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Tetranuclear *N*-Heterocyclic Carbene Palladium Acetate—The Fast-Initiating Precatalyst of Suzuki Coupling

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Abstract: A tetranuclear *N*-heterocyclic palladium carbene acetate, characterised by a [Pd]/[NHC] = 2/1 ratio, was synthesised and shown to be catalytically active in Suzuki coupling. Single crystal XRD studies of the complex revealed its unprecedented geometry, with the presence of three coordinated palladium centres. The catalytic activity of the complex is significantly higher than that of analogues containing the same N-heterocyclic carbene ligand. Preliminary studies have been carried out to determine the catalytic properties of the complex.

Keywords: palladium; cross-coupling; *N*-heterocyclic carbene complexes

Citation: Ostrowska, S.; Rogalski, S.; Kubicki, M.; Pietraszuk, C. Tetranuclear *N*-Heterocyclic Carbene Palladium Acetate—The Fast-Initiating Precatalyst of Suzuki Coupling. *Catalysts* **2024**, *14*, 836. https://doi.org/10.3390/catal14110836

Academic Editor: Tomasz K. Olszewski

Received: 28 October 2024
Revised: 18 November 2024
Accepted: 19 November 2024
Published: 20 November 2024

1. Introduction

N-heterocyclic carbenes (NHCs) have become versatile ligands for catalysis with metal complexes due to their strong σ-donor nature and steric bulk [1–5]. Since their first use [6], significant progress has been made in the design of NHC-based active Pd precatalysts for catalytic organic synthesis, particularly in cross-coupling reactions to form C-C and C-heteroatom bonds [7–10]. A number of complexes with high selectivity, productivity, and activity have been described in the literature. These well-defined, pre-formed complexes should efficiently generate [(NHC)Pd(0)] complexes, which are generally considered to be active catalysts [11]. The development of palladium precatalysts that efficiently generate Pd(0) active species has recently been reviewed by Shaughnessy [12].

The state of the art of NHC palladium acetates was described by Nolan in 2008 [13]. NHC complexes of palladium with acetate ligands have been successfully used as catalysts for a variety of transformations, such as aerobic oxidation of alcohols [14], hydroarylation of alkynes [15,16], α-arylation of ketones [17], polycondensation of haloaryl ketones [18], direct C5-arylation of imidazoles with aryl chlorides [19], direct arylation of pentafluorobenzene with aryl bromides [20], direct C2-arylation of indoles with aryl sulfonyl hydrazides [21], intramolecular direct arylation [22], oxidative coupling of terminal alkynes [23], and intramolecular amination of alkenes [24,25]. Applications of the NHC palladium acetates in Suzuki coupling were reported by Nolan [26], who demonstrated their high activity towards a wide range of aryl chlorides and aryl and alkyl boronic acids. Efficient examples of the Heck reaction have been described [27–29], tandem Heck alkynylation/cyclisation between 2-iodophenol and phenylacetylene [30], desulphinative Sonogashira coupling of arylsulphonyl hydrazides with arylalkynes [31], and sterically hindered C-N coupling reactions [32]. Recently, efficient Suzuki–Miyaura coupling of arylamides with boronic acids in the presence of [(NHC)Pd$(OAc)_2$] was proposed by Szostak [33].

Within the family of heterocyclic carbene complexes, dimeric complexes of the type [{Pd(NHC)Cl(μ-Cl)}$_2$] (**1**, Figure 1) [34] have attracted much attention due to their catalytic activity in coupling reactions. Our contribution to this field is the development of hydroxo-bridged palladium dimers of the type [{Pd(NHC)Cl(μ-OH)}$_2$] (**2**, Figure 1) [35–38], which exhibit attractive catalytic properties in coupling reactions.

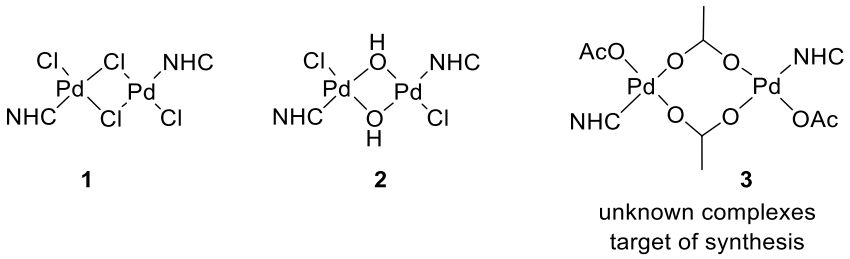


Figure 1. NHC palladium dimeric precatalysts (**1**, **2**) and a hypothetical acetate analogue (**3**).

Here, we report on our efforts in the synthesis of acetate-bridged NHC–palladium complexes (e.g., **3**, Figure 1) or similar complexes and the investigation of their catalytic properties.

2. Results and Discussion

The dimeric complex (**1**) was considered a convenient starting material for this study. Treatment of a toluene solution of the chloride dimer [{Pd(IMes)Cl(μ-Cl)}$_2$] (**1a**) with a 20-fold molar excess of Ag(OAc) in toluene, at room temperature, resulted in a gradual colour change of the solution from pale yellow to colourless within 2 h, indicating the formation of a new complex. The complex was successfully isolated. However, its ^{1}H NMR spectrum was difficult to interpret due to the broadening of all signals (see ESI). Fortunately, using passive diffusion between dichloromethane, in which the complex was dissolved, and n-hexane, it was possible to obtain a single crystal. Its XRD analysis made it possible to determine the crystal structure (Figure 2). Instead of the target complex **3** (Figure 1), a tetranuclear complex **4** (Scheme 1) was obtained. The geometry of the resulting complex is unprecedented. No similar case could be found in the Cambridge database. In principle, it is a four-centred symmetrical (C_i) complex, built of two two-centred units connected by two acetate anions. In each of the subunits' two Pd ions are again connected by two acetates (Pd···Pd distance is quite short, 2.914 Å), and one of this ions is additionally bound through a Pd-C bond (1.936 Å) to the NHC ligand. So, one of the Pd centres in the subunit is three-coordinated, by three oxygen atoms from acetate anions, and the other is four coordinated, in a distorted square-planar manner. The Pd-O distances are within typical values (mean value from the CSD for acetate Pd complexes is 2.06(5) Å). Due to the disorder, a detailed analysis of the geometry of the complex cannot be performed.

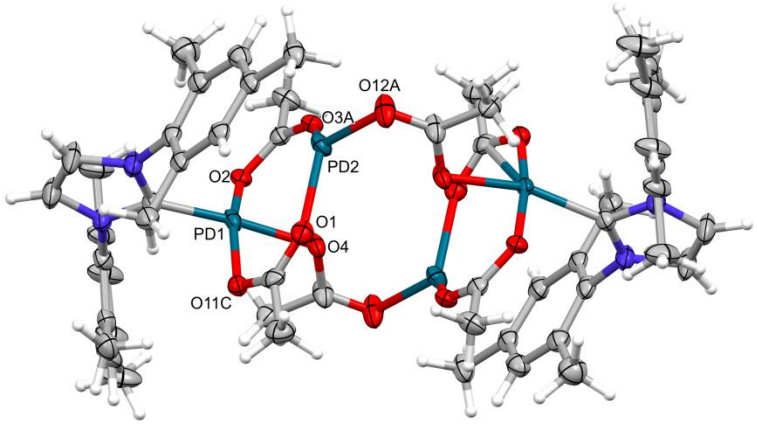
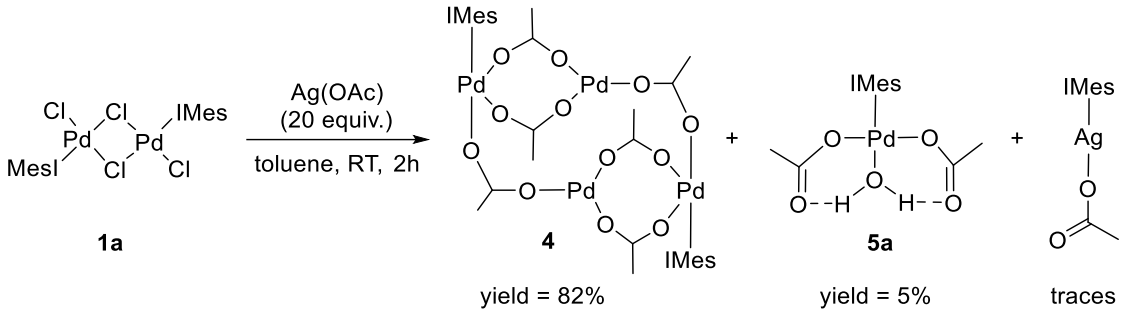


Figure 2. Perspective view of complex **4**. Ellipsoids are drawn at the 50% probability level, and hydrogen atoms are shown as spheres of arbitrary radii. The disorder is not shown; the unlabelled part is related to the labelled one by symmetry operation 1-x,1-y,1-z. Selected bond distances (Å): Pd1-O11 2.04(1), Pd1-O2 1.99(1), Pd1-O1 1.94(1), Pd2-O12 2.34(1), CCDC 2382539.

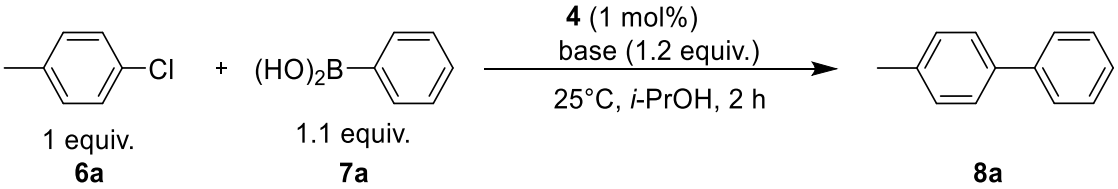


Scheme 1. Synthesis of tetranuclear complex **4**.

The complex was found to be unstable in solution, transforming nearly quantitatively to mononuclear complex [Pd(IMes)$(OAc)_2(H_2O)$] (**5a**) within 48 h. On the other hand, when stored as a solid for a week, in an inert atmosphere, it showed no signs of decomposition.

Detailed analysis of the reaction mixture showed the formation of complex **4** in fairly high yields, the formation of small amounts of mononuclear complex **5a**, and trace amounts of NHC silver acetate (Scheme 1). [39] The silver complex was unstable, so it was not possible to record its ^{13}C NMR spectrum. Under the conditions and scale described (see experiment), the synthesis of complex **4** is reproducible. Compared to the synthesis of complex **5a** reported in the literature [22], a larger excess of silver acetate was used in the synthesis of **4** (20-fold vs. 4-fold) and the reaction was carried out in toluene (instead of methylene chloride). Attempts to obtain analogues of complex **4** with other commonly used NHC ligands (SIMes, IPr, and SIPr) and to obtain dimeric complexes of type **3** (Figure 1) were unsuccessful. The syntheses led in each case to the corresponding monomeric complexes, i.e., [Pd(NHC)$(OAc)_2(H_2O)$] (**5**).

Since, in complex **4**, there are two coordinationally unsaturated palladium atoms and, as a result of dimer cleavage, the release of coordination sites at palladium atoms bonded to NHC is to be expected, it was reasonable to investigate the catalytic activity of the complex. Suzuki cross-coupling was chosen as the test reaction. The activity of NHC palladium acetate in Suzuki–Miyaura coupling was reported by Nolan [30], who demonstrated its high activity towards a wide range of aryl (as well as alkyl) chlorides and arylboronic acids. Using the conditions reported in Nolan's publication, reactions of 4-chlorotoluene with phenylboronic acid were carried out in the presence of complex **4**. Chromatographic (GC) analysis performed after the reaction had proceeded for two hours revealed complete conversion of the aryl halide. The selective course of the reaction towards the cross-coupling product was confirmed by GC/MS and ^1H NMR spectroscopy (Scheme 2).



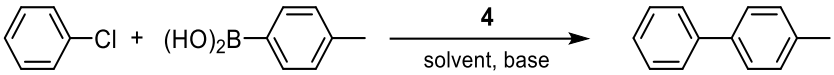
Scheme 2. Coupling of 4-chlorotoluene with phenylboronic acid in the presence of **4**.

In search of the optimum conditions, a number of catalytic tests were performed. The results are shown in Table 1.

To test the possibility of running the reaction in air, KOH was used as the base. This modification did not lead to a decrease in reaction yield. The results showed that the Suzuki coupling carried out in the presence of precursor **4** is efficient in isopropanol, in the presence of KO*t*-Bu or KOH as the base. Under base-free conditions, no conversion was observed. Further investigations showed that complex **4** at a loading of 0.5 mol% and 0.25 mol% (per palladium atom) allows yields of the product exceeding 90%. Further

reduction in the catalyst loading to 0.125 mol% results in a significant decrease in the yield. The reaction can be carried out successfully in ethanol. An efficient course of the reaction was obtained by carrying out the process in an air atmosphere.

Table 1. Suzuki coupling; selection of optimal conditions.



Entry	Loading Cat. [mol%]	Solvent	Base	Temp. [°C]	Time [h]	Conversion [%] [a]
1	1	*i*-PrOH	KO^{t}Bu	25	2	>99
2	1	*i*-PrOH	KOH	25	2	>99
3	0.5	*i*-PrOH	KOH	25	2	>99
4	0.25	*i*-PrOH	KOH	25	2	91
5	0.125	*i*-PrOH	KOH	25	2(24)	46(50)
6	0.125	*i*-PrOH	KOH	50	2	55
7	0.5	EtOH	KOH	25	2	95
8	0.5	MeOH	KOH	25	2	32
9	0.5	H_2O	KOH	25	24	NR

Reaction conditions: chlorobenzene (0.5 mmol); 4-tolylboronic acid (0.55 mmol;); 25 °C, 2 h, [ArCl]/[Ar′B(OH)$_2$] = 1/1.1; [KOH]/[Ar′B(OH)$_2$] = 1.2/1; air; cat. Pd (**4**); solvent (2.0 mL); [a] GC yield, dodecane as internal standard; NR—no reaction.

A reaction profile of the coupling of 4-chlorotoluene with phenylboronic acid in the presence of precatalyst 4 was determined and compared with profiles obtained for other precatalysts containing the IMes ligand, namely, [{Pd(IMes)Cl(μ-Cl)}$_2$] (**1a**) [34], [Pd(IMes)(OAc)$_2$(H$_2$O)] (**5a**) [22], and [Pd(IMes)(allyl)Cl] (**9**) [40]. The results (Figure 3) showed no significant differences in the activity of the complexes **1a**, **5a**, and **9**. In contrast, particularly high activity was observed for complex **4**. In this case, complete conversion of 4-chlorotoluene occurred after 10 min.

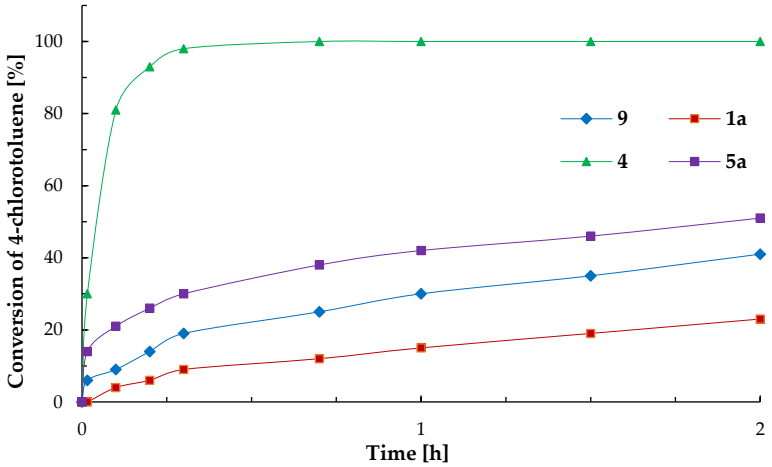


Figure 3. Reaction profiles for the coupling of 4-chlorotoluene with phenylboronic acid in the presence of [{Pd(μ-Cl)Cl(IMes)}$_2$] (**1a**), [Pd(IMes)(OAc)$_2$(H$_2$O)] (**5a**), [{Pd$_2$(IMes)(OAc)$_3$}$_2$] (**4**), and [Pd(IMes)(allyl)Cl] (**9**). Reaction conditions: [Pd] (0.5 mol%), *i*-PrOH, 25 °C, [4-chlorotoluene]/[PhB(OH)$_2$] = 1/1.1, [KOH]/[PhB(OH)$_2$] = 1.2/1, air, dodecane (internal standard); conversion monitored by GC.

Since, assuming a homogeneous reaction, similar transition states are to be expected for all catalysts used, differences in activity must be due to the rate of the catalyst initiation pathway [41]. To obtain additional information indicating the homogeneous nature of the reactions studied in the presence of all the catalysts tested, mercury tests (Figure S1) and

tetramethylaminothiourea (TMTU) poisoning tests were performed. The TMTU poisoning test was originally proposed by Elsevier, C.J. et al. [42]. The mercury tests carried out show no change in reaction performance for any of the catalysts tested (Figure S1). In contrast, the catalyst poisoning tests indicate that the addition of 2 equivalents of TMTU relative to 1 equivalent of palladium results in suppression of the reaction for all precatalysts tested. The results suggest a homogeneous reaction pathway for all the complexes tested.

To gain a better understanding of the mechanism of catalyst initiation, a quantitative Suzuki poisoning test was carried out by cross-coupling 4-chlorotoluene with phenylboronic acid using 0 to 2 TMTU equivalents relative to palladium. The conversion of 4-chlorotoluene over time was measured for different amounts of TMTU added (Figure 4).

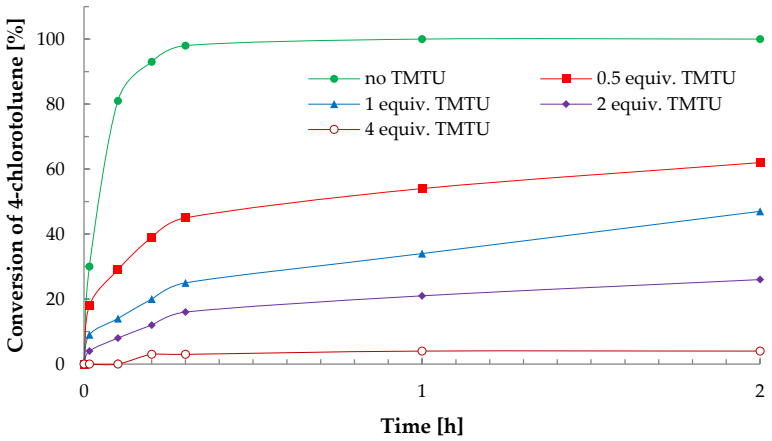
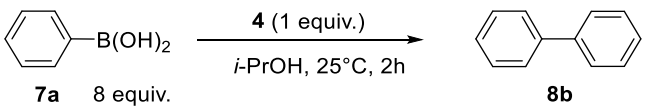


Figure 4. Cross-coupling of 4-chlorotoluene with phenylboronic acid in the presence of **4**. Conversion of 4-chlorotoluene over time for different amounts of TMTU added. The legend gives the numbers of TMTU equivalents per 1 equiv. of Pd.

The results presented in Figure 4 demonstrate that the addition of 0.5 equiv. of TMTU causes a significant decrease in the catalytic activity of complex **4**, while the addition of 1–2 equiv. of TMTU allows us to obtain results comparable to those obtained for complexes **1a**, **5a**, and **9** (see Figure 3). Such results indicate that the reason for the high activity of catalyst **4** may be the coordinational unsaturation of the palladium atoms in the complex.

To learn more about the mechanism of reduction of complex **4** under Suzuki reaction conditions, a solution of **4** in isopropanol was treated with an excess of phenylboronic acid at room temperature. After two hours, GC/MS analysis of the mixture showed the presence of biphenyl (Scheme 3), suggesting a mechanism involving the transfer of two phenyl groups to a palladium atom via transmetallation and subsequent reductive elimination of the biaryl.



Scheme 3. Reduction of **4** in the presence of boronic acid.

To determine the reagent scope, selected coupling reactions of 4-tolylboronic acid with aryl chlorides were performed in the presence of complex **4**. Analysis of the results revealed satisfactory catalytic activity for the challenging reactants (i.e., chloropyridines and 2-chloro-1,3-dimethylbenzene) (Figure 5).

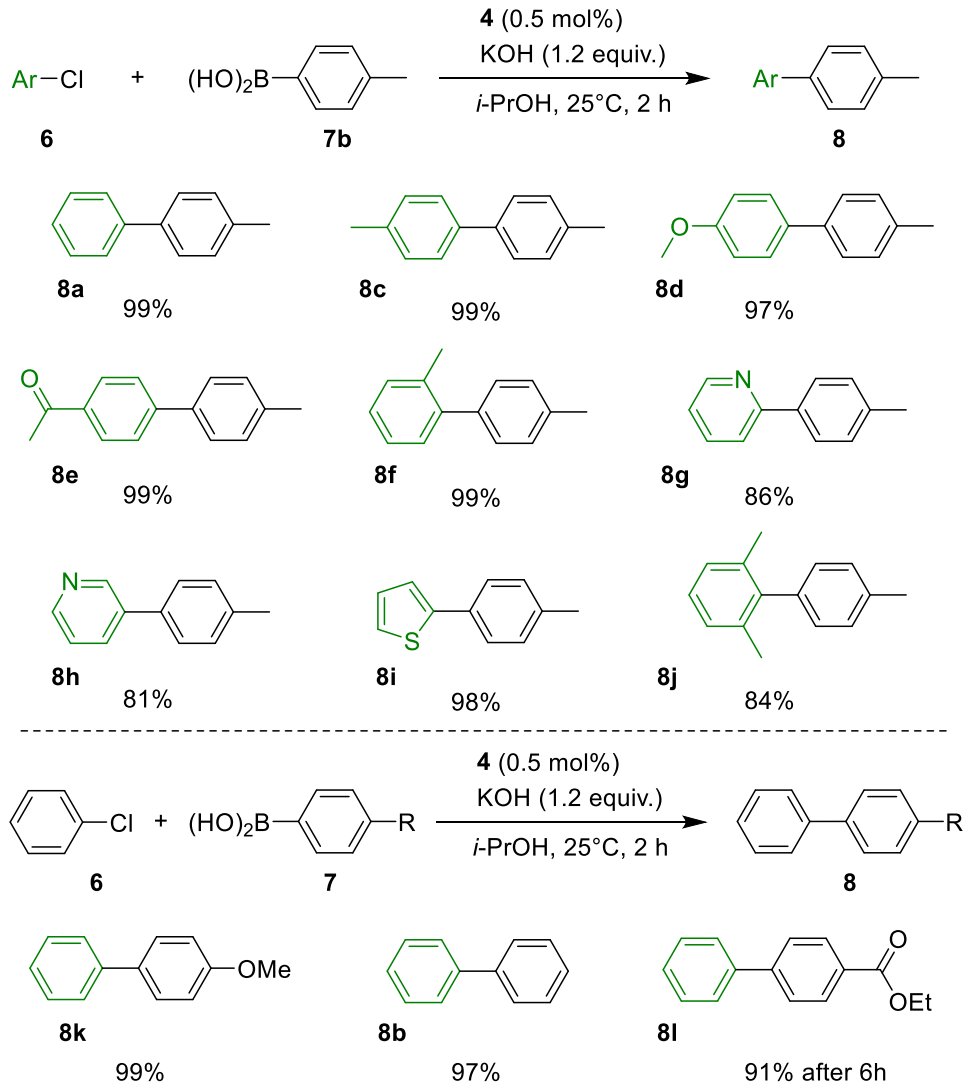


Figure 5. Yields of Suzuki cross-coupling products of 4-tolylboronic acid with aryl chlorides in the presence of complex **4**. Reaction conditions: [Pd] (0.5 mol%), *i*-PrOH, 25 °C, 2 h, [ArCl]/[Ar′B(OH)$_2$] = 1/1.1; [KOH]/[Ar′B(OH)$_2$] = 1.2/1; air; isolated yields.

3. Materials and Methods

3.1. General Methods and Chemicals

^{1}H and ^{13}C NMR spectra were recorded on a Varian 400 operating at 402.6 and 101.2 MHz or Bruker Avance 600 MHz operating at 600.1 and 151.2 MHz, respectively. GC/MS analyses were performed on a Varian Saturn 2100T equipped with a DB-5, 30 m capillary column and Ion Trap Detector. The HRMS spectrum was recorded on a MaldiSYNAPT G2-S HDMS (Waters, Milford, MA, USA). GC analyses were performed using a Varian CP-3800 (column: RTX-5 30 m, ID 0.53 mm), equipped with TCD. The chemicals were obtained from the following sources: Pd(OAc)$_2$ from Angene, Ag(OAc) from Merck, potassium hydroxide, aryl halides, boronic acids, and toluene, were purchased from Aldrich. Isopropanol, dichloromethane, hexane, and ethyl acetate were purchased from Fisher Scientific. [{Pd(IMes)(μ-Cl)Cl}$_2$] [34], [Pd(IMes)(OAc)$_2$(H$_2$O)] [22], and [Pd(IMes)(allyl)Cl] [40] were prepared according to the published procedures.

3.2. Methods

3.2.1. Synthesis of [{Pd(IMes)Cl(μ-Cl)}$_2$] (**1a**)

In a 15 mL vial equipped with a magnetic stirrer and a stopper, [Pd(IMes)(allyl)Cl] (0.4 g, 0.63 mmol), dichloromethane (2 mL), and 2 M hydrogen chloride in diethyl ether

(2 mL) were placed in air. The mixture was stirred at room temperature for 2 h. The mixture was then evaporated to dryness and washed several times with small portions of n-hexane (4 × 1 mL). The residue was evaporated and dried in vacuo to give the product as an orange solid with a yield of 98%.

^{1}H NMR: (600 MHz, $CDCl_3$, ppm) δ: 7.04 (broad s, 2H), 6.94 (s, 1H), 2.44 (s, 3H), 2.23 (broad s, 3H), 2.08 (broad s, 3H); ^{13}C NMR: (151 MHz, $CDCl_3$, ppm) δ: 145.23, 139.33, 135.82,134.62, 129.54, 124.62, 21.45, 19.01. Spectrum is consistent with literature data [34].

3.2.2. Synthesis of Complex [{Pd_2(IMes)$(OAc)_3$}$_2$] (**4**)

In a 10 mL Schlenk flask equipped with a magnetic stirrer and a glass stopper under an inert atmosphere, we placed 0.009 g (0.00932 mmol) [{Pd(IMes)Cl(μ-Cl)}$_2$], silver acetate (0.0064 g, 0.17 mmol), and 2 mL deoxygenated and dried toluene. The reaction mixture was vigorously stirred at room temperature for 2 h. Then, the mixture was filtered through Celite, and the light-yellow filtrate was evaporated to dryness in a vacuum to give the complex, a pale-yellow solid in an 82% yield. The single crystal was obtained by passive diffusion between dichloromethane, in which the complex was dissolved, and n-hexane. ^{1}H NMR (600 MHz, $CDCl_3$, ppm) δ: 7.16 (s, 4H), 7.08(bs, 4H), 7.07 (bs, 2H), 7.04 (s, 2H), 2.44 (s, 6H), 2.41 (s, 6H), 2.16 ((partially covered) s, 6H), 2.15 (s, 12H), 2.07 (s, 12H), 1.78 (s, 6H), 1.67 (s, 6H). ^{13}C NMR (151 MHz, $CDCl_3$, ppm) δ: 180.63, 178.09, 148.49, 139.39, 138.83, 135.12, 134.78, 133.62, 133.56, 128.53, 128.35, 122.98, 122.62, 22.47, 22.06, 20.40, 17.29, 16.77. ATR/FT-IR (cm^{-1}): 3139, 2966, 2921, 2866, 1588, 1487, 1367, 1322, 1236, 1018, 929, 850, 684. HRMS calculated for $C_{54}H_{66}N_4O_{12}Pd_4$ (M^+): 1386.0809; found: 1386.0817.

3.2.3. Synthesis of [Pd(IMes)$(OAc)_2(H_2O)$] (**5a**)

In a 5 mL round-bottomed flask equipped with a magnetic stirrer and a glass stopper, we placed 19.3 mg (0.01 mmol; 1 equiv.) of di-μ-chlorobis[chloro{1,3-bis(2,4,6-trimethylphenyl) imidazol-2-ylidene}palladium(II)], 13.4 mg (0.04 mmol; 4 equiv.) of silver acetate, and 2 mL of dichloromethane (DCM) (technical grade) in air. The reaction mixture was vigorously stirred at room temperature for 2 h. The mixture was then filtered through Celite and the light-yellow filtrate was evaporated to dryness in vacuo to give the complex as a light-yellow solid. ^{1}H NMR (600 MHz, $CDCl_3$, ppm) δ: 7.08 (s, 4H), 7.04 (s, 2H), 2.42 (s, 6H), 2.16 (s, 12H), 1.68 (s, 6H). ^{13}C NMR (151 MHz, $CDCl_3$, ppm) δ: 181.64, 149.33, 139.81, 135.76, 134.55, 129.52, 123.63, 23.23, 21.37, 17.76; spectrum is consistent with literature data [22].

3.2.4. Synthesis of [Pd(IMes)(allyl)Cl] (**9**)

In a 10 mL Schlenk flask equipped with a magnetic stirrer and a glass stopper, we placed 44.3 mg (0.0755 mmol, 2.1 equiv.) of the IMes·Cl—salt, 131 mg (0.358 mmol, 1.0 equiv) of [{Pd(allyl)Cl}$_2$], and 101 mg KO*t*-Bu (0.905 mmol, 2.5 equiv) under an argon atmosphere. To this, 1.5 mL of THF was added, and the reaction was stirred at room temperature. After 5 h, a small amount of silica gel was added and the solvent removed in vacuo. The product was loaded directly on a silica gel column and purified by flash chromatography (60% ether/hexanes) to give an off-white solid with a yield of 83%.

^{1}H NMR: (600 MHz, $CDCl_3$, ppm) δ: 7.08 (s, 2H), 6.96 (s, 4H), 4.90–4.77 (m, 1H), 3.86 (dd, J = 7.4 Hz, 2.0 Hz, 1H), 3.19 (d, J = 7.1 Hz, 1H), 2.80 (d, J = 13.4 Hz, 1H), 2.32 (s, 6H), 2.21 (s, 6H), 2.19 (s, 6H), 1.79 (d, J = 11.9 Hz, 1H); ^{13}C NMR: (151 MHz, $CDCl_3$, ppm) δ: 183.82, 138.96, 136.00, 135.59, 129.20, 129.13, 123.06, 114.38, 77.21, 72.48, 49.30, 21.26, 18.42, 18.36. Spectrum is consistent with literature data [40].

3.2.5. Suzuki–Miyaura Coupling—Catalytic Tests

In the air, the 4 mL scintillation vial equipped with a magnetic stirring bar was charged with phenylboronic acid (0.55 mmol; 1.1 equiv.) and isopropanol (2 mL). The reaction mixture was stirred at 25 °C for 2 min. until complete acid dissolution. Then, 4-chlorotoluene (0.5 mmol; 1 equiv.), dodecane (10 μL) (internal standard), palladium complex (0.5 mol%), and KOH (0.66 mmol; 1.3 equiv.) were added. The mixture was stirred

at 25 °C for 2 h. The reaction course was monitored by gas chromatography and GC/MS. The reaction products were identified by their mass spectra.

3.2.6. Mercury Poisoning Experiment

In the air, a scintillation vial (4 mL) equipped with a magnetic stirring bar was charged with phenylboronic acid (0.55 mmol; 1.1 equiv.) and isopropanol (2 mL). The reaction mixture was stirred at 25 °C for 2 min. until complete acid dissolution. Then, 4-chlorotoluene (0.5 mmol; 1 equiv.), dodecane (10 µL) (internal standard), palladium complex (0.5 mol%), and KOH (0.66 mmol; 1.3 equiv.) were added. The mixture was stirred at 25 °C for 0.5 h (5 min. for [{(IMes)$Pd_2(OAc)_3$}$_2$]). Then, Hg (500 equiv. in relation to catalyst) was added. The reactions were carried out at 25 °C upon vigorous stirring for the next 1.5 h. The reaction course was monitored by gas chromatography.

3.2.7. Tetramethylthiourea (TMTU) Poisoning Experiment

In the air, a scintillation vial (4 mL) equipped with a magnetic stirring bar was charged with phenylboronic acid (0.55 mmol; 1.1 equiv.) and isopropanol (2 mL). The reaction mixture was stirred at 25 °C for 2 min. until complete acid dissolution. Then, 4-chlorotoluene (0.5 mmol; 1 equiv.), dodecane (10 µL) (internal standard), palladium complex (0.5 mol%), KOH (0.66 mmol; 1.3 equiv.), and tetramethylthiourea (TMTU) (2 equiv. of TMTU per 1 equiv. of Pd) were added. The mixture was stirred at 25 °C for 2 h. The reaction course was monitored by gas chromatography.

3.2.8. General Procedure for the Synthesis of Suzuki Coupling Products

Arylboronic acid (0.53 mmol) and *i*-PrOH (2 mL) were placed in the air in a 5 mL glass reactor equipped with a magnetic stirrer. The reaction mixture was stirred at room temperature until the acid was completely dissolved (approximately 5 min). Then, aryl chloride ([Ar'B$(OH)_2$]:[ArCl] = 1:1.1), [{Pd_2(IMes)$(OAc)_3$}$_2$] complex (0.5 mol%), and KOH ([Ar'B$(OH)_2$]:[KOH] = 1:1.2) were added. The reaction mixture was stirred at room temperature for 2 h. Gas chromatography (GC) and gas chromatography with mass detection (GC-MS) monitored the reaction progress. The purity of all obtained biaryl products was determined by comparing ^{1}H and ^{13}C NMR spectroscopic data of the post-reaction mixture with spectroscopic data obtained for previously isolated biaryls.

4-methyl-1,1′-biphenyl (**8a**)

^{1}H NMR (400 MHz, $CDCl_3$, ppm) δ: 7.63–7.61 (m, 2H), 7.54 (d, *J* = 8.0 Hz, 2H), 7.49–7.44 (m, 2H), 7.38–7.34 (m, 1H), 7.30–7.28 (m, 2H), 2.44 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$, ppm) δ: 141.29, 138.48, 137.14, 129.61, 128.84, 127.12, 127.10 (2C), 21.24. MS (EI) *m*/*z* (%) = 168 (M^+, 100), 154 (47), 76 (21). Spectrum is consistent with literature data [43].

1,1′-biphenyl (**8b**)

^{1}H NMR (600 MHz, $CDCl_3$, ppm) δ: 7.63 (dd, *J* = 9.7, 1.7 Hz, 4H), 7.47 (t, *J* = 7.7 Hz, 4H), 7.40–7.35 (m, 2H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm) δ: 141.38, 128.89, 127.38, 127.30. MS (EI) *m*/*z* (%) = 154 (M+, 100), 76 (21). Spectrum is consistent with literature data [44].

4,4′-dimethyl-1,1′-biphenyl (**8c**)

^{1}H NMR (400 MHz, $CDCl_3$, ppm) δ: 7.49 (d, *J* = 8.1 Hz, 4H), 7.25 (d, *J* = 8.1 Hz, 4H), 2.40 (s, 6H). ^{13}C NMR (101 MHz, $CDCl_3$, ppm) δ: 138.41, 136.84, 129.57, 126.94, 21.23. MS (EI) *m*/*z* (%) = 182 (M+, 100), 167 (54), 152 (15). Spectrum is consistent with literature data [44].

4-methoxy-4′-methyl-1,1′-biphenyl (**8d**)

^{1}H NMR (300 MHz, $CDCl_3$, ppm) δ: 7.54–7.50 (m, 2H), 7.46 (d, *J* = 8.1 Hz, 2H), 7.24 (d, *J* = 8,1 Hz, 2H), 7.00–6.96 (m, 2H), 3.85 (s, 3H), 2.39 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$, ppm) δ: 159.07, 138.11, 136.49, 133.89, 129.57, 128.09, 126.72, 114.29, 55.48, 21.19. MS (EI) *m*/*z* (%) = 198 (M^+, 100), 183 (47), 167 (50), 153 (24). Spectrum is consistent with literature data [43].

1-(4′-methyl-[1,1′-biphenyl]-4-yl)ethan-1-one (**8e**)

^{1}H NMR (400 MHz, $CDCl_3$, ppm) δ: 8.02 (d, *J* = 8.2 Hz, 2H), 7.67 (d, *J* = 8.2 Hz, 2H), 7.54 (d, *J* = 8.1 Hz, 2H), 7.30–7.27 (m, 2H), 2.64 (s, 3H), 2.42 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$, ppm) δ: 197.90, 145.86, 138.38, 137.09, 135.73, 129.82, 129.04, 127.24, 127.09, 26.80, 21.32. MS (EI) *m*/*z* (%) = 198 (M^+, 100), 183 (47), 167 (50), 153 (24). Spectrum is consistent with literature data [45].

2,4′-dimethyl-1,1′-biphenyl (**8f**)

^{1}H NMR (400 MHz, $CDCl_3$, ppm) δ: 7.16–7.12 (m, 8H), 2.30 (s, 3H), 2.18 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$, ppm) δ: 142.01, 139.16, 136.49, 135.51, 130.41, 129.99, 129.20, 128.90, 127.20, 125.88, 21.30, 20.65. MS (EI) *m*/*z* (%) = MS (EI) *m*/*z* (%) = 182 (M^+, 100), 167 (44), 153 (23), 91 (52). Spectrum is consistent with literature data [43].

2-(p-tolyl)pyridine (**8g**)

^{1}H NMR (400 MHz, $CDCl_3$, ppm) δ: 8.74–8.56 (m, 1H), 7.91–7.87 (m, 2H), 7.76–7.68 (m, 2H), 7.32–7.27 (m, 2H), 7.22–7.18 (m, 1H), 2.41 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$, ppm) δ: 157.58, 149.69, 139.11, 136.87, 136.69, 129.63, 126.91, 121.95, 120.43, 21.43. MS (EI) *m*/*z* (%) = 170 (M+H, 100), 171 (13), 169 (32), 168 (31), 167 (14). Spectrum is consistent with literature data [46].

3-(p-tolyl)pyridine (**8h**)

^{1}H NMR (400 MHz, $CDCl_3$, ppm) δ: 8.84 (d, *J* = 1.7 Hz, 1H), 8.57 (dd, *J* = 4.8, 1.6 Hz, 1H), 7.86 (ddd, *J* = 7.9, 2.4, 1.6 Hz, 1H), 7.48 (d, *J* = 8.1 Hz, 2H), 7.35 (ddd, *J* = 7.9, 4.8, 0.9 Hz, 1H), 7.29 (d, *J* = 7.9 Hz, 2H), 2.41 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$, ppm) δ: 148.24, 138.19, 136.72, 135.02, 134.33, 129.94, 127.10, 123.67, 21.30. MS (EI) *m*/*z* (%) = 170 (M+H, 100), 169 (78), 168 (57), 167 (31), 115 (17). Spectrum is consistent with literature data [47].

2-(p-tolyl)thiophene (**8i**)

^{1}H NMR (400 MHz, $CDCl_3$, ppm) δ: 7.53 (d, *J* = 8.1 Hz, 2H), 7.29 (dd, *J* = 3.5, 1.2 Hz, 1H), 7.26 (dd, *J* = 5.1, 1.2 Hz, 1H), 7.20–7.19 (m, 2H), 7.08 (dd, *J* = 5.1, 3.6 Hz, 1H), 2.39 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$, ppm) δ: 144.70, 137.44, 131.77, 129.67, 129.56, 128.05, 126.93, 125.99, 124.39, 122.69, 21.30. MS (EI) *m*/*z* (%) = 174 (M^+, 100), 159 (84), 91 (45), 83 (67), 77 (42), 15 (31). Spectrum is consistent with literature data [48].

2,4′,6-trimethyl-1,1′-biphenyl (**8j**)

^{1}H NMR (400 MHz $CDCl_3$, ppm) δ: 7.26–7.23 (m, 2H), 7.18–7.10 (m, 3H), 7.05 (d, *J* = 7.9 Hz, 2H), 2.42 (s, 3H), 2.05 (s, 6H).^{13}C NMR (101 MHz, $CDCl_3$, ppm) δ: 141.98, 138.14, 136.37, 136.20, 129.24, 129.01, 127.36, 127.00, 21.39, 21.04. MS (EI) *m*/*z* (%) = 196 (M^+, 100), 181 (72), 167 (51), 153 (34), 105 (21), 91 (17). Spectrum is consistent with literature data [49].

4-methoxy-1,1′-biphenyl (**8k**)

^{1}H NMR (600 MHz, $CDCl_3$, ppm) δ: 7.61–7.59 (m, 2H), 7.59–7.56 (m, 2H), 7.48–7.44 (m, 2H), 7.37–7.33 (m, 1H), 7.04–7.01 (m, 2H), 3.88 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$, ppm) δ: 159.28, 140.94, 133.89, 128.85, 128.27, 126.85, 126.78, 114.33, 55.43. MS (EI) *m*/*z* (%) = 184 (M^+, 100), 153 (45), 141 (78), 107 (11). Spectrum is consistent with literature data [50].

ethyl [1,1′-biphenyl]-4-carboxylate (**8l**)

^{1}H NMR (600 MHz, $CDCl_3$, ppm) δ: 8.14–8.11 (m, 2H), 7.68–7.61 (m, 4H), 7.50–7.44 (m, 2H), 7.42–7.38 (m, 1H), 4.42 (q, *J* = 7.1 Hz, 2H), 1.43 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (151 MHz, $CDCl_3$, ppm) δ: 166.72, 145.68, 140.17, 130.19, 129.35, 129.04, 128.23, 127.40, 127.13, 61.13, 14.48. MS (EI) *m*/*z* (%) = 226 (M^+, 100), 181 (33), 152 (10). Spectrum is consistent with literature data [50].

3.2.9. X-Ray Crystallography

Diffraction data were collected by the ω-scan technique, at 100(1) K, using graphite-monochromated MoK_α radiation (λ = 0.71073 Å), on a Rigaku XCalibur four-circle diffractometer with an EOS CCD detector. The data were corrected for Lorentz polarisation as well as for absorption effects [51]. Precise unit-cell parameters were determined by a least-squares fit of the reflections of the highest intensity, chosen from the whole experiment. The structures were solved with SHELXT [52] and refined with the full-matrix least-squares procedure on F^2 by SHELXL [53]. All non-hydrogen atoms were refined anisotropically.

Hydrogen atoms were placed in idealised positions and refined as a 'riding model' with isotropic displacement parameters set at 1.2 times U_{eq} of appropriate carrier atoms. The crystal structure appeared to be heavily disordered, and the disorder was successfully modelled; however, some constraints were necessary (Table 2).

Table 2. Crystal data, data collection, and structural refinement.

Compound	**4**
Formula	$C_{54}H_{66}N_4O_{12}Pd_4$
Formula weight	1388.71
Crystal system	monoclinic
Space group	$P2_1/n$
a (Å)	14.4381(3)
b (Å)	16.2457(2)
c (Å)	14.5752(2)
β (°)	107.948(2)
V(Å^3)	3252.35(10)
Z	2
D_x (g cm^{-3})	1.418
F(000)	1396
μ(mm^{-1})	1.142
Reflections:	
collected	45,626
unique (R_{int})	5717 (0.0284)
with I > 2σ(I)	5153
R(F) [I > 2σ(I)]	0.0408
wR(F^2) [I > 2σ(I)]	0.0874
R(F) [all data]	0.0455
wR(F^2) [all data]	0.0888
Goodness of fit	1.072
max/min Δρ (e·Å^{-3})	0.44/−0.39
CCDC deposition number	2,382,539

4. Conclusions

The synthesis of an air-tolerant tetranuclear palladium precatalyst containing four palladium atoms in its structure, two of which are directly linked to the IMes ligand, and six acetate groups forming a network of bridging ligands between the individual palladium atoms is presented. We show that one of the Pd centres in the subunit is tricoordinated, via three oxygen atoms of the acetate anions, and the other is tetra-coordinated, in a distorted square pattern. The developed precatalyst has been shown to exhibit high catalytic activity (>90%) in the Suzuki coupling reaction at precatalyst loadings of up to 0.25 mol%. An efficient protocol for the synthesis of various substituted biaryls with low precatalyst loading (0.5 mol%) at room temperature in environmentally friendly isopropanol is developed. The investigated tetranuclear complex containing coordinationally unsaturated palladium atoms shows high catalytic activity in the initial step of the Suzuki coupling reaction, significantly higher than common precatalysts containing ligand IMes: ([{Pd(IMes)Cl(μ-Cl)}$_2$], [Pd(IMes)(OAc)$_2$(H_2O)], [Pd(IMes)(allyl)Cl], indicating a rapid catalyst initiation process. The mechanism of palladium reduction was elucidated. The results obtained, in particular, the high initiation rate of the active catalyst, may be useful in the design of new generations of palladium catalysts.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/catal14110836/s1, ^{1}H and ^{13}C NMR spectra of palladium complexes and Suzuki coupling products and FT-IR spectra complexes (**4**); Figure S1: Reaction profiles for the coupling of 4-chlorotoluene with phenylboronic acid in the presence of [{Pd(IMes)Cl(μ-Cl)}$_2$] (**1a**), [Pd(IMes)(OAc)$_2$(H$_2$O)] (**5a**), [{Pd$_2$(IMes)(OAc)$_3$}$_2$] (**4**), and [Pd(IMes)(allyl)Cl] (**9**). Reaction conditions: [Pd] (0.5 mol%), i-PrOH, 25 °C, [4-chlorotoluene]/[PhB(OH)$_2$] = 1/1.1, [KOH]/[PhB(OH)$_2$] = 1.2/1, air, Hg (500 equiv. added after 10 min. reaction), dodecane (internal standard); conversion monitored by GC.

Author Contributions: Conceptualization, C.P. and S.O.; methodology, S.O. and S.R.; formal analysis, S.O. and C.P.; investigation, S.O., S.R. and M.K.; resources, S.R. and C.P.; data curation, S.O., S.R. and C.P.; writing—original draft preparation, S.O., M.K. and C.P.; writing—review and editing, S.O. and C.P.; visualization, S.O. and C.P.; supervision, C.P.; project administration, C.P.; funding acquisition, C.P. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge the financial support of the Faculty of Chemistry, Adam Mickiewicz University, Poznan, from the funds awarded by the Ministry of Education and Science in the form of a subsidy for the maintenance and development of research potential in 2024.

Data Availability Statement: All experimental data are contained in the article and Supplementary Materials.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Hopkinson, M.N.; Richter, C.; Schedler, M.; Glorius, F. An overview of N-heterocyclic carbenes. *Nature* **2014**, *510*, 485–496. [CrossRef] [PubMed]
2. Nolan, S.P. *N-Heterocyclic Carbenes: Effective Tools for Organometallic Synthesis*, 1st ed.; Wiley-VCH: Hoboken, NJ, USA, 2014; ISBN 9783527334902.
3. Diez-Gonzalez, S.; Marion, N.; Nolan, S.P. N-heterocyclic carbenes in late transition metal catalysis. *Chem. Rev.* **2009**, *109*, 3612–3676. [CrossRef] [PubMed]
4. Nolan, S.P. *N-Heterocyclic Carbenes in Synthesis*; Wiley-VCH: Weinheim, Germany, 2006; ISBN 978-3-527-60940-6.
5. Herrmann, W.A. A new concept in organometallic catalysis. *Angew. Chem. Int. Ed.* **2002**, *41*, 1290–1309. [CrossRef]
6. Herrmann, W.A.; Elison, M.; Fischer, J.; Kocher, C.; Artus, G.R.J. Metal complexes of N-heterocyclic carbenes—A new structural principle for catalysts in homogeneous catalysis. *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2371–2374. [CrossRef]
7. Hoyos, M.; Guest, D.; Navarro, O. *(N-Heterocyclic Carbene)-Palladium Complexes in Catalysis: In N-Heterocyclic Carbenes: Effective Tools for Organometallic Synthesis*; Wiley-VCH: Weinheim, Germany, 2014; pp. 85–109. ISBN 9783527334902.
8. Li, H.; Johansson Seechurn, C.C.C.; Colacot, T.J. Development of preformed Pd catalysts for cross-coupling reactions, beyond the 2010 Nobel Prize. *ACS Catal.* **2012**, *2*, 1147–1164. [CrossRef]
9. Valente, C.; Calimsiz, S.; Hoi, K.-H.; Mallik, D.; Sayah, M.; Organ, M.G. The development of bulky palladium NHC complexes for the most-challenging cross-coupling reactions. *Angew. Chem. Int. Ed.* **2012**, *51*, 3314–3332. [CrossRef]
10. Fortman, G.C.; Nolan, S.P. N-Heterocyclic carbene (NHC) ligands and palladium in homogeneous cross-coupling catalysis: A perfect union. *Chem. Soc. Rev.* **2011**, *40*, 5151–5169. [CrossRef] [PubMed]
11. Firsan, S.J.; Sivakumar, V.; Colacot, T.J. Emerging Trends in Cross-Coupling: Twelve-Electron-Based L$_1$Pd(0) Catalysts, Their Mechanism of Action, and Selected Applications. *Chem. Rev.* **2022**, *122*, 16983–17027. [CrossRef]
12. Shaughnessy, K.H. Development of palladium precatalysts that efficiently generate LPd (0) active species. *Isr. J. Chem.* **2020**, *60*, 180–194. [CrossRef]
13. Marion, N.; Nolan, S.P. Well-defined N-heterocyclic carbenes−palladium (II) precatalysts for cross-coupling reactions. *Acc. Chem. Res.* **2008**, *41*, 1440–1449. [CrossRef]
14. Jensen, D.R.; Schultz, M.J.; Mueller, J.A.; Sigman, M.S. A well-defined complex for palladium-catalyzed aerobic oxidation of alcohols: Design, synthesis, and mechanistic considerations. *Angew. Chem. Int. Ed.* **2003**, *42*, 3810–3813. [CrossRef] [PubMed]
15. Viciu, M.S.; Stevens, E.D.; Petersen, J.L.; Nolan, S.P. N-heterocyclic carbene palladium complexes bearing carboxylate ligands and their catalytic activity in the hydroarylation of alkynes. *Organometallics* **2004**, *23*, 3752–3755. [CrossRef]
16. Saravanakumar, R.; Ramkumar, V.; Sankararaman, S. Synthesis and structure of 1, 4-diphenyl-3-methyl-1, 2, 3-triazol-5-ylidene palladium complexes and application in catalytic hydroarylation of alkynes. *Organometallics* **2011**, *30*, 1689–1694. [CrossRef]
17. Singh, R.; Nolan, S.P. An efficient and mild protocol for the α-arylation of ketones mediated by an (imidazol-2-ylidene) palladium (acetate) system. *J. Organomet. Chem.* **2005**, *690*, 5832–5840. [CrossRef]
18. Matsubara, K.; Okazaki, H.; Senju, M. Polycondensation of haloarylketones catalyzed by palladium compounds bearing N-heterocyclic carbene (NHC) ligands. *J. Organomet. Chem.* **2006**, *691*, 3693–3699. [CrossRef]

19. Kumar, P.V.; Lin, W.-S.; Shen, J.-S.; Nandi, D.; Lee, H.M. Direct C5-arylation reaction between imidazoles and aryl chlorides catalyzed by palladium complexes with phosphines and N-heterocyclic carbenes. *Organometallics* **2011**, *30*, 5160–5169. [CrossRef]
20. Dan Yuan, D.; Huynh, H.V. 1, 2, 3-Triazolin-5-ylidenes: Synthesis of hetero-bis (carbene) Pd (II) complexes, determination of donor strengths, and catalysis. *Organometallics* **2012**, *31*, 405–412. [CrossRef]
21. Yang, J.; Zong, L.-L.; Zhu, X.-T.; Zhu, X.-Y.; Zhao, J.-Y. Well-defined (NHC)Pd(*N*–heterocyclic carboxylate)(OAc) complexes-catalyzed direct C2-arylation of free (NH)-indoles with arylsulfonyl hydrazides. *Appl. Organomet. Chem.* **2020**, *34*, e5985. [CrossRef]
22. Campeau, L.-C.; Thansandote, P.; Fagnou, K. High-yielding intramolecular direct arylation reactions with aryl chlorides. *Org. Lett.* **2005**, *7*, 1857–1860. [CrossRef]
23. Hsiao, T.-H.; Wu, T.-L.; Chatterjee, S.; Chiu, C.-Y.; Lee, H.M.; Bettucci, L.; Bianchini, C.; Oberhauser, W. Palladium acetate complexes bearing chelating N-heterocyclic carbene (NHC) ligands: Synthesis and catalytic oxidative homocoupling of terminal alkynes. *J. Organomet. Chem.* **2009**, *694*, 4014–4024. [CrossRef]
24. Rogers, M.M.; Wendlandt, J.E.; Guzei, I.A.; Stahl, S.S. Aerobic intramolecular oxidative amination of alkenes catalyzed by NHC-coordinated palladium complexes. *Org. Lett.* **2006**, *8*, 2257–2260. [CrossRef] [PubMed]
25. Scarborough, C.C.; Bergant, A.; Sazama, G.T.; Guzei, A.; Spencer, L.C.; Stahl, S.S. Synthesis of Pd^{II} complexes bearing an enantiomerically resolved seven-membered *N*-heterocyclic carbene ligand and initial studies of their use in asymmetric Wacker-type oxidative cyclization reactions. *Tetrahedron* **2009**, *65*, 5084–5092. [CrossRef] [PubMed]
26. Singh, R.; Viciu, M.S.; Kramareva, N.; Navarro, O.; Nolan, S.P. Simple (imidazol-2-ylidene)-Pd-acetate complexes as effective precatalysts for sterically hindered Suzuki− Miyaura couplings. *Org. Lett.* **2005**, *7*, 1829–1832. [CrossRef]
27. Han, Y.; Huynh, H.V.; Koh, L.L. Pd (II) complexes of a sterically bulky, benzannulated N-heterocyclic carbene and their catalytic activities in the Mizoroki–Heck reaction. *J. Organomet. Chem.* **2007**, *692*, 3606–3613. [CrossRef]
28. Yeung, A.D.; Ng, P.S.; Huynh, H.V. Co-ligand effects in the catalytic activity of Pd(II)–NHC complexes. *J. Organomet. Chem.* **2011**, *696*, 112–117. [CrossRef]
29. Guo, S.; Huynh, H.V. Dipalladium complexes with triazolidin-diylidene bridges and their catalytic activities. *Organometallics* **2012**, *31*, 4565–4573. [CrossRef]
30. Kumar, A.; Gangwar, M.K.; Prakasham, A.P.; Mhatre, D.; Kalita, A.C.; Ghosh, P. Accessing a Biologically Relevant Benzofuran Skeleton by a One-Pot Tandem Heck Alkynylation/Cyclization Reaction Using Well-Defined Palladium N-Heterocyclic Carbene Complexes. *Inorg. Chem.* **2016**, *55*, 2882–2893. [CrossRef]
31. Yang, J.; Lu, J.-Z.; Wang, T.; Zhao, Y.-Y.; Zhu, G.-H. A series of (NHC)Pd(N^O)(OAc) complexes: Synthesis, characterization and catalytic activities towards desulfinative Sonogashira coupling of arylsulfonyl hydrazides with arylalkynes. *Appl. Organomet. Chem.* **2020**, *34*, e5558. [CrossRef]
32. Li, Y.-J.; Zhang, J.-L.; Li, X.-J.; Geng, Y.; Xu, X.-H.; Jin, Z. (IPr) Pd (pydc)(pydc= pyridine-2, 6-dicarboxylate)–A highly active precatalyst for the sterically hindered C–N coupling reactions. *J. Organomet. Chem.* **2013**, *737*, 12–20. [CrossRef]
33. Zhu, Y.; Yang, S.; Zhou, T.; Szostak, M. [(NHC)Pd$(OAc)_2$]: Highly Active Carboxylate Pd(II)–NHC (NHC = N-Heterocyclic Carbene) Precatalysts for Suzuki–Miyaura and Buchwald–Hartwig Cross-Coupling of Amides by N–C(O) Activation. *J. Org. Chem.* **2024**, accepted. [CrossRef]
34. Jensen, D.R.; Sigman, M.S. Palladium catalysts for aerobic oxidative kinetic resolution of secondary alcohols based on mechanistic insight. *Org. Lett.* **2003**, *5*, 63–65. [CrossRef] [PubMed]
35. Ostrowska, S.; Lorkowski, J.; Kubicki, M.; Pietraszuk, C. [{Pd(μ-OH)Cl(IPr)$\}_2$]—A Highly Efficient Precatalyst for Suzuki–Miyaura Coupling also Able To Act under Base-Free Conditions. *ChemCatChem* **2016**, *8*, 3580–3583. [CrossRef]
36. Ostrowska, S.; Rogalski, S.; Lorkowski, J.; Walkowiak, J.; Pietraszuk, C. Efficient homocoupling of aryl-and alkenylboronic acids in the presence of low loadings of [{Pd(μ–OH)Cl(IPr)$\}_2$]. *Synlett* **2018**, *29*, 1735–1740.
37. Ostrowska, S.; Szymaszek, N.; Pietraszuk, C. Selective dimerization of terminal acetylenes in the presence of PEPPSI precatalysts and relative chloro- and hydroxo-bridged *N*-heterocyclic carbene palladium dimers. *J. Organomet. Chem.* **2018**, *856*, 63–69. [CrossRef]
38. Ostrowska, S.; Rogalski, S.; Pietraszuk, C. Key Role of Water in Copper- and Base-free Sonogashira Coupling in Ethanol with [{Pd(μ-OH)Cl(IPr)$\}_2$] as a Highly Effective Precatalyst. *ChemCatChem* **2024**, *16*, e202400012. [CrossRef]
39. Frith, A.; Clarke, A.K.; Heyam, A.; Lynam, J.M.; Newman, P.D.; Unsworth, W.P.; Willans, C.E. Silver−N-Heterocyclic Cabenes in π−Activation: Synergistic Effects between the Ligand Ring Size and the Anion. *Organometallics* **2024**, *43*, 598–604. [CrossRef]
40. Viciu, M.S.; Navarro, O.; Germaneau, R.F.; Kelly III, R.A.; Sommer, W.; Marion, N.; Stevens, E.D.; Cavallo, L.; Nolan, S.P. Synthetic and Structural Studies of (NHC)Pd(allyl)Cl Complexes (NHC = *N*-heterocyclic carbene). *Organometallics* **2004**, *23*, 1629–1635. [CrossRef]
41. D'Alterio, M.C.; Casals-Cruañas, È.; Tzouras, N.V.; Talarico, G.; Nolan, S.P.; Poater, A. Mechanistic aspects of the palladium-catalyzed Suzuki-Miyaura cross-coupling reaction. *Chem. Eur. J.* **2021**, *27*, 13481–13493.
42. Drost, R.M.; Rosar, V.; Dalla Marta, S.; Lutz, M.; Demitri, N.; Milani, B.; de Bruin, B.; Elsevier, C.J. Pd-Catalyzed *Z*-Selective Semihydrogenation of Alkynes: Determining the Type of Active Species. *ChemCatChem* **2015**, *7*, 2095–2107. [CrossRef]
43. Zhang, J.; Xu, J.; Xu, Y.; Sun, H.; Shen, Q.; Zhang, Y. Mixed NHC/Phosphine Ni(II) Complexes: Synthesis and Their Applications as Versatile Catalysts for Selective Cross-Couplings of ArMgX with Aryl Chlorides, Fluorides, and Methyl Ethers. *Organometallics* **2015**, *34*, 5792–5800. [CrossRef]

44. Mayer, M.; Czaplik, W.M.; von Wangelin, A.J. Thieme Journal Awardees-Where Are They Now? On Cobalt-Catalyzed Biaryl Coupling Reactions. *Synlett* **2009**, *18*, 2919–2923.
45. Tsuchiya, N.; Nojiri, T.; Nishikata, T. Oxazaborolidinones: Steric Coverage Effect of Lewis Acidic Boron Center in Suzuki–Miyaura Coupling Reactions. *Chem. Eur. J.* **2024**, *30*, e202303271. [CrossRef] [PubMed]
46. Hu, Y.; Gao, Y.; Ye, J.; Ma, Z.; Juntao Feng, J.; Liu, X.; Lei, P.; Szostak, M. Suzuki−Miyaura Cross-Coupling of 2-Pyridyl Trimethylammonium Salts by N−C Activation Catalyzed by Air- and Moisture-Stable Pd−NHC Precatalysts: Application to the Discovery of Agrochemicals. *Org. Lett.* **2023**, *25*, 2975–2980. [CrossRef] [PubMed]
47. Cervantes-Reyes, A.; Smith, A.C.; Chinigo, G.M.; Blakemore, D.C.; Szostak, M. Decarbonylative Pd–Catalyzed Suzuki Cross-Coupling for the Synthesis of Structurally Diverse Heterobiaryls. *Org. Lett.* **2022**, *24*, 1678–1683. [CrossRef]
48. Zhang, G.; Yi, H.; Chen, H.; Bian, C.; Liu, C.; Lei, A. Trisulfur Radical Anion as the Key Intermediate for the Synthesis of Thiophene via the Interaction between Elemental Sulfur and NaO*t*-Bu. *Org. Lett.* **2014**, *16*, 6156–6159. [CrossRef]
49. Ke, H.; Chen, X.; Zou, G. N-heterocyclic carbene-assisted, bis (phosphine) nickel-catalyzed cross-couplings of diarylborinic acids with aryl chlorides, tosylates, and sulfamates. *J. Org. Chem.* **2014**, *79*, 7132–7140. [CrossRef] [PubMed]
50. Hong, Z.-S.; Kao, S.-C.; Cheng, Y.-T.; Chen, C.-J.; Wu, Y.-K. Photoinduced arylation of chloroarenes in flow: Synthesis of unsymmetrical biaryls. *Org. Biomol. Chem.* **2022**, *20*, 8212–8216. [CrossRef]
51. Sheldrick, G.M. SHELXT-Integrated Space-Group and Crystal-Structure Determination. *Acta Crystallogr.* **2015**, *A71*, 3–8. [CrossRef]
52. Sheldrick, G.M. Crystal Structure Refinement with SHELXL. *Acta Crystallogr.* **2015**, *C71*, 3–8.
53. Dolomanov, O.V.; Bourhis, L.J.; Gildea, R.J.; Howard, J.A.K.; Puschmann, H. OLEX2: A Complete Structure Solution, Refinement and Analysis Program. *J. Appl. Cryst.* **2009**, *42*, 339–341. [CrossRef]