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[Pd(C^N)(X)(PPh$_3$)] palladacycles react with 2,4,6-trifluorophenyl boronic acid to give stable transmetallation products of the type [Pd(C^N)(2,4,6-F$_3$C$_6$H$_2$)(PPh$_3$)]†

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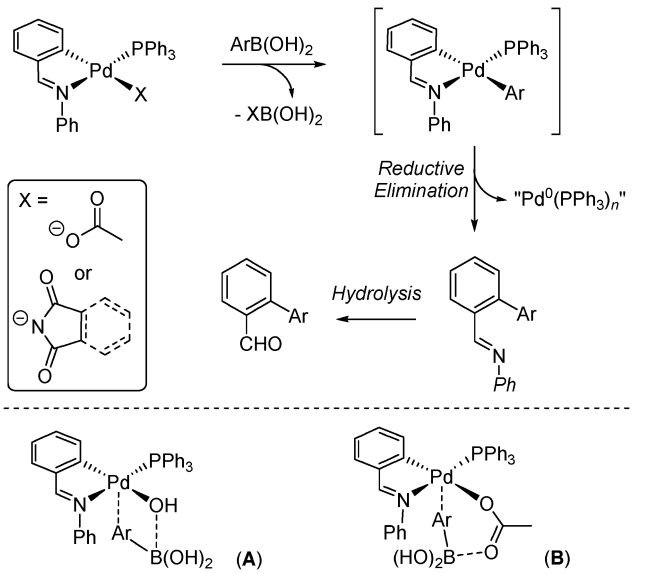
Direct transmetallation between palladacyclic complexes and arylboronic acid occurs to give isolable transmetallation products. In THF, the reaction occurs <0.5 h. Prolonged reaction leads to the generation of a dinuclear Pd complex bearing bridging μ-hydroxo and μ-acetoxy ligands. Insight into precatalyst activation for Suzuki–Miyaura cross-couplings mediated by palladacycles has been gained, where acetate and *N*-imidate anions activate a neutral arylboronic acid.

Cross-coupling reactions mediated by Pd allow rapid access to an eclectic array of organic products.[1] Such reactions are arguably the *go-to-transformation* in synthetic chemistry for the synthesis of biaryls.[2] Suzuki–Miyaura cross-coupling (SMCC) of an organohalide and organoboron-containing species, mediated by a Pd catalyst and exogenous base, are ubiquitous reactions, and one of the most widely applied.[3] In recent years much has been learnt about the reaction mechanisms of SMCCs, especially the involvement of Pd-hydroxo species in activating neutral arylboronic acid species (by an oxo-palladium pathway).[4] In addition, the involvement of higher order Pd species has been demonstrated, including some evidence for a heterogeneous SMCC reaction.[5]

The improvement of SMCC catalysts often derives from altering oxidative addition, transmetallation or reductive elimination steps. Controlling and understanding the precatalyst activation step is however, absolutely critical – an aspect that is poorly understood. Indeed, there are limited detailed studies[6] concerning the mechanism of the precatalyst reduction step, *i.e.* how is the active catalyst species generated in SMCCs?

In previous studies we[7] and others[6b,8] have examined palladacycles as precatalysts for SMCCs and related cross-couplings. In our catalytic work,[7a] involving [Pd(phbz)(X)(PR$_3$)] palladacycles (phbz = *N*-phenylbenzaldimine; X = acetate or *N*-imidate; R = aryl; Scheme 1), a reaction with arylboronic acid in the absence of base to release a common catalyst species of the type Pd^0(PPh$_3$)$_n$ was noted. The process involves arylation of the palladacyclic ligand backbone yielding an imine (the reductive elimination organic product), which is hydrolysed to 2-phenylbenzaldehyde either in the reaction or during work-up (depending on the conditions used). Similar observations were made by Bedford and co-workers for other palladacycles in the presence of base.[8a]

Indirect evidence by electrospray ionisation mass spectrometry (ESI-MS) showed that arylated Pd^{II} species could be present under the SMCC reaction conditions[7a] however, in all the studies to date no *direct evidence* has been gathered for the



Scheme 1 Proposed activation of arylboronic acids by palladacyclic complexes.

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initial transmetallation product, [Pd(C^N)(aryl)(PR_3)] (where C^N is the palladacyclic backbone). To address this gap in the field, in this paper we present the first direct evidence for transmetallation of [Pd(C^N)(X)(PR_3)] complexes with an arylboronic acid.

Our starting point was to take advantage of the important contribution made by Osakada and co-workers,[9] who showed that the employment of an excess 2,4,6-trifluorophenyl moiety retards reductive elimination from diarylpalladium(II) complexes containing strongly basic triethylphosphine ligands.

In the first experiment, 2,4,6-trifluorophenylboronic acid **1** was reacted with [Pd(phbz)(OAc)(PPh_3)] in THF[10] at 25 °C for 0.5 h. The ratio of the palladacycle and **1** was varied (1 : 6, 1 : 2 and 1 : 1), and in all experiments one new product dominated (mixed with the precursor only in the 1 : 1 reaction) as a white solid (*ca.* 70% yield), which contained one new phosphorus chemical environment, *e.g.* $^{31}P\{^1H\}$ NMR δ 19.86 (s), considerably shifted from that of 41.80 (s) displayed by [Pd(phbz)(OAc)(PPh_3)]. The IR (typical internal vibrational modes of 2,4,6-trifluorophenyl group at 1390, 1100 and 990 cm^{-1})[11] and ^{19}F NMR spectroscopic data, with two resonances at δ −84.50 (2F)/−120.30 (1F), in combination with the ESI-MS data (M^+ = 680), suggested that the product was [Pd(phbz)(2,4,6-$F_3C_6H_2$)(PPh_3)]. The structure of [Pd(phbz)(2,4,6-$F_3C_6H_2$)(PPh_3)] was verified by single crystal X-ray diffraction (Fig. 1, left structure).[12a] Interestingly, the 2,4,6-trifluorophenyl moiety is positioned *cis* to the carbon found within the palladacycle, which would therefore be receptive to reductive elimination.

The structure around Pd can be described as nearly planar, and its deviation from the planar coordination has been quantified by measures of improper torsion angles: = 0.00 and −2.88°, which means C(1)–N(1)–Pd(1)–C(14) defining a plane and P(1) slightly above that plane.[13] The angle between the planes C(1)–C(5)–C(7)–N(1)–Pd(1) and C(14)–C(15)–C(16)–C(17)–C(18)–C(19) is 86.20(13)°.

The reaction of related [Pd(phbz)(*N*-imidate)(PPh_3)] complexes with **1** under similar conditions also gave [Pd(phbz)(2,4,6-$F_3C_6H_2$)(PPh_3)] as the product (*N*-imidate = *N*-succinimidate – 56% yield; = *N*-maleimidate – 71% yield).[12b]

A similar series of reactions of [Pd(phbz)(OAc)(PPh_3)] with either phenylboronic acid or *p*-fluoroboronic acid did not give [Pd(phbz)(aryl)(PPh_3)] type products; in keeping with our previous observations, facile reduction was observed.[7a]

In an independent reaction, an alternative palladacycle containing a *N*-phenylazabenzene (phazb) backbone, namely [Pd(phazb)(OAc)(PPh_3)], was reacted with **1** in a ratio of 1 : 6, cleanly affording a new product as a white solid (68%), which contained one new phosphorus chemical environment, *e.g.* $^{31}P\{^1H\}$ NMR δ 19.85 (s). The IR and other NMR spectroscopic data mirrored that obtained for [Pd(phbz)(2,4,6-$F_3C_6H_2$)(PPh_3)], suggesting that an analogous complex [Pd(phazb)(2,4,6-$F_3C_6H_2$)(PPh_3)] was obtained. The ESI Accurate-Mass TOF LC/MS data accounted for the change in the orthometallated moiety to phazb, showing fragments with one unit increase with respect to those displayed by [Pd(phbz)(2,4,6-$F_3C_6H_2$)(PPh_3)]. The structure of [Pd(phazb)(2,4,6-$F_3C_6H_2$)(PPh_3)] was verified by single crystal X-ray diffraction (Fig. 1, right structure).[12c] Again, a near planar geometry is seen at Pd^{II}, which closely resembles the phbz analogue.

Finally, it is important to note that when reactions of [Pd(phbz)(AcO)(PPh_3)] with **1** were left for prolonged periods (*ca.* 16–24 h), other minor phosphorus signals were also observed in the ^{31}P NMR spectrum (at 24.26 ppm) of the crude reaction mixture. In one particular case, we observed the formation of a different set of crystals. The absence of phbz resonances in its ^1H NMR spectrum, and shifted signals in the ^{19}F NMR δ −87.30 (2F)/−119.26 (1F) were also noticeable changes. The structure of this new product was confirmed by X-ray diffraction as [Pd_2(2,4,6-$C_6F_3H_2$)$_2$(PPh_3)$_2$(μ-OH)(μ-OAc)] (Fig. 2). A similar species was recently reported by Wei and co-workers[14] in the catalytic borylation of aryl halides by electron-rich Pd catalysts, in the presence of *n*-Bu_4NOAc. Therefore, this and

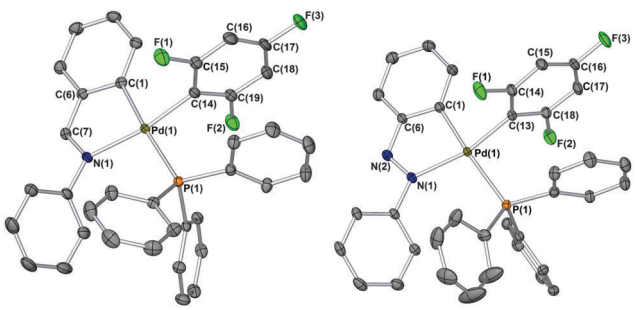

Fig. 1 X-ray structures of [Pd(phbz)(2,4,6-$F_3C_6H_2$)(PPh_3)] (left) and [Pd(phazb)-(2,4,6-$F_3C_6H_2$)(PPh_3)] (right). Selected bond angles (°) and lengths (Å): C(1)–Pd(1)–C(14) 88.49(6); C(1)–Pd(1)–N(1) 80.40(5); C(1)–Pd(1)–P(1) 175.05(4); C(14)–Pd(1)–N(1) 168.86(5); C(14)–Pd(1)–P(1) 88.55(4); N(1)–Pd(1)–P(1) 102.58(3); Pd(1)–C(1) 2.0377(14); Pd(1)–C(14) 1.9945(13); Pd(1)–N(1) 2.1534(11) and Pd(1)–P(1) 2.3756(4) for [Pd(phbz)(2,4,6-$F_3C_6H_2$)-(PPh_3)]. C(1)–Pd(1)–C(13) 89.38(8); C(1)–Pd(1)–N(1) 78.02(8); C(1)–Pd(1)–P(1) 170.65(6); C(13)–Pd(1)–N(1) 165.92(8); C(13)–Pd(1)–P(1) 88.78(6); N(1)–Pd(1)–P(1) 104.66(5); Pd(1)–C(1) 2.020(2); Pd(1)–C(13) 2.005(2); Pd(1)–N(1) 2.1427(17) and Pd(1)–P(1) 2.3746(6) for [Pd(phazb)(2,4,6-$F_3C_6H_2$)(PPh_3)].

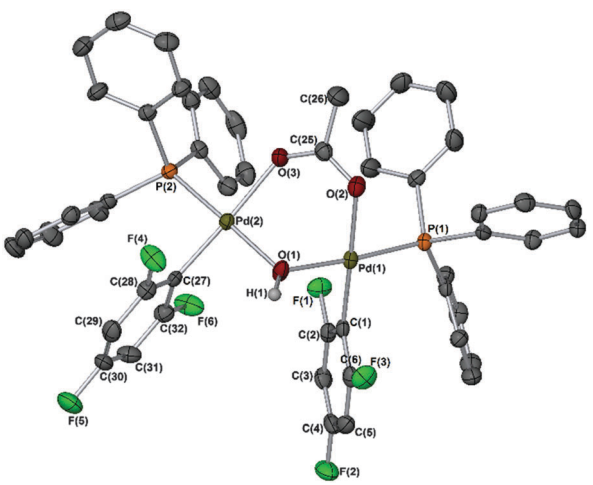

Fig. 2 X-ray structure of a dinuclear Pd^{II}–hydroxo complex. Selected bond angles (°) and lengths (Å): C(1)–Pd(1)–O(1) 91.10(14); C(1)–Pd(1)–O(2) 178.02(13); C(1)–Pd(1)–P(1) 92.40(10); O(1)–Pd(1)–O(2) 88.55(12); O(1)–Pd(1)–P(1) 176.06(9); O(2)–Pd(1)–P(1) 87.88(8); Pd(1)–C(1) 1.996(4); Pd(1)–O(1) 2.058(3); Pd(1)–O(2) 2.087(3) and Pd(1)–P(1) 2.2303(10). C(27)–Pd(2)–O(1) 88.24(13); C(27)–Pd(2)–O(3) 176.18(13); C(27)–Pd(2)–P(2) 90.99(10); O(1)–Pd(2)–O(3) 92.76(11); O(1)–Pd(2)–P(2) 176.02(9); O(3)–Pd(2)–P(2) 88.25(7); Pd(2)–C(27) 1.984(4); Pd(2)–O(1) 2.072(3); Pd(2)–O(3) 2.124(3) and Pd(2)–P(2) 2.2417(10).

related species could be present in SMCCs under working catalyst conditions.

In conclusion, direct evidence for transmetallation between several palladacycles of the type [Pd(C^N)(X)(PPh_3)] (where C^N = *N*-phenylbenzaldimine and *N*-phenylazabenzene and X = acetate or *N*-imidate ligands) with 2,4,6-trifluorophenylboronic acid has been gathered. The reactions occur rapidly in THF in <0.5 h. Prolonged reaction leads to the generation of other species, one of which is a novel dinuclear Pd–hydroxo complex. The findings provide insight into the precatalyst activation step for SMCCs mediated by palladacycles. Our results indicate that acetate and *N*-imidate anions can activate arylboronic acids in palladacycles,[15] which adds to the mechanistic debate about transmetallation in SMCCs. Moreover, mixing an organoboronic acid with the palladacyclic precatalyst in SMCCs can lead to a reaction taking place[7a] prior to adding exogenous base – the latter is a mandatory requirement for catalysis but not for catalyst activation.

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