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A new precatalyst for the Suzuki reaction—a pyridyl-bridged dinuclear palladium complex as a source of mono-ligated palladium(0)

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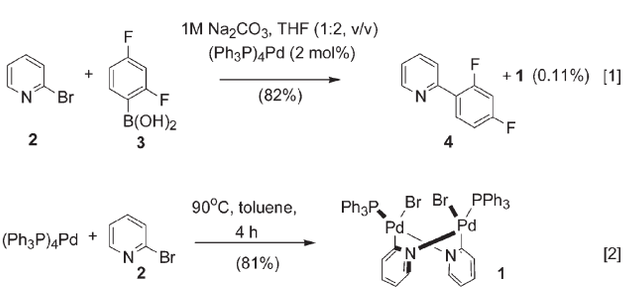
A dinuclear pyridyl-bridged palladium complex, *trans*-(*P*,*N*)-[PdBr(μ-C_5H_4N-C^2,N)(PPh_3)]$_2$ **1**, was obtained from material isolated from the Suzuki cross-coupling reaction of 2-bromopyridine with 2,4-difluorophenylboronic acid in the presence of catalytic $(PPh_3)_4Pd$. Complex **1** is an effective precatalyst for the Suzuki cross-coupling reactions of a variety organoboronic acids and aryl bromides, and represents a useful source of mono-ligated palladium(0), "$(Ph_3P)Pd(0)$".

Introduction

Palladium-catalyzed C–C and C–X bond forming processes are amongst the most important reactions in organic synthesis.[1] The Pd-catalyzed cross-coupling reaction of organohalides with organoboronic acids, the Suzuki reaction, represents a key transformation in both academic and industrial sectors.[2] The catalyst of choice, particularly in natural product synthesis, is *still* $(Ph_3P)_4Pd(0)$, even though a significant step change in the field has been recently observed in the development of highly active, electron rich Pd-catalysts, possessing increased catalytic lifetimes.[3] The nature of the 'catalytically active' species, in particular, the number of phosphine ligands necessary to aid transmetallation, reductive elimination and to stabilize the Pd-centre, has often been questioned.[4] Classically it has been assumed that *two* phosphine ligands are required for catalyst activity, but studies with electron rich, bulky ligands, such as $(t\text{-Bu})_3P$ and $(t\text{-Bu})_2$-(biphenyl)P, have demonstrated that it is very likely that only one ligand remains on Pd.[5] It would be interesting to study Pd-precursors that allow for the generation of mono-ligated Pd-species in the absence of dibenzylideneacetone (dba).[6] Herein we describe the use of *trans*-(*P*,*N*)-[PdBr(μ-C_5H_4N-C^2,N)(PPh_3)]$_2$ **1**[7] in the Suzuki reaction, which is expected to give "$(Ph_3P)Pd(0)$". Our findings, suggesting **1** as a suitable precursor catalyst, are discussed.

Results and discussion

Our initial studies were concerned with a side-product obtained from the Suzuki reaction of 2-bromopyridine **2** with 2,4-difluorophenylboronic acid **3** catalyzed by $(Ph_3P)_4Pd$ (Scheme 1, eqn. [1]). The expected cross-coupled product **4** was isolated in 82% yield; however, we were somewhat curious about the presence of a yellow component obtained from chromatography, which crystallized on evaporation to give pale brown diamond crystals in 0.11% yield. Suitable crystals for X-ray diffraction studies were chosen, which revealed the component to be a co-crystal of **1** and **4** (Fig. 1).†



Scheme 1 Eqn. [1], first isolation of **1** Suzuki reaction of **2** and **3**. Eqn. [2], direct reaction of **2** with $(Ph_3P)_4Pd$ to give **1**.

Each palladium atom exhibits a square-planar geometry with the bromide and carbon bonds in a *trans* configuration. The Pd–Pd interatomic distance is 3.2338(4) Å and is consistent with the structure reported[8] (3.194(2) Å) and the chlorine analogue[9] (3.165(3) Å), previously published. This suggests that the interaction may be weak; although a search of the Cambridge Structural Database[10] (Version 1.5, November 2002, 272 066 entries) using ConQuest[11] shows that similar species occupy a range of 2.543–3.315 Å with a mean average of 2.795 Å. The central ring of our structure possesses two pyridine rings bridging the palladium atoms with the nitrogen *trans* to triphenylphosphine and carbon *trans* to bromine in both cases. These planes are inclined at an angle of 81.2° forming a six-membered ring in a boat conformation. The oxidative

† Chemical formula: $C_{46}H_{38}Br_2N_2P_2Pd_2$, $0.5(C_{11}H_7NF_2)$, $M_r = 1148.93$, $T = 120$ K, triclinic ($P\bar{1}$), $a = 10.4525(4)$ Å, $b = 13.0911(5)$ Å, $c = 17.7535(6)$ Å, $\alpha = 81.5170(10)°$, $\beta = 78.849(2)°$, $\gamma = 70.8180(10)°$, $V = 2241.84(14)$ Å^3, $Z = 2$, $\mu = 2.699$ mm^{-1}, Data/restraints/parameters = 11754/1/561, $R_{int} = 0.0418$, Final $R_1 = 0.0431$ $wR_2 = 0.0898$ [$I > 2\sigma(I)$]. CCDC reference number 207524. See http://www.rsc.org/suppdata/nj/b4/b401077a/ for crystallographic data in .cif or other electronic format.

DOI: 10.1039/b401077a

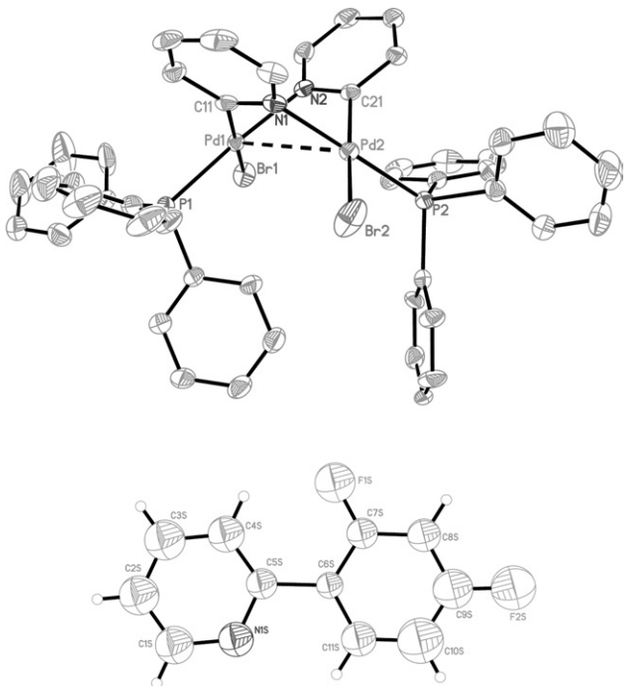
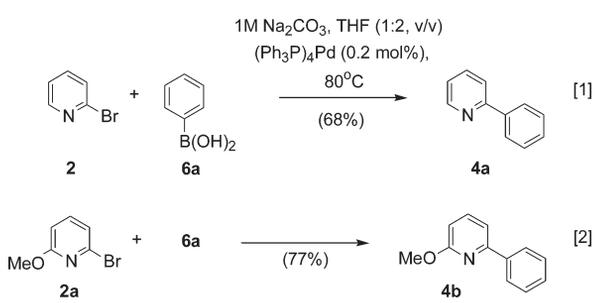


Fig. 1 Crystal structure of **1** with thermal ellipsoids at 50%. The structure of 2-(2,4-difluorophenyl)pyridine, **4**, with which **1** is co-crystallised, is also shown. The disorder is omitted for clarity.

addition of 2-, 3- and 4-bromopyridines to $(Ph_3P)_4Pd$ results in the formation of dimeric metallated pyridine species, such as **1**.[8] Complex **1** was thus synthesised by direct reaction of $(Ph_3P)_4Pd$ with **2** to give **1** in 81% yield, possessing identical ^1H, ^{31}P NMR spectroscopic and ESI spectrometric data to the material isolated in the reaction of **2** and **3** (Scheme 1, eqn. [2]).

We questioned whether **1** represented an intermediate catalyst resting state in the reaction of **2** and **3**, which led us to study **1** as a general precatalyst for the Suzuki cross-coupling reaction.[12] In the first reaction, **1** (0.2 mol%) was added to a mixture of **2** and phenylboronic acid **6a** in THF–1 M Na_2CO_3 at 80°C (Scheme 2, eqn. [1]). After 15 h the reaction was judged complete (TLC), with workup and purification by flash chromatography, affording the cross-coupled product **4a** in 68% yield.

Reaction of 6-methoxy-2-bromopyridine **2a** with **6a** under the same conditions gave the cross-coupled product **4b** in 77% yield (Scheme 2, eqn. [1]). We subsequently found that the reaction of **2** with **6a** could be conducted at 60 °C, proceeding in slightly higher yield (74%). Room temperature reactions with these substrates in the presence of **1** were sluggish, but encouraged by our results, we investigated the cross-coupling reactions of several aryl bromides and aryl boronic acids in the presence of **1** at 60 °C (Table 1).



Scheme 2 Eqn. [1], use of **1** as a precatalyst for reaction of **2** and **6a**. Eqn. [2], use of **1** as a precatalyst for reaction of **2a** and **6a**.

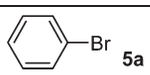
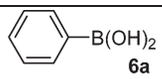
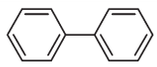
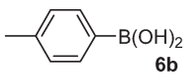
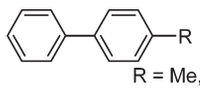
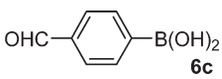
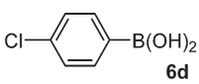
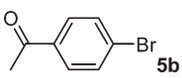
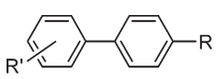
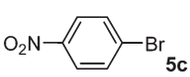
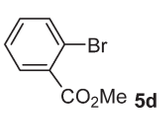
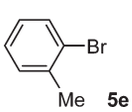
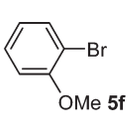
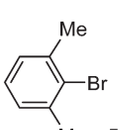
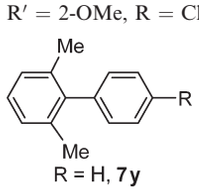
Bromobenzene **5a** reacts with **6a**, 4-methylbenzeneboronic acid **6b**, 4-formylbenzeneboronic acid **6c** and 4-chlorobenzeneboronic acid **6d** in yields between 62–75% (entries 1–4). The turnover numbers per hour for these reactions were good (206–250 TON h^{-1}). 4-Bromoacetophenone **5b** couples effectively with **6a–d** in yields of 64–76% (entries 5–8). The turnover numbers per hour were lower than seen in reactions with **5a** (107–127 TON h^{-1}). A similar observation is apparent with the activated substrate, 4-nitro-1-bromobenzene **5c** (108–122 TON h^{-1}, entries 9–12). Methyl benzoate **5d** couples satisfactorily with **6a–d** (52–72% yields, entries 13–16). The less activated substrate, 2-methyl-1-bromobenzene **5e** couples well with **6a–d** (62–75% yields, entries 17–20), with surprisingly higher values observed for the turnover numbers per hour (207–250 TON h^{-1}). Indeed, 2-methoxy-1-bromobenzene **5f** couples equally well (74–81% yields, entries 21–24) in good turnover numbers (123–135 TON h^{-1}). The sterically hindered, deactivated substrate 2,6-dimethyl-1-bromobenzene **5g** (50–71% yields, entries 25–28) gave the lowest turnover numbers per hour seen in this series (21–30 TON h^{-1}). However, the fact that the unactivated substrates **5e** and **5f** couple more effectively than the more activated substrates **5b** and **5c** is an interesting observation.

The effect of additional Ph_3P on the reaction rate was probed systematically (Table 2). We chose 2-bromopyridine **2** as the substrate for reaction with phenylboronic acid **6a** under identical conditions to those given in Table 1. All reactions were stopped after 3 h (quenched by passing the mixture through a plug of silica gel).[13] The Ph_3P ligand (1, 2 and 4 equivalents of Ph_3P were added per equivalent of **1**; from a stock solution in dry THF) was added *via* microsyringe prior to addition of **1** to the reaction mixture. An obvious trend was seen in these reactions, where additional Ph_3P clearly reduces the turnover numbers per hour (entries 1–4, Table 2). In the absence of the additional Ph_3P, the cross-coupled product **4a** was produced in 74% after 3 h (entry 1, 123 TON h^{-1}). In the presence of 1 equivalent of Ph_3P (0.5 equivalent per Pd), **4a** was produced in 69% (entry 2, 115 TON h^{-1}). On increasing to 2 equivalents of Ph_3P (1 equivalent per Pd), **4a** was produced in 62% (entry 3, 103 TON h^{-1}). Finally, increasing the amount of Ph_3P to 4 equivalents (2 equivalents per Pd), **4a** was produced in 51% (entry 4, 85 TON h^{-1}). A comparison of entries 1, 3 and 4 formally allows us to correlate the effect of mono-ligated palladium(0) (Ph_3P-Pd(0)), bis-ligated palladium(0) ($(Ph_3P)_2Pd(0)$) and tris-ligated palladium(0) ($(Ph_3P)_3Pd(0)$). Thus in these reactions, excess Ph_3P slows down catalysis.

Complex **1** has previously been employed as a precatalyst for the cross-coupling reaction of chloropyridine with methylmagnesium bromide.[14] The occurrence of the reaction was rationalised generally by displacement of the bromide ligand from a monomeric species by an incoming nucleophile (Nu), to generate $[Pd(Nu)(\eta^1\text{-}C_5H_4N\text{-}C^n)(PPh_3)_2]$ (where $n = 3$ or 4).[15] Reductive elimination provides Nu-C_5H_4N as the cross-coupled product and regenerates $(Ph_3P)_2Pd$ as the active catalytic species. However, such a proposal would have to occur through disproportionation of Ph_3P from the mono-phosphine palladium species to give the bis-phosphine palladium and a naked palladium species, which presumably would aggregate and precipitate out of solution. In our reactions we do not observe the formation of palladium black.[16]

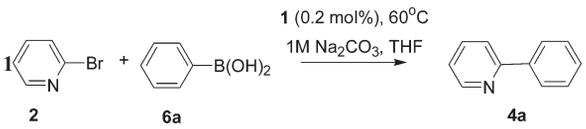
Given our results, we propose that a mono-ligated phosphine species (Ph_3P-Pd(0)) is essential for higher turnover numbers. A precatalytic cycle based on the classical mechanism is proposed from precatalyst **1** (Fig. 2).[17] The dimeric precatalyst **1** is expected to be in equilibrium with a 14-electron monomeric species **1′**.[18] Transmetallation with an activated arylboronic acid will then occur through formal displacement of bromide to give Pd(II) intermediate **I**. Reductive elimination will then generate the cross-coupled product **4a** and give the

Table 1 Suzuki cross-coupling of aryl bromides and aryl boronic acids catalysed by pyridyl complex **1**

Entry	Aryl bromide	Arylboronic acid	Product	Time/h	Yield (%)[b]	TON h^{-1} [c]
1	 **5a**	 **6a**	 **7a**	1.5	62	206
2	**5a**	 **6b**	 R = Me, **7b**	1.5	63	210
3	**5a**	 **6c**	R = CHO, **7c**	1.5	75	250
4	**5a**	 **6d**	R = Cl, **7d**	1.5	74	247
5	 **5b**	**6a**	 R' = 4-$COCH_3$, R = H, **7e**	3	64	107
6	**5b**	**6b**	R′ = 4-$COCH_3$, R = Me, **7f**	3	69	115
7	**5b**	**6c**	R′ = 4-$COCH_3$, R = CHO, **7g**	3	71	118
8	**5b**	**6d**	R′ = 4-$COCH_3$, R = Cl, **7h**	3	76	127
9	 **5c**	**6a**	R′ = 4-NO_2, R = H, **7i**	3	65	108
10	**5c**	**6b**	R′ = 4-NO_2, R = Me, **7j**	3	66	110
11	**5c**	**6c**	R′ = 4-NO_2, R = CHO, **7k**	3	68	113
12	**5c**	**6d**	R′ = 4-NO_2, R = Cl, **7l**	3	73	122
13	 **5d**	**6a**	R′ = 2-CO_2Me, R = H, **7m**	4	62	78
14	**5d**	**6b**	R′ = 2-CO_2Me, R = Me, **7n**	4	52	65
15	**5d**	**6c**	R′ = 2-CO_2Me, R = CHO, **7o**	4	71	89
16	**5d**	**6d**	R′ = 2-CO_2Me, R = Cl, **7p**	4	72	90
17	 **5e**	**6a**	R′ = 2-Me, R = H, **7q**	1.5	63	210
18	**5e**	**6b**	R′ = 2-Me, R = Me, **7r**	1.5	62	207
19	**5e**	**6c**	R′ = 2-Me, R = CHO, **7s**	1.5	74	247
20	**5e**	**6d**	R′ = 2-Me, R = Cl, **7t**	1.5	75	250
21	 **5f**	**6a**	R′ = 2-OMe, R = H, **7u**	3	76	127
22	**5f**	**6b**	R′ = 2-OMe, R = Me, **7v**	3	81	135
23	**5f**	**6c**	R′ = 2-OMe, R = CHO, **7w**	3	74	123
24	**5f**	**6d**	R′ = 2-OMe, R = Cl, **7x**	3	77	128
25	 **5g**	**6a**	 R = H, **7y**	12	63	26
26	**5g**	**6b**	R = Me, **7z**	12	50	21
27	**5g**	**6c**	R = CHO, **7a'**	12	61	25
28	**5g**	**6d**	R = Cl, **7b'**	12	71	30

[a] *Reaction conditions*: aryl bromide (1.05 eq.), aryl boronic acid (1.0 eq.), **1** (0.2 mol%), 1 M Na_2CO_3–THF (1 : 2 v/v), 60 °C with magnetic stirring. [b] Isolated yields after chromatography. [c] TON h^{-1}: calculated by considering the number of moles of desired product produced per mole of catalyst used per hour.

Table 2 Effect of excess triphenylphosphine on Suzuki coupling of **2** with **6a** using precatalyst



Entry	Additional Ph_3P (%)[b]	Time/h	Yield (%)[c]	TON h^{-1} [d]
1	0	3	74	123
2	0.1	3	69	115
3	0.2	3	62	103
4	0.4	3	51	85

[a] Reactions performed with 0.2 mol% catalyst using the conditions and reagents described in Table 1. [b] Ph_3P stock solutions were prepared using dry THF and the appropriate aliquot added to the reaction mixture at $t = 0$. [c] Yields calculated from the ^1H NMR spectra of the isolated material (crude). [d] TON h^{-1}: calculated by considering the number of moles of desired product produced per mole of catalyst used per hour.

mono-ligated species **II**. This species can now proceed into the standard catalytic cycle. Standard oxidative addition with the appropriate organohalide gives **III**. Transmetallation of **III** with the activated arylboronic acid affords **IV**, which then undergoes reductive elimination to reveal the cross-coupled product, regenerating the monomeric palladium(0) species **II** as a consequence.

Support for the precatalytic cycle comes by following the reaction of 4-nitrobromobenzene **5c** with phenylboronic acid **6a**, in the presence of precatalyst **1** (5 mol%) at 60 °C, by GC-MS analysis. The first turnover should produce 2-phenylpyridine **4a**. After *ca.* 1 min of the reaction, **4a** is produced, *via* the precatalyst cycle. The formation of **7i** and disappearance of **5c** is then observed (over 3 h), which is expected if mono-ligated palladium(0) species **II** then enters the standard catalytic cycle.

To summarise, we have conducted the first Suzuki cross-coupling reactions employing precatalyst **1**. A great advantage of this complex is its stability under ambient conditions (air and moisture stable), unlike other commonly employed Pd(0) catalysts, *e.g.* $(Ph_3P)_4Pd$, which are readily oxidised to Pd(II) species in air. Complex **1** is easily synthesised in high yield and may be used at low catalyst loadings (0.2 mol%), under relatively mild conditions (60 °C). Investigations into the effect of additional phosphine on the rate of reaction demonstrated an interesting trend. Here it was shown that excess phosphine (> 1 Ph_3P per Pd) slows downs catalysis, which is presumably associated with transmetallation and reductive elimination steps, key events that are ultimately dependant on ligand dissociation. Finally, this study demonstrates how important it is to isolate every component from a reaction mixture—by doing this we have ultimately been led to the identification of a new precatalyst for the Suzuki reaction.

Experimental

THF was dried over sodium–benzophenone ketyl (distilled prior to use). All reactions were conducted under an inert atmosphere of Ar or N_2 on a Schlenk line. $Pd(PPh_3)_4$ was prepared by reduction of $(Ph_3P)_2PdCl_2$ with hydrazine.[19] $(PPh_3)_2PdCl_2$ was prepared from $PdCl_2$ (provided by Johnson Matthey as a loan) in refluxing DMSO and PPh_3 (2 eq.) using a known procedure.[20] Melting points were recorded on an electrothermal IA9000 Digital Melting Point Apparatus and are uncorrected. TLC analysis was performed on Merck 5554 aluminium backed silica gel plates and compounds visualized by ultraviolet light (254 nm), phosphomolybdic acid solution (5% in EtOH), or 1% ninhydrin in EtOH. ^1H NMR spectra were recorded at 270 MHz using a JEOL EX270 spectrometer or at 400 MHz using a JEOL ECX400 spectrometer; ^{13}C NMR spectra at 67.9 or 100.5 MHz. Chemical shifts are reported in parts per million (δ) downfield from an internal tetramethylsilane reference. Coupling constants (J values) are reported in hertz (Hz), and spin multiplicities are indicated by the following symbols: s (singlet), d (doublet), t (triplet), q (quartet), qn (quintet), sx (sextet), m (multiplet), br (broad).

The following compounds were characterized by ^1H, ^{13}C NMR and mass spectrometry and compared to the known

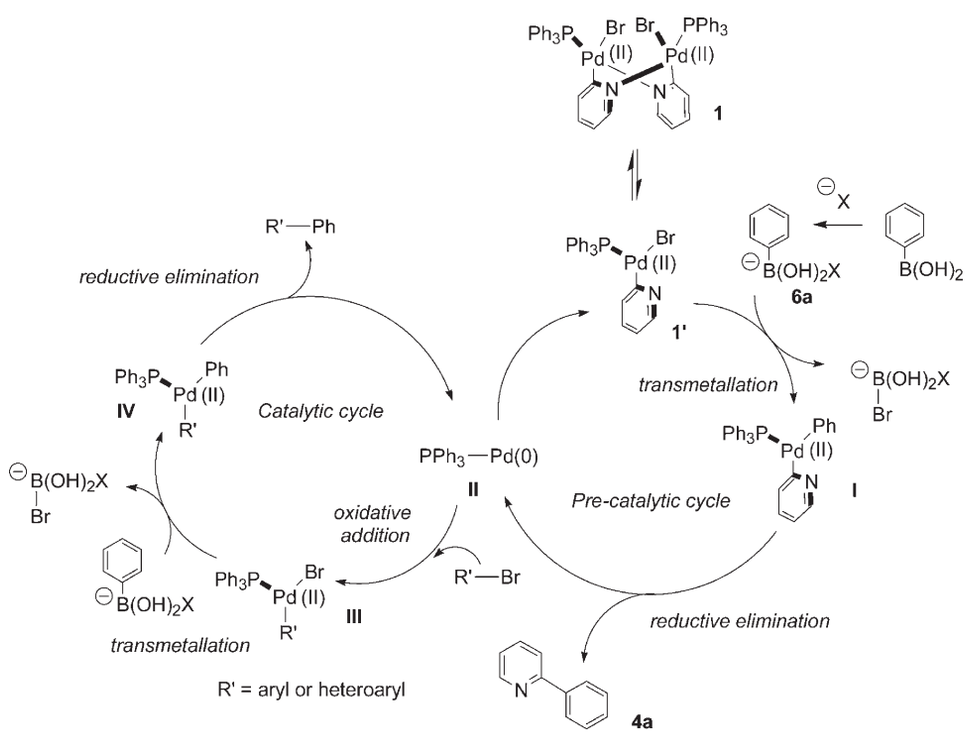


Fig. 2 The catalytic cycle employing precatalyst **1** in Suzuki cross-coupling reactions.

literature data: 4-acetylbiphenyl **7c**,[21] biphenyl **7a**,[22] 4-nitrobiphenyl **7i**,[23] 2,6-dimethylbiphenyl **7y**,[24] 2-methoxycarbonylbiphenyl **7m**,[25] 2-methylbiphenyl **7q**,[26] 2-methoxybiphenyl **7u**,[27] 4-methylbiphenyl **7b**,[22] 4-acetyl-4′-methylbiphenyl **7f**,[28] 2,6-dimethyl-4′-methylbiphenyl **7z**,[21] 2-methoxycarbonyl-4′-methylbiphenyl **7n**,[29] 2,4′-dimethylbiphenyl **7r**,[28] 2-methoxy-4′-methylbiphenyl **7v**,[21] 4′-formylbiphenyl **7c**,[26] 4-acetyl-4′-formylbiphenyl **7g**,[30] 2-methyl-4′-formylbiphenyl **7s**,[26] 4′-chlorobiphenyl **7d**,[26] 4-acetyl-4′-chlorobiphenyl **7h**,[31] 4-nitro-4′-chlorobiphenyl **7l**,[32] 2,6-dimethyl-4′-chlorobiphenyl **7b′**,[33] 2-methoxycarbonyl-4′-chlorobiphenyl **7p**,[32] 2-methyl-4′-chlorobiphenyl **7t**,[33] 2-methoxy-4′-chlorobiphenyl **7x**[26] and 2-methoxycarbonyl-4′-formylbiphenyl **7p**.[34]

2-Phenylpyridine 4a

δ_H (300 MHz, $CDCl_3$) 8.66 (1H, dt, $J = 4.2$ Hz, *CH*), 7.91 (2H, m, $2 \times CH$), 7.70 (2H, m, $2 \times CH$), 7.42 (3H, m, $3 \times CH$), 7.21 (1H, m, *CH*); MS (ES+): 156.1 $(M + H)^+$.

2-Methoxy-6-phenylpyridine 4b

δ_H (300 MHz, $CDCl_3$) 8.09 (2H, d, $J = 7.2$ Hz, $2 \times CH$), 7.65 (1H, t, $J = 7.5$ Hz, *CH*), 7.45 (4H, m, $4 \times CH$), 6.73 (1H, d, $J = 8.1$ Hz, *CH*), 4.08 (3H, s, CH_3); MS (ES+): 186.1 $(M + H)^+$.

4-Nitro-4′-methylbiphenyl 7j

δ_H (400 MHz, $CDCl_3$) 8.22 (2H, d, $J = 7.9$ Hz, *CH*), 7.66 (2H, d, $J = 7.9$ Hz, $2 \times CH$), 7.64 (2H, d, $J = 8.1$ Hz, *CH*), 7.24 (2H, d, $J = 8.1$ Hz, $2 \times CH$), 2.35 (3H, s, CH_3); δ_C (100 MHz, $CDCl_3$) 149.05, 139.05, 135.91, 132.60, 129.88, 127.45, 127.19, 124.07, 21.19; MS (EI) m/z 213 (M^+, 100), 75, 152, 115, 165, 183.

4-Nitro-4′-formylbiphenyl 7k

δ_H (400 MHz, $CDCl_3$) 10.08 (1H, s, *CHO*), 8.10 (2H, d, $J = 8.8$ Hz, $2 \times CH$), 8.01 (2H, d, $J = 8.8$ Hz, $2 \times CH$), 7.98 (2H, d, $J = 8.5$ Hz, $2 \times CH$), 7.66 (2H, d, $J = 8.5$ Hz, $2 \times CH$); MS (EI) m/z 227 (M^+, 78), 152, 210, 76.

2,6-Dimethyl-4′-formylbiphenyl 7a′

δ_H (400 MHz, $CDCl_3$) 9.98 (1H, s, *CHO*), 7.36 (2H, d, $J = 6.7$ Hz, $2 \times CH$), 7.34 (1H, d, $J = 7.1$Hz, *CH*), 7.33 (2H, m, $2 \times CH$), 7.29 (2H, m, $2 \times CH$), 1.93 (6H, s, $2 \times CH_3$).

2-Methoxy-4′-formylbiphenyl 7w

δ_H (400 MHz, $CDCl_3$) δ 10.00 (1H, s, *CHO*), 7.85 (2H, d, $J = 8.2$ Hz, $2 \times CH$), 7.42 (2H, d, $J = 8.2$ Hz, $2 \times CH$), 7.23–7.13 (4H, m, $4 \times CH$), 2.208 (3H, s, OCH_3); δ_C (100 MHz, $CDCl_3$) 192.31, 148.70, 140.88, 135.19, 130.20, 129.27, 128.34, 128.22, 127.57, 127.50, 56.38.

Original isolation of *trans*-(P,N)-[PdBr-(μ-C_5H_4N-C^2,N)$(PPh_3)]_2$ (1)

2,4-Difluorophenylboronic acid **3** (5g, 32 mmol), 2-bromopyridine **2** (5.5 g, 3.3 mL, 35 mmol. 1.1 eq.), Na_2CO_3 (1M aq., 50 mL), THF (100 mL) and $Pd(PPh_3)_4$ (0.75 g, 0.6 mmol, 2 mol %) were heated overnight in a nitrogen atmosphere at 80 °C with continuous stirring. The reaction was cooled to room temperature and water (200 mL) was added. The resulting mixture was extracted with ethyl acetate (5×100 mL), dried ($MgSO_4$), filtered and evaporated *in vacuo*. Flash chromatography afforded 2-(2,4-difluorophenyl)pyridine **4**, as a pale yellow liquid (5.0 g, 82%). Complex **1** was isolated from a fraction containing the impure product as pale brown diamond shaped crystals (20 mg, 1.1×10^{-3}%). δ_H (400 MHz, $CDCl_3$) 8.58 (1H, m), 7.85 (6H, m), 7.36 (3H, m), 7.28 (6H, m), 6.61 (1H, m), 6.49 (2H, m); δ_P (121 MHz, $CDCl_3$) 30.79. Electrospray mass spectrometry in acetonitrile gives similar results to those reported previously.[15]

Direct preparation of *trans*-(*P*,*N*)-[PdBr-(μ-C_5H_4N-C^2,N)$(PPh_3)]_2$(1)

Tetrakistriphenylphosphine palladium(0) (600 mg, 0.48 mmol) was dissolved in toluene (40 mL) to produce a bright clear yellow solution. 2-Bromopyridine (137 mg, 0.87 mmol, 1.8 eq.) was then added. The resulting mixture was heated to 90 °C for 4 h, during which time the solution became cloudy and a pale green-yellow colour. The reaction mixture was cooled to room temperature and filtered. The green-yellow precipitate was collected and washed thoroughly with diethyl ether (5×10 mL) and subsequently dissolved in chloroform. The filtrate was evaporated to dryness and the solid recrystallized from chloroform and *n*-hexane to give the pure product as a green-yellow crystalline solid (205 mg, 81%). δ_H and δ_P data were identical to that given above.

Typical Suzuki reaction

Phenylboronic acid (50 mg, 0.41 mmol), 2-bromopyridine (71.3 mg, 0.45 mmol, 1.1 eq.), Na_2CO_3 (1 M (aq.), 1 ml), THF (1.5 mL) and Pd-dimer crystals (1 mg, 0.95 μmoles, 0.21 mol%) were degassed *via* three 'freeze–pump–thaw' cycles. The resulting mixture was heated at 60 °C overnight during which the clear solution became bright yellow in colour. The reaction mixture was allowed to cool to room temperature after which water (10 mL) was added. The mixture was then extracted with dichloromethane (3×10 mL) and the organic extracts dried ($MgSO_4$), filtered and concentrated *in vacuo*. Purification by flash chromatography gave the pure cross-coupled product, 2-phenylpyridine, as a pale yellow liquid (43 mg, 68%). ^{1}H NMR 300 MHz ($CDCl_3$) δ: 8.66 (1H, dt, $J = 4.2$ Hz), 7.91 (2H, m), 7.70 (2H, m), 7.42 (3H, m), 7.21 (1H, m); MS (ES+): 156.1 $(M + H)^+$.

Crystal structure determination of *trans*-(P,N)-[PdBr(μ-C_5H_4N-C^2,N)$(PPh_3)]_2$†

Single crystal X-ray diffraction experiments were carried out at 120 K using graphite monochromated Mo Kα radiation ($\lambda = 0.71073$ Å) on a Bruker SMART-CCD 1K area detector diffractometer. The temperature was controlled using a Cryostream N_2 open-flow cooling device.[35] Five series of narrow ω-scans (0.3°) were performed at several φ-settings to cover a sphere of data to a maximum resolution of between 0.70 and 0.77 Å. Cell parameters were initially determined using the SMART software,[36] and raw frame data were integrated and cell parameters refined using the SAINT program. The structure was solved by direct methods and refined by full-matrix least squares on F^2 using the SHELXTL software.[37] The reflection intensities were corrected by numerical integration based on measurements and indexing of the crystal faces (using SHELXTL software). The structure is of a co-crystal of **1** and **4**. Both **1** and **4** have disorder which is modeled. For **1**, one of the phenyl rings from the each PPh_3 ligand is disordered such that there are two positions, each with 50% occupancy. All non-hydrogen atoms were refined with anisotrpic displacement parameters. **4** occupies a possition on an inversion centre, which relates the two components. Anisotropic refinement of **4** is unstable, so all atoms were refined with isotropically. Hydrogen atoms for both **1** and **4** were refined using a riding model.

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