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Towards environmentally friendlier Suzuki–Miyaura reactions with precursors of Pd-NHC (NHC = N-heterocyclic carbene) complexes†‡

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The preparation of [NHC·H][Pd(η³-R-allyl)Cl₂] complexes is disclosed and represents a facile, atom-economical, environmentally friendly and rapid synthesis. These palladates are immediate synthetic precursors to the well-known [Pd(NHC)(η³-R-allyl)Cl] complexes. Their activation leading to catalytically relevant species has been studied in the Suzuki–Miyaura reaction. The need for an activation step prior to the catalysis was examined. The reaction scope showcases its ease and breadth in terms of functional group tolerance. Electron-donating and electron-withdrawing aryl chlorides and bromides were coupled effectively as well as heteroatom-containing and sterically hindered aryl halides. The catalytic reaction was conducted in ethanol with a weak and inexpensive inorganic base.

Introduction

The formation of C–C bonds is one of the most important and common reactions in modern synthetic chemistry.[1–3] Using an organopalladium complex as catalyst has revolutionized this field and the area has been rewarded with the 2010 Nobel Prize in Chemistry. Palladium complexes are nowadays widely used for this purpose.[4] As the area effects the polymer, fine chemical and pharmaceutical industries, research continues to be focused on improving existing methodologies and developing novel transformations using this metal-catalyzed strategy.[5–7] The approach to catalyst formation has been perfected over the past 15 years. Initially, a palladium source and a ligand (or ligand precursor) were used to generate the active complex *in situ*. This situation evolved into approaches using complexes having a well-defined metal-to-ligand ratio (usually 1 : 1) permitting the formation of the putative L-Pd active species.[8] This approach has offered simpler operational protocols and has greatly simplified reaction condition optimization leading to improved catalytic performance. The latest developments have focused on the nature of the throw-away ligand in palladium(II) precursors.[9] Concerning the latter, one fragment which has emerged as favored in cross-coupling catalysis is the η³-R-allyl ligand[10] in complexes of the type [Pd(NHC)(η³-R-allyl)Cl] (NHC = N-heterocyclic carbene), obtained through dimer cleavage of the [Pd(η³-R-allyl)(μ-Cl)]₂ **1** synthon. This methodology was first reported through a free carbene generation or isolation step prior to reaction with **1**.[10,11] A number of synthetic protocols using either well-defined or *in situ* generated palladium catalysts have recently been disclosed using either **1** or related allyl-substituted congeners.[12] Others have followed our approach with NHCs and tertiary phosphines.[9b,11] As part of these advances, the search for novel architectures for catalysis and investigations into the reaction mechanism continues with the goal of understanding and designing ever better performing systems. In this context, we have recently reported on the isolation of a key intermediate along the synthetic pathway leading to [Pd(NHC)(η³-R-allyl)Cl] complexes, namely an imidazolium palladate [NHC·H][Pd(η³-R-allyl)Cl₂] **2** (Scheme 1).[13]

These palladates can be converted into the well-defined Pd-NHC complexes by the action of a simple inorganic base (K_2CO_3) in acetone.[13] The strong bases previously required to generate the free NHC, typically KO^{t}Bu or KHMDS, proved unnecessary, a key advance as these are expensive reagents.

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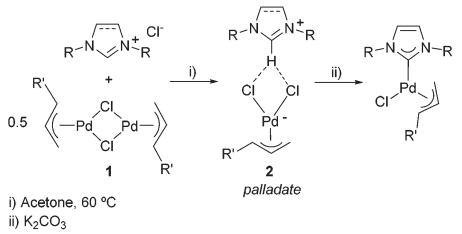
† Dedicated to Professor Carl D. Hoff, mentor and friend, on the occasion of his 70th birthday and to the memory of Prof. Elena Rybak-Akimova.

‡ Electronic supplementary information (ESI) available: Materials, methods, optimisation data, detailed synthetic procedures and spectroscopic data and spectra. See DOI: 10.1039/c8gc00860d



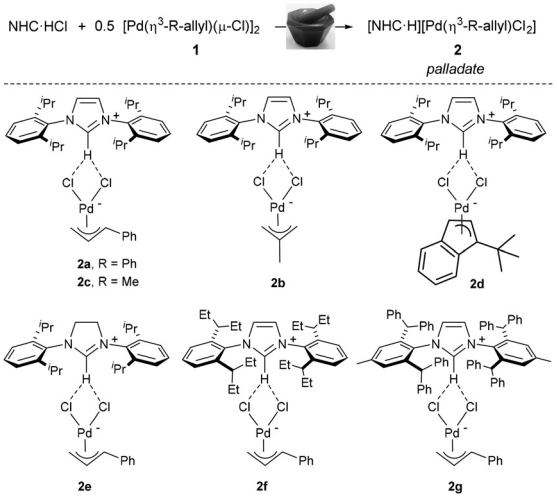
Scheme 1 Synthesis of [Pd(NHC)(η^3-R-allyl)Cl] complexes *via* palladate **2**.[13]

Our earlier synthetic work made use of solvents such as tetrahydrofuran or dichloromethane under an inert atmosphere,[14–16] and our most recent work was conducted in acetone. All these synthetic protocols leading to well-defined Pd-NHC complexes could benefit from the use of a more industrially friendly solvent.[17] Therefore, the development of operationally greener synthetic routes to pre-catalysts and to catalytic systems using mild conditions remains an extremely desirable outcome. Herein, we report on the generality of a synthetic method to access complexes of the type [Pd(NHC)(η^3-R-allyl)Cl], on the versatility of the synthesis of palladates in solvent-free conditions, and on the involvement of these palladates as pre-catalysts in the Suzuki–Miyaura reaction using a weak inorganic base in a green solvent.

Results and discussion

The recently synthesized [NHC·H][Pd(η^3-R-allyl)Cl_2] (**2**) complexes are easily accessible by simply mixing [Pd(η^3-R-allyl)(μ-Cl)]$_2$ (**1**) and two equivalents of an NHC salt in acetone (Scheme 1).[13] This protocol is reminiscent of our previous reports on the syntheses of gold- and copper-NHC complexes that proceed through metallate intermediates.[18] In this study,[13] we have shown that palladates **2** are intermediates along the synthetic pathway leading to the known N-heterocyclic carbene complexes [Pd(NHC)(η^3-R-allyl)Cl].[19] It should be stated that both palladates and [Pd(NHC)(η^3-R-allyl)Cl] are air- and moisture-stable Pd(II) complexes. The recently reported synthesis consists of solubilizing the starting reagents, [Pd(η^3-R-allyl)(μ-Cl)]$_2$ (**1**) and NHC·HCl, in acetone and heating to 60 °C for 1 hour [Scheme 1, (i)].[13] In order to improve these conditions from an environmental perspective, the role of the solvent was examined. Several solvents were tested in the reaction involving [Pd(η^3-cin)(μ-Cl)]$_2$ (**1a**) (cin = cinnamyl) and IPr·HCl[20] (IPr = *N*,*N*′-bis-[2,6-(di-iso-propyl)phenyl]imidazol-2-ylidene) and to our surprise the polarity of these solvents did not influence the yield or purity of the isolated palladate complex (see the ESI, Table S1‡). It became apparent that a vast number of solvents could be used efficiently. Among the solvents tested, acetone, cyclopentylmethylether (CPME), ethyl acetate, ethanol and water are noteworthy. A number of these solvents have been identified as desirable by industry.[21] All experiments in this solvent screening resulted in quantitative yields and analytically pure palladate complexes. As all solvents examined led to the palladate in high yields, we were drawn to the idea of performing the reactions in the solid-state and observed that grinding both reagents in a mortar with a pestle led to the formation of the palladate in >98% yield after grinding times of only 5 minutes! In fact, the solvent-free route became the easiest to launch and we have used this method, akin to ball-milling,[22] to synthesize all complexes reported in the Experimental section (Scheme 2). We have exemplified the method with a number of NHCs [IPr* = (*N*,*N*′-1,3-bis[2,6-bis(diphenylmethyl)-4-methylphenyl]imidazol-2-ylidene, IPent = *N*,*N*′-bis(2,6-di-iso-pentylphenyl)imidazol-2-ylidene, SIPr = *N*,*N*′-bis(2,6-di-iso-propylphenyl)imidazolin-2-ylidene and IPr = *N*,*N*′-bis-[2,6-(di-iso-propyl)phenyl]imidazol-2-ylidene)] to examine the effect of substituents on the NHC and on the allyl fragment (2-crotyl, 2-Me-allyl, cinnamyl and ^{t}Bu-indenyl[23]). We can gladly report that variations at these positions do not lead to significant variations in yields and purity and that the method proves general thus far. Note that although some of these compounds are known, we carried out full analytical characterization, including elemental analysis to unambiguously establish the identity and purity of the complexes obtained using the grinding synthetic route.

While the solvent-free method is the most satisfactory, the compatibility of ethanol as a solvent in this synthesis is especially interesting as ethanol proves a very desirable solvent from environmental and economic aspects. As the synthesis of the palladate is possible, and quite efficient in ethanol, we probed the feasibility of the next step in ethanol, namely the synthesis of the neutral [Pd(NHC)(η^3-R-allyl)Cl] complexes from the palladate. This also proves efficient and the product is obtained in pure form after 5 h at 60 °C. As the palladate can be obtained from **1** and the neutral [Pd(IPr)(η^3-cin)Cl] can be synthesized from the palladate, both in ethanol, we reasoned that [Pd(η^3-cin)(μ-Cl)]$_2$ (**1a**) and IPr·HCl (IPr = *N*,*N*′-bis-[2,6-(di-iso-propyl)phenyl]imidazol-2-ylidene) in the pres-



Scheme 2 Palladates synthesized using the grinding method.

ence of K_2CO_3, in ethanol, might lead to the well-defined [Pd(IPr)(η^3-cin)Cl] product. Gratifyingly, the reaction progresses smoothly in ethanol (reaction time non-optimized) at 60 °C providing 98% isolated yield of the desired product on the multi-gram scale (Scheme 3). This reaction illustrates the feasibility of the synthesis of [Pd(NHC)(η^3-cin)Cl] complexes in a green solvent in high yield and purity.

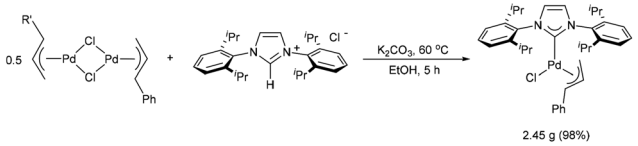
We next investigated the Suzuki–Miyaura reaction in ethanol, using the palladate **2a** as a pre-catalyst. Extensive screening of bases and solvents was undertaken using phenylboronic acid and 4-chloroanisole as benchmark substrates (see the ESI‡ for details). Unsurprisingly, K_2CO_3/EtOH led to the best results, presumably due to the ease of access to the Pd-NHC active species under such conditions.

We then probed the influence of the nature of the boron reagent on catalytic activity. In this regard, three types of boron substrates were selected: boronic acid, boronic ester and potassium trifluoroborate (Scheme 4). When no thermal pre-activation was carried out, the reaction with phenyl boronic acid did not proceed, while the pinacol ester substrate led to poor conversion and the trifluoroborate derivative led to a moderate yield (40%). This is in line with the relative reactivity/stability of the boron coupling partners.[24]

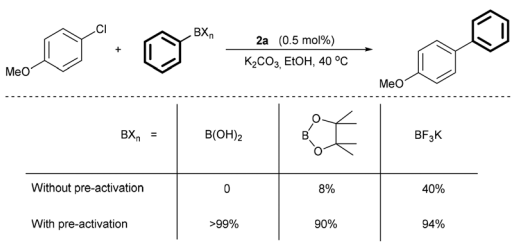
On the other hand, with a pre-activation step (60 °C, 1 h), the cross-coupling reaction involving boronic acid reaches completion while those involving boronic ester and the trifluoroborate derivatives lead to high conversion (90 and 94%, respectively). Hence, pre-activation of the palladate to form the [Pd(NHC)(η^3-cin)Cl] derivative is a crucial step, and this independently of the boron source. Further experiments were thus carried to determine the optimum activation time, which was shown to be 1 hour (Scheme 5). These studies illustrate the importance of this step, since if not enough or too much time is allowed for pre-activation, poorer catalyst performance is observed.

We next turned our attention to the palladates themselves to probe the influence of the carbene and of the leaving-ligand (η^3-R-allyl) on catalyst performance (Table 1). The ease of synthesis of these robust complexes is noteworthy as is the fact that the catalytic reaction can be conducted under aerobic conditions. As expected, the nature of the leaving allyl moiety is important (Table 1, entries 1–4), and the bulky cinnamyl group leads to the best activity amongst **2a–d**. Variation of the NHC ligand is also of great importance, and amongst the pre-catalysts tested (**2a**, **2e–g**) the IPr derivative **2a** leads to the best results (Table 1, entries 1 and 5–7).

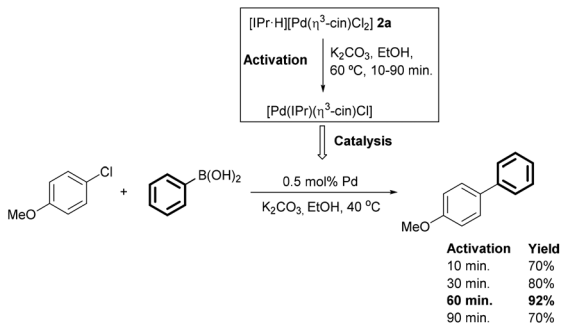
Further optimization (stoichiometry of the reagents, reaction time, temperature) was therefore undertaken using [IPr·H][Pd(η^3-cin)Cl_2] **2a** as the pre-catalyst (see the ESI‡ for details). With our set of optimized reaction conditions in hand, we next examined the scope of the reaction (Scheme 6). First a range of aryl chloride derivatives was selected, and the



Scheme 3 One-pot large-scale synthesis of [Pd(IPr)(η^3-cin)Cl].

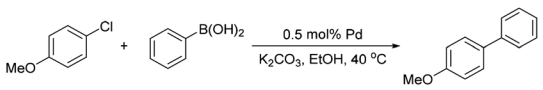


Scheme 4 Nature of the boron reagent in the Suzuki–Miyaura reaction. Reaction conditions: [IPr·H][Pd(η^3-cin)Cl_2] **2a** (0.5 mol%), K_2CO_3 (0.7 mmol), EtOH (1 mL) [pre-activation 60 °C, 1 h], ArCl (0.5 mmol), $PhBX_n$ (0.55 mmol), EtOH (1 mL), 40 °C, 16 h. Yield determined by GC using mesitylene as the internal standard.



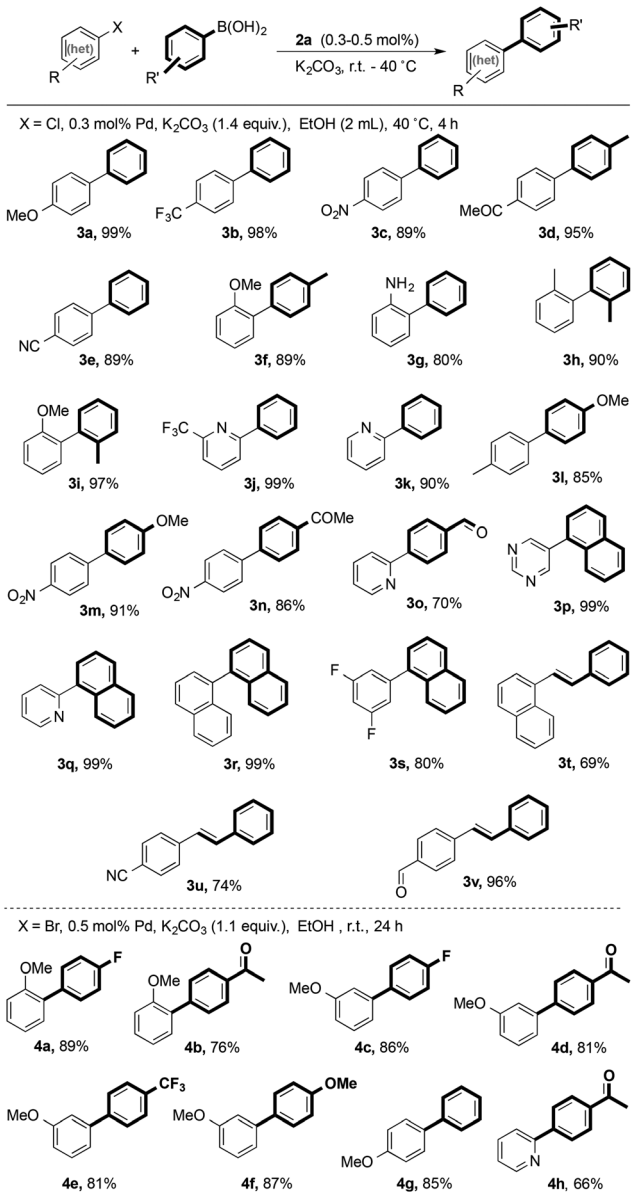
Scheme 5 Nature of the boron reagent in the Suzuki–Miyaura reaction. Reaction conditions: [IPr·H][Pd(η^3-cin)Cl_2] **2a** (0.5 mol%), K_2CO_3 (0.55 mmol), EtOH (1 mL) [pre-activation 60 °C, 10–90 min], ArCl (0.5 mmol), $PhB(OH)_2$ (0.55 mmol), EtOH (1 mL), 40 °C, 16 h. Yield determined by GC using mesitylene as the internal standard.

Table 1 Catalyst optimization (in air)[a]



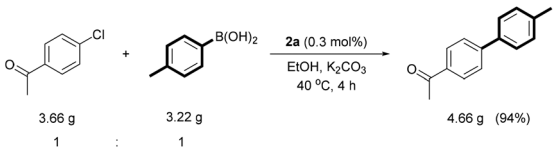
Entry	Palladate pre-catalyst	Yield[b] (%)
1	[IPr·H][Pd(η^3-cin)Cl_2] **2a**	92
2	[IPr·H][Pd(η^3-2-Me-allyl)Cl_2] **2b**	80
3	[IPr·H][Pd(η^3-crotyl)Cl_2] **2c**	8
4	[IPr·H][Pd(η^3-Ind$^{t\mathrm{Bu}}$)Cl_2] **2d**	n.r.
5	[SIPr·H][Pd(η^3-cin)Cl_2] **2e**	30
6	[IPent·H][Pd(η^3-cin)Cl_2] **2f**	n.r.
7	[IPr*·H][Pd(η^3-cin)Cl_2] **2g**	88

[a] [NHC·H][Pd(η^3-R-allyl)Cl_2] pre-catalyst (0.5 mol%), K_2CO_3 (0.55 mmol), EtOH (1 mL) [pre-activation 60 °C, 1 h] ArCl (0.5 mmol), $PhB(OH)_2$ (0.55 mmol) EtOH (1 mL), 40 °C for 16 h. [b] Yield determined by GC, using mesitylene as the internal standard, average of at least two reactions.



Scheme 6 Scope of the Suzuki–Miyaura reaction using **2**. Reaction conditions: (a) X = Cl, [IPr·H][Pd(η^3-cin)Cl_2] **2a** (0.3 mol%), K_2CO_3 (0.7 mmol), EtOH (1 mL) [pre-activation 60 °C, 1 h] ArCl (0.5 mmol), $ArB(OH)_2$ (0.5 mmol), EtOH (1 mL), 40 °C for 4 h; (b) X = Br, [IPr·H][Pd(η^3-cin)Cl_2] **2a** (0.5 mol%), K_2CO_3 (0.55 mmol), EtOH (2 mL) [pre-activation 60 °C, 1 h] $ArB(OH)_2$ (0.5 mmol), ArBr (0.5 mmol), r.t., 24 h. Isolated yields average of two reactions.

reactions were carried out using [IPr·H][Pd(η^3-cin)Cl_2] **2a** (0.3 mol%) in EtOH with K_2CO_3 at 40 °C for 4 h (with a pre-activation of 1 h at 60 °C). Of note the fact that these reactions are carried out in air, and that room temperature reactions are also possible, albeit requiring a longer reaction time (see the ESI‡). The catalytic system was found efficient for all substrates tested. Variations of electronic and/or steric properties on the aryl fragments from both aryl chloride or aryl boronic acid substrates such as styryl boronic acid were well tolerated (Scheme 6, **3u** and **3v**), as well as heterocycles, fragments of



Scheme 7 Large-scale Suzuki–Miyaura reaction.

great importance in particular in the pharmaceutical industry. Functional groups of different nature are compatible with the catalytic system (*e.g.* NO_2, C(O)Me, CN, NH_2). Of note the fact that reactions involving aryl chlorides containing a heteroatom at the *ortho*-position lead to high yields of cross-coupling products within 4 hours, while such substrates often lead to sluggish reactions. Finally, the scope of the reaction was further extended using aryl bromide derivatives. The reactions were carried out at room temperature after a pre-activation step (1 h, 60 °C) using boronic acids bearing various functional groups. Hence the palladates are highly efficient pre-catalysts for a wide range of aryl halide and boronic substrates, and compatible with numerous functional groups.

The scalability of the system was tested in a larger scale catalytic reaction (Scheme 7) in which 4-chloroanisole was reacted with 4-tolylboronic acid in the presence of 0.3 mol% of **2a**, leading to the isolation of 4.66 g of the cross-coupling product within 4 h. Noteworthy, a 1 : 1 aryl chloride to boronic acid ratio was used in the larger size reaction, establishing that an excess of boronic acid, a common operational practice, is not required here.

Conclusions

A newly synthesized class of Pd(II) pre-catalysts was studied, focusing on its synthesis and its catalytic activity under mild reaction conditions while using environmentally acceptable conditions (solvent and base). The palladates require an activation step to permit their conversion into [Pd(NHC)(η^3-cin)Cl] complexes *in situ* prior to them being active for catalysis. The palladate and neutral Pd-NHC syntheses are easy to carry out, even in air. A wide reactivity scope was demonstrated for their use in the Suzuki–Miyaura reaction, where various classes of substrates were investigated and proved compatible with this simple catalytic protocol. Furthermore, the Suzuki–Miyaura reaction and the pre-catalyst synthesis can both be easily scaled up. The use of ethanol affords a green alternative as a reaction medium in both pre-catalyst synthesis (which can also be carried out under solvent-free conditions) and as solvent to perform the Suzuki–Miyaura reaction. The role of these simple palladates in related transformations is presently being investigated.

Experimental

Synthesis of [NHC·H][Pd(η^3-R-allyl)Cl_2] complexes

General procedure: In air, the corresponding NHC·HCl and [Pd(R-allyl)(μ-Cl)]$_2$ were added to a mortar. The two solids were

mixed and ground using a pestle for 5 min. A crystalline solid was obtained.

[IPr·H][Pd(η³-cin)Cl₂] (2a). Following the general procedure from IPr·HCl (49.2 mg, 0.116 mmol) and [Pd(η³-cin)(μ-Cl)]₂ (30.0 mg, 0.057 mmol), the product was obtained as a yellow powder in a 99% (80 mg) yield. **¹H NMR (400 MHz, $CDCl_3$):** δ (ppm) = 9.19 (s, 1H, $NCHN_{Imid}$), 8.32 (d, J = 1.6 Hz, 2H, CH_{Imid}), 7.54 (t, J = 8.1 Hz, 2H, CH_{Ar}), 7.45 (dd, J = 6.1 Hz, 2H, $CH_{Ar(cin)}$), 7.33 (d, J = 7.9 Hz, 4H, CH_{Ar}), 7.21 (m, 3H, $CH_{Ar(cin)}$), 5.69–5.62 (m, 1H, $CH_{(cin)}$), 4.46 (m, 1H, $CH_{2(cin)}$), 3.86 (d, J = 6.6 Hz, 1H, $CH_{2(cin)}$), 2.90 (d, J = 11.9 Hz, 1H, $CH_{(cin)}$), 2.48–2.41 (m, 4H, $CH_{(IPr)}$), 1.27 (d, J = 6.8 Hz, 12H, $CH_{3(IPr)}$), 1.19 (d, J = 6.7 Hz, 12H, $CH_{3(IPr)}$). **$^{13}C\{^1H\}$ NMR (400 MHz, $CDCl_3$):** δ (ppm) = δ 145.1 (C_{Ar}), 136.9 (CH_{NCN}), 132.1 (CH_{Ar}), 129.9 (C_{Ar}), 128.7 (CH_{cin}), 127.9 (CH_{cin}), 127.7 (CH_{imid}), 124.7 (CH), 105.2 (CH_{cin}), 81.8 (CH_{cin}), 58.4 ($CH_{2(cin)}$), 29.0 ($CH_{(IPr)}$), 24.7 ($CH_{3(IPr)}$), 23.9 ($CH_{3(IPr)}$). **Elemental Analysis**: Expected C 63.02, H 7.05, N 4.08; found: C 63.11, H 6.95, N 4.14.

[IPr·H][Pd(η³-2-Me-allyl)Cl₂] (2b). Following the general procedure using IPr·HCl (75.7 mg, 0.178 mmol) and [Pd(η³-2-Me-allyl)(μ-Cl)]₂ (35 mg, 0.089 mmol), the product was obtained as a yellow powder in a 99% (113 mg) yield. **H NMR (400 MHz, $CDCl_3$):** δ (ppm) = 9.20 (s, 1H, $NCHN_{Imid}$), 8.36 (s, 2H, CH_{Imid}), 7.58 (t, J = 8.5 Hz, 2H, CH_{Ar}), 7.36 (d, J = 9.1 Hz, 4H, CH_{Ar}), 3.72 (br. s, 2H, $CH_{2(allyl)}$), 2.69 (br. s, 2H, $CH_{2(allyl)}$), 2.51 (sept, J = 7.1 Hz, 4H, $CH_{(IPr)}$), 2.03 (br. s, 3H, $CH_{3(allyl)}$), 1.31 (d, J = 6.8 Hz, 12H, $CH_{3(IPr)}$), 1.23 (d, J = 7.1 Hz, 12H, $CH_{3(IPr)}$). **$^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$):** δ 145.3 (C_{Ar}), 136.9 (CH_{NCN}), 132.2 (CH_{Ar}), 130.0 (C_{Ar}), 127.8 (CH_{imid}), 124.8 (CH_{Ar}), 60.5 ($CH_{2(allyl)}$), 29.2 ($CH_{(IPr)}$), 24.8 ($CH_{3(IPr)}$), 24.1 ($CH_{3(IPr)}$), 22.8 ($CH_{3(allyl)}$). **Elemental Analysis**: Expected C 59.86, H 7.13, N 4.50; found: C 59.58, H 7.19, N 4.67.

Synthesis of [IPr·H][Pd(η³-crotyl)Cl₂] (2c). Following the general procedure using IPr·HCl (75.7 mg, 0.178 mmol) and [Pd(η³-crotyl)(μ-Cl)]₂ (35.0 mg, 0.089 mmol), the product was obtained as a yellow powder in a 99% (113 mg) yield. **¹H NMR (400 MHz, $CDCl_3$):** δ (ppm) = 9.20 (s, 1H, $NCHN_{Imid}$), 8.33 (s, 2H, CH_{Imid}), 7.56 (t, J = 10.5 Hz, 2H, CH_{Ar}), 7.33 (d, J = 7.3 Hz, 4H, CH_{Ar}), 5.08 (br. s, 1H, $CH_{(crotyl)}$), 3.07 (br. s, 2H, $CH_{2(crotyl)}$), 2.57 (br. s, 1H, $CH_{(crotyl)}$), 2.48 (sept, J = 13.5 Hz, 4H, $CH_{(IPr)}$), 1.30 (s, 3H, $CH_{3(crotyl)}$), 1.28 (d, J = 7.2 Hz, 12H, $CH_{3(IPr)}$), 1.20 (d, J = 7.2 Hz, 12H, $CH_{3(IPr)}$). **$^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$):** δ (ppm) = 145.2 (C_{Ar}), 137.0 (CH_{NCN}), 132.2 (CH_{Ar}), 130.0 (C_{Ar}), 127.7 (CH_{imid}), 124.8 (CH_{Ar}), 110.3 ($CH_{(allyl)}$), 79.4 ($CH_{(allyl)}$), 57.0 ($CH_{2(allyl)}$), 29.1 ($CH_{3(IPr)}$), 24.8 ($CH_{3(IPr)}$), 24.0 ($CH_{3(IPr)}$), 18.1 ($CH_{3(allyl)}$). **Elemental Analysis**: Expected C 59.86, H 7.13, N 4.50; found: C 59.70, H 6.95, N 4.69.

Synthesis of [IPr·H][Pd(η³-Ind^{tBu})Cl₂] (2d). Following the general procedure using IPr·HCl (100 mg, 0.235 mmol) and [Pd(η³-Ind^{tBu})(μ-Cl)]₂[23a] (74 mg, 0.118 mmol), the product was obtained as a brown/beige powder in a 99% (173 mg) yield. **¹H NMR (400 MHz, $CDCl_3$):** δ (ppm) = δ 9.22 (s, 1H, $NCHN_{Imid}$), 8.27 (s, 2H, CH_{Imid}), 7.57 (t, J = 8.2 Hz, 2H, CH_{Ar}), 7.34 (d, J = 7.8 Hz, 4H, CH_{Ar}), 7.11–7.07 (m, 1H, CH_{Ind}), 6.80–6.57 (m, 4H, CH_{Ind}), 5.51–5.41 (m, 1H, CH_{Ind}), 2.47 (sept, J = 7.2 Hz, 7.3 Hz, 4H, $CH_{(IPr)}$), 1.36–1.31 (m, 9H, $CH_{3(Ind)}$), 1.29 (d, J = 7.2 Hz, 12H, $CH_{3(IPr)}$), 1.20 (d, J = 6.9 Hz, 12H, $CH_{3(IPr)}$). **$^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$):** δ (ppm) = 145.2 (C_{Ar}), 137.0 (CH_{NCN}), 132.2 (CH_{Ar}), 130.0 (C_{Ar}), 127.7 (CH_{imid}), 127.4 (CH_{Ind}), 125.4 (CH_{Ind}), 125.3 (CH_{Ind}), 124.8 (CH_{Ar}), 124.1 (CH_{Ind}), 120.2–117.7 (CH_{Ind}), 109.1–107.0 (CH_{Ind}), 70.7 (CH_{Ind}), 34.3 (CH_{Ind}), 29.2 ($CH_{3(IPr)}$), 29.0 ($CH_{3(Ind)}$), 28.8 ($CH_{3(Ind)}$), 24.9 ($CH_{3(IPr)}$), 24.0 ($CH_{3(IPr)}$). **Elemental Analysis**: Expected C 65.08, H 7.10, N 3.79; found: C 64.87, H 7.17, N 3.94.

Synthesis of [SIPr·H][Pd(η³-cin)Cl₂] (2e). Following the general procedure from SIPr·HCl (65 mg, 0.152 mmol), [Pd(η³-cin)(μ-Cl)]₂ (40.0 mg, 0.076 mmol), the product was obtained as a yellow powder in a 99% yield (107 mg) yield. **¹H NMR (400 MHz, $CDCl_3$):** δ (ppm) = 7.71 (s, 1H, $NCHN_{Imid}$), 7.53–7.48 (m, 4H, $CH_{Ar(IPr+cin)}$), 7.31–7.26 (s, 7H, $CH_{Ar(IPr+cin)}$), 5.80–5.72 (m, 1H, $CH_{(cin)}$), 4.97 (s, 4H, $CH_{2(Imid)}$), 4.55 (d, J = 11.1 Hz, 1H, $CH_{2(cin)}$), 3.96 (d, J = 6.7 Hz, 1H, $CH_{2(cin)}$), 3.15–3.08 (m, 4H, $CH_{(SIPr)}$), 3.01 (d, J = 11.9 Hz, 1H, $CH_{(cin)}$), 1.42 (d, J = 6.3 Hz, 12H, $CH_{3(SIPr)}$), 1.23 (d, J = 6.3 Hz, 12H, $CH_{3(SIPr)}$). **$^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$):** δ (ppm) = 156.9 (CH_{NCN}), 146.6 (C_{Ar}), 131.6 (CH_{Ar}), 129.5 (C_{Ar}), 129.1 (CH_{cin}), 128.4 (CH_{cin}), 128.1 (CH_{cin}), 125.1 (CH_{Ar}), 105.9 (CH_{cin}), 81.3 (CH_{cin}), 59.0 ($CH_{2(cin)}$), 56.0 ($CH_{2(imid)}$), 29.1 ($CH_{(IPr)}$), 25.6 ($CH_{3(IPr)}$), 24.1 ($CH_{3(IPr)}$). **Elemental analysis**: Expected: C 63.02, H 7.05, N 4.08; found: C 63.28, H 6.96, N 4.15.

Synthesis of [IPent·H][Pd(η³-cin)Cl₂] (2f). Following the general procedure from IPent·HCl (62.2 mg, 0.116 mmol) and [Pd(η³-cin)(μ-Cl)]₂ (30 mg, 0.06 mmol), the product was obtained as a yellow powder in a 99% (92 mg) yield. **¹H NMR (400 MHz, $CDCl_3$):** δ (ppm) = 8.43 (d, J = 1.6 Hz, 2H, CH_{Imid}), 8.37 (br. s, 1H, $NCHN_{Imid}$), 7.60 (t, J = 7.9 Hz, 2H, CH_{Ar}), 7.50 (d, J = 7.5 Hz, 2H, $CH_{Ar(cin)}$), 7.27 (m, 7H, CH_{Ar}), 5.75 (br. s, 1H, $CH_{(cin)}$), 4.60 (br. s, 1H, $CH_{2(cin)}$), 3.93 (br. s, 1H, $CH_{2(cin)}$), 3.00 (br. s, 1H, $CH_{(cin)}$), 1.96 (sept, J = 8.1 Hz, 4H, $CH_{(IPent)}$), 1.75–1.60 (m, 16H, $CH_{2(IPent)}$), 0.86 (t, J = 7.1 Hz, 12H, $CH_{3(IPent)}$), 0.76 (t, J = 7.4 Hz, 12H, $CH_{3(IPent)}$). **$^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$):** δ (ppm) = δ 142.7 (C_{Ar}), 134.9 (CH_{NCN}), 132.8 (C_{Ar}), 132.0 (CH_{Ar}), 129.2 (CH_{cin}), 128.9 (CH_{cin}), 128.3 (C_{cin}), 128.1 (CH_{imid}), 125.4 (CH_{Ar}), 105.6 (CH_{cin}), 81.2 (CH_{cin}), 59.2 ($CH_{2(cin)}$), 43.5 ($CH_{(IPent)}$), 29.4 ($CH_{2(IPent)}$), 28.5 ($CH_{2(IPent)}$), 12.6 ($CH_{3(IPent)}$), 12.4 ($CH_{3(IPent)}$). **Elemental analysis**: Expected: C 65.07, H 7.85, N 3.52; found: C 64.77, H 7.94, N 3.68.

Synthesis of [IPr*·H][Pd(η³-cin)Cl₂] (2g). Following the general procedure from IPr*·HCl (109.9 mg, 0.115 mmol) and [Pd(η³-cin)(μ-Cl)]₂ (30.0 mg, 0.058 mmol), the product was obtained as a yellow powder in a 99% yield (139 mg). **¹H NMR (400 MHz, $CDCl_3$):** δ (ppm) = 12.52 (s, 1H, $NCHN_{Imid}$), 7.31–7.23 (m, 20H, CH_{Ar}), 7.19–7.06 (m, 19H, CH_{Ar}), 6.77–6.75 (m, 10H, CH_{Ar}), 5.87–5.75 (br. m, 1H, $CH_{(cin)}$), 5.41 (s, 4H, $CH_{(IPr*)}$), 5.33 (s, 2H, CH_{Imid}), 4.60–3.85 (br. m, 2H, $CH_{2(cin)}$), 2.97–2.58 (m, 1H, $CH_{(cin)}$), 2.18 (s, 6H, $CH_{3(IPr*)}$). **$^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$):** δ (ppm) = 142.6 (C_{Ar}), 142.5 (CH_{NCN}), 142.1 (C_{Ar}), 140.7 (C_{Ar}), 140.6 (C_{Ar}), 130.7 (CH_{Ar}), 130.2 (CH_{Ar}), 129.1 (CH_{Ar}), 128.3 (CH_{Ar}), 127.9 (CH_{Ar}), 126.6 (CH_{Ar}), 126.5 (CH_{Ar}), 122.8 (CH_{imid}), 105.6 (CH_{cin}), 82.2 (CH_{cin}), 59.3 (CH_{cin}), 51.0 ($CH_{3(IPr)}$), 21.7 ($CH_{3(IPr)}$). **Elemental analysis**: Expected: C 77.38, H 5.66, N 2.31; found: C 77.25, H 5.47, N 2.36.

Suzuki–Miyaura reaction, general procedure

(a) With ArCl substrates: in air, a vial was charged with [IPr·H][Pd(η^3-cin)Cl_2] (0.3 mol%, 1.7 mg), K_2CO_3 (0.7 mmol, 97 mg), ethanol (1 mL) and a magnetic stir bar and sealed with a screw cap. The mixture was left stirring at 60 °C for 1 h. The vial was removed from the heating block and the corresponding aryl boronic acid (0.5 mmol) was added followed by the corresponding aryl chloride (0.5 mmol). The reaction was left to stir for 4 h at 40 °C. Ethyl acetate (10 mL) and water (10 mL) were added to the reaction mixture. The aqueous phase was extracted with ethyl acetate (3 × 10 mL). The combined organic phases were dried over $MgSO_4$ and filtered. The solvent was removed under reduced pressure. The crude product was dissolved in CH_2Cl_2 (5 mL), filtered through silica gel and recrystallized (CH_2Cl_2/pentane); (b) with ArBr substrates: in a screw caped vial (5 mL) [IPr·H][Pd(η^3-cinnamyl)Cl_2] (0.5 mol%), K_2CO_3 (0.55 mmol), ethanol (2 mL) and a magnetic stir bar were charged. The mixture was stirred at 60 °C for 1 h. The mixture was allowed to cool to room temperature. Then the corresponding boronic acid (0.5 mmol) was added followed by the corresponding aryl bromide (0.5 mmol). The reaction was left to stir at r.t. for 24 h. Water (20 mL) was added to the reaction mixture and the product was extracted with ethyl acetate (3 × 15 mL). The combined organic layers were washed with brine (20 mL) and dried over Mg_2SO_4. The crude was concentrated under reduced pressure and purified by column chromatography using ethyl acetate/*n*-hexane as eluent.

Larger scale Suzuki–Miyaura reaction procedure

In air, a 100 mL round bottom flask was charged with [IPr·H][Pd(η^3-cin)Cl_2] (48 mg, 0.078 mmol, 0.3 mol%), K_2CO_3 (4.56 g, 33.1 mmol), ethanol (50 mL) and a magnetic stir bar. The mixture was stirred at 60 °C for 1 h. The flask was removed from the heating block and 4-chloroacetophenone (3.65 g, 23.6 mmol), followed by 4-tolylboronic acid (3.22 g, 23.6 mmol), were added as solids. The reaction was left stirring for 16 h at 40 °C. After this time, the reaction was allowed to reach room temperature and then ethyl acetate (50 mL) and water (50 mL) were added. The solution was transferred to a separating funnel (250 mL) where aqueous/organic phases were separated and the aqueous phase was further extracted with ethyl acetate (3 × 50 mL). The combined organic extractions were dried over $MgSO_4$, filtered and volatiles removed under vacuum. The resulting crude solid product was dissolved in CH_2Cl_2 (25 mL), filtered through silica gel and recrystallized (CH_2Cl_2/pentane). The reaction yielded 4.66 g (94%) of the desired product as a white solid. ^{1}H NMR spectroscopy confirmed the identity and purity of the product.[25] ^{1}H NMR (400 MHz, $CDCl_3$): δ (ppm) = δ 8.03 (d, J = 8.2 Hz, 2H), 7.69 (d, J = 8.6 Hz, 2H), 7.55 (d, J = 8.6 Hz, 2H), 7.29 (d, J = 8.6 Hz, 2H), 2.64 (s, 3H), 2.41 (s, 3H). ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ (ppm) = δ 197.9 (COMe), 145.9 (C_{Ar}), 138.4 (C_{Ar}), 137.1 (C_{Ar}), 135.7 (C_{Ar}), 129.8 (CH_{Ar}), 129.1 (CH_{Ar}), 127.2 (CH_{Ar}), 127.1 (CH_{Ar}), 26.8 (CH_3), 21.3 (CH_3).

Conflicts of interest

The authors declare no conflict of interest.

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