Upon addition of Et_2O, the product precipitated as a pale-yellow solid. The complex **5b** was prepared in a similar manner starting from **2a** (0.58 g, 0.5 mmol) and BrC_6H_4Me-4 (1.71 g, 10 mmol) and heating the mixture at 110 °C for 20 min. All the compounds were further purified by recrystallization from CH_2Cl_2/Et_2O.

Complex 1b. (0.24 g, 66%) (Found C 54.18, H 3.40, N 1.94%; $C_{33}H_{26}BrF_3NOPPd$ requires C 54.53, H 3.61, N 1.93%); ν_{max}/cm^{-1} (C=N) 1611 ms (Nujol); δ_H ($CDCl_3$) 8.21 (1 H, s, N=CH), 7.8–7.1 (18 H, m, aryl protons), 6.94–6.90 (2 H, m, *m*-H of C_6H_4OMe-4), 6.87–6.83 (2 H, m, *m*-H of $C_6H_4CF_3$-4), 3.83 (3 H, s, OCH_3), δ_P ($CDCl_3$) 28.3 (s).

Complex 2b. (0.26 g, 78%) (Found C 52.74, H 3.71, N 2.20%; $C_{29}H_{26}BrF_3NPPd$ requires C 52.53, H 3.95, N 2.11%); ν_{max}/cm^{-1} (C=N) 1628 ms (Nujol); δ_H ($CDCl_3$) 8.15 (1 H, s, N=CH), 7.8–7.1 (16 H, m, aryl protons), 6.88–6.84 (2 H, m, *m*-H of $C_6H_4CF_3$-4), 5.48 (1 H, spt, ^3J(HH) = 6.4 Hz, CHMe), 1.25 (6 H, d, ^3J(HH) = 6.4 Hz, CH_3); δ_P ($CDCl_3$) 28.7 (s); δ_F (toluene-d_8) −61.54 (s).

Complex 3b. (0.27 g, 75%) (Found C 56.14, H 3.80, N 1.95%; $C_{34}H_{28}BrF_3NPPd$ requires C 56.33, H 3.89, N 1.93%); ν_{max}/cm^{-1} (C=N) 1622 m (Nujol); δ_H ($CDCl_3$) 8.27 (1 H, s, N=CH), 7.9–7.0 (19 H, m, aryl protons), 6.87–6.83 (2 H, m, *m*-H of $C_6H_4CF_3$-4), 2.37 (6 H, s, CH_3); δ_P ($CDCl_3$) 22.7 (s).

Complex 4b. (0.22 g, 56%) (Found C 58.31, H 4.39, N 1.80%; $C_{38}H_{36}BrF_3NPPd$ requires C 58.44, H 4.65, N 1.79%); ν_{max}/cm^{-1} (C=N) 1609 m (Nujol); δ_H ($CDCl_3$) major isomer: 8.28 (1 H, s, N=CH), 7.9–7.0 (19 H, m, aryl protons), 6.83–6.79 (2 H, m, *m*-H of $C_6H_4CF_3$-4), 3.23 (2 H, spt, ^3J(HH) = 6.8 Hz), $CHMe_2$), 1.50 (6 H, d, ^3J(HH) = 6.8 Hz, CH_3) 0.94 (6 H, d, ^3J(HH) = 6.8 Hz, CH_3), minor isomer: 8.12 (s, N=CH), 3.10 (spt, ^3J(HH) = 6.8 Hz, $CHMe_2$), 1.41 (d, ^3J(HH) = 6.8 Hz, CH_3), 0.80 (d, ^3J(HH) = 6.8 Hz, CH_3); δ_P ($CDCl_3$) major isomer: 22.1 (s), minor isomer: 23.9 (s).

Complex 5b. (0.21 g, 70%) (Found C 56.81, H 4.60, N 2.33%; $C_{29}H_{29}BrNPPd$ requires C 57.21, H 4.80, N 2.30%); ν_{max}/cm^{-1} (C=N) 1627 m (Nujol); δ_H ($CDCl_3$) 8.13 (1 H, s, N=CH), 7.8–7.0 (16 H, m, aryl protons), 6.53–6.49 (2 H, m, *m*-H of C_6H_4Me-4), 5.47 (1 H, spt, ^3J(HH) = 6.4 Hz, $CHMe_2$), 2.06 (3 H, s, CH_3), 1.21 (6 H, d, ^3J(HH) = 6.4 Hz, CH_3); δ_P ($CDCl_3$) 26.8 (s).

Preparation of the intermediate 6b

A mixture of complex **2b** (0.33 g, 0.5 mmol), $PhB(OH)_2$ (0.31 g, 2.5 mmol), anhydrous K_2CO_3 (0.69 g, 5 mmol) and dmfu (0.07 g, 0.5 mmol) in dry toluene (50 cm^3) was stirred at room temperature for 45 min. The insoluble material was filtered off and the solution was evaporated to dryness at 20 °C under reduced pressure. The solid residue was dissolved in anhydrous methanol (*ca.* 6 cm^3). After stirring for a few minutes an off-white product precipitated. The product was purified by recrystallization from toluene/*n*-hexane (1 : 1.5 v/v) at −20 °C. The compound must be stored at −20 °C because it decomposes slowly at room temperature. Freshly recrystallized samples were used for each measurement. A certain amount of dmfu in the reaction mixture is required in order to prevent the formation of metallic palladium from further reactions of the intermediate. The presence of Br^- ions in the insoluble material resulting from the initial filtration of the reaction mixture in toluene was ascertained by qualitative analysis with $AgNO_3$.

Any attempt to isolate intermediates of type **6** from analogous reactions of **2b** with 4-$R^2C_6H_4B(OH)_2$ (R^2 = Me, OMe, Cl) or of **5b** with $PhB(OH)_2$ failed because of the greater solubility of the intermediates in methanol.

Intermediate 6b. (0.20 g, 45%) (Found C 63.28, H 4.86, N 1.45%; $C_{47}H_{43}B_2F_3NO_3PPd$ requires C 63.72, H 4.89, N 1.58%); ν_{max}/cm^{-1} (O–H) 3627 m, 3430 m (br), (B–O) 1322 vs, (C=N) 1637 m (Nujol); δ_H ($CDCl_3$) 8.1–6.8 (35 H, m, aryl protons and N=CH), 5.20 (1 H, spt, ^3J(HH) = 6.4 Hz, $CHMe_2$), 2.20 (0.8 H, s, OH), 1.17 (6 H, d, ^3J(HH) = 6.4 Hz, CH_3); δ_P (toluene-d_8) 33.2 (s), ($CDCl_3$) 32.8 (s); δ_F (toluene-d_8) −62.01 (s). Selected MS peaks: *m*/*z* 105 (21%), 165 (18), 436 (12), 582 (70), 598 (38), 688 (20).

Reaction of 6b with aqueous NaCl

A saturated solution of NaCl in water (10 cm^3) was added to a solution of **6b** (60 mg, 0.068 mmol) in CH_2Cl_2 (10 cm^3). The mixture was vigorously stirred for 30 min at room temperature. The organic layer was separated, dried over anhydrous Na_2SO_4 and concentrated to a small volume (*ca.* 3 cm^3) at reduced pressure. Addition of Et_2O caused the precipitation of the off-white product **2c** which was reprecipitated from a CH_2Cl_2/Et_2O mixture.

Complex 2c. (34 mg, 82%) (Found C 55.94, H 3.95, N 2.25%; $C_{29}H_{26}ClF_3NPPd$ requires C 56.33, H 4.24, N 2.27%); ν_{max}/cm^{-1} (C=N) 1627 m, (Pd–Cl) 284 m (Nujol); δ_H ($CDCl_3$) 8.17 (1 H, s, N=CH), 7.8–7.1 (16 H, m, aryl protons), 6.90–6.85 (2 H, m, *m*-H of $C_6H_4CF_3$-4), 5.43 (1 H, spt, ^3J(HH) = 6.4 Hz, CHMe), 1.28 (6 H, d, ^3J(HH) = 6.4 Hz, CH_3); δ_P ($CDCl_3$) 30.1 (s).

Synthesis of [$PdCl_2$(2-(PPh_2)C_6H_4-1-CH=NCHMe_2)]

The iminophosphine 2-(PPh_2)C_6H_4-1-CH=NCHMe_2[5c] (0.17 g, 0.5 mmol) was added to a stirred solution of [$PdCl_2$(N≡CMe)$_2$][14] (0.13 g, 0.5 mmol) in CH_2Cl_2 (25 cm^3). After 30 min the solution was evaporated to *ca.* 3 cm^3 and diluted with Et_2O to precipitate the product as a yellow microcrystalline solid. The compound was reprecipitated from CH_2Cl_2/Et_2O (0.22 g, 86.5%) (Found C 51.75, H 4.21, N 2.65%; $C_{22}H_{22}Cl_2NPPd$ requires C 51.94, H 4.36, N 2.75%); ν_{max}/cm^{-1} (C=N) 1624 m, (Pd–Cl) 346 m, 268 m (Nujol); δ_H ($CDCl_3$) 8.06 (1 H, s, N=CH), 7.8–6.9 (14 H, m, aryl protons),

5.59 (1 H, spt, ^3J(HH) = 5.6 Hz, CHMe), 1.14 (6 H, d, ^3J(HH) = 5.6 Hz, CH_3); δ_P ($CDCl_3$) 32.5 (s).

Synthesis of [PdCl(C_6H_4Me-4)(2-(PPh_2)C_6H_4-1-CH=NCHMe$_2$)] (5c)

A mixture of [$PdCl_2$(2-(PPh_2)C_6H_4-1-CH=NCHMe$_2$)] (0.51 g, 1 mmol), 4-Me$C_6H_4B(OH)_2$ (0.41 g, 3 mmol), anhydrous K_2CO_3 (1.38 g, 10 mmol) and dmfu (0.14 g, 1 mmol) in dry toluene (50 cm^3) was stirred at room temperature for 30 min. The insoluble material was filtered off and the solution was evaporated to dryness at reduced pressure. The solid residue was dissolved in CH_2Cl_2 (20 cm^3) and the solution was filtered over Celite. Upon addition of methanol (30 cm^3) the solution was concentrated to a small volume (*ca.* 5 cm^3) and stored at −20 °C for 2 h. The resulting yellowish precipitate was filtered, washed with cold methanol and recrystallized from CH_2Cl_2/Et_2O to give the off-white microcrystalline product **5c**.

Complex 5c. (0.21, 37%) (Found C 61.31, H 4.86, N 2.49%; $C_{29}H_{29}ClNPPd$ requires C 61.72, H 5.18, N 2.48%); ν_{max}/cm^{-1} (C=N) 1627 m, (Pd–Cl) 270 m (Nujol); δ_H ($CDCl_3$) 8.16 (1 H, s, N=CH), 7.8–7.0 (16 H, m, aryl protons), 6.54–6.50 (2 H, m, *m*-H of C_6H_4Me-4), 5.43 (1 H, spt, ^3J(HH) = 6.4 Hz, $CHMe_2$), 2.06 (3 H, s, CH_3), 1.23 (6 H, d, ^3J(HH) = 6.4 Hz, CH_3); δ_P ($CDCl_3$) 29.3 (s).

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