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# Palladium Complexes with Phenoxy- and Amidate-Functionalized N-Heterocyclic Carbene Ligands Based on 3-Phenylimidazo[1,5-*a*]pyridine: Synthesis and Catalytic Application in Mizoroki–Heck Coupling Reactions with Ortho-Substituted Aryl Chlorides

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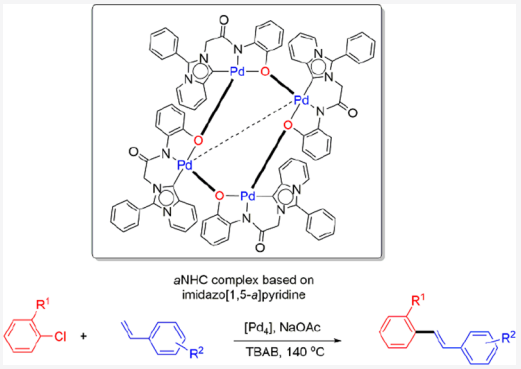
**ABSTRACT:** Mononuclear and tetranuclear palladium complexes with functionalized "abnormal" N-heterocyclic carbene (*a*NHC) ligands based on 3-phenylimidazo[1,5-*a*]pyridine were synthesized. All of the new complexes were structurally characterized by single-crystal X-ray diffraction studies. The new complexes were applied in the Mizoroki–Heck coupling reaction of aryl chlorides with alkenes in neat *n*-tetrabutylammonium bromide (TBAB). The mononuclear palladium complex with a tridentate phenoxy- and amidate-functionalized *a*NHC ligand displayed activity superior to that of the palladium complex with a bidentate amidate-functionalized *a*NHC ligand. The new tetranuclear complex with the tridentate ligand displayed the best activities, capable of the activation of deactivated aryl chlorides as substrates with a low Pd atom loading. Even challenging sterically demanding *ortho*-substituted aryl chlorides were successfully utilized as substrates. The studies revealed that the robustness of the catalyst precursor is crucial in delivering high catalytic activities. Also, the promising use of tetranuclear palladium complexes with functionalized *a*NHC ligands as the catalyst precursors in the Mizoroki–Heck coupling reaction in neat TBAB was demonstrated.




## INTRODUCTION

Currently, N-heterocyclic carbene (NHC) ligands are widely used in synthetic organic chemistry because of their distinctive catalytic properties.[1] Among the different NHC ligands, imidazole-based NHC ligands have been highly popular. Crabtree et al. had shown that imidazole-based NHCs can have an alternative binding mode via the C4/5 atom, instead of the commonly observed C2-bound counterpart.[2] These variants of NHC ligands, commonly termed "abnormal NHCs (*a*NHCs)",[3] feature less heteroatom stabilization of the carbenic carbon and have been shown to be more electron-rich than their normal NHCs (*n*NHCs)[4] and thus improved catalytic activities of their transition-metal complexes have been reported.[4b−d,5] As a matter of fact, imidazole-based *a*NHCs are a subclass of mesoionic carbenes that contain no resonance form having all-neutral formal charges. Mesoionic and related less heteroatom-stabilized NHC complexes are attracting much attention, and a range of heterocyclic compounds have been successfully utilized in the construction of mesoionic NHC ligands such as 1,2,3-triazolylidene, 4-imidazolylidene, pyrazolylidene, oxazolylidene, etc.[6]

We have been interested in benzannulated derivatives of imidazol-2-ylidenes (Figure S1 in the Supporting Information), and palladium complexes with *a*NHC ligands based on imidazo[1,2-*a*]pyridine were reported by us recently.[7] On the other hand, the isomeric imidazo[1,5-*a*]pyridine has been shown to be a versatile architecture for a stable N-heterocyclic carbene.[8] While a vast number of metal complexes with *n*NHCs based on imidazo[1,5-*a*]pyridine have been reported,[9] *a*NHC complexes based on the heterocyclic compound are rarer in the literature.[7b,8,10] In a previous work, we had shown that a tetranuclear palladium complex with an amidate- and phenoxy-functionalized imidazole-based *a*NHC ligand (**A**) was highly versatile in catalyzing the Mizoroki–Heck coupling reaction, capable of utilizing deactivated aryl chlorides as substrates (Figure 1).[11] In this work, we intend to prepare mononuclear and tetranuclear palladium complexes bearing mutidentate ligands with *a*NHC moieties based on imidazo-

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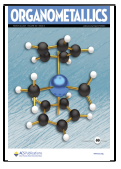







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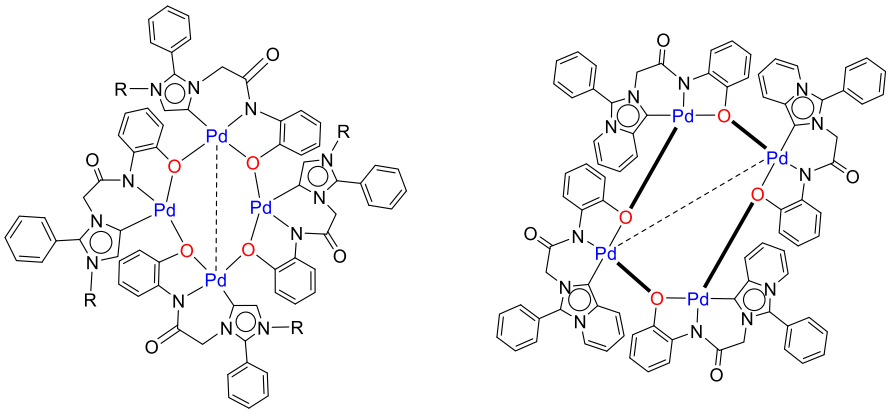


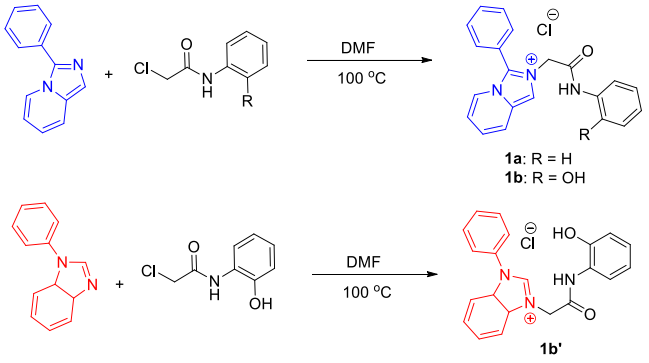

**Figure 1.** Tetranuclear palladium complexes bearing a functionalized *a*NHC derived from imidazole and imidazo[1,5-*a*]pyridine.

[1,5-*a*]pyridine and investigate their catalytic potentials in the Mizoroki–Heck coupling reaction. Their catalytic activities would be compared with those catalyzed by complex **A** and a similar palladium complex with a benzimidazole-based *n*NHC ligand. To our delight, the new tetranuclear palladium complex was also highly active in catalyzing the Mizoroki–Heck coupling reaction. Remarkably, even sterically hindered aryl chlorides were successfully applied as substrates.

## RESULTS AND DISCUSSION

**Preparation of Ligand Precursors.** The preparation of the ligand precursors is shown in Scheme 1. The abnormal

**Scheme 1. Synthesis of Ligand Precursors**




NHC ligand precursors **1a**,**b** were derived from 3-phenylimidazo[1,5-*a*]pyridine, whereas the normal NHC ligand precursor **1b′** was prepared from its isomeric analogue, 1-phenyl-1*H*-benzo[*d*]imidazole. The ionic products **1** were prepared readily by a quanternization reaction of the heterocyclic compound with *N*-aryl 2-chloroacetamide in DMF at 100 °C, producing the products in good yields (72–77%). The downfield signal at 10.94 ppm was assignable to the N*H* proton in **1a**. The singlet at 8.53 ppm was attributed to the proton on the imidazole ring. According to the HMBC spectrum of **1b**, the two downfield signals at 9.83 and 10.09 ppm are due to the N*H* and O*H* protons, respectively. The proton on the imidazole ring was observed at 8.50 ppm, which was similar to that observed for **1a**. In the $^{1}$H spectrum of NHC precursor **1b′**, three downfield signals were observed at ca. 10 ppm. According to the HMBC spectrum, the most downfield, relatively sharp signal at 10.34 ppm was attributable to the NC*H*N on the imidazole ring. This proton is significantly downfield in comparison with those in **1a**,**b** because the acidic proton is situated between two electron negative atoms, instead of only one in the cases of **1a**,**b**. The other two broad signals at 10.13 and 10.17 ppm were attributed to the N*H* and O*H* protons, respectively.

**Preparation of Palladium Complexes.** The preparation of new palladium carbene complexes is shown in Scheme 2. The reaction of ligand precursor **1a**, $Pd(OAc)_2$, and pyridine in the presence of NaOAc as a base in DMF at 50 °C produced pure palladium complex **2a** with a bidentate *a*NHC/amidate ligand in a good yield of 77%. The disappearance of the downfield N*H* proton signal suggested the successful coordination of the ligand around the palladium center. Interestingly, the use of the amidate-functionalized imidazo-[1,5-*a*]pyridine precursor **1a** led to the formation of the palladium *a*NHC complex **2a**, but a similar amidate-functionalized imidazo[1,2-*a*]pyridine precursor reacted with palladium(II) ion, resulting in the deprotonation of the methylene and N*H* protons and the formation of a palladalactam instead.[12]

Under reaction conditions similar to those for **2a**, ligand precursor **1b** reacted with $Pd(OAc)_2$ to produce the palladium *a*NHC complex **2b** with a tridentate CNO ligand scaffold in a similar yield of 80%. The disappearance of the two downfield O*H* and N*H* signals suggested the successful chelation of the tridentate ligand. Its isomeric palladium complex **2b′** with a normal NHC ligand was obtained in 74% yield from the ligand precursor **1b′** using pyridine as the solvent. Again, the disappearance of the three downfield signals due to N*H*, O*H*, and NC*H*N protons at ca. 10 ppm unequivocally proved the successful chelation of the tridentate ligand. Notably, the use of palladium acetate as the metal precursor was essential for the formation of pure compounds; the use of $PdCl_2$ instead gave a complex mixture with an appreciable amount of *trans*-$PdCl_2(py)_2$ as a side product.

It has been shown that when a lone pair donor, such as pyridine, is absent in the complexation reaction between a tridentate CNO ligand and palladium(II) ion, the phenoxyl oxygen can switch to a bridging coordination mode, delivering a lone pair to an adjacent palladium center and thus forming a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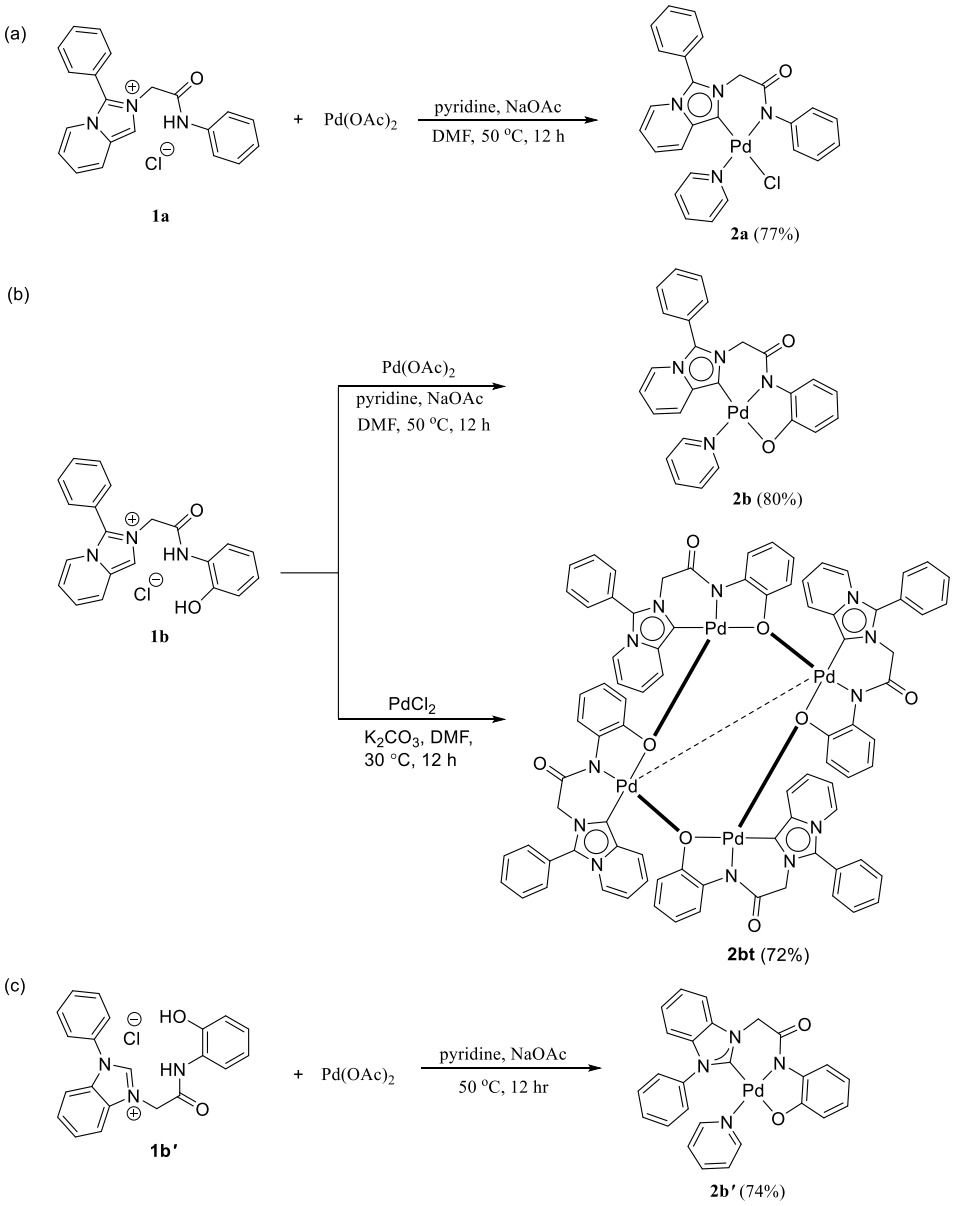
**Scheme 2. Synthesis of Palladium Complexes**




tetranuclear palladium complex.[11] In the preparation of **2b**, pyridine was added, which ligated around the palladium center. In the absence of pyridine, compound **1b** reacted with $PdCl_2$ in DMF, affording the tetranuclear palladium *a*NHC complex **2bt**, featuring a tridentate CNO ligand (see Scheme 2b).

Interestingly, the two hydrogen atoms on the methylene group in **2a**,**b** and **2b′** appeared as singlets at ca. 5.15 ppm, indicating that a fast flipping of the six-membered chelate ring occurred in solution such that the two methylene protons became equivalent. In sharp contrast, the structure of **2bt** is rigid in structure, as evidenced by the stereochemical nonequivalence of the two methylene protons, which led to two distinct doublets at 4.77 and 5.28 ppm with a geminal coupling constant of 21 Hz. The rigidity of **2bt** can be explained by the energetically unfavorable ring flipping in the closely spaced tridentate ligands in the tetranuclear complex (see Figure 5).

To unambiguously locate the carbenic carbon signals in the $^{13}C$ NMR spectra of the new complexes, their HMBC spectra were obtained. The coordinated carbon signals for the palladium *a*NHC complexes **2a**,**b** were observed at 126.9 and 131.8 ppm, whereas the corresponding signal for the palladium NHC signal in **2b′** was much more downfield at 169.4 ppm. The carbenic signal for the tetranuclear palladium *a*NHC complex was identified at 129.5 ppm, which was comparable to those in mononuclear complexes **2a**,**b**.

**Structural Analysis.** All of the new complexes have been successfully analyzed by single-crystal X-ray diffraction studies (Figures 2−5). The Pd atom in **2a** adopts an almost ideal square coordination geometry with the four bond angles around the palladium center close to the ideal 90° (87.5−92.6°). The $\tau_4$ and $\tau'_4$ parameters that describe the extent of distortion around a four-coordinate complex ($\tau$ = 0 for a perfect square-pyramidal geometry and $\tau$ = 1 for a perfect tetrahedral geometry)[13] are indeed very close to zero (0.02 and 0.01, respectively). The pyridyl nitrogen is *trans* to the carbenic carbon, and the amidate nitrogen is *trans* to the Cl atom. In contrast, the coordination environment around the Pd atoms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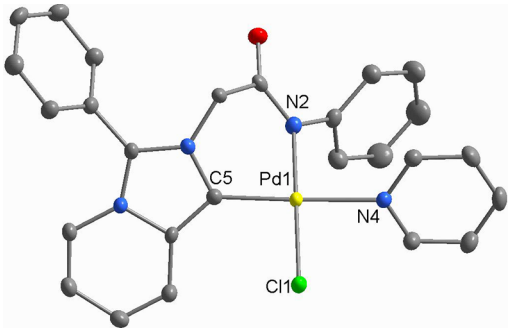


**Figure 2.** Molecular structure of **2a** with 50% probability ellipsoids. Hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (deg): Pd1−C5, 1.964(2); Pd1−Cl1, 2.3151(6); Pd1−N4, 2.1083(19); Pd1−N2, 2.027(2); C5−Pd1−N4, 178.09(9); N2−Pd1−Cl1, 179.57(6); C5−Pd1−Cl1, 92.57(7); Cl1−Pd1−N4, 89.18(6); N4−Pd1−N2, 90.79(8); N2−Pd1−C5, 87.47(9).

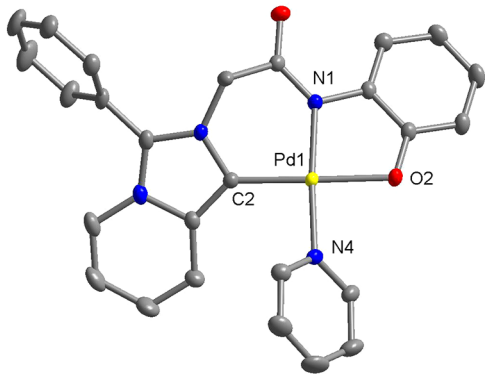


**Figure 3.** Molecular structure of **2b** with 50% probability ellipsoids. Hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (deg): Pd1−C2, 1.9637(15); Pd1−N4, 2.0399(13); Pd1−O2, 2.0443(11); Pd1−N1, 1.9983(13); C2−Pd1−O2, 170.57(5); N1−Pd1−N4, 174.77(5); C2−Pd1−N4, 92.23(6); N4−Pd1−O2, 92.44(5); O2−Pd1−N1, 83.61(5); N1−Pd1−C2, 92.18(6).

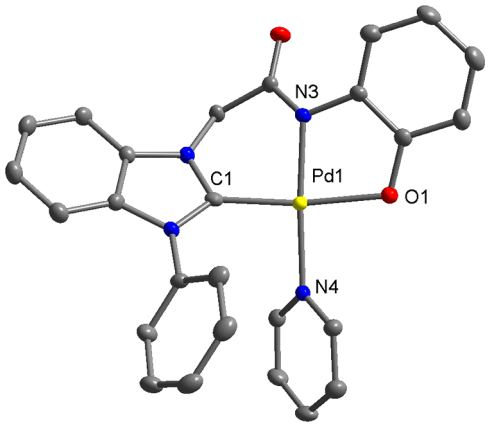


**Figure 4.** Molecular structure of **2b′** with 50% probability ellipsoids. Hydrogen atoms are omitted for clarity. Selected bond distances (Å) and angles (deg): Pd1−C1, 1.958(4); Pd1−N4, 2.043(3); Pd1−O1, 2.047(3); Pd1−N3, 1.994(3); C1−Pd1−O1, 168.17(13); N3−Pd1−N4, 174.24(13); C1−Pd1−N4, 94.35(14); N4−Pd1−O1, 93.82(12); O1−Pd1−N3, 83.23(12); N3−Pd1−C1, 89.33(14).

in the isomeric pair **2b**,**b′** are more distorted due to the five-membered chelate rings from the tridentate ligands, resulting in small N−Pd−O bite angles of 83.61(5) and 83.23(12)° in **2b**,**b′**, respectively. The $\tau_4$ and $\tau'_4$ parameters for **2b**,**b′** are larger. The values for **2b** are 0.10 and 0.09, respectively, whereas those for **2b′** are 0.12 and 0.11, respectively. Also due to the tridentate chelation of the ligand in **2b**,**b′**, the pyridine ligand is *trans* to the amidate nitrogen, instead of *trans* to the carbene moiety in **2a**. The Pd−C bonds in **2a**,**b** are almost identical (ca. 1.964 Å). However, both the Pd−N(amidate) and Pd−N(pyridine) bonds in **2a** (2.027(2) and 2.1083(19) Å, respectively) are longer than those in **2b** (1.9983(13) and 2.0399(13) Å, respectively). Despite the generally accepted higher electron-donating property of the *a*NHC moiety, the Pd−carbene bond of 1.9637(15) Å in the *a*NHC complex **2b** is marginally longer than that in its isomeric *n*NHC complex **2b′**, which has a bond length of 1.958(4) Å. The other bond distances around the Pd atoms are also similar in the two isomeric complexes.

Complex **2bt** is a tetranuclear palladium complex, as confirmed by the X-ray analysis. In the complex, each palladium center is chelated by a tridentate CNO ligand. The coordinating oxygen atom forms a $\mu$-bridge linking with an adjacent palladium center. The fourth coordination site is completed by another $\mu$-oxygen atom from another palladium center. The Pd atoms adopt a slightly distorted square planar coordination environment with $\tau_4$ and $\tau'_4$ parameters in the ranges of 0.07−0.11 and 0.06−0.10, respectively. The Pd−carbene bonds in the tetranuclear complex (1.951−1.964 Å) are comparable to those in the mononuclear complexes (1.958−1.964 Å). The Pd−C bonds in **2bt** are longer than those observed in the previously reported tetranuclear palladium *a*NHC complex **A** (ca. 1.932 Å).[11] Nevertheless, these Pd−carbene bonds from amidate-functionalized *a*NHC ligands are short in comparison with the average Pd−carbene bond distance of 1.99(3) Å in reported Pd−aNHC complexes.[3b] In the tetranuclear complex, the Pd1 and Pd2 atoms make a close contact with a nonbonding distance of 3.2122(18) Å, which is smaller than the sum of the van der Waals radii of Pd atoms (3.26 Å).[14] This nonbonding distance was, however, significantly longer than that in the reported tetranuclear complex **A** (3.1759(11) Å).[11] In contrast, the Pd(3) and Pd(4) do not interact with each other, with a longer noninteracting distance of 3.275 Å.

**Catalytic Reactions.** The catalytic activities of the new palladium complexes in Mizoroki−Heck coupling reaction in neat tetrabutylammonium bromide (TBAB) were investigated. The reaction between 4-chloroacetophenone and styrene was chosen as the benchmark reaction, and the reported reaction conditions were followed.[11] Initially, the new palladium complexes were screened (Table 1). Entries 1 and 2 showed that under the same monopalladium loading of 0.2 mol % (i.e., a catalyst loading of 0.05 mol % for **2bt** since it is composed of four Pd atoms), the tridentate complex **2b** delivered a quantitative yield of the coupled product, in comparison to the yield of 88% from the bidentate complex **2a**. The tetranuclear complex **2bt** also delivered a quantitative yield of coupled product. Notably, the mononuclear *n*NHC complex **2b′** delivered a much inferior yield of 46% (entry 4); the lower activity may be related to a poorer electron donating nature of *n*NHC in comparison with that of *a*NHC moieties such that the rate-determining C−Cl bond activation in **2b′** was much slower. The monopalladium loading was then reduced to 0.1 mol %, and under such conditions, the tetranuclear complex **2bt** still delivered an excellent yield of 96% (entry 6), while the mononuclear complex **2b** delivered a lower yield of 88% (entry


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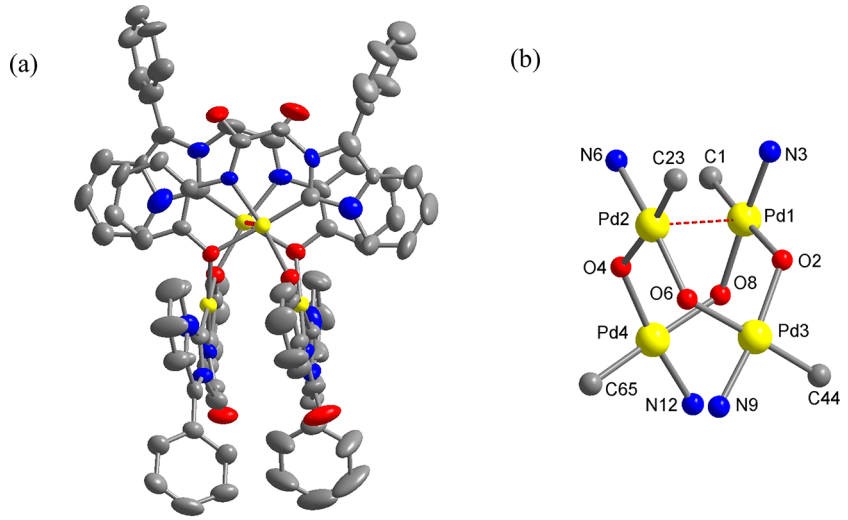
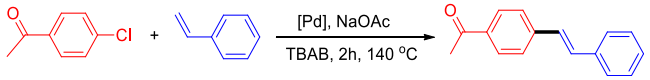



**Figure 5.** (a) Molecular structure of **2bt** with 50% probability ellipsoids. Hydrogen atoms are omitted for clarity. Pd1−C1, 1.951(19); Pd1−N3, 1.985(13); Pd1−O2, 2.041(11); Pd1−O8, 2.042(11); C1−Pd1−O2, 177.6(6); N3−Pd1−O8, 171.8(6); C1−Pd1−O8, 93.4(6); O8−Pd1−O2, 88.6(5); O2−Pd1−N3, 83.5(5); N3−Pd1−C1, 94.6(7); Pd2−C23, 1.958(19); Pd2−N6, 1.984(15); Pd2−O4, 2.054(12); Pd2−O6, 2.072(11); C23−Pd2−O4, 174.4(6); N6−Pd2−O6, 170.4(6); C23−Pd2−O6, 95.9(7); O6−Pd2−O4, 88.6(4); O4−Pd2−N6, 82.0(6); N6−Pd2−C23, 93.6(8); Pd3−C44, 1.956(17); Pd3−N9, 1.989(14); Pd3−O6, 2.053(11); Pd3−O2, 2.051(11); C44−Pd3−O6, 177.2(6); N9−Pd3−O2, 172.6(5); C44−Pd3−O2, 93.5(6); O2−Pd3−O6, 88.9(4); O6−Pd3−N9, 83.9(5); N9−Pd3−C44, 93.8(6); Pd4−C65, 1.964(19); Pd4−N12, 2.010(14); Pd4−O8, 2.069(12); Pd4−O4, 2.044(11); C65−Pd4−O8, 178.5(6); N12−Pd4−O4, 171.6(6); C65−Pd4−O4, 92.7(6); O4−Pd4−O8, 88.7(5); O8−Pd4−N12, 83.0(6); N12−Pd4−C65, 95.7(7); Pd(1)···Pd(2), 3.2122(18).

**Table 1. Screening of Catalysts and Conditions**[a]




| entry | complex | Pd atom (mol %) | temp (°C) | solvent | yield (%) |
|---|---|---|---|---|---|
| 1 | **2a** | 0.2 | 140 | TBAB | 88 (97:3) |
| 2 | **2b** | 0.2 | 140 | TBAB | >99 (96:4) |
| 3 | **2bt** | 0.2 | 140 | TBAB | >99 (95:5) |
| 4 | **2b′** | 0.2 | 140 | TBAB | 46 (98:2) |
| 5 | **2b** | 0.1 | 140 | TBAB | 88 (96:4) |
| 6 | **2bt** | 0.1 | 140 | TBAB | 96 (95:5) |
| 7 | $Pd(OAc)_2$ | 0.2 | 140 | TBAB | 76 (97:7) |
| 8 | $PdCl_2$(IMes)(3-Clpy) | 0.2 | 140 | TBAB | 26 (92:8) |
| 9 | **2bt** | 0.1 | 130 | TBAB | 7 |
| 10 | **2bt** | 0.2 | 140 | toluene | 0 |
| 11 | **2bt** | 0.2 | 140 | DMF | 0 |
| 12 | **2bt** | 0.2 | 140 | THF | 0 |
| 13 | **2bt** | 0.2 | 140 | 1,4-dioxane | 0 |
| 14 | **2bt** | 0.2 | 140 | TBAB | 72 (92:8)[b] |
| 15 | **2bt** | 0.2 | 140 | TBAB | >99 (93:7)[c] |

[a]Reaction conditions unless specified otherwise: 1.4 mmol of styrene, 1 mmol of aryl halide, 1.1 mmol of NaOAc, 2 g of TBAB, 0.1−0.2 mol % of monopalladium loading, 140 °C. NMR yield using 1,3,5-trimethoxybenzene as an internal standard. [b]1 mmol of styrene. [c]Preheating of the catalytic solution for 2 h prior to the addition of substrates.

5), reflecting the desirable use of multinuclear palladium complexes as catalyst precursors. Also, the yield afforded by **2bt** was superior to those by ligandless $Pd(OAc)_2$ and the broadly used, commercially available PEPPSI complex $PdCl_2$(IMes)(3-Clpy)[15] (entriy 3 vs entries 7 and 8).

After catalyst screening, the reaction conditions were further investigated. The optimal reaction temperature was at 140 °C; performing the reaction at a lower temperature led to a drastic reduction in the product yield (Table 1, entry 6 vs entry 9). Neat TBAB was proven to be the best solvent, as the catalytic reaction did not proceed at all in other organic solvents such as toluene, DMF, THF, and 1,4-dioxance (entries 10−13). The fact that the catalytic reaction only proceeds in TBAB, which is an ionic liquid and is a general stabilizer for a colloidal Pd system, strongly indicates the involvement of Pd nanoparticles in the catalytic pathway (*vide infra*). The use of ionic liquids as solvents in Pd-catalyzed cross-coupling reactions has been well-documented,[16] and most recently, tunable aryl alkyl ionic liquids containing different palladate counteranions have also been developed.[17] The use of a slight excess of styrene was essential to give a quantitative yield, as the use of 1 equiv


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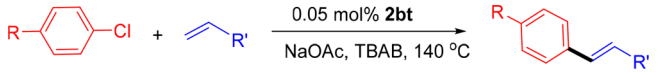
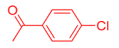
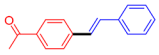
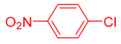
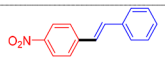
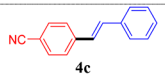
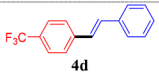
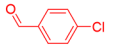
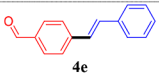
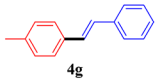
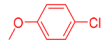
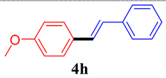
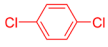
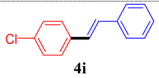
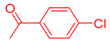
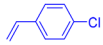
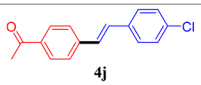
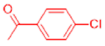
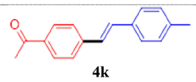
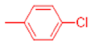
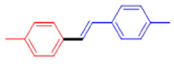
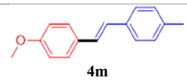
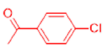
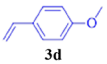
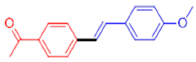
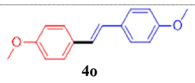
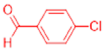
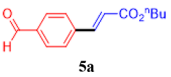
**Table 2. Mizoroki–Heck Coupling Reactions of Aryl Halides and Styrene Derivatives**[a]




| Entry | ArX | Alkene | Product | Time | Yield (%) |
|---|---|---|---|---|---|
| 1 |  |  3a |  4a | 2 | 99 |
| 2 |  | 3a |  4b | 2 | 99 |
| 3 |  | 3a |  4c | 2 | 99 |
| 4 |  | 3a |  4d | 6 | 99 |
| 5 |  | 3a |  4e | 6 | 87 |
| 6 |  | 3a |  4f | 12 | 91 |
| 7 |  | 3a |  4g | 12 | 52 |
| 8 |  | 3a |  4h | 12 | 64 |
| 9 |  | 3a |  4i | 12 | 72 |
| 10 |  |  3b |  4j | 2 | 90 |
| 11 |  |  3c |  4k | 6 | 96 |
| 12 |  | 3c |  4l | 12 | 56 |
| 13 |  | 3c | 4g | 12 | 70 |
| 14 |  | 3c |  4m | 12 | 60 |
| 15 |  |  3d |  4n | 12 | 99 |
| 16 |  | 3d | 4h | 12 | 32 |
| 17 |  | 3d | 4m | 12 | 45 |
| 18 |  | 3d |  4o | 12 | 22 |
| 19 |  | |  5a | 6 | 88 |

[a]Reaction conditions: 1.4 mmol of styrene, 1 mmol of aryl halide, 1.1 mmol of NaOAc, 2 g of TBAB, 0.05 mol % of **2bt** (i.e., 0.2 mol % Pd atom loading), 140 °C. Isolated yields are given.

afforded only a lower product yield of 72% instead (entry 3 vs entry 14).

After the identification of the best palladium complex and reaction conditions for the catalytic reaction, the substrate scope was then thoroughly investigated (Table 2). A range of styrene derivatives could be used as substrates for the reaction. Entries 1–4 showed that a wide range of electron-withdrawing aryl chlorides was able to couple effectively with styrene in 2–6 h, delivering quantitative yields of coupled products. However, a slightly lower product yield of 87% was obtained when the electron-poor 4- chlorobenzaldehyde was used (entry 5). Electron-neutral chlorobenzene reacted with styrene in 12 h to deliver a good product yield of 91% (entry 6). However, only mediocre yields were obtained when electron-donating 4-chlorotoluene and 4-chloroanisole were used as substrates (entries 7–8). When 1,4-dichlorobenzene was used, the monocoupled product, (*E*)-4-chlorostilbene, was obtained in 72% yield (entry 9). The catalyst system also allowed the use of various substituted styrenes as substrates (entries 10–18). 4-Methylstilbene (**4g**) was obtained from the reaction between 4-methylstyrene and chlorobenzene, in a yield of 70% (entry 13), which is higher than that of 52% from the reaction between 4-chlorotoluene and styrene (see entry 7). A quantitative yield was obtained in the reaction between 4-chloroacetophenone and 4-methoxystyrene (entry 15). In contrast, the product yields were reduced significantly when the activated aryl chloride was replaced by chlorobenzene, 4-chlorotoluene, or 4-chloroanisole (entries 16–18). Entry 16 showed that 4-methoxystilbene (**4h**) was obtained in a poor yield of 32% from the reaction between chlorobenzene and 4-methoxystyrene. This compound was best obtained from the reaction between 4-chloroanisole and styrene, which doubled the product yield (see entry 8). Similarly, to obtain 1-methoxy-4-[2-(4-methylphenyl)ethenyl] benzene (**4m**), the best synthetic route was via the coupling reaction between 4-chloroanisole and the less electron-releasing 4-methylstyrene, giving a product yield of 60% (entry 14), instead of using the highly electron releasing 4-methoxystyrene, which gave **4m** in an inferior 45% yield (entry 18). For *n*-butyl acrylate, a good yield of 88% was obtained with 4-chlorobenzaldehyde (entry 19).

Then we tested the applicability of the catalyst system in using sterically hindered substrates (Table 3). Electron-withdrawing groups at the *meta* positions were effectively utilized as substrates, delivering the coupled products with quantitative yields in 2 h (entries 1 and 2). An electron-donating group, however, reduced the product yield significantly (entry 3). Most importantly, the catalyst system based on the tetranuclear complex can tolerate a high degree of steric bulkiness in the substrates with *ortho* substitutions


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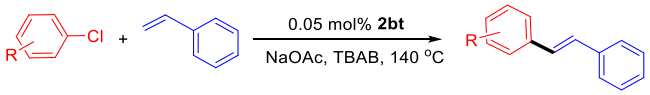
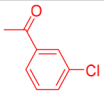
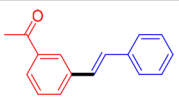
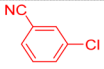
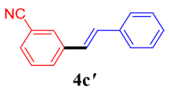
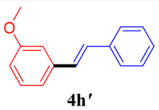
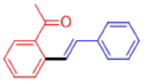
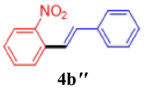
**Table 3. Mizoroki–Heck Coupling Reactions of Sterically Hindered Aryl Halides**[a]




| Entry | ArX | Product | Time | Yield (%) |
|---|---|---|---|---|
| 1 |  |  **4a′** | 2 | 99 |
| 2 |  |  **4c′** | 2 | 99 |
| 3 |  |  **4h′** | 12 | 55 |
| 4 |  |  **4a″** | 2 | 77 |
| 5 |  |  **4b″** | 2 | 84 |
| 6 |  |  **4c″** | 2 | 93 |
| 7 |  |  **4d″** | 6 | 89 |

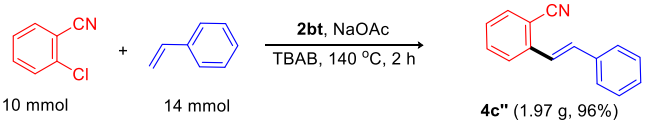
[a]Reaction conditions: 1.4 mmol of styrene, 1 mmol of aryl halide, 1.1 mmol of NaOAc, 2 g of TBAB, 0.05 mol % of **2bt** (i.e., 0.2 mol % Pd atom loading), 140 °C. Isolated yields are given.

(entries 4–7). In the literature, there has been only a single report describing the coupling reaction of 2-chloroacetopheone with styrene using a palladium/magnesium–lanthanum mixed oxide catalyst, giving 70% of the product in 20 h with a Pd loading of 1.5 mol %.[18] In our case, a good 77% yield of product was obtained in 2 h with a 0.2 mol % of Pd loading (entry 4). In the literature, various catalyst systems based on palladium nanoparticles and palladium complexes allowed the production of 1-nitro-2-[(*E*)-2- phenylethenyl]benzene (**4b″**) from 1-chloro-2-nitrobenzene and styrene with good yields using Pd loadings of 0.1–1.0 mol %.[19] However, a prolonged heating time of 20–24 h was needed in all of these cases. In sharp contrast, entry 5 shows that 1-chloro-2-nitrobenzene reacted smoothly with styrene to give **4b″** in a yield of 84% in just 2 h. 2-Chlorobenzonitrile also coupled effectively with styrene to give an excellent product yield of 93% in 2 h (entry 6). The product was prepared in a similar yield but using a 2.5 times higher Pd loading of (1,3-dimesitylimidazol-2-ylidene)-(benzoquinone)palladium(0) in TBAB with a reaction time of 24 h.[20] Finally, the aryl chloride with an *o*-trifluoromethyl group was also successfully applied as a substrate, affording a good 89% yield in 6 h (entry 7). The only reported catalyst system describing the same reaction was based on a palladium-supported zinc oxide nanoparticle, affording a yield of 95% in 15 h.[21]

Next, we compare the catalytic performance of **2bt** and the reported complex **A**.[11] In general, complex **A** showed a better catalytic activity with unhindered substrates. For example, the coupling reaction between styrene and the challenging deactivated substrate 4-chloroanisole **A** afforded a quantitative yield,[11] whereas **2bt** gave a yield of 64% under the same Pd atom loading and reaction conditions (see entry 8, Table 2). Also, in the reaction between 4-methystyrene and 4-chloroanisole, complex **A** produced a quantitative yield of product,[11] instead of the 60% obtained from **2bt** (see entry 14, Table 2). In contrast, **2bt** was much more reactive with sterically hindered substrates. As an example, under identical conditions, complex **2bt** afforded a good 93% yield of the coupled product with 2-chlorobenzonitrile (see Table 3, entry 6) in 2 h, whereas **A** gave a yield of 36% in 12 h. These differences in catalytic properties can be attributed to the differences in steric and electronic properties between the two tetranuclear complexes. Complex **A** featuresan imidazole-based *a*NHC moiety and a flanking group on the imidazole ring, whereas **2bt** contains an *a*NHC moiety based on imidazo[1,5-*a*]pyridine without a flanking group. From the structural data, complex **A** possesss shorter Pd–carbene bonds in comparison with those in **2bt**. Also, the nonbonding Pd···Pd distance in **A** is shorter than that in **2bt**. In solution, the overall robustness of **A** may lead to its better catalytic activities at high temperature in comparison to thos of **2bt**. In contrast, the lack of a flanking group rendered **2bt** less sterically congested and thus more favorable for sterically hindered substrates.

Finally, to demonstrate the practicality of complex **2bt** in synthetic organic chemistry, we carried out an upscaled reaction between sterically hindered 2-chlorobenzonitrile (10 mmol) and styrene (14 mmol). The reaction successfully afforded the coupled product **4c″** in an excellent yield of 1.97 g (96%) (Scheme 3).

**Scheme 3. Mizoroki–Heck Reaction of 2-Chlorobenzonitrile and Styrene on a Preparative Scale**




**Mechanistic Aspects.** It is worth noting that palladium nanoparticles (NPs) in TBAB have been successfully used in the Mizoroki–Heck coupling reaction with aryl chloride substrates.[22] For the catalytic systems based on **2bt** and **A**, in addition to homogeneous catalytic centers, the plausible involvement of heterogeneous species cannot be excluded.[23] In this regard, complex **2bt** may undergo a cleavage reaction under the catalytic conditions to generate ligand-disconnected Pd nanoparticles.[24] To understand the stability of **2bt**, a DMF solution of **2bt** was heated at 140 °C for 2 h. No distinct peaks appeared in the $^1$H NMR spectrum, showing that the compound was quite thermally robust. However, when the same solution was heated under the same conditions in the presence of NaOAc, 16% of **2bt** was converted to new species. Also, the solution became dark with the formation of palladium black being observed (Figure S2). This result reflects the possible formation of palladium nanoparticles under basic conditions. The fact that the catalytic reaction only occurred in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TBAB, which is a general stabilizer for palladium nanoparticles, is also consistent with such a claim (see Table 1). In fact, a mercury drop test[25] was performed on the benchmark reaction between 4-chloroacetophenone and styrene catalyzed by **2bt**. In the presence of a drop of Hg (ca. 50 mg), the product yield was markedly reduced from 99 to 11%, suggesting a predominantly heterogeneous pathway. To unambiguously confirm the presence of palladium nanoparticles, a TEM image from the benchmark catalytic solution was obtained after 2 h, indeed showing the presence of palladium nanoparticles with sizes of ca. 2−3 nm (Figure S3). Importantly, it should be noted that the catalytic systems based on **2bt** and **A** showed strong ligand effects, allowing the activation of aryl chlorides and even sterically hindered aryl chloride substrates (see Tables 2 and 3). In this regard, it is generally accepted that NHC-ligated active centers, which are molecular complexes, nanoclusters, or nanoparticles, should be involved.[24b] To confirm the involvement of ligand-connected species, a preliminary preheating experiment on the benchmark reaction was also conducted (Table 1, entry 15). The catalytic solution was preheated for 2 h prior to the addition of substrates, and such preheating should lead to a preliminary decomposition of precatalyst **2bt**, favoring the formation of palladium nanoparticles.[24a] Markedly, the same quantitative yield as that without preheating was obtained (Table 1, entries 15 vs 3). It should be noted that this product yield from the preheating experiment was higher than that given by ligandless $Pd(OAc)_2$, which was a precursor for ligandless palladium nanoparticles (Table 1, entry 15 vs entry 7). All of these results suggest the possible involvement of ligand-connected palladium nanoparticles in the catalytic pathway.[24b] In fact, the precursor complex **2bt** bears a strong chelating *a*NHC ligand which should be much more stable to decoordination in comparison to common monodentate NHC ligands. Also, **2bt** is a tetranuclear complex, and after its *in situ* reduction of Pd(II) to Pd(0), it should form ligated-NHC palladium nanoclusters or nanoparticles more readily in comparison to a mononuclear palladium complex. Notably, the more robust complex **A** may be a better precursor for a slow release of Pd NPs in comparison to complex **2bt**.

## CONCLUSIONS

We successfully prepared new mononuclear and tetranuclear palladium complexes with functionalized *a*NHC ligands based on 3-phenylimidazo[1,5-*a*]pyridine. Theses complexes were effective catalyst precursors in the Mizoroki−Heck coupling reaction of aryl chlorides with alkenes in TBAB. The palladium complex with a tridentate amidate- and phenoxy-functionalized *a*NHC ligand displayed an activity superior to that of the palladium complex with a bidentate amidate-functionalized *a*NHC ligand. The new tetranuclear complex with the tridentate ligand displayed the best activities, capable of the activation of deactivated aryl chlorides as substrates with a low Pd atom loading of 0.2 mol %. Most importantly, the new catalyst system developed also allowed the use of challenging sterically hindered aryl chlorides to couple effectively with styrene. The studies again demonstrated the promising use of tetranuclear palladium complexes with chelating *a*NHC ligands in Mizoroki−Heck coupling reactions conducted in an ionic liquid.

## EXPERIMENTAL SECTION

**General Information.** All manipulations were performed under a dry nitrogen atmosphere using standard Schlenk techniques. Solvents were dried with standard procedures. Starting chemicals were purchased from commercial sources and used as received. $^1H$ and $^{13}C\{^1H\}$ NMR spectra were recorded at 300.13 and 75.47 MHz, respectively, on a Bruker AV-300 spectrometer. Elemental analyses were performed on a Thermo Flash 2000 CHN-O elemental analyzer. ESI-MS was carried out on a Finnigan/Thermo Quest MAT 95XL mass spectrometer at National Chung Hsing University (Taiwan). TEM images were obtained from a Jeol JEM-2010 200 kV transmission electron microscope. 3-Phenylimidazo[1,5-*a*]pyridine[26] and 1-phenyl-1*H*-benzo[*d*]imidazole[7a] were prepared according to literature procedures.

**Synthesis of 2-(2-Oxo-2-(phenylamino)ethyl)-3-phenylimidazo[1,5-*a*]pyridin-2-ium Chloride (1a).** A mixture of 3-phenylimidazo[1,5-*a*]pyridine (1.00 g, 5.15 mmol) and 2-chloro-*N*-phenylacetamide (0.87 g, 5.15 mmol) was placed in a 50 mL Schlenk flask. DMF (20 mL) was added via a syringe. The mixture was stirred at 100 °C for 72 h under nitrogen. The solvent was then removed under vacuum. The residue was washed with THF and diethyl ether several times. The gray solid was then collected on a frit and dried under vacuum. Yield: 1.36 g, 72%. Mp: 213.2−213.8 °C. $^1H$ NMR (DMSO-$d_6$): $\delta$ 5.40 (s, 2H, $CH_2$), 7.06−7.16 (m, 2H, Ar *H*), 7.29−7.31 (m, 3H, Ar *H*), 7.50 (d $^3J_{HH}$ = 6.0 Hz, 2H, Ar *H*), 7.73 (br s, 5H, Ar *H*), 7.99 (d, $^3J_{HH}$ = 9.0 Hz, 1H, Ar *H*), 8.10 (d, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 8.53 (s, 1H, imi *H*), 10.94 (s, 1H, N*H*). $^{13}C\{^1H\}$ NMR (DMSO-$d_6$): $\delta$ 52.5 ($CH_2$), 116.5, 119.3, 119.4, 120.2, 121.1 (quaternary *C*), 123.2, 124.9, 125.8, 129.5 (quaternary *C*), 129.7, 130.8, 131.5, 133.5, 135.4 (quaternary *C*), 138.7 (quaternary *C*), 163.4 (*C*═O). HRMS (ESI): *m*/*z* calcd for $C_{21}H_{18}N_3O$ $[M - Cl]^+$ 328.1444, found 328.1440.

**Synthesis of 2-(2-((2-Hydroxyphenyl)amino)-2-oxoethyl)-3-phenylimidazo[1,5-*a*]pyridin-2-ium Chloride (1b).** The compound was prepared following a procedure similar to that for **1a**. 2-Chloro-*N*-(2-hydroxyphenyl)acetamide (0.96 g, 5.15 mmol) was used. A gray solid was obtained. Yield: 1.46 g, 77%. Mp: 201.1−201.3 °C. $^1H$ NMR (DMSO-$d_6$): $\delta$ 5.42 (s, 2H, $CH_2$), 6.73 (t, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 6.89−6.97 (m, 2H, Ar *H*), 7.16 (t, $^3J_{HH}$ = 9.0 Hz, 1H, Ar *H*), 7.35 (t, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 7.70−7.77 (m, 6H, Ar *H*), 8.02 (d, $^3J_{HH}$ = 9.0 Hz, 1H, Ar *H*), 8.13 (d, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 8.50 (s, 1H, imi *H*), 9.83 (s, 1H, N*H*), 10.09 (s, 1H, O*H*). $^{13}C\{^1H\}$ NMR (DMSO-$d_6$): $\delta$ 52.3 ($CH_2$), 116.0, 116.4, 118.9, 119.2, 119.3, 121.0 (quaternary *C*), 122.8, 123.0, 125.5, 125.6 (quaternary *C*), 125.7, 129.2, 130.5, 131.4, 133.2, 135.1 (quaternary *C*), 148.8 (quaternary *C*), 164.0 (*C*═O). HRMS (ESI): *m*/*z* calcd for $C_{21}H_{18}N_3O_2$ $[M - Cl]^+$ 344.1394, found 344.1390.

**Synthesis of 3-(2-((2-Hydroxyphenyl)amino)-2-oxoethyl)-1-phenyl-1*H*-benzo[*d*]imidazol-3-ium (1b′).** The compound was prepared following a procedure similar to that for **1a**. 2-Chloro-*N*-(2-hydroxyphenyl)acetamide (0.96 g, 5.15 mmol) was used. A pale orange solid was obtained. Yield: 1.46 g,75%. Mp: 217.6−217.9 °C. $^1H$ NMR (DMSO-$d_6$): $\delta$ 5.37 (s, 2H, $CH_2$), 6.72−6.78 (m, 1H, Ar *H*), 6.97 (d, $^3J_{HH}$ = 3.0 Hz, 2H, Ar *H*), 7.71−7.81 (m, 5H, Ar *H*), 7.84−7.90 (m, 4H, Ar *H*), 8.17 (d, $^3J_{HH}$ = 9.0 Hz, 1H, Ar *H*), 10.13 (s,1H, N*H*), 10.17 (s, 1H, O*H*), 10.34 (s, 1H, NC*H*N). $^{13}C\{^1H\}$ NMR (DMSO-$d_6$): $\delta$ 50.1 ($CH_2$), 114.1, 114.9, 116.1, 119.4, 122.6, 125.7, 125.7, 126.0 (quaternary *C*), 127.8, 128.1, 131.1, 131.2, 132.4 (quaternary *C*), 133.6 (quaternary *C*), 144.3, 148.7 (quaternary *C*), 163.9 (*C*═O). HRMS (ESI): *m*/*z* calcd for $C_{21}H_{18}N_3O_2$ $[M - Cl]^+$ 344.1394, found 344.1395.

**Synthesis of Palladium Complex 2a.** In a 20 mL Schlenk tube were placed **1a** (0.1 g, 0.27 mmol), $Pd(OAc)_2$, (0.062 g, 0.27 mmol), and NaOAc (0.045 g, 0.54 mmol). Pyridine (22.14 $\mu$L, 0.27 mmol) and DMF (8 mL) were then added via a syringe. The mixture was then heated at 50 °C for 12 h. After the mixture was cooled, the solvent was removed completely under vacuum. Dichloromethane and water were added. The product was extracted into the organic phase, which was separated and dried with anhydrous $MgSO_4$. The


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solvent was removed under vacuum. The yellow solid that formed was washed thoroughly with diethyl ether, filtered, and dried under vacuum. Yield: 77%. Mp: 198.2−198.6 °C. $^1$H NMR ($CDCl_3$): $\delta$ 5.17 (s, 2H, $CH_2$), 6.71−6.79 (m, 2H, Ar *H*), 6.82−6.88 (m, 1H, Ar *H*), 6.94 (t, $^3J_{HH}$ = 9.0 Hz, 2H, Ar *H*), 7.06 (t, $^3J_{HH}$ = 9.0 Hz, 2H, Ar *H*), 7.41 (d, $^3J_{HH}$ = 9.0 Hz, 2H, Ar *H*), 7.49−7.53 (m, 3H, Ar *H*, Py *H*), 7.61−7.65 (m, 3H, Ar *H*, Py *H*), 7.74 (d, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 8.48 (d, $^3J_{HH}$ = 9.0 Hz, 1H, Ar *H*), 8.54 (d, $^3J_{HH}$ = 6.0 Hz, 2H, Py *H*). $^{13}$C{$^1$H} NMR (DMSO-$d_6$): $\delta$ 57.8 ($CH_2$), 118.1, 119.2, 120.3, 112.5, 123.2, 124.2, 125.0, 126.0, 126.7, 126.9 (Pd−*C*), 127.5, 130.2, 130.3, 131.7, 132.0, 132.5, 137.2, 150.7, 167.1 (*C*═O). Anal. Calc. for $C_{26}H_{21}ON_4ClPd$: C, 57.05; H, 3.87; N, 10.24; found: C, 57.22; H, 4.25; N, 10.30%. Crystals suitable for single-crystal X-ray analyses were obtained by vapor diffusion of diethyl ether into a solution of **2bt** in dichloromethane.

**Synthesis of Palladium Complex 2b.** The complex was prepared following a procedure similar to that for **2a**. Compound **1b** (0.1 g, 0.26 mmol), $Pd(OAc)_2$ (0.059 g, 0.26 mmol), and NaOAc (0.065 g, 0.78 mmol) were used. A pale yellow solid was obtained. Yield: 0.11 g, 80%. Mp: 202.6−202.9 °C. $^1$H NMR ($CDCl_3$): $\delta$ 5.11 (s, 2H, $CH_2$), 6.17 (d, $^3J_{HH}$ = 9.0 Hz, 1H, Ar *H*), 6.41−6.46 (m, 2H, Ar *H*), 6.63 (t, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 6.72−6.79 (m, 2H, Ar *H*), 7.44 (t, $^3J_{HH}$ = 6.0 Hz, 2H, Ar *H*), 7.50−7.54 (m, 2H, Ar *H*), 7.65−7.72 (m, 4H, Py *H*, Ar *H*), 7.90 (t, $^3J_{HH}$ = 9.0 Hz, 1H, Py *H*), 7.99 (d, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 8.94 (d, $^3J_{HH}$ = 6.0 Hz, 2H, Py *H*). $^{13}$C{$^1$H} NMR ($CDCl_3$): $\delta$ 57.5 ($CH_2$), 114.1, 116.0, 117.6, 119.1, 120.9, 122.0, 122.5, 123.3, 123.7, 125.6, 128.7, 129.9, 130.2, 130.3, 131.8 (Pd−*C*), 132.0, 138.3, 141.8, 153.0, 163.6 (*C*═O), 164.0 (*C*−O). Anal. Calcd for $C_{26}H_{20}O_2N_4Pd$: C, 59.27; H, 3.83; N, 10.63. Found: C, 59.44; H, 3.93; N, 10.26. Crystals suitable for single-crystal X-ray analyses were obtained by slow evaporation of a solution of **2b** in chloroform.

**Synthesis of Tetranuclear Palladium Complex 2bt.** In a 20 mL Schlenk tube were placed **1b** (0.1 g, 0.26 mmol), $PdCl_2$ (0.047 g, 0.26 mmol), and $K_2CO_3$ (0.15 g, 1.04 mmol). DMF (8 mL) was added via a syringe. The mixture was then heated at 30 °C for 12 h. After the mixture was cooled, the solvent was removed completely under vacuum. Dichloromethane and water were added. The product was extracted into the organic phase, which was separated and dried with anhydrous $MgSO_4$. The solvent was removed under vacuum. The yellow solid that formed was washed thoroughly with methanol and diethyl ether, filtered, and dried under vacuum. Yield: 72%. Mp: 280.1−280.6 °C. $^1$H NMR ($CDCl_3$): $\delta$ 4.77 (d, $^2J_{HH}$ = 21.0 Hz, 4H, $CH_aH_b$), 5.28 (d, $^2J_{HH}$ = 21.0 Hz, 4H, $CH_aH_b$), 5.94−6.03 (m, 8H, Ar *H*), 6.33−6.38 (m, 4H, Ar *H*), 6.49 (t, $^3J_{HH}$ = 6.0 Hz, 4H, Ar *H*), 7.31 (d, $^3J_{HH}$ = 9.0 Hz, 4H, Ar *H*), 7.52−7.63 (m, 12H, Ar *H*), 7.73 (d, $^3J_{HH}$ = 9.0 Hz, 8H, Ar *H*), 7.81 (d, $^3J_{HH}$ = 9.0 Hz, 4H, Ar *H*), 7.99−8.01 (m, 4H, Ar *H*), 8.54 (d, $^3J_{HH}$ = 9.0 Hz, 4H, Ar *H*). $^{13}$C{$^1$H} NMR ($CDCl_3$): $\delta$ 56.5 ($CH_2$), 115.4, 117.5, 118.0, 119.3, 120.8, 121.4, 122.6, 122.7, 123.8, 125.9, 129.5 (Pd−*C*), 129.6, 130.7, 131.3, 131.5, 142.0, 159.0 (*C*−O), 165.1 (*C*═O). Anal. Calcf for $C_{84}H_{60}O_8N_{12}Pd_4$: C, 56.32; H, 3.37; N, 9.38. Found: C, 56.17; H, 3.79; N, 9.14. Crystals suitable for single-crystal X-ray analyses were obtained by slow evaporation of a solution of **2b′** in acetone/toluene.

**Synthesis of Palladium Complex 2b′.** In a 20 mL Schlenk tube were placed **1b′** (0.1 g, 0.26 mmol), $Pd(OAc)_2$, (0.059 g, 0.26 mmol), and NaOAc (0.065 g, 0.78 mmol). Pyridine (8 mL) was added via a syringe. The mixture was then heated at 50 °C for 12 h. After the mixture was cooled, the solvent was removed completely under vacuum. Dichloromethane and water were added. The product was extracted into the organic phase, which was separated and dried with anhydrous $MgSO_4$. The solvent was removed under vacuum. The pale yellow solid that formed was washed thoroughly with diethyl ether, filtered, and dried under vacuum. Yield: 74%. Mp: 196.1−196.4 °C. $^1$H NMR ($CDCl_3$): $\delta$ 5.20 (s, 2H, $CH_2$), 6.52 (t, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 6.65 (d, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 6.76 (t, $^3J_{HH}$ = 6.0 Hz, 1H, Ar *H*), 6.99 (t, $^3J_{HH}$ = 6.0 Hz, 2H, Ar *H*), 7.12 (d, $^3J_{HH}$ = 9.0 Hz, 1H, Ar *H*), 7.19−7.21 (m, 3H, Ar *H*), 7.28 (t, $^3J_{HH}$ = 9.0 Hz, Ar *H*), 7.35−7.45 (m, 3H, Ar *H*, Py *H*), 7.50−7.59 (m, 2H, Ar *H*, Py *H*), 8.05 (d, $^3J_{HH}$ = 9.0 Hz, 1H, Ar *H*), 8.31 (d, $^3J_{HH}$ = 9.0 Hz, 2H, Py *H*). $^{13}$C{$^1$H} NMR ($CDCl_3$): $\delta$ 53.4 ($CH_2$), 111.1, 111.4, 114.7, 115.7, 123.7, 123.9, 124.4, 124.9, 127.3 (Py *C*), 129.1, 129.3 (quaternary *C*), 129.6, 133.1 (quaternary *C*), 134.7, 136.3 (quaternary *C*), 137.6 (Py *C*), 141.7 (quaternary *C*), 152.1(Py *C*), 163.6 (*C*═O or *C*−O), 163.7 (*C*═O or *C*−O), 169.4 (Pd−*C*). Anal. Calcd for $C_{26}H_{20}O_2N_4Pd$: C, 59.27; H, 3.83; N, 10.63. Found: C, 59.37; H, 4.01; N, 10.71. Crystals suitable for single-crystal X-ray analyses were obtained by slow evaporation of a solution of **2b′** in acetone/hexane.

**General Procedure for Mizoroki−Heck Reactions.** In a typical reaction, a mixture of aryl halide (1 mmol), styrene (1.4 mmol), base (1.1 equiv), palladium catalyst (0.1−0.2 mol %), and TBAB (2 g) was stirred at 140 °C for an appropriate period of time (2−12 h). After the reaction mixture was cooled, the product was extracted with ethyl ether (3 × 10 mL) and the organic layer was dried with anhydrous $MgSO_4$. The solvent was removed completely under high vacuum. The NMR yield was determined by using 1,3,5-trimethoxybenzene as an internal standard. The crude product was purified by column chromatography.

**Single-Crystal X-ray Diffraction.** Samples of **2b** and **2b′** were collected on a Bruker D8 VENTURE instrument equipped with a PHOTON 100 CMOS detector. Samples of **2a** and **2bt** were collected on a Bruker SMART APEX II instrument equipped with a CCD area detector. Data collections were performed at 150(2) K utilizing Mo K$\alpha$ radiation ($\lambda$ = 0.71073 Å). The unit cell parameters were obtained by least-squares refinement. Data collection and reduction were performed using the Bruker APEX and SAINT software.[27] Absorption corrections were performed using the SADABS program.[28] All of the structures were solved by direct methods and refined by full-matrix least-squares methods against $F^2$ with the SHELXL software package.[29] All non-H atoms were refined anisotropically. All H atoms were fixed at calculated positions and refined with the use of a riding model. The structure of complex **2bt** contains a large solvent-accessible volume that was occupied by toluene molecules. The total accessible volume was calculated to be 3183 Å$^3$ (34% of the cell volume). In the asymmetric unit, 3.5 molecules of toluene were successfully modeled and these molecules occupied a total volume of 2713 Å$^3$, leaving a void space of 470 Å$^3$. Each toluene molecule occupied about 2713/(3.5 × *Z*) = 193 Å$^3$ (*Z* = 4). Thus, the void space contained about 470/193 ≈ 2 strongly disordered toluene molecules (i.e., half of a molecule in the asymmetric unit), which were not modeled successfully. Also, a twin matrix was applied in the refinement of **2bt**. CCDC files 2015837 (**2a**), 2015846 (**2b**), 2023606 (**2bt**), and 2015845 (**2b′**) contain supplementary crystallographic data for this paper.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.organomet.0c00791.

Additional drawings, crystallographic data, $^1$H NMR assignment of coupled products, NMR spectra of ligand precursors, palladium complexes, and coupled products, and ESI-MS spectra of ligand precursors (PDF)

### Accession Codes

CCDC 2015837, 2015845−2015846, and 2023606 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.


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### Author Contributions

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### Notes

The authors declare no competing financial interest.

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